5G-enhanced Teleoperation in Real-Life Port Environments: Lessons Learned from the 5G-Blueprint Project

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***Abstract*—The challenge of ensuring safety in autonomous driving or sailing involves predicting and replicating various potential scenarios on roads and waterways, posing difficulties and high costs. In response, the European project 5G-Blueprint addresses this by introducing a complementary technology, i.e., teleoperation, which leverages 5G connectivity to enable human interventions in complex situations beyond autonomous capabilities, thereby removing the physical link between the human operator and the remotely controlled vehicle/vessel. This operational mode brings stringent connectivity requirements, including high uplink bandwidth for transmitting video streams from onboard cameras to the teleoperation center, low latency, and an ultra-reliable connection for relaying commands from the teleoperator to the remote vehicle/vessel. Additionally, it emphasizes minimal interruption time when the teleoperated vehicle/vessel crosses international borders, ensuring seamless connectivity and uninterrupted remote operation. Therefore, this paper summarizes extensive evaluations of network and service performance, highlighting key results across pilot locations and providing conclusions and analysis of 5G-enhanced teleoperation in various use cases. Additionally, it outlines lessons learned from pilot activities.**

***Index Terms*—5G, teleoperation, automation, transport & logistics, 5G-Blueprint**

I. Introduction

Close to thirty years ago, researchers from Carnegie Mellon University's Robotics Institute embarked on an experiment spanning the United States using an autonomous minivan [1]. The results of this experiment revealed that while achieving autonomous mode for 98.2% of the trajectory, the remaining almost 2% still required human intervention due to unpredictable and challenging road situations. This outcome holds significant implications for the automotive industry, emphasizing the critical importance of ensuring safety in all potential edge-case scenarios [2]. Such edge cases encompass uncommon operating circumstances in traffic situations, which are typically intricate or costly to replicate and train in real-world settings. To address this challenge, the 5G-Blueprint project adopted an alternative strategy, i.e., teleoperation as a complementary technology to handle these edge cases in conjunction with autonomous driving/sailing modes even when crossing the country borders (see Fig. 1). In teleoperation, either a portion or the entirety of driving/sailing tasks is carried out by a remote operator, typically facilitated through reliable wireless communication [2].

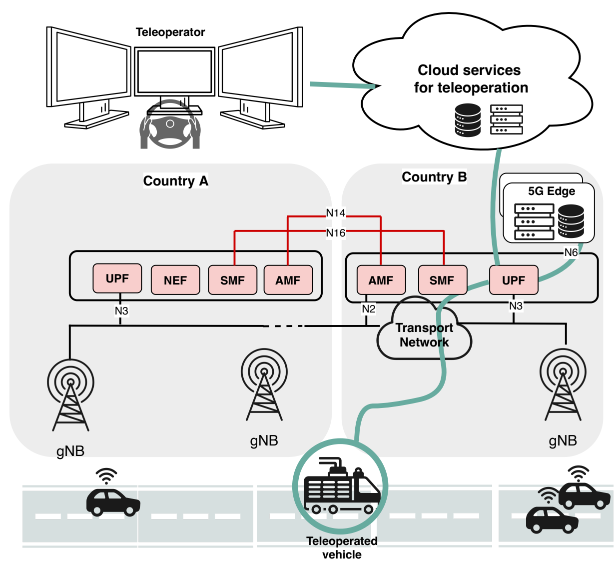

Fig. 1: The system overview of the 5G-enhanced teleoperation across the country borders.

Adopting such a complementary approach of automation and teleoperation was not possible earlier due to the stringent network connectivity requirements. The required network quality, such as sufficient bandwidth for uploading multiple parallel High-Definition (HD) video streams from the vehicle or barge to the operator station (at least 30Mbps, or 5Mbps per camera/sensor with six cameras in total), and ultra-low latency for remote control commands (less than 35ms round trip time, or end-to-end latency) [3], was not feasible with the previous generations of mobile communication systems. On top of that, extremely challenging cross-border conditions, which are applicable in the case of international transport & logistics, are posing additional requirements as the User Equipment (UE) connectivity should seamlessly roam between network operators, enabling a total interruption time of less than 150ms [3,4].

Therefore, the main objective of the 5G-Blueprint project is to design and validate technical architecture and business and governance models for uninterrupted cross-border teleoperated transport based on 5G connectivity [5]. The 5G-Blueprint is leveraging 5G Non-Standalone (NSA) and Standalone (SA) network deployments to validate safe and efficient teleoperation technology. This is possible due to the inherent characteristics of 5G, which is designed not as a horizontal infrastructure that supports all applications with the same type of performance, but with sufficient flexibility to tailor network deployments to specific verticals by applying concepts of network slicing [6]. In this paper, we present the technical aspects of the 5G-Blueprint objective, in particular, the design of the final technical architecture that combines all the actors and interactions between them that are essential for achieving seamless teleoperation across country borders. To test and validate 5G capabilities that could be leveraged large scale in future deployments, we developed use cases such as Automated barge control (UC1), Autodocking of trucks and skid steer teleoperation (UC2), and Teleoperation-based platooning (UC3 & UC4). Thus, this paper reflects on the validation aspects, i.e., providing the presentation and analysis of pilot activities and obtained results from the network and use case performance campaigns, along with the lessons learned.

II. The architecture of 5G system tailored to teleoperation use cases

In this Section, we present the final overview of the overarching 5G-Blueprint architecture, which combines the pieces of a 5G SA network with seamless roaming mechanisms, and service/application components. Thus, the architecture presented in this paper captures the blueprint of components that are altogether necessary for achieving safe and efficient remote operation within and across country borders.

In general, 5G SA network architecture represents the evolved version of 5G deployment, and due to being almost entirely service-based, it boosts network scalability and flexibility by allowing different network components to evolve and scale independently. Therefore, such flexible design enables a more robust and efficient network, tailored to vertical industries such as automotive and transport & logistics, i.e., for use cases such as 5G-based teleoperation in our case. The architecture presented in Fig. 2 captures the high-level configuration on the radio and core network sides, especially including specific core functions that need to interact with each other to enable seamless cross-border roaming with negligible interruption time (less than 150ms). In addition, this architecture also includes the final deployment aspects related to the use case components placed at the edge or at the cloud computing units.

On the UE side, the full-scale cars, trucks, barges, and skid steers, have been used for piloting activities in the final phase of the project, and as such, they are all equipped with 5G capabilities to obtain 5G SA signal on 3.5GHz in all three pilot sites. Depending on the use case, as well as the piloting scenario, additional equipment has been connected with the 5G network, such as intelligent Traffic Light Controllers (iTLC), handsets of Vulnerable Road Users (VRUs), and lidars installed on top of the testing vehicles for real-time object detection, which are also considered as 5G UEs. The next in the end-to-end 5G chain is the Radio Access Network (RAN), which consists of advanced base stations (gNodeBs) anchored on 3.5GHz, operating independently from 4G while providing enhanced coverage, higher data rates, and lower latency. Finally, 5G Core is the most evolved segment of the overall 5G SA network, as it is entirely based on a service-based architecture enabling more flexibility and scalability. This means that network functions for authentication, access, session and mobility management, slice management, etc., are deployed as virtual machines or containers on commodity infrastructure while communicating with each other via RESTful Application Programmable Interfaces (APIs).

The 5G SA architecture embodies the principles of *control* and *data* plane separation. Therefore, in Fig. 2, data traffic is marked with solid red lines, while dashed ones represent 5G control traffic. The control traffic is being exchanged between UEs, gNodeBs, and 5G Core network functions, during the registration and authentication process, as well as during the establishment of UE sessions. For example, when a Teleoperated Vehicle (ToV) is connecting to the network to transfer video data and receive steering commands from the control center, the Access and Mobility Management Function (AMF) interacts with Authentication Server Function (AUSF), which is checking UE credentials and finalizes the authentication process. Upon successful authentication, AMF consults the Unified Data Management (UDM) to retrieve important data about UE, and afterward proceeds with interaction with Session Management Function (SMF) to establish UE session and enable data path.

In case a ToV is crossing the border between two countries, i.e., Belgium and the Netherlands in 5G-Blueprint, peering 5G Core instances are interacting between two 5G Cores to transfer UE state and maintain its session to minimize the interruption time. The seamless roaming process is in detail described in [7], but here we briefly recap the essential procedures for minimizing interruption time when UE crosses the border. The 5G-Blueprint roaming solution combines the home-routed roaming (based on interfaces between SMFs and User Plane Functions (UPFs), i.e., N16 and N9, respectively) and the N2 handover over the N14 interface. In Fig. 2, once the ToV that is connected to Home Public Land Mobile Network (HPLMN) moves towards Visited Public Land Mobile Network (VPLMN), the radio network of the HPLMN detects the need for handover (e.g., based on the signal strength) and informs the AMF in HPLMN about that. Afterward, this AMF instance communicates via N14 with its peering instance in VPLMN that the handover is about to start. The AMF on the VPLMN side is using N16 to establish a new N9 tunnel between UPFs, which are routing the UE traffic after the handover procedure. The novelty of the 5G-Blueprint procedure reflects a more efficient exchange of messages between peering core functions, which in turn minimizes the overall interruption time (from a few minutes in 5G NSA to less than 150ms). In particular, to restore the connectivity of ToV faster, additional information on the UE context is being exchanged between AMFs in the first step (before the handover starts) so that the peering SMFs do not need to exchange data during the handover phase. Therefore, after ToV is connected to a new cell in the visiting network, the uplink traffic is established again.

Let us now focus on the data traffic. For the remotely operated UEs (cars, trucks, skid steers, and vessels), Central Control Unit (CCU) is necessary for translating and executing the commands sent from the remote driver or captain via 5G network (downlink), and for transferring HD video data towards teleoperation services running on the cloud (uplink).

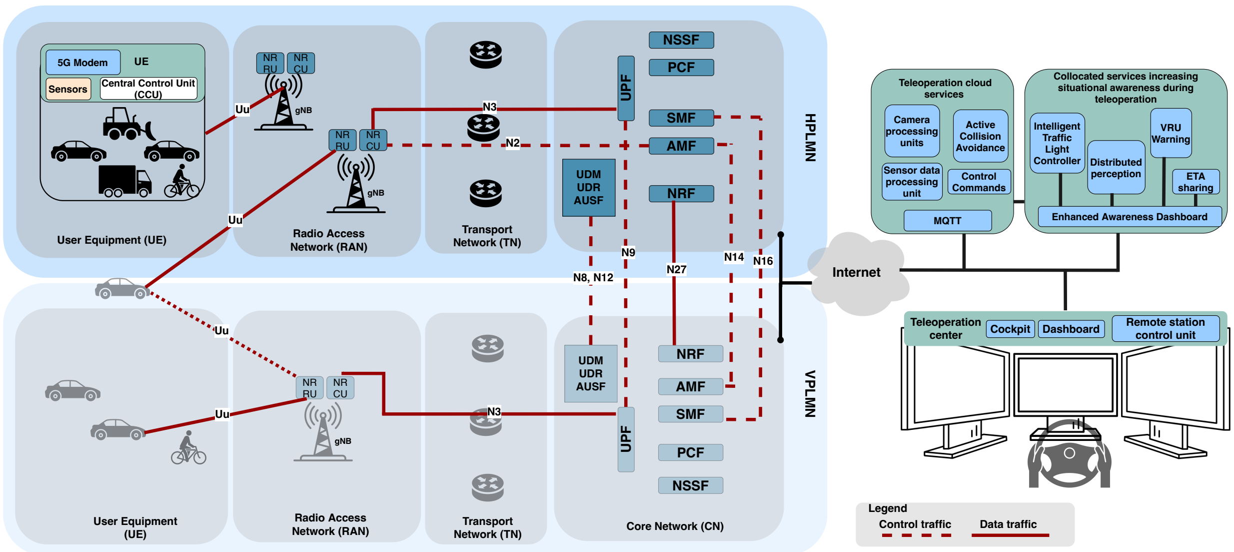

Fig. 2: The 5G-Blueprint architecture.

In addition, other types of traffic are being transferred in the uplink direction, such as Cooperative Intelligent Transport System (C-ITS) messages from intelligent traffic lights to respective traffic management systems, or from the VRU handsets to VRU path prediction services, or lidar data from platoon cars to Machine Learning (ML)-based object detection service. Thus, for both downlink and uplink traffic, use case applications/services network quality that can be offered by 5G network slices, such as Ultra-Reliable Low-Latency Communication (URLLC) and enhanced Mobile Broadband (eMBB), which are tailored to their specific requirements.

III. The Overview of Pilot Sites

The national pilot sites, i.e., Vlissingen and Antwerp, both provide network coverage for 5G NSA (commercial) and SA (test) networks. Depending on the spectrum regulations on a country level, SA and NSA deployments are available at different frequencies. In particular, 5G NSA is provided at 700 MHz (anchored 1800 MHz) in Vlissingen, and at 2.1 and 3.7GHz in Antwerp. On the other hand, 5G SA is available at 3.7 GHz in both national sites (center frequency with bandwidth of 100 and 50MHz, in Vlissingen and Antwerp, respectively), as well as in the cross-border site.

Regarding the national site in the Netherlands, Vlissingen port provides three potential testing sites. For instance, MSP Onions[1] presents an exclusive environment covered by 5G NSA, featuring a docking area with five docking stations and parking spaces. This setup is particularly convenient for evaluating the integration of teleoperation and autodocking capabilities, where our solutions from the autodocking use case (UC4) have been testbed from a scaled truck and trailer combination in the initial testing phases, to the full-scale setup in the last year of the project [4]. To assess the improvements facilitated by the 5G SA connection, teleoperation activities involving cars, trucks, and skid steers have predominantly taken place at the Verbrugge Scaldia Terminal[2] (the second testing location in Vlissingen). The teleoperation-based platooning drives over 5G NSA were conducted at the third testing location, specifically on the public road connecting MSP Onions and the Kloosterboer terminal[3].

Within the national site in Belgium, the right bank site of the Scheldt River in Antwerp serves as a location for periodic testing of *shadow-mode* teleoperated navigation for automated barge control (UC1), conducted via both 5G SA and NSA. The second Antwerp pilot location, i.e., the Transport Roosens Kallo[4] site (a hub for picking up and dropping off the containers) is on the left bank of the Scheldt River, and it offers a longer stretch of public road testing of teleoperation on both 5G NSA and SA. In addition, the Antwerp pilot site spilled over to a new location with 5G SA coverage, i.e., the Mechelen city center with one gNodeB deployed at the Telenet headquarters. This location has been subsequently added for two purposes: i) to have an ad-hoc testing and debugging setup of 5G New Radio (NR), and ii) to create an urban environment setting for testing VRU awareness capabilities, which are out of scope of this paper.

In terms of network deployment, Zelzate, the third pilot site in the 5G-Blueprint project, attracted significant attention during the project's final year, being the most challenging site that includes the border between Belgium and The Netherlands. The network deployment consists of two gNodeBs deployed near the geographical and administrative border between Belgium and the Netherlands. The goal of this pilot site is to enable session and service continuity when crossing the border while performing the remote operation of vehicles and vessels. The ultimate network configuration consists of a gNodeB installed on the Dutch side of the border (SA @ 3.5GHz, provided by the KPN network operator) and another on the Belgian side (SA @ 3.5GHz, provided by the Telenet network operator). To

[1]MSP Onions website: https://www.msp-onions.com/nl/

[2]Verbrugge Scaldia Terminal website: https://www.verbruggeinternational.com/en/locations/scaldia-terminal-vlissingen-flushing

[3]Kloosterboer terminal: https://www.kloosterboer.com

[4]Transport Roosens website: https://www.roosens.be

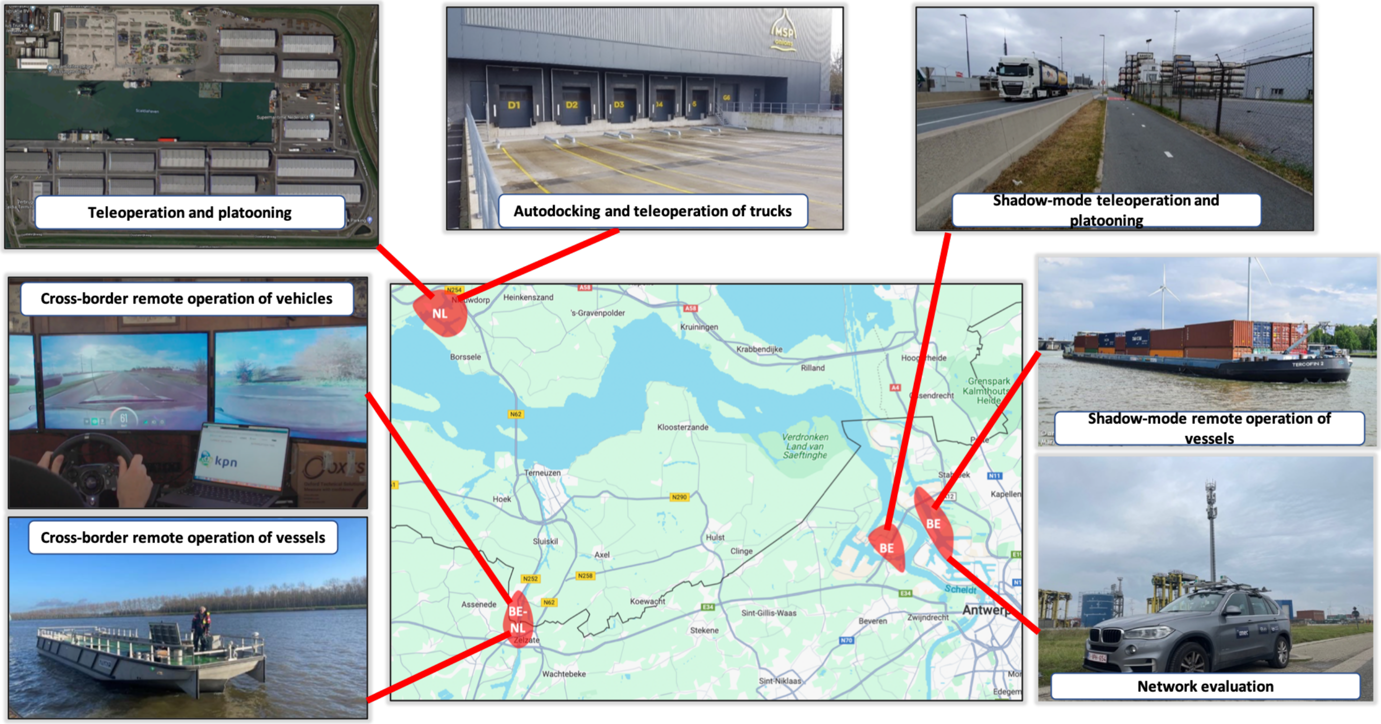

Fig. 3: 5G-Blueprint pilot sites.

TABLE I: 5G SA network performance digest [3,4].

KPI	Pilot site	Median	5th percentile	95th percentile	Average
RSRP (dBm)	Vlissingen: Verbrugge/MSP Onions/public road	-89/-97/-96	-96/-97/-105	-68/-96/-84	-86.6/-96.6/-95.3
	Antwerp: Right bank/Roosens	-95/-97	-115/-112	-78/-76	-96.8/-95.3
	Zelzate	-86	-103	-69	-86.3
TCP UL (Mbps)	Vlissingen: Verbrugge/MSP Onions/public road	(53.1, 37)/35.8/28.6	(37.1, 10.5)/24.5/11.8	(61.8, 60.6)/38.5/57.8	(52.8, 38.3)/34.9/30.1
	Antwerp: Right bank/Roosens	4.94/4.76	0.33/0	29.9/28.8	9.14/10.2
	Zelzate	24.3	1.42	51.5	24.1
RTT (ms)	Vlissingen: Verbrugge/MSP Onions/public road	(14.4, 12.6)/23/24.7	(11.7, 11.6)/20.1/21.4	(20.9, 17.8)/34.2/34.2	(15.0, 13.1)/24.1/29.6
	Antwerp: Right bank/Roosens	27.4/19.3	19.4/17.7	36.7/35.7	27.1/36.6
	Zelzate	24.7	12.7	36.227	24.38
Service interruption time (ms)	Zelzate	NA	96.4	109.0	108.3

support advanced seamless cross-border roaming mechanisms, the gNodeBs are linked to their respective 5G Core instances, as described in Section II.

IV. Results and Lessons learned from piloting activities

A. Network-related learnings

To provide a sufficient understanding of the 5G capabilities in the national and international pilot sites, we leverage the extensive network performance analysis presented in [8], and summarized in Table I. From the results obtained in all three pilot sites, it is clear that the 5G SA network deployed at the 3.5 GHz struggles with a limited range, which offers good and stable signal quality but only up to 2 km away from the gNB. This highlights the importance of proper dimensioning of 5G SA networks, with careful gNodeB placement decisions, as a good signal quality is essential for uplink throughput and end-to-end latency, required for latency-sensitive applications such as teleoperation. In addition to challenges related to limited coverage, the challenging network conditions in the busy port area with many metal constructions and large trucks and ships/vessels passing by, represent a significant impact factor for network performance.

Nevertheless, despite the challenging conditions, careful and extensive network evaluation resulted in measurements that are displaying promising results, showing that both SA and NSA can support the teleoperation requirements (5 Mbps uplink throughput per sensor/camera, below 30 ms end-to-end latency for remote control commands, and below 150 ms interruption time during handover process). In particular, service interruption time has been measured to evaluate how much time is needed for a UE to continue using the previously established session in the home network when it attaches to the visiting one. This value is specific for the cross-border site and as such it needs to be minimized to ensure seamless teleoperation across country borders. The values obtained during testing show that various optimizations in the handover procedure significantly contribute to the minimization of interruption time by proactively starting the handover process (Packet Data Unit (PDU) session relocation prepared before handover happens),

TABLE II: Service evaluation results with respect to use cases: UC1: Automated barge control, UC2: Autodocking, and UC3 & UC4: Teleoperation-based platooning. In addition, metrics Mean Absolute Error (MAE) and Root Mean Squared Error (RMSE) are introduced.

Use case	KPI	Definition	Pilot site	Target value	Average
UC3, UC4	Steering accuracy	Difference between the input on the steering wheel and the action on the ToV.	Antwerp	Mean <0.1 deg, MAE <3.0 deg, RMSE <5.0 deg	Mean = 0.077 deg, MAE = 4.56 deg, RMSE = 6.29 deg
			Vlissingen	Mean <0.1 deg, MAE <3.0 deg, RMSE <5.0 deg	Mean = 0.11 deg, MAE = 2.41 deg, RMSE = 3.85 deg
	Brake / Throttle Pedals accuracy	Difference between the input on the brake/ throttle pedals and the action on the ToV.	Antwerp	Mean <1.0 %, MAE <4.0 %, RMSE <6.0 %	Mean = 0.32 %, MAE = 0.702 %, RMSE = 1.22 %
			Vlissingen	Mean <1.0 %, MAE <4.0 %, RMSE <6.0 %	Mean = 0.33%/0.88%, MAE = 0.51%/1.27%, RMSE = 1.08%/2.09 %
	Following distance (Headway time)	Minimum achievable headway to the lead vehicle in a platoon.	Vlissingen	1 s	0.8 s
	Distance error	Difference between actual and desired distance between vehicles in a platoon.	Vlissingen	Less than 5% (in steady state condition)	2-4%
	Latency - V2V communication	Delay in communicating the message from the lead vehicle.	Vlissingen	20 ms	18 ms
	Packet loss	Number of packets lost in the V2V communication.		Less than 5% (within 100 m distance)	2%
UC2	Path Planning Time	Time for path planner to plan the desired docking path.	Vlissingen	<60 s	15 s
	Tracking Error Real Time	Lateral deviation of the actual trailer's position and path during maneuvering.	Vlissingen	<0.5 m	0.16m
	Final Docking State Error	Difference between the actual docking position and the planned docking position: (A) Lateral, B) Longitudinal, and C) Orientation angle	Vlissingen	A = <10 cm B = <10 cm C = <2 deg	A = 3.6 cm, B = 8.4 cm, C = 0.4 deg
	Elapsed time	Time between the initial movement and the final stop of movement at the end position.	Vlissingen	<150 s	<117.3 s
	GPS position accuracy	Accuracy of the GPS positioning system in cm.	Vlissingen	<10 cm	3.7 cm
	GPS heading accuracy	Accuracy of the GPS Orientation in degrees.	Vlissingen	<1 deg	0.25 deg
UC1	End-to-end latency	Delay in transferring a control command from a remote center to the vessel, and back.	Antwerp/Zelzate round 1	<35 ms	27.23 ms/40.47 ms
			Antwerp/Zelzate round 2	<35 ms	33.35 ms/39.07 ms
			Antwerp/Zelzate round 3	<35 ms	20.02 ms/35 ms

and minimizing the number of messages exchanged between 5G Core functions during the actual handover. The results show that both the average and 95th percentile are significantly below 150 ms, making service interruption time unnoticeable for cross-border teleoperation of both vehicles and barges.

In addition, the benefits that network slicing brings in 5G SA settings are also visible [8]. Our tests in the national sites, i.e., Antwerp and Vlissingen, showed that URLLC slicing offers improvements in the overall latency and higher resilience to background traffic over eMBB, which is crucial for remote control of multiple UEs connected to the same network.

B. 5G-enhanced teleoperation aspects

To be able to *remotely operate barges*, it is important to ensure high-quality network connectivity for two network flows that are essential in communication between a barge and a remote skipper in the control office. The uplink one is used for transferring camera streams and positional information that the remote skipper needs to properly navigate the barge. This uplink data is streamed from the computing unit on the barge to the private cloud, from where the data is further visualized on the screens of the skippers in the operation center/control room. The downlink one conveys the skipper's commands (change in heading and speed of the barge) to the navigational instrument installed on the barge which further translates the commands to signals that physically change the heading and speed of the physical barges. The uplink throughput results obtained for both Antwerp and Zelzate (Table I) and end-to-end latency (Table II show that 5G SA offers sufficient network quality for safe teleoperation of barges.

For a *truck & trailer* system to be capable of both teleoperation and autodocking, certain functionalities are necessary at both the teleoperation center and teleoperated vehicle sides. Apart from the hardware equipment that is used for physical actions that the remote operator takes (steering wheel, paddle shifts, pedals, buttons, screens), software for teleoperation and autodocking is running either in the cloud or on the computer in the teleoperation center. On the user side, components such as video streamers, cameras, the Drive-By-Wire (DBW) system, autodocking manager, Global Positioning System (GPS), and 5G modem, need to be installed. For teleoperation to take place, video camera streams are being transferred over the 5G network to the teleoperation software running on the computer in the remote center. In the downlink direction, teleoperation software is processing commands from the remote driver and transferring them further to the DBW system onboard that is making changes in the steering process. Afterwards, when autodocking is needed, the remote driver initiates it from the teleoperation computer choosing the 'automatic mode'. Similarly, as in the case of teleoperation, autodocking software receives camera streams and vehicle telemetry data, and it interacts with the autodocking manager to transfer instructions for docking, which are further translated to the DBW system on the vehicle that is performing the actual control of the truck. When it comes to autodocking tests, the delay variation in relaying remote commands from the operator to the truck is usually associated with network impact. Based on the results presented in Table II, it is evident that the performance of the autodocking functionality is highly reliant on the network quality. A stable network with an end-to-end latency of less than 100 ms will of course give optimal results. Given the network analysis digest in Table I, this requirement is met in all pilot sites, including the MSP Onions location where the autodocking is tested. Other service Key Performance Indicators (KPIs) relevant for autodocking have been measured as well, such as path planning efficiency which is not directly impacted by the network, but the performance of the underlying computing platform. Another one is the final docking state error, which corresponds to the end position of the trailer, and if large, it means that the truck-trailer combination is not parked properly. As this KPI is also affected by the network, obtained values of below 10 cm are considered sufficient for a safe autodocking process, validating the positive impact of stable 5G connectivity.

The *teleoperation of cars* is performed in the same way as it has been described above for the truck & trailer combination. The platooning process involves additional communication between the lead vehicle (teleoperated) and the following vehicle (human-driven or teleoperated), and cooperation between them in terms of maintaining a certain distance and following the speed advice. This cooperation is exchanged directly between platoon vehicles, i.e., via Vehicle-to-Vehicle (V2V) communication based on PC5[5], and it includes acceleration and speed values of the lead vehicle via On-board Units (OBUs). The following vehicle fuses that input with additional data that it collects from its own sensors, and performs necessary changes in the driving process (acceleration/deceleration) to stay in a platoon. The tests obtained for teleoperation-based platooning in Vlissingen and Antwerp (Table II) show that the controller is able to steadily control the following vehicle in the platoon over a 5G network with minimal distance error, thereby validating the overall performance of the platoon. In addition to that, the overall platoon setup with PC5-based communication between the vehicles in the platoon showed no deactivations caused by delays imposed by the 5G network, which confirms the stability of the teleoperation over 5G. Other service KPIs such as steering accuracy, which are relevant for the teleoperation chain, exhibit values that belong to acceptable ranges, thereby reinforcing the validity of the results obtained during piloting campaigns both within and across the country boundaries.

[5]PC5 interface is a cellular sidelink, i.e., a direct interface between users.

V. Conclusion

As can be seen from all results summarized in Section IV, 5G Standalone plays an essential role in achieving strict network requirements in both network flows, i.e., uplink and downlink, and for crossing the border between two countries. With 5G SA being available at all pilot sites, the obtained results show a promising future of 5G-based teleoperation in European cross-border corridors, especially given the resilience of URLLC slices when it comes to mission-critical operations such as remote control. However, with large-scale deployments of remotely operated barges/trucks/cars/skid steers, it will be extremely important to dimension the network to offer higher uplink throughput for multiple parallel camera streams, and low end-to-end latency which is critical for transferring remote commands, and dissemination of safety-critical notifications to VRUs and teleoperated vehicles. Therefore, this paper provides valuable insights into realistic results obtained during extensive testing of all necessary technical elements in the 5G-enhanced teleoperation chain (network and teleoperation use cases). Such insights will further pave the way towards achieving large-scale teleoperated transport based on uninterrupted in-country and cross-border 5G connectivity.

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