Performance Validation Strategies for 5G-enhanced Transport & Logistics: The 5G-Blueprint Approach

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***Abstract*—A big challenge of autonomous mobility is guaranteeing safety in all possible extreme and unexpected scenarios. For the last 25 years, the sector therefore focused on improving the automation functions. Nevertheless, autonomous mobility is still not part of daily life. The 5G-Blueprint project follows an alternative approach: direct control teleoperation. This concept relies on 5G connectivity to remove the physical coupling between the human driver or sailor and the controlled vehicle or vessel. This way, automation and teleoperation can be combined as complementary technologies, assigning them to different segments of a single trajectory, realizing driverless mobility in a safe, scalable, and cost-efficient manner. However, this mode of operation brings demanding connectivity requirements, such as high uplink bandwidth, low latency and ultra-reliability at the same time, for which the potential of 5G needs to be studied and explored. In this paper, we present our performance validation strategies to pursue 5G-enhanced teleoperation in real-life environment (e.g., public roads, busy sea ports), including some initial results that we collected during the in-country piloting phase.**

***Index Terms*—5G, teleoperation, automation, transport & logistics, automated docking, cooperative adaptive cruise control-based platooning, remote takover**

I. Introduction

In the summer of 1995, Dean Pomerleau and Todd Jochem from Carnegie Mellon University's Robotics Institute took a journey from Pitsburgh to San Diego in an autonomous minivan. This famous trip called "No Hands Across America" was 2 850 miles long, and was driven in an autonomous mode for 2 800 miles, or 98.2% of the trajectory [1]. This implies that despite the great attention and extra financial impulses it received over the last decade, the sector of autonomous mobility is actually working on getting the last 2% right for more than 25 years now.

The main challenge behind this is guaranteeing safety in all possible so-called edge/corner cases. These are traffic situations where one or more operating parameters are at extreme values, or in other words, where one or more unusual operating circumstances take place. From an engineering perspective, such circumstances are difficult and expensive to identify, reproduce, test, and optimize, for all such edge/corner cases before launching driverless L4 or L5 autonomous vehicles on the roads. That is why the 5G-Blueprint project is focusing on an alternative approach to solve this problem, i.e., teleoperation. When teleoperating, part or all of the tasks in the act of driving a vehicle or sailing a barge are performed by a remote operator, usually over wireless communications. In general, two main different types of teleoperation can be distinguished: indirect control teleoperation, and direct control operation [2]. In the first type, the operator performs the tactical-level operations (pathway planning), but not the dynamic driving task (real-time braking, steering, acceleration and transmission shifting). It corresponds with what has been defined by SAE International as Remote Assistance in the latest update of their taxonomy and definitions for terms related to driving automation systems [3]. This means that in this case the role of the remote operator is to provide information or advice (waypoints) to an automated vehicle when it encounters a situation that it cannot manage. Until now, this was typically the role envisaged for teleoperation technology in the context of automated driving, being a backup solution for stranded L4 and L5 autonomous vehicles. This approach has been explored before in several research projects such as 5G-Mobix[1] and 5G-Croco[2]. However, 5G-Blueprint focuses on the second type: direct control teleoperation. In that paradigm, the operator performs the actual dynamic driving task. This corresponds with what SAE defined as Remote Driving. It is not a form of driving automation, and therefore has not received that much attention in the context of bringing L4 or L5 autonomous vehicles to our roads so far. In general, and also by definition of the L4 and L5 concepts, the focus in the sector is on making sure that the vehicle automation system can work everywhere (L5) or at least everywhere on the trajectories for which they have been approved, i.e., L4, where its Operational Design Domain (ODD) covers the entire trajectory.

Nevertheless, even though the direct control teleoperation is not a form of automation, it does remove the physical coupling between the human driver/captain and the vehicle/vessel that he/she controls. Due to this single characteristic, in 5G-Blueprint we are exploring this technology as the missing piece of the puzzle for deploying L4 autonomy in real-life environments. Instead of making sure that the automation function can cover 100% of the trajectory, direct control teleoperation allows to split up L4 trajectories in different segments with different ODDs, and to assign each of them to either automated driving or remote driving, depending on how difficult the ODD is to automate. In other words, by looking at automation and direct control teleoperation as two complementary technologies instead of seeing one as the fallback of the other, the 2% problem can be solved by doing exactly the same as what Dean Pomerleau and Todd Jochem did in 1995, i.e., relying on human drivers to navigate those challenging 2%. But the main difference with 1995 is that today this human does not need to be physically present in the vehicle anymore. Instead, a remote operator can jump in and out of different vehicles or vessels to take over where needed. And this single delta between then and now makes this approach viable from a

[1]5G-Mobix: https://www.5g-mobix.com/
[2]5G-Croco: https://5gcroco.eu/

business perspective. Because this way a human should only be tied to a vehicle for 2% instead of 100% of the trajectory, reducing the corresponding personnel cost with a factor 50.

The reason for not adopting this approach already in 1995 are the stringent network connectivity requirements when performing direct control teleoperation. That connectivity does not only need sufficient bandwidth for uploading multiple parallel High-Definition (HD) video streams from the vehicle or barge to the operator station, it should at the same time provide ultra low latency and ultra high reliability, in both directions of communication (uplink/downlink). Thus, when used for international transport, the connectivity should seamlessly roam between network operators at the border crossing, which is a combination of characteristics that so far was not possible to provide with mobile network technology, until 5G came into play. Compared to all previous generations of mobile network technologies, 5G for the very first time is designed not as a horizontal infrastructure that supports all applications with the same type of performance, but as an infrastructure that can be tailored to meet the needs of specific verticals through applying concepts of network slicing. But even then, the direct control teleoperation network requirements seem to combine elements of both enhanced Mobile Broadband (eMBB) and Ultra-Reliable Low-Latency Communication (URLLC) at the same time, while also putting the emphasis on uplink instead of downlink bandwidth consumption. Since even for 5G technology this specific combination might be challenging to realize, it needs to be validated in depth how 5G can provide the connectivity needed for direct control teleoperation. This validation, both from a technology but also from a business and governance perspective, is the main purpose of the 5G-Blueprint project. Thus, in this paper, we present our performance validation strategies that are leveraged to pursue extensive testing and piloting in real-life environment (e.g., public roads, busy sea ports), including some initial results collected during the in-country piloting phase.

II. 5G-Blueprint use cases and enabling functions

To leverage upon URLLC and eMBB network slices, and to validate their benefits in the real-world environment, we have defined four main Use Cases (UCs) and several enabling functions. The enabling functions are deployed as modular services with the purpose of enabling, facilitating, and enhancing the teleoperated transport of User Equipments (UEs) such as barges, cars, trucks, skid steers, and reach stackers. In particular, [4] presents a detailed overview of the UCs and enabling functions (listed in Table I), and here we provide their brief outlook as an introduction to the 5G-Blueprint architecture that consists of 5G network and UC elements that are coupled to create a fully-fledged teleoperation system supported by eight enabling functions.

a) UC1 Automated barge control: Due to an unprecedented impact on the economy, shipping sector needs to be optimized through digitalization, thereby improving safety and reliability of the ship control by enabling autonomous operation of ships. Although such a mode of operation is an ultimate goal for the shipping sector, teleoperation is an intermediate enabler that needs to be further explored, while studying its impact on the improvement of port entry efficiency by reducing crew requirements for barging. In the 5G-Blueprint project, the navigation of barges is performed by the captain onboard in collaboration with the captain from the teleoperation center, eliminating further crew interventions. The navigation of the barges through canals will be teleoperated along with partial automation, both in an in-country setup (Antwerp Pilot site), and a cross-border setup (Zelzate pilot site).

TABLE I: The list of enabling functions that are used in different use cases, and tested/validated on different pilot sites.

Enabling function	Use case	Pilot site
EF1: Enhanced Awareness Dashboard	2, 3, 4	Vlissingen, Antwerp
EF2: Vulnerable Road User Interaction	2, 3, 4	Vlissingen, Zelzate
EF3: Time Slot Reservation at Intersections	3, 4	Vlissingen, Zelzate, Antwerp
EF4: Distributed Perception	2, 3, 4	Vlissingen, Antwerp
EF5: Active Collision Avoidance	2, 3	Vlissingen, Zelzate, Antwerp
EF6: Container ID Recognition	2	Vlissingen
EF7: Estimated Time of Arrival (ETA) Sharing	2, 3, 4	Vlissingen, Zelzate, Antwerp
EF8: Scene Analytics	4	Antwerp

b) UC2 Automated driver-in-the-loop docking: To enhance the safety of docking operations in busy port areas, we are enabling the trucks with standardized connectivity solutions as a prerequisite for an optimized docking operation with respect to time and space requirements. Positioning of these yard trucks is performed via Real-Time Kinematic (RTK) based localization system. The optimal driving paths are communicated to the truck, given that such operations in safety-critical situations are strongly time-critical. The overall use case is being piloted in the Vlissingen (NL) pilot site (MSP Onions Terminal and Verbrugge Scaldia Terminal).

c) UC3 Cooperative Adaptive Cruise Control (CACC)-based platooning: The concept of platooning is enabling a group of several vehicles to be driven together at the same time, while maintaining a close distance between respective vehicles in a platoon. It also requires a stable network connectivity between the vehicles, which enables an efficient message exchange between them [5]. Given the aerodynamic drag improvements of the trucks in platoons, the idea of applying platooning principles to the truck maneuvering on the highways has been recognized as promising for achieving significant fuel gains and emission reductions [6]. However, there are still many limiting factors as for truck platooning the drivers still need to be on-board, while there is an ever-increasing trend of the shortage of skilled truck drivers. Since adopting the platooning mechanism itself would not solve the issue of driver shortage, we focus on building on top of the existing knowledge related to platooning, thereby leveraging on 5G connectivity on the highways to combine platooning with teleoperation and full automation (combination of teleoperated leading truck and teleoperated/automated following vehicles). With such enhancements of truck platooning operations, we are creating a blueprint for a significant cost reduction, even on the segments of the highways that stretch over multiple countries, thereby leveraging on the 5G cross-border connectivity enhancements. The pilot of this use case is being performed in all three project pilot sites, i.e., Vlissingen (NL), Zelzate (NL-BE), and Antwerp (BE).

d) UC4 Remote takover: Remote takeover is a process in which a teleoperation center takes control of a vehicle from a remote location, thus, steering and driving the vehicle remotely [4]. In this particular UC, we are defining and deploying the basic principles of the teleoperation functionality, which is then further applied to the aforementioned UCs 2 and 3. As a prerequisite for remote takeover operations, the teleoperated vehicle needs to be equipped with an onboard unit, network

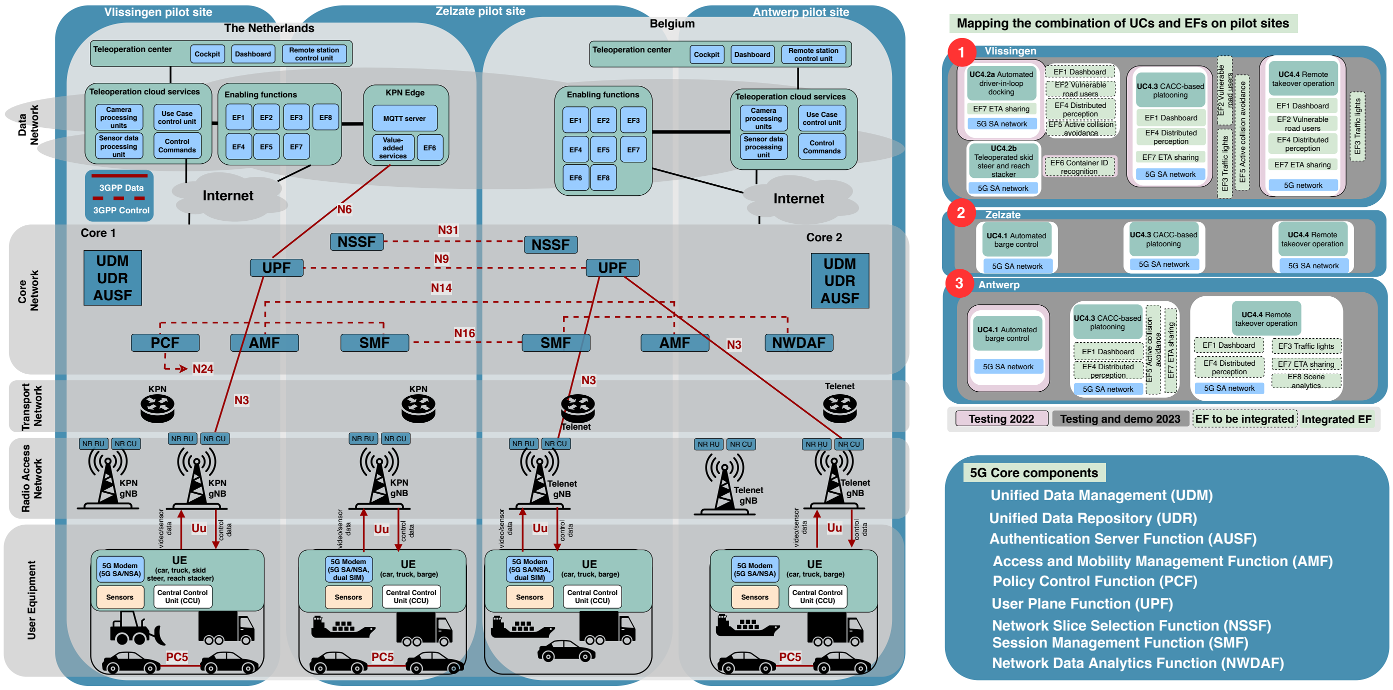


Fig. 1: 5G-Blueprint Network Architecture based on the 5G Standalone (SA) deployment (left); Piloting matrix and list of 5G Core components (right).

connectivity, and cameras, while the teleoperation center is providing the technical means to manage vehicles by remote operators. Such use case is piloted in all three pilot sites as well, setting the base for crucial activities with a real deployment of teleoperation. Going step further, the smooth transfer of control between different operators is tested and validated as well, thereby optimizing the operations and driving time by avoiding the stops, and minimizing the vehicle idle time. Given the time sensitivity of operations, high reliability and ultra-low latency of the network connectivity are one of the principal requirements, pushing the need for 5G network deployment along the harbor and public road areas where the pilot is being performed.

III. The Initial Technical Blueprint for 5G-Enhanced Teleoperated Transport

In this section, we present the features of an initial technical blueprint for 5G-supported teleoperation of vehicles, trucks, barges, and skid steers, thus, detailing on the network architecture that is leveraging on 5G connectivity elements in both in-country and cross-border pilot sites. Such a blueprint is being tested and validated in the real-life environments, i.e., pilot sites that involve busy port areas such as Vlissingen and Antwerp, focusing also on the cross-border scenarios between Belgium and the Netherlands.

A. *5G-Blueprint architecture*

The high-level overview of the overall network architecture designed and leveraged upon in the 5G-Blueprint project is shown in Fig. 1. Starting from the UE side, in the integration and piloting activities of teleoperation in both in-country and cross-border pilot sites, we use either proof-of-concept or commercial cars, trucks, barges, skid steers, and reach stackers, depending on the use case and the testing scenario. Such UEs are equipped with 5G communication capabilities (5G modem and necessary antennas), sensors, and Central Control Unit (CCU) that executes the commands sent by the teleoperator. As such, UEs produce the HD video and sensor data that needs to be processed by teleoperation cloud services and enabling functions (either running on the cloud or on the network edge), thereby requiring URLLC and eMBB connectivity.

All the aforementioned traffic is then transferred through 5G Radio Access Network (RAN) and transport, to the core network (via 3GPP N3 reference point), by leveraging on the defined end-to-end network slices (both URLLC and eMBB). Afterwards, the HD video feed and sensor data are processed by additional services running in the cloud, and then sent to the teleoperation center that remotely monitors data and further steers/controls the vehicle/barge remotely, thus, sending the control commands to the UE's CCU. The detailed network requirements for each of our UCs, considering both uplink communication for transferring HD video data and downlink one for control commands from the teleoperator to the teleoperated vehicle/barge, are presented in [4].

Concerning the roaming scenarios, to achieve session and service continuity across the border between Belgium and the Netherlands, we are taking various approaches on extending the roaming mechanisms, as well as the state-of-the-art 5G core components and their interaction between different mobile network operators. As this task is challenging, a more detailed overview of interaction between 5G SA core components, such as Access and Mobility Management Functions (AMFs), Session Management Functions (SMFs), User Plane Function (UPF), and Network Slice Selection Functions (NSSFs), between two domains, is part of our ongoing research and development activities.

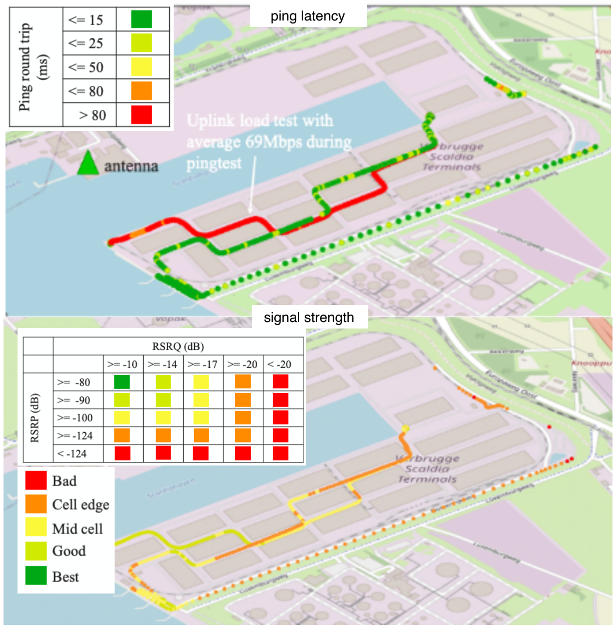


Fig. 2: Ping latency and signal strength measurements in the Vlissingen pilot site.

B. Pilot sites

In this section, we briefly describe each of the three pilot sites designed and developed within the 5G-Blueprint project.

a) Vlissingen pilot site: has both 5G Non-Standalone (NSA) and SA (Test network) coverage, and as such, it is being extensively used for piloting UCs 2, 3, and 4. The pilot site consists of three locations. First of them is the terminal of MSP onions at Nieuwdorp, which offers sufficient space and flexibility to deploy and test automated driver-in-loop docking. This test site contains a docking area with five docking stations, and a parking lot where trucks and cars can park or maneuver. Second is the Verbrugge Scaldia Terminal, where the teleoperation of cars, trucks, and skid steers, is being performed, while being isolated from the personnel at the terminal. The driving tests for UC3 are performed on the public road in the terminal area, as well as in the confined area within the terminal where a maximum speed of 25km/h is possible, due to the pedestrians and terminal vehicles randomly crossing the path of the teleoperated vehicles. The third site stretches the public road from the MSP Onions terminal to the Kloosterboer terminal, where the shadow-mode testing[3] of UCs 3 and 4 happens.

b) Antwerp pilot site: combines two locations with both 5G NSA and SA coverage. The first one refers to the Right bank of the Port of Antwerp Bruges, where the shadow-mode teleoperation is being performed on the commercial barge that sails from Liege to Antwerp on a weekly basis. The second location is the Transport Roosens Kallo site, which is a hub for picking up and dropping off containers from depots located at the MPET and Medrepair terminals on the Schelde's left bank at Port of Antwerp Bruges. On this location of the pilot site, both shadow-mode testing and real teleoperation on the closed roads is performed.

[3] Shadow-mode testing of teleoperation described in Section IV.

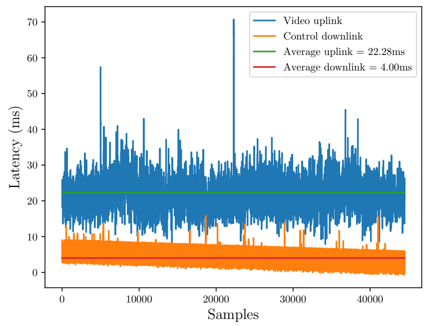
c) Zelzate pilot site: is the most challenging pilot site in terms of network connectivity tests as it spans two countries, i.e., the Netherlands and Belgium, and as such, it requires further extensions of the 5G Core network functionalities of both mobile network operators towards enabling session and service continuity when crossing the border. For automated barge control operations, the barge will be sailing through the canal Gent-Terneuzen, which contains a bridge on the border between two countries. This bridge is an important obstacle due to which the piloting of UC1 needs to switch from automated mode to teleoperation. Furthermore, for piloting UCs 3 and 4, we defined a detailed cross-border trajectory that contains a significant variety in environmental conditions (urban center/rural area/industrial area/highway with civilian cars/trucks, pedestrians, and bikers).

IV. Performance Validation Strategies

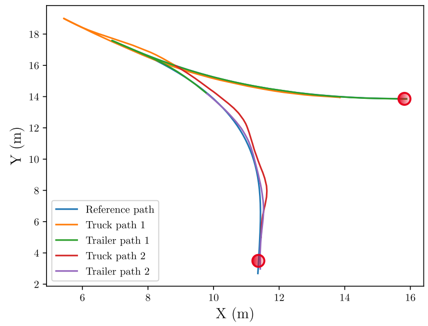
The overall teleoperation testing and validation process is performed in the two main stages. During the first stage, the System Under Test (SUT) for each of the UCs is being integrated in a lab environment, thereby performing the integration of components developed by different partners in each of their respective labs. In this paper, we entirely focus on the second stage, which focuses on the validation of UCs and enabling functions, and their performance while using 5G network connectivity, in the pilot sites. Thus, in the second stage, the validation is being performed in the three different pilot sites, i.e., Vlissingen (NL), Antwerp (BE), and Zelzate (cross-border area NL-BE). For each of the tests, specific trajectories have been defined, combining confined areas (e.g., parking lots) and public roads with 5G coverage. In case of testing on the public road, in regular traffic conditions, some specific exemptions are required, and thus, various permits need to be obtained from both the Dutch and Belgian public authorities. To mitigate such challenges, in the 5G-Blueprint project, we organize the testing in the pilot site as a combination of the two following testing modes:

- *Shadow-mode teleoperation* means that the control commands sent from the teleoperator via 5G network to the vehicle/barge are not directly translated to the local commands, thus, being disabled by the drive-by-wire system of the vehicle. This mode of testing is being extensively used when testing on the public roads in the pilot sites.
- *Real teleoperation* happens in the confined areas such as parking lots within 5G-covered pilot sites, or on the closed public roads. As for this type of testing on the public roads a particular permit is required, we focus on testing in confined areas and the shadow-mode testing on the public roads to collect a sufficient amount of results and learnings before performing the same test with a more stable teleoperation, leveraging on a mixed traffic public roads environment.

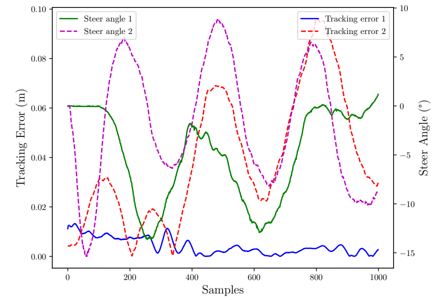
The integration activities involve i) interfacing of different UC components and the relevant enabling functions (Table I), and ii) the testing and validation of the performance of these interfaced components using 5G network deployed in the pilot sites, and in particular the network slices (e.g., URLLC and eMBB). For that purpose, in Fig. 1 (right) we present a high-level overview of our current planning of the integration and pilot testing for each of the UCs, and their mapping to each of the pilot sites. In particular, after performing an initial lab testing (first testing stage) in the first half of 2022, we have started with the extensive testing in the pilot sites (second stage). As it can



(a) Latency measurements.

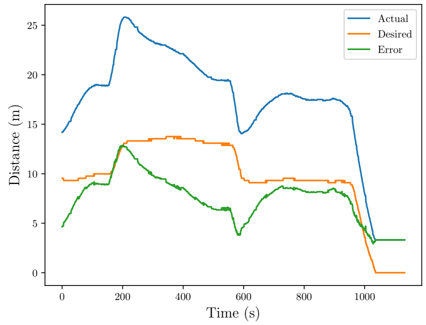


(b) Paths for UC2.

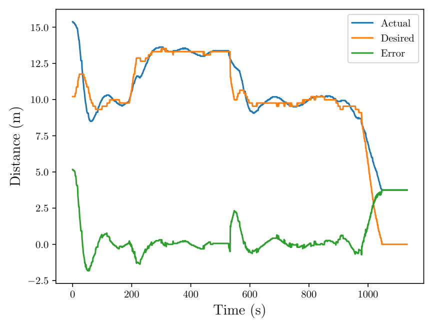


(c) Steering angle and tracking error for UC2.

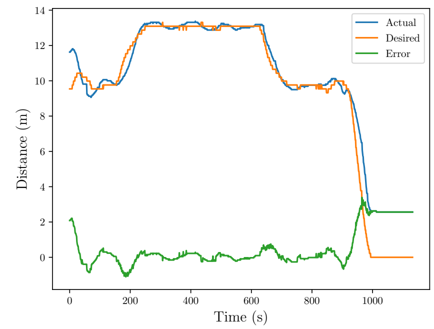
Fig. 3: The results from network measurements and UC2.



(a) Adaptive Cruise Control (ACC).

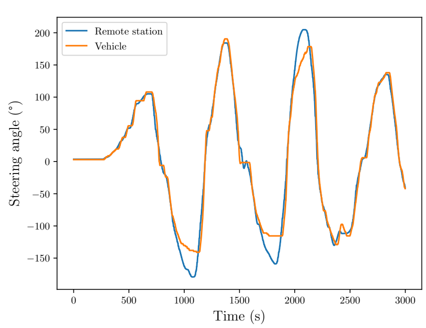


(b) Cooperative ACC (CACC) using WiFi-p/ITS-G5.

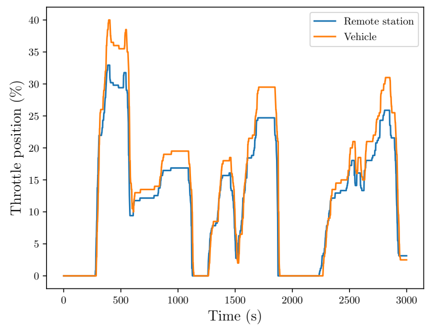


(c) CACC using CV2X.

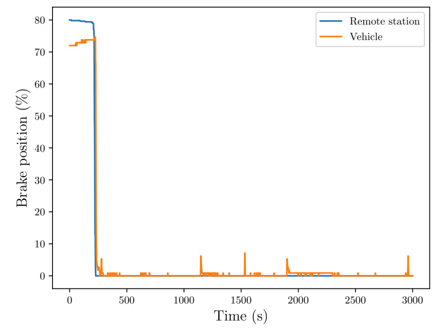
Fig. 4: The results of the distance between the lead and follower vehicles in UC3.



(a) Steering angle.



(b) Throttle position.



(c) Brake position.

Fig. 5: The results of the teleoperation in UC4.

be seen in Fig. 1 (right), all four UCs have been tested either in Vlissingen or in Antwerp pilot site (Testing 2022), together with their respective integrated enabling functions. The main focus was mostly on the Vlissingen pilot site, given the timely availability of both 5G SA and NSA in both confined areas and the public roads. One of the ongoing activities this year is to transfer the learnings from the Vlissingen pilot site, and proceed with the testing of UCs 3 and 4 on the Antwerp pilot site as well.

All the tests performed during this year are so far focused on the in-country pilot sites, which are less complex compared to the cross-border one, thereby testing the impact of 5G system on enabling and enhancing teleoperation, and learning about the integration success between UCs, enabling functions, and 5G network. Thus, the next step in the project is to entirely focus on the cross-border area, implementing different roaming strategies that involve direct communication between: i) two UPF components over N9 interface for the purpose of steering the traffic from user (car, truck, or barge) connected to the network on the Belgian, to the network on the Dutch side of the border, ii) two NSSF components over N31 interface to synchronize the selection of network slices in different domains, iii) two AMF components over N14 interface to exchange the access and mobility data about the connected user between two mobile network operators, and iv) two SMF components over N16 interface for the purpose of managing the session of the connected user while crossing the border between two countries. In parallel to testing these advanced network capabilities for enabling service and session continuity when reconnecting from the network of one mobile operator to the other, further piloting of UCs and enabling functions is planned in Zelzate pilot site for this year, with the plan to perform extensive testing of service and session continuity features in the context of UCs in 2023.

V. Initial results of the 5G-supported tele-operation

As an outcome of the extensive trialing of all UCs in the Vlissingen pilot sites, here we briefly present and discuss some of our initial results. Due to the space constraints in this paper, we present only a subset of results, whereas the details of all results will be presented in an extended version.

a) Network measurements: Based on the detailed network requirements for all our UCs (defined in [4]), uplink/dowlink latency for transferring HD camera video feeds needs to be less than 50ms, with more stringent requirement of 35ms for an end-to-end vehicle control latency [4]. The results shown in Fig. 2 and 3a are promising, as average uplink latency is 22.28ms, and downlink 4ms, which also meets the requirement of end-to-end latency (26.28ms less than 35ms). Concerning throughput measurements, an average value of 69Mbps has been achieved, which also meets the requirement of between 5 and 25Mbps. However, more measurements while stressing the video upload need to be performed.

b) Automated driver-in-loop docking (UC2): In this test, UC2 and ETA Sharing enabling function (EF7) have been integrated and tested over 5G network, whereas the setup included a scaled truck trailer combination equipped with the HAN[4] drive-by-wire system. The result shown in Fig. 3b displays a path of the truck in case of Bi-Directional Manoeuvring Path (BDMP) autodocking, while in Fig. 3c we show the steering angle and the tracking error accuracy. The maximum value of this error is 1.3cm, with the average of 0.4cm, which is a promising result as it meets the requirements of less than 2.5cm.

c) CACC-based platooning (UC3): This test included 5G-based CACC-based platooning integrated with the Enhanced Awareness Dashboard (EF1), Distributed Perception (EF4), and ETA Sharing (EF7), as shown in Fig. 1 (right), and it was performed in a *shadow-mode* on the public road. In particular, EF1 and EF4 provided an extended and enhanced awareness to the teleoperator to increase the safety of teleoperation, by presenting the alerts, and displaying/detecting the obstacles (3D object detection), respectively. The role of EF7 was to re-calculate ETA values for teleoperated vehicle based on the real-time locations and road data. The results shown in Fig. 4 show the superiority of 5G-based Cellular Vehicular-to-Everything (C-V2X) compared to WiFi-p/ITS-G5 and simple adaptive cruise control, in terms of the distance error between lead and follower vehicle, which is calculated as percentage of difference between actual and desired distance. The result shows less than 5% error, which falls into the target value domain, while maximum achievable speed was 90km/h. Also, the minimum achievable headway to the lead vehicle resulted in 0.8s, where 1s was the target.

d) Remote takover (UC4): The remote driving, together with Enhanced Awareness Dashboard (EF1), Vulnerable Road User Interaction (EF2), Distributed Perception (EF4), Active Collision Avoidance (EF5) and ETA Sharing (EF7), was tested over 5G connectivity. The results displayed in Fig. 5 show the steering, throttle, and brake accuracy, which are measured as the mean error, Mean Absolute Error (MAE), and Root Mean Squared Error (RMSE), via comparing the values between the teleoperator and teleoperated vehicle. The vehicle was teleoperated driving at the speed that corresponds to the maximum allowed speed in the Vlissingen pilot site area (15km/h). The results show that MAE and RMSE values for throttle are 2.2% and 3%, respectively, which meets the requirements of less than 4%, and 6%. Similar results are obtained for brake accuracy, where MAE and RMSE are 4% and 5%, respectively. Somewhat larger errors are achieved in the case of steering angle, where MAE and RMSE are larger than expected for 4%, but only during slalom tests, while during regular driving the error was minimal (less than 1%).

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VI. Conclusion

In this paper, we provided a glimpse of the 5G-Blueprint performance validation methodology for 5G-enhanced teleoperation in real-life environments. We also presented some of our initial results collected during the piloting phase in Vlissingen, the Netherlands, thereby testing the feasibility of 5G NSA and SA in real-life harbour and surrounding environments. The results show enhancements of the network performance (latency, throughput), as well as teleoperation key performance indicators, such as accuracy in steering angles, throttle positions, brake positions, and the distance between lead and ego vehicles in CACC-based platooning scenarios. The main focus of our planned testing and validation is on the challenging cross-border scenarios for barge/vehicles/trucks sailing/driving between Belgium and the Netherlands, thereby testing and validating the impact of enhancements on the 5G SA roaming on achieving the service continuity for cross-border teleoperation. In addition, more tests with higher traffic load (e.g., multiple camera feeds), and various weather conditions, are planned as well.

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