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Next generation connectivity for enhanced, safe & efficient transport & logistics

Next-Gen Teleoperation: 5G Applications in Modern Ports

Version 1.0

EXECUTIVE SUMMARY

The objective of this whitepaper is to discuss the learnings and insights about the enhancements that 5G brings to vertical industries such as transport & logistics, focusing particular on teleoperation and automation as two complementary technologies. The learnings we present are backed by a comprehensive set of results obtained during the extensive piloting testing activities performed during the final stage of the 5G-Blueprint project. These lessons learned cover both the 5G network performance, but also its impact on the performance of vertical services.

Before deep-diving into those learnings, we start with the overarching architecture, which glues together 5G network components (spanning the user, radio, core, and edge), use case services that enable teleoperation, and enabling functions that increase operational efficiency and situational awareness during the teleoperation process. Importantly, the architecture captures the essential advancements brought by 5G Standalone (SA), highlighting specific interfaces between 5G Core components that are developed in the 5G-Blueprint project to enable smooth and seamless roaming procedures. Such advancements enable the remote operators to perform uninterrupted teleoperation (with less than 150ms service interruption time) when crossing the border between two countries. Being service-based, 5G SA offers flexible network design that enables more efficient utilization of network functions and their independent scalability and connectivity with each other. Such design allowed us to create necessary optimizations in the handover procedures on the 5G Core side, which in turn resulted in significantly shorter interruption time. Also, it brought performance improvements tailored to vertical industries such as transport & logistics, and in particular for use cases such as 5G-enhanced teleoperation.

To provide sufficient understand the 5G capabilities in the above mentioned pilot sites, this whitepaper summarizes the main lessons learned when it comes to 5G performance in different pilot sites. From the results obtained in all three pilot sites, it is clear that the 5G SA network in the 3.5GHz range suffers from limited range, which offers good and stable signal quality but only up to 2km away from the gNB. This highlights the importance of proper placement of gNBs as good signal quality is essential for uplink throughput and end-to-end latency, required for latency-sensitive applications such as teleoperation. Also, the harsh environment in the busy port area is a significant impact factor for network performance. All presented results are promising as they show that both SA and NSA are able to support the teleoperation requirements (5Mbps uplink throughput per sensor/camera, below 30ms end-to-end latency for remote control commands, and below 150ms interruption time during handover process). Specific for the cross border site, service interruption time has been measured to evaluate how much time is needed for UE to continue using the previously established session in the home network when it attaches to the visiting one. The values obtained during testing show that optimized version of seamless handover brings significant improvements, and as both median and 95th percentile are significantly below 150ms, making service interruption time unnoticeable for cross-border teleoperation process.

After understanding how the network performs in each testing location, final conclusions and analysis of pilot results for all Use Cases (UCs) and Enabling Functions (EFs) developed and deployed in the 5G-Blueprint project are presented. In the case of 5G-Blueprint, we developed use cases such as Automated barge control (UC4.1), Autodocking of trucks and skid steer teleoperation (UC4.2), and Teleoperation-based platooning (UC4.3 & UC4.4), and several enabling functions (Enhanced awareness dashboard, Vulnerable Road User (VRU) Warning, intelligent Traffic Light Controllers (iTLCs), Distributed perception, Container ID recognition, and Estimated Time of Arrival Sharing) to test and validate 5G capabilities that could be leveraged large scale in future deployments. The relevant service KPIs are studied for all of these use cases and enabling functions, analyzing in particular the impact 5G network imposes on those service KPIs. Finally, this whitepaper summarizes valuable insights obtained during extensive piloting activities in real-life network settings. The summary covers all necessary technical elements in the 5G-enhanced teleoperation chain (network, teleoperation use cases, and

enabling functions providing increased situational awareness), highlighting insights that 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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ABBREVIATIONS

5G AA	5G Automotive Association
5G IA	5G Industrial Association
5G PPP	5G Infrastructure Public Private Partnership
5G SA	Standalone 5G
5G NSA	Non-Standalone 5G
AB	Advisory Board
AECC	Automotive Edge Computing Consortium
AI	Artificial Intelligence
BDVA	Big Data Value Association
CACC	Cooperative Adaptive Cruise Control
CAD	Connected and automated driving
CAM	Connected and Automated Mobility
CAPEX	Capital Expenditure
CAV	Connected and autonomous vehicles
CCAM	Cooperative, Connected and Automated Mobility
CNF	Containerized Network Functions
DMI	Dutch Mobility Innovation
DPO	Data Protection Officer
EC	European Commission
ECTS	European Credit Transfer System
ETA	Estimated Time of Arrival
GDPR	General Data Protection Regulation
GPU	Graphics Processing Unit
IoT	Internet of Things
iTLC	Intelligent Traffic Light Controllers
IP	Internet Protocol
iTLC	Instant Thin Layer Chromatography Medium
KPI	Key Performance Indicator
M	Month
MANO	Management and Orchestration
MEC	Multi-access Edge Computing
MIW	Ministry of Infrastructure and Water Management
MNO	Mobile Network Operator
MOOC	Massive Open Online Course
NFVI	Network Function Virtualization Infrastructure
NGI	Next Generation Internet
NGIoT	Next Generation Internet of Things
NIST	National Institute of Standards and Technology (USA)
NR	New Radio
OBU	On-board Units
OPEX	Operational Expenditures
ORD	Open Research Data
RAN	Radio Access Network
RAT	Radio Access Technology
RSU	Road Site Units
RTTI	Run-time Type Information
SAE	Society of Automotive Engineers
SEO	Search Engine Optimization
TC	Teleoperation Consortium
TCP	Transmission Control Protocol

TMC	Technical Management Committee
TO	Teleoperation
ToD	Teleoperated Driving
TOV-ratio	Teleoperated-to-vehicle ratio
TRL	Technological Readiness Level
V2V	Vehicle-to-vehicle
V2X	Vehicle-to-everything
VIM	Virtual Infrastructure Manager
VNF	Virtual Network Function
WG	Working Group
WP	Work Package

1 INTRODUCTION

The 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. This objective is achieved through several aspects, such as:

- Teleoperation enabled by 5G enhanced performance, such as low latency, reliable connectivity, and high bandwidth.
- Teleoperated and telemonitored transport on roadways and waterways alleviating the increasing shortage of manpower and bringing transport and logistics to a higher level of efficiency through data sharing in the supply chain and the use of AI.
- Technical and operational (pre)conditions that need to be in place to get the full value of 5G tooled transport and logistics. This includes implementing use cases that increase cooperative awareness to guarantee safe and responsible teleoperated transport.

Those aspects have been tested and validated in the three pilot sites, two national sites: Antwerp (Belgium) and Vlissingen (The Netherlands), and one international site called Zelzate, which is the most challenging one in terms of network connectivity as is placed at the border between Belgium and the Netherlands. The project's outcomes are creating the blueprint for operational pan-European deployment of teleoperated transport solutions in the logistics sector and beyond.

This following subsections focus on the overarching 5G-Blueprint architecture, which captures the essential functions from the 5G Standalone (SA) network as well as the service/application components running on the network edge or on the cloud. The network functions interact in a unique way to enable seamless roaming for a teleoperated vehicle/barge that is about to cross the administrative border between two countries, but to also reconnect from one MNO's network (home) to another (visiting). The final list of all Use Cases (UCs) and Enabling Functions (EFs) is presented in Table 1 and Table 2, respectively. These UCs and EFs are collocated within 5G-capable pilot sites, as presented in the latest overview of the overarching 5G-Blueprint architecture, which is further tackled in Sections 1.1 and 1.2.

Table 1 - List of Use Cases (UCs).

Use case ID	Full name
UC4.1	Automated barge control
UC4.2	Autodocking of full scale trucks and skid steers
UC4.3 & UC4.4	Teleoperation-based platooning

Table 2 - List of Enabling Functions (EFs).

Enabling Function ID	Full name
EF1	Enhanced Awareness Dashboard
EF2	Vulnerable Road User (VRU) Warning
EF3	Intelligent Traffic Light Controller (iTLC)
EF4	Distributed Perception
EF5	Collision Avoidance System
EF6	Container ID Recognition
EF7	Estimated Time of Arrival (ETA) Sharing

1.1 Vertical-centric 5G architecture: Cross-domain connectivity

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 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 Figure 1 (condensed view) and Figure 2 (extended view with pilot sites), 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 roaming with negligible interruption time (less than 150ms). In addition, this architecture also includes the final deployment aspects related to use case and enabling function components placed at the edge or cloud computing units. To increase readability of both Figure 1 and Figure 2, Table 3 provides the list of acronyms and their definition.

On the User Equipment (UE) side, the full-scale cars, trucks, barges, and skid steers, have been used for piloting activities in the 5G-Blueprint project, and as such, they are all equipped with 5G capabilities to reach 5G SA signal on 3.5GHz in all three pilot sites. Depending on the use case and enabling function, as well as 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 the purpose of 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 improved 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 new 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 APIs.

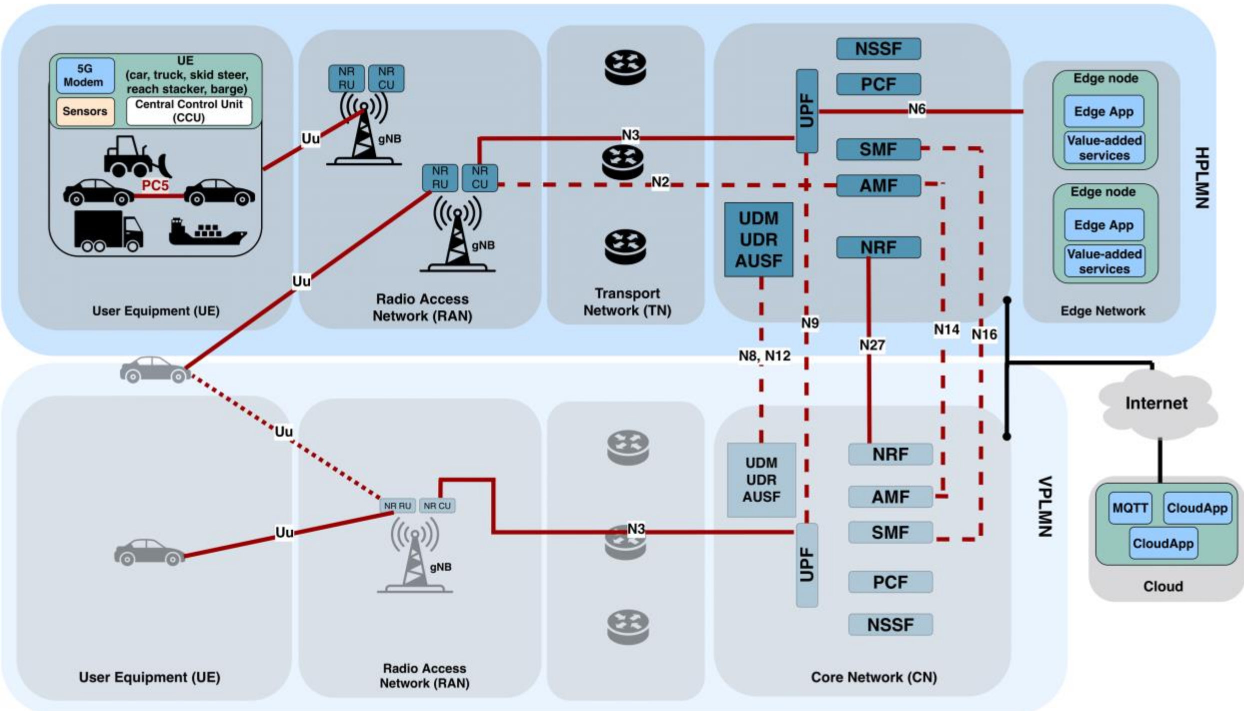

Figure 1 - Final 5G-Blueprint architecture.

The 5G SA architecture embodies the principles of user and data plane separation. Therefore, in Figure 1 and Figure 2, data traffic is marked with solid red lines, while dashed ones represent 5G control traffic. The **control traffic** is being exchanged between UE, gNodeB, and 5G Core network functions, during registration and authentication of UEs, as well as during establishment of UE session. For example, when Teleoperated Vehicle (ToV) is connecting to the network to transfer video data and receive steering commands from the control center, the Authentication Management Function (AMF) interacts with Authentication Server Function (AuSF), which is checking UE credentials and finalizes the authentication process. Upon successful authentication, AMF is consulting the Unified Data Management (UDM) to retrieve important data about UE, and afterwards proceeds with interaction with SMF to establish UE session and enable data path.

Table 3 - Acronyms used in the 5G-Blueprint architecture.

Acronym	Definition
SA	Standalone
NSA	Non Standalone
CCU	Central Control Unit
RAN	Radio Access Network
UDM	Unified Data Management
UDR	Unified Data Registry
AUSF	Authentication Server Function
UPF	User Plane Function
SMF	Session Management Function
NSSF	Network Slice Selection Function
PCF	Policy Control Function
AMF	Authentication Management Function
NRF	Network Repository Function
HPLMN	Home Public Land Mobile Network
VPLMN	Visited Public Land Mobile Network
Edge App	Edge Application
Cloud App	Cloud Application
MQTT	Message Queueing Telemetry Transport

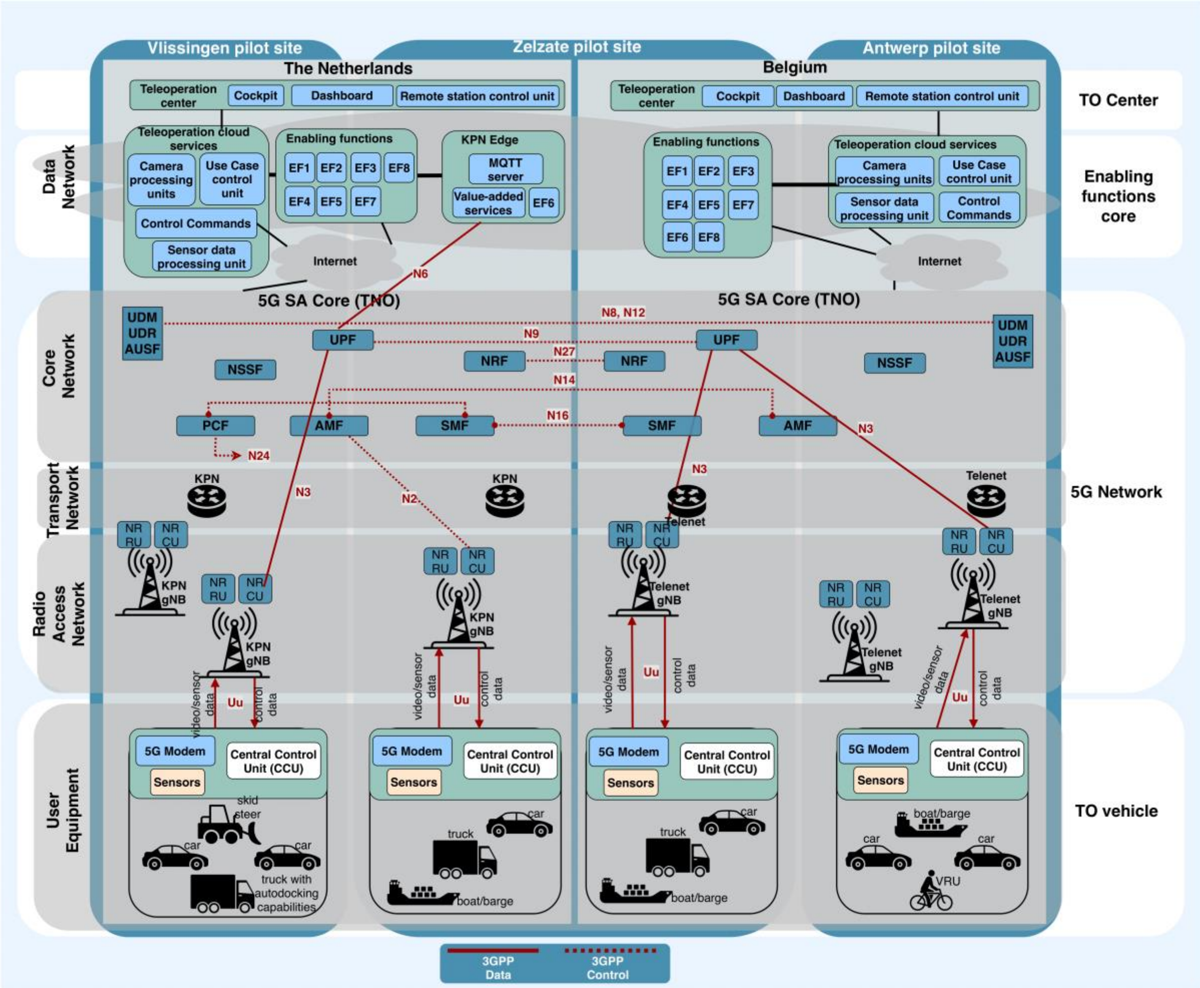

Figure 2 - Final overview of 5G-Blueprint architecture spanning three pilot sites.

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 in order to minimize the interruption time. The seamless roaming process is in detail described in [1] and [2], 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 (HR) roaming (based on interfaces between SMFs and UPFs, i.e., N16 and N9, respectively) and the N2 handover over the N14 interface. In Figure 1, once the ToV that is connected to Home Public Land Mobile Network (HPLMN) moves towards VPLMN, radio network of the HPLMN detects the need for handover (e.g., based on the signal strength) and informs AMF in HPLMN about that. Afterwards, this AMF instance communicates via N14 with its peering instance in VPLMN that handover is about to start. The AMF on the VPLMN side is using N16 to establish a new N9 tunnel between User Plane Functions (UPFs), which are routing the UE traffic after the handover procedure. The novelty of the 5G-Blueprint procedure reflects in a more efficient exchange of messages between peering core functions, which in turn minimizes the overall interruption time (from a few minutes in 4G and 5G NSA to below 150ms). In particular, to restore 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 High Definition (HD) video data towards teleoperation services running on the cloud (uplink). In addition, other types of traffic are being transferred in the uplink direction, such as, C-ITS messages from iTLCs to respective traffic management systems, such as Urban Data Access Platform (UDAP) and Traffic Light Exchange (TLE), 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 cases and enabling functions require network quality that can be offered by 5G network slices, such as ultra-Reliable Low-Latency (uRLLC) and enhanced Mobile Broadband (eMBB), which are tailored to their specific requirements. The mapping of the overarching 5G-Blueprint architecture (Figure 1) on the three pilot sites: two national (Antwerp and Vlissingen in BE and NL, respectively) and one cross-border (Zelzate), is presented in Figure 2.

1.2 Vertical-centric 5G architecture: Vertical operations in 5G-Blueprint ecosystem

In addition to the overall 5G architecture shown in Figure 1, Figure 3 shows more details about the teleoperation services and situational-awareness services or enabling functions, which are software functions designed and developed to increase the situational-awareness of the remote driver/captain.

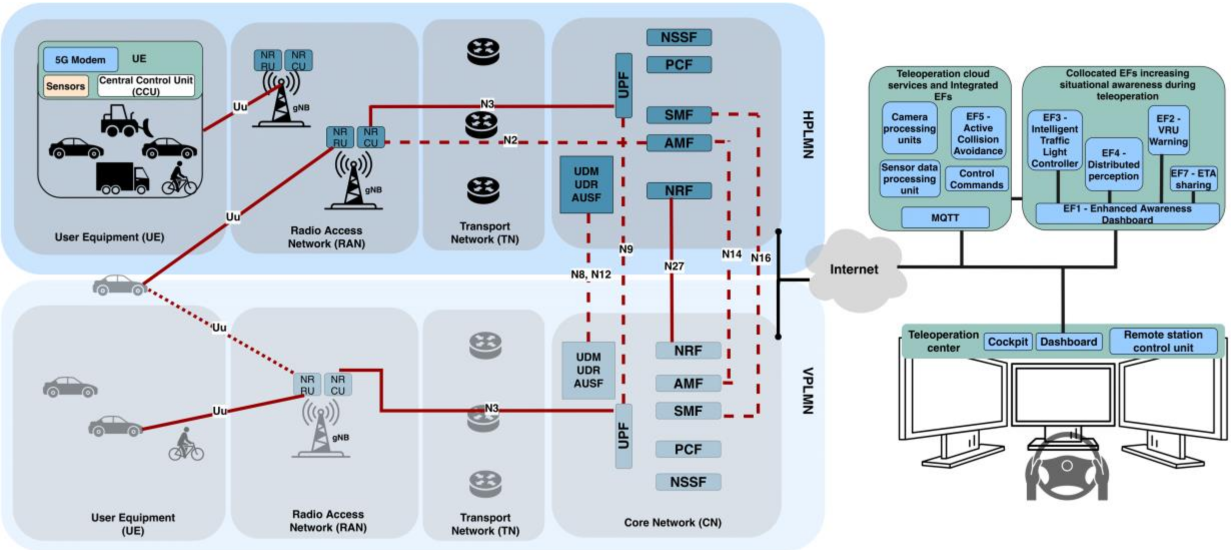

Figure 3 - Enhancing situational awareness of teleoperated driving across countries by leveraging collocated EFs.

In Figure 4, we illustrate the connectivity between the platoon of the teleoperated and regular cars and the Distributed perception enabling function. In particular, this enabling function is running in the cloud and is collecting lidar point clouds from vehicles in the platoon over 5G SA (eMBB slice), after which it proceeds with fusing and object detection operations. At the same time, it retrieves GPS coordinates of platoon vehicles. Once it detects obstacles, this enabling function communicates the findings with the enhanced dashboard, which is visible by the remote driver/captain (Figure 4). It is important to note that for this enabling function, the high signal quality on the uplink offered by 5G SA is essential for obtaining a robust obstacle detection, which in turn could have significant impact on the perception of the remote driver, and thus the safety of all participants in the platoon (teleoperated and regular cars).

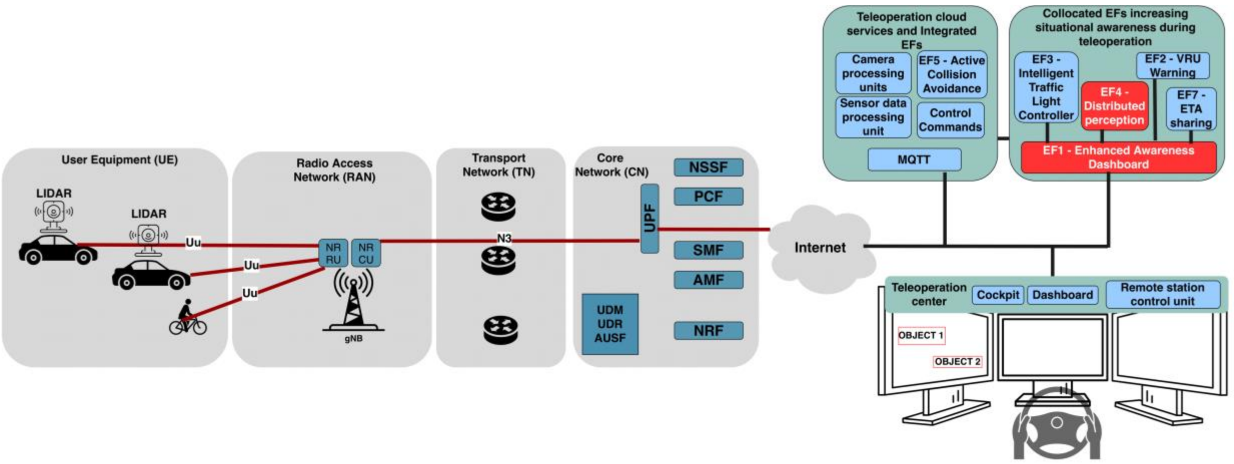

Figure 4 - 5G-boosted distributed perception for teleoperated vehicles.

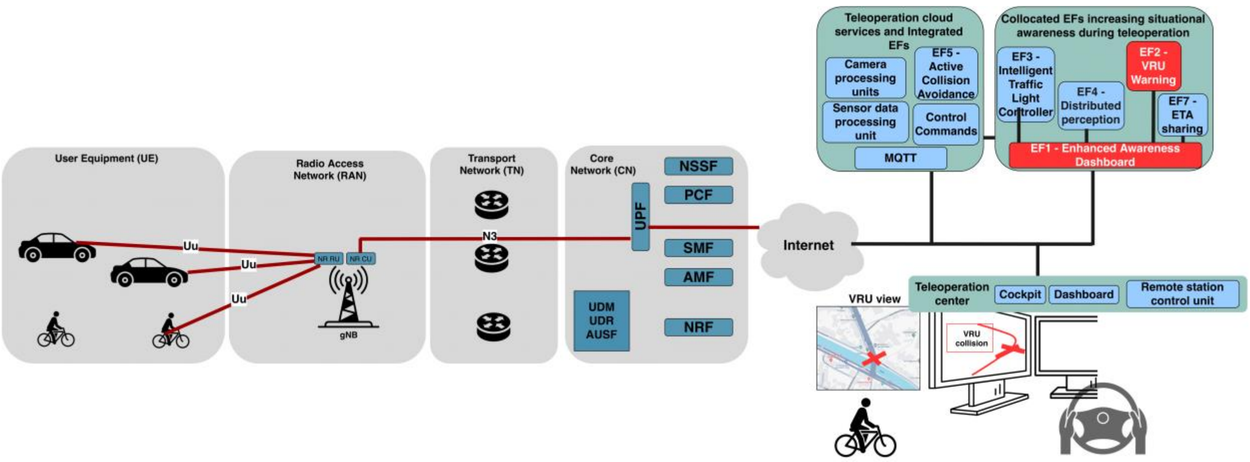

Figure 5 - Enhancing mutual awareness of both VRUs and teleoperated vehicles.

Similarly as in the case of distributed perception, Vulnerable Road User (VRU) warning enabling function is increasing mutual awareness and safety of VRUs and teleoperated vehicles in the mixed traffic scenarios (with regular and teleoperated vehicles), in both urban and industrial settings. Therefore, Figure 5 presents on a high-level the uplink data retrieval from the VRUs and vehicles (C-ITS messages indicating their location, speed, heading) over 5G SA (uRLLC slice) to the EF2 processing functions running in the cloud. The predicted paths and the locations of potential collisions are being displayed on both dashboard (teleoperator view) and VRU dashboard on the handset (VRU view) for the purpose of efficient collision avoidance. Due to the time criticality of such messages, uRLLC slice in both urban and industrial environments are utilized.

To further enhance the teleoperation process with a more streamlined crossing at intersections, intelligent traffic light controllers (iTLC) are placed at critical locations in urban and port environments. More details on the critical actors in the iTLC chain are offered in other sections of this deliverable, and Figure 6 illustrates the retrieval of C-ITS messages from the infrastructure (iTLC) and vehicles that enables their communication and collaboration.

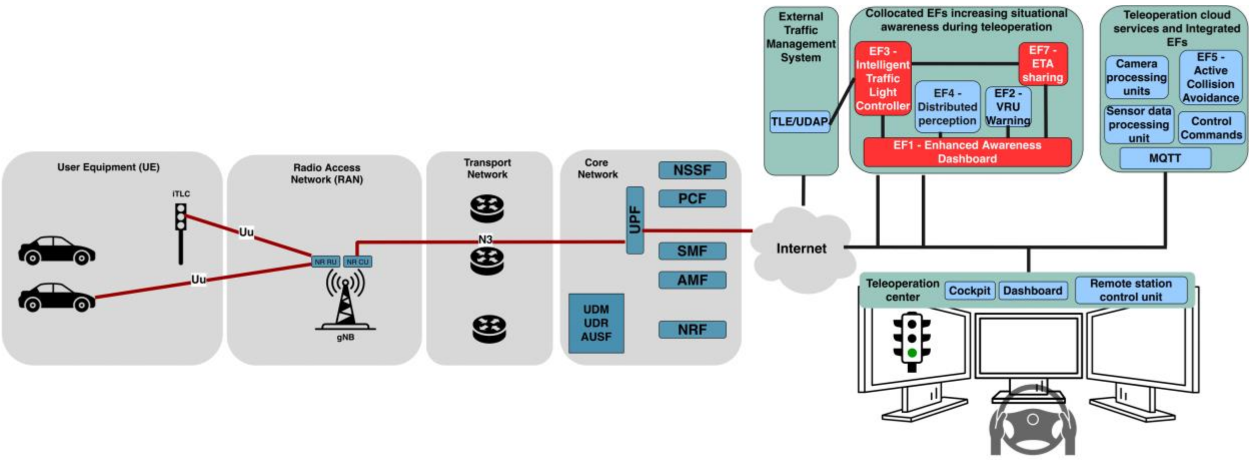

Figure 6 - More efficient teleoperation with 5G-connected intelligent Traffic Light Controllers.

Concerning Container ID recognition (Figure 7), this specific enabling function is placed at the network edge. By placing the processing functionalities of container ID recognition at the edge, we gain two benefits: i) the UE setup (camera and 5G modem) becomes quite scalable and easy to move from one suitable location to the other in the busy port environments with many containers to load/unload, and ii) capturing container IDs and their processing needs to be fast due to the high speed of their moving (containers moving on trails), while edge deployment offers significantly lower latency and better bandwidth utilization, which are essential for streaming high-quality video and ensuring reliability in catching the frames relevant for container ID recognition.

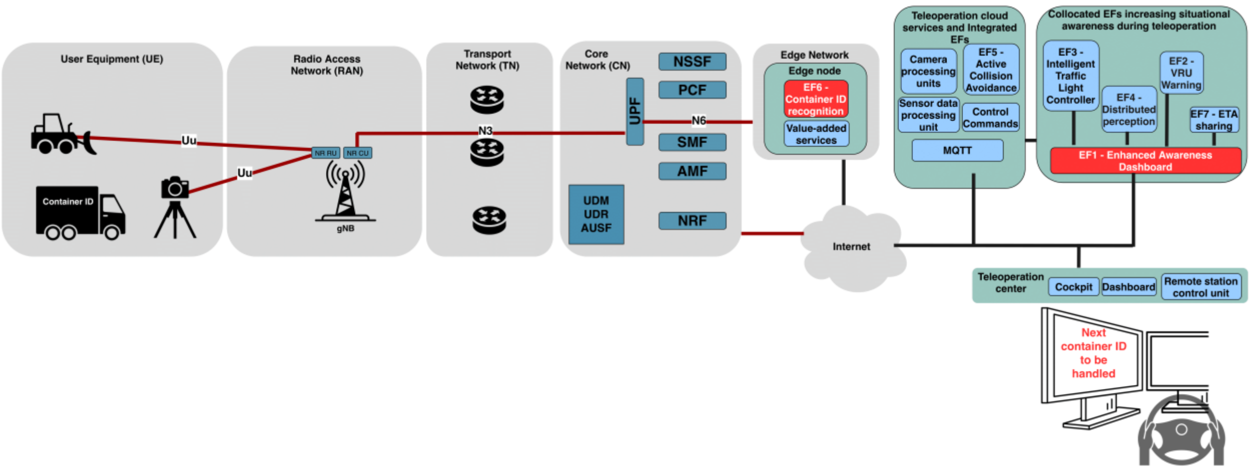

Figure 7 - Creating more efficient skid steer and crane teleoperation with 5G-based container ID recognition.

2 CROSS-SITE NETWORK PERFORMANCE DIGEST

To thoroughly evaluate the network performance, 5G-Blueprint has conducted a series of testing sessions at different locations in Antwerp, Vlissingen, and Zelzate pilot sites, which are covered by 5G NSA and SA network. The performance results are in detail presented and discussed in [3], while in this section, we extract the main findings and highlight those results that refer to uplink throughput, end-to-end latency or Round Trip Time (RTT), and service interruption time, as those three metrics are considered the most critical for teleoperation processes. To better understand the results, the connectivity requirements for teleoperation use cases in 5G-Blueprint project are the following: i) uplink throughput of at least 30Mbps in case six cameras are simultaneously streaming High-Definition (HD) videos (or 5Mbps per camera/sensor), ii) ultra-low latency for remote control commands (RTT less than 35ms), and iii) service interruption time of less than 150ms.

2.1 Antwerp pilot site

Due to the very dynamic environment in the port area of Antwerp site, with massive metal constructions, container parks, trucks passing by on the roadside and large ships and vessels sailing on waterways, having proper understanding of 5G performance is essential. Such diversity in terms of obstacles creates challenging circumstances for propagation of 5G SA signal, which due to shadowing and fading phenomena can be blocked or reflected, thereby in turn impacting the quality of service experiences by teleoperated barges, cars, and trucks. Although [3] provides a comprehensive analysis of metrics at various testing locations in Antwerp, here we briefly summarize the main results related to the Right bank (test location for teleoperation of barges, obstacle detection, and VRU warning), and Transport Roosens site where teleoperation of cars was extensively tested.

Concerning round-trip time, which is reflecting how fast the control commands from the remote driver/skipper can reach the teleoperated vehicle/barge, or relevant messages from enabling functions to VRUs and teleoperated vehicles, the obtained value is 27.1ms on average (maximum one is 99.3 ms, measured at the edge of cell) in the case of Right bank, and 36.6ms at the Roosens site. The average value measured at Roosens is higher due to the big peak that occurs near the Medrepair site where the connection was lost, which is confirmed by relatively low median value of 19ms. Given the requirement of less than 35ms, it can be confirmed that remote commands and essential messages can be safely and reliably propagated over 5G SA network in the tested locations in case of no additional background load. When the background traffic is introduced, as done at the Right bank of Antwerp pilot site, the impact on the RTT values is noticed, resulting in peaks of up to 666ms. Nevertheless, even in these conditions, the average and median values remained within acceptable range.

In the case of uplink throughput measurements, similar observations are made at both Right bank and Roosens site. Although the average UDP uplink throughput is 12Mbps, the 95th percentile reaches 29.5Mbps, which is sufficient for teleoperation. Similarly as in the case RTT, measurements obtained closer to the edges of the cell yield poorer network signal quality. However, as video streaming from cameras installed onboard is usually performed over Real-time Streaming Protocol (RTSP), which uses TCP as transport protocol, it is important to evaluate TCP uplink throughput as well. At the tested trajectory, the TCP uplink throughput significantly drops when the UE moves away from the gNB, resulting in mean value of only 9.14Mbps. Although the 95th percentile is close to 30Mbps, the trajectory for testing has been subsequently adjusted to avoid signal loss at cell edges.

From the extracted results presented and discussed above, it is clear that the 5G SA network in the 3.5GHz range suffers from limited range, which offers good signal quality up to 2km away from the gNB. Therefore, the placement of gNBs needs to be strategically planned as good signal quality is essential for uplink throughput and end-to-end latency, required for successful teleoperation of cars, trucks, and barges. Also, the harsh environment in the busy port area is a significant impact factor for network performance.

2.2 Vlissingen pilot site

Testing of network performance at the Vlissingen pilot site was performed at three different locations, i.e.,: Verbrugge terminal (relevant for trialing of teleoperation-based platooning and Container ID recognition), MSP Onions (relevant for testing autodocking capabilities), and public road between MSP Onions and Kloosterboer terminal in the Vlissingen pilot (relevant for trialing of teleoperation-based platooning in shadow mode, and intelligent traffic light controllers).

Let us first tackle the results from the Vlissingen site. Concerning throughput on the uplink, the mean value with no background traffic introduced is 52.8Mbps, which drops to 23.3Mbps when there is impact of the background traffic. This impact is significant, which can be seen due to 95^{th} percentile being 62Mbps when there is no impact and 30.3Mbps when background traffic is introduced. As the impact of background traffic affects end-to-end latency as well (~80% increase in 95% cases), it is important to carefully dimension cells, and define gNB placement, with denser deployments at busy areas.

The **MSP Onions** is covered only with 5G NSA signal, thus there is no slicing involved. The TCP uplink throughput is 34.9Mbps on average, with 95^{th} percentile of 38.5Mbps. The RTT measurements indicate the average value of 24.1ms, while the highest values stretch to 63.8ms which are considered outliers due to scheduling of resource blocks.

The third location is the stretch of the **public road** between the MSP Onions and the Kloosterboer terminal. Similarly as in case of Antwerp pilot site, values obtained near the cell edges are lower in case of uplink throughput and end-to-end latency. The maximum value reached 69.5Mbps, signifying the important of good cell coverage for obtaining sufficient uplink throughput values, which are essential for safe teleoperation. The end-to-end latency is 29.6ms on average, with the 95^{th} percentile of 34.2ms, which is slightly exceeding the expected values for the remote control of trucks at MSP Onions.

In overall, the 5G SA performance evaluation at Vlissingen pilot site shows that URLLC slice is more stable than eMBB when background traffic is introduced. This highlights the importance of proper network design and slice choice when it comes to latency-sensitive applications as teleoperation, where URLLC should be always used for transferring mission-critical messages and control commands. All presented results show that both SA and NSA networks at tested locations are able to support the teleoperation requirements. Similarly as in case of Antwerp pilot site, providing good coverage is crucial to meet the connectivity requirements, as moving towards cell edges drastically degrades signal quality, thus achieving lower throughput values.

2.3 Zelzate pilot site

The cross-border site consists of two gNBs that are covering both the waterways (Gent-Terneuzen canal) and the stretch of the public road in parallel with the canal. The locations of gNBs are shown in Figure 8. The driving tests with the test vehicle and sailing tests with the boat have been performed in the selected area between two base stations (Figure 8). It is important to note that more tests have been done on the roadways due to the limited availability of the test boats.

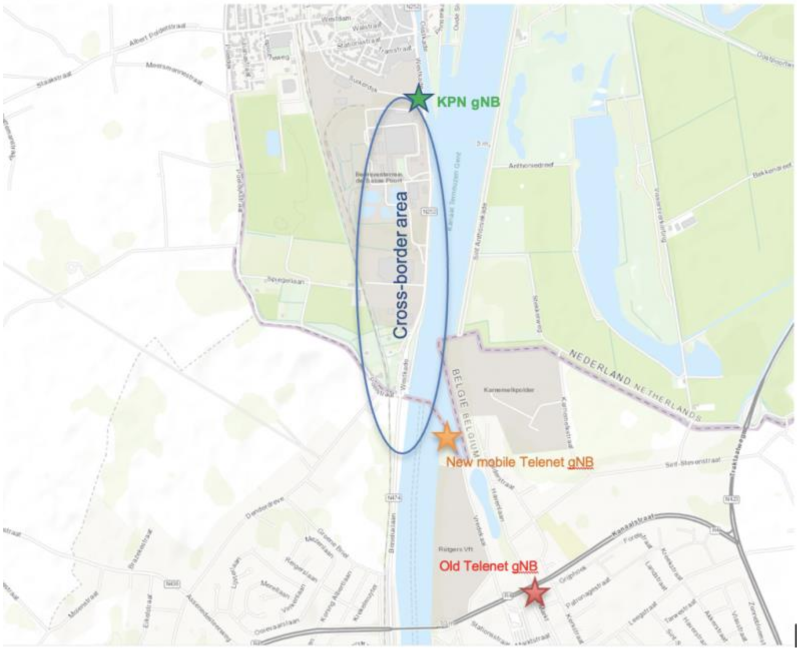

Figure 8 - Cross-border area and locations of gNBs.

Given the presence of active antenna on the Belgian side of the border, the TCP uplink throughput values are higher on the Belgian than on the Dutch network. The median value of uplink throughput is 24.3Mbps and 95th percentile of 51.5Mbps. These values are high as the UE has been connected to Belgian network longer than on the Dutch. The range of obtained values for both uplink throughput and end-to-end latency is acceptable for achieving safe teleoperation across country border, as per requirements mentioned earlier in this paper.

Another important metric that is specific for the cross-border setting is the service interruption time, or network downtime. The metric is defined as the time between the last packet the UE could send while being connected to HPLMN, and the first packet it sends over the VPLMN when crossed the border. The optimizations of the seamless handover performed in the 5G-Blueprint project yield lower values of interruption time, and as both median and 95th percentile are significantly below 150ms, service interruption time is unnoticeable for cross-border teleoperation process. This optimization is obtained by preparing the PDU session as much as possible beforehand to further reduce the downtime (fewer messages are exchanged between 5G Core functions in two networks). Finally, to further reduce the end-to-end latency (between UE and application servers), it would be important to study aspects of edge deployments and deploying teleoperation services and EFs at the network edge to avoid home-routing roaming, which is out of scope of the 5G-Blueprint project.

3 PERFORMANCE OF TELEOPERATION AND AUTOMATION

During the teleoperation piloting activities in all three pilot sites, **shadow-mode testing** has been used on the public roads. In the 5G-Blueprint project, this mode of testing refers to direct control teleoperation, in which all subsystems of the teleoperation solution are active. This means that the camera streams are normally sent to the remote operator station, and the control signals created by the remote operator (steering wheel, pedals, joysticks) are normally sent to the teleoperated vehicle/barge. The specificity of the shadow mode testing is that these commands sent from the teleoperation center over 5G to the UE in the vehicle, do not obey to final translations to mechanical signals that perform the actual steering, acceleration or braking. As a result, the remote driver/skipper is not in the control of the vehicle/barge but the safety driver/skipper in the vehicle/barges. Nevertheless, all data collected during these processes are identical in both situations (remote operator in control and not in control). Shadow mode testing has proved extremely useful for testing scenarios when there is no permit to perform direct remote control, such as in the case of public roads. All results obtained during shadow mode testing allow us to fully assess if teleoperation would have been possible on these public roads or not, in normal mixed traffic, without introducing any safety risks to the surrounding traffic or infrastructure.

The tests obtained for teleoperation-based platooning in Vlissingen and Antwerp show that the controller is able to steadily control the following vehicle in the platoon over 5G network with minimal distance error (obtained 2-4%, target below 5% to keep steady position), thereby validating the overall performance of the CACC system. Although the results reported the maximum speed of 60kmph, it is important to note that same quality of service is observed for higher speeds (up to 100kmph) when they were allowed on the public roads using the shadow mode testing. In addition to that, the overall CACC setup with PC5-based communication between the vehicles in the platoon showed no deactivations caused by delays imposed by 5G network, which confirms the **stability of the teleoperation over 5G**. Other service KPIs such as steering accuracy, which are relevant for teleoperation chain, exhibit values that belong to acceptable ranges (mean error 0.077 [º], with target of less than 0.1 [º]), thereby reinforcing the validity of the results obtained during piloting campaigns both within and across the country boundaries.

When it comes to autodocking tests, the delay variation in relaying remote commands from the operator to the truck are usually associated with network impact. From the obtained results, 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 100ms (control loop speed and TC cut-off threshold) will of course give the best results. Given the network analysis digest in Section 2.2, this requirement is met in all test locations, including the MSP Onions location where the autodocking is tested. Other service KPIs relevant for autodocking have been measured as well, such as path planning efficiency which is not directly impacted by network, but the performance of the underlying computing platform. Another one is final docking state error, which corresponds to the end position of the trailer, and if large, it means that truck trailer combination is not parked properly. As this KPI is also affected by network, obtained values of below 10cm are considered sufficient for safe autodocking process, **validating the positive impact of stable 5G connectivity**. For the purpose of localization, RTK GPS has been used and it proved as a robust and suitable method for precise localization during autodocking of full-scale trucks. However, the high prices of RTK systems motivate further studies of alternative solutions, such as localization based on cellular networks, which is out of scope of this project.

In the context of testing network connectivity for intelligent traffic light controllers in the Zelzate pilot site, we obtained results that show interesting findings related to **slice isolation**, which is important for ensuring stable network connectivity for iTLCs. In a broader sense, the effective isolation is essential for ensuring that the performance of one slice does not impact another. Our findings show that although there is some level of isolation, the impact of high-load conditions across slices shows that more refined isolation mechanisms are needed. In the context of the intelligent traffic lights in particular, this is essential to guarantee that each slice can independently meet specific service requirements for efficient traffic control, regardless of the overall load on the network caused by other users (e.g., teleoperated vehicles approaching intelligent traffic lights at busy intersections). The current deployment of network slicing in the Zelzate city center 5G SA environment shows promising capabilities, particularly in handling diverse network demands through eMBB and URLLC slices. Nevertheless, there is still room for improvement, particularly in enhancing latency management for the eMBB slice and ensuring consistent performance and better isolation for the URLLC slice under varying network traffic load conditions.

Another interesting result is obtained during VRU Warning trialing activities in Antwerp pilot site, in both industrial and urban settings. Having network reliability as one of the key KPIs for ensuring efficient dissemination of VRU-related notifications and potential collisions, the results shows that the urban setting resulted in many lost messages when connected on 5G SA. However, given that the urban trials were carried out using the 3.5GHz band in a test site with only one 5G node, whereas the 4G reference network has a dense configuration in this urban area, this is not a surprising result. In the respective industrial setting in the Port of Antwerp area, where multiple 5G nodes are available, the **5G network provides the required reliability** of at least 98% in real-life conditions. Such result reinforces the learning from the network evaluation test that shows essential value in proper network dimensioning at higher frequency ranges such as the one centered around 3.5GHz.

4 LESSONS LEARNED

Having deployed both 5G Non Standalone (NSA) and Standalone (SA) networks at different pilot sites in two countries, 5G-Blueprint created a diverse environment for real-life testing and validation of teleoperation, aiming to optimize the transport & logistics operations in busy port environments. Along with teleoperation, autodocking aspects have been significantly studied and functionality developed and validated to ensure smooth interaction between two modes: teleoperation and automation.

To provide sufficient understanding of the 5G capabilities in the national and international pilot sites, we leverage the extensive network performance analysis from [3] as a reference. From the results obtained in all three pilot sites, it is clear that the 5G SA network deployed in the 3.5GHz range suffers from limited range, which offers good and stable signal quality but only up to 2km away from the gNB. This signifies the importance of **proper dimensioning of 5G SA** networks, with careful gNB 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 are able to support the teleoperation requirements (5Mbps uplink throughput per sensor/camera, below 30ms end-to-end latency for remote control commands, and below 150ms interruption time during handover process). In particular, service interruption time has been measured to evaluate how much time is needed for 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 minimization of interruption time by proactively starting handover process (PDU session relocation prepared before handover actually happens), and minimizing the number of messages exchanged between 5G Core functions during the actual handover. The results show that both median and 95th percentile are significantly below 150ms, making service interruption time unnoticeable for cross-border teleoperation of both vehicles and barges.

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 remote skipper needs to properly navigate the barge. This uplink data is being streamed from the computing unit on the barge to the private cloud, from where the data is further being visualized on the screens of the skippers in the office. 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.

For a **truck & trailer system** to be capable of **both teleoperation and autodocking**, certain functionalities are necessary at both teleoperation center and teleoperated vehicle sides. Apart from the hardware equipment that is used for physical actions that 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 DBMW system, autodocking manager, 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 addition, the teleoperator is making use of the additional display that shows the Enhanced Awareness Dashboard that is capturing detected obstacles, VRUs, recommendations on speed, and information on ETA, as well as container ID in the case of skid steer and container (un)loading. 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 case of teleoperation, autodocking software is receiving camera streams and vehicle telemetry data, and it interacts with the autodocking manager for transferring instructions for docking, which are further translated to the DBW system on the vehicle that is performing the actual control of the truck. In case of teleoperated skid steers or cranes, EF6 is offering enhanced capabilities for improving logistics in the port environments. Using this enabling function, it is possible to load/unload containers from barges or trucks by timely detecting the **container IDs**, and showing those IDs to the teleoperator.

The **teleoperation of cars** is performed in the same way as it has been described above for the truck & trailer combination, or for the skid steers. 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 certain distance and following the speed advice. This cooperation is exchanged directly between platoon vehicles, i.e., via V2V communication based on PC5, and it includes acceleration and speed values of the lead vehicle via 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 platoon.

Once the teleoperated vehicles or platoons of teleoperated vehicles are in vicinity of the intelligent traffic lights, the controller is calculating the time slot for each vehicle, for which the green light passage can be granted. Concerning warnings, **VRUs** are using mobile phones to indicate their presence over 5G connectivity to VRU and collision detection services, and as this communication is considered safety critical, it is important to highlight that uRLLC slice is being utilized. After the possible collision paths are identified by the service, notifications are being displayed both at the teleoperation center and shared with the VRUs using the 5G SA downlink channel. The other type of warning, i.e., **detected obstacles** are in real-time displayed on the enhanced dashboard, and they are created based on GPS data retrieved from teleoperated vehicles via MQTT and Lidar point clouds fused from sensors deployed on the vehicles themselves. In the 5G-Blueprint project, all the above mentioned components (various services implementing teleoperation use cases and their increased situational awareness via enabling functions) are coupled together in a 5G ecosystem shown in the final architecture (Figure 1).

As it can be seen from all results summarized in this whitepaper, 5G Standalone plays an essential role for 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 promising future of 5G-based teleoperation in European cross-border corridors. 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 final deliverable of WP7 provides valuable insights into realistic results obtained during extensive testing of all necessary technical elements in the 5G-enhanced teleoperation chain (network, teleoperation use cases, and enabling functions providing increased situational awareness). 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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