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5G BLUEPRINT

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

D7.3: Final Architecture Revisited

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Abstract

When it comes to autonomous driving or sailing, one of the biggest challenges is guaranteeing safety in all scenarios. Since it is extremely difficult and expensive to predict and replicate all possible scenarios that could happen on the roads and waterways, we see teleoperation as a completely complementary technology that can be used to provide human interventions and solve complex scenarios that cannot be tackled by autonomous mode. Therefore, in the 5G-Blueprint project we have worked on the direct control teleoperation, which could be assigned to specific segments of the road/waterways. The 5G-Blueprint teleoperation approach is a concept that relies on 5G connectivity to remove the physical coupling between the human operator (driver or captain/skipper) and the controlled vehicle/vessel. This mode of operation reflects demanding connectivity requirements such as: i) high uplink bandwidth for transferring video streams from cameras onboard to the teleoperation center, ii) low latency and ultra-reliable connection for relaying commands from the teleoperator to the remote vehicle/vessel, and iii) low interruption time when the teleoperated vehicle/vessel is crossing the border between two countries to ensure seamless connectivity and uninterrupted remote operation. Therefore, in this deliverable, we present the final overview of the overarching 5G-Blueprint architecture, combining the pieces of 5G Standalone network with seamless roaming mechanisms, and service/application components (use case and enabling functions), to deliver safe and efficient remote operation. Along with the final architectural view, this deliverable also presents the blueprint of components (use cases and enabling functions) that are altogether essential for achieving safe and efficient remote operation within and across country borders.

Keywords: 5G SA, network slicing, teleoperation, seamless roaming, TOV, cross-border, safety, VRU, intelligent traffic lights, enhanced awareness, distributed perception

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DEM: Demonstrator, pilot, prototype, plan designs

DEC: Websites, patents filing, press & media actions, videos, etc.

OTHER: Software, technical diagram, etc

EXECUTIVE SUMMARY

This deliverable reports the latest status of the 5G-Blueprint 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.

In this deliverable, we make a brief overview of the relevant teleoperation aspects, discussing them from a perspective of future mixed traffic conditions where teleoperated vehicles will be present along with regular and autonomous ones. In the 5G-Blueprint project, we consider automation and teleoperation as complementary technologies, which could and should be assigned to different segments of a trajectory, depending on the conditions. This way, edge cases that are difficult or impossible to replicate and train in case of fully autonomous vehicles, could be tackled by remote takeover of control, thereby realizing driverless mobility in a safe, scalable, and cost-efficient manner. However, teleoperation has demanding connectivity requirements, such as high uplink bandwidth, low latency and ultra-reliability at the same time, which become even more stringent in the cross-border scenarios where service interruption needs to be minimized for teleoperation to perform smoothly. 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.

Furthermore, we detail on the final version of the overarching 5G-Blueprint architecture. It showcases on a high-level the configuration on the radio and core network, especially combining 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 (between AMFs), to enable seamless roaming with negligible interruption time (less than 150ms in case of teleoperation use cases). This architecture also includes the final deployment aspects related to use case and enabling function components placed at the edge or cloud computing units.

In addition to the final architecture overview, we give a glimpse on the final blueprint for deployment of all use cases and enabling functions, which are collocated with use cases to provide enhanced awareness to the remote driver in the form of obstacles and VRUs detected in real time to prevent possible collisions, assistance at complex crossings with the help of intelligent traffic light controllers, container ID recognition to help with loading/unloading process, among others.

In particular, the final blueprint of the deployment is provided for the following use cases: i) automated barge control with the goal of remote operation of barges over 5G, in both national and cross-border sites, ii) the teleoperation and autonomous docking of a truck-trailer combination, as an innovative solution that addresses the challenges of docking processes in the logistics domain by enabling autonomous docking of a truck and trailer combination, as an operation traditionally reliant on human expertise, and iii) the teleoperation-based platooning as a driver assistance system designed for highway and constant-speed zone driving scenarios,

where the lead vehicle is teleoperated and the following vehicle is initially driven by a human driver.

Also, the following aspects of enabling functions are captured, focusing on the interactions between the use cases and enabling functions, and enabling functions among themselves. For instance, the Enhanced Awareness Dashboard (EAD) or Enabling Function 1 (EF1) is created for the remote operators to enhance their situational awareness, displaying the following three types of information: Speed advice, Warnings, and Navigation and Route Features. Concerning the warnings, one of them is VRU Warning generated by EF2, which is in charge of calculating the likely path of all VRUs around the teleoperated vehicle, and based on such paths, it creates early warnings to VRUs and teleoperators about potential collisions. Another type of warning is related to detected obstacles, retrieved from EF4 that is performing 3D object detection to create a shared situational awareness for platoons that consist of regular and teleoperated vehicles, along with EF5 which is a collision avoidance system that prevents driven/teleoperated/autonomous vehicles from collisions and protects workers and property in the area. For the speed advice, the EF3 plays an important role as it ensures conflict-less crossings for teleoperated transport at intersections. Concerning EFs running on the network edge, EF6 is designed in such a way to place the processing functionalities of container ID recognition close to the UEs (camera with 5G modem), which in turn offers the possibility for more scalable and flexible UE setups that can be easily moved from one suitable location to the other in the busy port environments with many containers to load/unload. Importantly, container ID recognition needs to be fast due to the high speed of moving of trailers, and 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.

While this document reports on the necessary technical elements in the 5G-enhanced teleoperation chain, D7.4 offers statistical analysis of the relevant results that are obtained during piloting activities in real-life network deployments in in-country and cross-border port environments.

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ABBREVIATIONS

5G NSA	5G Non Standalone
5G SA	5G Standalone
AMF	Authentication Management Function
AuSF	Authentication Server Function
APF	Artificial Potential Function
CACC	Cooperative Adaptive Cruise Control
CAM	Cooperative Awareness Messages
CAN	Controller Area Network
CCU	Central Control Unit
C-ITS	Cooperative Intelligent Transportation System
Cloud App	Cloud Application
C-V2X	Cellular Vehicle-to-Everything
DBW	Drive-By-Wire
EAD	Enhanced Awareness Dashboard
ECU	Electric Control Unit
Edge App	Edge Application
EF	Enabling Function
eMBB	enhanced Mobile Broadband
ETA	Estimated Time of Arrival
HD	High Definition
HPLMN	Home PLMN
HR	Home-Routed
iTLC	intelligent Traffic Light Controller
MAPem	MAP Extended Message
MPC	Model Predictive Controller
MQTT	Message Queuing Telemetry Transport
MVP	Minimum Viable Platform
NRF	Network Repository Function
NSSF	Network Slice Selection Function
OBU	On-Board Unit
PCF	Policy Control Function
PLMN	Public Land Mobile Network
PPC	Pure Pursuit Controller
RAN	Radio Access Network
SMF	Session Management Function
SPaTM	Signal Phase and Timing Messages

SRM	Signal Request Messages
SRTI	Safety Related Traffic Information
SSM	Signal Status Messages
TLEX	Traffic Light Exchange
ToV	Teleoperated Vehicle
UDAP	Urban Data Access Platform
UDM	Unified Data Management
UDR	Unified Data Registry
UE	User Equipment
UPF	User Plane Function
uRLLC	ultra-Reliable Low-Latency Communication
V2V	Vehicle-to-Vehicle
VPLMN	Visited PLMN
VRU	Vulnerable Road User

1 INTRODUCTION

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. In this deliverable, we present the technical aspects of this objective, in particular, the design of the final technical architecture that reflects all the actors and interactions between them that are essential for achieving seamless teleoperations across country borders. The validation aspects, i.e., the presentation and analysis of pilot activities and obtained results are presented in deliverable D7.4.

In this section, we will briefly tackle the motivation behind pursuing 5G-enhanced teleoperation, including the rationale behind the architectural design and use case and enabling function components that are presented in the later sections of this deliverable.

Almost thirty years ago, a group of scientists from the Carnegie Mellon University’s Robotics Institute conducted an experiment across USA in an autonomous minivan. The outcome of this experiment shows that although being able to achieve autonomous mode during 98.2% of the trajectory, the remaining 2% of the trajectory still required human intervention due to unpredictable and difficult to handle situations on the roads. Such result has a greater implication on the automotive sector, as guaranteeing safety in all possible edge case scenarios is an utmost priority. Such edge cases are traffic situations where one or more unusual operating circumstances take place, which are usually difficult or expensive to replicate and train in the real-life environments. This is why in the 5G-Blueprint project we focused on an alternative approach to solve this problem, i.e., teleoperation, as a complementary technology that involves human in the loop to resolve the edge case scenarios in combination with the autonomous mode of driving/sailing. The teleoperation process means that at least a part or all of the driving/sailing tasks are performed by a remote operator, usually over wireless communications [1].

Table 1 Overview of 5G-Blueprint use cases and enabling functions.

Acronym	Use case/Enabling function	Objective	Collocated with
UC4.1	Automated barge control	Remote operation of barges from the control center via 5G connectivity	NA
UC4.2	Autodocking of trucks and skid steer teleoperation (UC4.2)	Combination of teleoperation and autodocking capability for full-scale trucks (truck and trailer combination) and skid steers over 5G network; addressing challenges of docking processes in the logistics domain	EF1, EF7
UC4.3 & UC4.4	Teleoperation-based platooning (UC4.3 & UC4.4)	Providing a driver-assistance system for highway and constant-speed zone driving scenarios, with the lead vehicle being teleoperated over 5G while the following one could be still human-driven or teleoperated as well	EF1, EF2, EF3, EF4, EF5, EF7
EF1	Enhanced Awareness dashboard	Enhancing situational awareness of remote drivers by displaying the following three types of information: Speed advice, Warnings, and Navigation and Route Features	UC4.2-4.4, EF2, EF3, EF4, EF7
EF2	Vulnerable Road User (VRU) Warning	Increasing VRU safety by calculating possible collisions between VRUs and teleoperated vehicles, while collecting real-	EF1, EF7, UC4.3-4.4

		time awareness messages from VRUs over 5G network and showing dynamic notifications of possible collisions on the awareness dashboard	
EF3	Intelligent Traffic Light Controllers	Ensuring conflict-less crossing of teleoperated vehicles at complex intersections by enabling smooth communication between teleoperators and intelligent traffic lights over 5G	UC4.3-4.4, EF1, EF7
EF4	Distributed perception	Creating situational awareness of teleoperated platoons by performing 3D object detection based on fused lidar point clouds collected over 5G	EF1, EF7
EF5	Collision Avoidance System	Preventing human driven, teleoperated, and autonomous, vehicles from collisions and protecting workers and property in the area where the mixed maneuvers are happening	UC4.3-4.4
EF6	Container ID recognition	Providing the capability of fast identification of shipping containers on video streams collected over 5G SA on the edge computing nodes	EF1, UC4.2
EF7	Estimated Time of Arrival (ETA) sharing	Calculation of ETA values for teleoperated vehicles and other participants in the traffic (VRUs)	EF1, EF2, EF3, EF4, UC4.2-4.4

The reason for not adopting the complementary approach of automation and teleoperation earlier (e.g., in the experiment performed by the aforementioned group of scientists) are the stringent network connectivity requirements, which were not possible to achieve with the previous generations of mobile communication systems. The connectivity requirements for teleoperation use cases in 5G-Blueprint project are in-detail described in D5.1 [2], 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). Tackling extremely challenging cross-border conditions, which are applicable in case of international transport & logistics, the connectivity should seamlessly roam between network operators at the border crossing, enabling total interruption time of less than 150ms. This combination of characteristics has not been 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. The validation of this technology over 5G NSA and SA has been thoroughly performed for all use cases and enabling functions in real-life environments within three pilot sites, and the results and analysis are provided in D7.4 deliverable.

To test and validate 5G capabilities that could be leveraged large scale in future deployments, 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 increase the readability of the following sections in this deliverable, we provide the overview of all use cases and enabling functions in Table 1, summarizing their objectives and collocation with each other. While the details of the overarching architecture are provided in Section 2, the collocation aspects and interaction between use cases and enabling functions are explained and illustrated in operational and message sequence diagrams in Section 3.

2 FINAL 5G-BLUEPRINT ARCHITECTURE

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

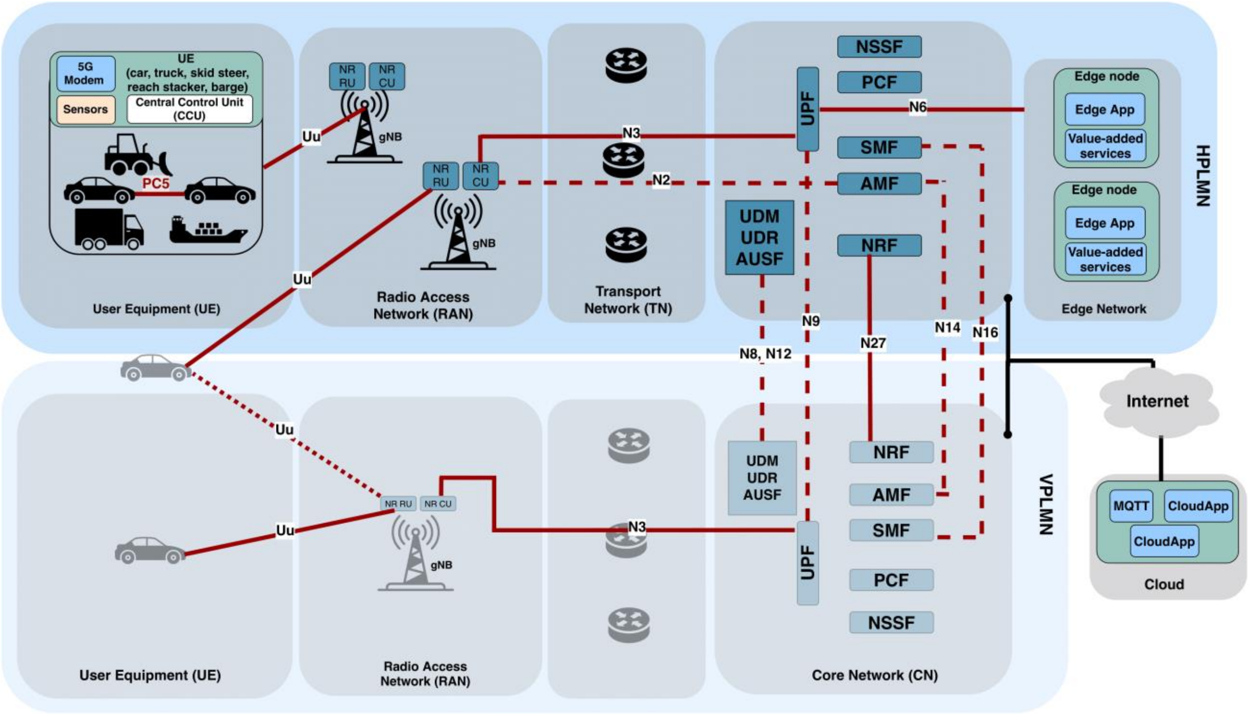

Figure 1 Final 5G-Blueprint architecture.

Table 2 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

In general, 5G Standalone (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. From a specific 5G-Blueprint perspective, the first version of 5G-Blueprint architecture was presented in D7.2 [3], as a result of an evolving exercise that started from Initial Defined Architecture or IDA in D7.1 [4]. Compared to those two versions, 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 1 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 final phase of the project (M25 onwards), 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.

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.

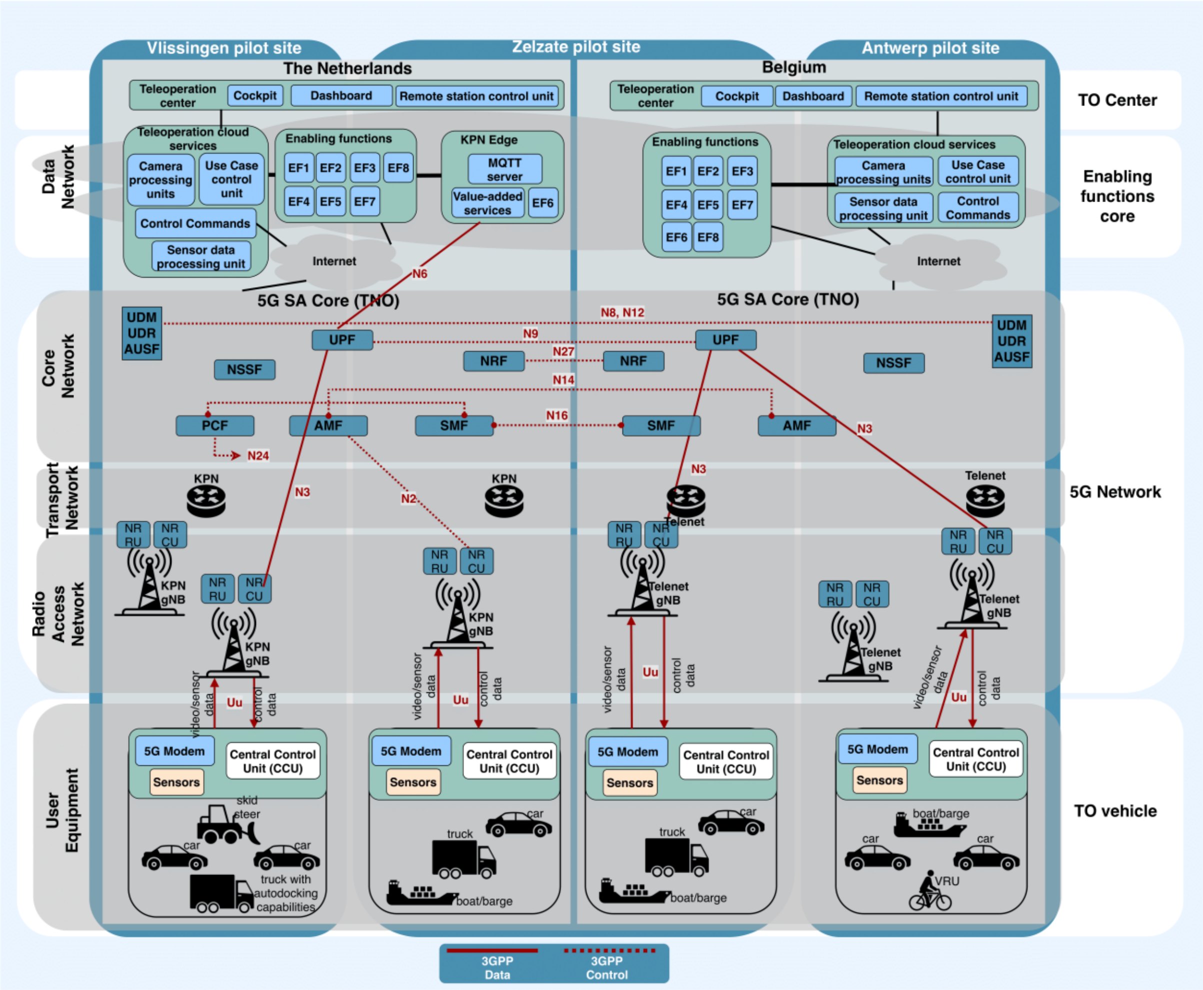

Figure 2 Final overview of 5G-Blueprint architecture spanning three pilot sites.

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 D5.3 [5] and [6], 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 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. Furthermore, Figure 3 provides an overview of the collocation of EFs with the teleoperation use cases for the purpose of enhancing the situational awareness of the remote driver and thus increasing the safety of the overall teleoperation process. It is important to note that the EFs are not formally integrated with the teleoperation chain, and the collocation of EFs with use cases is an intentional design choice. To be more precise, by keeping EFs and teleoperation chain as decoupled as possible, the robustness of the system is increased, as we minimize the possible propagation of any software faults or other similar issues from one domain to the other, which is essential for safety-critical applications such as teleoperation. The EFs and use cases are therefore collocated to provide valuable input for the remote driver in the form of enhanced awareness dashboard where detected obstacles, VRUs, signaling from the iTLCs, containers IDs to be loaded/unloaded, and relevant ETAs, are presented. This is in line with the safety and infotainment features in modern vehicles, as those are presented to the driver at the same time, but in fact belong to parallel systems.

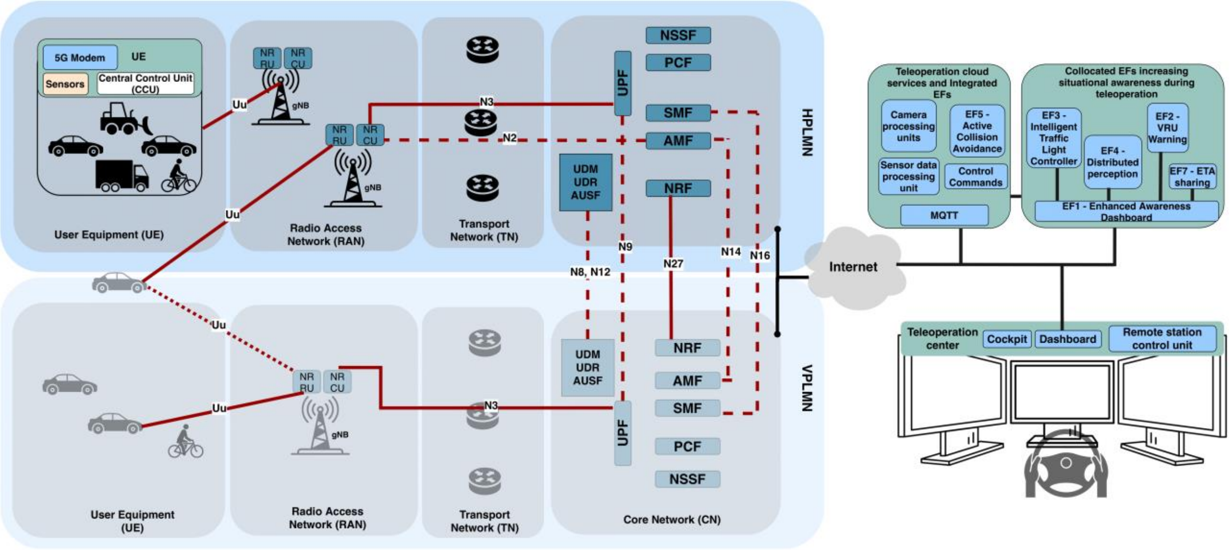

Figure 3 Enhancing situational awareness of teleoperated driving across countries by leveraging collocated EFs.

In particular, Figure 2 also presents the specific placement of the EFs and teleoperation services, i.e., cloud or edge. While most of the teleoperation services that are in charge of processing camera/sensor data and producing control commands are placed in the public/private cloud deployments of responsible partners, EF6, or Container ID recognition enabling function is placed at the network edge (KPN premises). It is important to note that the asymmetric edge deployment displayed in Figure 2 is a practical choice specific to implementation in the project pilot sites. In particular, EF6 has been extensively piloted in the Vlissingen pilot (NL) site and thus only the KPN edge deployment has been used for camera processing operations and ID recognition. A similar deployment could be spawned at different locations, including the Belgian side of the border if other functions would require edge computing capabilities. In addition, edge deployments have not been used in the cross-border setup, where the piloting activities of automated barge control and teleoperation-based platooning (reported in D4.1, D4.3, and finally in D7.4) included interaction with services deployed in the public cloud environment.

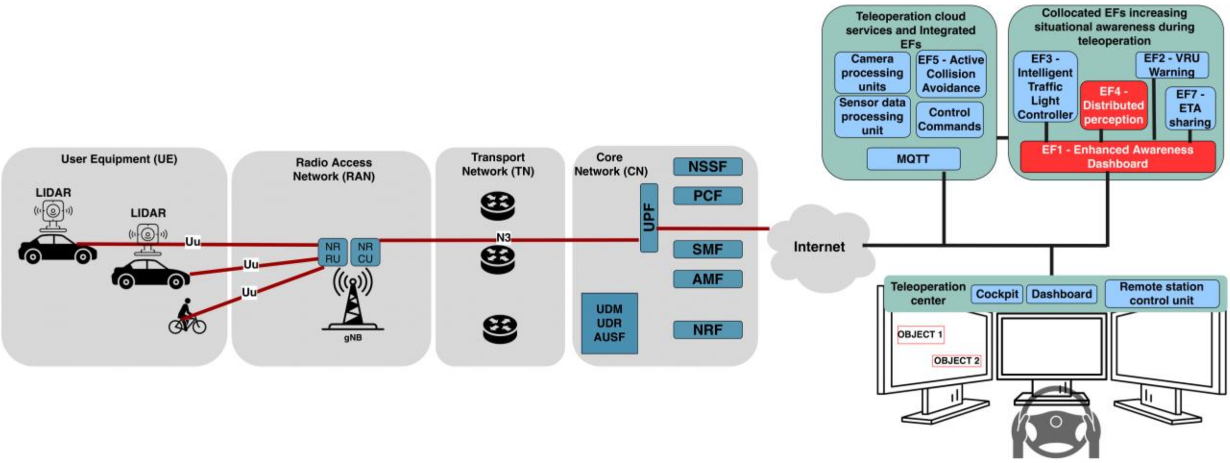

Figure 4 5G-boosted distributed perception for teleoperated vehicles.

In Figure 4, we illustrate the connectivity between the platoon of the teleoperated and regular cars and the EF4, i.e., Distributed perception enabling function. More details on how this enabling function operates are provided in Section 3.7, but Figure 4 shows how the distributed perception for teleoperated vehicles is deployed in 5G-Blueprint. In particular, EF4 running in the cloud 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, EF4 retrieves GPS coordinates of platoon vehicles from the Enhanced Awareness Dashboard (EAD) enabling function. Finally, EF4 communicates the detected obstacles to the EAD, which displays them to the remote driver (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). The performance results of this EF, as for the other use cases and enabling functions, are provided in D7.4.

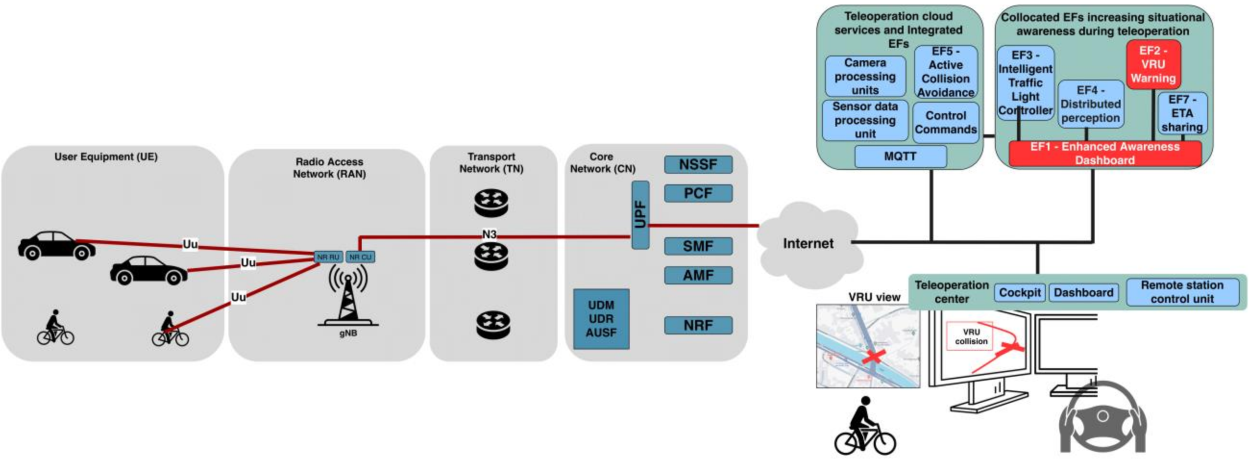

Figure 5 Enhancing mutual awareness of both VRUs and teleoperated vehicles.

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 EAD (teleoperator view) and VRU dashboard on the handset (VRU view) for the purpose of efficient collision avoidance. More details on the overall operation are presented in Section 3.5. Due to the time criticality of such messages, uRLLC slice in both urban and industrial environments are utilized, and corresponding results and performance analysis are presented in D7.4.

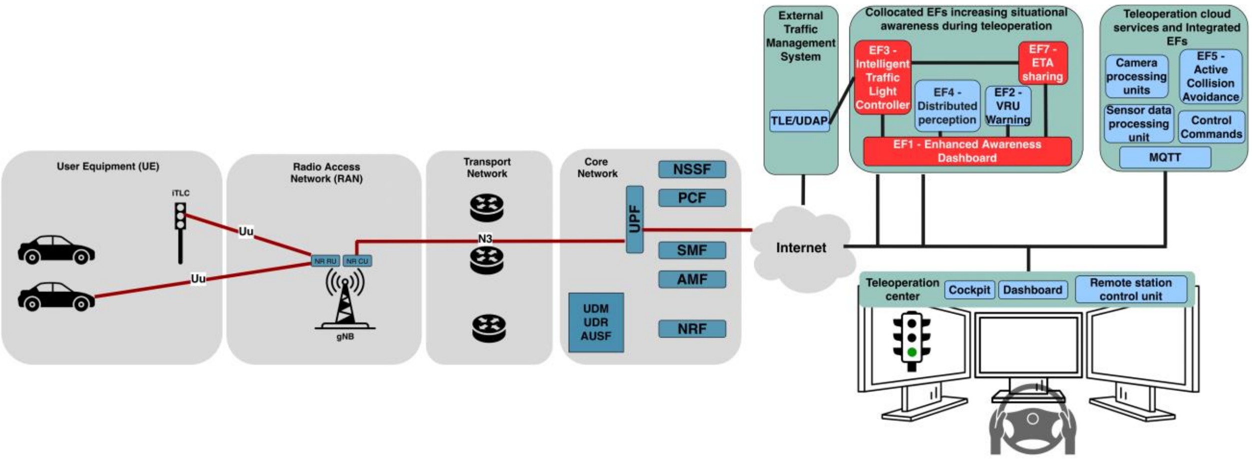

Figure 6 More efficient teleoperation with 5G-connected intelligent Traffic Light Controllers.

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. In this deliverable, Section 3.6 provides more details on the critical actors in the iTLC chain, and Figure 6 illustrates the retrieval of C-ITS messages from the infrastructure (iTLC) and vehicles that enables their communication and collaboration.

Concerning Container ID recognition (Figure 7), we mentioned earlier that this specific EF 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.

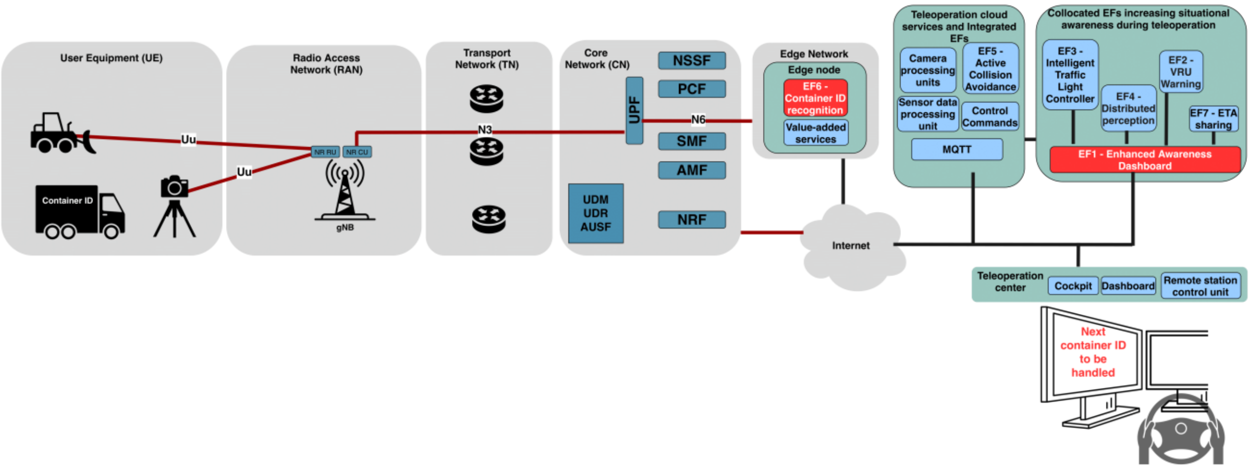

Figure 7 Creating more efficient skid steer and crane teleoperation with 5G-based container ID recognition.

3 FINAL BLUEPRINT OF USE CASES AND ENABLING FUNCTIONS

In this Section, we further provide the final blueprint of all use cases and enabling functions, describing their final functionalities and illustrating the operational and/or message sequence diagrams that capture the most important interactions between different actors (use cases and enabling functions).

3.1 Automated barge control

3.1.1 Short description

The automated barge control is a use case with the goal of remote operation of barges, using Seafar remote operation center. The captains/skippers sit at the office and sail the vessel with the information provided to them on the monitors. Connectivity plays an important role in tele-operation. In the 5G-blueprint project, we utilize 5G-enabled modems onboard the vessel for connectivity to the remote operation center. Two main sites are considered for the test. One in the Port of Antwerp (PoA) and one in Zelzate. The focus in the PoA area is on testing connectivity with both 5G standalone and non-standalone. The focus in Zelzate is on cross-border experience with low-latency operation.

3.1.2 Message sequence diagram

The message sequence diagram for a remotely operated barge is illustrated in Figure 1.

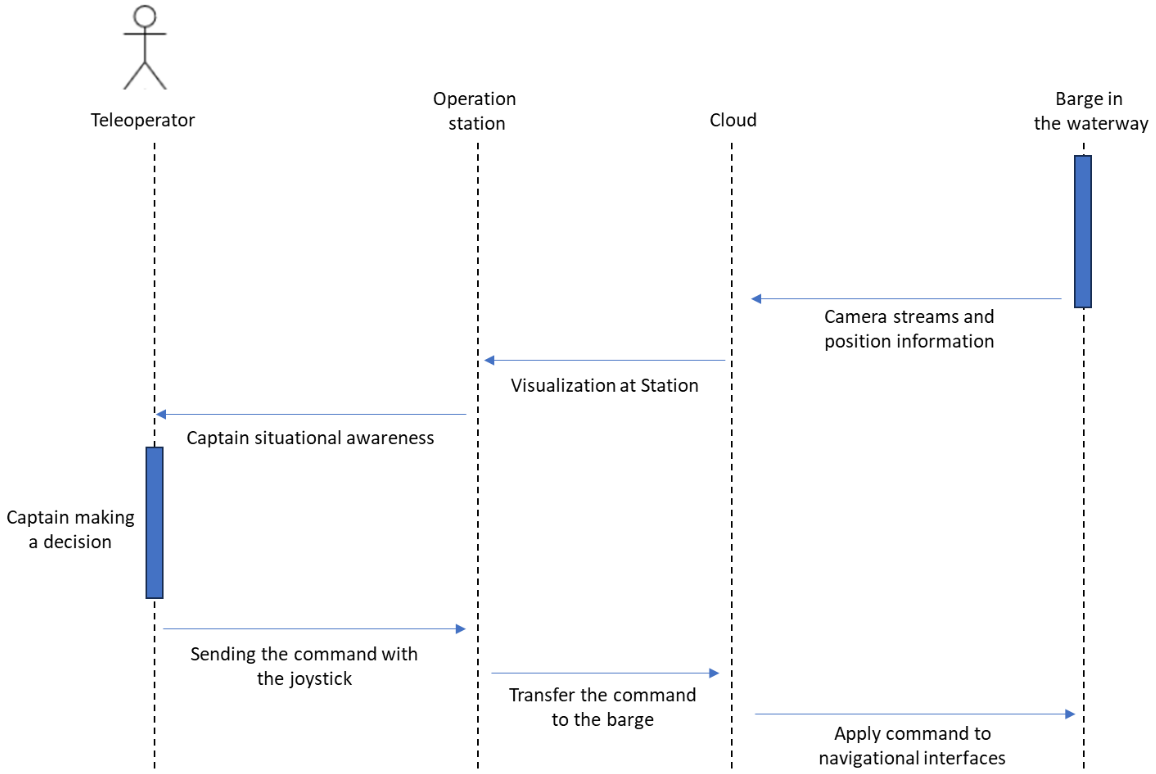

Figure 8 Message sequence diagram for a tele-operated barge scenario.

For a barge operated remotely from a shore control center, there are two main important messages to be transferred. One are all the data from the surroundings of the vessel including the camera streams and positional information to be provided to the remote captain. The second one is the skipper's command which should be transferred to the vessel. If we start from the vessel sensors, we have cameras and a GNSS receiver onboard the vessel. The data of these sensors are collected with a processor and the collected data is then transferred to the cloud. The data in the cloud is then visualized at the remote operation center, providing enough information for the skipper to make a decision. The skipper will then navigate the vessel, and if needed change the heading or speed of the vessel. This command will be transferred to the cloud and then from the cloud to the navigational instrument onboard the vessel.

3.2 Autodocking functionality

3.2.1 Short description

The use case on Teleoperation and Autonomous docking of a truck-trailer combination, from now on referred to as "Autodocking", represents an innovative solution that addresses the challenges of docking processes in the logistics domain. This use case delves into the development, implementation and testing of an autodocking functionality that can autonomously dock a truck and trailer combination, an operation traditionally reliant on human expertise.

To achieve this, the 5G-Blueprint project developed both hardware and software components, and connected them and tested over a 5G network. On the software side, essential components include a high-fidelity model, a path planner, and a path-following controller. Two different versions of the path-following controller were tested: a Pure Pursuit Controller (PPC) and a Model Predictive Controller (MPC). The hardware elements encompass a teleoperation center, communication hardware, localization hardware, and a real vehicle (the truck).

The Autodocking functionality was unfolded in three phases: the modelling phase, the Minimum Viable Platform (MVP) phase (presented in D7.2 [3]), which introduced a 1:3 scaled truck for initial testing, and finally, the full-scale phase, where all components were implemented and tested on a real truck and trailer combination operating in logistic center environments. The final blueprint, i.e., the full-scale setup is explained here, while the results and performance analysis are provided both in D4.2 and D7.4 deliverables.

3.2.2 Operational diagram

The operational diagram in Figure 9 displays the components that are developed and deployed in the full-scale prototype for the purpose of implementing teleoperation and autodocking functionalities and to share the required data to the relevant EFs. The Figure 9 shows the schematic of the overall architecture of the autodocking functionality. The architecture is divided in two parts, the first being the architecture of the system in the teleoperation center and the second being the one in the teleoperated vehicle.

The primary components of the **teleoperation center** are the teleoperation center computer, teleoperation input cluster (steering wheel, paddle shifts, pedals and buttons), 5G modems, and the displays. The autodocking software and the teleoperation software are executed on the teleoperation center computer. During teleoperation, the inputs from the driver are captured by the teleoperation input cluster and are processed and communicated through the teleoperation software, via the 5G modems and network. The autodocking software receives the video streams and the vehicle telemetry from the vehicle to display it in the primary display.

When the teleoperator wants the autodocking operation to take place, it initiates an input to the teleoperation computer. The autodocking software communicates with the teleoperation software to enable ‘automatic mode’ in the teleoperation software and sends the control signals for docking the truck through the 5G network to execute the docking maneuver. The autodocking software manages it by receiving the position and orientation of the vehicle which are captured by the GPS units installed in the vehicle.

The primary components of the **teleoperated vehicle** are the Video streamers, cameras, the Drive-By-Wire (DBW) system, autodocking manager, GPS units, 5G modems on the vehicle side, the steer controller and motor, the brake controller and actuator, gear controller and selector and the throttle spoofing. When operating in a teleoperated mode, the signals from the teleoperation software are transmitted through 5G to the vehicle modems, and the signals are translated by the DBW system on the truck to convey the required signals to the low level controllers which drive the truck. Also, the video streamers take their inputs from cameras placed in various locations on the truck, and package and send them through 5G back to the teleoperation center to provide the teleoperator with the required views.

When the teleoperator wants to engage the autodocking, the command is given in the teleoperation computer. As mentioned above, the autodocking software communicates with the teleoperation software to enable ‘automatic mode’ in the teleoperation software, which in turn enables the DBW system to communicate with the Autodocking manager and receive instruction from it. The Autodocking manager receives the control signal from the autodocking software as mentioned above, translates the messages so that the DBW can understand it and also, sends the GPS signal back to the Autodocking software so that the positions and orientations of the vehicle are updated and new control signals can be calculated. Just like in teleoperation mode, the DBW in the truck conveys the required signals to the low level controllers in autodocking mode as well. All the messages for the relevant EFs are communicated from the vehicle by the Autodocking manager to an MQTT Server, from which the other parties can access the data. In addition, all signals and data exchanged between different entities in Figure 9 are listed and described in Table 3.

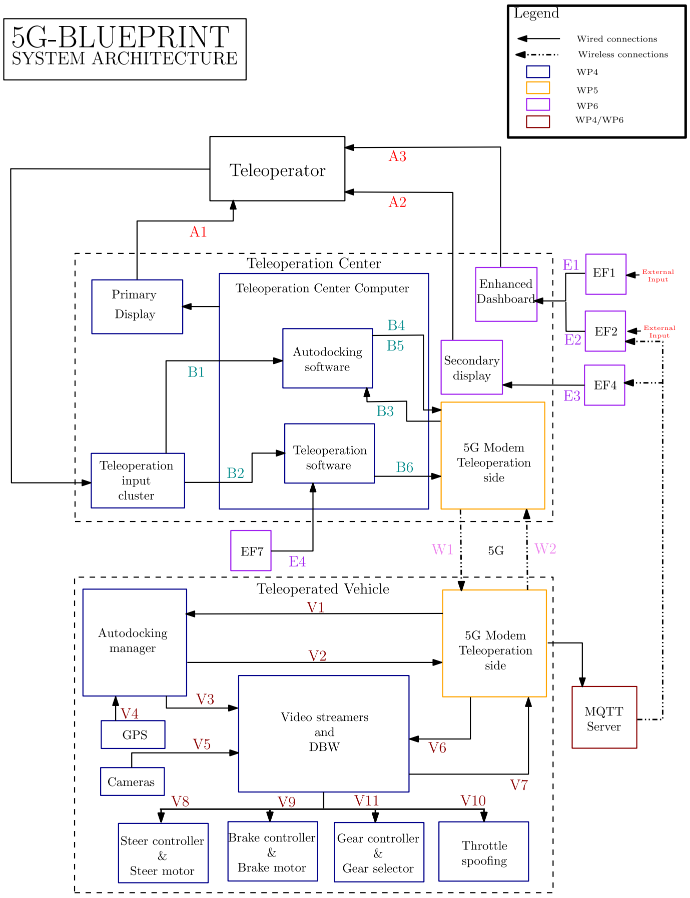

Figure 9 Operational diagram of the Full-scale prototype of Autodocking functionality.

Table 3 Signal description of Autodocking functionality.

Connection	Signals	Units/Values	Protocol
A1	Video stream	-	-
	Speed	km/h	
	Driving mode	yes/no	
	Gear selected	[254,255,3,4,5,6] = [RT,R,N,D,DT]	

A2	Map based view	-	-
A3	Driver awareness dashboard	-	-
B1	Autodocking activation	[1/0]	-
B2	Steering	[-]	-
	Brake	[-]	
	Throttle	[-]	
	Gear	[-]	
	Teleoperation activation	1/0	
	Autodocking activation	1/0	
B3	Position	[m]	TCP
	Yaw angles	[deg]	
B4	Steering	[deg]	TCP
	Throttle	[%]	
	Brake	[%]	
	Gear	[254,255,3,4,5,6] = [RT,R,N,D,DT]	
B5	Planned path	[m]	TCP
B6	Steering	[deg]	TCP
	Throttle	[%]	
	Brake	[%]	
	Gear	[254,255,3,4,5,6] = [RT,R,N,D,DT]	
	Driving mode	?	
E1	Speed advice	[-]	-
	Warning	[-]	
	Routing messages	[-]	
E2	Collison Warning	[-]	-
E3	Shared world model with detected objects’ pose	[-]	-
E4	ETA	[hr-m]	HTTP Server
	Dock number	[-]	
W1	Vehicle + System control messages	[-]	TCP
W2	Video streams	[-]	TCP
	GPS signals	Position [m]	
		Yaw angles [deg]	

		Speed [m/s]	
	Vehicle telemetry	Speed [km/hr]	
		Gear [-]	
V1	Vehicle control signals	Steer angle [deg]	TCP
		Throttle [%]	
		Brake [%]	
		Gear [-]	
V2	GPS signals	Position [m],	TCP
		Yaw angles [deg]	
		Speed [m/s]	
	Tracking error	[m]	
V3	Vehicle control signals	Steer angle [deg]	CAN
		Throttle [%]	
		Brake [%]	
		Gear [-]	
V4	Positions	[m]	CAN
	Yaw angles	[deg]	
V5	Video Streams	[-]	-
V6	Vehicle & System control messages	Steer angle [deg]	TCP
		Throttle [%]	
		Brake [%]	
		Gear [-]	
		TO and AD activation	
V7	Vehicle telemetry	Speed [km/hr]	TCP
		Gear [-]	
	Driving mode	TO and AD activation	
V8	Steer signal	[deg]	CAN
V9	Brake signal	[%]	CAN
V10	Throttle signal	[%]	CAN
V11	Gear Selector	[254,255,3,4,5,6] = [RT,R,N,D,DT]	CAN
M1	GPS signals	Position [m]	TCP?
		Yaw angles [deg]	
		Speed [m/s]	
	Tracking error	[m]	
	Planned path	[m]	

3.3 Teleoperation based platooning

3.3.1 Short description

The Teleoperation-Based Platooning is a driver assistance system designed for highway and constant-speed zone driving scenarios. In this system, the lead vehicle is teleoperated by a teleoperator, while the following vehicle, is initially driven by a human driver. Cooperative Adaptive Cruise Control (CACC) mode is engaged when entering a constant speed zone. This CACC operation is enabled by PC5-based Cellular Vehicle-to-Everything (C-V2X) communication, allowing real-time data exchange between vehicles. Crucially, the system incorporates a remote takeover capability, ensuring that the teleoperator can take control of the following vehicle too during CACC operation if necessary. Upon leaving the constant speed zone, control returns to the human driver, ensuring both safety and efficiency in the platooning scenario.

3.3.2 Operational diagram

The schematic of high-level architecture of the teleoperation-based platooning system is given in Figure 10. The acceleration (a_{lead}) and velocity (v_{lead}) of the lead vehicle are obtained from the Electric Control Unit (ECU) and are sent to the On-Board Unit (OBU) through the On-board computer. The OBU then communicates this data to the following vehicle through Vehicle-to-Vehicle (V2V) communication. The OBU of the following vehicle receives the communicated data and transfers it to the controller. The controller along with the other data inputs from vehicle RADAR (distance to the vehicle in front - D_{actual}) and vision system (headway time - H), computes the required acceleration to closely follow the lead vehicle. The vehicle states are obtained from the vehicle ECU and the Controller Area Network (CAN) messages are decoded and translated to real values.

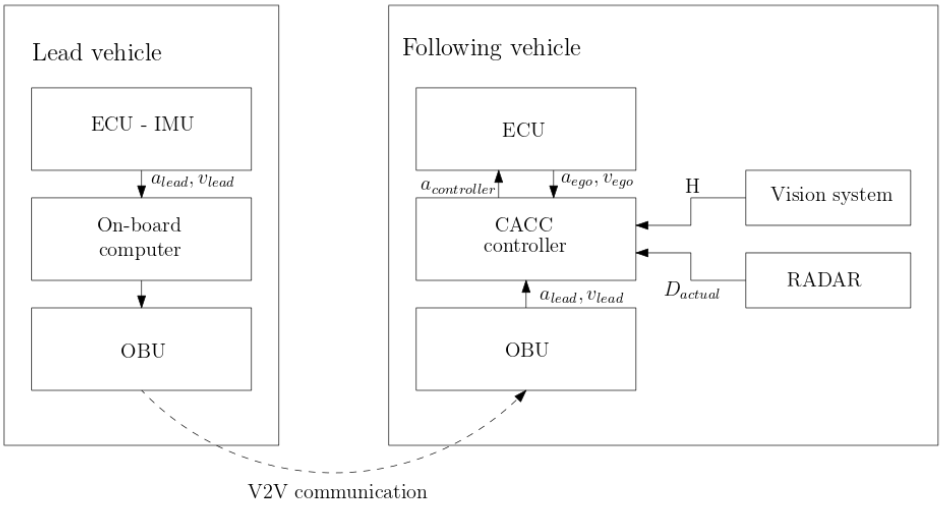

Figure 10 High level architecture of teleoperation-based platooning.

An Artificial Potential Function (APF) controller strategy is used in the system to maintain the vehicle at the desired distance. The acceleration or deceleration required to maintain this desired distance is computed by this controller and is injected into the vehicle. The controller uses both feedforward and feedback loop to compute this acceleration. The lead vehicle acceleration is used for the feedforward control and the distance and velocity error is used for the feedback control. The aim of the CACC system is to control the platooning vehicle’s longitudinal motion by means of an external controller added to the vehicle. The scope of the project is limited to longitudinal control and lateral control is carried out by the safety driver present in the test vehicle.

The abovementioned controller should communicate with the vehicle to execute the specific control of acceleration and deceleration ($a_{controller}$). The primary approach was to inject vehicle specific messages into the communication network as a way of manipulating its motion. This enables to perform the specific control without altering the production vehicle hardware by a large degree. Through this approach, the desired control is achieved and restores full control to the driver if the pedals are pressed.

Concerning the teleoperation part, the heart of the system is called the Gateway. The vehicles and remote stations connect to the Gateway where the vehicle or the remote station is authenticated. Once they are authenticated, they report their status to the Gateway, which in turn sends the data to fleet management where it is visualized. Then, the teleoperator chooses to connect a vehicle and a remote station using fleet management. Once connected, the teleoperator is able to see the video streamed from the vehicle, as well as its speed and other data. The teleoperator may then choose to take over the vehicle and drive it remotely to its desired location. Upon reaching the destination, they can release the vehicle and switch to driving another one. The high-level architecture for teleoperation is illustrated in Figure 11.

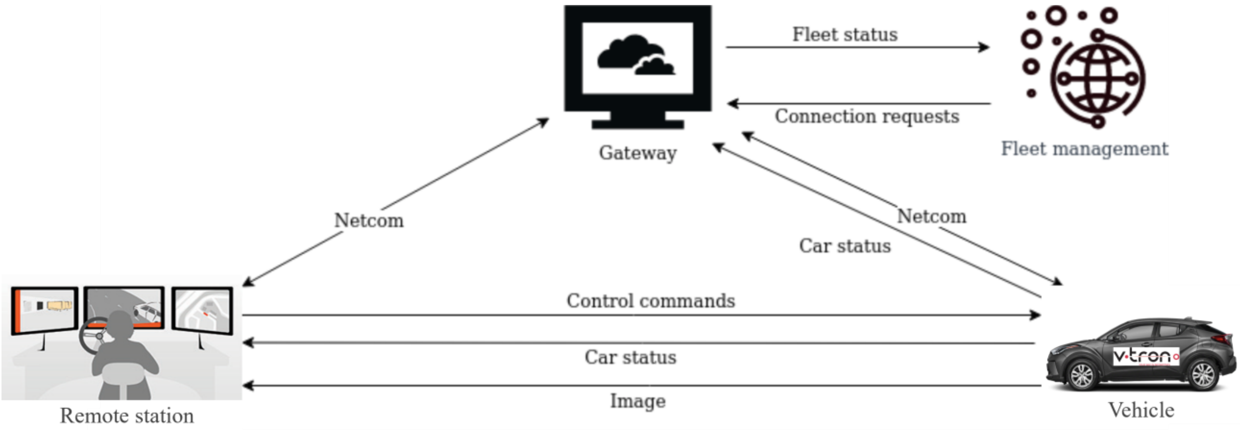

Figure 11 Teleoperation architecture.

Because the On-Board-Unit that is used for communication with the remote station is not connected to the vehicle interface itself and uses an interface to the Roboauto Drive-By-Wire (RDBW) to send commands instead, it can be placed into any vehicle with any interface. On the other side of this vehicle-agnostic interface is the V-tron DBW that runs a vehicle-specific program that translates the protocol to the vehicle's commands and sends them to the vehicle's interface (CAN communication protocol).

To increase the safety and reliability of the system, a redundant connection using multiple LTE carriers with independent networks is employed as shown in Figure 12. Thus, in the case of a temporary signal loss of one carrier, the control commands are still transmitted to the vehicle and the image stream and vehicle data are still being sent to the remote station. Because multiple routers are used, there is also hardware redundancy for the case when one of the routers fails.

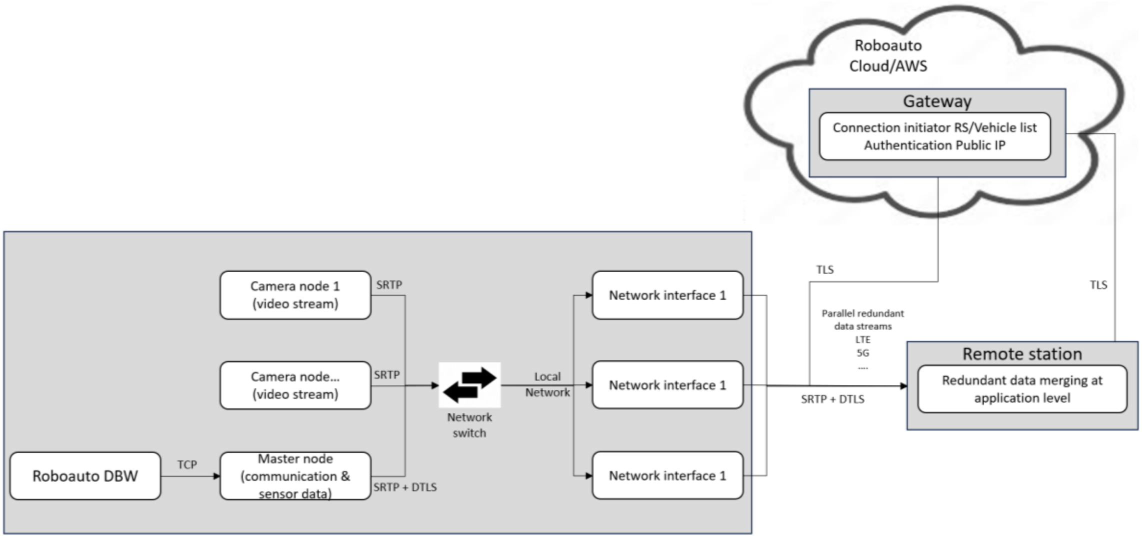

Figure 12 Teleoperation protocol.

A detailed interaction between use case components and enabling functions, as well as between the teleoperated lead vehicle, following vehicle, and teleoperation center, is provided in Figure 13, whereas the explanation of the signals is provided in Table 4.

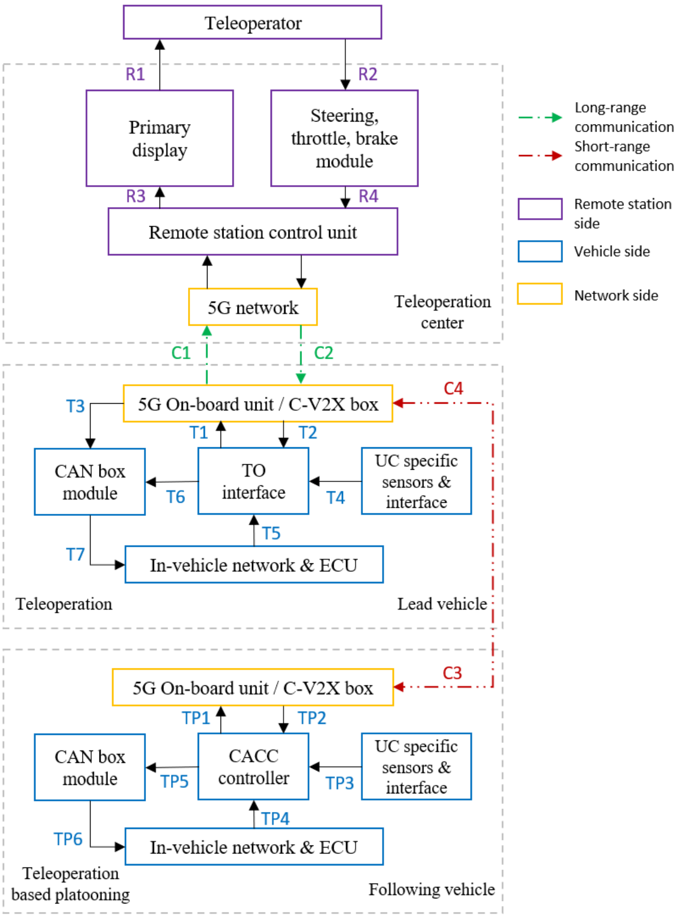

Figure 13 Operational diagram for teleoperation based platooning system.

Table 4 Signal description for Teleoperation based platooning.

Connection	Signals	Units	Protocol
TP1	Lead vehicle acceleration	m/s^2	PC5
	Lead vehicle velocity	m/s	
TP2	Lead vehicle data received by OBU and sent to controller	-	-
TP3	Following vehicle (in-vehicle) sensor data [headway time]	s	CAN
	Following vehicle (in-vehicle) RADAR data [actual distance to lead vehicle]	m	
TP4	Following vehicle acceleration [from ECU]	m/s^2	CAN
	Following vehicle velocity [from ECU]	m/s	
TP5	Controller output (Computed value - Desired acceleration)	m/s^2	-
TP6	Acceleration request to following vehicle (CAN message conversion)	m/s^2	CAN
TP7	Status information to lead vehicle	-	PC5

3.4 Enhanced Awareness Dashboard

3.4.1 Short description

The Enhanced Awareness Dashboard (EAD) or Enabling Function 1 (EF1) is provided to the teleoperators to increase their situational awareness, displaying the following three types of information:

- **Speed advice**: The starting point is the speed limit which is taken on-board in real-time using in-vehicle signage of static and dynamic speed limits. The adjustments are also made to reflect the limit at which the particular type of Teleoperated Vehicle (TOV) can be expected to drive. The speed advice is then adjusted according to timeslot reservations at intersections equipped with intelligent Traffic Light Controller (coming from EF3). This way, speed might be adjusted to ensure that the TOV arrives on time for the designated time slot. For example, it may well be that, at current speeds, the TOV will reach the time slot too early, causing unnecessary deceleration and acceleration. In that case, the advised speed will be adjusted downward. The speed advice is shown to the teleoperator along with the actual speed.
- **Warnings**: Warnings are presented to the teleoperator through succinct visuals (possibly along with auditive cues). These warnings originate from different sources:
    - Obstacles detected in an extended perceptive range (from EF4)
    - Path conflicts with VRUs (from EF2).
    - Traffic light responses at intersections equipped with iTLC. Time slot reservation may be granted or declined, and this information is displayed accordingly.

- **Navigation and routing features**: Based on input received from the provider of the Estimated Time of Arrival (ETA) (from EF7), the route is also presented along with an ETA to the destination. In the back-end, the enabling function starts from a datahub in which all relevant data is collected in real-time, either directly from the vehicle or infrastructure.

The data is then consolidated into information that is useful to the teleoperator, through the three aforementioned key pieces of data that will be presented to the teleoperator: Speed advice, relevant warnings, and routing information. The consolidated information is displayed via a web based interface, a real-time dynamic map with information on the route, detected obstacles, VRUs, and distribution perception.

3.4.2 Message sequence diagram

The main goal of EF1 is to provide concise and clear information to the teleoperator related to the situation on the road ahead. The teleoperator sees information on his/her screen that supplements his/her own observations while driving. This will increase safety of the teleoperated transport as well as his/her driving comfort. As described above, the teleoperator is able to see information on speed advice, warnings and routing presented on a map-based view.

In Figure 14 we display the interaction between EF1 and other EFs. First, the EAD provides speed advice. Afterwards, the EAD starts from the effective speed limit (dynamic or static). The speed advice is then adjusted depending on Safety Related Traffic Information (SRTI), coming from public traffic information feeds, or from the time slot provider, if relevant (e.g., EF3 iTLC via EF7 ETA sharing).

Second, the EAD provides visuals showing relevant warnings. These warnings come from input received from the obstacle detection (EF4) and VRU warning providers (EF2 sharing VRU position and paths), which are aggregated in a way that urgent information is prioritized.

Finally, the EAD also shows navigation and routing features, based on input received from the ETA provider (EF7). The EAD presents the route along with an ETA to the destination.

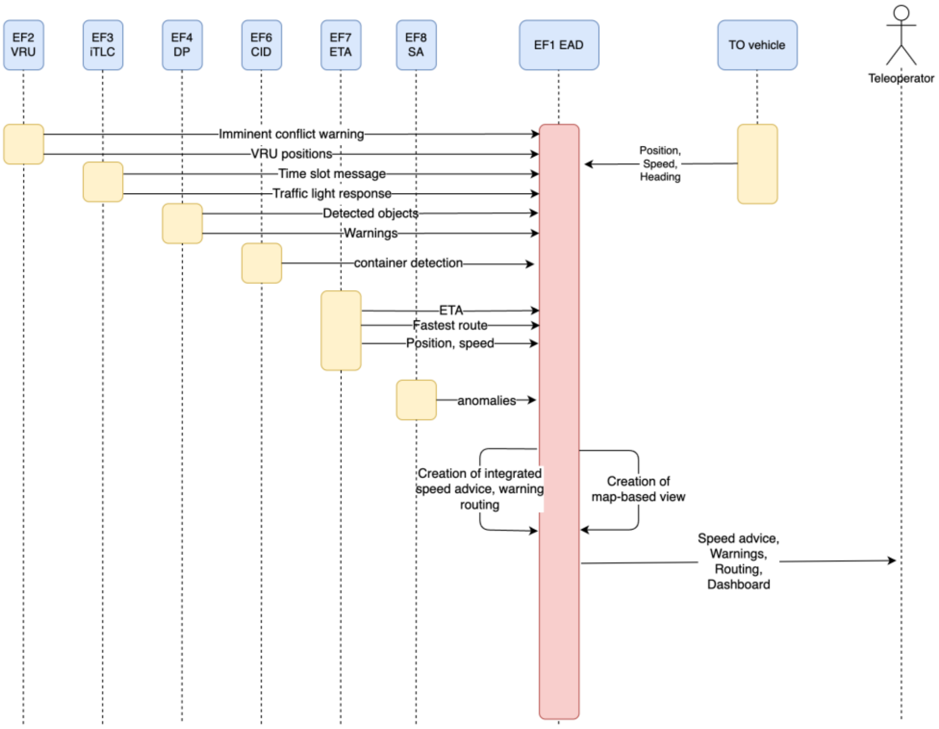

Figure 14 Sequence Diagram for Enhanced Awareness Dashboard.

3.5 Vulnerable Road User (VRU) Warning

3.5.1 Short description

Enabling Function 2 (EF2) or VRU Warning has a dual objective:

- It **calculates the likely path of all Vulnerable Road Users** (VRUs) that participate in the service. The likely path is derived from real-time sensory handset data, the environment (port area, road topology), and VRU type characteristics. The path can have multiple branches from which the most likely one is selected. This likely path is then shared via the exchange service with interested parties, such as the enhanced awareness dashboard of EF1, which is further used to increase awareness about VRUs on the roads, as support for teleoperation use cases.
- Second, EF2 aims to **provide early warnings** to VRUs and teleoperators **about potential collisions between VRUs and TOVs**. The likely path of the VRU is compared with the anticipated paths of the nearby TOVs. For each VRU-TOV combination, the probability of collision is calculated. Potential collision location and time are shared with the TOV through the exchange service and the VRU will be warned through the HMI with visual, haptic and sound cues. EF1 will warn the TO through the Enhanced Awareness Dashboard (EAD).

3.5.2 Message sequence diagram

In Figure 15, we show the overview of interaction between different actors participating in the creation of increased awareness of VRUs on the roads.

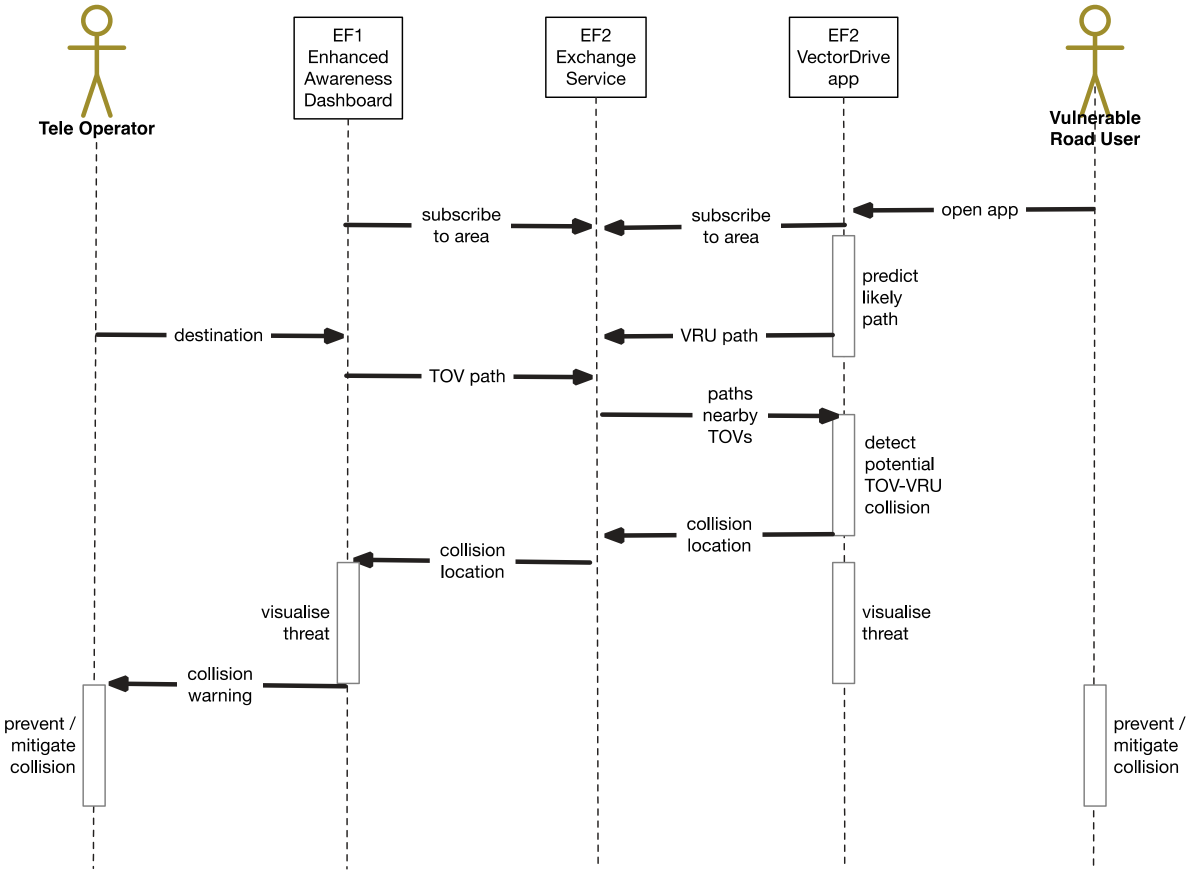

Figure 15 The interaction between various actors in EF2 context.

When the VRU starts the VectorDrive app on its handset (mobile phone), it will connect to the Exchange Service and subscribe to nearby messages. The Exchange Service will push any message published nearby to the app.

The connections between the app and Exchange Service are established over a 5G SA network that routes all traffic over the uRLLC slice. This slice is designed to provide high priority and low latency to safety critical network traffic.

The app will continuously calculate possible paths the VRU will take based on the topology of the road network for the selected modality. For example, possible paths of a cyclist will follow cycle paths where available. From all possible paths the app will select the most likely path based on the heading of the VRU in relation to the orientation of the possible paths. This too is a continuous process. The likely path is updated every second.

EF1 determines the likely path of the TOV based on the destination of the TOV, the TOV's current position and speed. The Exchange Service will push paths published for any TOV to all VRU in the area.

When the app receives the path of a nearby TOV, it will determine whether the VRU's and TOV's path intersect at a specific moment in time. If so, the app publishes a collision warning on the Exchange Server for the specific TOV. The app will display the location of the approaching TOV and the potential collision location on a map on the VRU's device. The app will also sound an alarm and vibrate the VRU's device to warn the VRU, e.g. when the device is carried in the VRU's pocket.

The Enhanced Awareness Dashboard (EAD) or EF1 is then warning the tele operator in a similar fashion, as described in Section 3.4. Based on the warnings received, both the VRU and TO can take action to avoid the collision.

3.6 Time Slot Reservation

3.6.1 Short description

The Intelligent Traffic Light Controller (iTLC) cluster, or Enabling Function 3 (EF3), ensures conflict-less crossings for teleoperated transport at intersections with intelligent TLCs. ITLC is part of a traffic light which steers the whole functionality and is connected to a national access point so that vehicles/applications that use the C-ITS message protocol can interact with the traffic light.

Teleoperators can request a timeslot during which the TOV (and possibly, all TOVs part of the same platoon) is guaranteed a green-lighted passage over the intersection, without any possibility that conflicting traffic has a green light at the same time. The teleoperator receives a time slot and an advised speed which ensures the time slot can be made in time. If the assigned time slot can no longer be made in time by the TOV (or any other TOV in the platoon), a new time slot is provided to the teleoperator. The guarantee of passing an intersection without stopping as a whole platoon reduces the time required to pass the intersection, as well as fuel usage and increases the chance that the platoon can stay intact.

For communication, Signal Phase and Timing Messages (SPaTMs), Cooperative Awareness Messages (CAMs), Signal Status Messages (SSMs), Signal Request Messages (SRMs), and MAP (topology) Extended Message (MAPem), are used. The type of messages such as SPaT and CAM are used in a standardized format in any situation. However, SRM and SSM are slightly adapted for this Use Case to make the time slot reservation possible.

As reported in D7.2 [3] there was no deployment of EF3 in the Minimum Viable Platform (MVP) phase, thus, the overall deployment took place during the preparation of the final system.

The network connectivity for the iTLC is achieved through both 5G NSA and SA using the 5G network, which is compared with the 4G commercial network. For connectivity in the Vlissingen pilot site, Sierra Wireless modems with two SIM slots (4G, 5G) are provided by KPN including SIM cards. Same goes for Peplink modems and SIM cards provided by Telenet for testing in the urban area of the Zelzate pilot site.

3.6.2 Message sequence diagram

Concerning the time slot reservation, the interaction between the iTLC and two vehicles in a platoon, is a two-step approach.

1. In the first step, the platooning vehicles get in range of the iTLC (the corresponding range is indicated by ETA being less than 5 minutes). A time slot is derived from the ETA coming from EF7 sent out per approaching vehicle, described in Section 3.11) and submitted to the iTLC by an SRM for each vehicle. The iTLC (EF3) calculates a time slot based on the separate ETAs of the approaching vehicles and the time to clear the crossing by the last vehicle and replies to the request by SSM (processing or rejected), informing each vehicle of the possibility of giving priority for a greenlight passage. If priority is not possible at the given ETA, a new ETA, which is later, is proposed through SSM by EF3.
2. Once a TOV is on the MAP, CAM and SPaT become available. If, for the given ETA of the platooning vehicles, it is not possible to give a priority, the iTLC will propose a new ETA and time slot later in time. The vehicles will receive priority if they adjust their speed to change their ETA to the proposed ETA. When the traffic light is green and with the current ETA vehicles can pass the intersection within the current green phase, a granted pass is given through an SSM.

The two-step approach is shown in Figure 16. Furthermore, priority is handled as described within

D3047-15 Functional Priority Handling v1.1.0.[1]

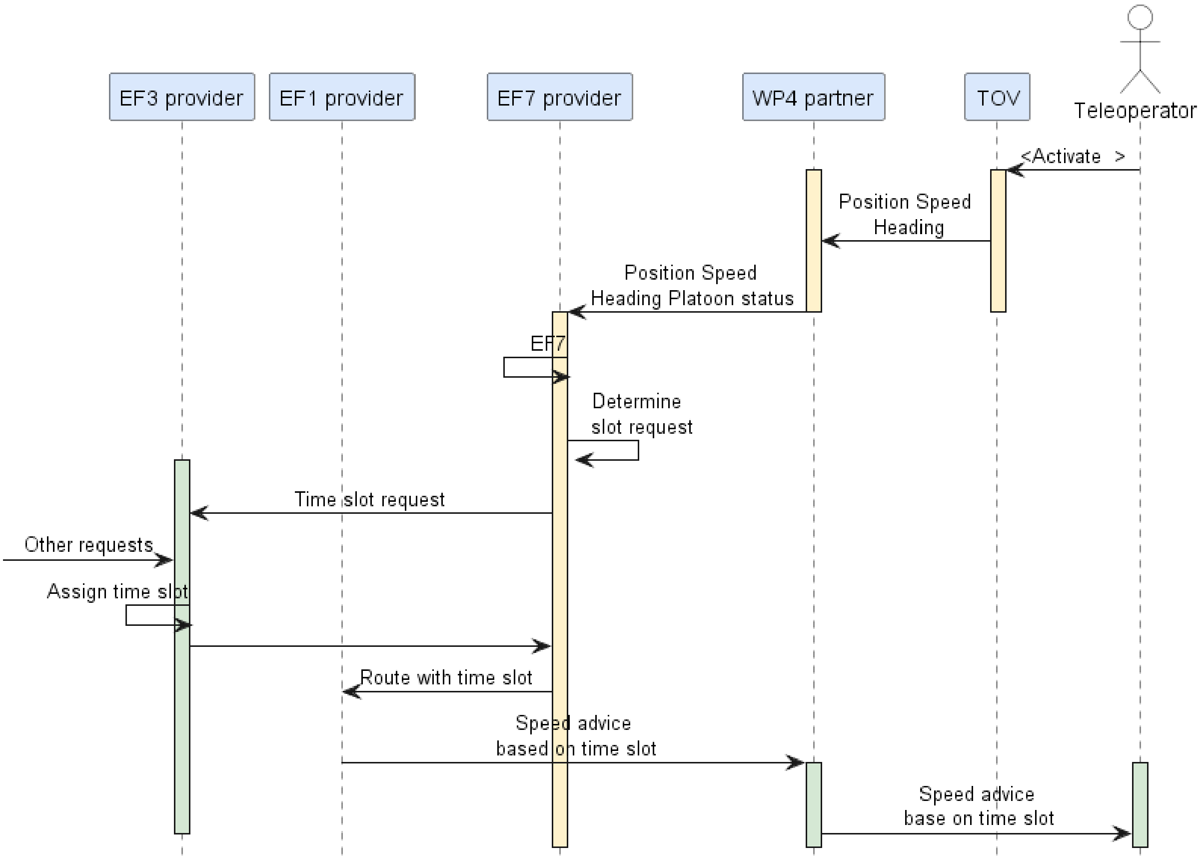

Figure 16 Sequence diagram, stakeholders are: EF3 = ITS-App, EF1 = in-car dashboard, EF7 = ETA for Time slot Request, WP4 partner = providing OBU TOV = TeleOperatedVehicle, Teleoperator = driver of the TOV.

Step 1

Figure 17 presents the required steps for Time Slot Reservation in a flowchart, and it describes the SSM status possibilities as follows:

- The vehicle is not on MAP.
- Vehicles will send GPS location and heading through an app from the EF3 provider. The EF3 provider will make and send standardized CAM and SRM with adjustments for this EF to iTLC
- In this step, the vehicles notify the iTLC to reach the intersection within <5 minutes through SRM.
- The iTLC reserves a timeslot for the vehicles, if feasible.
- Vehicles are notified if priority is feasible through SSM.
- The process is described below in a functional flowchart.
- The reserved time slot can still be overwritten by specials, such as a closing rail-crossing, or an opening bridge.
- The reserved time slot can still be overwritten by emergency vehicles.
- In these cases, the iTLC notifies the vehicles through SSM and may propose a new ETA

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[1] CROW. (2021). *Priority services for target groups: Functional description for Emergency Services, Public Transport and Logistics version 1.1.0* (1.1.0).

for which priority is feasible.

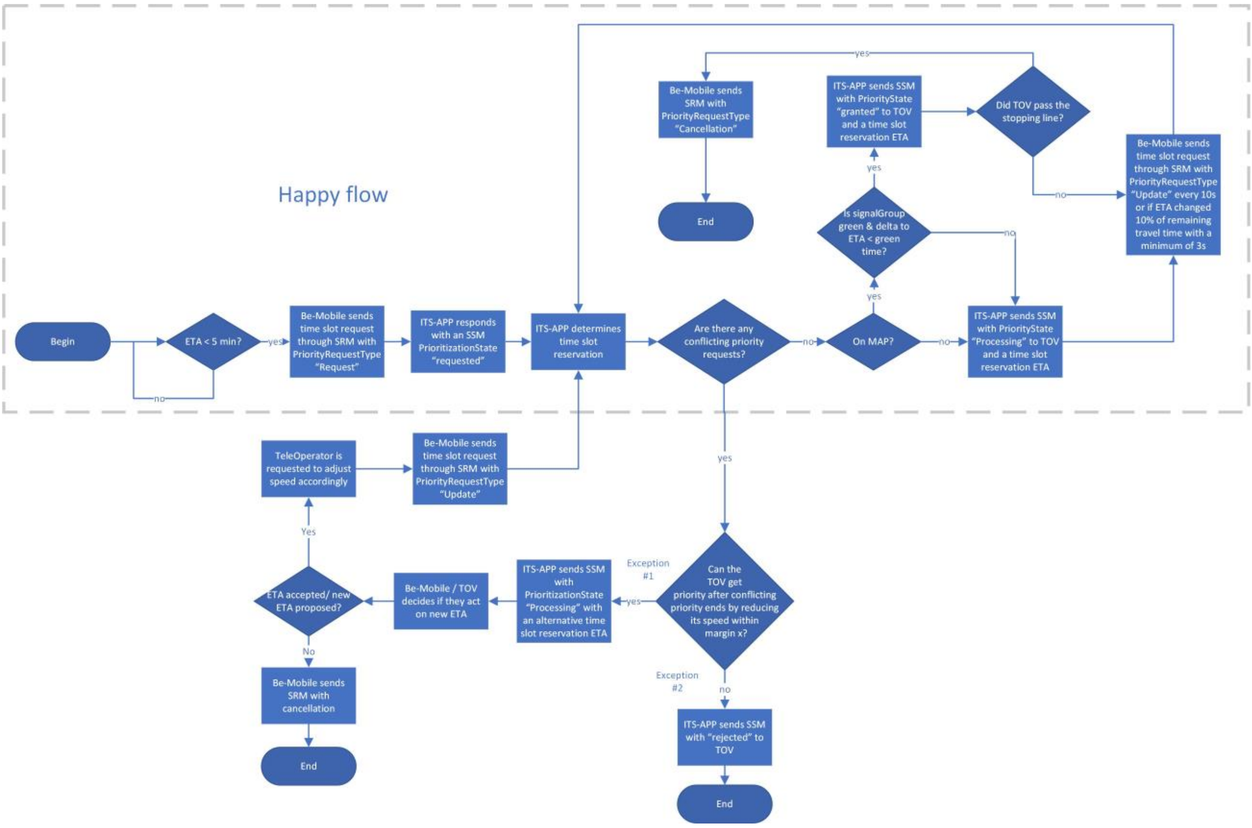


Figure 17 Functional flowchart of the Time Slot Reservation process when a vehicle is not on the MAP.

<u>Step 2</u>

- During step 2, the vehicles are on the MAP (which is extended to 1km)
- EF7 sends out CAM and SRM, SSM and SPaT are received from the iTLC.
- Convoy priority is handled as specified in the "D3047-15 Functional Priority Handling v1.1.5" document.
- When the requested time slot is not feasible, iTLC proposes a new ETA through SSM
- The vehicle is required to adjust its speed to adjust the ETA and receive priority
- iTLC / ITS-app adds up the required time for all vehicles to pass the intersection
- The process is described in a functional flowchart in Figure 17.
- The reserved time slot can still be overwritten by specials, such as a closing rail-crossing, or an opening bridge.
- The reserved time slot can still be overwritten by emergency vehicles.
- In these cases, the iTLC notifies the vehicles through SSM and may propose a new ETA for which priority is feasible.

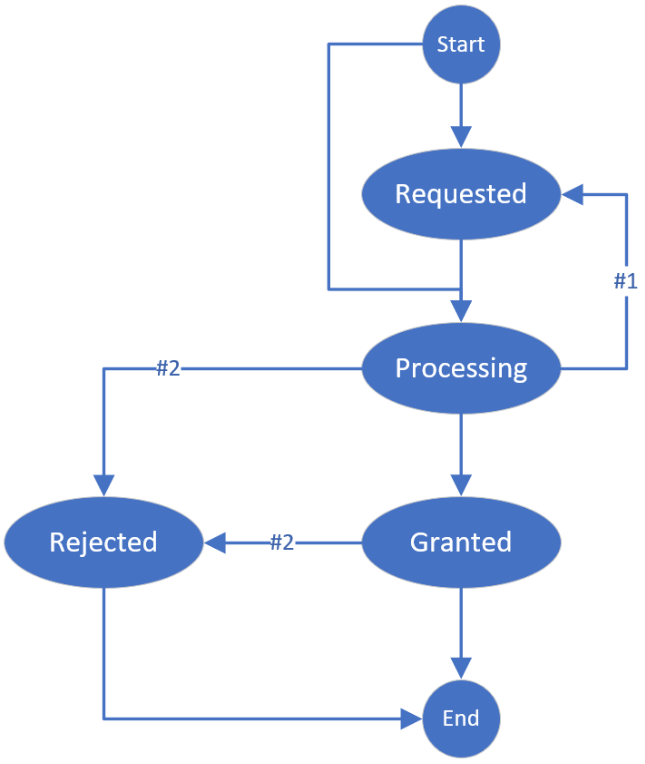


Figure 18 SSM state change diagram.

Figure 18 shows the state change diagram. To go from granted to rejected through #2 is only possible in case of special disruptions, such as closing of a train crossing, opening of a bridge or intervention by emergency services.

3.7 Distributed Perception

3.7.1 Short description

This enabling function demonstrates the Distributed Perception (EF4), performing 3D object detection to create a shared situational awareness for platoons that consist of regular and teleoperated vehicles. The detection is performed on the objects surrounding the ego vehicle by fusing point clouds (feature maps) received from other vehicles in the platoon and that of the ego vehicle point. The detected 3D objects are then presented in the EF1 dashboard, which is displayed at the TO side.

EF4 was developed and deployed in the MVP phase of WP7, and as such, the features and initial performance evaluation were presented in D7.2 [3]. Further tests were conducted to verify that objects are detected in timely manner, and bounding boxes were correctly corresponding to what could be seen in reality.

5G plays a vital role for the success of EF4 and its integration with EF1 and involved WPs. Firstly, 5G is used to share LiDAR point clouds retrieved from the vehicles in the platoon. Secondly, it is used to publish the JSON file of the detected objects to EF1 to be displayed on the EAD. This will be elaborated further in Figure 19 and Figure 20.

3.7.2 Message sequence diagram

The overview of cooperation between different enabling functions, use case, and teleoperator, is shown in Figure 19 (messages exchanged between entities) and Figure 20, showcasing the interaction that happens during the 3D obstacle detection process.

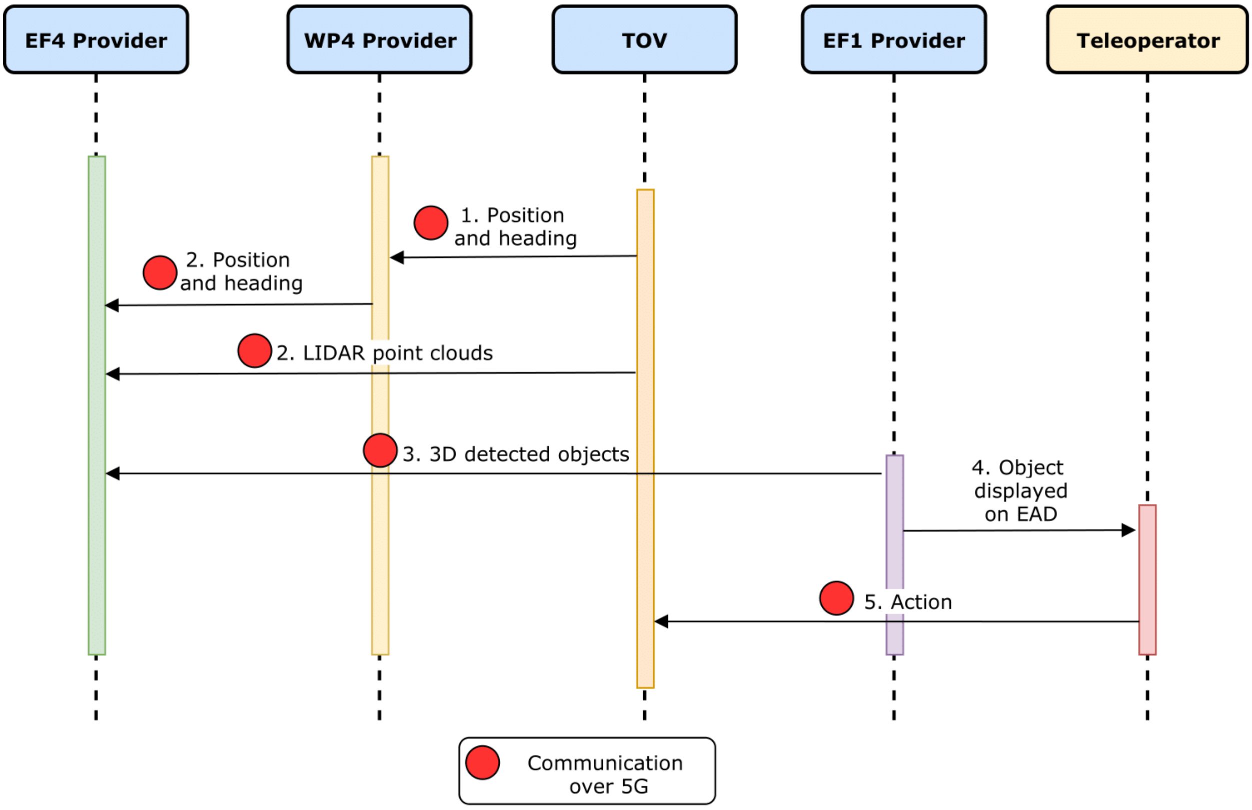
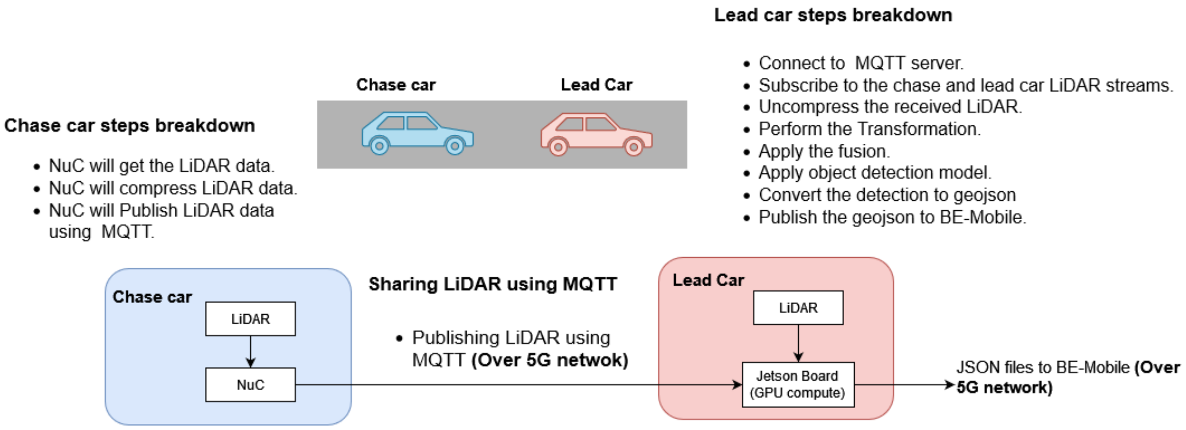


Figure 19 Sequence diagram, stakeholders are: WP4, EF4, EF1. EF1 (enhanced awareness dashboard), WP4 partner: use case owner, TOV: Teleoperated Vehicle, EF4 (distributed perception).

The sequence of messages is listed as follows:

1. Vehicles send GPS location and heading to WP4 provider,
2. WP4 sends the GPS location and heading using 5G network over MQTT to EF4 and the TOV sends the LiDAR point cloud using 5G network over MQTT to EF4 provider
3. EF4 starts to fuse the data received (GPS location, heading and LiDAR point clouds) to perform object detection for distributed perception. EF4 sends a JSON file containing the class and 3D bounding boxes using 5G network as an HTTP message to the enhanced awareness dashboard of EF1.
4. EF1 parses the received JSON file so the objects can be displayed with the right label and location on the EAD.
5. The Teleoperator uses the EAD to make the action and steer the TOV accordingly.



Lead car steps breakdown

- Connect to MQTT server.
- Subscribe to the chase and lead car LiDAR streams.
- Uncompress the received LiDAR.
- Perform the Transformation.
- Apply the fusion.
- Apply object detection model.
- Convert the detection to geojson
- Publish the geojson to BE-Mobile.

Chase car steps breakdown

- NuC will get the LiDAR data.
- NuC will compress LiDAR data.
- NuC will Publish LiDAR data using MQTT.

- Publishing LiDAR using MQTT **(Over 5G netwok)**

Figure 20 EF4 Operation overview.

3.8 Collision avoidance system

3.8.1 Short description

A collision avoidance system – CAS or Enabling Function 5 (EF5), is a driver-assistance system, which prevents driven/teleoperated/autonomous vehicles from collisions and protects workers and property in the area. The obstacles on the planned/predicted path are considered as hazardous situations. In this case, the CAS system forces the vehicle to an emergency stop.

EF5 provides a vehicle-independent system that works as a stand-alone system but is compatible with teleoperation solution. CAS is a complex collection of hardware and software. The hardware consists of sensors such as Lidar. The data from the sensors are processed in a dedicated computing unit designed for CAS. This unit is interfaced with the onboard unit.

3.8.2 Message sequence diagram

The teleoperator uses a teleoperation station to control a vehicle, transferring information about steering wheel angle, speed and braking power. Vehicle then performs action based on this information and sends similar information (speed, vehicle turning rate) and data from lidar sensors to the CAS system. The CAS system then evaluates possible collision objects and calculates time to collision. If the system evaluates this time to collision as too low based on the braking curve of a given vehicle it sends a message to vehicle to engage braking with given force. Vehicle then informs the teleoperation station that it has engaged brakes based on CAS input.

The Figure 21 shows the message sequence diagram.

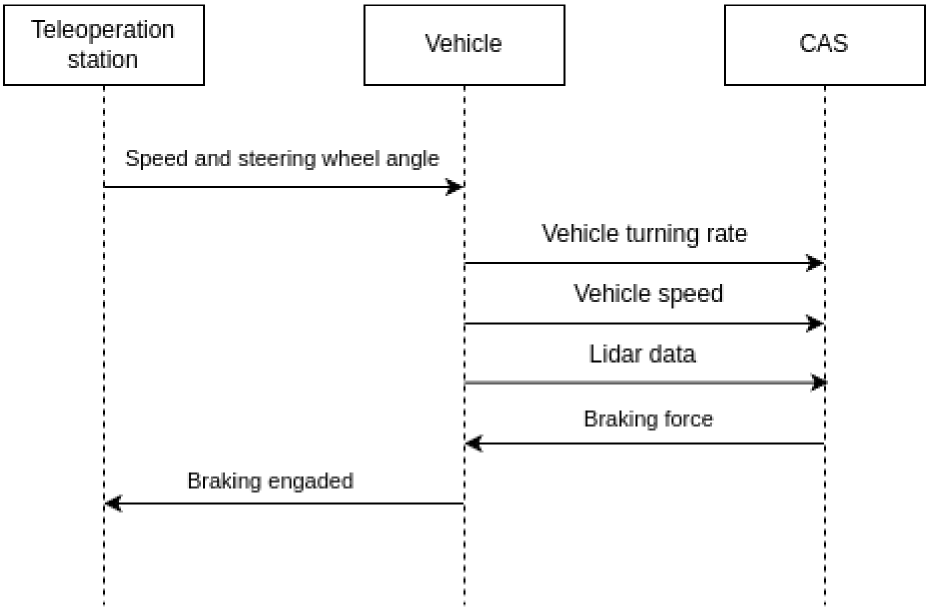


Figure 21 Message sequence chart of the collision avoidance system.

3.10 Container ID recognition

3.10.1 Short description

Container ID recognition or Enabling Function 6 (EF6) provides the capability to identify shipping containers on video streams. Shipping containers are uniquely identified by using the so-called BIC[2] code, which is globally standardized in ISO6346[3]. The BIC appears on all visible angles at any shipping container.

The recognized BIC code can directly be used for automation purposes, e.g., to automatically register this container as being arrived/departed from a train or truck, or loaded/unloaded from a crane or reach stacker.

In the MVP phase of WP7, described in D7.2 [3], the system has been extended as a 5G logging tool, where the radio quality and network performance are measured in duration tests in the course of several months. This way, the usability of the 5G Stand Alone (SA) network is tested for edge computing[4] purposes.

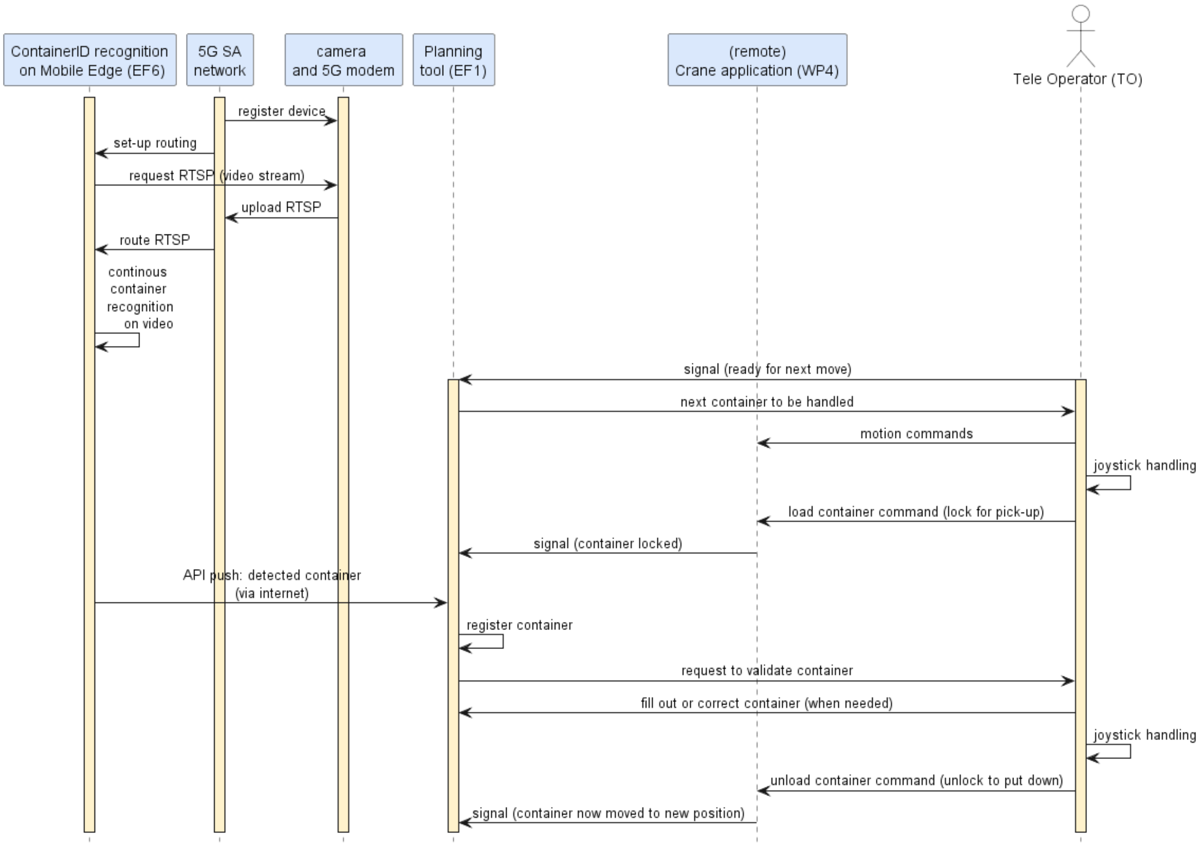


Figure 22 Operations of handling containers using a crane.

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[2] BIC is an abbreviation of Bureau International des Containers, refer to https://en.wikipedia.org/wiki/Bureau_International_des_Containers

[3] https://en.wikipedia.org/wiki/ISO_6346

[4] Multi-Access Edge Computing, https://www.etsi.org/technologies/multi-access-edge-computing#:~:text=Multi%2Daccess%20Edge%20Computing%20(MEC)%20offers%20application%20developers%20and,the%20edge%20of%20the%20network.

3.10.2 Message sequence diagram

Depending on the use case, the EF can be integrated in multiple ways. The most obvious usage of this EF is when the TO controls a machine such as a crane or skid steer to load/unload containers from barges, or a reach stacker to load/unload containers on truck trailers.

In this case, the TO uses an operational planning tool, where the manifest is kept of what containers shall be loaded/unloaded, and where in the stack the containers are positioned. In this project, the dashboard from EF1 was emulating this purpose.

The video feed is streamed 24/7 to the image recognition software, which runs in an edge node in the network, rather than physically next to the camera. For edge setup to work properly, the network connection should be stable enough so that continuous monitoring of the rail carts and containers is possible. Any connectivity breakdown results in lost frames (in the camera stream), and increases the probability that containers/rail wagons are missed in the camera stream. This stability and reliability of the network connection is the key requirement towards the 5G SA network.
In parallel, the TO operates the crane, and via the planning software (EF1) is gets information on what container to handle next. Figure 22 shows the message sequence diagram to illustrate these operations.

3.11 Estimated Time of Arrival sharing

3.11.1 Short description

ETA Sharing or Enabling Function 7 (EF7) provides two useful functionalities:

- The estimated time of arrival of the teleoperated transport will be calculated on a continuous real-time basis. This ETA is based on the fastest route from the current position of the TOV to a relevant waypoint, taking into account real-time traffic data. In addition, the ETA calculation process takes into account other data generated within the scope of the 5G-Blueprint project, in particular those from other enabling functions. The ETA to the final destination will be sent towards EF1 EAD, together with the route and turn-by-turn navigation, and other interested parties (such as the logistic planner). EF 1 EAD will then display this information in a user-friendly way.
- Calculating (intermediate) ETAs for important intermediate waypoints. The ETA to intermediate waypoints will be relevant for other enabling functions such as for EF2 and EF3. In particular, EF3 iTLC needs this information to provide a timely timeslot reservation. The ETA is as such sent to the iTLC and the iTLC then offers feedback at which exact ETA the iTLC can grant permission to the TOV to pass the intersection. At this point a speed advice is offered to the TO to ensure the TOV can indeed reach the ETA offered by the iTLC. For EF2, at regular intervals, EF7 transmits the trajectory of the TOV to EF2. This trajectory contains a list of coordinates and the estimated Time of Arrival (ETA). EF2 utilizes this data for the VRU collision detection algorithm.

3.11.2 Message sequence diagram

The primary objective of EF7 is to deliver precise and easily understandable information regarding the estimated time of arrival (ETA) and the progression of the TOV (Teleoperated Vehicle) trajectory or route. In Figure 23, we display the interaction between this EF and other EFs relevant for the teleoperation process.

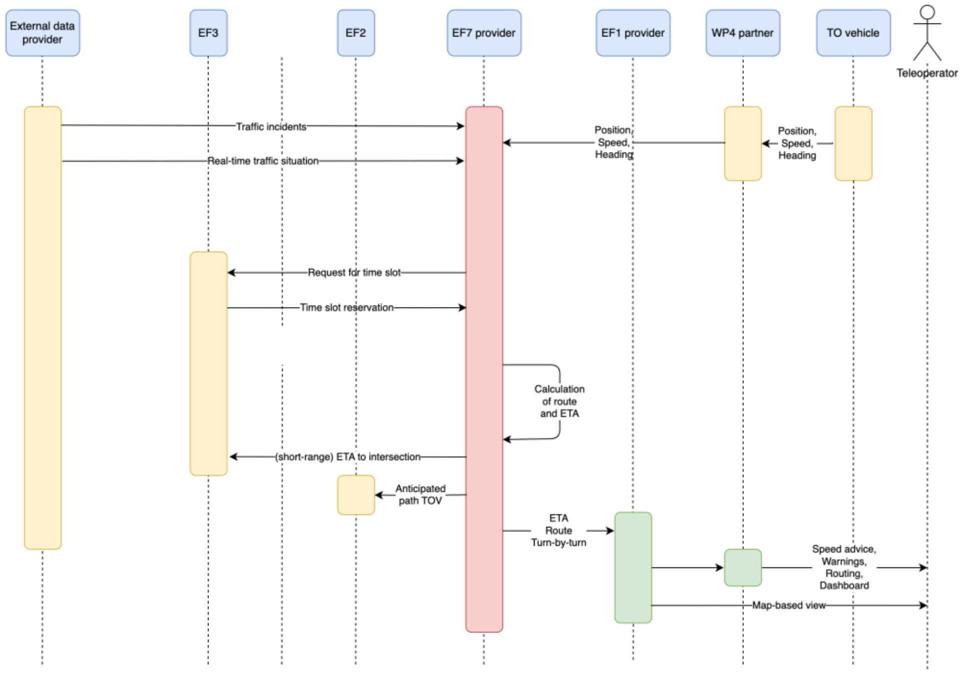

Figure 23 Sequence diagram - EF7.

To compute a concise ETA, EF7 relies on two crucial pieces of information: i) the current traffic conditions and ii) time slot reservations, which may occur at intersections or terminals.

Calculation and Communication of ETA is performed as follows:

- Initially, EF7 calculates an overall ETA in real-time based on continuous data. This ETA is communicated to the teleoperator.
- EF7 begins its calculations using speed, heading, and position data provided by WP4 through onboard GPS units. It determines the fastest route and shares the ETA from this route with relevant parties, including EF1 EAD for final visualization.
- EF7 further breaks down the route into waypoints and computes an ETA for each waypoint. These intermediate waypoints play a crucial role in supporting other enabling functions, particularly EF2 VRU and EF3 iTLC. They require this information for collision assessment with VRUs and timely timeslot reservation calculations.

After the ETA is calculated, the teleoperator has access to the ETA information in the EAD (Enhanced Awareness Dashboard), which complements their own observations while driving. This enables the teleoperator to better plan their arrival time at the destination and navigate using waypoints and their associated ETAs.

This integrated approach enhances the efficiency of teleoperated transport and optimizes the planning for pick-up, delivery, and timeslot reservations. For example, EF2, as the VRU warning provider, receives real-time updates on relevant waypoints and their corresponding ETAs continuously. EF2 utilizes this information to issue collision warnings for potential path conflicts between the TOV and VRUs. These warnings include the anticipated path of the VRU, including coordinates and timestamp, as well as the type of VRU.

Furthermore, EF3 serves as the timeslot provider and receives priority requests for relevant waypoints along with their real-time ETAs. This information allows EF3 to allocate appropriate timeslots efficiently.

In summary, EF7 plays a pivotal role in providing timely and accurate ETA information for TOV routes, supporting the overall efficiency and safety of teleoperated transport operations.

4 CONCLUSION

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.

The EAD (EF1) **increases situational awareness** of above described teleoperated vehicles by providing real-time information on speed, warnings, and routes. The **speed** is being dynamically adjusted based on the real-time input coming from the intelligent traffic light controllers (EF3). Once the teleoperated vehicles or platoons of teleoperated vehicles are in vicinity of the iTLC, the controller is calculating the time slot for each vehicle, based on their indicated ETAs that are derived from the **ETA** sharing function (EF7), for which the green light passage can be granted for them. Based on the traffic conditions, the ETA values can be dynamically changed for the teleoperated vehicles, so that they get a new time slot when their passage on the intersections can be prioritized. 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. To improve the responsiveness of the remote operator to the detected obstacles, EF5 is implementing the collision avoidance system that calculates time to collision with the obstacle, and thus instructs the remote driver to start breaking or to change the breaking curve. Finally, the awareness dashboard is also showing navigation and routing features, based on input received from EF7, which along with the route displays the ETA to the destination as well.

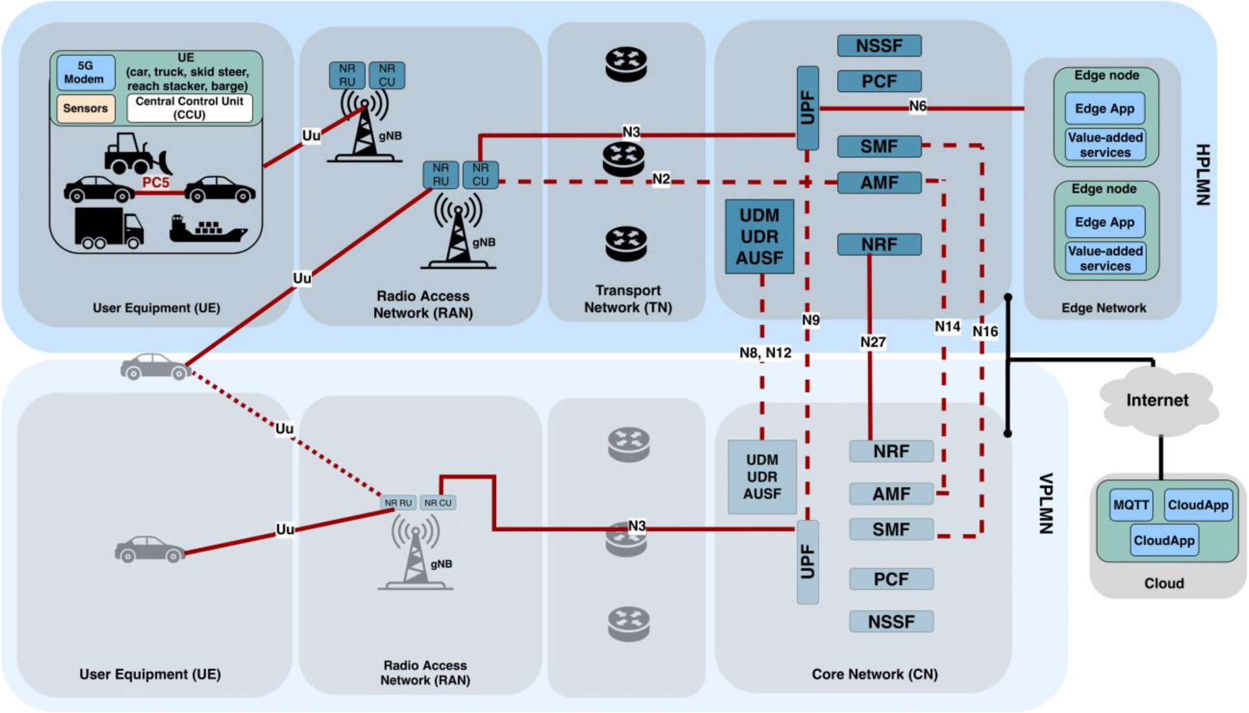

Figure 24 Final revisited 5G-Blueprint architecture.

In the 5G-Blueprint project, all the abovementioned 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 24).

As it can be seen from the final implementation of use cases and enabling functions, 5G Standalone plays an important role for both network flows, i.e., uplink and downlink, and for crossing the border between two countries. It is offering network slicing, and to achieve at least 30Mbps on uplink (in case of 6 cameras/sensors installed onboard) and less than 35ms in end-to-end latency (round-trip time), eMBB and uRLLC are utilized, respectively. Importantly, with innovative seamless roaming mechanisms presented in D5.3 [5] and summarized in Section 2, teleoperation can be performed in a seamless manner with less than 150ms interruption time. 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 document provides essential information about all the necessary technical elements in the 5G-enhanced teleoperation chain, offering blueprints of various use cases, enabling functions, and their collocation, which altogether have a goal to achieve uninterrupted in-country and cross-border teleoperated transport based on 5G connectivity.

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