Path to deploy 5G-based teleoperation in Transport Logistics: The 5G Blueprint lessons learned

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***Abstract*—The Transport and Logistics (T&L) sector, encompassing road vehicles and river barges, faces several challenges, including the recruitment of skilled drivers and skippers as well as improving safety and work-life balance for these operators. Teleoperation technology, supported by advancements in 5G connectivity and Network Slicing technology to guarantee critical services, offers solutions to the issues faced by the T&L sector. Remote operation of both cars and barges from a Teleoperation Center (ToC) is now becoming feasible. The European project 5G-Blueprint, funded by the European Union, has successfully demonstrated the viability of 5G-based teleoperation, considering cross-border scenarios. This paper outlines the final technical architecture of the 5G-Blueprint project, designed for seamless teleoperation of vehicles and barges across borders. We discuss the validation of 5G standalone (SA) technology presenting specific teleoperation scenarios, such as real-world teleoperated vehicles and teleoperated barges. Key findings and lessons learned from the project's experimental phase are also summarized, highlighting how these insights could enhance future teleoperation deployments.**

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

I. Introduction

The European Transport and Logistics (T&L) sector faces a diverse array of challenges, including the urgent need to reduce emissions following environmental regulations and the critical shortage of qualified personnel in roles such as truck drivers and barge operators i.e., captains and skippers [1]. The T&L sector also encounters issues related to the safety and work-life balance of operators, the protection of human life on roads and waterways, and the overall security of road transport and waterways transport [1]. These complex challenges necessitate innovative and effective solutions, where advanced telecommunication strategies and digitalization play key roles. In this context, teleoperated vehicles and barges emerge as a significant innovation, offering the potential to enhance safety for drivers/captains/skippers and operators, and improve the security of transport through the effective intervention of teleoperators in challenging situations. The success of teleoperation fundamentally depends on high-performance connectivity e.g., end-to-end latency less than 50ms and uplink bandwidth of more than 5Mbps [2]. These high-performance are essential for maintaining fast, safe, and reliable communication between teleoperated vehicles or barges and Teleoperation Center (ToC) under all circumstances [2]. To address the need for such high-performance connectivity, 5G is a good candidate. 5G offers extremely low latency (1-10 ms), near absolute reliability (99.999%), and an impressive data transfer capacity (up to 20 Gbps) [3]. These goals are achieved by deploying logical virtual networks, known as network slices, which overlay the common network infrastructure [4]. Therefore, thanks to the implementation of Ultra-Reliable Low-Latency Communication (URLLC), enhanced Mobile Broadband (eMBB), and massive Machine-Type Communications (mMTC), the 5G Standalone (SA) is capable of delivering teleoperated vehicles or barges in the same network where other services are running in the meantime. In this context, the 5G-Blueprint project has designed, executed, and demonstrated real-world technical solutions to support teleoperations of vehicles and barges, even considering continuous cross-border teleoperation, using 5G SA and 5G Non-Standalone (NSA). Nevertheless, the application of teleoperation is not limited only to the remote control of vehicles or barges, and the high-quality network. For the successful implementation of teleoperated vehicles and barges on our roads and seas, it is essential to provide advanced services that enhance the teleoperator's awareness of the surrounding environment of the teleoperated vehicles or barges. These services include improved perception for the teleoperator through features like advanced notifications and dashboards, as well as integration into the teleoperation chain to allow for automatic adjustments in the maneuvering process.

In this paper, we present the technical aspects of the 5G-Blueprint project, particularly the design of the final technical architecture. This architecture represents the synergistic integration of the various actors and their interactions, which are crucial to realizing a seamless teleoperation system across national borders. We present the experimental methodologies adopted during the project to test and validate 5G SA capabilities, which could be exploited on a large scale in future deployments. These include application scenarios related to teleoperated barges and vehicles [5]. Finally, we discuss the lessons learned gained during the experimental phases of the project.

II. The 5G-Blueprint architecture

The 5G SA network architecture significantly improves the scalability and flexibility of the 5G network [6]. Due to its advanced, service-based design, the different components of the 5G SA network architecture can be developed separately from each other. This makes the 5G SA network particularly suitable for vertical industries such as automotive and T&L, i.e., for Use Case (UC) such as 5G-based teleoperation. In this section, we describe the final architecture developed within the 5G-Blueprint project, which integrates the features of the 5G SA network with continuous roaming solutions and dedicated service/application components. Such architecture, shown in Figure 1, involves all three pilot sites of the project, two national sites located in Antwerp (BE) and Vlissingen (NL), and one cross-border site in Zelzate. The pilot sites, UCs, and Enabling Functions (EFs) are described in [7].

Our architecture is designed to ensure secure and efficient remote operations, within a single country and across national borders. In addition, Figure 1 also includes the deployment aspects related to the UCs and the EFs components located at the edge or cloud computing units. The EFs, in combination with teleoperation UCs, play a crucial role in increasing the situational awareness of remote drivers, consequently improving the safety of the entire system. For instance, an enhanced awareness dashboard shows to the remote drivers i) detected obstacles, ii) the location of Vulnerable Road User (VRU), iii) information from intelligent traffic light controllers intelligent Traffic Light Controllers (iTLC), iv) IDs of containers to be handled, and v) Estimated Arrival times (ETAs). These awareness elements are in line with the safety and entertainment features available in modern vehicles, which although presented simultaneously to the remote driver, actually operate in independent systems. In fact, in the architecture in Figure 1, EFs are not directly integrated into the teleoperation chain. Their placement alongside the UCs is a precise design choice, intending to keep the EFs as isolated from each other as possible, and also isolated from the 5G core elements. Such approach increases the resilience of the 5G SA network and the teleoperation system to potential software bugs and other technical problems, ensuring continued service to critical applications, such as teleoperation applications.

The User Equipments (UEs), which includes cars, trucks, barges, and skid steers, are used in the trial activities during the last phase of the project and are equipped with 5G capabilities. In that way UEs can be connected to the 5G SA network (at 3.5 GHz) at each pilot site. Depending on the specific needs of each UC and EF, additional equipment such as iTLC, VRU devices, and lidar mounted on the test vehicles for real-time object detection, are connected to the network (each additional equipment is considered as 5G UE).

In the 5G SA architecture, the distinction between data traffic, shown in Figure 1 with solid red lines, and control traffic, represented by dashed lines, is critical. The control traffic occurs between UEs, base stations, and core functions of the 5G network when i) registering and authenticating UE, and ii) establishing their session in the network. For example, when a teleoperated car or barge, connects to transmit video data and receive commands, the Access and Mobility Management Function (AMF) interacts with the Authentication Server Function (AUSF) to verify the UE's credentials and complete the authentication process. Next, AMF consults the Unified Data Management (UDM) to obtain crucial data about the UE and interacts with the Session Management Function (SMF) to initiate the session and enable data flow. Regarding data traffic, remote units (such as cars, trucks, and barges) require the intervention of the Central Control Unit (CCU), which translates and executes commands sent by the remote driver or captain over the 5G network (downlink) and sends high-definition video to cloud-based teleoperation services (uplink). In the same way, other types of data are transmitted in the uplink direction, including C-ITS messages, VRU data, and lidar data for real-time object detection. Thus, for both downlink and uplink traffic, UCs and EFs require network quality that can be offered by 5G network slices, such as URLLC and eMBB, which are tailored to their specific requirements. The network requirements considered within the 5G-Blueprint project for teleoperation scenarios, are illustrated in [2].

In scenarios where a teleoperated vehicle crosses national borders i.e., between Belgium and the Netherlands in the context of the 5G-Blueprint project, an interaction process between the two 5G Core (5GC) is initiated to transfer the UE status between the two 5GC and keep the UE session active. This is aimed at minimizing the outage time during handover between different network operators operating in different nations (roaming). The handover procedure developed as part of the 5G-Blueprint project, described in [5], provides a more efficient message exchange between peering core functions, reducing the outage time to less than 150 ms. For example, to quickly reestablish the connection of the teleoperated vehicle, additional UE context information is exchanged between AMF before the handover begins, to avoid data exchanges between SMF during the handover. As a result, once the teleoperated vehicle or barge connects to a new cell in the host network, uplink traffic is restored immediately with an interruption time of less than 150 ms [5].

III. Remote barge control

Within the scope of the 5G-Blueprint project, one of the main challenges consists of implementing a 5G SA network to deliver remote barge control and validate their true impact in real-world environments such as busy seaports in Europe i.e., Port of Antwerp and Port of Vlissingen. In such a UC, the captains/skippers located at the ToC control the barge with the information provided by the dashboard. To realize such a use case, the remote barge is equipped with various sensors and several cameras that are installed on board the barge and send to the ToC to provide situational awareness around the barge. Furthermore, the remote barge is equipped with a 5G modem that provides 5G connectivity to communicate with the captain/skipper at the remote operation center.

Video feeds from various cameras installed in the barge are transferred to services running on the cloud, to which the teleoperation center is connected. The cloud services are used by both the barge and the teleoperation center. The ToC makes decisions about the maneuvering of the barge, thereby generating control commands (captain/skipper). Figure 2 outlines the sequence diagram for message exchange during remote barge teleoperation. In the context of remote barge operation from a teleoperation center, two main streams of data transmission are critical to the process. The first stream includes a complete set of environmental data, including live video feeds and position information, which are aggregated and transmitted to the command dashboard for situation assessment by the teleoperator. Data from cameras positioned on the barge and the GNSS module to acquire real-time visibility and position data are then interfaced with an onboard processing unit in the barge, which performs initial data compression and prepares the payload for transmission to the cloud. Once the data is securely uploaded to a cloud-based facility, it is transformed into an operational dashboard at the remote control station. The second data stream, on the other hand, includes navigation commands from the remote pilot that need to be transmitted to the barge control systems. Such control commands are transferred back to the barge over the 5G infrastructure (downlink), and once the commands are translated into electrical signals on the Programmable Logic Controller (PLC) of the barge control unit, the remote operation is achieved.

A. *Experiments and Results*

To validate the importance of 5G SA connectivity for the teleoperation of barges, we conduct experiments focused on

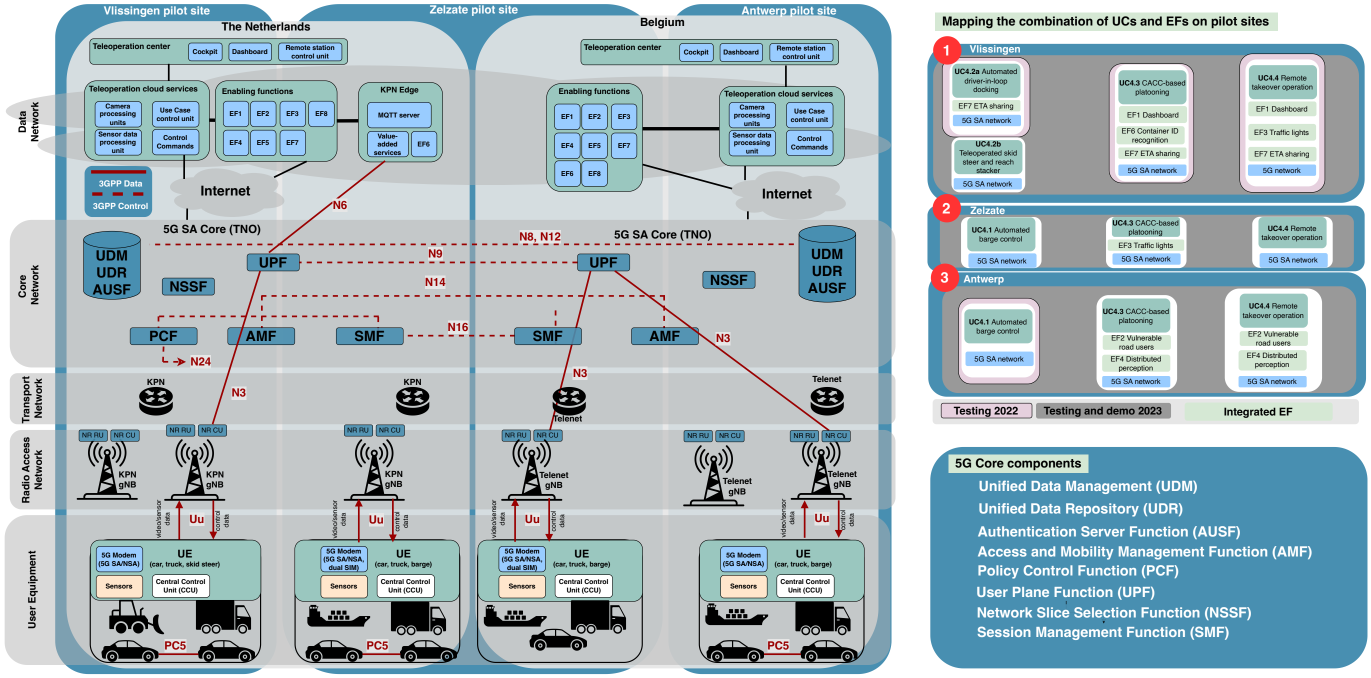

Fig. 1: The architecture of the 5G-Blueprint teleoperation pilot sites integrates with Enabling Functions (EFs) and Use Cases (UCs).

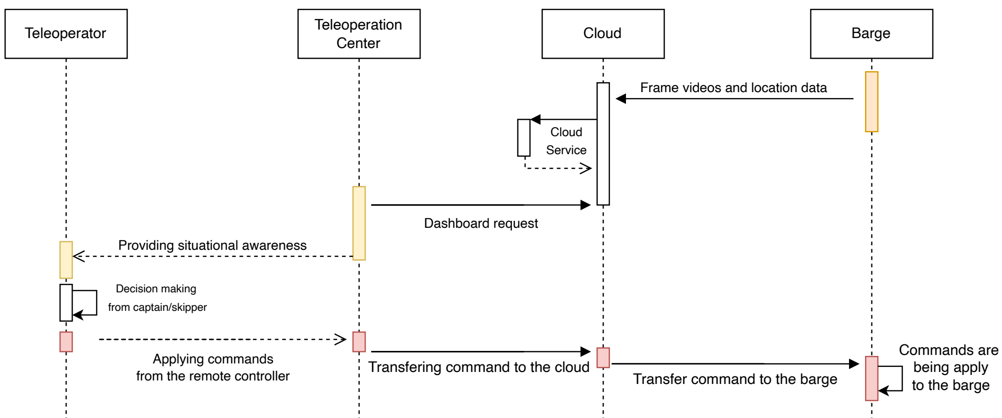

Fig. 2: Message sequence diagram for a teleoperated barge scenario.

evaluating the capabilities of the 5G SA network in difficult connectivity environments typical of waterway transport. In particular, we selected two critical areas: the port area of Antwerp (BE) which is characterized by a high volume of other barge traffic, and the cross-border area of Zelzate (BE-NL), which in the context of the 5G-Blueprint project is known for its potential connectivity losses while crossing national borders. Furthermore, the Zelzate pilot site includes the presence of a bridge on the border between the two countries, which is an important obstacle in terms of signal strength for connectivity.

We conduct the tests using two types of barges, both equipped with cameras, GNSS receivers, radar, multiple compute units to collect and process data, and a 5G modem with a sim card enabled to attach to the 5G base station. These equipment are described in detail in [5]. We used a 110-meter-long commercial barge in the port of Antwerp. For the cross-border area of Zelzate, on the other hand, we used a 5-meter urban barge to avoid waterway traffic limitations due to the bridge openness request. During these tests, video feeds were transmitted from the barges to the teleoperation center, and guidance commands were transmitted to the barges from the teleoperation center, over the 5G SA network.

The Antwerp results showed a Round Trip Time (RTT) latency between 21ms and 50ms, with an average latency of 25ms and a standard deviation of 13ms. Furthermore, we experienced a throughput of 35Mbps in the uplink, sufficient to send high-quality videos to the teleoperator (captain/skipper). The results demonstrate the suitability of 5G SA for safe and effective teleoperation. In the Zelzate pilot site, during cross-border operations from Belgium to the Netherlands, we experienced a throughput of 38Mbps and an average latency of 40ms with a standard deviation of 6.05ms. The increased latency in the Zelzate area respects the port of Antwerp area is related to the different signal strength, reduced by the environmental characteristic of the Zelzate pilot site i.e., the presence of the bridge.

More details and results about our tests can be found [5].

B. Lessons learned

In the context of teleoperated barges, network connectivity is crucial, especially in relation to two critical data streams: uplink and downlink. The uplink channel facilitates the transmission of video streams captured by onboard cameras to the cloud infrastructure of the teleoperation center, ensuring that remote operators can obtain an accurate picture of the environment around the barge and perform navigational tasks with precision. Such a network flow is essential for the continuous transmission of high-definition video feeds and geospatial data, which are essential for the remote operation of the vessel.

As for the downlink, this flow fulfills the reverse task, transferring operational inputs from the teleoperation center to the onboard systems in charge of navigation. These commands, including instructions for trajectory adjustment and speed regulation, are processed by the control system of the vessel to implement real-time operational fluctuations.

Our analysis in the experimental phase of the project has highlighted relevant technical issues, particularly regarding the configuration of the antenna arrangement on the barge. It emerges that the strategic design of antenna positioning and size of the 5G modem is of critical importance to maximize network performance. Experiments have revealed that suboptimal installation of the 5G modem and its antenna can result in marked signal attenuation, an increase in latency values, and a higher rate of data packet losses.

IV. Teleoperated road-vehicles

The 5G-Blueprint project aims to develop, test, and validate uninterrupted cross-border teleoperation, utilizing the advanced capabilities of 5G connectivity, as defined in the 3GPP Release 16 standards [6]. In this section, we explain how 5G SA networks enable uninterrupted cross-border teleoperation for teleoperated road vehicles. The architecture of a real teleoperation system used in the 5G-Blueprint project, illustrated in Figure 3, consists of (i) a teleoperation center, (ii) the vehicle, and (iii) a crucial component known as the Gateway. The Gateway is the heart of the system, where all vehicles and remote stations are connected. The Gateway authenticates each component of the teleoperation system, allowing them to communicate their status. Once authentication has taken place, a stable connection is established between the vehicle and the teleoperation center enabling the remote driver to access real-time data, such as vehicle speed, location, and visual feeds transmitted directly from the vehicle.

To enable teleoperation, within the 5G-Blueprint project we equipped the vehicles with onboard communication units, various sensors, integrated cameras, and a 5G modem to connect to the 5G network. More details on these teleoperation components can be found in [5]. The equipment mounted on the vehicle is essential to ensure teleoperation. Specifically, the 5G modem installed on the vehicle ensures communication between the teleoperated vehicle and the teleoperation center, guaranteeing that high-definition videos captured by the cameras in the vehicle are transmitted to the teleoperation center. In addition, the 5G modem also ensures the reception of control commands, coming from the teleoperator, with high reliability and low latency. Within the 5G-Blueprint project, the 5G SA network infrastructure supports network slicing, guaranteeing uninterrupted service, and respecting Quality of Service (QoS) for teleoperation services e.g., vehicle control commands URLLC and high-definition video transmission eMBB.

However, teleoperators face challenges in situational awareness due to the lack of direct perceptual feedback, such as feeling the acceleration of the vehicle or inclination and responses to driving actions like steering or braking. To address these challenges, the 5G-Blueprint project includes the development of EFs designed to support UCs and enhance road safety. One such feature, the Enhanced Awareness Dashboard (EAD) or EF1, significantly augments the teleoperator's situational awareness by providing i) speed advice, ii) obstacle warnings, iii) collision alerts, and iv) traffic light responses, alongside navigation and routing features displayed on a map-based view. This not only enhances the safety of teleoperated transport but also improves the comfort and confidence of the operator by augmenting the visual and data-driven inputs available to them during remote vehicle operation. This cohesive integration of advanced communication technology and user-focused interfaces in teleoperation systems promises to revolutionize the efficiency and safety of international transportation and logistics.

A. Experiments and Results

To assess the capabilities of 5G SA connectivity for teleoperated vehicles, we conduct a series of experiments focusing on the performance of the network in challenging environments typical of the transport and logistics sectors, such as port environments. Specifically, we chose the pilot site in Vlissingen (NL), which has road transportation between ports/terminals and distribution centers. Additionally, we extend our testing to Zelzate (BL-NL) due to its pivotal role in cross-border scenarios.

Our experimental setup includes a test vehicle equipped with teleoperation hardware e.g., cameras, and a 5G modem to send video traffic, and other data generated from the sensor in the vehicle, via the 5G SA network. More details about the equipment are illustrated in [5]. We perform tests on isolated roads at both pilot sites i.e., Vlissingen and Zelzate, with safety drivers present in the vehicle to assume manual control if necessary.

In Vlissingen, the tests yielded an average network throughput of 52.8Mbps in uplink and an average RTT end-to-end latency between the car and the teleoperator of 15ms. However, during our tests, we encountered RSRP values of about -100 dB in certain segments of our path, not far from the 5G SA base station. More detailed results and statistical analysis are presented in [8] Meanwhile, the Zelzate tests involved remotely driving the vehicles from the Netherlands to Belgium and back. This scenario was crucial for assessing network reliability during cross-border transitions, with different Mobile Network Operator (MNO) base stations strategically positioned to manage the handover process. Our tests in Zelzate indicate an average throughput of 24Mbps in uplink, an average RTT end-to-end latency of 24ms, and a service interruption time of approximately 120ms during handovers (roaming) between different MNO base stations. For more detailed information about the results of the steering wheel, pedals, joysticks, and the handover mechanism, we refer the reader to [5]. The uplink and latency capacity of the 5G SA network demonstrates the ability to support teleoperation scenarios in both pilot sites i.e.,

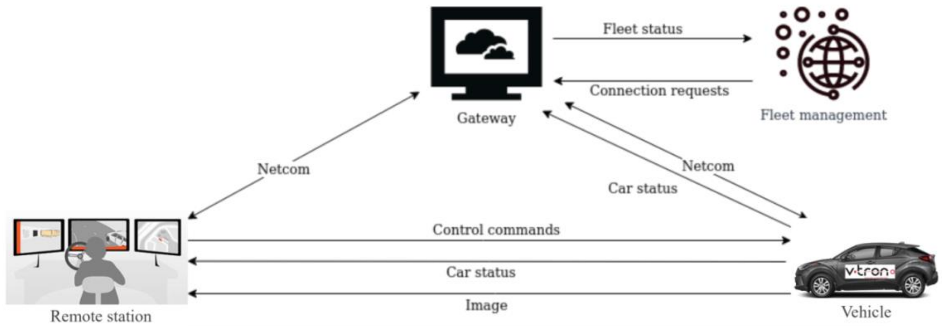

Fig. 3: Architecture of the real teleoperation system used within the 5G-Blueprint project.

Vlissingen and Zelzate. Throughput and latency are sufficient to send and receive respectively high-definition video data from more than one camera and control commands to control the teleoperated vehicle. Furthermore, the minimal downtime observed confirms that the 5G SA network supports seamless teleoperation, allowing teleoperators to efficiently manage vehicles in cross-border situations without significant interruptions.

B. Lessons learned

The experimental results from both pilot sites i.e., Vlissingen and Zelzate, highlight the limitations of the 5G SA network operating in the 3.5GHz frequency range. While the network offers good and stable signal quality, its effective range is limited to approximately 2 kilometers from the base station, as shown in the detailed analysis of the results from our tests [8]. Hence, is critical to focus on the deployment of 5G SA networks, particularly in the strategic placement of base stations. Ensuring high-quality signal reception is vital for achieving the necessary uplink throughput and end-to-end latency, both of which are crucial for latency-sensitive applications like teleoperation. Moreover, the complex busy port areas characterized by numerous metal structures and the frequent movement of large trucks and ships—significantly affect network performance. The presence of bridges also contributes to these challenges, further complicating signal transmission and reception.

Furthermore, shadow mode testing has emerged as an extremely valuable tool in this context, especially for scenarios where the direct remote control is not allowed, such as on public roads. This testing method allowed us to evaluate the feasibility of teleoperation under typical mixed traffic conditions without compromising public safety or infrastructure. By evaluating the capabilities of teleoperation in shadow mode, we were able to determine conclusively whether remote operation would be feasible on these roads under normal traffic conditions.

V. Conclusion

The present study explored the deployments, methodologies, and key technical aspects employed used in the 5G-Blueprint project to realize vehicle and barge teleoperation, also considering border scenarios with uninterrupted solution. The outcomes obtained from extensive testing of all technical components involved in the teleoperation chain confirmed the effectiveness of 5G Standalone technology as an effective support for teleoperation. 5G Standalone emerges as a strategic element to meet rigorous performance criteria for uplink and downlink data flows. The flexibility and modularity of the 5G Standalone architecture has emerged as decisive in ensuring the secure and reliable handover across national borders. With the large-scale expansion of teleoperated vehicles such as barges, trucks, and cars , it becomes essential to design 5G networks capable of handling high uplink throughput for numerous simultaneous video feeds while maintaining very low transmission delay (end-to-end latency). This aspect is vital for accurate remote command communication and timely transmission of critical safety alerts for both Vulnerable Road Units (VRUs) and telecontrolled vehicles.

Our work highlights the importance of a carefully designed and optimized 5G network to support teleoperation in the transportation sector, with tangible benefits in terms of safety and efficiency, building the foundation for a future in which remote mobility becomes an integral and reliable component of the road fabric and transportation infrastructure

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