Next-Gen Connectivity: Dynamic QoS Optimization for 5G Standalone and Vertical Integration

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***Abstract*—The evolving landscape of 5G Standalone (SA) and beyond networks is being increasingly focused on vertical industries. To unlock the full potential for verticals, it is important to tightly integrate Edge Network Applications (EdgeApps) tailored to vertical use cases, with the 5G SA network, while allowing them to interact with each other at the same time. Such interaction enables more transparency in expressing Quality of Service (QoS) demands from verticals in the form of intent while hiding the network complexity from them. In this paper, we propose two EdgeApps, which by interacting with both User Equipments (UEs) and 5G SA network, are becoming aware of network quality (quality-awareness) and context around UEs (situational-awareness). Such awareness is also enabled by initiatives such as GSMA Open Gateway and CAMARA, where network and IT functionality are exposed to application developers through standardized Application Programming Interfaces (APIs) that abstract the underlying complexity on the telco and IT systems. In this paper, we utilize the Nokia Network as Code (NaC) platform that exposes the capabilities of the Telenet 5G SA network through CAMARA APIs allowing our EdgeApps to dynamically and in real-time create events that trigger changes in QoS levels required by vertical applications. The paper showcases this concept through a case study within the Transport and Logistics (T&L) sector, which is focused on improving the safety and efficiency of remote vessel operation in busy port environments. The overall solution is deployed and tested on the Antwerp 5G SA testbed, which consists of the UEs (vehicle and vessel) and 5G network infrastructure in the Port of Antwerp-Bruges, as well as the 5G edge where EdgeApps are running. This research contributes to the broader objective of incorporating diverse industrial applications into the 5G and beyond ecosystem, showcasing tangible benefits for vertical industries.**

***Index Terms*—QoS optimization, 5G SA, EdgeApp, NaC, 5G testbeds, verticals, remote operation**

I. Introduction

Given the rapid advancements in 5G, significant opportunities are unlocked for tailoring 5G and beyond services to vertical industries. The vertical services that are being created to address the specific needs of verticals are deployed in the form of Edge Network Applications (EdgeApps), which abstract the network complexity from the vertical application developers. However, if not network-aware, i.e., not able to interact with the network towards balancing and adjusting Quality of Service (QoS), EdgeApps still cannot seize the full potential of 5G and beyond in terms of high levels of QoS. This becomes even more pertinent with the transition to an evolved version of 5G, known as 5G-Advanced, specified by 3rd Generation Partnership Project (3GPP) in Release 18, which ultimately paves the way towards 6G [1,2].

A crucial long-term objective in the evolution of 5G and beyond networks is the creation of intelligent networks spanning from the Radio Access Network (RAN) layer to the edge layer (Fig 1). Such an ecosystem aims to enable enhanced services not only for customers and enterprises but also for various vertical industries, such as Transport & Logistics (T&L), Healthcare, and Automotive, among others. To accelerate and facilitate the adoption of 5G in vertical industries, the European Commission has initiated several H2020 projects, including VITAL-5G [3], 5G Blueprint [4], 5G-EPICENTRE [5], 5G-INDUCE [6], etc., with the ultimate goal of incorporating more industry verticals into the 5G and beyond landscape. The objective is to showcase to these verticals how 5G and beyond technologies can significantly enhance their day-to-day operations.

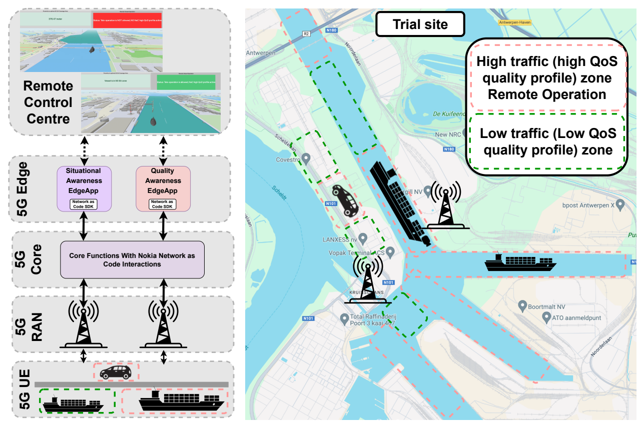

Fig. 1: QoS optimization for vertical industries.

This paper focuses specifically on the dynamic optimization of QoS by enabling EdgeApps to seamlessly interact with the 5G Standalone (SA) network through context-specific events, which trigger the modifications of the QoS in the 5G SA network (Fig. 1). Recognizing that QoS requirements may evolve based on the current state of the end-user and to maximize the efficient utilization of limited network resources, we introduce the event-driven network programming concept by creating Situational Awareness and Quality Awareness through the use of EdgeApps (Fig. 1). These EdgeApps are capable of dynamically configuring their QoS in the 5G SA network in real-time by leveraging Nokia's solution Network as Code (NaC)[1]. The Nokia NaC platform allows us to expose CAMARA[2] standard Application Programming Interfaces (APIs) implemented within the Telenet 5G SA network to adjust the

[1]Nokia's NaC: https://www.nokia.com/networks/network-as-code/

[2]https://www.gsma.com/futurenetworks/ip_services/understanding-5g/camara-telco-global-api-alliance/

5G network behavior and extract the information needed from the network to fulfill the requirements of the EdgeApps that can vary dynamically depending on the specific situations they are facing. To validate and showcase this concept, we conduct a comprehensive case study, demonstrating its efficacy for a specific vertical (Fig. 1), i.e., maritime industry. Presently, remote vessel operations rely on 4G and partially on 5G, but these are constrained by the limited availability of services for remote operators and the absence of guaranteed network performance. Thus, starting from this example, our objective is to illustrate to vertical industries how the integration of enhanced 5G SA and beyond network vertical services can improve their day-to-day operations within the 5G SA ecosystem (Fig. 1). In the following sections (II-1, II-2), we show the advantages of the Situational Awareness and Quality Awareness EdgeApps within the maritime vertical industry through a remote vessel control use case (Fig. 1). We illustrate how 5G SA and beyond services, facilitated by EdgeApps, can significantly improve maritime operations by optimizing remote vessel operations and ensuring their safety (Fig. 1).

Our proposed EdgeApps interact with the 5G SA network, thereby enhancing situational awareness by dynamically adjusting QoS parameters based on the vessel's context (e.g., current location, or potential obstacles) (Fig. 1). This addresses existing limitations in both 4G and 5G, leading to more efficient and secure remote vessel operations. To assess and validate these improvements, we leverage the advanced capabilities of the open Antwerp 5G SA experimentation testbed, of the VITAL-5G project [3,7–9] situated at the Port of Antwerp-Bruges. Through real-life testing and validation on this testbed, we showcase the EdgeApps that optimize remote vessel operations and enhance safety. This approach directly addresses practical challenges in the maritime sector and contributes to the overall enhancement of future port operations with the help of enhanced 5G and beyond systems.

II. 5G-ENHANCED VERTICAL SERVICES

The pervasive adoption of wireless 5G SA and beyond connections has resulted in an increasing number of interconnected devices, both within the general population and the corporate landscape, seeking to enhance their day-to-day operations [7]. Consequently, the pivotal role of vertical services within 5G SA and beyond ecosystems is poised to grow in significance in the foreseeable future. In this context, EdgeApps emerge as crucial software components facilitating the realization of the next generation of vertical services deployed at the edge of 5G SA and beyond networks [3,7,10,11]. To illustrate the potential of EdgeApps in addressing complex industrial processes through 5G SA-enhanced vertical services, we present a maritime use case, i.e., remote vessel operation, whose situational awareness is enabled by a vertical service, realized as a set of EdgeApps. The key objective of this vertical service is to enhance the remote operation of a vessel navigating a congested port area, specifically the Antwerp-Bruges port. This scenario is noteworthy as remote operation becomes essential, particularly when large vessels rely on manual control due to the limitations of autonomous features and preventing port regulations for fully autonomous sailing (e.g., bridges over the river, busy port areas with other vessels) [4]. Accidents during the entry of vessels into port environments, up to the point where they need to moor, can lead to blockages in the port, causing delays that translate to significant economic repercussions. Moreover, a successful and safe remote operation of vessels requires the robust performance of the network.

This is why our proposed vertical service, composed of the Situational Awareness and Quality Awareness EdgeApps, aims to enable more optimized and safer remote operations. This addresses existing limitations in both 4G and 5G networks, where the availability of services to assist remote operators is limited, and network performance lacks guarantees for remote vessel operations. Our vertical service interacts with the 5G SA network, enhancing situational awareness by adjusting QoS based on the vessel's specific conditions, such as its current location and potential obstacles. This improvement contributes to more efficient and secure remote vessel operations.

*1) **Situational awareness with event-driven network programming**:* The situational awareness feature is realized through an EdgeApp that interacts both with User Equipment (UE), i.e., vessel, and 5G SA network. This way, the EdgeApp can detect special events that require a dynamic modification in the QoS. For instance, it can adjust QoS levels based on vessel context, such as specific areas where the vessel is sailing, where the demand for higher or lower QoS may vary (Figures 1, 3). This increased awareness enables EdgeApps to dynamically and in real-time generate events, and trigger changes in QoS. Leveraging the NaC solution, this approach ensures the delivery of QoS levels required by vertical applications on demand.

This EdgeApp is implemented in our specific case study with the primary objective of optimizing and enhancing the safety for the remote operation of the vessel through efficiently utilizing network resources during remote vessel operation (Fig. 3). Specifically, when vessels operate in fully autonomous mode or are manually controlled by the onboard captain, there is no necessity to transmit high-quality video streams over the 5G network to the remote control center where the remote captains are situated. It is crucial to stress the network only when required and allocate network resources judiciously among remotely operated vessels entering the port. However, during the transition from fully autonomous sailing to teleoperated sailing in designated areas within the port (e.g., bridges over the river, busy port sections with numerous vessels), or when traversing from a less busy to a more busy area in the port, it is important to ensure the required uplink capacity for transferring videos to the remote center. To this end, our EdgeApp can detect the event of the vessel entering an area where a higher QoS is needed (because remote operation needs to take place, or the area is busier than usual), utilizing geofencing (Fig 2). This allows the 5G Core functions (Fig. 3) to proactively enhance video quality specifically for the remote captain during scenarios where remote operation of the vessel is necessary. In our use case, when a vessel enters specific geofenced regions (e.g., bridges over the river, busy port areas with numerous vessels, or when traversing from a less busy to a more busy area in the port), the EdgeApp initiates a request to the 5G Core for a higher-bandwidth slice profile. This request demands increased network performance for a defined duration, enabling the remote captain to take control. Moreover, the EdgeApp can be extended as a further opportunity for enhancing situational awareness. This can be achieved by integrating an Artificial Intelligence (AI)/Machine Learning (ML) object detection mechanism into the EdgeApp, capable of analyzing incoming camera feed footage from vessels within a designated region. When the mechanism detects a higher density of obstacles or identifies scenarios requiring a remote operation, the EdgeApps can in advance initiate a request for a high-bandwidth profile. This proactive measure ensures that the remote captain can swiftly take control, effectively addressing dynamically evolving situations where a static geofencing mechanism might fall

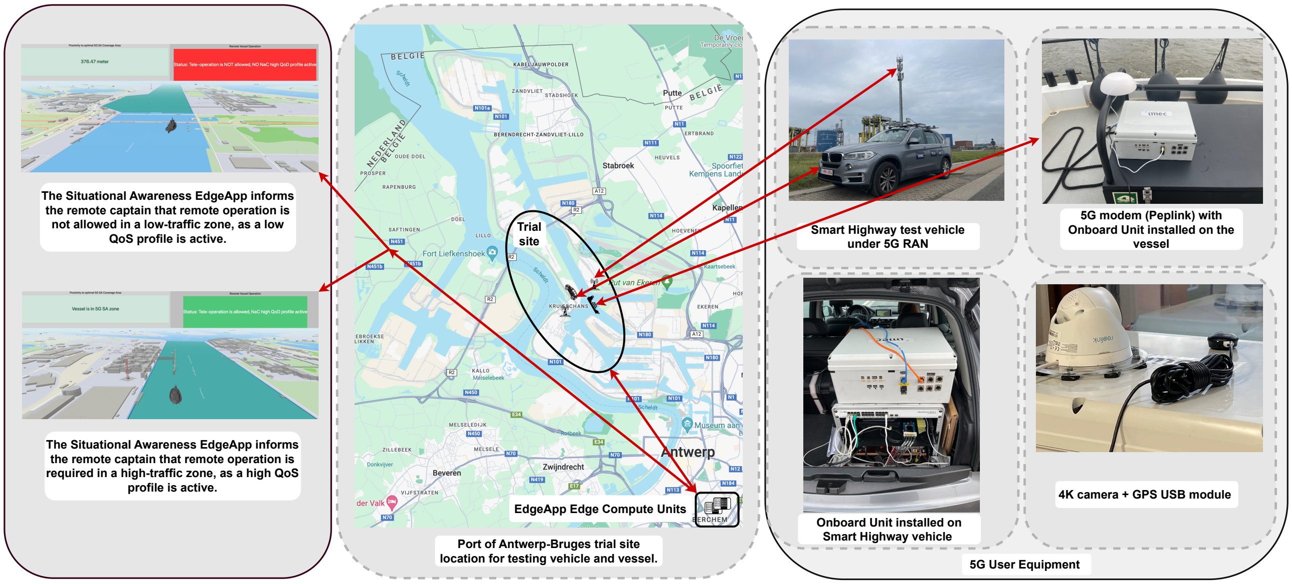

Fig. 2: Trial site location with 5G User Equipment and EdgeApp interaction.

short.

*2) **Quality Awareness with event-driven network programming**:* Same as in the case of situational awareness, this EdgeApp is also interacting with both UEs and 5G SA network, to become aware of the network quality of the link utilized by UEs (quality-awareness). This way, this EdgeApp can perform quality control on the obtained network performance and execute dynamic modification in the QoS. The event to trigger a QoS change is similar to the Situational Awareness EdgeApp explained above, but the event in this case is the quality of the network (quality-awareness) and not a specific situation such as detected obstacles or presence in specific geographic areas. It is important to monitor the quality of the network and thus be able to detect if the network is under-performing, to guarantee optimal QoS for the specific UEs. Leveraging the NaC solution, this approach ensures the delivery of QoS levels required by vertical applications.

In our use case, when vessels are being remotely operated and require high network performance, it is crucial to monitor the quality of the network and be able to detect if the network is underperforming to guarantee the safe remote operation of the vessel. This EdgeApp detects if the network quality is deteriorated, thereby allowing the 5G SA network to enhance video quality specifically for the remote captain during scenarios where remote operation is necessary. In our use case, when the Quality Awareness EdgeApp detects a deterioration in network quality for a specific vessel, it can take two actions. First, in anticipation of potential network deterioration, the EdgeApp performs a proactive performance boost for the camera application. This ensures that the remote captain continues to receive a high-quality camera feed, mitigating the impact of degraded network conditions. Second, if the performance boost is unsuccessful, and the network performance remains deteriorated, the EdgeApp notifies the remote captain of the specific teleoperated vessel with a notification message. The message advises the remote captain to slow down and proceed with mooring until the network has recovered, ensuring safety before resuming normal operations.

*3) **Nokia Network as Code (NaC)**:* The EdgeApps (i.e., the Situational- and Quality Awareness EdgeApps) responsible for delivering these 5G services operate at the edge of the 5G SA and beyond network within the designated area in the Port of Antwerp (Fig 3). These distinctive features (i.e., the Situational Awareness EdgeApp and the Quality Awareness EdgeApp) are made possible by the inherent characteristics of EdgeApps, encompassing their network awareness and programmability. The Situational-awareness EdgeApp achieves this functionality by programming the network using Nokia NaC [12], establishing communication between the EdgeApp and the Telenet 5G Core (based on Nokia technology) (Fig. 3). This approach enables the EdgeApp to dynamically request a low-bandwidth profile for upstream camera feeds from vessels operating outside the remotely controlled area. Conversely, for vessels within the remotely controlled areas, the EdgeApp can request high-bandwidth profiles, ensuring high-quality video streams for upstream camera feeds. This distinction is crucial for facilitating remote takeovers by the remote captain. Similar to the Situational-awareness EdgeApp, the Quality-awareness EdgeApp also utilizes Nokia's NaC for establishing a performance boost while detecting the network performance is deteriorating.

*4) **CAMARA**:* The Open Gateway Initiative (OGI), initiated by GSMA[3], plays a pivotal role in standardizing APIs within the telecommunications sector, promoting interoperability between Mobile Network Operators (MNOs) and third-party developers. The GSMA Open Gateway APIs are defined, developed, and published within CAMARA[4], an open-source project aimed at providing developers with access to enhanced network capabilities. CAMARA is driven by the Linux Foundation in collaboration with TM Forum[5]. As such, CAMARA serves as a collaborative project dedicated to defining, advancing, and validating APIs relevant to telecommunications infrastructure. By leveraging established industry standards and best practices, CAMARA presents a cohesive taxonomy of APIs, covering essential domains such as network slicing, virtualized infrastructure management, and software-defined networking. Furthermore, CAMARA advocates for transparency and accessibility, with its source code repository publicly hosted, fostering community engagement, peer review, and collaborative

[3]GSMA: https://www.gsma.com/
[4]CAMARA: https://camaraproject.org/
[5]TM Forum: https://www.tmforum.org/

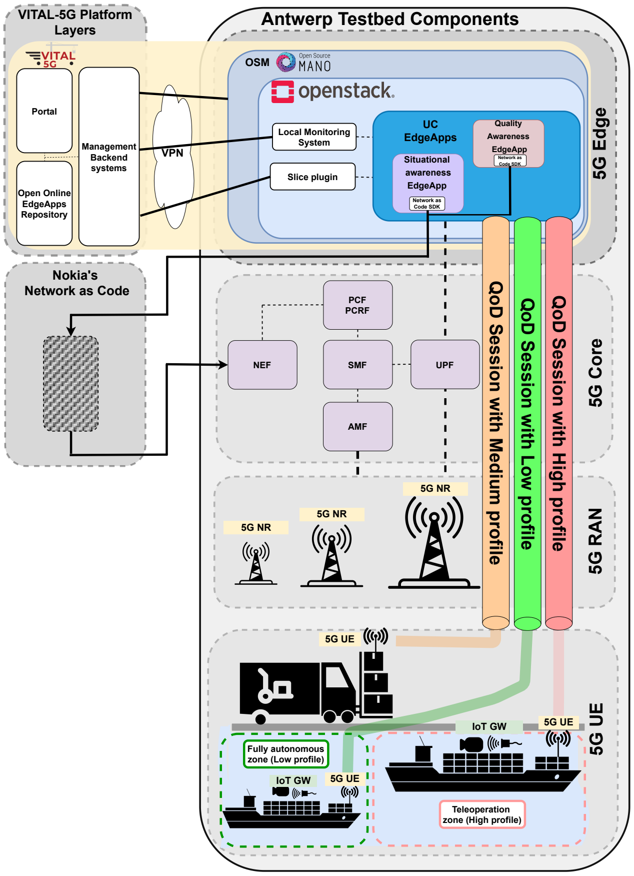

Fig. 3: Testbed architecture with EdgeApps.

innovation.

The Nokia NaC platform, integrated with the NaC SDK on the EdgeApps (Fig. 3), enhances and exposes CAMARA standard APIs within the 5G SA network. It facilitates the adjustment of 5G network behaviour and extraction of the necessary information for EdgeApps, which may vary dynamically based on specific situations. This is how the Situational Awareness EdgeApp and the Quality Awareness EdgeApp presented in this paper (Section II) can make over the standardized CAMARA APIs enhanced with the Nokia NaC requests (i.e., Quality-of-Service on Demand (QoD) and the Device Location NaC APIs) to dynamically program the underlying 5G network. Potentially enabling the deployment of these EdgeApps with any network operator worldwide.

III. 5G SA TESTBED WITH DYNAMIC QoS

A. Validation on Real Systems and Testbeds

To test and deploy specific vertical services tailored for various industries, the EdgeApps forming these services must be integrated into the 5G SA ecosystem. This integration involves utilizing dedicated platforms that abstract the network complexity. For the deployment of our vertical services, i.e., the Situational Awareness and the Quality Awareness EdgeApps, within the 5G SA ecosystem, we have chosen the comprehensive suite of enabling technologies from the VITAL-5G project [3,7–11] (comprising both the VITAL-5G platform and the VITAL-5G testbeds) (Fig. 3). The VITAL-5G platform facilitates the seamless onboarding of vertical services into the 5G SA ecosystem, while the VITAL-5G testbeds [7–9] provide the infrastructure for testing and validating these services in real-life 5G SA networks (Fig. 3). This approach allows us to deploy, test, and validate our proposed vertical services aimed at optimizing QoS for various industries, as exemplified by our case study in the maritime vertical sector. This ensures that our experimentation goes beyond theoretical and simulated environments, establishing a robust foundation for exploring new systems and advancing the field.

In the subsequent subsections, we present an overview and discuss our trial site, which serves as the experimental site for QoS optimization for vertical industries.

B. How the Situational Awareness and Quality Awareness EdgeApps are deployed at Antwerp VITAL-5G testbed?

Our choice for the VITAL-5G Antwerp EdgeApp testbed is motivated by its geographical location within the Port of Antwerp (Fig. 2) at the edge of the 5G SA network (Fig. 3), aligning with the specific requirements of our T&L use case. The EdgeApps deployed in the Antwerp VITAL-5G testbed exhibit inherent characteristics, namely: i) full network awareness, ii) complete QoS awareness, iii) total network control, and iv) adaptability to dynamic network conditions. The features above are enabled by interaction with 5G Core and by monitoring network performance performed by the VITAL-5G platform [3,7–11]. The encompassing capabilities of the Antwerp VITAL-5G testbed enable the development of innovative EdgeApp vertical services, fostering research and advancement in deploying new 5G SA and beyond network services at the edge of the network. An example of such a vertical service is presented in this paper, featuring the Situational Awareness EdgeApp and the Quality Awareness EdgeApp.

In alignment with the VITAL-5G design philosophy [3,7], each EdgeApp presented in this paper adheres to the necessary VITAL-5G blueprints, Virtual Network Function Descriptors (VNFDs), Network Service Descriptors (NSDs), and software images. These components must be onboarded into the VITAL-5G ecosystem, encompassing the VITAL-5G platform and testbed, to operate within the 5G SA and beyond network (Fig. 3). The guidelines provided by the VITAL-5G project, extensively discussed in our prior work [7], serve as the foundation for this process.

C. RAN and Core infrastructure upgrades on the testbed for the Network as Code (NaC)

In comparison to our prior work described in [7], upgrades have been made to the 5G RAN and Core layer of the Antwerp VITAL-5G testbed such that the testbed supports Nokia's NaC [12] functionalities. On the RAN site of the testbed, the installation of increasingly powerful Next-Generation Node B (gNodeB) units, expanded both coverage and capabilities within the testing area. On the other hand, the 5G Core layer is upgraded to incorporate the essential software components integral to Nokia's NaC, involving the integration of Network Functions remotely hosted on the cloud. This enhancement also facilitates the experimentation on federated testbeds. The 5G Core is directly linked to the 5G Edge platform (Fig. 3) via a 7.2 km optical fibre connection, reflecting the close proximity between the Edge and the Core. This setup allows for a single-core environment, with all 5G Core functions centralised. During our trial, we achieved a round-trip latency averaging 22.03 milliseconds from sending sensor data from the UE (i.e., our testing vehicle or trial vessel) at our trial site (Fig. 2) to the EdgeApps running on the Edge platform (Fig. 3). The performance analysis of this system is not covered in this paper and is presented in our ongoing publication. In that publication, we address various design aspects and test the variances in end-to-end latency achieved.

The NaC, as conceptualized by Nokia, embodies a transformative approach that seeks to radically simplify network functionalities [12]. This paradigm empowers applications to dynamically optimize network configurations, thereby enhancing both performance and user experience through APIs [12]. The NaC establishes a novel synergy between business and technology, positioning distributed service chains as a cornerstone in the telecommunications landscape [12]. In the context of such network advancements, the QoD feature emerges as a crucial capability, allowing users to establish prioritized connections between mobile devices and other services on the internet [12]. This feature enables users to manage stable bandwidth and latency for each device based on current demand, facilitated through QoD sessions [12]. Given the shared nature of networks and the competition for bandwidth among various applications and devices, QoD profiles play a pivotal role [12]. Users can specify parameters such as upload and download speeds, programming the network to adhere to their desired behaviour [12]. As detailed in Section II-3, the EdgeApps facilitating the use case (specifically, the Situational Awareness and the Quality Awareness EdgeApp) leverage the NaC QoD profile feature. In this context, the user serves as our testing vehicle or trial vessel, enabling them to establish a prioritized connection to those EdgeApps at the Edge of the 5G SA network, where the service is provided (Figs. 2, 3).

However, it is important to recognize that the time elapsed from applying the QoD profile to its full adaptation across the entire network varies depending on the underlying network infrastructure, with each network experiencing a unique time-frame. In our case, requests originating from EdgeApps enabled with the NaC SDK take less than 2 milliseconds to reach the NaC backend services (Fig. 3). However, within our network, the full adaptation process, where the NaC backend services contact our 5G Core and configure the network, typically completes in less than 10 seconds. Further assessment needs to take place in order to optimize the overall time to apply QoS change in the network. In the meantime, we are proactively triggering the QoS change taking into account the time needed for a change to applied, e.g., around 20 m before the vessel enters the geofenced area. This ensures the necessary uplink capacity is guaranteed for transferring videos to the remote captain.

D. User equipment

To validate and test the Situational Awareness and the Quality Awareness EdgeApps on the 5G SA testbed (Fig. 3), we employ a testing vehicle and a vessel (Fig. 2). Both are equipped with a Global Positioning System (GPS) Universal Serial Bus (USB) module, a 4K camera for remote operation activities, and a 5G SA modem (Peplink). All aforementioned components are interconnected to a computing On Board Unit (OBU) (Fig. 2), establishing a connection to the Situational Awareness and the Quality Awareness EdgeApps running on the edge of the testbed (Fig. 3).

The 4K camera for remote operation (Fig. 2) is connected to the OBU (Fig. 2) computing box to stream the capture video feed from the vehicle or vessel towards the EdgeApps running at the Edge part of the 5G SA network (Fig. 3). The 4K camera feed from this camera will be improved in its overall quality (through a change in the QoS) in scenarios where the vehicle or vessel enters a remotely operated region or when more obstacles are detected.

The GPS USB module (Fig. 2) is connected to the OBU computing box. This configuration enables the Situational Awareness EdgeApp to monitor the vehicle or vessel, detecting its entry or exit from a remote operation zone and anticipating heightened network requirements during these instances.

The 5G SA Peplink modem (Fig. 2) is connected to the computing OBU box, serving as the gateway that connects the vehicle and vessel to the Edge part of the 5G SA network where the EdgeApps operate (Fig. 3). This configuration facilitates the transfer of the 4K camera feed for the remote operation and the GPS positions from the USB module.

The OBU computing box (Fig. 2) is a custom-made portable computing platform equipped with i) a Next Unit of Computing (NUC), ii) a switch, iii) a Power over Ethernet (PoE) module to power the 5G SA Peplink modem, and iv) USB slots to connect the portable GPS USB module and 4K camera for remote operation.

Testing Vehicle and Vessel (Fig. 2) the vehicle, a Smart Highway BMW (Fig. 2), is part of the open Cellular Vehicle-to-Everything (C-V2X) Smart Highway testbed located in Antwerp, Belgium [13]. On both the vehicle and the vessel, the computing OBU box can be easily installed and connected to the GPS USB module, the 4K camera for remote operation, and the 5G SA Peplink modem (Fig. 2).

E. Location of the testbed

The trial site of the VITAL-5G EdgeApp 5G SA testbed is situated in the Port of Antwerp-Bruges, Belgium (Fig. 2, 3) [7–9]. One of the primary objectives is to inspire other researchers from both academia and industry to utilize the testbed in novel and impactful ways, validating their research ideas to enable new 5G SA and beyond EdgeApps vertical services across various verticals. Given the relatively recent emergence of 5G SA, there is limited existing literature addressing its application in vertical industries and the potential enhancement it brings to their day-to-day operations. The overarching objective is to integrate additional industry verticals into the evolving landscape of 5G SA and beyond. Therefore, we utilize this testbed for our case study to test and validate our vertical services in this case applied to the maritime vertical industry. The maritime industry is of particular significance due to the slower adoption by port authorities and shipping companies in providing necessary infrastructure and applications, making the testbed particularly valuable. Telco operators may find high interest in offering new services, such as the proof-of-concept presented in this paper.

Initially, we conducted trials with our testing vehicle (Fig. 2), which is equipped with the same UEs as installed on the vessel, for several reasons. First, due to *cost-effective testing*, because renting a vessel with a captain for extended trial periods can be expensive. Using our test vehicle provides more flexibility in the testing equation as we can drive directly alongside the canal at the Port of Antwerp-Bruges, where our use case is situated. Second, due to *Accessibility and Safety* reasons, as during the initial testing phases, it is more convenient and safer to halt a vehicle at a designated spot than to stop a vessel in one of the busiest canals in the Port of Antwerp-Bruges. After completing the initial testing campaigns, we transitioned to conducting tests with the vessel.

IV. Future of 5G and beyond vertical services

Starting from 5G and going towards 6G systems, network programmability is paving the way for more dynamic and adaptive communication technologies that cater to diverse and evolving use cases. Allowing vertical applications to detect context-specific events and to trigger QoS changes based on these events increases the overall use case efficiency and safety of users, as the network will automatically adapt to accommodate the required QoS levels. In the automotive sector, for example, the future of mobility will be mixed, thereby combining autonomous, teleoperated, and regular vehicles, where increased situational awareness of all traffic participants is a must for ensuring safety. In the case of autonomous vehicles, sufficient bandwidth can be ensured on-demand and dynamically in situations where remote control is needed to resolve edge cases that autonomous vehicles cannot handle by themselves. This could be an obstacle on the road, a busy area with other autonomous or teleoperated vehicles, or simply a situation in the maneuvering process that cannot be resolved. On the other hand, the dynamically allocated bandwidth could be also used for offloading data from autonomous vehicles to Edge or Cloud servers in case the vehicle cannot efficiently fuse and process all the sensor data. The same principles would apply to other vertical applications such as remote surgeries for e-health, teleoperation of trucks and cranes in logistics chains, automated guided vehicles in warehouses, and metaverse, among others.

To this end, the use of real-life open 5G SA and beyond testbeds is essential, as they constitute essential environments for advancing research and development in the realm of next-generation services. The utilization of the open Antwerp 5G SA and beyond testbed facilitated our research and development to create our vertical services for QoS optimization for vertical industries applied to a case study presented in this paper.

Despite significant progress with proof of concepts, there are numerous untapped opportunities for 5G SA and beyond vertical services enabled by EdgeApps, e.g., within port areas. The dynamic nature of port environments is evident, with unloading activities involving various tasks, such as those related to container ships, trucks, etc., including the use of cranes, trucks (Automotive vertical), and ground personnel. It is anticipated that, in the near future, cranes and trucks will increasingly perform autonomous tasks, necessitating remote operation for certain edge cases. This reliance on QoS optimization underscores the importance of ensuring that 5G SA and beyond networks can deliver these services effectively. EdgeApps play a crucial role in deploying these services into the 5G and beyond ecosystems, positioning them as versatile solutions with the potential to address multiple vertical services.

Furthermore, the integration of EdgeApp-enabled 5G and beyond services holds promise for enhancing the connectivity of Vulnerable Road Users (VRUs), such as individuals working outdoors in port environments. This connectivity can digitally integrate them with autonomous and remotely operated trucks and cranes involved in the unloading activities of shipping containers. The Antwerp 5G SA testbed plays a pivotal role as an enabler, facilitating the research, development, and validation of these advanced EdgeApp services (Fig. 3). Therefore, the flexibility offered by network programmability in 5G and beyond can lead to more personalized and context-aware services, thereby creating intelligent, adaptable, and highly efficient communication systems for vertical industries.

V. Conclusion

In this paper, we addressed the evolving landscape of 5G SA and beyond networks, with a particular focus on vertical industries. To fully harness the potential of these networks for vertical applications, the integration of EdgeApps tailored to specific vertical services is crucial. We discussed our two proposed EdgeApps (the Situational Awareness EdgeApp and the Quality Awareness EdgeApp) which can dynamically and in real-time create events triggering changes in QoS, leveraging the NaC solution to deliver the requisite QoS levels for vertical services. We then discussed this concept through a case study within the T&L sector, which is focused on improving the safety and efficiency of remote vessel operation in busy port environments. We also illustrated how the overall solution is deployed and validated on the real-life 5G SA testbed in the Port of Antwerp-Bruges. This research contributes to the broader objective of incorporating diverse industrial applications into the 5G and beyond ecosystem, showcasing tangible benefits for vertical industries.

Acknowledgment

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