Paving the Way towards Safer and More Efficient Maritime Industry with 5G and Beyond Edge Computing Systems

Vincent Charpentier*, Nina Slamnik-Kriještorac*, Giada Landi†, Matthias Caenepeel‡,
Olivier Vasseur*, and Johann M. Marquez-Barja*
* University of Antwerp - imec, IDLab - Faculty of Applied Engineering, Belgium
† Nextworks, Italy
‡Telenet, Belgium

Abstract—**The Maritime and Road Transport and Logistics (T&L) vertical industries account for 92.5% of the European total freight transport. Therefore, efficient T&L systems in busy port environments are critical for Europe's global competitiveness. The emergence of 5G and beyond, including Standalone (SA) with data rates up to 20 Gbps, latencies as low as 5 milliseconds (ms), and exceptional reliability (99.999%), offers a significant opportunity for innovation in the Maritime sector, in terms of smarter and safer operations. In this paper, we investigate the enhancements brought forth by Edge Network Applications (EdgeApps) strategically positioned at the network edge, focusing on a practical maritime use case denominated as "Assisted Vessel Navigation," all within the overarching framework of the edge-cloud/core continuum paradigm. We utilize the so-called edge network softwarization and intelligence that allows us to create EdgeApps, capable of running on 5G and beyond-enabled edge and cloud infrastructure to increase the safety and efficiency of maritime operations. The EdgeApp framework simplifies the creation of complex 5G and beyond vertical services and fosters collaboration between industry stakeholders, network experts, and EdgeApp developers. The contributions of this paper are threefold: i) this paper focuses on the significance of edge computing systems within the 5G ecosystem and their role in enhancing vertical industries such as transport and logistics (T&L), with a specific focus on maritime applications, ii) the core contribution of this paper lies in the design and implementation of EdgeApps tailored to vertical industries. We explore their deployment in a real-life maritime environment, and iii) we share valuable insights derived from our real-life experiments conducted in the Port of Antwerp-Bruges, analyzing network and service performance results based on the use case requirements. Therefore, we examine the deployment options of EdgeApps, comparing edge versus cloud environments to assess where they need to run in the edge-cloud continuum. The outcomes and lessons learned from this article hold important implications for vertical industries.**

Index Terms—**5G SA, Edge, EdgeApp, Edge Network Softwarization, AI/ML, Assisted Vessel Navigation, Edge-Cloud/Core Continuum, Maritime Vertical Industry, Transport and Logistics (T&L), Real-Life Experiments, Network Performance**

I. Introduction and Motivation

The maritime and road Transport & Logistics (T&L) vertical industries account for 92.5% of the total freight transport in Europe [1]. Approximately 74% of goods in Europe are transported via ships and barges, making the T&L industry, particularly the maritime sector, a significant economic force nowadays [2]. Translating the well-established concepts of Internet of Things (IoT) on the mechanisms of automation of vessel operations, the Internet of Ships (IoS) has been recently developed as a concept that is creating networks of interconnected ships and ports in the maritime environment. The principal goal of the IoS is to boost the shipping industry by increasing safety, efficiency, and environmental sustainability [2,3]. In particular, in such

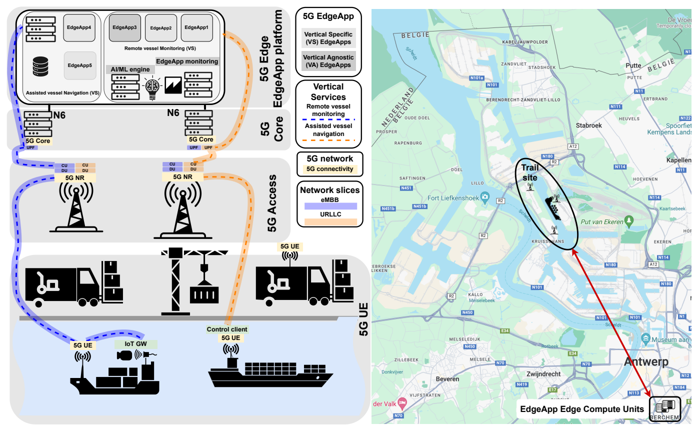

Fig. 1: VITAL-5G Antwerp 5G testbed and T&L pilot site.

IoS systems, barges and other essential users of ports, such as cranes, trucks, and vehicles, are equipped with sensing and communication capabilities that allow them to collect, process, and distribute information from the surroundings, which ultimately improves the decision-making process in their day-to-day operations. However, the time-sensitivity of communication between vessels and ports, along with an evident lack of efficient navigation systems, is imposing risks for various accidents, leading to delays in sailing operations that hinder all other port operations.

According to Aslam et al. [2] and their thorough survey of IoS systems and their components, the communication between barges and ports, as well as between barges themselves, is entirely based on satellite networks, which are expensive to deploy and cause significant delays and insufficient bandwidth for most of the automation operations. On the other hand, one of the principal goals of 5G and beyond networks is to provide reliable connectivity for any connected entity, at any place. In particular, cellular systems such as 5G and beyond are enabling ultra-low latency (1-10 ms), ultra-high reliability (99.999%), and high data rates (up to 20 Gbps) [4], by creating logical and virtualized networks, i.e., network slices, over the common network infrastructure. Thus, by implementing Ultra-Reliable Low-Latency Communication (URLLC), enhanced Mobile Broadband (eMBB), and massive Machine-Type Communication (mMTC), 5G and beyond systems offer grand opportunities to boost the operation and efficiency of many industry verticals, enabling new use cases and applications whose stringent connectivity requirements could not be met with the previous generations of mobile communications systems [5]. Given the lack of research on the true potential of leveraging 5G systems in the context of industry verticals such as T&L, in this paper, we present one of the first attempts to create an end-to-end 5G-based system for enabling assisted and automated vessel control.

As illustrated in Fig. 1 and 3, we have created a pilot site in the utmost busy area of Port of Antwerp-Bruges (Belgium), which is a real-life environment used for testing and validating the impact of an orchestrated 5G system with vertical services deployed at the network edge, on enhancing the vessel control operations, where the vessel is sailing while being connected to the 5G network. Whilst the challenges of leveraging 5G on the open seas still persist due to the lack of infrastructure, in this work we focus on inspecting the potential of softwarized 5G edge systems and vertical services for inland waterways, focusing on the enablers of assisted vessel navigation.

To be able to benefit from 5G technologies in terms of ultra-low latency, high reliability, and extensive throughput, the vertical services need to be properly managed and orchestrated, but their design also needs to be tailored to particular use cases, considering vertical service-specific requirements towards 5G. Thus, by applying the cloud-native principles and programmability of service function chains to the design and development of vertical services in 5G ecosystems, we can define Edge Network Applications (EdgeApps) as a fundamental building block of the 5G-enhanced vertical service chains [6]. Specifically, EdgeApps within the VITAL-5G project (EU ICT-41 project) (Section V), the EdgeApp framework (Section IV) empowers vertical industries to specify their network, service, and hardware requirements through the EdgeApp blueprint (Section V-A). These requirements are then interpreted by network controllers and orchestrators, facilitating changes and service deployments aligned with the specifications outlined in EdgeApp blueprints. Such EdgeApps are deployed on top of the edge and cloud 5G-enabled infrastructure and used for creating any complex 5G vertical service by abstracting the underlying 5G network complexity and thus bridging the knowledge gap between vertical stakeholders, network experts, and application developers.

The main contributions of this paper are threefold: i) this paper focuses on the significance of edge computing systems within the 5G ecosystem and their role in enhancing vertical industries such as T&L, with a specific focus on maritime applications, ii) the core contribution of this paper lies in the design and implementation of EdgeApps tailored to vertical industries. We explore their deployment in a real-life maritime environment, and iii) we share valuable insights derived from our real-life experiments conducted in the Port of Antwerp-Bruges, analyzing network and service performance results based on the use case requirements. Therefore, we examine the deployment options of EdgeApps, comparing edge versus cloud environments to assess where they need to run in the edge-cloud continuum. The outcomes and lessons learned from this article hold important implications for vertical industries. For instance, this paper addresses a specific maritime use case, highlighting its relevance. This is particularly noteworthy considering that maritime systems play a crucial economic role within the European Union (EU).

The remainder of this paper is structured as follows. Section II presents a state-of-the-art section on EdgeApps in 5G Standalone (SA) and beyond networks. Section III presents an overview of edge computing and outlines our vision for its future with EdgeApps. Section IV discusses the need for EdgeApps in 5G and beyond networks. In Section V, we explore 5G edge services for assisted vessel navigation using the VITAL-5G project. Therefore we provide i) the design principles of VITAL-5G EdgeApps, ii) the VITAL-5G definition of EdgeApps, iii) an overview of VITAL-5G testbeds, and finally iv) an overview of the VITAL-5G platform from the perspective how the VITAL-5G platform contributes to the intelligent softwarization and management of any VITAL-5G tested. Section VI introduces the integration of the UE-edge-cloud/core continuum with EdgeApps in the context of a maritime T&L use case, emphasizing the role of edge network softwarization and intelligence. This section also presents important insights gained from experiments conducted in the maritime T&L use case. Section VII summarises the findings, emphasises the lessons learned, and concludes the paper.

II. STATE-OF-THE-ART

Due to the increased network and service quality, the advanced deployments of 5G SA networks are opening up new opportunities for vertical sectors, such as automotive, e-health, and T&L. In their study [7], Malandrino and Chiasserini comment on the potential that 5G brings to different industries, with a focus on high-traffic applications, and what they can gain from integrating 5G in their day-to-day operations.

The analysis provided by Malandrino and Chiasserini is based on a large-scale, real-world, crowdsourced mobile traffic trace [7], and it proves that a large group of applications could vastly benefit from a tight 5G integration. Talking more specifically about deploying vertical services and constituting network applications or EdgeApps, Patachia et al. [8] provide their telco-specific perspective while talking about the advanced 5G architectures for future EdgeApps and verticals. They focus on the architectural and infrastructural adjustments that need to be applied in the 5G networks, in order to facilitate the accommodation of new vertical services [8].

As gaps in current network deployments are hindering the implementation of innovative use cases, Patachia et al. [8] propose deeper integration of DevOps and AI/ML-based cognition into the network infrastructure, which is expected to deliver higher levels of end-to-end network automation capabilities. In [8], Patachia et al. summarize these integration efforts in the form of additional 5G functionalities and services, such as i) EdgeApps on-boarding procedures, which enable deployment and managing of EdgeApp packages from various tenants/verticals/users, ii) creation of EdgeApp experimentation APIs, based on standardized OpenAPIs, to provide access to the lifecycle management of EdgeApps and EdgeApp catalogues, iii) EdgeApp orchestrator, in charge of the overall EdgeApp deployment, iv) MANO client API service that interfaces experimentation and operation with EdgeApp orchestrator, and v) Continuous Integration and Continuous Delivery (CI/CD) service that will provide CI/CD pipelines to coordinate the test and experiment execution by interacting with various orchestrators. Such architectural and infrastructural changes are expected to increase chances of broader involvement of vertical industries, which will be able to develop and test their vertical services and EdgeApps in the real-life 5G ecosystem. In addition, such changes are expected to create means for dynamic and automatic allocation of resources (network, computing, and storage resources), as well as flexible deployment of vertical services in distributed cloud and edge infrastructures.

However, the aforementioned changes may not be sufficient, as EdgeApp-oriented 5G frameworks are not standardized yet. Since 2021, several European projects have been funded with the goal of enabling the design and deployment of Network Applications, or EdgeApps, supporting vertical industries towards better understanding and integration of 5G in their service paradigms. For instance, 5G-ASP[1] focuses on the vertical services that fall into automotive and Public Protection and Disaster Relief (PPDR) categories, facilitating the path from initial ideas (design of Network Applications) to market that targets Small and Medium-sized Enterprises (SMEs). Similarly, 5G-EPICENTRE[2] innovates further in the PPDR sector, providing means to test the readiness of 5G systems to support various mission-critical scenarios for PPDR services. In particular, Apostolakis et al. [9] present an interesting initiative to design EdgeApps tailored for PPDR use cases, which will be deployed in a fully virtualized containerized 5G network within the 5G-EPICENTRE project. For such a use case, the benefits are two-fold: enhancements in the network performance, and automated operations supported by Kubernetes (K8s)-based support.

While 5G-IANA[3] provides opportunities for creating intelligent Network Applications for the automotive sector, 5G-INDUCE[4] focuses on transport & logistics, defining use cases such as autonomous indoor fleet management, smart operation based on human gesture recognition, virtual reality immersion and Automated Guided Vehicle (AGV) control, Machine Learning (ML)-Supported Edge Analytics for Predictive Maintenance, among others. Finally, 5GENESIS[5] project steers the focus towards the integration of satellite networks in the 5G ecosystem. In line with that work, Fornes-Leal et al. [10] demonstrate how the integration of satellite backhauling could extend 5G coverage in challenging scenarios, in the rural and underserved areas, by deploying 5G applications on the network edge, i.e., by creating EdgeApps, as a part of a smart farming use case.

With reference to the early works reported in these projects, in this paper, we go a few steps further and focus on a realistic deployment of EdgeApps for transport and logistics. We detail the design requirements and deployment for those EdgeApps, using the edge computing capabilities with the 5G Standalone infrastructure, and describe our real-life setup for deploying and testing EdgeApp performance in the 5G-enhanced maritime context.

III. Evolution of Edge Computing

Recent advancements in intelligent connected vehicles and Intelligent Transport Systems (ITS) are grounded in the acquisition and analysis of extensive sensor data such as Radio Detection and Ranging (RADAR) and Light Detection and Ranging (LiDAR) [11]. This translated to a move to semi-autonomous vehicles (i.e., cars, trucks, buses, vessels, ships, aeroplanes, etc). However, ITS encompasses various modes of transportation, besides land-based vehicles, including maritime vessels also known as IoS, as maritime transport plays an indispensable role in global trade and the T&L vertical for freights also here these advancements heavily rely on an array of outward-looking sensors, encompassing cameras, RADAR and LiDAR [11,12].

[1]5G-ASP: https://www.5gasp.eu/

[2]5G-EPICENTRE: https://www.5gepicentre.eu/

[3]5G-IANA: https://www.5g-iana.eu/

[4]5G-INDUCE: https://www.5g-induce.eu/

[5]5GENESIS: https://5genesis.eu/

However, managing this diverse range of data (e.g., RADAR and LiDAR), requires preprocessing before the data becomes suitable as input data for relevant Artificial Intelligence (AI) applications. Achieving meaningful results through on-device processing demands significant computational resources [11]. Consequently, current research emphasizes the offloading of computational tasks to the edge of 5G and beyond networks, as discussed in [11]. To facilitate the offloading of AI computing tasks to the edge of 5G and beyond networks for advanced AI applications, the research community has shown increasing interest in a technique known as Federated Learning (FL), as discussed in [13]. This has also prompted the research community to shift its focus more towards the concept of the UE-edge-cloud/core continuum [14]. This is one out of the many reasons we see how edge computing enhanced with EdgeApps (Section IV) (Table II) (Fig. 2 and Fig. 3) makes 5G and beyond networks even more compelling and how it evolves the so-called edge network softwarization and intelligence [15,16].

A. Cloud computing

The initial step in offloading computing capabilities from the primary device and relocating computational tasks to a data center is achieved through cloud computing. That is why cloud computing as a concept and industry gained significant prominence in 2006 [17]. Cloud providers, such as Microsoft, Amazon, Google and Salesforce provide and provision large data centers to host this cloud-based resources [17,18]. Cloud computing is the overarching concept that refers to the delivery of various computing resources and services over the Internet. Those cloud providers typically offer a wide range of service models, including Infrastructure as a Service (IaaS), Platform as a Service (PaaS) and Software as a Service (SaaS). IaaS provides virtualized infrastructure components like virtual machines, storage, and networking. PaaS builds on IaaS and provides a platform for application development, allowing developers to focus on coding rather than infrastructure management. SaaS offers fully hosted software applications and services accessible over the Internet, with users having no responsibility for the underlying infrastructure or platform. In this way, users can flexibly choose the most appropriate service model based on their needs and the level of control and responsibility they desire.

However, limitations of the network infrastructure to cloud servers prevent some types of services, such as those requiring ultra-low-latency or high bandwidth [11]. Most of the traditional cloud suppliers are located in highly connected areas of countries which can be negative on the latency, see the real-life maritime experiment in Section VI, aspect due to the long distance between the user and the cloud data center [11].

B. Edge computing

Cloud computing faces limitations, including those related to ultra-low latency and high bandwidth requirements [11]. That is why Edge, Multi-access Edge Computing (MEC) and fog computing are aimed at solving the issues of latency and bandwidth, faced within cloud computing, and when integrated with 5G and beyond networks edge computing can offer new types of services not previously achievable with traditional cloud [11,18]. One of the key distinctions between fog computing and edge computing is their proximity to the user [19]. Edge computing operates directly on devices located at the immediate network edge, aiming to minimize latency by processing data as close as possible to its source [19]. In contrast, fog computing

TABLE I: Comparison of RADAR and LiDAR sensors.

Attribute	RADAR	LiDAR
Bandwidth Requirement	Several Mbps for transmitting object presence and tracking data in real-time.	50+ Mbps for high-resolution point cloud data, increasing with scanning rate and resolution.
Latency	Low latency, typically under 10 milliseconds, suitable for real-time applications in busy ports.	Moderate to low latency, around 10-20 milliseconds, depending on processing and network conditions.
Reliability	Well-established technology with high reliability for object detection and tracking in various weather conditions.	Reliable but sensitive to environmental factors like fog or heavy rain, with redundancy measures in place.
Data Volume	Moderate data volume, suitable for tracking ships and objects in the port.	High data volume due to detailed 3D point cloud data, with multiple GBs of data generated per hour.
Data Density	Moderate data density for broad area coverage within the port.	High data density for precise mapping and object recognition in specific areas.
Range	Effective at medium to long-range distances, covering the entire port area.	Effective at shorter to mid-range distances, typically up to a few hundred meters.
Environmental Impact	Less sensitive to environmental conditions, with stable performance in most port environments.	Sensitive to environmental conditions affecting laser pulse transmission and reflection.
Cost	Lower hardware and infrastructure cost.	Higher initial cost due to the complexity of LiDAR sensors and related equipment.

operates one or more hops away from the immediate edge, providing computational resources that are still relatively close to the edge but not necessarily on the devices themselves [19]. This slight difference in proximity enables fog computing to offer more centralized control and data aggregation compared to edge computing whereas edge computing takes place within the edge devices themselves. Alawadhi et al. [19] refer to edge computing as the enabling technologies allowing computation to be performed at the edge of the network, on downlink data particularly of cloud services and uplink data on behalf of IoT services. Where shi et al. [20] define the edge as any computing and network resources along the path between data sources and cloud data centers [20]. Yousefpour et al. [18] mentions that OpenEdge Computing[6] defines edge computing as computation done at the edge of the network through small data centers that are close to users. Shi et al. [21] define edge computing as enabling technology that enables computation to be performed at the network edge so that computing happens near data sources. However, as also mentioned by Arthurs et al. [11], a precise definition for any paper covering edge cloud technologies is required to avoid confusion. That is why for us, edge computing means computing, memory, and storage facilities located within the 5G and beyond network as depicted in Fig. 2. We align our definition of edge computing with the definition provided by European Telecommunications Standards Institute (ETSI), as also adopted by Arthurs et al.

1) ETSI MEC: In late 2014, the ETSI Mobile Edge Computing Industry Specification Group (MEC ISG) introduced the concept of MEC [22]. Since then, ETSI MEC has emerged as a leading standard and foundational framework, playing a pivotal role in enabling edge computing capabilities within telecommunications networks and beyond. Notably, ETSI MEC has achieved significant advancements in refining architectural principles and interfaces to facilitate efficient edge computing deployment. These standardization efforts have fostered an ecosystem of interoperable MEC components and applications, empowering service providers and enterprises to leverage edge computing for diverse use cases, particularly within vertical industries. ETSI MEC is utilized in various network environments, including 5G, 4G, Wi-Fi, and others. In the context of 5G, 3rd Generation Partnership Project (3GPP), established in 1998, serves as the main driver for creating a unified global standard, in collaboration with its seven worldwide Organizational Partners (OPs), including ETSI. To achieve its objectives, 3GPP has defined three primary Technical Specification Groups (TSGs): TSG Radio Access Network (RAN), TSG CT (Core Network & Terminals), and TSG SA (Service and System Aspects). The TSG SA group, particularly TSG SA WG6 (SA6), is responsible for defining enablers for edge vertical applications, aiming to evolve the network into a platform that enables verticals to run their services effectively. Herein lies the intersection of 3GPP and ETSI MEC, as both entities work towards deploying applications on the edge of the 5G and beyond network. While ETSI MEC and 3GPP (Service Enabler Architecture Layer (SEAL), Common API Framework (CAPIF), and Edge Application enablement (EDGEAPP)) have developed their own architectures for edge computing within their respective scopes, their collaboration underscores the collective effort to realize the potential of edge computing in next-generation networks [23].

However, as noted by Pham et al. [22], despite the various opportunities and potential benefits, several challenges persist, necessitating a thorough examination to establish an edge ecosystem that benefits all stakeholders in the network, including IoT users, service/infrastructure providers, and Mobile Network Operators (MNOs). Among these challenges is network integration, particularly in enabling seamless interaction between MEC and 5G networks [22]. This is precisely where the EdgeApp framework (Section IV) within the VITAL-5G project (Section V), through the EdgeApp blueprint (Section V-A), extends beyond the ETSI MEC and the existing 3GPP service frameworks (SEAL, CAPIF, and EDGEAPP) as these frameworks do not take into account the specific requirements (network, service, and hardware) from verticals when deploying them into the 5G and beyond network. The EdgeApp framework present in this paper identifies its own network, service, and hardware requirements, which are further interpreted by network controllers and orchestrators, applying changes and service deployments that correspond to the requirements listed in the EdgeApp blueprints.

C. What is next for edge computing?

The domain of edge computing stands at the threshold of a continuous evolutionary phase marked by ongoing advancements [11,18–21]. These advancements are intricately linked to the progressive deployment and refinement of 5G and beyond networks and the anticipation of forthcoming 6G infrastructures. As the research community increasingly directs its focus towards the concept of the UE-edge-cloud/core continuum, an

[6] OpenEdge Computing: https://openedgecomputing.org/index.html

extensive and in-depth exploration of this subject can be found in the work authored by et al. Moreschini [14]. Therefore, we see with the UE-edge-cloud/core continuum an opportunity for integrating the EdgeApps concept (Section IV). The current generation of applications deployed on the edge lack awareness of real-time network conditions, making them unable to communicate and adapt when the network performs below Quality of Service (QoS) expectations [15,16,24]. Firstly, our envisaged trajectory for 5G and its successors underscores the pivotal role of EdgeApps as also accentuated by 5G-Infrastructure Public Private Partnership (PPP) [25]. This is one out of the many reasons we see how edge computing enhanced with EdgeApps makes 5G and beyond networks even more compelling and how it evolves the so-called edge network softwarization and intelligence [15,16]. Secondly, a reasonable projection for 6G networks anticipates marked enhancements in bandwidth capacity, both in uplink and downlink transmission, coupled with substantial reductions in latency compared to their 5G predecessors. Thirdly, a salient feature of 6G networks lies in their profound integration of AI across all network components, specifically emphasising the network edge. This integration is poised to fortify and expand advanced localized processing and decision-making capabilities, harnessing the intrinsic potential of AI to augment real-time and intelligent operations at the network edge. This paradigm is widely recognized as Edge AI [12].

D. Processing sensor data at the network edge

The Maritime T&L vertical for freights plays an indispensable role in global trade especially for Europe where 74% of goods are being transported via vessels [2]. Thus, the integration of advanced sensing technologies, such as RADAR and LiDAR, is of paramount importance in the ongoing optimization of the Maritime and Offshore vertical industries. These technologies play a crucial role in collecting essential data about a vessel's surrounding environment, facilitating object detection, and ultimately enhancing maritime safety [26]. The significance of edge processing lies in its ability to efficiently collect and process RADAR or LiDAR data, making the edge a crucial computing component for modern sensing systems. Therefore, it is essential to begin with a comprehensive overview of these two widely used sensing technologies, RADAR and LiDAR, to gain a deeper understanding of their essence. In the remainder of this paper, we concentrate on a real-life maritime vessel use case known as Assisted Vessel Transport at the Port of Antwerp-Bruges (Section VI-A) (Fig. 3). This use case leverages RADAR sensing technology, with all main computing taking place at the edge of the 5G SA network using EdgeApps (Sections IV-D, VI-B) to evolves the so-called edge network softwarization and intelligence.

RADAR, is a remote sensing technology that uses radio waves to detect and analyze objects. RADAR operates by transmitting radio waves and analyzing their reflections to determine the presence, distance, speed, and direction of objects. RADAR is crucial in maritime T&L for a wide range of use cases including safety, navigation, and situational awareness, including collision avoidance, navigation assistance, and vessel traffic management. On the other hand, LiDAR is a remote sensing technology that uses laser light and creates detailed 3D representations of objects and environments by emitting laser pulses and measuring their return time. This allows for precise distance measurements, enabling high-resolution 3D point cloud creation. LiDAR technology, similar to RADAR, plays a significant role in a wide range of maritime T&L use cases such as vessel berth optimization within the sector. The choice between utilizing RADAR and LiDAR sensor technologies encompasses factors such as the requisite level of granularity in data, the prevailing environmental conditions, budgetary constraints, the customized requirements of the particular use case at hand and the divergent characteristics in terms of their network prerequisites as presented in Table I.

IV. Edge Network Applications (EdgeApps) in 5G and Beyond Networks

To understand the extensive benefits that EdgeApps bring to 5G SA and beyond networks, it is important to explore the EdgeApps foundational concepts within the 5G ecosystem, especially in their deployment at the 5G edge. This understanding not only helps in comprehending EdgeApps (Subsection IV-D) but also prepares the groundwork for subsequent sections of this paper, namely Sections V and VI. As discussed in Trichias et al. work [24], EdgeApps simplify the complexity of the underlying 5G and beyond infrastructure for vertical industry (e.g., T&L) application developers and vertical stakeholders.

A. Network Function Virtualization (NFV)

Network Function Virtualization (NFV) signifies a generational shift in networking and the delivery of network-based services as defined by ETSI [27–29]. NFVs forms an integral component of the broader trend of Software-Defined Networking (SDN), i.e., Software-based Networking [27]. SDN constitutes a networking paradigm rooted in the concept of programmable network devices, wherein the decoupling of the forwarding plane from a logically centralised control plane is a fundamental characteristic [27]. However, NFV refers to the overall concepts of Virtual Network Functions (VNFs) (Section IV-B) that were historically executed on dedicated hardware appliances such as firewalls, load balancers, routers and etc. With the advent of NFV, the conventional hardware-centric approach is replaced with software-based counterparts, which can be executed on commonplace servers, virtual machines, or cloud-based infrastructures. The primary objective of NFV is to enhance the agility, scalability, and cost-effectiveness of network operations by disentangling network functions from specialized hardware components.

Along with NFVs is the Network Functions Virtualization Infrastructure (NFVI), which is used to provide the necessary hardware and software resources for the virtualization and operation of network functions as software-based instances. As such, NFVI provides the following components: virtualization layer, networking resources, storage resources and compute resources.

B. Virtual Network Function (VNF)

VNFs encapsulate the functionality of traditional hardware-based network appliances, such as firewalls, routers, load balancers, etc. VNFs are specific instances of these NFV (Section IV-A) principles that have been virtualized. In this context, a VNF is a concrete manifestation of a network function that is implemented as software, for instance, a virtualized router. VNFs serve as essential building blocks that can be combined to create more complex and comprehensive network services (in this paper also referred to as vertical services, Section V-B). They possess the capability to be instantiated, managed, and scaled within a virtualized computing environment. Through the NFV framework, these virtualized network functions enable greater flexibility, scalability, and efficiency in modern network architecture.

In contrast to a VNF, there's the Virtual Network Function Descriptor (VNFD). A VNF is always associated with a template or blueprint, known as the VNFD. This descriptor outlines the characteristics, requirements, and instructions for instantiating, configuring, and managing a VNF within a virtualized network. A VNFD includes information on virtual hardware requirements, software dependencies, configuration parameters, and performance metrics.

Furthermore, going hand in hand with VNFs are the so-called Virtual Deployment Units (VDUs) as it is a term widely used in the context of NFV to represent a specific instance of a running VNF instance on a virtualized infrastructure. As such is a VDU as simple as an instance of a running VNF. However, a VDU also encapsulates all the necessary metadata of a VNF like the virtual hardware resources, operating system, software dependencies, configuration settings, and the actual VNF software. VDUs are managed by the NFVIs components, which provide the underlying computing, storage, and networking resources necessary for VDUs to operate.

C. Network Service (NS)

A Network Service (NS) is a collection of VNFs and accompanied by components, such as virtual links and connectivity requirements. These constituents operate together to establish a comprehensive end-to-end network solution or service. The role of an NS is to deliver precise functionalities to users or applications, encompassing the entire chain of network functions needed to achieve a desired outcome.

Analogous to the relation between the VNF and VNFD (Section IV-B) is there also serving a descriptor describing the characteristics and requirements of a NS, named Network Service Descriptor (NSD). A NS is always fully described with a template or blueprint that describes the characteristics and requirements of itself, this blueprint or template is named the NSD. As the NSD provides detailed information about the VNFs that makeup the NS, how they are connected, the sequence of their deployment, and any other relevant information for orchestrating the complete service. As such, NSDs plays an important role in orchestrating the deployment and operation of NS, ensuring that the required VNFs are instantiated, connected, and configured appropriately to deliver the desired network functionality.

D. Edge Network Applications (EdgeApps)

Building upon the foundational concepts in the above subsections, such as NFV, VNF, NS, we can now delve into the concept of EdgeApps. EdgeApps will play a central role in the subsequent sections of this paper, starting from Sections V and VI (Fig. 2 and 3). Let's begin with a thorough analysis and discussion of EdgeApps.

The term "Edge" in the context of EdgeApps is indicative of their deployment at the edge of 5G, and beyond, networks as evolved VNFs (Section IV-B) to enable and evolve the so-called edge network softwarization and intelligence. But why do we need those EdgeApps and why are they potentially so novel? Well, in the current landscape of deployed applications that run at the edges of the 5G and beyond networks, particularly within the domain of edge computing (Section III-B) certain limitations come to the forefront. As they are isolated from the overall network in all its aspects. These limitations manifest themselves across several key facets:

- Limited Network Awareness: The current generation of applications running at the edge often lack comprehensive visibility into the overall network conditions they are running on top of. They may not have access to real-time information about network congestion, latency variations, or available bandwidth across the entire network. This limitation can affect applications that require dynamic adjustments based on changing network conditions.
- Incomplete QoS Information: QoS metrics, such as latency, jitter, and packet loss, are crucial for applications to ensure optimal performance. However, the current applications running at the edge may not have access to accurate and up-to-date QoS information for the entire network. This can lead to suboptimal decision-making, in the application itself.
- Limited Network Control: Applications on the edge typically lack the authority to make significant changes to the network infrastructure. While they might be able to optimize their own operations within their scope, they usually cannot perform broader network-level actions, such as rerouting traffic, adjusting network configurations to optimize performance, or dynamically provisioning new 5G and beyond network slices to enhance their overall network performance.
- Dynamic Network Conditions: Network conditions can change rapidly due to factors like varying user loads, network congestion, and device mobility. The current generation applications placed on the edge may struggle to adapt quickly to these dynamic changes without accurate real-time network information and control capabilities.

Moreover, existing applications deployed at the network edge lack access to critical network metrics in 5G and beyond networks. They also lack real-time insights into the status of the underlying physical machines they run on, as well as access to infrastructure metrics. Consequently, these current-generation edge applications operate in a state of relative blindness to the real-time conditions of the network, rendering them unable to self-adjust in response to unexpected network performance variations. This is where EdgeApps play a pivotal role. In essence, EdgeApps possess real-time awareness of network conditions and have the capability to interact directly with the 5G and beyond network, allowing them to be both network-aware and conscious of their specific QoS requirements. As such, will this new generation of applications named EdgeApps improve the current shortcomings of current applications deployed at the edge, see Sections V and VI. To enable and evolve the so-called edge network softwarization and intelligence.

V. 5G EDGE SERVICES FOR ASSISTED VESSEL NAVIGATION

In Section IV, we provide an extensive overview of the significance and necessity of EdgeApps in 5G and beyond networks that enable and evolve edge network softwarization and intelligence. These EdgeApps play also a vital role in the vertical industries e.g., in the T&L sector. To support the rapid development and integration of EdgeApps, the European Commission has co-financed the H2020 VITAL-5G project [30]. The VITAL-5G project consists of two key components: the VITAL-5G platform (Section V-D) (Fig. 2) and the VITAL-5G edge testbeds (Section V-C) (Fig. 2). The VITAL-5G platform connects with three VITAL-5G 3GPP release 16[7] 5G

[7]5G Release 16: https://www.3gpp.org/specifications-technologies/releases/release-16/

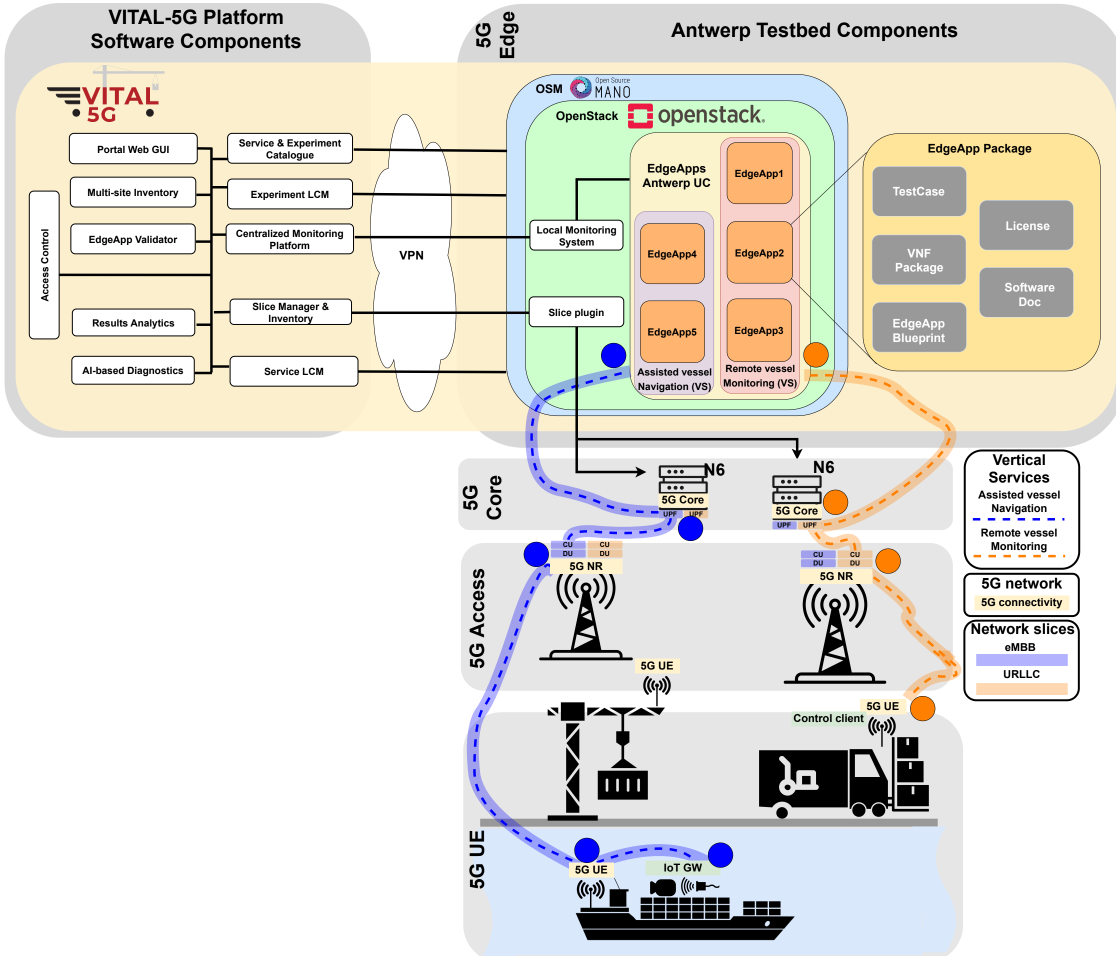

Fig. 2: VITAL-5G architecture and testbed ecosystem.

SA testbeds, each offering dedicated 5G SA architecture for dynamic instantiation and orchestration of EdgeApps. These testbeds employ custom 5G network slices, including URLLC and eMBB slices, tailored to each experiment, as shown in Fig. 2.

A. Principles Governing the Design of VITAL-5G EdgeApps

Illustrated in Fig. 2, we can see the building blocks of EdgeApps within the VITAL-5G project. These building blocks include the following components: the VNF package (Section IV-B), the EdgeApp Blueprint, test cases, software documentation, and the license [31]. Traditionally, Network Applications consist only of a VNF package (Section IV-B) and an NS package (Section IV-C). However, the VITAL-5G initiative extends EdgeApps to gain a comprehensive understanding of real-time 5G and beyond network, service, and infrastructure metrics by specifying the metrics in the EdgeApp blueprint to evolve the overall edge network softwarization and intelligence. This expansion is achieved while maintaining compliance with the ETSI standards for VNF packages and VNF descriptors, as detailed in the ETSI GS NFV-SOL 004 [28] and NFV-SOL 006 [29] specifications.

First, let us delve into the construction of EdgeApps within the VITAL-5G framework and explore the fundamental building blocks that constitute their composition:

- **VNF Package:** Within VITAL-5G the VNF package is composed out the following package elements: Virtual Function (VF) Descriptor, Software images, Hardware requirements [31]. *VF Descriptor:* Offers comprehensive information on orchestrating EdgeApps in virtualized environments, including lifecycle management [31]. It covers component interconnections, external connections, essential virtual resources, configurations, monitoring metrics, and related attributes [31]. *Software Images:* These are representations of necessary software for deploying EdgeApp components within virtual environments [31]. They can be Virtual Machine (VM) images or container images, depending on the chosen virtualization method [31]. *Hardware Requirements:* This category delineates the essential prerequisites concerning the physical servers that are designated for the execution of the virtualized components constituting the EdgeApp [31].
- **EdgeApp Blueprint:** The metadata embedded within the VITAL-5G EdgeApp blueprint and integrated into the corresponding EdgeApp package functions as a model for this supplementary information [31]. The VITAL-5G Platform, as expounded in section V-D, leverages this metadata for dual purposes [31]. Firstly, it employs it to define the intrinsic logic of the EdgeApp itself. Secondly, it utilizes this metadata to enhance the ease of navigation and

searchability within the VITAL 5G EdgeApp catalog [31]. It is within this EdgeApp Blueprint that the EdgeApp becomes network, service and infrastructure aware. Regarding the perspective of 5G slicing and orchestration capabilities, we refer to our previous work [16].
- **Test case:** The VITAL-5G EdgeApp paradigm further encompasses the integration and validation stages within the EdgeApp development lifecycle in the form of test cases [31]. In this context, the VITAL-5G EdgeApp delineation encompasses not only the specification of the test scripts but also the identification of the metrics and Key Performance Indicators (KPIs) that enable the evaluation of the EdgeApp in specific scenarios, addressing both functional integration and overall performance considerations [31]. All of this information is provided in the EdgeApp blueprint.
- **Software doc:** The specification documents of the software design of the EdgeApp [31]. In order to provide comprehensive software documentation, intending to streamline the integration of the EdgeApp into vertical services by third-party software developers [31]. For more information we refer to our prior work [15].
- **License:** Describes the licensing terms that apply to the entire EdgeApp, including provisions for its individual components when necessary [31].

B. Vertical Services in VITAL-5G

As previously elaborated in our prior work [15], within the VITAL-5G project a vertical service, following the NFV (Section IV-A) NS (Section IV-C) methodology, represents an amalgamation of multiple EdgeApps operating collaboratively to address specific vertical industry challenges, as exemplified in Section VI-A. While the primary emphasis of the VITAL-5G project centers on T&L services, the concept of 5G-enabled vertical services, comprising multiple EdgeApps, possesses applicability across diverse sectors, extending beyond T&L services [31]. An example of a vertical service is Assisted Vessel Navigation (II) from the Antwerp VITAL-5G use case (Section VI-A), where a group of EdgeApps work together to reduce fuel consumption and dwell times while navigating vessels across busy waterways [32].

C. VITAL-5G Testbeds

As shown in Fig. 2, the VITAL-5G testbeds are connected with the southbound interface of the VITAL-5G platform (Section V-D), VITAL-5G testbeds are the enablers of EdgeApps. That is why, the VITAL-5G project comprises three established 5G 3GPP Rel.16 open, to any SME company and exerimenters, 5G SA edge testbeds. i) Antwerp VITAL-5G edge testbed, located in the Port of Antwerp-Bruges, primarily used for Assisted Vessel Transport (Fig. 1). ii) Galati VITAL-5G testbed in the Danube River area, Romania, offering 5G connectivity and data-enabled navigation with IoT sensors and cameras. iii) Athens VITAL-5G testbed in Athens, focusing on automation and remote operation of freight logistics. Concerning the management and orchestration on each VITAL-5G Testbed, each VITAL-5G testbed uses as Management and Orchestration (MANO) Open Source MANO (OSM) together with OpenStack as shown in Fig. 2). For more information, we refer to our previous work [15] and the public deliverables of the VITAL-5G project [31–34].

As depicted in Fig. 2, we can observe the connection of the Antwerp VITAL-5G testbed (Fig. 3) with the VITAL-5G platform (Fig. 2)(Section V-D), encompassing all the layers from which the testbed is composed. These layers, delineated from the uppermost to the lowermost layer, encompass the 5G edge layer where the Antwerp use case EdgeApps are running, the 5G Core layer, the 5G Access layer (i.e., RAN), and ultimately the 5G User Equipment (UE) layer. The Antwerp testbed is built upon Telenet's (Belgian MNO) [24] commercial infrastructure. The testbed presents a fully-fledged 5G SA network, akin to Telenet's 5G commercial trajectory. As illustrated in Fig. 3, the 5G Core is directly connected to the 5G edge platform via a, 7.2 km optical fibre link (bird's eye). Although centralized, the 5G Core is fully compliant with service-based architecture, where 5G Core functions can be completely distributed. Nevertheless, due to the size of the Antwerp area (Fig. 3), placing all 5G Core functions in a single core environment is a viable approach. In this case, the User Plane Functions (UPFs) are typically positioned closer to the users, which holds true in our case as the 5G Core is closely located to our trial site and edge platform (Fig. 3). More in-depth information towards the end-to-end 5G SA edge testbed can be found in our previous work [15].

D. VITAL-5G Platform

The VITAL-5G platform, as depicted in Fig. 2, is facilitating the management of edge computing resources, and the deployment and management of vertical services (Section V-B) deployed at the edge part of each testbed. Therefore, is the VITAL-5G platform connected with its southbound interface to the edge part of each VITAL-5G testbed (Section V-C), designed for testing and validating vertical services (Section V-B) [24,31]. The VITAL-5G platform evolves the overall edge network softwarization and intelligence at each edge part of each VITAL-5G testbed and improves the adoption of 5G and beyond solutions within the vertical industry domain by bridging the knowledge gap between industry stakeholders, network experts, and EdgeApps developers. With the real-world Maritime use case outlined in Section VI-A, we directly benefit from the VITAL-5G platform to address challenges including workforce shortages, port operation delays, high fuel consumption, and suboptimal goods scheduling and delivery [24,30]. That is why, we discuss the most important components of the VITAL-5G platform that contribute to the intelligent softwarization and management of any VITAL-5G testbed.

- **Service Lifecycle Manager (Service LCM):** In the context of the VITAL-5G platform, EdgeApps play a crucial role. Fig. 2 illustrates how the Service LCM manages the lifecycle of EdgeApps within a vertical service instance. This includes tasks such as creating, terminating, querying, and updating these EdgeApps. For a more comprehensive understanding of the Service LCM we refer to its public deliverable [32].
- **Centralised Monitoring Platform:** In the VITAL-5G platform, the Centralised Monitoring Platform as shown in Fig. 2, is responsible for the collection and distribution of metrics (i.e., network, infrastructure, and service) and KPIs coming both from the dedicated VITAL-5G testbeds and the VITAL-5G platform itself (i.e., platform metrics). In this way, EdgeApps can subscribe to the network metrics and become fully network aware of the 5G and beyond services they are consuming and the general state of the network. For a more comprehensive understanding of the Centralised Monitoring Platform, we refer to our previous work [15,16] and its public deliverable [32].
- **Slice Manager & Inventory:** In the VITAL-5G platform, the Slice Manager & Inventory as shown in Fig. 2, is

responsible for managing the available slices that are available at the edge of each VITAL-5G testbed for the EdgeApps. In this way, the Slice Manager & Inventory can properly select a slice, within the available VITAL-5G testbed, for the EdgeApps that composes the T&L vertical service and matches with the requirements, specified in the blueprint. For a more comprehensive understanding of the Slice Inventory, an in-depth discussion can be found in its dedicated paper [16] and in its public deliverable [32].

VI. Experimental evaluation in the real-life setup

In our use case (Section VI-A), low-latency communication over the 5G SA link, the commercial infrastructure provided by Telenet, is important (Fig. 3). This link connects the vessel (i.e., the 5G UE) to the EdgeApps running on the edge computing units of the Antwerp 5G edge testbed, as depicted in Fig. 2, where EdgeApps process the observed sensor data (i.e., RADAR) (Section III-D) data captured from the vessel (Fig. 2 and Fig. 3) (Section VI-A). Through this link, all the required data, such as sensor data, location and speed data, for our use case is transferred to enable performing the main computing logic at the EdgeApp edge level EdgeApp3 and the EdgeApp4 (Section VI-B). In this way, the edge computing units on the Antwerp 5G SA edge platform enable and evolve the so-called edge network softwarization and intelligence. That is why for this paper the experiment is focused on the performance evaluation of the capabilities that could be achieved over the 5G SA link, i.e., URLLC slice and eMBB slice (Table IV). Therefore, we conducted a performance analysis to compare the total time required to transmit the observed sensor data from the vessel to two destinations: the edge computing units of the Antwerp 5G edge platform and the closest public cloud provider in Section VI-C and as depicted in Fig. 3 and Fig. 4. We also conducted simultaneously a performance analysis on the end-to-end latency in Section VI-D (Fig. 3 and 4). The obtained results are provided in Table IV. The discussion on the obtained results is provided in Section VI-E.

The primary distinction in transmitting sensor data from the vessel to either the edge computing units of the Antwerp 5G edge platform or the nearest public cloud provider is illustrated in Fig. 4. In both scenarios, the sensor data traverses the same access medium, namely the RAN part of the commercial 5G SA network of Telenet (Fig. 4, step 1), reaching the 5G Core (Fig. 4, step 2). However, when directed towards the edge computing units of the edge platform (Fig. 3), the sensor data travels via an optical fiber connection between the 5G Core and the edge platform (Fig. 4, step 3). Conversely, when directed towards the public cloud, the sensor data traverses the public internet, thereby introducing additional latency (Fig. 4, step 3).

A. Antwerp VITAL-5G use-case

The Antwerp trial site (Fig. 3) serves as the location for a real-life maritime vessel use case named Assisted Vessel Transport, situated within the Port of Antwerp-Bruges, Europe's second-largest port [35]. The primary objective of this use case spans several objectives, including remote vessel monitoring, the augmentation of situational awareness for vessels arriving at the port and the optimization of vessel navigation. To realize these objectives, the use case is underpinned by three foundational goals: enhancing port safety, minimizing dwell times, and reducing fuel consumption as presented in Table II. These goals are achieved through the implementation of two distinct vertical services (Section V-B), namely Remote Vessel Monitoring and Assisted Vessel Navigation, as depicted in Fig. 2. These vertical services, composed out of EdgeApps (Section VI-B), are implemented and evaluated upon the VITAL-5G Antwerp 5G SA testbed (Section V-C) making use of the VITAL-5G platform (Section V-D) as illustrated in Fig. 2. In this way, the use case directly benefits the so-called edge network softwarization and intelligence through EdgeApps (Section VI-B) with the VITAL-5G initiative. The network requirements for the EdgeApps in the use case, specifically for sensor data and ship awareness notification messages, are specified in Table III. For a more in-depth overview of the vertical services in the Antwerp use case we refer to our previous work [15,16] and deliverables [31,32,36,37].

B. EdgeApps Constituting the Antwerp Use Case

Table II already provides a concise enumeration and delineation of all the EdgeApps aligned with the Antwerp use case. These EdgeApps are operational within the Antwerp VITAL-5G testbed as shown in Fig. 2, the Remote vessel Monitoring vertical service as already mentioned above is comprised of the EdgeApps: EdgeApp1, EdgeApp2 and EdgeApp3.

- EdgeApp1: This web-based EdgeApp is developed with the objective of offering support to vessel captains, by showing the output of other EdgeApps such as optimized speed, detected obstacles and optimized route. This EdgeApp is developed by Seafar[8], and it is in detail explained in deliverable [32].
- EdgeApp2: This EdgeApp bears the responsibility for real-time data acquisition, predominantly Global Navigation Satellite System (GNSS) data encompassing speed, heading, and precise location, as well as the subsequent processing of onboard data procured from the Antwerp use case vessel, or any other vessel deployed for the purpose of trial and demonstration activities [32]. The accumulated data is sourced through the URLLC slice, facilitating the exchange of this acquired information among all EdgeApps within the context of the use case [32]. More information on this EdgeApp can be found in the VITAL-5G deliverable 2.4 [32].
- EdgeApp3: This EdgeApp functions as a real-time digital twin coexisting with the vessel, providing essential support to facilitate the remote control and eventual autonomy of vessels [30]. Within the use case, this EdgeApp employs the complete range of accessible sensor data, coming from the vessel, to construct a dynamic obstacle map, reflecting the immediate environmental conditions around the vessel situated within the Port of Antwerp-Bruges. More information on this EdgeApp can be found in the VITAL-5G deliverable 2.4 [32].

Consequently, the EdgeApps that make out the second vertical service, named Assisted vessel Navigation, of the Antwerp use case are EdgeApp4 and EdgeApp5.

1) EdgeApp4: This EdgeApp is designed to provide navigational assistance to vessel captains through the facilitation of trajectory recommendations encompassing global trajectory prediction coupled with real-time obstacle avoidance. Drawing from specified vessel position and associated parameters, including factors such as anticipated arrival time at a designated destination and comprehensive knowledge of the navigation area, this EdgeApp undertakes the formulation of a path to the desired endpoint

[8]https://seafar.eu

TABLE II: Overview of Assisted Vessel Navigation with EdgeApps and 5G SA.

Goals	Operations	Enablers (EdgeApp)	Vertical Service
Improving port safety	Remote vessel Monitoring	(EdgeApp1) Remote vessel Monitoring: displaying notifications for the captain	Remote vessel Monitoring
		(EdgeApp2) Onboard data collection & interfacing with vessels:collecting speed/heading/location data	
Reducing dwell times	Increasing situational awareness in real-time	(EdgeApp3) Real-time digital twin: creating a dynamic map of the environment in real-time, based on the vessel sensor data, via the 5G and EdgeApp2	
		(EdgeApp4) Assisted Vessel Navigation: assisting the captain with navigation suggestions (global trajectory)	Assisted vessel Navigation
Reducing fuel consumption	Optimizing assisted vessel navigation	(EdgeApp5) Navigation speed optimizer: calculating the optimal speed for remote or autonomous equipment	

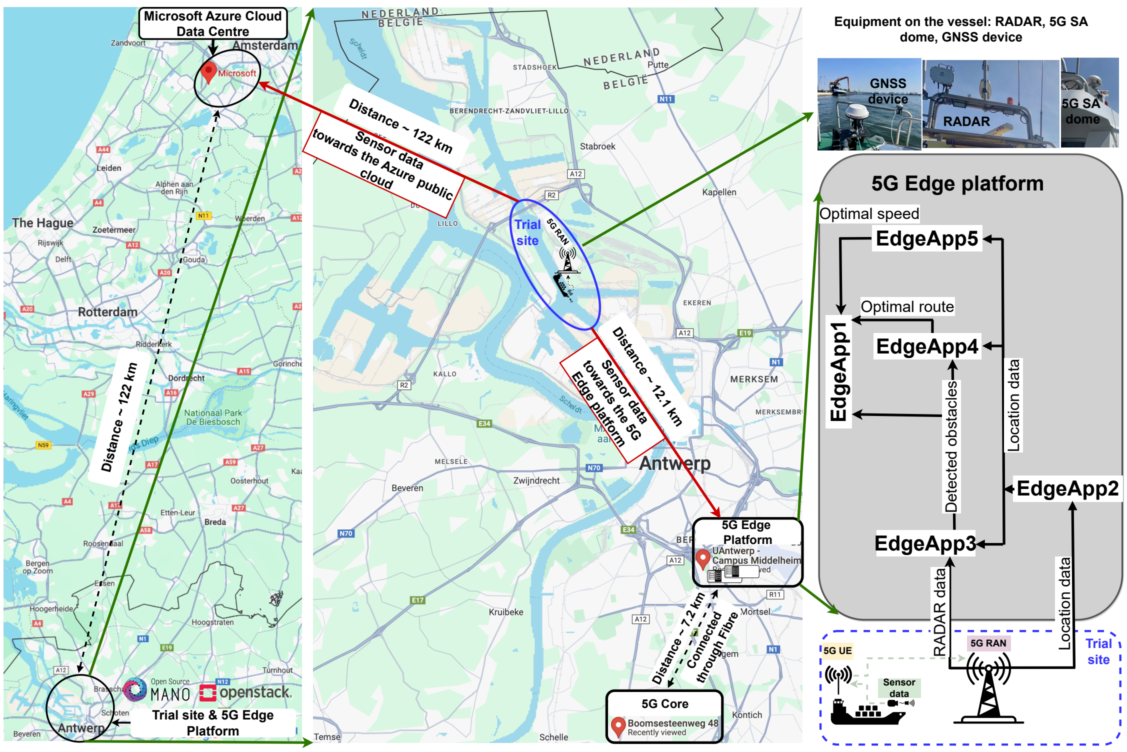

Fig. 3: Experiment environment with Azure cloud, and VITAL-5G Antwerp 5G testbed.
Real-life experiment sessions with a small boat were organized by partners from Seafar NV (provider of the equipment), with an in-kind contribution from the Port of Antwerp-Bruges (provider of the boat).

TABLE III: Network requirements for EdgeApps of the Antwerp use case.

Traffic flow	RADAR sensor data	Ship awareness notifications
Service Type	Uplink	Uplink
Ideal Latency End-to-end	<35 ms	<22 ms
Bandwith Requirement	>= 15 Mbps/sensor	<2 Mbps

and concurrently determines an optimized local trajectory. More information on this EdgeApp can be found in the VITAL-5G deliverable 2.4 [32].

2) EdgeApp5: This particular EdgeApp serves the role of real-time route planning and is strategically deployed to enhance the efficiency of port operations while mitigating potential idle periods. Constructed upon the foundation of berthing time slots furnished by port authorities and terminal operators, this EdgeApp is underpinned by optimization procedures guided by ML and AI methodologies [30]. The synergy between this EdgeApp and various port planning systems, inclusive of those catering to automated vessels, is conceivable. This EdgeApp is developed by DigiTrans, and it is in detail explained in [32].

C. Outdoor sensor data experimentation results in a Busy Maritime Port Environment

In this subsection, we present the obtained results of the sensor data (i.e., the RADAR data images from the vessel) (Table IV) (Fig. 3 and 4). But before presenting and elaborating on the obtained results, an important remark is that these results are obtained in real-life outdoor environments. This means a quite busy port area (the second largest in Europe), i.e., the Port of Antwerp-Bruges (Fig. 3), with many metallic constructions, moored and passing by ships, and trucks with containers that all together have a severe impact on the signal propagation

TABLE IV: Results edge platform vs. Azure cloud: Vessel End-to-end Latency And Total Time of Transmitting the Observed sensor image dataset of the Vessel Over an eMBB Slice.

Type of Location	Distance from Telenet 5G NR SA base station [km]	Over eMBB slice towards: Antwerp edge platform								
		Experiment: End-to-end latency		Experiment: transmitting full sensor data image dataset (260 images)						
		End-to-end latency		Total time		Lost sensor data images		Total time to transmit one sensor data image		Achieved throughput over slice (uplink)
		Average [ms]	Standard deviation [ms]	Average [s]	Standard Deviation [s]	Average [# images]	Standard Deviation [# images]	Average [ms]	Standard Deviation [ms]	Average [Mbps]
Close	0.10	22.03	3.29	28.169	1.67	4.40	1.65	110.00	6.33	42.97
Medium	1.00	31.99	8.97	50.99	6.50	4.60	1.90	205.00	26.1	23.59
Far	3.00	40.29	20.81	185.22	23.53	3.50	0.71	722.00	9.40	6.50
Type of Location	**Distance from Telenet 5G NR SA base station [km]**	**Over eMBB slice towards: Microsoft Azure Cloud**								
		Experiment: End-to-end latency		**Experiment: transmitting full sensor data image dataset (260 images)**						
		End-to-end latency		**Total time**		**Lost sensor data images**		**Total time to transmit one sensor data image**		**Achieved throughput over slice (uplink)**
		Average [ms]	**Standard deviation [ms]**	**Average [s]**	**Standard Deviation [s]**	**Average [# images]**	**Standard Deviation [# images]**	**Average [ms]**	**Standard Deviation [ms]**	**Average [Mbps]**
Close	0.10	38.58	6.63	34.75	3.65	5.30	1.34	136.45	14.30	34.56
Medium	1.00	50.36	11.07	52.54	5.79	5.30	1.48	198.00	31.10	22.92
Far	3.00	63.42	80.17	258.30	71.60	7.00	2.83	1020.00	0.29	4.66

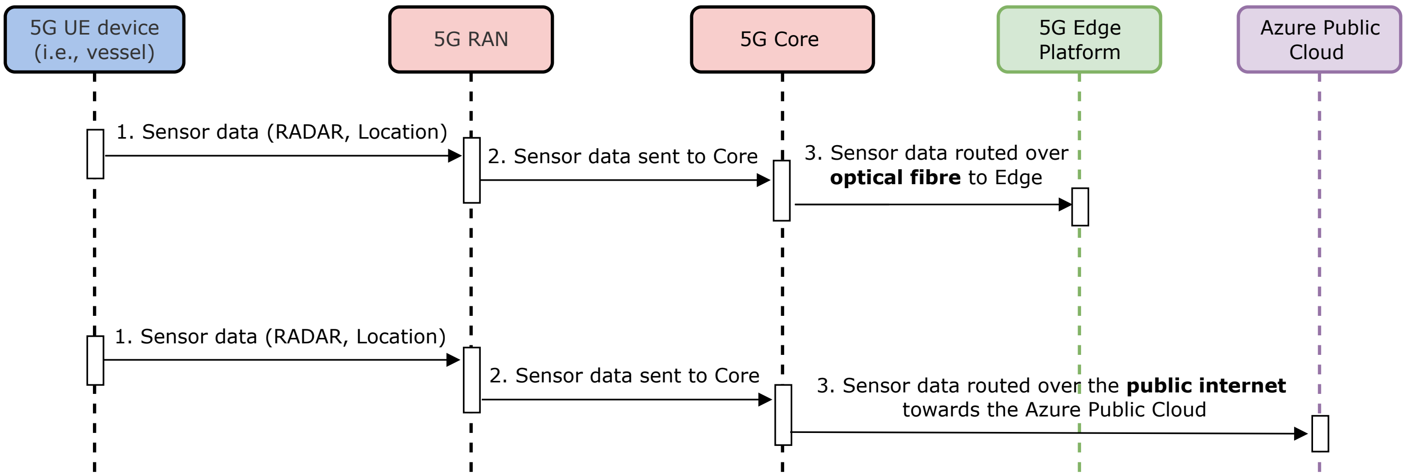

Fig. 4: Path for Sensor Data Transmission from Vessel to 5G Edge Platform or Azure Public Cloud

[15,35]. In addition, the radio part of the Telenet network is shared among Non-standalone (NSA) and SA users (Fig. 4). For our setup and testing, two slices (eMBB and URLLC) were configured dedicated to our UE, making us the only UE connected to those slices during our experiment (Fig. 3).

*1) Results experiment 1, sensor dataset edge vs. cloud, **close location**, **eMBB** slice:* As depicted in Fig. 5, and Table IV, the UE (i.e., the vessel) took on average 28.2 seconds, with a standard deviation of 1.67 seconds, to transmit the collected sensor data (150.4 MB of 260 RADAR images) to the EdgeApps running on the edge computing units of the Antwerp 5G testbed (Fig. 3 and Fig. 4). This translates to an average uplink throughput of 42.97 Mbps over the eMBB slice. However, in the case of the Azure public cloud, the values are 34.7 seconds, with a standard deviation of 3.65 seconds (34.56 Mbps). The measurement has been performed under the same conditions, with a close location of 100 meters between the vessel and the 5G New Radio (NR) base station, utilizing an eMBB slice. Examining Fig. 6, we observe the graphs depicting the number of sensor data images lost during each attempt to transmit the sensor data from the UE to both the EdgeApps running on the edge computing units of the Antwerp 5G testbed and the Azure public cloud (Fig 3 and Fig. 4). On average, we experience a loss of 4.4 sensor data images out of the 260 (1.69%) when transmitting them to the edge. In other words, we have successfully retrieved 255.6 sensor data images on average, with a standard deviation of 1.65 when transmitting them to the edge. The average time it takes to transmit one sensor data image towards the edge is 110 milliseconds (ms) with a standard deviation of 6.33 ms. However, as illustrated in Fig. 6, we observe an average loss of 5.3 sensor data images out of the total 260 when transmitting them to the Azure public cloud (Fig 3 and Fig. 4). This results in an average receipt of 254.7 sensor images, with a standard deviation of 1.34. The average time it takes to transmit one sensor image towards the Azure public cloud is 136 ms with a standard deviation of 14.3 ms.

*2) Results experiment 2, sensor data dataset edge vs. cloud, **close location**, **URLLC** slice:* For the second experiment, we utilized the URLLC slice (Fig 2). This slice is specifically designed to offer ultra-low latency and high reliability for mission-critical applications that demand real-time communication with minimal delay and minimal risk of failure. We only conducted an experiment towards the EdgeApps running on the edge computing units of the Antwerp 5G testbed (Fig. 2 and Fig. 3). This choice was made due to its proximity, only 12.1 km away, as opposed to the closest Azure cloud, which was located 122 km away in a bird's-eye view (Fig. 3). Additionally, using the Antwerp testbed allowed us to avoid the public internet, making it a more realistic option, especially for latency-sensitive testing with the URLLC slice. For the reasons mentioned above, we exclusively conducted the experiment towards the EdgeApps running on the edge computing units of the Antwerp 5G edge platfrom. As depicted in Fig. 7, using the URLLC slice, the vessel requires an average of 33.8 seconds to transmit its observed dataset of 260 sensor data images towards the EdgeApps running on the edge computing units of the Antwerp 5G edge platform. This is for the same close location, of a 100-meter distance between the vessel and the 5G NR base station making use of a eMBB slice. This translates to an achieved throughput over the URLLC slice of 35.58 Mbps. When comparing Fig. 5 to Fig. 7, it becomes

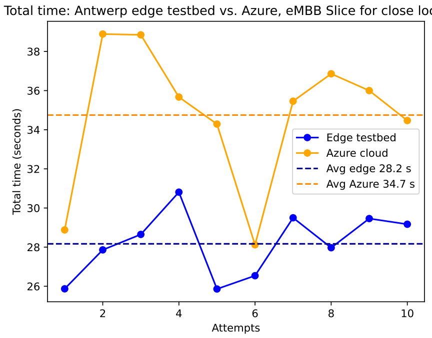

Fig. 5: Total time for close location, eMBB slice edge vs. Azure.

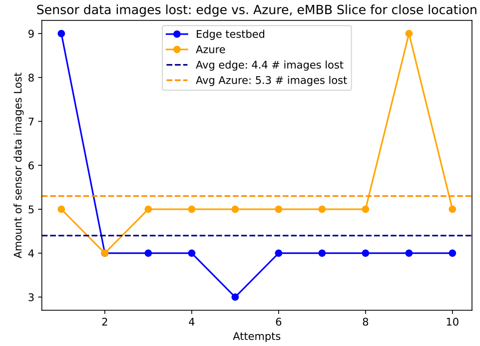

Fig. 6: Amount of file losses for close location, eMBB slice edge vs. Azure.

evident that the use of the URLLC slice results in a 5.6-second improvement compared to the same experiment conducted over the eMBB slice. When examining Fig. 8, we observe the graph depicting the number of sensor data images lost during each attempt to transmit the sensor dataset from the vessel towards the EdgeApps running on the edge computing units of the Antwerp 5G edge platform. On average, we lose 5.8 sensor data images out of the 260 when transmitting them towards the EdgeApps running on the edge computing units of the Antwerp 5G edge platform. This is 1.4 sensor data images more than when we conducted the experiment over eMBB. A comparison between Fig. 6 and Fig. 8 reveals this difference. Furthermore, we retrieve an average of 254.2 sensor data images with a standard deviation of 2.35. The average transmission time for one sensor data image towards the EdgeApps running on the edge computing units of the Antwerp 5G edge platform over the URLLC slice is 136 millisecond (ms), with a standard deviation of 14.8 ms.

*3) Results experiment 3, sensor dataset edge vs. cloud, **medium location**, eMBB slice:* The results of this experiment are depicted in Fig. 9, and Table IV. At a medium location with a distance of 1 km between the UE and the 5G NR base station, we observe that the UE took an average of 50.99 seconds, with a standard deviation of 6.49 seconds, to transmit its collected sensor data to the edge. This translates to an uplink throughput of 23.59 Mbps over the eMBB slice. In the case of the public cloud, the UE took 52.5 seconds on average, with a standard deviation of 5.79 seconds, to transmit the same sensor data (22.92 Mbps uplink throughput). Concerning image loss, Fig. 10 shows the results of edge vs. cloud.

*4) Results experiment 4, sensor dataset edge vs. cloud, **far location**, eMBB slice:* In Fig. 11, which represents a far location with a distance of 3 km between the UE and the 5G NR base station, the UE requires an average of 185.22 seconds to transmit the sensor data to the edge over the eMBB slice (6.5 Mbps). In the case of the public cloud, the result is 4.66 Mbps.

D. Outdoor End-to-end latency experimentation results in a Busy Maritime Port Environment

As previously outlined, our real-life use case of Assisted Vessel Transport places a strong emphasis on achieving low-latency communication via the 5G SA link. Ensuring low-latency communication over the 5G SA link is crucial as it transfers data to the edge where EdgeApps process it and swiftly increases situational awareness of remote captains. In particular, Table III specifies the network requirements for the sensor

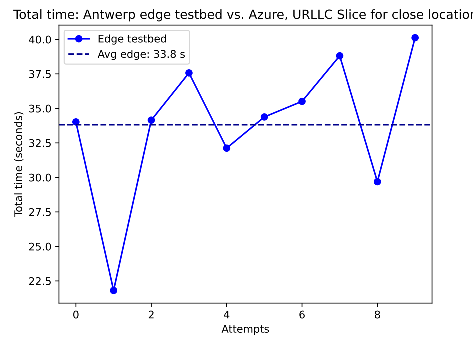

Fig. 7: Total time for close location, URLLC slice edge vs. Azure.

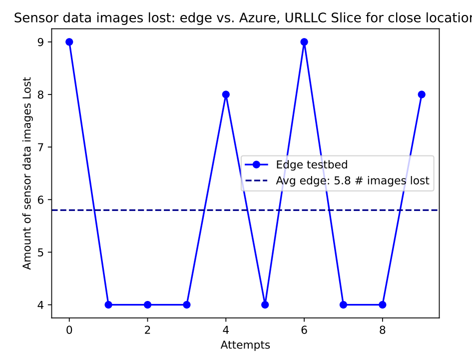

Fig. 8: Amount of file losses for close location, URLLC slice edge vs. Azure.

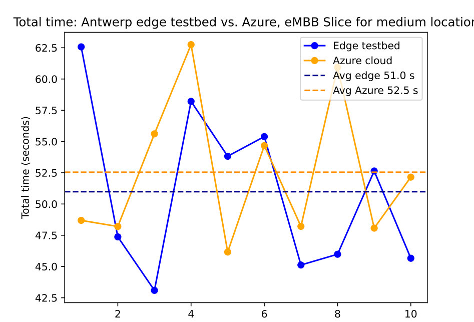

Fig. 9: Total time for medium location, eMBB slice edge vs. Azure.

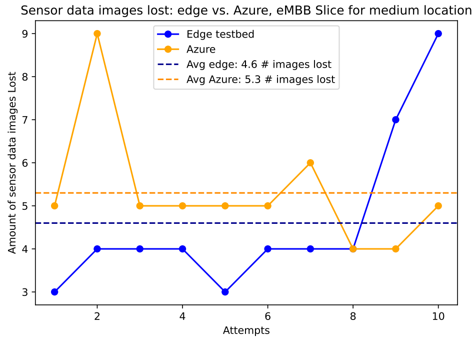

Fig. 10: Amount of file losses for medium location, eMBB slice edge vs. Azure.

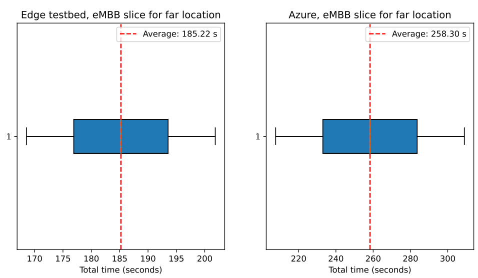

Fig. 11: Total time for far location, eMBB slice edge vs Azure.

data and ship awareness notifications. That is why in addition to the experiments concerning the throughput and image loss for both edge and cloud deployments, we conducted further experiments to assess the end-to-end latency along the 5G SA link. These experiments involved measuring the latency from the vessel to the edge and comparing it to the latency to the Azure cloud data center. The categorization of vessel locations as 'close,' 'medium,' and 'far' remains consistent with the previous experiments. In this specific latency assessment, to compare edge versus cloud performance, we employed the network diagnostic tool ping. [9].

The results Fig. 12 show that the vessel achieved an average end-to-end latency of 22.03 ms with a standard deviation of 3.29 ms from the close location to the EdgeApps running on the edge. In the case of cloud deployment, this end-to-end latency is 38.58 ms with a standard deviation of 6.63 ms. Moving to a medium location, latency increases to 31.99 ms (with a standard deviation of 8.97 ms) for edge, and 50.36 ms (standard deviation of 11.07 ms) for cloud deployment. Going farther from the base station (far location), there is more impact on the signal quality and thus end-to-end latency results in 40.29 ms, in the case of edge, and 63.42 ms for the cloud.

[9]The 'ping' tests enabled us to estimate network latency by measuring Round-trip time (RTT), where higher RTT values indicate longer delays in data transmission.

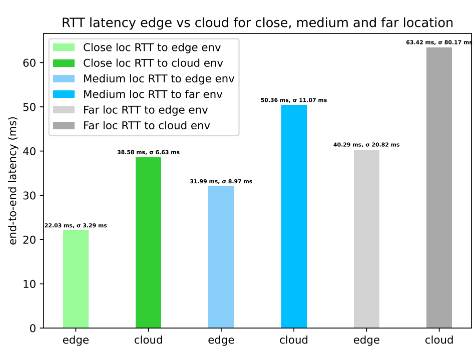

Fig. 12: End-to-end latency Difference: Edge vs. Cloud.

E. Discussions

As fast data transfer, and reliable and fast connectivity for providing control signals to vessels and captains, are required for ensuring safer port operations, a relatively high number of sensors/cameras needs to be connected to decision-making entities towards increasing the safety of the port operation, by e.g., preventing equipment collisions in autonomous navigation, or reacting to weather changes in advance. In addition, vertical services in this particular use case are provided through the delivery of 5G EdgeApps, which include 5G mobile connectivity requirements in their blueprints (Section V-A). In this use case, 5G is required for two main reasons: i) collecting high-bandwidth camera feeds (at least 15 Mbps per camera), and real-time sensor data, and ii) real-time assistance for the captain to navigate the vessel (latency lower than 35ms), as latency and bandwidth offered by previous generations are not sufficient. To provide the navigable predicted path for vessels, real-time data aggregation, i.e., efficient data collection from sensors and cameras on remote ships is required. The same applies to remote vessel monitoring which also requires an enhanced environmental perception, which is essential for obstacle detection and avoidance in the inland waterways. Thus, with the increase in connected ships in Antwerp, the requirement for larger uplink bandwidth becomes even more stringent. With the current 4G connectivity, the collection of camera feeds is limited, whereas 5G enables lower latency and significantly higher bandwidth for more HD video streams.

We will summarize here the discussion and findings related to results on **edge vs. cloud at close location**, presented earlier and shown in Fig. 5 and Fig. 6. The EdgeApps running on the edge computing units of the Antwerp 5G testbed exhibit an overall 6.5 second lower total time needed to transmit the collected sensor data images compared to the Azure public cloud on the eMBB slice, as demonstrated. The total amount of dropped RADAR images is slightly lower at the edge, with an average dropped packet rate of 4.4 out of 260, resulting in a 98.3% reliability, compared to 97.9% for the Azure public cloud. One of the contributing factors is that the EdgeApps running on the edge are 109.9 km closer to the area where the vessel operates compared to the Azure public cloud (Fig. 3). Furthermore, when utilizing the Azure public cloud or any other public cloud provider, data is transmitted over the public internet (Fig. 4).

Concerning the end-to-end latency, we see that on average the latency for the close location in the case of edge results in 22.03 ms compared to 38.58 ms obtained in the case of public cloud. This confirms the faster reception of collected RADAR data images from the vessel by EdgeApps running at the edge compared to the Azure public cloud. However, since these results are obtained in a real-life and challenging port environment with heavy maritime and vehicular traffic, external factors may have influenced these outcomes. Nevertheless, this is a scenario that is realistic and mirrors real-life conditions, particularly in port areas. When comparing the obtained real-life results against the use case and its network requirements (Table III) we can see that EdgeApps running at the edge can achieve an average uplink speed of 42.97 Mbps with an average end-to-end latency of 22.03 ms, which is sufficient for safe and high-quality assistance in the remote sailing process. In comparison, the nearest public cloud attained an average uplink speed of 34.56 Mbps but exhibited an average end-to-end latency of 38.58 ms. These results fail to meet the minimum requirements for both sensor data and ship awareness notifications, particularly on the latency aspect, which shows the importance of leveraging edge in case of latency-sensitive services and data retrieval from vessels even in upscale scenarios where multiple vessels are connected and upload their data.

When we sail the vessel to a **medium distance location** (1 km), using the eMBB slice as shown in Fig. 9 and Fig. 10, and Table IV, we observe an increase in the total amount of time needed to transmit RADAR data compared to the experiments done at a close location (100-meters). This is primarily attributed to a decrease in the uplink speed from 42.97 Mbps (for the close location) to 23.59 Mbps over the eMBB slice (when connected to the edge), resulting from the increased distance between the UE (i.e., the vessel) and the 5G NR base station, with more interference in the line of sight. In the case of the public cloud, the uplink throughput drops from 34.56 Mbps (for the close location) to 23.59 Mbps. The most significant difference is that the average total time difference between the EdgeApps running on the edge, and the ones running on the Azure public cloud, reduced from 6.5 seconds to 1.3 seconds. When we now compare this with the actual achieved end-to-end latencies from the vessel towards both the edge and cloud, we see that on average latency for the medium location and edge deployment results in 31.99 ms compared to 50.36 ms, in the case of the public cloud. This again confirms the faster reception of RADAR data for the edge cloud. The results also indicate that the Azure public cloud experienced a lower percentage increase (30.58% vs. 45.21%) in end-to-end latency when transitioning from the close to medium location, which is somewhat expected as the impact of public internet remains the same.

Studying again the obtained results (Table IV) with reference to requirements (Table III), the EdgeApps hosted at the edge achieve an average uplink speed of 23.59 Mbps and an average end-to-end latency of 31.99 ms, which again aligns with the use case requirements for sensor data transmission. However, the results do not meet the latency criteria specified for ship awareness messages. This highlights the importance of denser deployment of 5G NR base stations in such harsh environments that even for a 1 km distance for the 5G NR base station involves significant interference to the 5G signal, where uplink becomes seriously susceptible. Similarly, in the case of a close location, the nearest public cloud also fails to meet the use case requirements for both sensor data and ship awareness notifications.

When moving to a location that is even further away from the 5G NR base station (far location; 3 km), we observe a noticeable increase in the total amount of time needed to transmit the RADAR data (Fig. 11 and Table IV), which is attributed to a decrease in uplink speed and the distance of 3 km from the 5G NR base station. However, the difference between performance on the edge and the public cloud is even more visible. The average time to transmit the RADAR data from the vessel to the EdgeApps is 185.22 seconds for the edge deployment and 258.3 seconds for the cloud. However, the edge is still receiving each RADAR image in an average of 722 ms, compared to 1.02 seconds when sent to the Azure public cloud. The rate of lost data remains relatively stable. When we now compare this with the actual achieved end-to-end latencies from the vessel towards both the edge and public cloud, we achieve 40.29 ms and 63.42 ms, respectively. Comparing the obtained values against the requirements, we now observe that even on the edge, none of the use case requirements are satisfied (with an average uplink speed of 6.50 Mbps and end-to-end latency of 40.29 ms).

VII. Recommendations and Conclusion

A. The future of EdgeApps in the 5G and beyond ecosystem

EdgeApps have the potential to evolve and improve the current generations of applications placed at the edge of 5G and beyond networks. As presented in Sections IV-D and V-A EdgeApps have network awareness, QoS awareness, network control, and can adapt to dynamic network conditions. Within the use case presented in this paper VI-A these EdgeApps already enabled automated vessel control in the T&L vertical. However, EdgeApps in 5G and beyond systems offer grand opportunities to boost the operation and efficiency of many industry verticals, enabling new use cases and applications whose stringent connectivity requirements could not be met with the previous generations of mobile communications systems [5]. Given the lack of research on the true potential of leveraging 5G EdgeApps systems in the context of industry verticals such as T&L we present one of the first attempts to create an end-to-end 5G-based EdgeApps system for enabling assisted and automated vessel control.

a) ***Opportunities for engaging SMEs to explore the benefits of edge network softwarization and intelligence****:* One of the important objectives of the VITAL-5G Antwerp use case (Sections V-C and VI-A) is to engage maritime SMEs in exploring the potential of 5G and beyond technologies to enhance their daily operations. This endeavour has posed challenges, mainly because many maritime companies lack expertise and experience with 5G systems. We consider this challenge to be a significant opportunity for introducing EdgeApps frameworks, which hold great potential for large ports in Europe and beyond. This is especially relevant for Europe, given its proximity to two major global ports: the Port of Rotterdam and the Port of Antwerp-Bruges, located within approximately 64 km of each other.

b) ***Sustainability of open 5G edge and beyond testbeds****:* It is essential to establish open 5G and beyond edge testbeds in port areas that can support maritime SMEs in developing innovative solutions for their day-to-day operations to let them fully explore and embrace the benefits of edge network softwarization and intelligence. Unfortunately, many H2020 3GPP projects have faced the issue of terminating testbeds shortly after project completion. This represents a missed opportunity, especially for the maritime vertical T&L industry since this industry requires innovations and transformation in terms of smarter and safer operations. To address this, VITAL-5G has made the commitment to open its three testbeds to any SME T&L vertical interested in exploring how 5G and beyond technologies can benefit their daily operations. In general, all future 5G PPP testbeds should remain open for extended durations, allowing SMEs to explore how these new technologies can enhance their daily operations and ensure their future-proofing.

c) ***Future scale-up and reusability of EdgeApps****:* For vertical service developers, especially those from SMEs seeking to explore how 5G SA and beyond services can potentially enhance their day-to-day operations, it is crucial that the surrounding framework enabling them to explore and create those new vertical services is intuitive and straightforward to use. This necessity led us to introduce the EdgeApps framework, which is inherently vertical-agnostic, meaning that any type of vertical service (automotive, T&L, eHealth, etc.) can be deployed this way. Moreover, the VITAL-5G platform hosts an open repository of EdgeApps contributed by diverse vertical service developers, allowing for their combination to create novel services. This approach promotes the scalability and reusability of EdgeApps both presently and in the foreseeable future.

B. Real-life experiment edge vs. cloud applied to the maritime sector

One of the primary findings from our real-life maritime experiment (Fig. 3) (Section VI) conducted on the VITAL-5G Antwerp edge testbed (Sections VI-A and V-C), is the distinct advantage of the edge computing environment over the nearest available public cloud. In all the experiments conducted with the nearest public cloud, it never met the outlined use case requirements for the network as presented in Table III. This means that upcoming 5G and beyond assisted services for the maritime T&L vertical will need to use almost by de facto edge computing platforms as such we can say that the term ”Edge” in EdgeApp is appropriate. This advantage holds true for both the transmission of observed sensor data images from the vessel (Fig. 3) (subsection VI) and the end-to-end latency analysis (Section VI-D) presented in Table IV. However, we observed that the difference between the edge and the public cloud is not solely due to the physical geographic proximity, with the edge being closer and the public cloud farther from the computing source. Other significant factors come into play:

a) ***Harsh Port Environments**:* The challenging conditions in port areas, including the presence of vessels, bridges, cranes, trucks, and variable weather conditions, can interfere with signals and negatively impact the performance of 5G and beyond networks as shown in our results Sections VI-C and VI-D. Our trial site, depicted in Fig. 3, provided a clear illustration of these harsh conditions, underscoring the necessity for port authorities to strategically position 5G NR SA base stations. This strategic placement should take into account both the challenging port environment and the specific locations where vessels are most active.

b) ***Density of 5G NR SA Base Stations**:* The number of 5G NR SA base stations along the dock where vessels operate plays a crucial role in the performance of maritime services. Table IV clearly illustrates the impact of increasing distance from the 5G NR SA base station on network performance. Therefore, port authorities and telecom infrastructure providers must carefully plan and work together for the placement of 5G NR SA and beyond base stations to support advanced maritime services as presented in this paper.

c) ***Increasing the number of vessels**:* In our use case (Section VI-A) and experiment (Section VI), we used a single vessel (Fig. 3). It is worth noting that as the number of vessels connected to the same 5G NR SA base station increases, the results presented in Table IV will become even more significant. This is due to faster data processing and the avoidance of additional latency introduced by the public internet when processed at the edge.

d) ***Increasing the sensor data sample rate**:* Increasing the sensor data image resolution and sample rate would further impact the results shown in Table IV due to larger sensor data image sizes and sample rates. Public cloud providers may face bottlenecks with increased sensor data image resolution, highlighting the growing relevance of edge platforms in such scenarios.

e) ***Mission-critical messages to captains or remotely controlled vessels**:* Another significant advantage of edge computing arises when sending mission-critical messages to captains or remotely controlled vessels (Section VI-A). In edge environments, traffic does not traverse the public internet, as is the case with publicly available cloud services (e.g., the Azure cloud used in our experiment, Section VI). Consequently, mission-critical messages reach their destination more quickly. In our specific edge environment (as detailed in Subsection V-C), these messages arrive within 11.015 ms (Table IV), compared to 19.29 ms (Table IV) for the public cloud—nearly twice as long.

f) ***Variability in network performance the role of EdgeApps for maritime use cases**:* The results obtained and detailed in Table IV illustrate the significant variability in network performance, contingent upon the distance between the vessel and the nearest 5G NR SA base station. This variability underscores the relevance of EdgeApps, as they exhibit network awareness and possess the capability to adapt to dynamic network conditions. That is why, EdgeApps delivering vertical services to vessels have the potential to deliver safer and more efficient operations to vessels when compared to conventional edge applications that lack awareness of these fluctuating network conditions.

Thus, in this paper, we derive important conclusions i) the paper emphasizes the critical role played by edge computing systems within the 5G ecosystem, highlighting their potential to significantly enhance vertical industries like Transportation and Logistics (T&L). This paper, with a specific focus on maritime applications, delineates how edge systems can leverage advancements within the T&L domain, ii) this research contributes to the design and implementation of EdgeApps, specifically tailored to support assisted vessel navigation use cases, and further delves into their practical deployment in real-life maritime settings. The findings elucidate the feasibility and effectiveness of utilizing EdgeApps in such environments, and iii) valuable insights gleaned from our real-life experiments conducted in the Port of Antwerp-Bruges are presented, including a thorough analysis of network and EdgeApp performance results. These empirical observations provide practical knowledge that guides the future design and development of maritime systems. This is of particular significance given the substantial economic role that maritime industries play within the EU.

VIII. Acknowledgement

This work has been performed in the framework of the European Union’s Horizon 2020 project VITAL-5G co-funded by the EU under grant agreement No. 101016567. We thank partners from Seafar NV for their support in arranging the test sessions with the boat and giving us access to the RADAR equipment, which we leveraged for collecting sensor data.

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