On Assessing the Potential of 5G and beyond for Enhancing Automated Barge Control

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***Abstract*—As the shipping sector has been one of the major impact factors on economic growth over the past decades, its digitalization is expected to make unprecedented improvements in the safety and reliability of ship control, thereby ultimately enabling the autonomous operations of ships. The automated control of ships will not only mitigate the risks of human mistakes but will also improve the efficiency of operations by preventing unexpected delays while being environmentally sustainable. With the advent of the Internet of Ships (IoS) sector, well-known and mature concepts of the Internet of Things (IoT) are being applied to ships and ports, thereby making them more and more equipped with sensing and communication capabilities that set the ground for improved situational awareness and better decision-making. However, there are many challenges that need to be thoroughly studied, such as the communication between barges, ports, and services, as increased network latency and limitations on the bandwidth imposed by satellite communications could introduce significant risks for accident occurrence, ultimately affecting the overall automated operation/teleoperation of barges. In this paper, we present one of the first attempts to test the potential of 5G systems for automating barge operations, starting from teleoperation as an enabler of automation, thereby creating and validating a cellular-based automated barge control system in a real-life environment. In this system, the barge is sailing in a busy port area such as one of the Port of Antwerp Bruges, while being connected to the 5G network. We assess the quality of the 5G communication system and present and discuss our initial results on the enhancements that 5G could bring to teleoperation and automation of the barge control.**

***Index Terms*—5G, automated ships, teleoperation, shipping operations, 5G ports, real-life experimentation environments**

I. Introduction

By providing significant contributions to the macroeconomic development, the Transport & Logistics (T&L) sector is becoming one of the major components of any modern production system [1]. Nonetheless, to keep up with the pace of such production systems, the automation and optimization of T&L processes need to be improved, as they could highly affect the efficiency and safety of the overall T&L chains. In this paper, we focus on a particular sector within T&L industry, i.e., the T&L operations in the river/sea ports.

Given the trends over the past decades that are backing up the approximation that around 74% of the goods in Europe are being transported via ships/barges, the shipping sector has been considered as one of the major drivers for economic growth and prosperity [2]. With the digitalization trends that are affecting almost all industrial areas, the peak of the shipping digitalization process is expected to be reached when a full automation of barges is achieved, thereby making them significantly safer and more reliable [3]. The potential of increasing safety and reliability by developing autonomous ships is unprecedented, as remotely controlled and/or autonomous ships would reduce the risk of human mistakes [4], thereby improving safety levels by minimizing the risks of injuries or fatalities for the crew on-board, but also the damage to the ships.

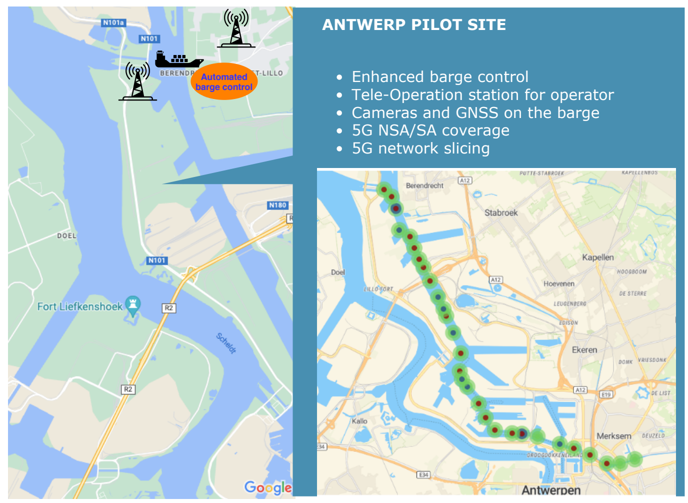

Fig. 1: A high-level overview of the Antwerp pilot site created for testing and validating automated barge control, with an indicated 4G/5G signal coverage on the sailing route (green indicating good signal quality).

To leverage on the well-known concepts of Internet of Things (IoT) toward enhancing the automation of barge operations, the Internet of Ships (IoS) has recently emerged as a concept that is enabling the networks of smart interconnected maritime objects (e.g., ships, and ports) to boost the shipping industry by providing increased levels of safety, efficiency, and environmental sustainability [2]. In particular, in such IoS systems, barges and other port elements (e.g., cranes, trucks, vehicles) are being equipped with sensing and communication capabilities, making them able to distribute, collect, and process, the information from the surroundings, which ultimately improves the decision-making process. Nevertheless, some of the challenges such as inefficient communication between barges and ports as well as the lack of efficient navigation systems are imposing considerable risks for accident occurrence, leading to delays in barge sailing that could hinder all 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, the 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) [5], 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 offers 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 [6]. Given the lack of research on the true potential of leveraging 5G systems in the context of industry vertical such as T&L, in this paper we present one of the first attempts to create a cellular-based system for enabling teleoperation and automated barge control, performed within the 5G-Blueprint project. As illustrated in Fig. 1, 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 5G system on the automation of barge control operations, where the barge is sailing while being connected to the 5G network. Whilst the challenges of leveraging on 5G on the open seas still persist due to the lack of infrastructure, in this work we focus on inspecting the 5G potential for inland waterways, focusing on the teleoperation of barges as an enabler of automation.

II. Background

One of the most important applications of IoS are the smart ships, which are equipped with communication, sensing, and data management capabilities [2]. With such capabilities, there is an opportunity for barges to operate more safely, more reliably, and more efficiently. In particular, reducing the human role in the ship operations might lead to reducing the number of accidents that involve human error, as this type of error is one of the most frequent causes of accidents in barge operations [7]. According to the statistical data from European Maritime Safety Agency, human error is proven to be the cause of accidents in 62% of the cases with EU-registered ships, while work on deck is considered 5 to 16 times more dangerous than work ashore. As pointed out by Levander [4], a report published by the Munich-based insurance company Allianz in 2012 states that between 75% and 96% of marine, accidents occur due to a human error such as fatigue. Some important efforts have been invested to put a spotlight on the importance of autonomous ships, such as Maritime Unmanned Ships through Intelligence in Network (MUNIN) for setting the base for unmanned merchant ships, and the DNV GL ReVolt project that focuses on developing unmanned zero-emission shortsea ships. An interesting study conducted by Ramos et al. [7] is focused on assessing the potential of human errors in ship operations, identifying possible human failure events in the ship operation supported by the interaction between the Shore control center and the ship system. However, there is still a lack of studying the impact of the network on the automation and teleoperation aspects when it comes to barge control.

In [7], Ramos et al. point out the importance of network connectivity for some of the remote-control mechanisms, which needs to be assessed prior to the journey, where in some cases the network requirements on latency and bandwidth might exceed those achieved through the use of satellite systems. However, they do not further detail such cases and the actual mitigation strategy for using other network technologies. During the sailing phase, barges are producing the data such as location, speed, heading, and potentially the Estimated Time of Arrival (ETA) to the next waypoint, camera feeds that contain data about the surrounding of the relevant barge, providing the means for increasing the overall situational awareness. If the threshold from the decision-maker exceeds, the operator is notified and can intervene. In [7], Ramos et al. study the interaction between the operators and the barge system, where an intervention, in which the system encounters an issue that cannot be solved locally and requires help, is considered successful if the operator solves the issue by taking control to bring the barge back to a safe status. However, as errors could occur in the communication and in the human operation from the control center, the barge risks not being recovered from an unsafe state. Their study identified three main types of human errors that could occur in such an operation, i.e., failure to respond to the alert from the barge, a failure to remotely operate the ship, and a failure to take over control from the barge when needed.

As the maneuvering of barges towards the dock is one of the phases in the overall operation of the automation that could potentially lead to collisions with the obstacles or even other barges, Shuai et al. [8] propose an efficient control strategy for collision-free maneuvering toward the docks. They developed an algorithm that steers the barges according to the pre-defined paths, taking into account their relative position and speed, as well as the collision risk factor. Although their results sound promising, thereby paving the way towards improving the safety in ship autonomous operations, they are purely based on numerical simulations, and thus not tested in real-life environments. One effort to pursue a more realistic experimental evaluation of collision avoidance mechanisms for ships has been presented by Perera et al. [9], leveraging on the proof-of-concept that consists of the navigation/control platform and a scaled barge (a vessel model with mathematical formulation). In this study [9], the barge model was in charge of taking decisions on avoiding potential collisions, whereas the obtained results show that intelligent systems developed for barges have a great potential in achieving collision avoidance, but the study needs to be further extended to include more barges and synchronization between their collision detections and respective decisions.

By enabling remotely supervised barges, not only the efficiency, safety, and reliability, are getting improved, but as such, they can be essential for rescue scenarios. However, as pointed out by Marten et al. [10], the limited bandwidth resources granted by satellite communication pose challenges on the success of such remote operation. To mitigate the issue of bandwidth limitations, Marten et al. [10] studied the impact of new types of interfaces on the remote supervision of barges, where they proposed a 3D-visualisation of the barges' surroundings, thereby trying to improve the situational awareness with an enhanced Graphical User Interface (GUI). Their study included 16 participants, who proved to have a better situational awareness when using 3D or Virtual Reality (VR), but it is limited only to a simulated vessel, therefore lacks a more realistic implementation in a real-life environment (i.e., including more impact factors from the environment).

As it could be seen from the above overview, there is a lack of research on the impact of the communication link for enabling remotely operated and autonomous barges. So far, satellite communication has been mostly used in sea transportation, however, it is a slow and expensive technology [2]. Given the availability of numerous types of networks (WiFi, 4G, 5G, satellite, etc.), creating a secure network that is able to meet the requirements of ship operations is significantly challenging [2,11]. The state-of-the-art satellite communication systems cannot offer high bandwidth and low latency, which could be even more affected by bad weather conditions due to the weakening of signal strength. Therefore, a more thorough and dedicated study of network connectivity and its impact on automated barge operations is necessary. Hence, in this paper, we show some of the first efforts to study the impact of cellular communication technologies on the operation of automated barge control, thereby focusing on the enhancements that 5G systems could offer for achieving more stable and reliable network connectivity with the barges.

III. System Description

In the scope of the 5G-Blueprint project, we are focused on implementing the 5G network slicing capabilities to achieve URLLC and eMBB, which enable the development and testing of innovative 5G-enhanced tele-operation services. To leverage upon such network slices, i.e., an ultra-reliable, low-latency, and high-bandwidth network connectivity, and to validate their benefits in the real-world environment such as busy sea ports in Europe, we have defined four main use cases, i.e., automated barge control, automated driver-in-loop docking, Cooperative Adaptive Cruise Control (CACC)-based platooning, and remote takover [6]. In this paper, we focus on the first use case, and in this section we discuss about the 5G system and its architecture leveraged in the pilot site, as well as the control system used for automated barge control.

A. 5G system

In Fig. 2, we show the 5G-Blueprint network architecture for the pilot site in Antwerp, developed for testing and validating automated barge control. Starting from the User Equipment (UE), which is a commercial barge in this case, the overall system is equipped with various sensors and several cameras that are installed on-board and used for improving environmental perception and hence situational awareness. To be able to communicate via cellular networks, this barge has a 5G modem installed, including the antennas necessary for signal transmission/reception.

The data such as video from different cameras is being transferred on the uplink, through the Radio Access Network (RAN), transport, and core network, from where it is further routed through the public internet towards the Control services

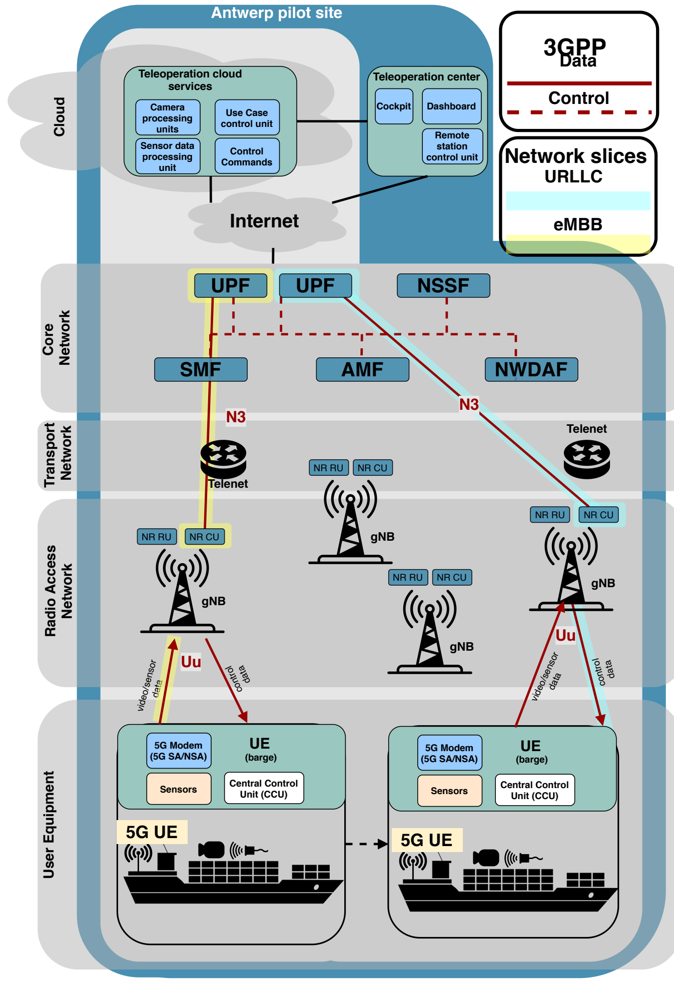

Fig. 2: 5G-Blueprint Network Architecture for Antwerp Pilot Site.

running on the cloud to which both the teleoperation center and the barge are connected. Concerning the core network, two deployments are possible, i.e., 5G Non-Standalone (NSA) based on the 4G Evolved Packet Core (EPC), and 5G Standalone (SA) with 5G Core functions (illustrated in Fig. 2) that, among the other features, enable network slicing as well. The cloud services are being used both by barge and the operator in the control center, who is further making decisions on the barge maneuvering, thereby generating the control commands. Such control commands are transferred back to the barge over the 5G infrastructure (downlink), and once the commands are translated into electrical signals on the Programmable Logic Controller (PLC) of the barge control unit, the remote operation is achieved. The overall network infrastructure used in the Antwerp pilot site is deployed by the mobile network operator Telenet.

To provide a clear understanding of network requirements in this type of use case, and to grasp the potential of applying 5G network slicing concept, in Table I we present particular requirements for High Definition (HD) camera streams, video screens, and ship control interface. These requirements are derived in the scope of the 5G-Blueprint project, after a thorough study of network capabilities and operational requirements for

TABLE I: Network requirements for automated barge control [6].

Description	HD camera stream	HD video screens	Ship control interface
From/To	barge → control center	barge → control center	control center → barge
Service type	Uplink	Downlink	End-to-end
Ideal latency	<22ms	<22ms	<35ms
Service interuption	<30s	<30s	<150ms
Bandwidth requirement	>5Mbps, <25Mbps	>5Mbps, <25Mbps	<2Mbps
Device scenario	Outdoor mobile	Outdoor stationary	Outdoor mobile + Outdoor stationary
Slice type	eMBB	eMBB	URLLC
Number of flows	10 per ship	6 per operator	1 per ship

barge control.

Given that automated control of barges requires bandwidth of 5-25Mbps in the uplink, and latency lower than 22ms, per HD video camera stream, and latency lower than 35ms for vessel control interface, the potential of leveraging the eMBB type of slice for the uplink traffic and the URLLC for the downlink is evident. For the uplink, such a use case requires an efficient data collection and encoding from sensors and cameras, so that advanced processing of such data could be performed on the cloud prior to decision-making that would affect maneuver of the barge. However, with an increased number of barges in busy ports such as Port of Antwerp Bruges, where the traffic load would be extremely heavy when all barges are connected, the bandwidth requirement on the uplink becomes even more stringent (leveraging on eMBB slice), pushing the need for 5G deployment. On the other hand, for the downlink connection with the barge, where control commands are being transferred, the end-to-end latency needs to be lower than 35ms so that the remote operation, i.e., control commands can be applied in an efficient and safe manner (leveraging on URLLC slice).

Hence, by studying such requirements, we can see there is an enormous potential of leveraging on 5G and beyond technologies to provide both faster and safer operations with ms-level end-to-end latency, data rates above 100Mbps, since such capabilities are usually not available in 4G systems nowadays, especially when it comes to future scaled-up systems with a large number of barges being simultaneously connected over the network.

B. Control system

One of the definitions of automation reflects on the systems as autonomous if they are capable to sense, perceive, make decisions, and act, towards achieving goals that are assigned by their human operator through a designed Human Machine Interface (HMI) [7]. However, there are various levels of automation between a completely manual control to a fully autonomous system, and they can by dynamically configured depending on the system and defined scenarios.

In Fig. 3, we demonstrate the components of the overall control system used in our testing scenarios. On the barge side, there are controllers and PLCs installed and connected with the sensor and camera processing units, which are further capable to transfer the signals towards remote control centers via 5G antenna onboard. In our testing environment, we use the a commercial barge, i.e., Tercofin II shown in Fig. 4, and thus there is a limitation in terms of autonomous operations that could be achieved. Instead, the testing is currently being performed in a so-called *shadow-mode*, which means that the control commands sent from the control center over 5G network to the barge are not translated to local control commands onboard that will execute the real actions on the barge (as marked in the system illustrated in Fig. 3).

To mitigate the limitations and increase the level of autonomy, as well as the opportunities for testing the benefits of autonomous shipping and teleoperation, Seafar[1] is working closely with the Port of Antwerp Bruges towards obtaining required permissions to navigate the barge from distance, thereby ensuring the safety of operation and environment. During this test, the network performance of the 5G infrastructure has been monitored and recorded for the detailed analysis. Thus, the impact of the network on the teleoperation, as an enabler of the automated operation of barges, needs to be assessed and thoroughly studied first, thereby measuring the performance of network at the barge side.

IV. Initial results on the 5G-supported automated barge control

Here we present and discuss some of the initial results obtained during the *shadow-mode* testing, with the goal to assess the 5G capabilities in the real-life port scenarios for achieving automated barge control, with reference to the network requirements indicated in Table I.

We performed the tests with the barge both connecting it to 4G and 5G network. Due to the larger 4G coverage in the testing area, i.e., with more base stations commercially deployed, we collected more measurements of the 4G signal. In Fig. 5, the obtained results of the latency are shown, where latency is measured as the time an Internet Protocol (IP) packet takes to arrive at its destination. The gain in latency achieved by 5G compared to 4G is evident, where the average latency of 26.62 ms is achieved using 4G (standard deviation of 10.53 ms), and 15.06 ms with 5G (standard deviation 3.693 ms). The values of jitter for both 4G and 5G can be considered as negligible, since the achieved values are 2.34 ms, and 3.57 ms, respectively.

Taking into account the requirements listed in Table I, the performance over 4G might not be sufficient for the uplink traffic (<22 ms), i.e., HD camera feeds transferred from the barge to the control services on the cloud. It could be reasonably expected that such performance could be even more hindered when more barges are simultaneously connected to the remote cloud services. On the other side, both 4G and 5G results comply with the requirements on the ship control interface (<35 ms). Concerning the bandwidth, as the maximum amount of data that could be transferred over the network per second, our measurements show that up to 24 Mbps could be achieved over 4G connectivity, and up to 36 Mbps over 5G. Although both results suffice the bandwidth requirements, the testing included only simple Iperf[2] measurements, whereas more tests

[1]Seafar NV is an independent ship management company, offering services to operate unmanned and crew-reduced vessels for ship owners and shipping companies.

[2]Iperf is a tool for network performance measurement and tuning.

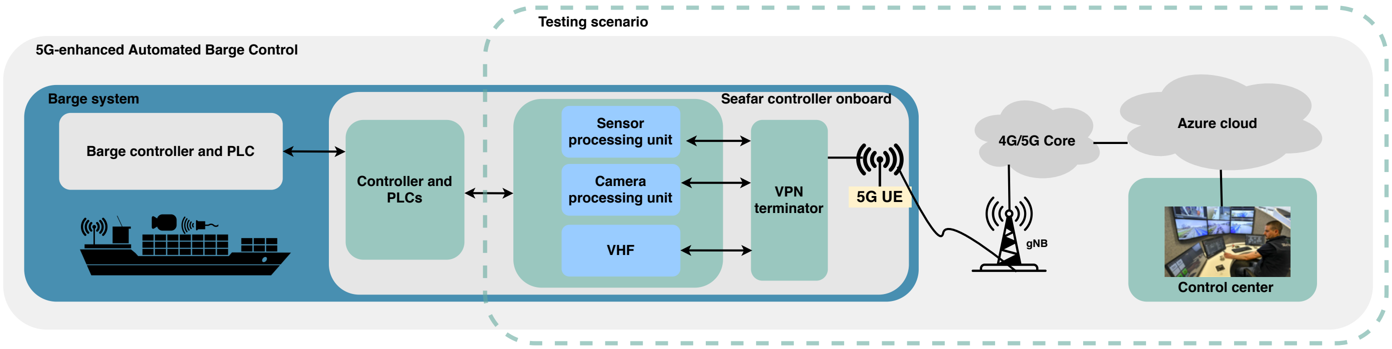

Fig. 3: Test environment.

Fig. 4: Tercofin II, a commercial barge used in the pilot scenarios.

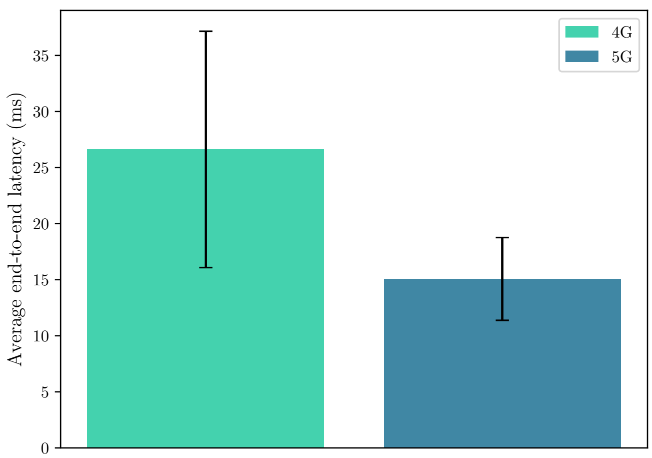

Fig. 5: Latency measurements.

need to be performed to evaluate the bandwidth improvements with e.g., 10 HD camera streams on the uplink and 6 video screens per operator (as indicated in Table I).

Further, Figures 6, 7, and 8, show more signal quality indicators that are collected during the above described latency and bandwidth measurements. In particular, Signal-to-Interference-Plus-Noise-Ratio (SINR) is a metric that indicates the strength of wanted signal compared to the strength of unwanted interference and noise, while Reference Signal Re-

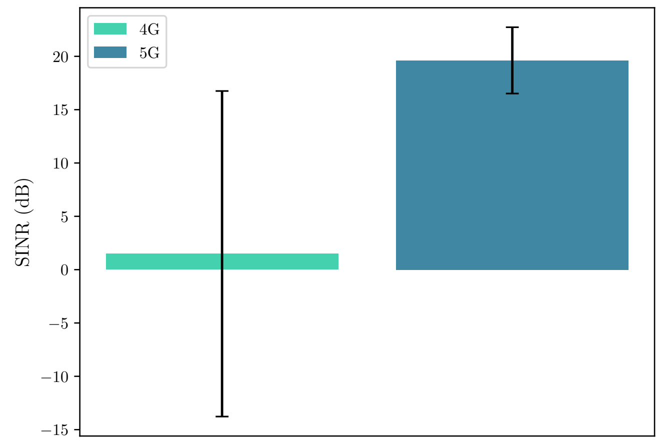

Fig. 6: SINR measurements.

ceived Power (RSRP) and Reference Signal Received Quality (RSRQ) are key measures of signal level and quality of 4G and 5G networks. The obtained values of SINR, RSRP, and RSRQ, show that the quality of 5G signal in the testing area can be considered as *excellent* and *very good*, as the average values are 19.62 dB (*excellent* considered between 13 and 30), -74.49 dBm (*excellent* considered between -85 and -43 dBm), and -11.02 dB (*very good* considered between -11 and -9), respectively. The respective values for 4G signal are 1.48 dB (*fair*), -69.64 dBm (*excellent*), and -10.38 dB (*very good*). The reference values for signal quality indicators have been provided by Seafar network measurement setup, which is standardized for 4G/5G network performance measurements.

We can see from the results that 5G signal is more stable and robust compared to the noise and interference, however the testing scenario for 5G included a limited area in a close proximity from the canal through barge was sailing, thus more testing needs to be performed to derive more insights. In particular, SINR values indicate a large variability with error or 15.26 dB in case of 4G, with 3.1 dB for 5G.

To statistically test the significance of the difference between results obtained for 4G and 5G, we have applied a non-parametric two-sample Kolmogorov-Smirnov statistical test. For all tested parameters shown in Figures 5, 6, 7, and 8, we obtained the *p-value* close to 0, which indicates the statistically significant difference in 4G and 5G performance.

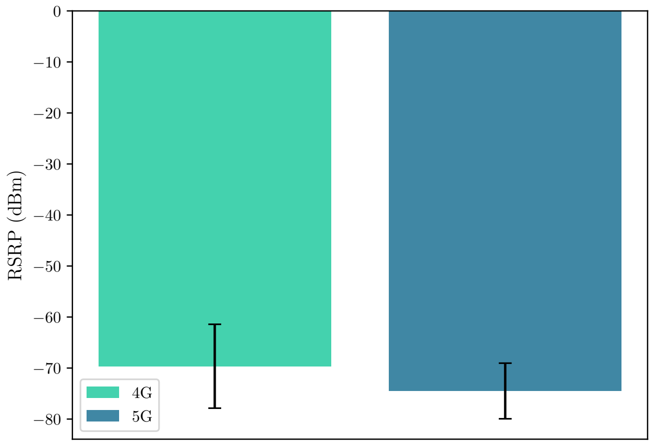

Fig. 7: RSRP measurements.

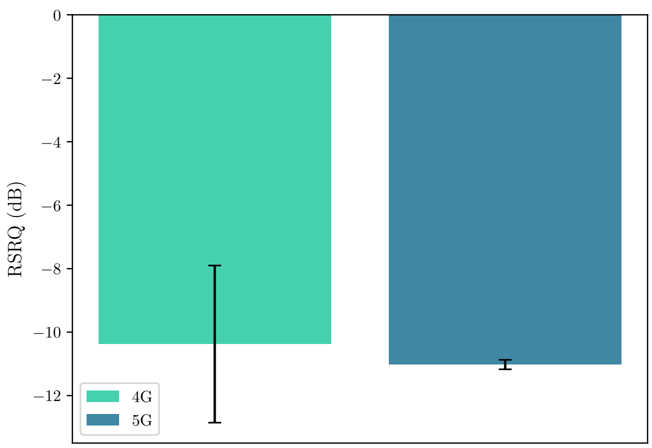

Fig. 8: RSRQ measurements.

V. Conclusions and Future work

Due to a myriad of opportunities such as mitigation of the risks of human mistakes and improvements of efficiency and safety in an environmentally sustainable way, automation of ship operations should be considered one of the major cornerstones in the digital era, being an inevitable part of the emerging IoS systems. However, there is a lack on studying the network performance and the impact of network connectivity on autonomous ship operations, and in general, a lack of performance assessments in real-life environments as most of the studies are based on the simulation results or scaled ship setups. Thus, in this paper, we presented one of the seminal approaches on automating barge control with the help of 5G systems, where we created a cellular-based automated barge control system in a real-life environment with the barge sailing in the Port of Antwerp Bruges, connecting dynamically to the available 5G network. Based on the results we presented, 5G outperforms 4G both in terms of latency and bandwidth, but in terms of the overall signal quality as well, thereby meeting the network requirements that are carefully defined in the scope of the 5G-Blueprint project. The measurements we obtained in the real-life environment provide promising initial results, whereas more tests with 5G SA and eMBB and URLLC network slices is planned, and will be presented in our future work.

In the scope of the 5G-Blueprint project, we are planning to further extend the testing to include more scenarios with higher traffic load (more camera feeds simultaneously), including cross-border scenarios for a barge sailing between Belgium and the Netherlands, and extending it to different weather conditions, in order to test possible bottlenecks in the setup. The results presented in this paper indicate the performance of 5G NSA, which is already promising, while the tests and further measurements on the 5G SA are currently ongoing, with the main goal to study the true impact of network slicing capabilities.

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