Controlling in real-time an ASV-carried ROV for quay wall and ship hull inspection through wireless links in harbor environments

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***Abstract*—Inspection of quay walls and ship hulls is necessary to assess the status of the structure, identifying potential deterioration which may compromise the safety of port and ship operations. The RoboVaaS project aims at reducing the level of human support required to accomplish these tasks by making use of an ASV-carried ROV equipped with multiple cameras and sensors. In this work, we focus on the challenges related to the communication systems needed to ensure the proper information exchange between the ROV, operating underwater, and the shore station. Notably, we propose to rely on the existing port cellular infrastructure and evaluate the end-to-end system performance considering different network configurations (including both 4G and 5G deployments) and system parameters.**

I. INTRODUCTION

The Robotic Vessels as-a-Service (RoboVaaS) project [1], funded by the MarTERA consortium, aims to revolutionize the shipping and near-shore operations by offering robotic aided services via interconnected unmanned vessels, equipped with specialized sensor technology, a reliable data transfer cloud network for above water and underwater communication, a monitoring station, and a real-time web-based user interface. The high level of autonomy implied in RoboVaaS is expected to be reached by using autonomous vessels such as Autonomous Surface Vessels (ASVs); however, some operations still involve human control through, e.g., Remotely Operated Vehicles (ROVs). Within the RoboVaaS vision, a number of services that have a positive impact on near-shore maritime operations have been identified, including: an environmental and bathymetry data collection service, an anti-grounding service, a ship hull inspection service, and a quay wall inspection service, with the last two, depicted in Figure 1, being the focus of this work.

Inspection of quay walls and ship hulls is necessary to assess the status of the structure, identifying potential deterioration which may compromise the safety of port and ship operations. For instance, biofouling on hulls and propellers is a major contributor of increased fuel consumption, ship emissions [2] and transfer of invasive aquatic species [3]. In addition, damage of ships and maritime infrastructures (e.g., sheet pilings, bridge pillars) due to collisions is the most common cause of minor marine accidents [4].

Currently, the inspection is performed by divers who visually determine the condition of the facility, however, the presence of turbid water may complicate their operations because of reduced visibility, introducing risks for the divers' safety. Moreover, the constrained oxygen supply limits the dive time, thus the tasks may take long to be accomplished. Due to the complicated logistics to support these operations, inspections are often performed periodically and scheduled in advance, and not upon request. Although this solution may be suitable for the regular maintenance of the facilities prone to wear and tear, it is not as effective when the damage is caused by an accident. For instance, if the operations are scheduled every 6 months, a damage to a ship hull (caused, for instance, by an undetected collision with the sea cliff) that occurred one month after the last inspection will be detected only after 5 months.

The RoboVaaS project proposes a novel human-assisted framework for quay wall and ship hull inspection, which aims to improve the level of automation and accuracy by making use of an ASV-carried ROV equipped with multiple cameras and sensors. In this work we focus on the design of the communication interface between the ROV and the shore control station, which has to be carefully taken into account to ensure proper system operations. Notably, we rely on a cellular-based communication architecture, and evaluate the system performance using different configurations, considering both 4G and 5G deployments, in order to figure out the best strategy to meet the requirements. Our results show that cellular technologies are able to meet the Quality of Service (QoS) requirements envisioned for the inspection services and therefore can be used to support the unmanned vessels during their operations.

The rest of the paper is organized as follows. In Section II, we review the current level of development of ship hull and quay wall inspection services. In Section III, we outline the automated framework designed within the RoboVaaS initiative, analyze the communication requirements to ensure proper

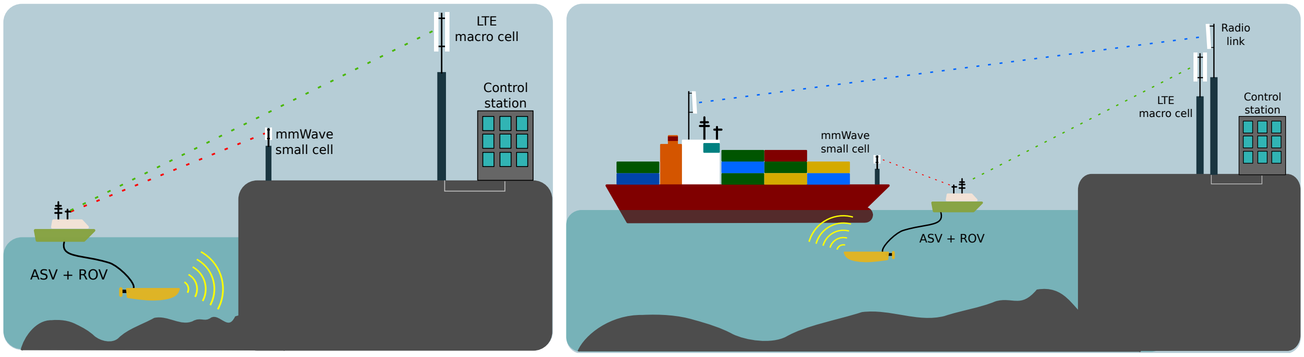

Fig. 1: Quay wall (left) and ship hull (right) inspection scenario.

system performance, and design communication interfaces. In Section IV, we present the performance evaluation of the system and comment the obtained results. Finally, in Section V, we conclude the paper and outline the future work.

II. STATE-OF-THE-ART

To ensure safety and efficient port and ship operations, quay walls and ship hulls have to be properly examined and maintained. In the following, we outline the importance of the inspection services and describe how they are currently carried out.

A. *Quay Wall Inspection Service*

Many historical harbors present aged structures, which are subject to deterioration due to severe service condition and environmental phenomena. In the last years, several catastrophic events happened due to the poor maintenance of port facilities. For instance, in 2013 a quay wall in Utrecht collapsed because of the dredged bottom below its foundation [5], while in 2019, for the same reason, a section of Arbroaths historic harbour wall broke apart [6]. To reduce the risk of failures and ensure the safety of port operations, periodic inspection and maintenance of quay walls is of primary importance. Currently, the inspection is performed by divers, who visually determine the presence of damages, such as cracks or corrosion, and write an after-action report which is then analyzed by port authorities to plan the maintenance work. However, this approach has many weak points that may determine a failure. First, it is very difficult to obtain a reliable and objective report about the status of the structure, because of the several difficulties which may happen during the inspection, such as the presence of turbid water or adverse weather conditions. Second, divers are able to inspect only the visible part of the quay wall, ignoring the possible presence of air holes behind the wall which compromise its stability [7]. Finally, divers operations are limited by the oxygen supply, thus the inspection may take long as it requires multiple missions. In recent years, novel techniques have been developed to overcome these limitations by using mobile or fixed sensors, such as sonars, acoustic cameras, lasers and fiber optic sensors. In [7], the authors describe an inspection method based on a boat equipped with a dual frequency identification sonar. The boat moves along the quay wall and captures sonar images which are then processed to obtain an overall representation of the wall surface. In [8], the authors propose a mobile lidar which can be used for the inspection of quay walls. In [9], the authors developed a scanning system using a multibeam echosounder and a lidar which produces a three-dimensional model describing the status of the infrastructure. Finally, in [10], the authors describe a system for continuous monitoring of the infrastructure using fiber optic sensors mounted on the quay wall.

B. *Ship Hull Inspection Service*

Corrosion is one of the main causes of ship failures [11], compromising passengers safety and possibly harming the marine ecosystem. In 1999, the tanker Erica broke in two parts and sank in the Bay of Biscay (France) because of corrosion of the vessel, causing an environmental disaster [12]. Also, damaged hulls may slow down the movement of vessels resulting in higher fuel cost [2]. To avoid unexpected accidents and ensure proper operations, ships have to be periodically inspected to determine the presence of damaged parts that have to be repaired. Usually the examination requires the ship to be dry docked in special facilities, or is carried out by divers who visually determine the status of the hull. However, both solutions are not suitable for commercial vessels and cruise ships which cannot stay docked for a long time. For this reason, the possibility to automate the inspection would improve the efficiency of ship operations by avoiding dead periods, thus maximizing the revenues. Indeed, this task can be performed when the ship is docked at the port, for instance during load and unload operations, or even when it is approaching the harbor. In the last years, advances in the underwater technology enabled the design of novel devices which can be employed to this aim. For instance, Kraken Robotics developed SeaVision [13], a subsea imaging laser device which can be installed in ROVs to obtain a 3D model of the hull. Similarly, in [14] and [15] the authors describe a vision system for automated ship hull inspection. Also, in [16] the authors present a ship hull inspection vehicle prototype equipped with an imaging sonar.

III. AUTOMATION OF QUAY WALL AND SHIP HULL INSPECTION

One of the objectives of the RoboVaaS project is to develop an innovative system based on unmanned underwater and surface vessels to improve the automation of nearshore operation services such as quay wall and ship hull inspection [1]. Indeed, by reducing the level of human support required to accomplish these tasks, it is possible to lower the operational expenses and improve safety and efficiency. As represented in Figure 1, the system is composed of a ROV and an ASV: the ROV is remotely operated from the shore control station to perform the inspection operations and is backed up by the ASV, which autonomously follows its movements by means of advanced thruster allocation and smart control algorithms [17]. Specialized sensors and cameras are installed on both vessels, and the captured data is upstreamed to the shore control station to facilitate the maneuvering and enable the accomplishment of the inspection tasks. Moreover, a real-time web-based user interface facilitates the monitoring of the system, while a cloud network handles the collection and processing of data acquired by the deployed sensors.

The management of the nearshore services by means of the RoboVaaS framework is regulated by a well-defined procedure. In particular, the service request is triggered by the shore center and handled by the RoboVaaS cloud, which decides whether to accept it or not based on the resource availability. When accepted, the ASV autonomously moves to the interested area and dispatches the ROV. Then, the operator takes control of the ROV to perform the inspection task, and, once this is concluded, fills an after-action report that is uploaded to the RoboVaaS cloud together with the collected data.

The design of such a promising but complex apparatus brings with it a number of challenges. For instance, [18]–[20] study the problem of tracking the ROV by the ASV considering different types of vessels and different positioning mechanisms, while in [21] a system based on collaborative autonomous underwater and surface vehicles is proposed for autonomous mine countermeasures. In this work, instead, we focus on the challenges related to the communication systems needed to ensure the proper information exchange between the ROV, operating underwater, and the shore station. Notably, our solution exploits the ASV as the interface between the underwater and the above water media, which relays the upstream and downstream flows between the two entities. In this context, an accurate design of both (i) the underwater link between the ROV and the ASV, and (ii) the above water connection between the ASV and the shore station is of primary importance.

In the following, we identify the main information flows needed to support the aforementioned services and derive the application requirements considering both the quay wall and the ship hull inspection scenarios. Finally, we provide details on the design of the underwater and above water connections.

A. Application Requirements

The information flows required to support the aforementioned services are:

- the request/response flow between the user, the RoboVaaS server (cloud), and the shore center, which carries the messages for the authentication of the users, the service description, and information about the service availability;
- the mission planning flow between the RoboVaaS cloud and the ASV, in which the information about the working area is sent to the ASV before the mission starts;
- the control and inspection flow between the unmanned vessels and the control station, which enables the remote control of the system and the execution of the required task;
- the after-action report flow, used to upload the outcome of the mission and the data collected during the inspection to the RoboVaaS cloud.

Both request/response and mission planning data flows require a low data rate link with high reliability, and a large communication delay can be accepted. These operations are performed to initialize the task before the actual inspection, and can be performed through either AMQP [22] of SFTP communication protocol. The after-action report flow involves the upload of large files to the RoboVaaS cloud with strict requirements in terms of security, which can be achieved by means of FTPS or SFTP protocols. Instead, the requirements of the control and inspection flow are tightly related to the type of sensors installed in the vessels, and therefore differ between the two inspection tasks, as we describe in the following.

1) Quay Wall Inspection: To provide this service, the ROV is equipped with a sonar sensor and a high-resolution camera, and the captured data is upstreamed to the control station to enable the assessment of the infrastructures under examination and to provide to the operator a visual representation of the environment. Moreover, a controller enables the operator to remotely maneuver the system. The main challenges are related to the operation of the ROV during the inspection operations, as a stable, real-time, medium to high capacity communication link must be provided. Specifically, in order to support this service, the following transmission streams are needed:[1]

- two high quality UDP video streams of 1 Mbps each to monitor the ROV and ASV operations with high reliability;
- a joystick-like UDP control stream to control the ROV movements with rate of 5 kbps;
- a joystick-like UDP control stream to operate the ASV with rate of 50 kbps.

2) Ship Hull Inspection: As for the quay wall scenario, a video camera and a sonar sensor mounted on the ROV provides to the operator a visual representation of the environment,

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[1] The streams requirements are provided by the Fraunhofer Center for Maritime Logistics and Services (CML) [23], that owns the BlueROV and the ASV that will be used for the final RoboVaaS demonstration.

while a controller enables the remote maneuvering of the system. In this case, the ROV is also equipped with the Kraken SeaVision system, including an optical scanner used for the imaging of the ship hull and the propellers in a 3D point cloud format. The data captured by SeaVision have to be uploaded to the RoboVaaS cloud and then analyzed by a human expert that will evaluate the ship hull conditions and fill in a report for the client.

Also in this case, the main challenge is to provide a stable, medium to high capacity communication link to enable the real-time upstream of the data captured by sensors and cameras. Specifically, the following transmission streams are needed: [2]

- two high quality UDP video streams of 1 Mbps each to monitor the ROV and ASV operations with high reliability;
- joystick-like UDP control stream to control the ROV with a rate of 100 kbps;
- joystick-like UDP control stream to operate the ASV with a rate of 50 kbps;
- stream for the operational control of Kraken SeaVision 3D mapping system with rate of 3 Mbps;
- stream to upload the 3D images captured by the Kraken SeaVision 3D mapping system. This application produces a large amount of data to be transmitted (that varies depending on the desired resolution): in this work we evaluate the feasibility of uploading the images during the mission or at the end, e.g., when the ASV returns to the shore station. Given the results, the operator will decide the best approach.

The ROV control stream requirements are different for the quay wall and the ship hull inspection services because, while the former can be performed with a light inspection class ROV [25], the second requires the use of a sophisticated ROV [17], that provides stable position keeping and high precision position control, both required to operate the 3D image scanner, at the price of a higher ROV control traffic bitrate.

B. Design of the Underwater Link

ROVs are typically operated through the so-called umbilical cable, composed by an optical fiber for a broadband low latency communication link, and a power line to supply the vehicle. While the power consumption of working class ROVs is more than 50 kW, the power required by medium and small size inspection class ROVs is less than 6 kW [26], and might be supplied by Lithium batteries. In order to remove the umbilical cable for inspection class ROVs, it is therefore sufficient to transmit the control and the monitoring data required to pilot the vehicle wirelessly. However, performing this operation in the underwater domain is quite complicated, although establishing wireless communication links underwater is possible through radio frequency, optical, and acoustic modems [27]. These three technologies provide different performance and are used for different types of applications. Underwater radio frequency wireless signals are strongly affected by the high attenuation of electromagnetic waves in salty water: for this reason they can be employed only for short and very short broadband communication links, where the distance between the transmitter and the receiver is less than one meter. Also optical modems are used for high rate transmissions in short range, up to a distance of few tens of meters, and their performance strongly depends on water turbidity and sunlight noise. Acoustic signals, instead, can propagate up to tens of kilometers, but are characterized by low bandwidth and long propagation delay. In addition, acoustic signals are strongly affected by multipath in shallow water scenarios, and by the noise caused by shipping activity [28] and wind-generated waves [29]. The best communication performance is obtained when the three technologies are combined together into the so-called underwater multimodal networks [27], where the best performing channels in the experienced conditions are used simultaneously to achieve the desired quality of service. For instance, in [30] the authors proved via simulation the possibility to employ an underwater multimodal acoustic and optical link to control an inspection class ROV. Following the same concept, some offshore companies are currently developing commercial ROVs that can be piloted wirelessly for simple semi-autonomous inspection operations [31], [32]. Despite these recent improvements in the state of the art, this wireless system can be employed only in very favorable conditions, such as pipeline inspection in deep-water oil fields, where acoustic and optical communication work in their optimal conditions, thanks to the absence of acoustic multipath reflection with the sea surface, the low turbidity of deep water scenarios and the absence of solar light noise [33]. This scenario is very different from the conditions experience in a port, where the RoboVaaS services will be provided: harbor waters are indeed very shallow, and characterized by strong acoustic multipath, high shipping activity and solar and lighting optical noise. For this reason, in this work we assume a wired link between the ROV and the ASV.

C. Design of the Above Water Link

The above water link connects the ASV to the shore station and carries downstream flows used to control both the ROV and the ASV, and upstream flows to forward the data captured by sensors and cameras.

Traditionally, maritime communication systems (e.g., VSAT, GMDSS, AIS, LRIT, SSAS) utilizes satellites or radio links operating at medium (MF), high (HF) or very high (VHF) frequencies, and are mainly targeted for safety, identification and security services. These kinds of systems are able to guarantee reliable operations and very broad coverage, but cannot support high data rate applications, such as those envisioned in our scenarios. Technologies operating in unlicensed bands, such as IEEE 802.11b/g/a/n/ac/ax (WiFi), IEEE 802.11ad/ay (WiGig), and IEEE 802.16 (WiMax) may

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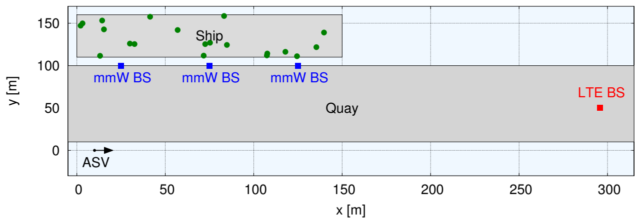
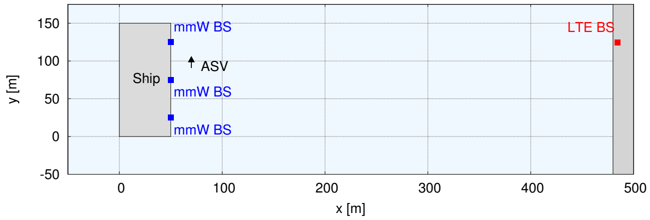
[2] The streams requirements are provided by the Centre for Robotics and Intelligent Systems of the University of Limerick [24], CML [23] and Kraken Robotics [13], that, in the context of the RoboVaaS project, provide the ROV, the ASV and the imaging system, respectively.



(a) Quay wall inspection scenario. The green dots represent the cruise ship passengers.



(b) Ship hull inspection scenario.

Fig. 2: Representation of the quay wall and ship hull inspection scenarios considered in our performance evaluation.

be suitable to support the inspection services, however they require the deployment and maintenance of an ad hoc network infrastructure covering the harbor area, thus increasing the capital costs. Moreover, communications over unlicensed bands may be hampered by the presence of other interfering systems operating at the same frequencies. Another option is to make use of cellular technologies to establish the connection between the ASV and the shore control station. Indeed, Long Term Evolution (LTE) mobile networks are already available in many harbors and coastal areas, and operators offer unlimited data plans at low cost, thus limiting both capital and operational expenses. Currently deployed LTE cellular systems are able to achieve peak data rates of up to 100 Mbps in downlink and 50 Mbps in uplink, and user plane latency of 10 ms [34]. LTE-Advanced (LTE-A), the evolution of LTE, further improves the achievable performance by enabling data rates of up to 1 Gbps in downlink and 500 Mbps in uplink [35]. Moreover, technical specifications for the next generation of cellular systems, i.e., 5G, have been released [36], and mobile operators are in the process of deploying a brand new cellular infrastructure. 5G not only provides better communication performance with respect to the previous generations, but also enables a more flexible network configuration, which is key to host multiple services with very diverse requirements within the same infrastructure. Among the novelties introduced by 5G, Dual Connectivity (DC) and millimeter wave (mmWave) communications may be particularly beneficial in the scenarios of interest, by improving the communication diversity and enabling extremely high data rates. In particular, DC allows users to be connected to multiple base stations simultaneously, using either the same or different Radio Access Technologies (RATs). For instance, users may be connected to an LTE and a 5G base station at the same time, reducing the risk of failures and interruption times. mmWave communications, instead, enable multi-Gbps data rates by making use of a new portion of the spectrum, between 24.25 and 29.5 GHz [37], where the large availability of radio resources allows the operator to allocate wide bandwidths to the users (up to 400 MHz). However, due to the characteristics of signal propagation at those frequencies, mmWave cells are not able to provide extensive coverage and the connectivity may be intermittent if the line-of-sight path between the transmitter and the receiver is obstructed and/or because of the frequent handover events [38]. DC and mmWave communications can be coupled together to build heterogeneous networks [38], in which, for instance, the coverage is guaranteed by an LTE macro cell, while mmWave small cells enable a high throughput data layer.

TABLE I: Simulation parameters.

	Quay Wall	**Ship Hull**
Number of passengers	$[0 \dots 20]$	N/A
Distance from the LTE base station	300 m	$[50 \dots 900]$ m
LTE carrier frequency	1.8 GHz	1.8 GHz
LTE bandwidth	20 MHz	20 MHz
LTE transmit power	30 dBm	30 dBm
Number of mmWave cells	3	3
mmWave carrier frequency	28 GHz	28 GHz
mmWave bandwidth	1 GHz	1 GHz
mmWave transmit power	30 dBm	30 dBm
ASV Speed	1 m/s	1 m/s
Ship dimension	$150 \times 50 \times 20$ m	$150 \times 50 \times 20$ m
Passengers source rate	500 kbps	N/A
SeaVision image size	N/A	10 MB

IV. PERFORMANCE EVALUATION

To assess the feasibility of supporting the above water connection by means of the port cellular infrastructure, we carried out a performance evaluation through system level simulations using ns-3 [39], an open source network simulator featuring accurate models for several communication technologies, such as LTE. For the simulation of 5G-like mmWave cellular networks we used the `mmwave` module [40], an ns-3 extension developed by NYU-Wireless and the University of Padova. In particular, we developed two simulation scenarios modeling the services under investigation, which are inspired by realistic deployments in the port of Hamburg, where the RoboVaaS project will be demonstrated. We considered different system configurations and parameters (see Table I), and derived the end-to-end communication performance in terms of throughput, latency and reliability by averaging over 20 independent simulation runs. We also considered the average Packet Delay Variation (PDV) [41], computed as $\sum_{N-1} |d_{i+1} - d_i|/(N-1)$, where d_i is the end-to-end delay of the i-th packet and N is the number of packets. This metric is used to evaluate the variation of packet delay, which has a strong impact on the QoS experienced by real time applications [42]. Indeed, a highly variable delay may distort the operator's perception of the system, making its control more challenging. In the following, we describe the simulation scenarios and comment the obtained results.

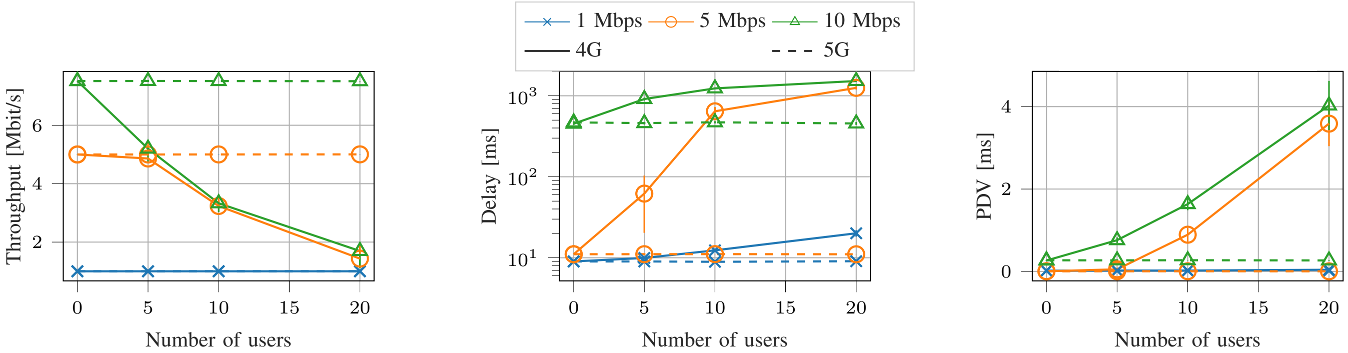


Fig. 3: Performance of the application used to upstream the video and sensor data captured by the vessels vs number of active users in the cruise ship. We considered different cellular deployments and different application source rates.

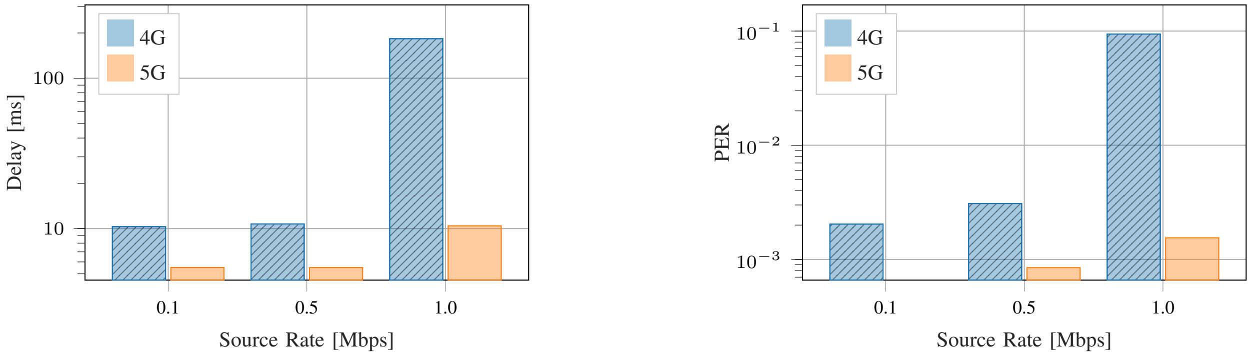


Fig. 4: Performance of the application used for the maneuvering of the vessels. We considered different cellular deployments and application source rates.

Quay Wall Inspection

The simulation scenario for the quay wall inspection service is depicted in Figure 2a. The ROV is assessing the status of the quay wall near a cruise terminal where a ship is docked. The ASV moves along the quay wall at a constant speed of 1 m/s and maintains the connectivity between the ROV and the shore control station. Both vessels are equipped with a streaming application to handle the UDP video streams for the operator view, and a controller which handles the joystick-like UDP streams for their maneuvering. At the same time, some passengers randomly move inside the cruise ship and use their mobile phone for video-chatting, thus generating a UDP data traffic of 500 kbps each. We evaluated the performance achieved by the applications installed in the vessels in presence of two different cellular configurations: (i) a legacy 4G deployment, in which a single LTE base station is used, and (ii) a 5G deployment, in which the LTE base station is used in conjunction with multiple mmWave small cells installed along the quayside. With the former configuration, both the vessels and the cruise ship passengers make use of the only available LTE connection. Instead, when the latter is used, the streams related to the inspection service are always carried over the LTE link, because more robust compared to the mmWave connection, while the traffic generated by the cruise passengers is offloaded to the small cells.

In Figure 3, we reported throughput, delay and PDV achieved by the streaming application in the presence of different numbers of active users in the cruise ship. We considered different source rates and compared the performance achieved when using either the LTE or the 5G deployments. It can be noticed that, with a source rate of 1 Mbps, both deployments are able to satisfy the offered traffic, thus limiting the experienced delay and the PDV. However, when considering higher source rates, the performance of the legacy solution is impacted by the presence of other active users, which reduces the amount of resources available for the RoboVaaS services, resulting in decreased throughput, increased delay, and higher PDV. Based on the application requirements listed in Section III-A1, when there are more than 20 active users, the system is not able to support both the required video streams simultaneously, thus preventing the monitoring of the ROV and ASV operations. Moreover, as demonstrated in [42], the operator's experience rapidly deteriorates with an increased delay variation, distorting the perception of the remote system when the PDV is larger than 2 ms. Instead, the presence of other active users does not affect the performance achieved over the 5G deployment, because their traffic is offloaded to the mmWave small cells. With a source rate of 10 Mbps, neither the 4G nor the 5G solutions are able to satisfy the offered traffic, even without any other active user, because of the limited capacity of the LTE link.

Figure 4 shows the average delay and Packet Error Rate (PER) achieved by the application used to maneuver the

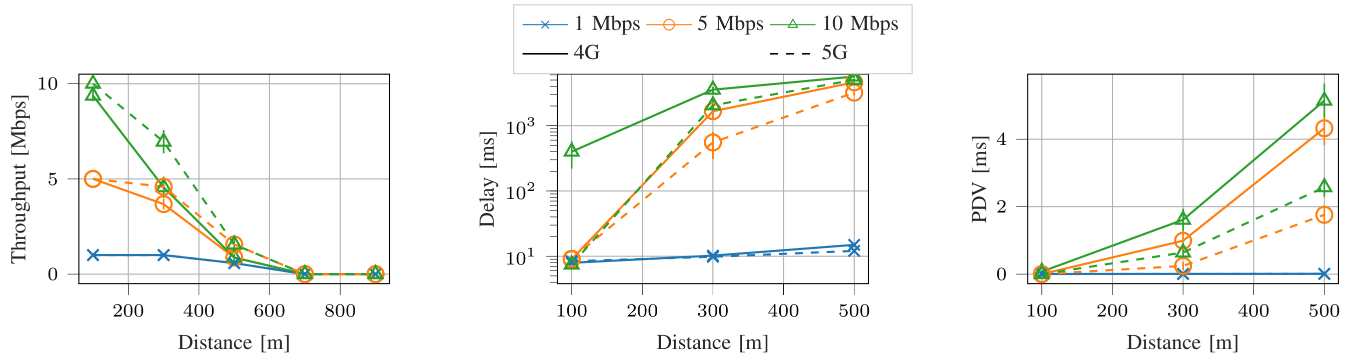


Fig. 5: Performance of the application used to upstream the video and sensor data captured by the vessels vs distance from the LTE base station. We cosidered different cellular deployment and application source rates.

unmanned vessels versus the source rate. Both the 4G and the 5G configurations are able to support the control streams needed to operate the ASV and the ROV, though with different performance in terms of delay and PER. Notably, the usage of the mmWave small cells significantly improves the performance, ensuring a delay lower than 11 ms and a packet loss below 0.15% even for the highest rate.

Ship hull inspection

Figure 2b represents the simulation scenario for the ship hull inspection service. A cargo ship is anchored in a dedicated area near the port, waiting for the permission to dock for loading and unloading operations. Meanwhile, the captain connects with the shore center and requires the port authorities to perform the inspection of the ship hull. The request is submitted to the RoboVaaS cloud, which accepts it and schedules a new task. Then, the ASV autonomously reaches the ship and deploys the ROV which starts the inspection of the hull.

The vessels are equipped with a controller handling the joystick-like UDP streams for their maneuvering, and a streaming application handling the UDP video streams and the stream for the SeaVision operational control. Additionally, a file transfer application manages the periodic upload of the 3D images captured by the SeaVision system. As for the quay wall scenario, we evaluated the application performance considering both 4G and 5G cellular deployments. In particular, the 4G deployment consists of a single LTE base station used to maintain the connection between the vessels and the shore control station. Instead, the 5G deployment includes the LTE base station and multiple mmWave small cells installed on the ship, providing the vessels with a secondary connection that can be exploited by means of DC. In this case, the streaming and maneuvering services make use of the LTE connection, while the SeaVision file transfer is offloaded to the small cells. We evaluated the performance achieved by the applications installed in the vessels in the presence of either the 4G or the 5G deployment. We considered different values for the distance between the ship and the LTE base station and for the source rates of the applications.

In Figure 5, we reported the average throughput, delay and PDV achieved by the streaming application. It can be seen that the system performance decreases with increased distance due to the higher propagation loss. The curves show a significant drop after 300 m and, when the ship is farther than 700 m from the base station, none of the solutions is able to support the streaming service. With a source rate of 1 Mbps, both the 4G and the 5G deployments provide similar performance, while with higher rates, the presence of an additional connection makes the latter perform better. Indeed, the secondary connection enables the possibility to offload the traffic generated by the file transfer application, which otherwise congests the primary LTE link, thus affecting the streaming performance. According to the requirements listed in Section III-A2, the 5G configuration is able to support the two video streams, as well as the stream for the SeaVision operational control needed by the application, up to a distance of 300 m, while the 4G solution has a more limited capacity.

Figure 6 shows the average throughput (left) and delay (right) achieved by the controller used for the maneuvering of the vessels. It can be noticed that both the 4G and the 5G solutions show similar performance and are able to satisfy the offered traffic up to 300 m. At higher distances instead, the harsher propagation conditions affects the achievable performance, decreasing the throughput and increasing the delay of both solutions.

In Figure 7, we represented the time needed to upload a 3D image captured by the SeaVision system. When using the 4G deployment, the image upload requires 7.8 to 13.4 s depending on the distance from the base station. When the 5G deployment is used, the upload is done via the secondary mmWave connection, and requires about 0.6 s. We notice that the upload process may represent the bottleneck in this scenario, because the ROV may have to wait for the transfer to be completed before capturing another image. Clearly, the better performance achieved by means of the DC architecture comes at the price of storing the images on the ship instead of uploading them to the RoboVaaS cloud. However, the acquired data could be transferred to the cloud once the inspection task is completed, for example by means of a point-to-point wireless link that can be established between the ship and the shore control station.

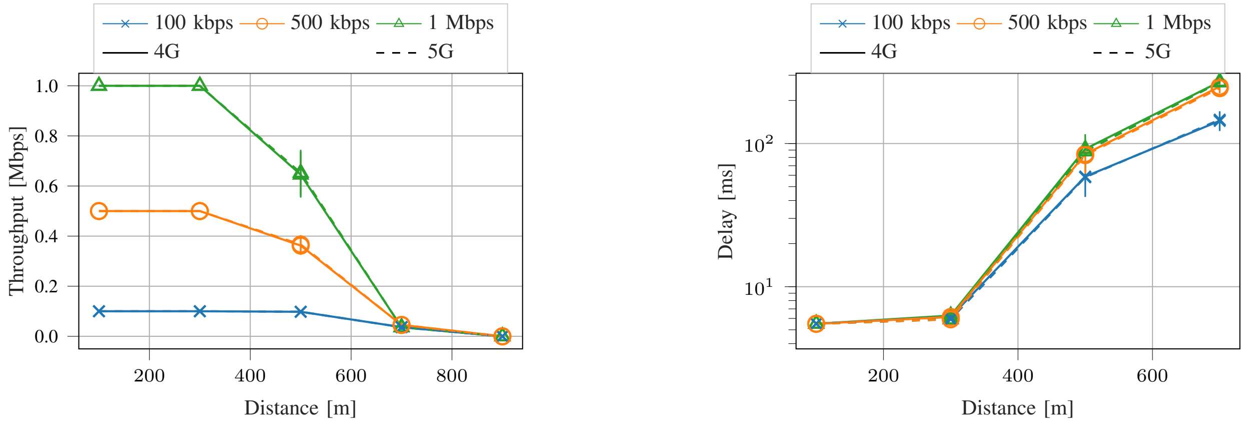


Fig. 6: Performance of the application used for the maneuvering of the vessels vs distance from the LTE base station. We considered different cellular deployments and application source rates.

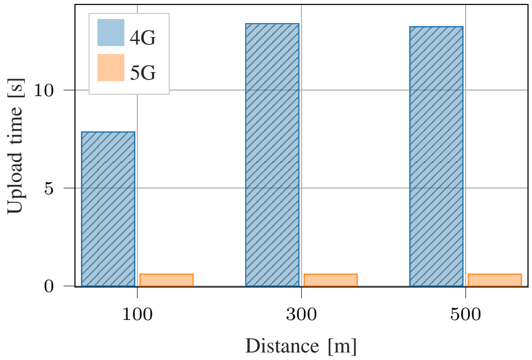


Fig. 7: Time to upload a 3D image captured by the SeaVision system.

V. CONCLUSIONS

In this paper we evaluated the feasibility of supporting the automated quay wall and ship hull inspection services by means of the port cellular infrastructure, considering both 4G and 5G deployments. In Section II, we described how quay wall and ship hull inspection services are currently accomplished, analyzing the main limitations of the current methodologies. In Section III, we outlined the RoboVaaS framework, investigated the communication requirements to ensure proper system performance, and reviewed the communication technologies that can be used in this context. Finally, in Section IV, we evaluated the system performance with different network configuration and parameters, considering both 4G and 5G cellular deployments. We plan to further improve this work by considering the usage of more advanced protocols for the real time streaming of video and sensor data, such as the one described in [43].

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