# On the feasibility of an Anti-grounding Service with Autonomous Surface Vessels


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***Abstract*—Grounding of ships is as of today one of the most common causes of maritime accidents. An effective anti-grounding service, where updated bathymetry data is sent in real time to a ship can improve maritime and human safety. The bathymetry data is collected by an autonomous surface vessel equipped with a multi-beam sonar while the ship is approaching the port. This data is then conveyed immediately to the ship, by employing a wireless communication link. In this paper, a study on the enabling technologies for an effective anti-grounding service is provided, with special focus on the wireless communication devices to employ for the real-time bathymetry data transmission.**



***Index Terms*—Anti-grounding, multi-beam sonar, LTE, LoRa, WiMAX, WiFi, V-SAT.**


## I. Introduction

Funded by the MarTERA consortium, the Robotic Vessels as-a-Service (RoboVaaS) project [1] aims at the design and the realization of on-demand robotic-aided services via small unmanned vessels (e.g., autonomous underwater vessels, AUVs, and autonomous surface vessels, ASVs) to revolutionize shipping and near-shore operations in what we imagine as the port of the future. Waterborne is, in fact, the largest international transport sector with 90% of transported goods as stated in [2]. The RoboVaaS vision includes interconnected UVs equipped with specialized sensor technology, a reliable data transfer cloud network for above- and underwater communication, a monitoring station, and a real-time web-based user interface. This disruptive concept has not only the potential to increase flexibility and accessibility of European waterways, and to reduce costs for a multitude of maritime stakeholders, but also to improve maritime and human safety. The high level of autonomy implied in RoboVaaS is expected to be reached by using autonomous vessels such as ASVs and AUVs, as shown in Fig. 1; however, some operations still involve human control through, e. g., remotely operated vehicles (ROVs). Within the high-level RoboVaaS vision, a number of services that have a positive impact on near-shore maritime operations have been identified, including: a ship hull inspection service, a quay walls inspection service, an environmental and bathymetry data collection service and an anti-grounding service, the last being the focus of this work.

Vessel groundings threaten maritime safety, accounting for about one-third of commercial ship accidents, second only to ship-on-ship collision [3]. Between 2011 and 2015, 1426 grounding accidents were reported for European Water [4] and 51 for the river Elbe of which almost 40% occurred in the port of Hamburg. Here, shallow riverbeds and tidal bore restrict the passage of large ships and recurring sedimentation requires frequent bottom mapping and dredging that involve expensive missions with manned vessels with a specialized crew able to operate high-tech equipment. In the RoboVaaS concept, the anti-grounding service will be provided with an ASV equipped with or towing a high-resolution sonar travelling ahead of the vessel (e.g., 20 minutes of navigation time ahead) and providing real-time high-quality bathymetry data to the ship's bridge in order to prevent groundings, see Fig. 2. In this paper we investigate the feasibility of the anti-grounding service from the communication network point of view. We overview the different technologies that enable the service, and for each one we discuss the quality of service provided and the costs to bear. Among the considered technologies we include radio point-to-point systems such as WiMax [5], [6], as well as satellite links [7]. We also include recent developments in long distance maritime communication that employs standard access technologies such as LTE and WiFi. Finally, we considered also the use of a long range low power wireless technology such as LoRa [8], to provide a backup alarm channel, to be used in case the primary communication

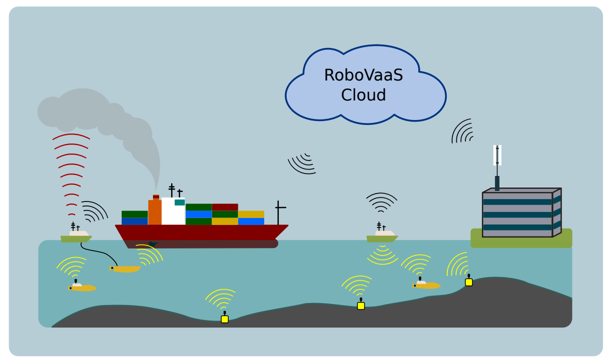


Fig. 1. RoboVaaS envisioned example scenario showing ship-hull inspection, anti-grounding and data collection services enabled through a fleet of ASVs and AUVs connected with acoustic underwater and radio communication.

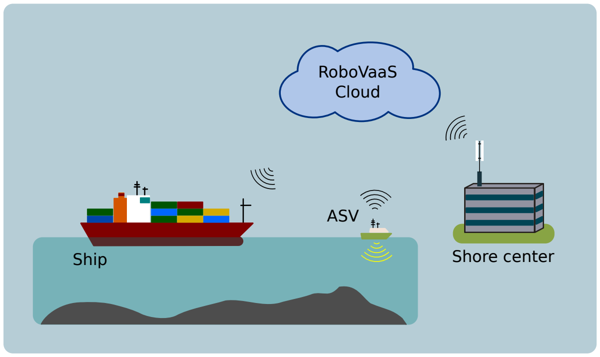


Fig. 2. RoboVaaS anti-grounding use case scenario.

channel fails. Our results are based on recently developed models for radio propagation over water surfaces [9], [10] and maritime oscillation models for the evaluation antenna alignment [11] and accurate network simulations, obtained with the NS3 [12] simulator.

The contribution of this paper is threefold. First, we analyze the requirements for an effective anti-grounding service, overviewing the enabling technologies to be employed, both from the sensors and from the communication perspective. Second, we present a study based on mathematical channel models, to assess the achievable quality of service for the considered wireless technologies, and identify the most suitable choice in different scenarios. Finally, through NS3 network simulations, we obtain some insights on the ASV mission design when employing a low power long range communication technology.

The rest of this paper is organized as follows: in Section II we present the anti-grounding service description, by providing some use case scenarios where this service can provide prominent benefits, in Section III we identify the technologies that should enable the feasibility of the anti-grounding service, with special focus on multi-beam sonar, ASVs and the communication technologies. The channel models used to simulate the wireless links during the anti-grounding test cases are detailed in Section IV, while the feasibility of the anti-grounding task is evaluated in Section V via simulations. Finally, in Section VI we present our concluding remarks.

## II. Anti-grounding service description

Safety of ships at sea is of paramount importance in the maritime field. The improvement of marine safety is always one of the targets for all the stakeholders involved. This is of even more concern in the case of ships carrying cargo harmful to the environment and/or ships carrying thousands of lives. Nevertheless, grounding is still one of the most frequent accidents [3]. Providing an anti-grounding service means being able to measure depth profiles ahead of a vessel in real-time, at service speeds and at a range of at least the stopping distance of the ship. Available commercial solutions are limited to different applications of forward looking sonars (FLS, e.g., [13], [14]). These methods are, however, highly inefficient and thus severely under utilized. Moreover, their life-cycle costs are unnecessarily high, and their general-purpose design degrades specific-purpose performance. The high frequency acoustic transducers utilized in forward looking sonars have a limited usable acoustic range which renders them incapable of detecting the seabed at the stopping distance of larger ships (e.g., a 191000 DWT tanker travelling at a speed of 10 knots takes up to 3 nautical miles to stop [15]). Finally, they are very expensive and require to be permanently mounted onto the vessel only to be used for the short period of time when approaching ports or carrying out other slow manoeuvres in shallow water.

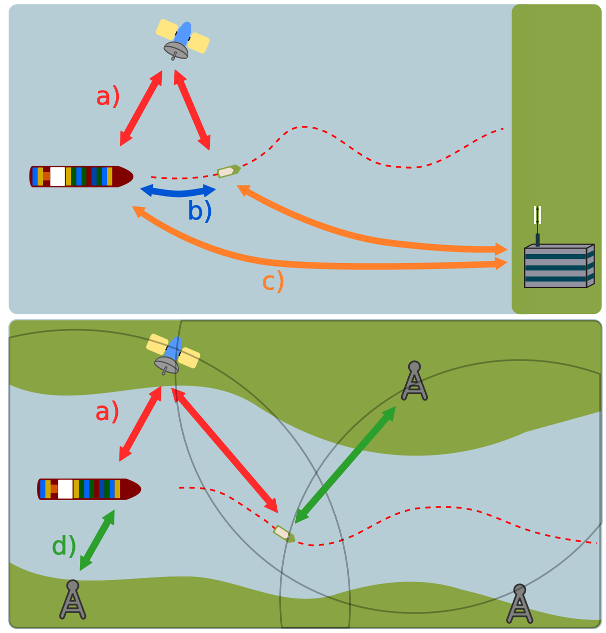


Fig. 3. Possible port approach and communication scenarios considered in the RoboVaaS anti-grounding service. Top figure: satellite link (a), direct link (b), long range two-hop link (c). Bottom figure: satellite link (a), terrestrial cellular network (d).

The on-demand anti-grounding service envisioned in RoboVaaS is meant to lower the operational and maintenance costs by transferring the sonar from the ship to an in-harbour autonomous surface vehicle. An ASV travelling ahead enables real-time under keel clearance data as far ahead as the stopping distance outperforming commercially available FLS system. Moreover, the performance trade-off of requiring balanced sonar performance in multiple different cluttered near-shore environments is removed. The anti-grounding service is thus envisioned to guarantee safe navigation in areas where bathymetry data are either not available (e.g., is some South American port areas) or outdated (e.g., in the case of the port of Hamburg because of frequent changes in the riverbed due to tidal bores and ship passages).

In order to cope with both an open water and a river approach, different scenarios should be considered, see Fig. 3. As shown in the top portion of Fig. 3, if a ship is approaching a sea port from open water, the communication infrastructure can only be placed on the ship, on the ASV, or on the shore.

In this scenario, different communication setups can be considered, namely:

a) **Satellite link**: where the communication is achieved using the Inmarsat (International Maritime Satellite Organization) system.
b) **Direct link**: where the communication between the ship and the ASV requires a direct Line Of Sight (LOS) link and can exploit technologies like 802.16, LTE or 802.11.
c) **Long range two-hop**: where the communication is achieved using a two-hop link going through a gateway equipped with a long range antenna on shore. In this setup, technologies such as LTE, 802.16, 802.11, but also a long range low power wireless technology such as LoRa, can be utilized.

The second scenario, bottom part of Fig. 3, considers a river approach to the port. Here the presence of the river banks and bends may prevent the existence of a LOS link between the ship and the ASV, but, in turn, may allow the presence of a cellular network infrastructure that can be exploited for communication. In this setup we identified the following possible solutions:

a) **Satellite link**: since the satellite communication only requires direct sky access, it is a viable solution also in this scenario.
d) **Terrestrial cellular network**: assuming that there exists a cellular network and that the network coverage is guaranteed along the whole navigation route, the cellular network can be used to provide the service.

Depending on the type of scenario, the communication technology used, the link quality, and the user needs, different service types can be envisioned. Sending the complete bathymetry data from the ASV to the ship bridge could be impossible in some situations, since the raw bathymetry signal from a multi-beam sonar needs fairly high bit rates, as will be detailed in Section III-A. In some scenarios, the data at the ASV could be reduced, either in space or in time, exploiting signal processing techniques and/or modulating the multi-beam sonar ping rate. As an extreme case, the ASV could send a single depth reading in each packet with the lowest value of the water depth. Finally, when the only available technology is low rate long range (e.g., LoRa), the bathymetry data should not be sent at all, but in its place some metadata (i.e., an alarm flag, time and position), should be computed and sent by the ASV. In any case, security measures must be put in place, and the ship should revert to standard protocol or be stopped in case the communication link fails for an extended period of time. An example of this will be given in Section V-C.

## III. Technology overview

In this section, we present the technologies that should enable the anti-grounding service by identifying the system requirements in terms of amount of traffic to be delivered from the ASV to the ship. Specifically, we calculate the amount of data generate by a multi-beam sonar to map an area with very high precision (Section III-A), we present which ASVs can perform the anti-grounding task in terms of speed, endurance and payload capacity (Section III-B), and we identify which communication technologies can be used to support the service (Section III-C).

### *A. Multi-beam Sonar*

A sonar system emits sound waves and measures the amount of time they take to bounce off the seabed and return to a receiver to determine the water depth. A multi-beam sonar employs an array of transmitters and an array of receivers to perform beamforming: in this way it can transmit directive sound waves and extract directional information from the returning signals, by mapping the seafloor with high accuracy. Each ping transmission produces a swath of depth readings, and therefore a big amount of data to process. For instance, the EM 2040 MKII Kongsberg multi-beam echosounder [16] provides an angular cover range up to 170 degree and a raw range resolution down to 10.5 mm for a depth up to 600 m. To achieve this accuracy, it transmits up to either 400 beams per ping in a single swath, or 800 beams in a dual swath, with a ping rate of up to 50 Hz. The overall maximum power consumption of the multi-beam sonar is 300 W. According to the Kongsberg XYZ datagram format [17], the processed data of a single ping with 400 beams requires 64.336 kbit. To obtain higher precision, the raw data can be processed on shore: this requires the raw range and angle datagram to be sent, for a total amount of 128.32 kbit per ping. With a ping rate of 50 Hz, the produced traffic is 3.22 Mbit/s for sending the XYZ datagrams, and 6.42 Mbit/s for the transmission of the raw data. The traffic can be reduced by using, for instance, a ping rate of 10 Hz: in this case the processed data would produce a traffic of 643.36 kbit/s, and the raw data a traffic of 1.28 Mbit/s.

### *B. Autonomous Surface Vessel*

An autonomous surface vehicle (ASV) is an unmanned vehicle that operates on the surface of the water. An ASV can either be directly piloted from a control station, or execute a pre-loaded mission. Different types of ASV can be used depending on the application requirements. Wave-powered vehicles, such as wave gliders, can be employed for long term deployment applications (more than 2 years), carrying, for instance, a meteorological instrument suite for environmental measurements. The NOC wave-glider is 2.9 m long and its battery is recharged with a 156 W photo-voltaic array [23]. It can be piloted via WiFi, cellular, or Iridium satellite, by patrolling an area of several thousand miles at a speed of two knots.

Fuel-powered very high speed ASVs reach more than 25 knots [24], and they are usually used for quick missions that last for few hours (less than half day) during a naval gunnery training. Their size is from 3 to 12 meters, and they are equipped with Ultra high frequency (UHF) communication capabilities, in order to perform quick and precise tasks within a range of 10 km from the control station.

TABLE I
COMMUNICATION TECHNOLOGIES COMPARISON.

| Technology | WiMAX (802.16-2012) | LTE | LoRa | 802.11 ac | V-SAT |
|---|---|---|---|---|---|
| **Frequency** | 6 GHz | 850-900 MHz [1] | 860-890 MHz | 5 GHz | 12 GHz [2] |
| **Bandwidth** | 5-20 MHz | 1.4 MHz | 125/250 kHz | 80-160 MHz | 0.5 GHz uplink, 1.85 GHz downlink |
| **Coverage** | up to 30 km | up to 30 km | up to 100 km | up to 5 km [3] | global |
| **Peak data rate** | 32.5 Mbit/s downlink, 14 Mbit/s uplink [4] | 6 Mbit/s | 5.4 kbit/s | 433 Mbit/s [5] | 5:10 Mbit/s downlink, 2:3 Mbit/s uplink |
| **Costs** | 0 USD/MB, 88 USD per antenna [18] | 0.01 USD/MB, 60 USD per antenna [19] | 0 USD/MB, 10 USD per antenna [20] | 0 USD/MB, 155 USD for a 120° antenna [21] | 19 USD/MB, 2000 USD per antenna [19] |

[1] Different frequencies with higher bandwidth are available: for the purpose of this paper we consider the one providing the longest range.
[2] Referred to Ku-band, as C-band requires a lange antenna ($\geq$ 1.2 m) compared to Ku-band (0.6 m) [22].
[3] Very directive antennas can reach a longer range, however they cannot be used in a scenario with mobile nodes.
[4] Rate for 5 MHz bandwidth, as it provides 6.5 bit/s/Hz in downlink and 2.8 bit/s/Hz in uplink.
[5] Can reach up to 1.69 Gbit/s, depending on antennas configuration.

ASVs used for up to seven day survey missions are usually diesel-powered. For instance, the C-Worker 5 [25] (5.5 m long) can reach a speed of 10 knots, has a payload capacity of 20 kg, and a payload power of 1 kW. Its missions can last up to 7 days when traveling at 7 knots, and it is equipped with radio communication capabilities, while other models of the same line are equipped with satellite communication as well. In this paper we refer to this last use-case type ASVs, as the C-Worker 5 has enough payload (1 kW) to supply the EM2040 multi-beam sonar, that has a power consumption of up to 300 W. This system, coupled with a high resolution single frequency civilian GPS [26] (that provides an accuracy of less than 1.9 meters 95% of the time), is the one considered to provide the anti-grounding service.

### C. Communication technologies

In recent years the growth of the maritime economy, with the introduction of new technologies in conventional industries and the development of new maritime activities such as oil exploitation, environmental monitoring and tourism, has led to an interest in developing maritime communication systems. Many new applications require high data rates and reliable wireless communication. Traditionally, maritime communication relied on satellite links and custom systems operating in the MF/HF/VHF bands that include the navigational telex (NAVTEX) system, the automatic identification system (AIS), and the under development VHF data exchange system (VDES) [27]. These systems, mainly adopted for tracking, vessel identification and security alerting, suffer from either low bandwidth or large propagation delays.

In the near future, it will be necessary to provide the users access to high-speed terrestrial mobile networks, thus providing also the quality of service needed to access on demand services such as those foreseen in RoboVaaS, at least for areas near the coast. Indeed, recently many research efforts and projects have been focusing on providing wide-area broadband coverage for offshore users with the aid of terrestrial base stations, utilizing different technologies, such as for WiFi [28], WiMAX [29] and LTE [30]. Projects such as the Nautical Ad-Hoc Network (NANET) [31], the TRI-media Telematic Oceanographic Network (TRITON) [32], the BLUECOM+ [33] and many others have been working on providing high speed data connections to ships and reliable inter-ship communication links.

The technologies considered in our analysis are presented in Table I. Satellite communication (V-SAT) is the most widely used technology in off-shore missions because it provides unlimited range, and can support the data rate required by the anti-grounding application (0.65 Mb/s), however its service cost is very high: the transmission of the multi-beam sonar traffic with a Ku-band antenna would cost 1.54 USD per second (5.5k USD per hour). Both WiMAX (802.16, release 2012) and WiFi (802.11 ac) support the multi-beam sonar traffic without any service cost, but they also require a dedicated deployment to be maintained. LTE, on the other hand, can exploit the existing cellular network to support the anti-grounding service at a low service cost (2.93 USD per hour), however, in case of no cellular coverage, an ad hoc deployment might not be affordable (the price of an LTE core starts from 300k USD, plus the cost of the bandwidth licence). We also consider a LoRa backup link, that provides very long range communication with no service costs. LoRa is a low bitrate technology and cannot support the multi-beam sonar traffic, but can be used for transmitting status and alarm messages in case none of the broadband links described above are available.

## IV. CHANNEL MODELS

The design of an appropriate channel model is essential for the study of efficient maritime communication systems. The modeling of near-sea-surface wireless channels (i.e., the links in ship-to-shore and ship-to-ship communications) has been recently targeted by researchers, that have conducted several studies and measurement campaigns to characterize it. The interested bands mainly focus on the unlicensed spectrum around 2.4 GHz and 5.2/5.8 GHz used by the most adopted communication technologies. Many literature works studied the near-sea-surface channels from different perspectives, building path

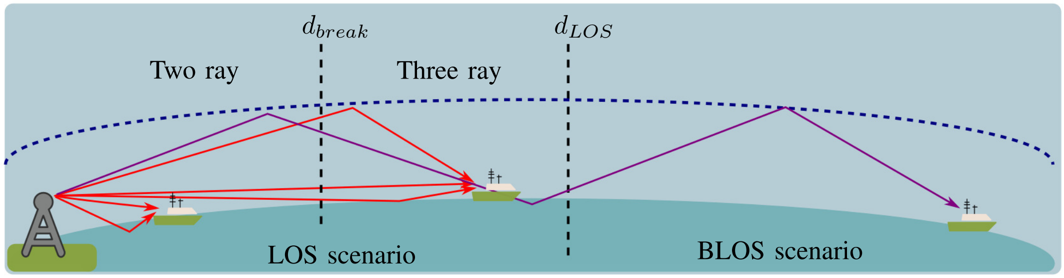


Fig. 4. Near-sea-surface propagation model.

loss models and investigating geometry-based stochastic models (GBSM) under two-ray and three-ray assumptions [34]; considering the small-scale fading characteristics, measuring and modeling the near-sea-surface duct channel [35].

The maritime communication environment, and the propagation of wireless signal over a water surface, have some important features which substantially affect the channel statistics and the channel modeling [9]. Specifically, sparsity, instability and the evaporation ducting phenomenon are the most noticeable.

Sparsity refers both to the sparsity of scattering objects in the communication environment, and to the spatial sparsity of users. The Rayleigh fading model, commonly assumed in the modeling and analysis of terrestrial communication systems is in general no longer suitable in most maritime environments, where the Line-Of-Sight (LOS) path component will dominate the link, and a reflection path from the sea surface exists in some conditions. Considering these two paths, a two-ray channel model is a good approximation up to a certain distance $d_{\text{break}} = 4h_r h_t/\lambda$, after which the two rays always interfere destructively. In this case the path loss in dB is given by:

$$L(h_t, h_r, d) = -10\log_{10}\left(\left(\frac{\lambda}{4\pi d}\right)^2\left(2\sin\left(\frac{2\pi h_t h_r}{\lambda d}\right)\right)^2\right), \tag{1}$$

where $\lambda$ is the wavelength, $h_t$ and $h_r$ are the transmitting and receiving antenna heights and $d$ is the distance.

Instability is a characteristic due mainly to the sea waves movement, and causes variability in the received signal strength. Studies have shown that the variation of antenna height and orientation can strongly influence the received signal strength [36]. The Pierson-Moskowitz sea state table classifies the sea state into 10 levels from calm to rough. With fierce sea wave movement, the incoming radio signal encounters more scattering and reflections due to the rough sea conditions. In this case, the simplified two-ray model has to be modified to account for the variation of the sea surface height when calculating the amplitude of the main reflection path, and for the multiple scattered components stemming from irregular sea surface.

Lastly, it is important to consider the atmospheric ducting effect caused by the change in refractivity at different heights of the atmosphere, which is caused by the change of pressure, temperature and humidity. The evaporation duct, caused by water evaporation over the sea surface, is commonly considered in maritime communications thanks to its ability of providing Beyond-Line-Of-Sight (BLOS) transmission. More importantly, the evaporation duct has appropriate appearance height (around 10m-20m, at most 40m) and high appearance probability (90% of the time in the equatorial and tropical areas). As illustrated in Fig. 4, part of the electromagnetic waves emitted in certain directions will be "trapped" between the sea surface and the evaporation duct layer. Empirical results have shown that this effect is noticeable at a distance $d > d_{\text{break}}$ and up to $d_{\text{LOS}} = \sqrt{h_t^2 + 2h_t R} + \sqrt{h_r^2 + 2h_r R}$ (with $R$ being the Earth radius), where the following three ray model becomes a good approximation for the path loss:

$$L(h_t, h_r, h_e, d) = -10\log_{10}\left(\left(\frac{\lambda}{4\pi d}\right)^2 (2(1+\Delta))^2\right), \tag{2}$$

where, $\Delta = 2\sin\left(\frac{2\pi h_t h_r}{\lambda d}\right)\sin\left(\frac{2\pi(h_e - h_t)(h_e - h_r)}{\lambda d}\right)$ and $h_e$ is the evaporation duct height. In Section V, for the near-sea-surface LOS transmission, the received signal strength is evaluated utilizing the two-ray path loss model in the range of $(0, d_{\text{break}})$, and the three-ray model in the range of $(d_{\text{break}}, d_{\text{LOS}})$.

## V. Numerical Results

In this section we present some numerical results obtained in different scenarios. Specifically, in Section V-A, we exploit the channel model of Section IV to evaluate the maximum communication distance when the considered technologies are employed in a long range two hops scenario. In Section V-B we discuss the direct link between ship and ASV, and in Section V-C we present a network simulation where we analyzed the impact of interference on a backup LoRa alarm link.

### A. Open sea range evaluation

We considered a setup where a ship is approaching a port from the open sea and an ASV travelling ahead is providing the anti-grounding service through a two-hop communication link. Independently from the communication technology, the antennas on the ship and on the ASV are assumed to be at a height of 10 m and 2 m respectively, while the antenna on

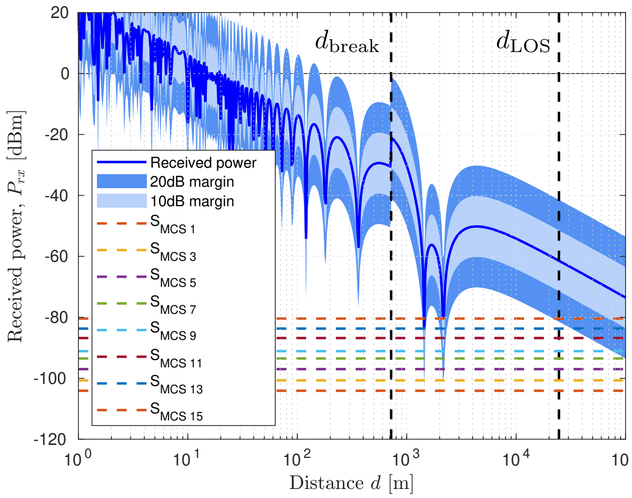


Fig. 5. LTE received power vs distance.

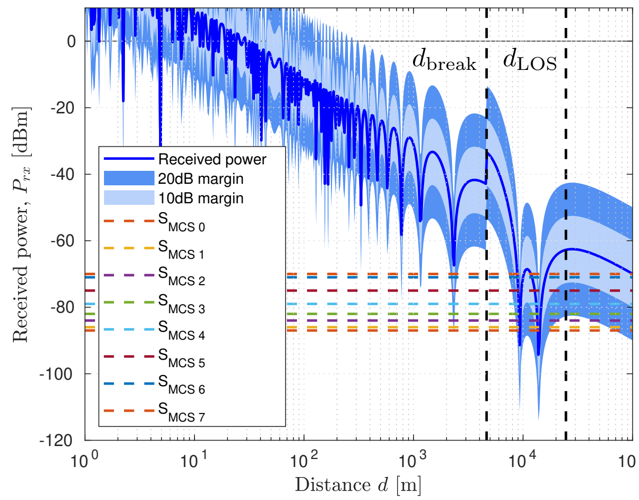


Fig. 6. Wimax received power vs distance.

shore is assumed to be at 30 m (i.e., to reach a sufficient LOS distance). We considered the presence of an evaporation duct with a height of 10 m. Moreover, we assumed that the communication equipment on shore can have a fairly high antenna gain, while the antennas on the ship and on the ASV must be omni-directional. To evaluate the maximum distance at which each technology can support the anti-grounding service, we show the received power versus the communication distance. In our results we always show the worst performing link (i.e., the link between the ASV and shore, since the transmission power is lower, and the antenna configuration is less favorable). We included a 10 dB and a 20 dB margin on the received power to account for any variation in received power due to sea conditions, see Section IV.

Figure 5 shows the performance of an LTE link in the 900 MHz band, with a bandwidth of 10 MHz, and a transmission power of 24 dBm. The two vertical dashed lines show the value of $d_{\text{break}}$ and $d_{\text{LOS}}$, while the horizontal dashed lines show the receiver sensitivity in dBm for different possible modulations and coding schemes ($S_{MCSi}$) in LTE. The plot shows how, according to the two-ray/three-ray channel model, communication can be achieved up to the Line-Of-Sight distance even with high MCSs, thus high data rates (10-30 Mbps). The received power gap at $d_{\text{break}}$ is caused by the change from the two-ray to the three-ray model.

Figure 6 shows the results for a 5.8 GHz 802.16 link, using a 20 MHz channel, a transmission power of 23 dBm, and different MCSs. In this case, we can notice that the service is supported up to the LOS distance, but there are some deep nulls in the received power when the distance is greater than 8 kilometers that may render the service unstable. For distances smaller that 8 km, in this configuration the achievable data rate can be as high as 54 Mbps.

In Figure 7 we show the received power for an 802.11ac communication link, using a 20 MHz channel in the 5 GHz band, and a transmission power of 20 dBm. With the considered setup, the received power starts to drop under the sensitivity threshold for some value of $d$. The service can however be supported up to a distance of roughly 6 km using the lowest setting for the MCS (i.e., MCS 0 with a data rate of 6.5 Mbps).

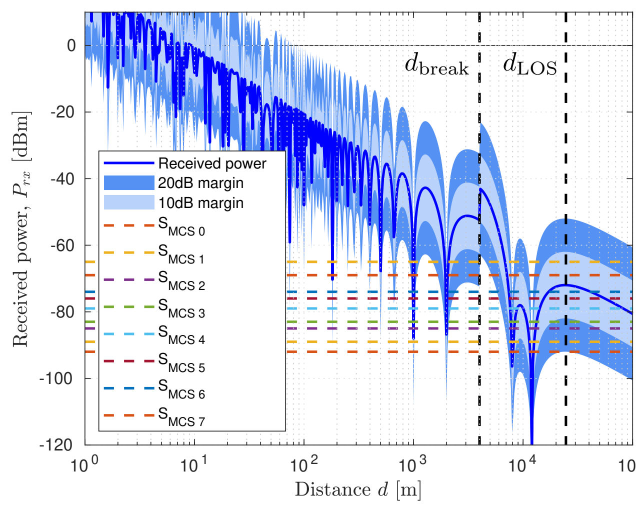


Fig. 7. Wifi received power vs distance.

Finally, in Figure 8 we show the received power versus the communication distance for a link using LoRa transceivers. LoRa has been recently shown to offer a communication range of over 15 kilometers on ground and close to 30 km on water [37] in real tests. We considered the 868 MHz EU frequency band, with a channel of 125 kHz, and a transmission power of 17 dBm. The results show that the service is supported for all values of the spreading factor, up to the LOS distance. The achievable data rate is however very low (i.e., at most 5.4 kbps in our configuration), due to the constraints of the LoRa physical layer. In addition, with the limitation on the duty cycle, the only service that can be supported with Lora is a backup alarm service.

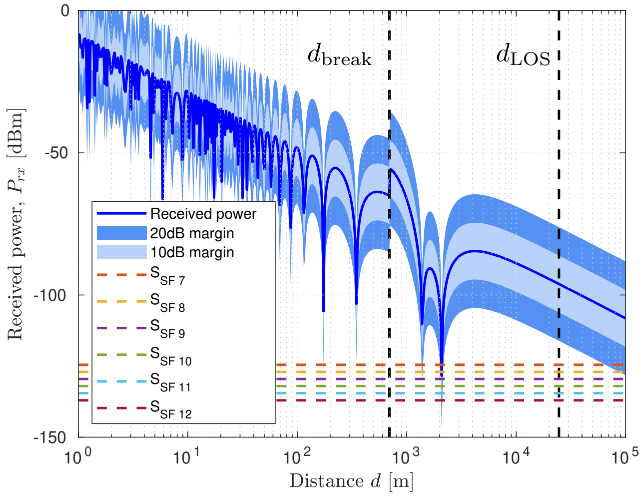


Fig. 8. LoRa received power vs distance.

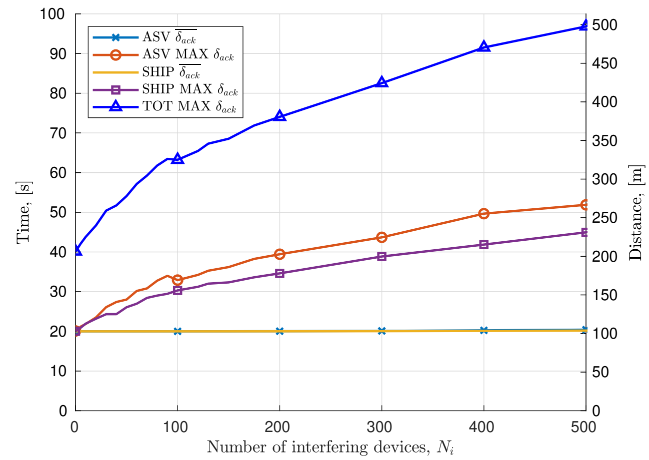


Fig. 9. Quality of service vs interference in LoRa.

The results suggest that the two-hop anti-grounding service could be supported using an LTE link, the only limitation is the Line-Of-Sight distance, that however could be increased, increasing the shore antenna height (e.g., with a height of 50 m the LOS distance increases to approximately 30 km) or using an offshore relay node such as a helium balloon [33].

### *B. Direct link scenario*

The direct link scenario (i.e., scenario b) in Figure 3), can be discussed from the results in Figures 5, 6, 7, 8. The distance at which the service should be supported in this scenario is given by the stopping distance of the ship, that can be up to 3 nautical miles (∼5.5 km) for very large tankers. At this distance the communication link is stable and the service can be supported by all the considered technologies, with 802.11 and 802.16 being the most suitable ones, thanks to their high availability and the low costs of devices. This scenario however entails other challenging design problems, e.g., how the service request should be sent to shore for the ASV dispatch, and how to perform the initial handshake between the ship and the ASV, that are left as future work.

### *C. LoRa scenario simulation*

In this last simulation scenario a ship requiring the anti-grounding service is approaching the port from the open sea. The anti-grounding task starts when the ship is 40 km from the port, and is performed by an ASV placed 3 nautical miles ahead of the ship. Both the ASV and the ship move at a speed of 10 knots. The ASV communicates with the ship by employing the LoRa network: both ASV and ship are LoRa nodes, while a LoRa gateway is deployed in the port. In the port area, a set of LoRa nodes are deployed for other port services: such nodes are uniformly distributed in a circular area with radius 1 km, and transmit data packets with 96 bits of payload every 5 minutes. The spreading factor of each node is randomly selected between 7 and 12. These nodes act as interfering devices: the anti-grounding service performance is evaluated by varying the number of interfering nodes $N_i$ between 0 and 500. All the simulations have been performed by using the LoRa extension for the NS3 simulator [38], averaging over 100 simulation runs with different random seeds.

In our simulation the ASV sends packets containing meta-data about position, time and alarm status to the gateway on shore as frequently as the duty cycle limitations on the 868 MHz band allows (we set 20 seconds as the minimum inter-packet interval), asking for a confirmation (ACK). The LoRa node on the ship sends dummy packets (packets with no payload) as frequently as possible as well, only to trigger the transmission of downlink data from shore to the ship. In fact, in the LoRaWAN media access control scheme, downlink data transmission can happen only if piggybacked in ACK packets after an uplink transmission [8]. These downlink transmissions carry the alarm status for the anti-grounding service to the ship's bridge. Figure 9 shows the average and the maximum inter arrival time for ACK packets ($\delta_{ack}$) for both the ASV and the ship communication links, when varying the interference level. This performance metric is related to the refresh rate of the information at the gateway and at the ship's bridge, and thus to the quality of service for the alarm signal propagation. As the graph shows, when the number of interfering devices grow the average inter arrival time remains constant, whereas the maximum values increase for both links as some uplink transmissions are lost due to the interference. On the right hand side y axis in Figure 9, we reported the distance travelled at 10 knots for the corresponding time indicated on the left side axis. In fact, considering the worst case scenario, an alarm could take up to TOT MAX $\delta_{ack}$ (solid blue curve in Figure 9) to be propagated to the ship. In this time interval the ship would have travelled up to 500 meters and would no longer have the necessary space to stop before the collision with the detected obstacle. Therefore this additional distance has to be considered during the service design. Moreover the ship should stop in any case if no new information is received within a maximum time interval, to be sized according to the scenario.

## VI. Conclusion

In this paper we analyzed the feasibility of the RoboVaas anti-grounding service, where an ASV, travelling ahead of a ship approaching a port area, maps the seabed. Our preliminary study reveals that the transmission of the complete real-time bathymetry data can be performed with an LTE communication link, when the ship is up to 25 km from shore. Wimax and WiFi instead are good options for a direct link scenario. Satellite communication can also support the service without coverage limit, but at a very high price per MB transmitted. Finally, although a LoRa backup channel cannot be employed to transmit the full bathymetry data, it can effectively transmit status and alarm messages whenever under keel clearance is not assured. In this case, we showed that in order to compensate for the delay in the propagation of the alarm signal caused by the LoRa network, an additional guard distance should be allowed between the ASV and the ship.

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