Collaboration of LoRaWAN and Underwater Acoustic Communications in Sensor Data Collection Applications

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***Abstract*—The Robotic Vessels as-a-Service (RoboVaaS) project aims to provide innovative services in a harbor scenario, exploiting new technologies to enhance different aspects of harbor activities. In this paper we analyze the data collection service from underwater sensor nodes. Specifically, we assess the End-To-End (E2E) communication, from sensor nodes deployed in the harbor to the gateway placed on the shore. The sensor data is collected by an autonomous underwater vehicle (AUV), and then forwarded to one or more surface buoys. Finally, the buoys convey the received data to the shore. Communication from the underwater sensors to the AUV and from the AUV to the surface buoys is performed through acoustic links, while the communication from the surface buoys to the shore gateway is performed via LoRaWAN. In this scenario we evaluate the performance of the E2E communication, by simulating both the underwater and the above water network.**

***Index Terms*—Underwater acoustic networks, polling protocol, LoRaWan, DESERT Underwater, ns-3.**

I. Introduction and state of the art

Waterborne handles about 90% of goods transportation [1]. New technologies can enhance the shipping activities in a port environment, to pursue both a cost reduction and improvements in safety of human operators and equipment. The goal of the Robotic Vessels as-a-Service (RoboVaaS) project [2] is to provide innovative services in a port scenario. Specifically, the project aims to exploit the most innovative communication technologies and advanced robotic vehicles to improve shipping operations, offering on-demand and robotic-aided services. To enhance harbor activities, inspection services for quay walls and ship hulls, anti-grounding service, bathymetry and environmental data collection have been included in the RoboVaaS vision.

In this paper we focus on the environmental data collection service, and perform an end-to-end evaluation of this communications system. Specifically, we will asses the performance of the whole communications pipeline, depicted in Figure 1, from the underwater sensor nodes generating the data to the collecting and monitoring station on the shore. In this scenario, an Autonomous Underwater Vehicle (AUV) retrieving data from underwater sensor nodes deployed in the harbor acts as a mule, forwarding all the collected data to surface buoys deployed along the network. These surface nodes, acting as sink for the underwater network, are equipped with two different communication interfaces, the first one being an underwater modem employed to gather packets from the AUV, and the second one used to send the received data to shore via radio.

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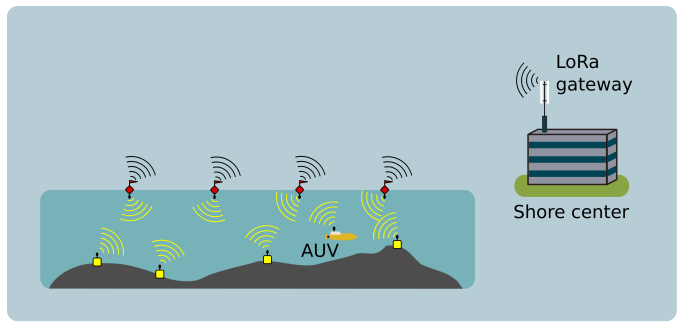

Fig. 1. RoboVaaS environmental data collection scenario: an AUV collects data from static underwater sensor nodes, and forwards the data to surface buoys connected to shore via LoRaWAN.

Acoustic communication is employed for data gathering from underwater sensor nodes. Acoustic technology has reached a considerable level of maturity: the transmission range can vary from hundreds of meters to tens of kilometers, depending on the frequency being used, and the bitrate can range from few bit/s to tens of kbit/s [3]. In an underwater scenario different technologies, such as Radio-Frequency (RF) or optical, are also available for communication; nevertheless, these technologies are not suitable for our scenario. Indeed, RF communications are strongly attenuated in the underwater environment and are only suitable for very short range, up to few meters [4], [5]. Optical transmission can reach high transmission bitrate (in the order of Mbit/s), but within a range of few tens of meters [6], [7]. Moreover, optical technologies suffer from misalignment between transmitter and receiver, and the maximum transmission range is strongly affected by external light sources, such as the sun; hence, their usage is more appropriate for deep and dark water, rather than shallow water (as in the case of our port environment) [8]. Although acoustic communications are the most suitable technology for the data collection service scenario, their usage still faces many challenges, such as the low propagation speed of acoustic waves (1500 m/s, on average), multipath propagation due to the reflections with the bottom and the surface, and the high delay spread [3], [9]. A proper MAC design is needed to mitigate these issues: for the data muling scenario we use a polling based MAC protocol (UW-POLLING), originally presented in [10] and further improved in [11]. The protocol works in two subsequent phases, the discovery phase and the polling phase: the former is used by the AUV to probe the channel and find out how many sensor nodes and sink nodes are in its communication range, while the latter is used to collect the data from sensor nodes and forward it to sink nodes connected to shore via RF.

The communication between surface nodes and the shore can be obtained using different RF technologies, from satellite to cellular networks, such as LTE [12], [13], each with different available bandwidth, coverage and cost [14]. Specifically, satellite communication is the most widely used technology in off-shore missions because it provides unlimited range, however its service cost is very high (e.g., the price of a V-SAT antenna is about 2000 €, with a service cost of 19 € per Megabyte) and does not suit well an IoT application. LTE, on the other hand, can provide a broadband link up to a range of 30 km in an open-sea scenario, at a lower price (an antenna price of less than 60 €, and a service cost of about 0.01 € per Megabyte). However, it requires the presence of an existing LTE cellular deployment: in case of no cellular coverage, an ad hoc deployment is not affordable for an IoT application, as the price of an LTE core starts from 300 k€, plus the cost of the bandwidth licence.

In our work we employ LoRaWAN [15], a Low Power Wide Area Network (LPWAN) technology [14], that seems particularly well suited for the application in this scenario: this kind of network operates in sub-GHz unlicensed bands, and has a transmission range in the order of kilometers, making it a very cost-effective solution, and enabling the communication between the shore gateway and the surface buoys deployed up to tens of kilometers away from the coast. The price of a LoRaWAN deployment is indeed very low, as one antenna costs less than 10 €, and the price of a LoRaWAN gateway is less than 100 €. It should be noted that these benefits come at the price of a low throughput and no delay guarantees, which however are usually not critical for sensor data collection applications.

To evaluate the performance of our system we use two different simulation tools for the underwater and above-water parts. In particular, the DESERT Underwater Network Simulator [16] is used to simulate data collection from the underwater sensor nodes, while a `lorawan` module for ns-3 [17], [18] is employed to analyze the behavior of the above-water network. The two simulators are connected by feeding the output of the DESERT simulator as the input for the ns-3 simulator: in such a way, we are able to track the arrival of the packets at the sink nodes and use this information to simulate the transmission of these packets to shore through the LoRaWAN network. In addition, we also implement in the ns-3 simulator the near-sea-surface propagation model presented in [14], which takes into account the characteristics of RF communications in a marine environment, such as the evaporation duct effect. This channel model allows us to simulate a scenario in which LoRaWAN nodes are deployed few kilometers in front of the harbor.

The goal of our work is to assess whether LoRaWAN is an enabling technology for the data collection service. In order to accomplish this, in this paper we analyze the performance of the network when using acoustic modems with different capabilities, a variable number of sink nodes, and data generation frequencies, with the aim of locating possible bottlenecks in the mixed acoustic and LoRaWAN network.

Previous works, such as [11], [19], only focused on the underwater communication part; in this work, instead, we also take into account that data needs to be forwarded above the water. Specifically, in this paper we assess the performance of the end-to-end communication system, analyzing the trade-offs involved in using LoRaWAN as an enabling technology for the data muling scenario.

The rest of this paper is organized as follows: Section II presents the data collection service for both the underwater and above-water parts, Section III describes the simulation scenario and parameters, Section IV shows the results obtained via simulations, and Section V draws some conclusions.

II. End-to-end data collection service

In this section we describe the protocols and the technologies used for the end-to-end data collection service.

A. Underwater data collection

For the data gathering from underwater sensors we employed a polling-based MAC protocol; specifically, we used the UW-POLLING protocol originally presented in [11]. The protocol defines three different types of nodes: sensors, AUVs and sink nodes. The AUV acts as a mule, moving along a predefined path, collecting data from sensor nodes and forwarding them to the sink nodes. The AUV is the master node of the network, since it decides when and from which nodes to collect the data. UW-POLLING works in two subsequent phases: first, an initial discovery phase is used by the AUV to find the surrounding sensor nodes, while a subsequent polling phase is employed to collect the data and to forward them to the sink nodes, if any.

The discovery phase starts when the AUV sends a TRIGGER packet (TrP) to reveal itself to the sensor nodes. Each sensor node or sink node that correctly receives the TrP and has data to transmit replies with a PROBE packet (PrP). The PrP is sent after a random backoff T_b, uniformly chosen between a minimum $T_{b_{min}}$ and a maximum $T_{b_{Max}}$ value. Values for $T_{b_{min}}$ and $T_{b_{Max}}$ are defined in the TrP: in particular, $T_{b_{Max}}$ is set by the AUV based on the estimated node density; more details about the node density estimation can be found in [11].

After the TrP transmission, the AUV waits for the reception of the PrPs from the other nodes. The discovery phase ends when either the maximum number of PrPs is received by the AUV or a timeout expires. At the end of the discovery phase, the polling phase begins, and the AUV decides in which order to poll the nodes that have sent back a PrP. The order is chosen according to a proportional fair scheduling algorithm, which aims to obtain a trade-off between fairness among nodes and the overall number of packets transmitted in the network. The idea is to obtain fairness by giving higher priority to the nodes from which the AUV has received fewer packets and, at the same time, not penalizing the throughput performance by increasing the priority of sensors that have more data packets to transmit (this information is available to the AUV since each node inserts in the PrP the number of packets that it needs to send). The AUV stores the order of the nodes that sent back a PrP into the poll list. The sink node is inserted in the list in the first position such that the sum of the packets in the AUV queue and the number of expected packets from the previous nodes in the list is greater than the maximum number of packets the AUV can transmit to the sink node in a round. Once the poll list is created, the AUV starts to poll all the nodes in the list one by one. The AUV transmits a POLL packet (PoP) to the first node in the list, and waits for the reception of the data packets. Once either all the expected packets are received or a timeout expires, the AUV proceeds through the list sending another PoP to the next node; a timeout is needed to avoid the protocol getting stuck in case of any packet loss. If the node in the list is a sink node, the AUV directly sends to it the data packets collected from the sensor nodes up to that moment. The number of packets the AUV can transmit in one round is limited, to avoid the AUV occupying the channel for too long, preventing the collection of data packets from the other sensors. Once all the nodes in the list have been served the polling phase ends, and a new discovery phase starts with a TrP. A detailed description of the UW-POLLING protocol can be found in [11].

B. LoRaWAN data forwarding

Packets collected by the underwater interface of sink nodes are forwarded via radio to the shore through LoRaWAN, an LPWAN technology that operates on top of the LoRa modulation, a Chirp Spread Spectrum (CSS) technique that allows to trade bitrate for range. This trade-off is parameterized through the Spreading Factor (SF) setting, which can take values between 7 and 12, with higher values achieving longer ranges (up to several km in urban scenarios) and lower values sacrificing range for throughput. At the MAC layer, the LoRaWAN standard defines three main entities that operate in a network: End Devices (EDs) are defined as typically low power devices, that collect data and send it to one or more Gateways (GWs), equipped with chips that enable them to listen to multiple frequencies simultaneously, lock on multiple packets in parallel, and correctly demodulate packets overlapping in time, provided that some conditions on the employed Spreading Factor and reception power are respected [18]. GWs, in turn, are typically connected through a fast and reliable connection to a Network Server (NS), which is tasked with de-duplicating packets and controlling the network configuration.

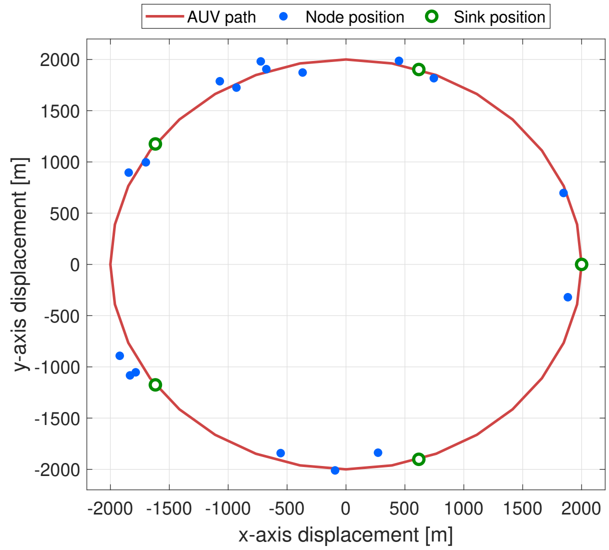

Fig. 2. Scenario example with 5 sink nodes

III. Scenario Description and Simulation Setup

In our scenario the underwater network is composed of an AUV that patrols an area collecting data from underwater sensor nodes. The AUV forwards the collected packets to the surface nodes equipped with a LoRaWAN interface, used to relay the data to the LoRaWAN gateway placed on the shore. We assess the performance varying the number of sink nodes N_s used in the network. In addition, a set of LoRaWAN nodes is placed on the shore, in order to take into account the possible presence of a parallel LoRaWAN deployment operating as part of the port infrastructure, and creating interference at the gateway. These devices generate one 12-byte packet once every 5 minutes, as was assumed in [14].

We assess the end-to-end performance with 3 different network configurations, analyzing whether the bottleneck is the underwater acoustic network or the LoRa network. In the first configuration, the commercial EvoLogics S2C HS [20] acoustic modem is used for all the underwater nodes. This modem is a high-performance commercial off the shelf acoustic modem, which provides a nominal bitrate up to 62.5 kbit/s with a bandwidth of 60 kHz around a central frequency of 150 kHz and a transmission power equal to 156 dB re 1μPa. As the bitrate varies depending on the scenario, and differs from the actual datarate due to the error correction code used by the modem, in our simulations we set the S2C HS datarate to 7 kbit/s. Indeed, we consider shallow water transmissions in a river port with mobile nodes, that is quite a challenging scenario for acoustic communications. The packet error rate of this modem is modeled according to [3], as we have no field measurements for this specific modem.

In the second configuration the AHOI modem [21] is used for all the underwater nodes. The AHOI modem is a prototype developed by the Technical University of Hamburg, with a transmission rate of 200 bit/s (potentially, a higher transmission rate is feasible in good conditions) and an extremely low cost (about 400€). This modem transmits at a frequency of 62.5 kHz with a bandwidth of 25 kHz and a transmit power equal to 156 dB re 1μPa. The model used for the AHOI modem is based on field measurements in very shallow water, whose integration into the DESERT Underwater simulation framework has been presented in [11].

The last configuration consists of a multimodal setting and considers the use of both modems described above. Specifically, the AHOI modems are employed for the communication between the AUV and the sensor nodes, while the S2C HS modems are used for the communication between the AUV and the sink nodes. The AUV is therefore equipped with both devices, while the sink nodes are equipped only with S2C HS, and the sensor nodes with the AHOI modem. In addition, the packet length in case AHOI modem is used is equal $L_{AHOI} = 24$ Byte, in order to limit the signal duration and, therefore, the Doppler effect [21]. With the S2C configuration, the packet length is limited by the maximum packet size allowed by the LoRaWAN standard, equal to $L_{S2C} = 220$ Byte.

The AUV moves at a constant speed of 2 m/s in a circular path of radius 2 km performing 10 laps. The nodes are randomly placed in an area 300 m wide around the AUV path according to a Poisson Point Process (PPP) with an average node density $\lambda = 5$ nodes/km^2. The sink nodes are equally spaced and placed along the AUV path. An example of the deployment with $N_s = 5$ sink nodes is depicted in Figure 2.

As soon as a packet is received by the underwater interface of a buoy node, it is directly forwarded to a LoRaWAN ED, which in turn transmits it to a GW placed on the shore using the LoRa modulation. Since we consider a European deployment of the LoRaWAN network, EDs have at their disposal three separate channels for uplink communication (at 868.1, 868.3 and 868.5 MHz), and randomly pick one for each transmission. Since the three frequencies are all placed inside the same regulatory sub-band, transmissions must respect a duty cycle of 1%: after each transmission of duration T seconds, a silent period of $99T$ seconds must be respected by the devices. Because of this limitation, data cannot typically be forwarded to the shore as soon as they are collected by a sink node but needs to be buffered until the next duty cycle, thus an additional delay will be experienced by the packets. On the shore, we assume the presence of a harbor deployment of a LoRaWAN network, creating additional interference and entailing the presence of a GW that will receive the packets forwarded by the surface buoys. In our application, we assume that all LoRaWAN nodes are using a Spreading Factor setting of 7 and a bandwidth of 125 kHz, thus employing the fastest available transmission rate that allows the usage of three separate channels for the uplink. Furthermore, we assume the presence of no confirmed traffic in the network, whose effect has been proven to be detrimental to the network performance if not carefully used [18].

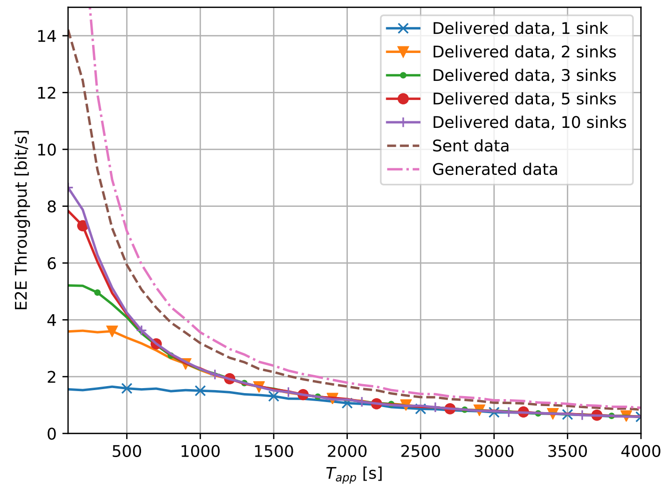

Fig. 3. E2E throughput of the network with only AHOI modems. The throughput has been analyzed for different numbers of sink nodes.

A. Channel model

To better characterize the communication performance in our scenario, the channel model for above-water communications, presented in [14], has been implemented in the ns-3 simulator. Indeed, in a marine environment such as the one studied in this paper, the Rayleigh fading model is no longer suitable, mainly because, as a result of the lack of obstacles between transmitter and receiver, the line-of-sight (LOS) component is usually the dominant part. In addition, reflections from the sea surface are probable and the evaporation duct, caused by water evaporation from the sea surface, makes communications possible even beyond the LOS. For these reasons, the path loss can be approximated with a two-rays model up to a given distance, where only the LOS component and the reflection with the sea surface take place. For longer distances, the model can be approximated with a three-ray channel model, which also includes reflections with the evaporation duct layer in the atmosphere.

IV. Results

In this section we present the results obtained through the simulation campaign. In order to simulate a realistic LoRaWAN deployment in the area akin to the port, we assume the presence of 300 interfering nodes, employing SF7 and sending packets once every 5 minutes, causing a loss of 3% of all packets sent by the surface buoys to the LoRaWAN GW.

Figure 3 shows the E2E throughput of a deployment in which AHOI modems are employed for all underwater communications, for varying values of the data generation period employed by the sensor nodes. Solid lines in the plot represent the throughput achieved by the network for different numbers of sink nodes, the dashed line represents the rate at which packets are transmitted by the sensor nodes to the

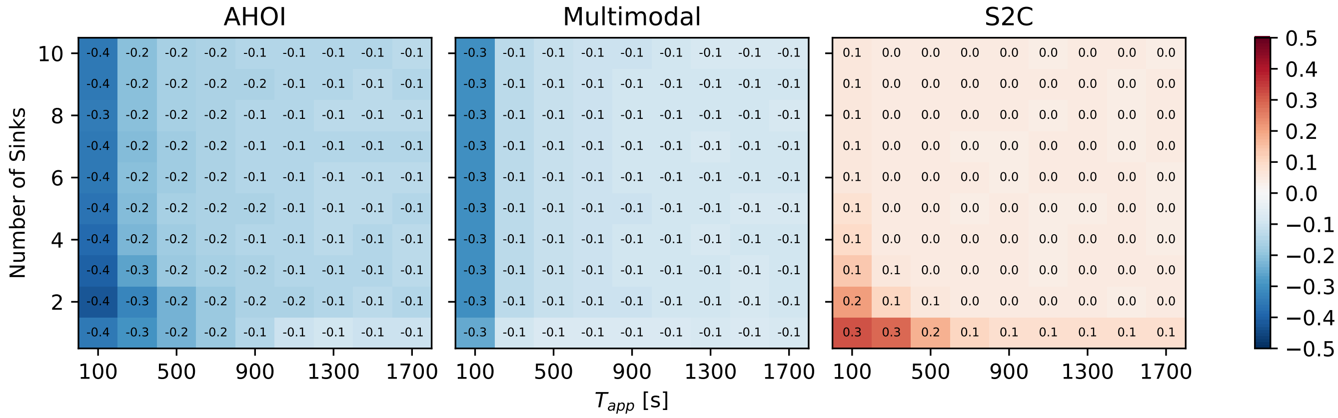

Fig. 4. Identification of the bottleneck for different network configurations.

AUV, and the dash-dotted line is plotted as a reference for the rate at which data is produced by the sensors. For data generation periods higher than 2000 s, all generated data can be transmitted from the sensors to the AUV, and around 65% of the packets reach the sink first and the LoRaWAN GW next (the difference between generated data packets and received packets is mostly caused by packet losses due to bad channel conditions). For lower data generation periods, instead, the deployment density of sink nodes plays a more and more significant role in the degradation of the throughput of the system. For the lowest simulated generation period of 100 s, for instance, of the 28.8 bit/s that are generated by the applications only 14 bit/s can be transmitted to the AUV, and only 9 bit/s reach the LoRaWAN GW. In this heavy traffic scenario, increasing the number of deployed sinks has a direct effect on both the underwater and the LoRaWAN sections of the pipeline. Underwater, the AUV will have more chances to empty its queues: since it moves at a constant speed, when its queues are full of data its data delivery rate is determined by the amount of time it can spend in range of a sink node; the more sinks are available, the larger the amount of data it will be able to deliver. Similarly, above the water, the duty-cycled LoRaWAN network will benefit from a larger number of nodes that can deliver data in parallel.

Since these two effects both influence throughput significantly, we decided to create a metric to help assess which one is the bottleneck. Let t_o be the offered traffic, t_s the rate at which data is received at the sinks, and t_e the rate at which data is received at the LoRaWAN GW. The throughput bottleneck indication metric is then computed as follows:

$$b = \frac{1}{2}\left(\frac{t_s - t_e}{t_s} - \frac{t_o - t_s}{t_o}\right), \tag{1}$$

where the first term between parentheses represents the throughput loss caused by LoRaWAN, while the second term represents the throughput loss caused by the underwater section of the network. When $b > 0$, we can say that LoRaWAN is the bottleneck; for $b < 0$, instead, underwater communication is the more limiting section between the two.

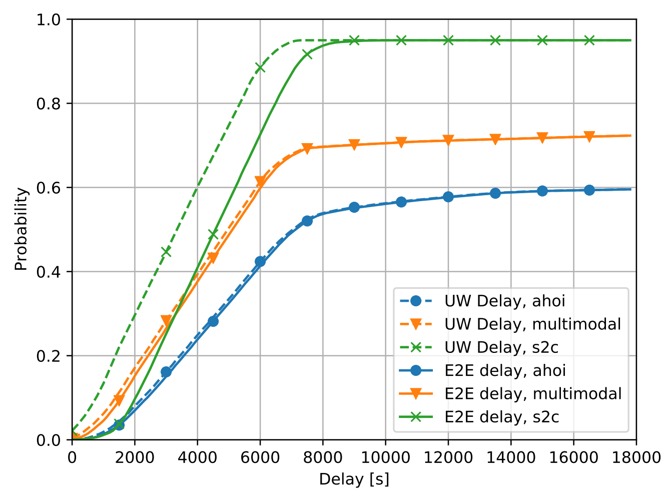

Fig. 5. Comparison between E2E delay and underwater delay for the three different configurations. Results obtained with $T_{app} = 600$ s and 3 sink nodes.

Figure 4 shows the value of b for various generation periods and numbers of sinks, for all considered underwater modem solutions. For the AHOI system, the values are negative for every network configuration, indicating that the modem bit rate (which is heavily influenced by packet losses) is the main limitation to the E2E throughput. While this is also true for the multimodal solution, it's worth noting that in this case b takes values closer to zero, implying a better underwater performance. Finally, Figure 4 shows that when the S2C modem is used for all underwater communications, LoRaWAN becomes the bottleneck when a small number of sinks has to serve sensor nodes that transmit very frequently. This effect, however, can be easily mitigated by either increasing the number of sink nodes or by reducing the data generation frequency.

Figure 5 plots the Experimental Cumulative Density Functions (ECDFs) of the packet delay for the three modem

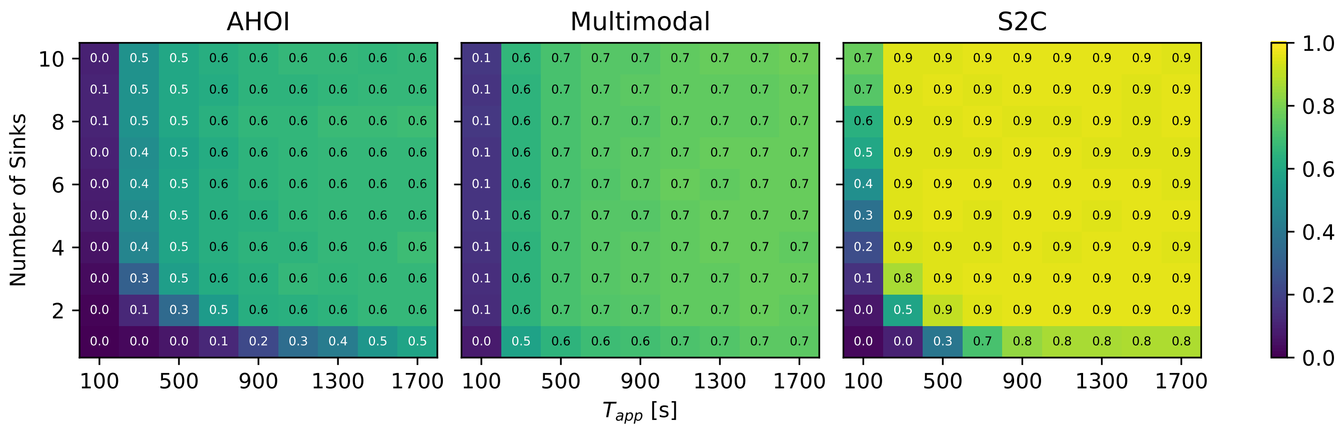

Fig. 6. Fraction of packets delivered (E2E) in two rounds for the three configurations

solutions, with dashed lines representing the delay introduced by the underwater section and solid lines representing the distribution of E2E delays. These results have been obtained considering 3 sink nodes. We note that ECDFs are computed by keeping into account all generated packets, which leads to the curves not reaching 1, since some generated packets are lost due to interference or noise and will never reach the GW. The contribution of LoRaWAN to the E2E delay can be estimated by comparing a dashed line with its solid counterpart: in the AHOI and multimodal cases, the additional delay introduced above the water is negligible, especially when compared to the underwater delay, which inherently suffers from the AUV having to physically move to collect the data, forcing some packets to wait in the node's buffer up to 6280 s before they can be retrieved by the AUV (i.e., the time it takes for the AUV to complete a lap of its path). In the S2C configuration, instead, LoRaWAN adds a considerable amount of delay, mainly because of its duty cycle constraints; this effect is significantly reduced when denser deployments of sink nodes are used.

Figure 6 reports the fraction of delivered packets within two AUV rounds in the three configurations described in Section III. In both the configurations with only AHOI acoustic modems and the multimodal setting, the network is not able to forward all the generated packets, even with low offered traffic and 10 sink nodes, mainly because of the packet losses suffered by the AHOI modems. Despite this, the multimodal configuration performs better than the setting with only AHOI modems. Considering the setting with only S2C modems, the network is able to handle the generated traffic in most cases. The network is not able to deliver any packets within two AUV rounds when $T_{app} < 300$ s and only one sink node is available; in this case, increasing the number of sink nodes is a solution. For all the other cases the fraction of delivered packets is greater than 90%. The reasons of these losses are various. First of all, packets are lost for bad channel conditions. Each packet is involved in three transmissions to reach the LoRaWAN GW to the shore, increasing the possibility of packet losses. We want to highlight that, according to the models used in our simulations, the AHOI modem performs worse than S2C in terms of packet delivery ratio. Indeed, the model used for the AHOI modem is based on field measurements retrieved in a very challenging scenario, while the S2C HS is modeled according to an empirical formula [3], that does not account for the multipath experienced in shallow water, as we had no field measurements for this specific modem. In addition, the different bitrate between the two underwater modem types allows S2C to deliver more packets. All these conditions favor configurations in which S2C is used. Other factors can decrease the fraction of delivered packets. In particular, when the AHOI modem is used to forward packets from AUV to sink nodes, the lower bitrate can cause some packets to be delayed in the AUV queue and thus to not be delivered to sink nodes within the two considered rounds. Similarly, if the number of packets received by a sink nodes is relatively high, the packets could be delayed due to the duty cycle restriction imposed by the LoRaWAN standard.

V. Conclusions

In this paper, we evaluated the E2E performance of a data collection service from an underwater sensor network. We considered the data gathering with an AUV from sensor nodes based on different underwater network configurations, and we also included in the analysis the use of an above-water network to forward data to the shore. Specifically, we analyzed a LoRaWAN network, that fits well in our scenario.

We assessed three different configurations for the underwater part of the network, using the low-cost prototype AHOI modem and the commercial S2C modem. We proved, via simulations, that LoRa is an enabling technology for data collection in most of the analyzed configurations. In particular, when considering the underwater network configuration with both only AHOI modems and the multimodal setting, LoRa does not introduce any further delay and does not act as the bottleneck of the network. Analyzing the configuration with only S2C modems, instead, we observed that LoRaWAN may become the bottleneck of the network when the traffic generated by sensor nodes is high, but this problem can be mitigated at the cost of adding more sink nodes in the network.

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