UDMSim: A Simulation Platform for Underwater Data Muling Communications

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***Abstract*—The use of Autonomous Underwater Vehicles (AUVs) is increasingly seen as a cost-effective way to carry out underwater missions. Due to their long endurance and set of sensors onboard, AUVs may collect large amounts of data, in the order of Gbytes, which need to be transferred to shore. State of the art wireless technologies suffer either from low bitrates or limited range. Since surfacing may be unpractical, especially for deep sea operations, long-range underwater data transfer is limited to the use of low bitrate acoustic communications, precluding the timely transmission of large amounts of data. The use of data mules combined with short-range, high bitrate RF or optical communications has been proposed as a solution to overcome the problem.**

In this paper we describe the implementation and validation of UDMSim, a simulation platform for underwater data muling oriented systems that combines an AUV simulator and the Network Simulator 3 (ns-3). The results presented in this paper show a good match between UDMSim, a theoretical model, and the experimental results obtained by using an underwater testbed when no localization errors exist. When these errors are present, the simulator is able to reproduce the navigation of AUVs that act as data mules, adjust the throughput, and simulate the signal and connection losses that the theoretical model can not predict, but that will occur in reality. UDMSim is made available to the community to support easy and faster evaluation of data muling oriented underwater communications solutions, and enable offline replication of real world experiments.

I. Introduction

The ability to perform manned missions at sea is very challenging, either for traditional activities such as fishing and transportation, or for new activities such as environmental monitoring and deep-sea mining. The harshness of the ocean requires expensive resources and logistics for supporting these missions, especially underwater. The use of Autonomous Underwater Vehicles (AUVs) is increasingly seen as a cost-effective alternative to carry out underwater missions [1]. For instance, in the implementation of the European Marine Strategy Framework Directive, AUVs are seen as a tool for habitat mapping, identification of geomorphological features, and detection of marine litter for promoting biodiversity preservation and the good environmental status of marine waters.

Due to their long endurance and set of sensors onboard, AUVs may collect large amounts of data, in the order of Gbytes, including video and bathymetric data. An AUV may have to travel several kilometers before reaching an area of interest near the seafloor. Surfacing frequently is unpractical in most cases, especially in deep-sea operations. AUVs typically upload the data at the end of the mission, which causes delay in data processing and visualization, and introduces significant dead-times between consecutive missions. This delay precludes possible adjustments in the AUV's mission (or other AUV's mission in a multiple-vehicle mission), due to the inability of onboard devices to process the collected data in real-time. The solution for this problem is to enable broadband communications between the AUV and a central station, so that the collected data can be timely uploaded along the mission.

Existing solutions for underwater communications can only provide either long-range narrowband communications or short-range broadband communications. Acoustic communications are the most commonly used solution. However, despite the long-range capability, their low propagation speed and low bitrate make them unsuitable for timely video transmission and transfer of high data volumes [2]. Optical communications, using LEDs or lasers, are able to increase the throughput to dozens of Mbit/s. Yet, despite the technological advancements, practical underwater optical communications range is limited to dozens of meters due to the water turbidity and the need of line-of-sight and proper beam alignment mechanisms. Radio Frequency (RF) communications offer the same broadband communications capabilities as optical communications, without the need of line-of-sight or beam alignment requirements. However, RF signals suffer from strong attenuation underwater, limiting the practical use of broadband RF communications to a few meters.

GROW [3] is a pioneering solution that aims to overcome the limitations of current underwater communications technologies and provide long-range, broadband underwater wireless communications between a survey unit (e.g., deep sea lander, AUV) and a central station unit at the surface (e.g., buoy, vessel, Autonomous Surface Vehicle) [3]. The GROW concept is illustrated in Fig. 1. At the core of the concept is a delay tolerant network (DTN) [4], [5] composed by small and agile AUVs – data mules – equipped with short-range high bitrate wireless capabilities (e.g., optical, RF) for data transfer, and long-range low bitrate acoustic communications for control purposes. The data mules, traveling back and forth between the survey unit and the central station, create a virtual bidirectional link between them. The GROW solution has been tested in lab environment using an underwater testbed composed of one survey unit, one central station unit and two data mule units [6], [7]. The experimental results obtained show it outperforms current acoustic communications by achieving equivalent throughputs up to 150 times higher within the

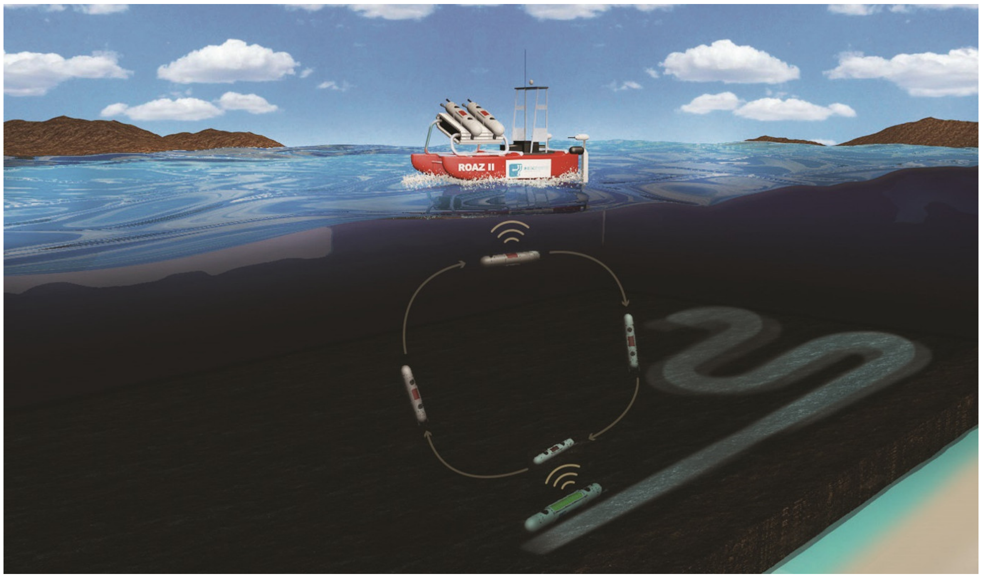

Fig. 1: The GROW concept, which consists of Data Mule Units that operate between a Survey Unit and a Central Station Unit.

typical range of operation of the acoustic communications. Underwater DTNs have been studied by different research groups [8], [9], [10], however most of the work has been focused on routing protocols for opportunistic and predicted contact between nodes, rather than on solutions for high bitrate wireless transfer. Autonomous underwater data muling systems have been considered in a few works [11], [12]. Yet, all of them used data mulling to retrieve data from static nodes. The GROW solution advances the state of the art by retrieving data from a mobile AUV.

The ability to accurately simulate the data mules motion and the communications network performance enables to study how a data muling system is affected by the variation of parameters such as the number of data mules, the distance between the central station unit and the survey unit, the amount of data to be transferred, and the control laws for a timely and accurate approach.

The main contribution of this paper is UDMSim, a simulation platform for underwater data muling oriented systems that combines an AUV simulator and ns-3. UDMSim is validated against a theoretical model and lab experiments. The results show a good match between UDMSim, the theoretical model, and experimental results obtained using an underwater lab testbed considering no localization errors. UDMSim is also capable of reproducing scenarios with localization errors, either simulated or from real traces. UDMSim is made available to the community [3] to support the evaluation of data muling oriented underwater communications solutions such as GROW.

The rest of the paper is organized as follows. Section II provides an overview of the GROW solution, Section III presents a simple theoretical model of a data muling oriented system, Section IV presents the UDMSim, Section V evaluates the equivalent throughput results, and Section VI draws the conclusions and points out the future work.

II. GROW Solution Overview

Long-range underwater wireless communications rely on narrowband acoustic communications [2], [13], which are unsuitable for uploading large amounts of data from an AUV. Although other technologies such as optical and RF are able to provide higher throughputs [14] [15], they are affected by turbidity and strong attenuation, respectively, limiting their practical usage to short-range communications.

The GROW solution, illustrated in Fig. 1, tackles this problem by employing AUVs that operate as data mules between a fixed or mobile Survey Unit (SU) – e.g., deep sea lander or an AUV – and a Central Station Unit (CSU) – e.g., buoy, vessel, and Autonomous Surface Vehicle (ASV). The CSU is assumed to be equipped with a permanent connection to an onshore station, reachable through the Internet. It is responsible for scheduling the available Data Mule Units (DMU). The SU executes the acquisition and the logging of the data. The DMU is a small and agile AUV that establishes a virtual bi-directional communications link between the CSU and the SU by travelling back and forth between the CSU and the SU.

The GROW solution considers two different communications technologies: a broadband, short-range communications link (optical or RF), used for data download from the SU to the DMU and upload from the DMU to the CSU; a narrowband, long-range acoustic communications link for controlling the DMU. Due to the intermittent connectivity of the short-range communications link, protocols designed for Delay Tolerant Networks (DTN) are more suitable since they are designed for delay/disruption tolerant wireless networks.

Due to the short distance required between the DMU and the mobile SU for enabling high bitrate underwater communications, GROW addresses the challenges of: 1) homing to a mobile target with uncertain or possibly corrupted information on its future trajectory; 2) precise positioning of an AUV with regard to a mobile target accommodating strong disturbances induced by the motion of the target.

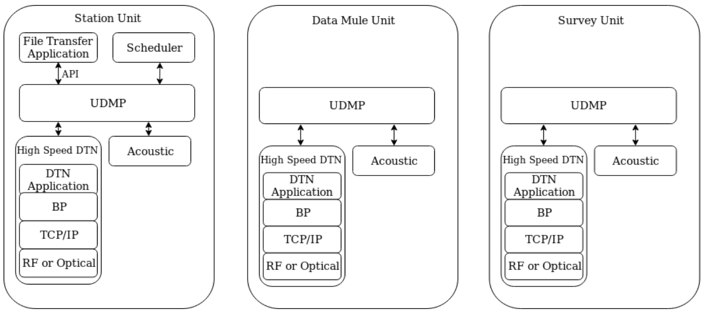

Fig. 2: The UDMP protocol stack.

The correct scheduling of the DMU is a key factor for GROW performance. In [6] we have proposed the Underwater Data Muling Protocol (UDMP), a communications protocol that enables the control and scheduling of the DMUs within the GROW framework for a file transfer application. The UDMP communications stack is presented in Fig. 2 and runs on every node of the network. The scheduler defines the number of mules deployed and their sequence. UDMP is then responsible for handling all the control messages over the acoustic network according to the scheduler commands. It is also responsible for handling the split and reconstruction of the data chunks sent over the high speed DTN network.

III. Simple Theoretical Model

The main metric to evaluate the performance of a data muling solution such as GROW is the equivalent throughput ($R_{b,eq}$), defined by Eq. 1, which considers the transferred data over the time it took to be delivered.

$$R_{b,eq} = \frac{Datasize}{time} \tag{1}$$

In Eq. 1 *Datasize* is the number of bits transferred. $time$ is given by Eq. 2 and depends on: 1) the undocking time (T_u), which represents the time for the DMU to move away from the CSU or the SU; 2) the travel time (T_t), which depends on the distance between the SU and the CSU and the travel speed of the DMU; 3) the number of DMU (N) available; 4) the docking time (T_d), which is the time that the high precision acoustic relative positioning and maneuvering system takes for approaching and accompanying the SU or the CSU; and 5) the transfer time (T_{SR}), which is the time required for the file (or a chunk of the file) to be transferred over the short-range, high speed underwater link. In turn, the transfer time depends on the data size and the short-range link throughput.

$$time = T_u + T_t + N \times \left(T_d + \frac{T_{SR}}{N} + T_u \right) + T_t + T_d + \frac{T_{SR}}{N} \tag{2}$$

Despite being a simple deterministic model, where no localization errors or other external factors are considered, this simple model shows the limits of a data muling solution and establishes a baseline for performance comparison.

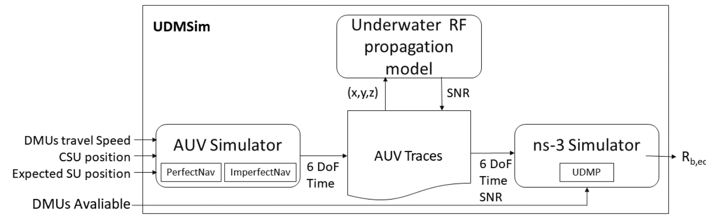

Fig. 3: UDMSim block diagram.

IV. Underwater Data Muling Simulator (UDMSim)

Due to the complex logistics of underwater testbeds and sea deployments, it is important to accurately predict the performance of the data muling solution when the number of DMUs, the distance between the CSU and the SU, and the amount of data to be fetched from the SU are varied. UDMSim is a simulation platform for underwater data muling oriented systems that combines an AUV simulator and ns-3, and goes beyond the simple mathematical model presented in Sec. III. In what follows, we describe each of these components. The UDMSim block diagram is shown in Fig. 3. UDMSim is made available to the community [3] to support the evaluation of data muling oriented underwater communications solutions.

A. Underwater AUV simulator

The mule simulation framework implements a six degrees of freedom (DoFs) model of an AUV [16]. The model is based on the standard nonlinear dynamics and kinematics equations for an underwater vehicle [17], whose parameters have been previously derived and validated. Along with the vehicle model, a target-tracking control algorithm running on-board the (real) vehicle is emulated, having the reference position (SU) and its own state (position, velocity) as inputs. It generates four actuation commands to the thrusters on the output side. The underwater AUV simulator outputs a set of traces that define the 6-axis position of the AUV (x, y, z, yaw, pitch and roll) along the mission.

In general, underwater robots do not know their location perfectly. Their localization, or pose estimation, relies on state estimators that fuse data coming from multiple sensors. As the sensors are corrupted by noise and other undesired effects such as biases, discrete sampling, and nonlinearity, the resulting estimate is imperfect, adding a variable error to the true pose. This has impact on the vehicle tracking performances as the controllers rely on the estimate to generate commands. In the present case, the impact of localization error is relatively higher when the DMU is in close to the SU, which in turn has impact on communications. Although an appropriate choice of sensors may mitigate the problem, there is no way to circumvent estimate errors.

B. ns-3 based simulator

Through the use of the traces provided by the AUV simulator, UDMSim implements a trace-based network simulation in ns-3 [18], an open-source, discrete-event network simulator mainly used for research and educational purposes. The trace-based simulation was presented in [19] and is a technique that

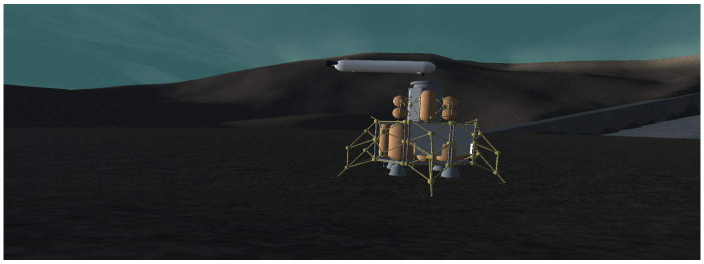

Fig. 4: 3D Simulation of a DMU approaching a Lander SU.

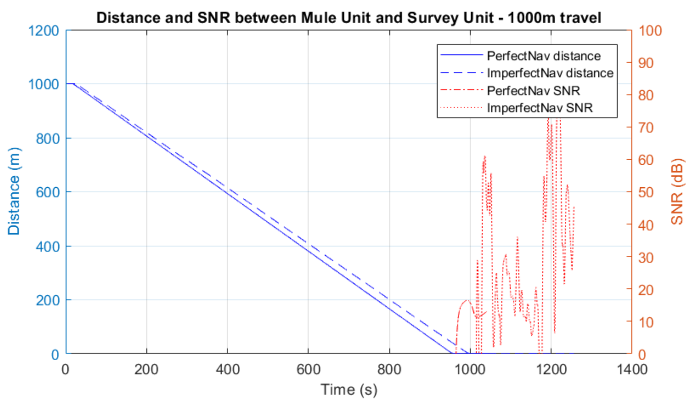

Fig. 5: Distance and SNR of a DMU travelling 1000 m from the CSU to the SU using PerfectNav and ImperfectNav.

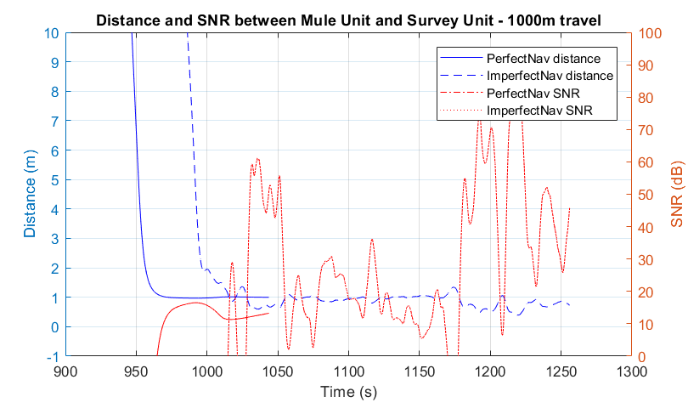

Fig. 6: A closer look on DMU approaching the SU for a 1000 m distance using PerfectNav and ImperfectNav.

feeds ns-3 with traces including node positions and radio link quality (SNR). It provides more accurate results and allows to reproduce real-world mobile testbed experiments.

Despite offering several models for devices and protocols for wired and wireless networks, ns-3 lacks a native underwater optical and RF propagation models. Therefore, the RF underwater model presented in [15] was used in UDMSim. The SNR value was added to each entry of the trace provided by the AUV simulator and was necessary to meet the requirements of ns-3 trace import. Through the trace-based simulation approach, the native mobility and propagation models of ns-3 are replaced by the position of the AUV and SNR provided by the traces.

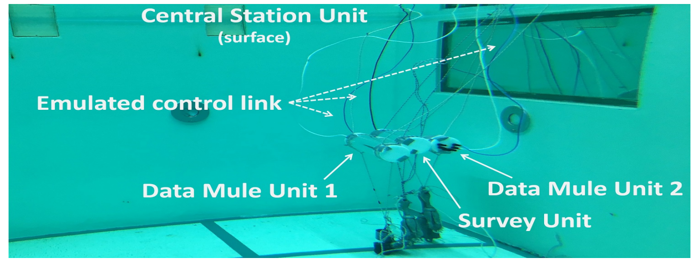

Fig. 7: Testbed used to evaluate the UDMP.

The ns-3 simulator implements the state machine of the UDMP protocol [15], including an out-of-band acoustic signalling channel to enable the control of DMU and a broadband short-range RF for data transfer. The UDMP starts by requesting the data size using the control link, and splits the file into different chunks according to the number of DMUs available. The DMUs depart from the CSU according to the positions defined in the traces. Reaching a distance of 2 m to the SU, a docking request is sent. If successful, the DMU continues its approach. When the short-range link is available, the ns3:.BulkSendApplication transfers the chunk of data. Due to the sharp SNR decay with the distance, the Minstrel auto rate mechanism is used and the data exchange application is monitored and restarted if the association between the DMU and SU is lost or in case of exceeding the TCP retransmission timeout. When the transfer is complete, the DMU performs the same process in reverse order. When the data upload to the CSU is complete, ns-3 computes the equivalent throughput $R_{b,eq}$, taking into consideration the overhead of the DTN stack.

V. Evaluation Results

The validation of the UDMSim was performed based on two scenarios. The first scenario considered that the DMU physically docks or is very close ($\leq$ 10 cm) to the SU using an umbilical antenna, similar to the refuel system of a jet plane. This scenario is more suitable for stationary SU, such as a sea lander, and allows to use a 20 MHz channel based on 802.11g/n operating on the 40 MHz - 2.4 GHz frequency range, as demonstrated in [20]. The second scenario considered that the DMU approaches and tries to maintain a 1 m distance from the SU, which can be fixed or mobile. An example of a fixed SU (Lander) is shown in Fig. 4. In this case, according to the attenuation of RF signals, especially in seawater [15], frequencies on the 10 - 20 MHz range have to be used. To minimize the SNR differences of the OFDM subcarriers on the 802.11 channel, and since it is not possible to use a 20 MHz channel on a 10 MHz carrier, the bandwidth should be reduced. In our case, a 5 MHz signal was considered.

To assess the impact of localization errors on the system, two sets of simulations were run: the first considered perfect localization – PerfectNav – and the second relied on a state estimator using imperfect measurements from sensors – ImperfectNav. The output of the simulator on the imperfect localization are the true poses of the DMU and SU. Fig. 5 shows the distance and SNR when the DMU travels 1000 m from the CSU to the SU on the second scenario and the corresponding SNR variation. Fig. 6 shows a closer view of the final approach, where we can see the position error, strong

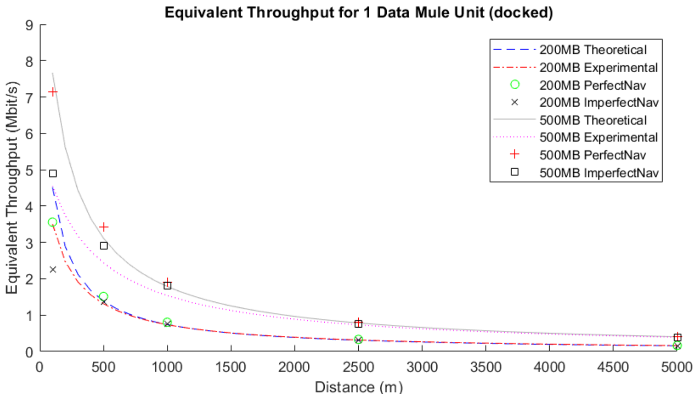

Fig. 8: Equivalent throughput for one DMU on the docked scenario.

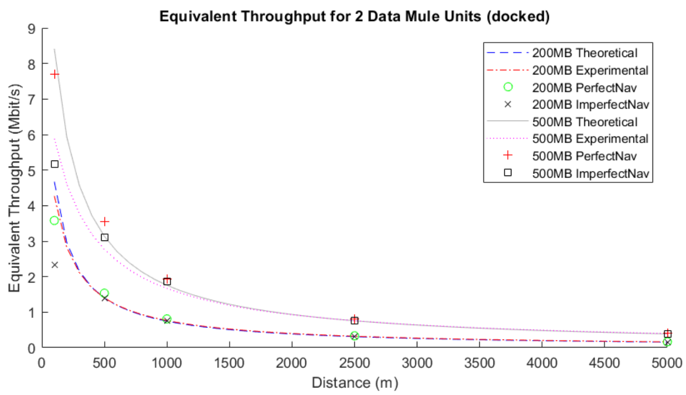

Fig. 9: Equivalent throughput for two DMU on the docked scenario.

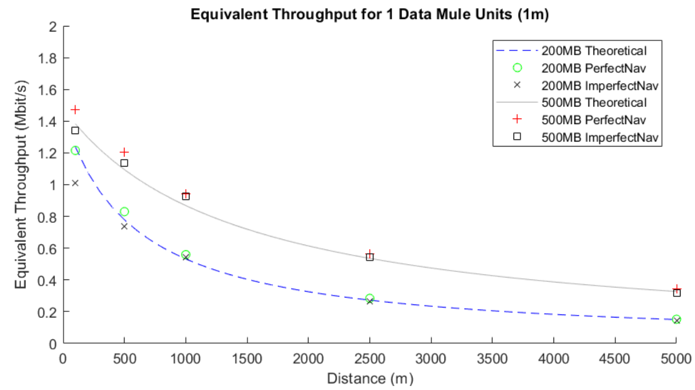

Fig. 10: Equivalent throughput for one DMU on the 1 m scenario.

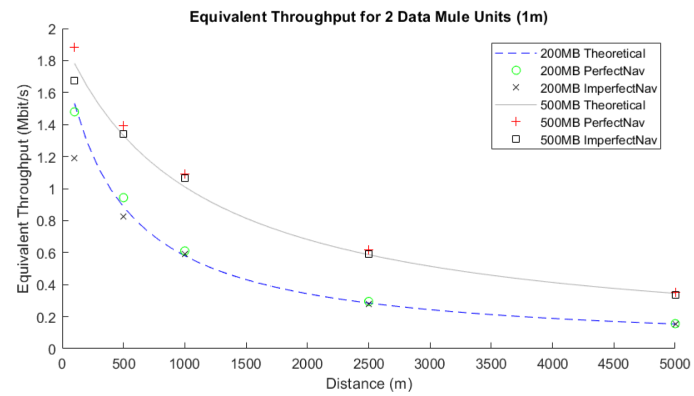

Fig. 11: Equivalent throughput for two DMU on the 1 m scenario.

SNR variations, and even connection loss (SNR ≤ 0), which will have a negative impact on the short-range throughput. Each ns-3 simulation was repeated 5 times with different seeds and the results were averaged. The confidence intervals obtained were short. For the sake of visualization, they were not represented in Figs. 8-11.

The UDMSim results were compared against the theoretical obtained using Eq. 1 and the parameters of Table I for 1 and 2 DMUs [6], a TxPower of 30 dBm and 2 dBi loop antennas. The results were also compared with experimental results obtained using a testbed composed by two DMUs, one SU, and one CSU, as shown in Fig. 7 [6]. Watertight cylinders were used, and a 2.4 GHz 802.11n network was used for the short-range link. Two different data sizes were considered: 200 and 500 MB. The maximum data was limited by the DTN implementation used on the testbed (IBR-DTN). Since the Wi-Fi card driver only supported 20 or 40 MHz channels, experimental results were only obtained for the first scenario.

Fig. 8 shows the equivalent throughput over distance between 100 m and 5000 m for 1 DMU, considering the transfer of 200 and 500 MB of data for the docked (shorter distance) scenario. We can observe that UDMSim matches the experimental and theoretical values for PerfectNav (no localization errors). Due to the position errors of ImperfectNav, as seen

TABLE I: DMU Parameters

Parameter	Value
Undocking time (T_u)	1 s
Docking time (T_d)	17 s
Data Mule Unit travel speed	1.05 m/s
Number of Data Mule Units available	1 - 2
Average short-range link throughput (20 MHz channel)	27,1 Mbit/s

in Fig. 6, the link quality changes accordingly and so does the short-range throughput. UDMSim is able to simulate this phenomenon, which results in the lower performance obtained, especially for ranges below 500 m. We can also observe that the equivalent throughput increases with the amount of data to be exchanged, since the travel time has the most impact on the equivalent throughput calculation.

When considering 2 DMUs for the docked scenario, we can observe in Fig. 9 that UDMSim also matches the theoretical and experimental values. The usage of 2 DMUs increases the equivalent throughput, which is more noticeable for short distances, where the data transfer time is more relevant.

Fig. 10 shows the equivalent throughput for the second scenario, where the DMU is at 1 m from the SU. With SNR around 15 dB, we expect a short-range throughput of 3 Mbit/s. Although this value was fixed in the theoretical model, the Minstrel auto rate mechanism on the UDMSim was kept active, which can justify the slightly higher results on PerfectNav and ImperfectNav for the 500 MB case. ImperfectNav still shows lower equivalent throughput due to the signal variations which in some cases led to TCP timeouts and re-associations, providing the realism lacking in the simple theoretical model presented in Sec. III.

When deploying two DMUs for the second scenario, we can observe that the UDMSim results match the theoretical values, with a 28% equivalent throughput increase for PerfectNav at 100 m and 25% equivalent throughput for ImperfectNav. Although this margin fades out along the distance, UDMSim is able to simulate the advantage of using multiple DMUs for exchanging large amounts of data.

These results show that UDMSim is a powerful tool for the validation of underwater communications solutions based on data muling. Although GROW was pioneer on a mobile SU approach, other data muling oriented solutions can be evaluated using UDMSim. Despite the data exchange analysis being limited to 500 MB, due to the specific DTN implementation used in our lab testbed, UDMSim is able to simulate larger amounts of data, which will highlight the advantages of a data muling solution for underwater communications. The experimental values obtained using the lab testbed considered no localization errors, which are very unlikely in a real scenario. In this case, UDMSim will be an important tool, since the position and signal variations make it difficult to derive an accurate theoretical system model. UDMSim can also benefit from other traces as input, including traces captured from real experiments, allowing offline replication of real world in simulation environment.

VI. Conclusion

The harshness of the sea environment is pushing the use of AUVs for a cost-effective alternative to carry out underwater missions. AUVs may collect large amounts of data from their sensors that needs to be transferred to shore. A data muling solution outperforms the current long-range narrowband communications solutions through the usage of data mules equipped with short-range high bitrate RF or optical communications that will collect data from a survey unit, such an AUV, and deliver it to a central station at surface.

In this paper we have proposed UDMSim, a simulator for data muling oriented underwater communications that combines an AUV simulator and ns-3. UDMSim matches the results obtained using a simple mathematical model and a lab testbed when no localization errors are considered. When localization errors are present, UDMSim is able to reproduce them through the traces, and simulate the signal and connection losses that will occur in reality, thus enabling the evaluation of underwater communications solutions based on data muling in more realistic conditions. Future work includes the inclusion of underwater antenna radiation patterns for more accurate SNR calculation, new AUV control laws for more precise simulations, a relative positioning system to cope with a mobile SU, and the comparison of UDMSim results with experimental results obtained in real environment.

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