DURIUS: A Multimodal Underwater Communications Approach for Higher Performance and Lower Energy Consumption

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***Abstract*—The exploration of the ocean has got an increasing interest, including activities such as offshore wind farms and deep-sea mining. However, the ocean environment and the high cost of operations, namely for manned missions, have led to the development of Autonomous Underwater Vehicles (AUVs) and other sensing platforms. AUVs play a vital role in these environments, relying on communications systems to operate and exchange sensor data. Yet, reliable and energy-efficient broadband wireless communications underwater remain an unsolved challenge, despite the recent advances in the field.**

We present a novel multimodal approach, named DURIUS, that considers the movement of the AUV to convey the sensor data and selects the most suitable underwater wireless communications technology – acoustic, optical or radio – according to the underwater context, targeting maximum performance and minimum energy consumption. Our analytical results show that DURIUS increases data throughput and reduces energy consumption when compared with the state of the art approaches.

I. INTRODUCTION

The concept of the Blue Economy has gained significant importance worldwide [1]. Activities such as ocean monitoring, aquaculture, and offshore wind farms have gathered attention from both governments and private companies, prompting investments in these innovative sectors. Additionally, the exploitation of the continental shelf offers opportunities for economic growth, and brings up the need for monitoring and surveillance activities. The development of such activities requires the adoption of new technologies and the collection of oceanic data.

Given the limitations of existing technologies, there is a need to explore alternative strategies for establishing reliable and efficient wireless communications underwater [2]. The three existing wireless approaches for underwater communications — acoustic, optical, and radio — have their own set of advantages and disadvantages [3]. Acoustic communications have a higher range, but they can only achieve very low bitrates. Optical communications offer higher bandwidth and are cost-effective, but they are easily affected by water turbidity. Radio-based communications can achieve high throughput at short distances, but the water conductivity causes strong attenuation of the electromagnetic waves. Recognizing this, the scientific community increasingly sees the use of a single technology as inadequate for establishing wireless communications underwater. The combination of different technologies in a multimodal approach, can lead to lower delays, more reliable connections and the use of less energy, increasing the endurance of the vehicles and originating smaller influence of these systems in marine life [4]. However, current multimodal solutions typically consider the mission scenario conditions in advance for defining the handover between different technologies – e.g. given the mission, the best technology to be used is predefined [5]. Also, they do not consider simultaneous transmission on multiple interfaces to increase reliability and data throughput.

The main contribution of this paper is a multimodal approach, named DURIUS, that integrates different types of technologies, selects the most suitable underwater wireless communications technology, according to the underwater context, and controls the AUV motion to improve short-range communications. DURIUS receives a set of input parameters such as data size, current AUV battery level and the average bitrate for each technology, and estimates the total delay and energy consumption for each of the communications technology available. Taking those estimations into account, DURIUS selects the most suitable physical wireless interface to forward the data (i.e. acoustic, optical, and radio), taking into account the operation mode selected – minimum delay or minimum energy consumption. DURIUS brings the concept of multimodal underwater networks to the next level, enabling the creation of a more adaptive communications solution for underwater environments.

The rest of the paper is organized as follows. Section II reviews the state of the art in underwater wireless communications, namely Multimodal Underwater Wireless Networks (MUWNs). Section III presents DURIUS and explains its rationale. Section IV describes the analytical results used to validate DURIUS. Section V draws the conclusions and points out the future work.

II. STATE OF THE ART

A. Introduction to Underwater Wireless Communications

Underwater wireless communications have been limited to ranges of just a few meters or to applications that use low data rates. Underwater wireless communications systems that consider a single-technology make use of one of three alternatives: acoustics, optical and radio. Acoustic communications, the most commonly used, enable long ranges, but the low bandwidth makes them unsuitable for broadband communications [6]. The speed of sound underwater mainly depends on a few aspects such as the pressure, salinity and temperature. The variation of sound speed due to temperature and pressure is high in shallow and deep water, respectively. These characteristics let us conclude that acoustic communications are not suitable to transfer large amounts of data such as videos, pictures or bathymetric data.

Optical wireless communications take advantage of the light (optics) proprieties to transmit information. They allow very high bitrates, but require line-of-sight and are easily affected by water turbidity [7]. The type of water can also be a factor that causes a strong influence in the performance of optical communications in underwater scenarios due to phenomena called absorption and scattering. As such, the use of a single technology is not able to achieve cost-effective broadband underwater wireless communications [3].

Finally, radio-based communications can achieve high bitrates however, the strong attenuation underwater limits their range up to a few meters [8]. The values of wavelength in terrestrial and underwater environments differ significantly from each other, making the design of antennas for these two scenarios very different. In [9], it is shown that the input impedance and resonance frequency of the antenna increased when the conductivity of the water increases, meaning that lower frequencies can be used in seawater for the same antenna size. Still, the communications range does not increase significantly. In summary, Radio Frequency (RF) underwater communications are useful for broadband short-range communications, provided that sub-GHz frequencies are used to cope with the higher signal attenuation.

As an alternative approach, the concept of Delay-Tolerant Network (DTN) was defined in [10]. A DTN is a network of smaller networks that support connections between network nodes with long delays and/or disruption. The use of DTNs can be found in several works, such as in [11] where it is shown that an approach combining DTNs and a data muling approach using AUVs in underwater scenarios may represent a possible alternative for long-term environmental monitoring or surveillance at the sea. At the same time, in [12] and [13] a similar underwater wireless communications system was implemented using AUVs as data mules that carry data between two distant physical nodes, where there is an out-of-band acoustic channel for control purposes and a short-range RF link to transmit data at high bitrates. Despite this novel strategy, this solution does not take advantage of advanced multimodal characteristics, since the two technologies are used separately, limiting the performance of the overall system.

B. Multimodal Underwater Wireless Networks

The idea of integrating several underwater wireless technologies into a single solution – Multimodal Underwater Wireless Network (MUWN) – has started a few years ago, in works such as [14], where the integration of acoustics and wireless optical is explored, defining a new path for the development of reliable communications systems for surface vessels and underwater vehicles. In [15], the authors propose the so-called "hybrid" underwater communications network architecture named MURAO that uses both wireless optical and acoustic communications. The network was physically splitted into two layers: 1) lower layer, that carries the data packet and 2) upper layer, responsible for supervising the routing on the lower layer. The nodes are grouped into clusters, having a supervisor node in each one of them. The routing technique employed was based in Q-learning, which uses Reinforcement Learning methods. MURAO improves the response to network topology changes and provides higher steady deliver rates, shorter delays and higher energy efficiency when compared to classic acoustic-only solutions. Several works followed this reasoning. In [16] a protocol stack is presented, where each node has both acoustic and wireless optical interfaces to communicate. The stack is implemented through an underwater framework called DESERT, that was previously defined in [17]. This system was developed for missions where human divers, that also work as network nodes with the help of a Remotely Operated Vehicle (ROV). Messages are put in queues with different priorities, depending on their type. Cross-layer communications capabilities were used for estimating PHY-level parameters (e.g. signal strength) in order to decide which of the PHY technologies should be used to send a particular packet.

A few works proposing the use of MUWNs in AUV missions can be found in the literature. In [18], an acoustic-based solution is chosen to encounter a submerged sensor node that is collecting data while optical communications were used to download the data when the AUV approaches. In [19] we find a multimodal approach where wireless optical modems are used for the data retrieval and acoustic communication solutions are used for control purposes. The majority of the already mentioned works tend to prefer wireless optical approach for higher throughput short-range communications. Despite this, in [20] a system that combines acoustic communication with Magnetic Induction (MI) is proposed.

More recently, in [21] a new heterogeneous network framework called MMNET was presented, with the intention of reducing network complexity. MMNET uses Network Function Virtualization (NFV) and Software Defined Radio (SDR) concepts, and connects the equipment with a so-called standard and unified interface to accommodate the different communication modes. The advantage of MMNET is to provide a custom network support for underwater applications, since most of the proposed solutions are limited to very specific operation scenarios.

C. Energy-aware MUWNs

One of the biggest challenges in sea operations is the reliability of rechargeable batteries [22]. Rechargeable seawater batteries (SWBs) are a new innovative type of batteries that take advantage of seawater to recharge themselves. Still, the endurance of autonomous vehicles is always limited. In [23] the authors propose a new MUWN-based solution with focus in obtaining higher energy efficiency. Using a multimodal approach, multiple paths with different transmission latency and energy consumption are used to perform underwater wireless data communications. Finally, in [24], to surpass the limitations of rechargeable batteries, several deep reinforcement learning techniques are presented as a possible solution to these problems. Several ideas can be employed in these scenarios, such as protocols that reduce the number of transmissions on the sender side, analysing which sender node is not being truly useful for the overall system.

D. Summary

Considering the solutions presented, we can conclude that, despite the existing works addressing MUWNs, there is a lack of solutions considering context variables in the design of the handover mechanisms between different underwater wireless communications technologies. This is the reason why we aim at exploring a novel solution that integrates multiple wireless technologies, considering both context variables, and other network inputs such as the type of information being sent, the distance between the nodes, and the mission assigned to the AUV.

III. THE DURIUS APPROACH

The approach proposed in this work – DURIUS – was designed for a scenario consisting of two communications nodes: a mobile node (i.e. an AUV) collecting data underwater and a fixed-position surface node, receiving the data, both supporting different types of physical communications interfaces (cf. Fig. 1). DURIUS selects the most suitable technology dynamically, taking into account estimations for both delay and energy consumption, considering the data request details, the characteristics of the different physical interfaces, and the AUV travel time. In what follows, we detail the DURIUS approach.

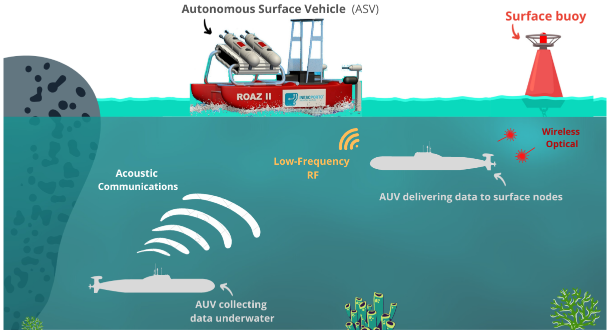


Fig. 1: DURIUS reference scenario.

DURIUS is divided into three phases: 1) Initialization Phase; 2) Estimation Phase; and 3) Decision Phase. During Initialization Phase, DURIUS receives a new data request and several inputs, namely the distance between nodes (d) in meters, the current AUV battery level ($batteryLevel$), in joule, the average speed of the AUV (v_{AUV}), in meters per second, the average power required to move the the AUV ($P_{AUV\,Moving}$), the average power required to keep the AUV in stationary mode, i.e. thrusters off ($P_{AUV\,Stationary}$), total data size of the data to send ($dataSize$), in bytes, as well as the expected average bitrate ($avgBitrate$), in bit per second and the average transmission power ($avgTxPower$), in Watt, for each physical network interface (e.g. acoustic, optical and radio). Then, it moves to the Estimation Phase, where multiple parameters are calculated. First, it calculates the total delay to deliver the data from the mobile sender node to the static receiver node for all physical network interfaces, which is obtained adding the AUV travel time (in case of the need to transmit through short-range technologies, i.e. optical and RF) to the transmission delay (Eq. 1). DURIUS has the ability of requesting the AUV to move in the direction of the other node in order to communicate using these short-range communications interfaces, if it finds to be the best solution for the current transmission.

$$totalDelay = \frac{dataSize}{averageBitrate} \times 1000 + i \times \frac{d}{v_{AUV}} \tag{1}$$

$$TxEnergy = \frac{dataSize}{averageBitrate} \times avgTxPower \tag{2}$$

$$energyStat = P_{AUV\,Stationary} \times \frac{dataSize}{averageBitrate} \tag{3}$$

$$energyMoving = P_{AUV\,Moving} \times \frac{d}{v_{AUV}} \tag{4}$$

$$\begin{aligned} totalEnergy = (&TxEnergy + energyStat \\ &+ i \times energyMoving) \times 2.78 \times 10^{-4} \end{aligned} \tag{5}$$

As said before, we only add the AUV travel time when we are estimating $totalDelay$ for the optical and RF interfaces. For this purpose, we consider a variable i, which is zero for the acoustic interface and one otherwise. This is because to communicate through the acoustic interface there is no need to move the mobile node to enable a connection with the surface node, since we are considering distances bellow the maximum range of the acoustic modems. Next, the Transmission Energy ($TxEnergy$) – the energy required (in joule) to transmit the data – is estimated using Eq. 2.

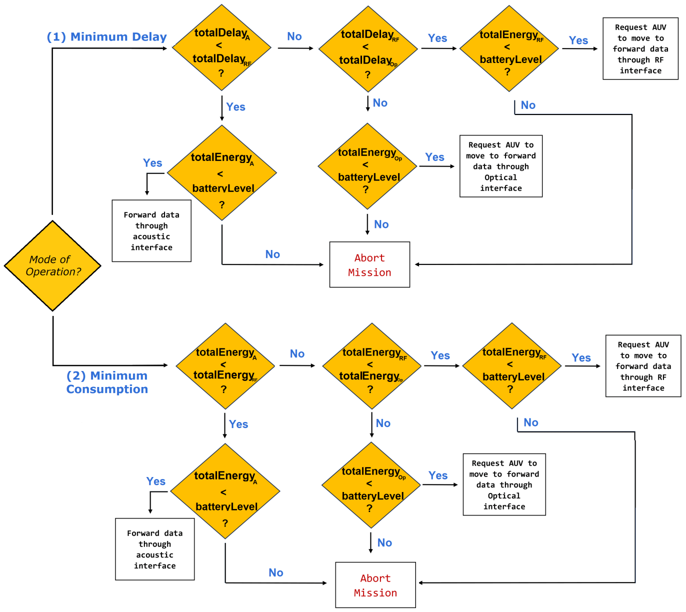
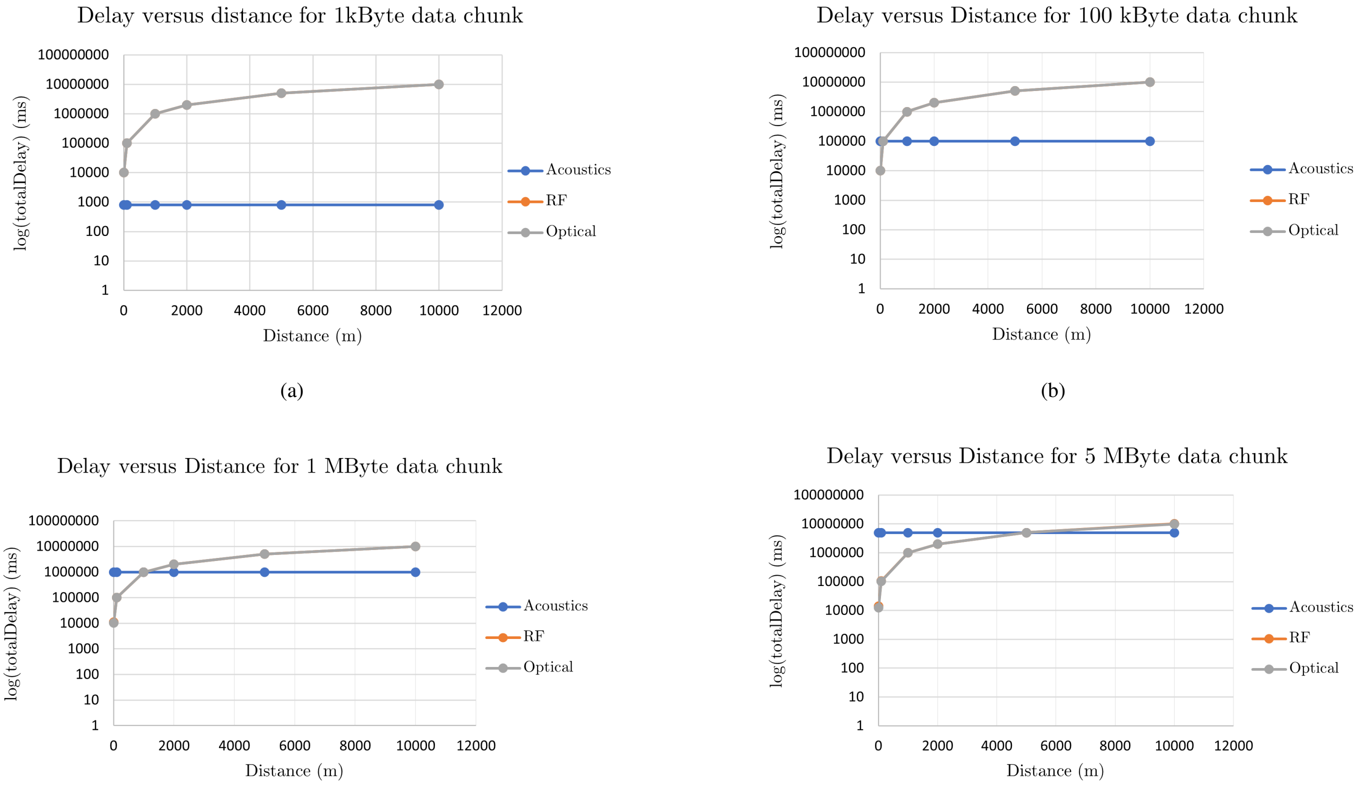


Fig. 2: Flowchart for the DURIUS Decision Phase.

Finally, the total energy ($totalEnergy$), which stands for the total energy required to send data, is calculated, including not just the energy spent in the transmission but also the energy consumption of the AUV itself. The energy consumed by the



(a) (b)

(c) (d)

Fig. 3: Delay versus Distance for different data chunk sizes.

AUV can be split in two categories: a) the energy consumed in stationary mode ($energyStat$), with the thrusters off (Eq. 3); and b) the energy required to travel the distance between the nodes ($energyMoving$) with the thrusters on (Eq. 4), both in joule. Considering this, the total energy is calculated using Eq. 5, adding $TxEnergy$, $energyStat$ and $energyMoving$.

In this case, we have once more added the i factor, which guarantees that the $energyMoving$ parameter is not added if we are forwarding the data through the acoustic interface. In the end, the result is multiplied by 2.78×10^{-4}, in order to convert joule to Wh. After these calculations, DURIUS enters the Decision Phase, in which the data is forwarded to the most suitable physical interface, considering both the values obtained for $totalEnergy$ and $totalDelay$ in every case, as well as the operation mode initially selected as input. The decision process is summarized in the flowchart of Fig. 2.

IV. DURIUS PRELIMINARY EVALUATION

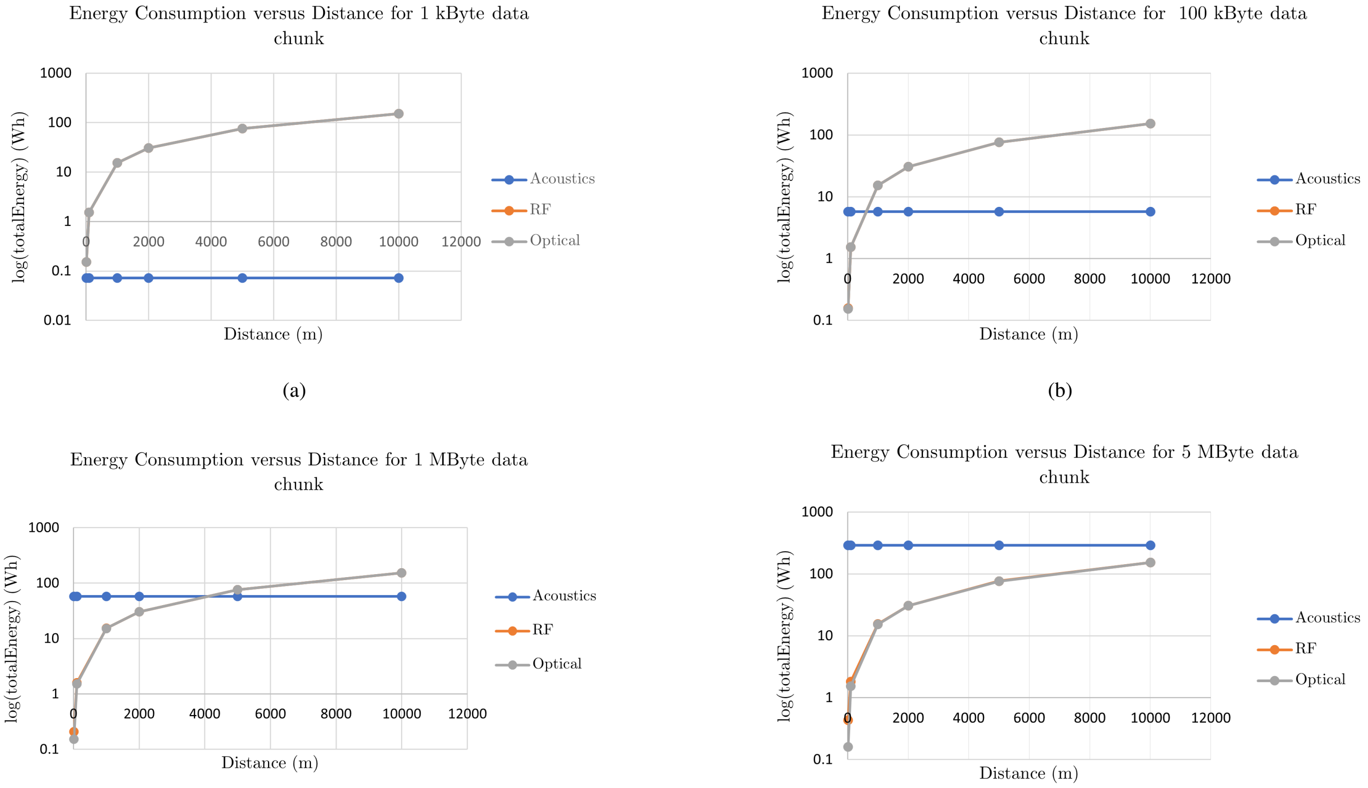
To evaluate DURIUS, we have chosen the scenario depicted in Fig 1, considering a single surface node. We have considered that both nodes have three physical network interfaces – acoustic, optical and radio – being the specifications for each of them based in the most commonly found in literature (cf. Table 2). Due to their limitations underwater, we need to move the AUV in the direction of the surface node to transfer data through RF and Optical. Considering the MARES AUV characteristics [25], we have defined $v_{AUV} = 1m/s$, $P_{AUVMoving} = 55W$, $P_{AUVStationary} = 20W$ and general ideal conditions (e.g. no packet loss, AUV with 100% energy level).

Technology	***avgTxPower***	***averageBitrate***
Acoustics	60W	10kbit/s
Optical	10W	20Mbit/s
RF	3W	10Mbit/s

TABLE I: Typical average transmission power and average bitrates for each underwater communications technology [26], [7], [27].

Starting from this reasoning and using the mathematical equations presented in Section III, we have obtained plots for both the total delay and the total energy consumption. To analyse the evolution of such variables, we have varied two input parameters: a) the size of the data chunk to be transmitted; and b) the distance between the two communicating nodes. The results are shown in Figs. 3(a) to 4(d).

The first aspect we notice in these plots is that the results for RF and Optical are almost coincident. This is explained by the same order of magnitude in their specifications, while acoustics have a much higher average transmission power and



(a) (b) (c) (d)

Fig. 4: Energy Consumption versus Distance for different data chunk sizes.

much lower average bitrate. Then, we can see that if we consider data chunks in the order of a few dozens of kbits, the acoustic interface has both better delay performance and lower energy consumption than the other two technologies for any distance considered. As previously said, we consider that the acoustic modem is always in its range of operation (i.e. 0-10km distance between nodes) and has no packet loss, which discards the need to move the AUV when communicating through acoustics. This is why both the energy consumption and delay in this case is represented as a straight line, because it does not depend on the AUV travel. Since the instantaneous power to move the AUV (in the direction of the surface node) is 2.75 times higher than the stationary power, and as the only way to communicate using RF and Optical is in short range, it becomes clear why the transmission of small chunks implies higher energy consumption, when using these two technologies.

Nonetheless, as the size of data chunk increases, the delay and the energy consumption of the acoustic interface increases in a much higher rate, when compared with the remaining two, as we can see in Figs. 3(b) and 3(c). Thus, Fig. 3(d) shows that the delay using the acoustic interface for a 5MByte data chunk is only lower than RF and Optical for very long distances ($\sim$10km), which are generally in the limit of the operation of the modems in real life, thus making the establishment of connections very hard. In the case of the total energy consumption, we can also see in Fig. 4(d) that when we are trying to send a 5MByte data chunk, the energy required to transfer it through acoustics is below both RF and Optical, no matter the distance between the nodes. These plots enable us to understand, in a more visual way, the decision phase of DURIUS. For instance, DURIUS only has to check where the plot for RF or Optical is below that line (in the y-axis), in order to check which technology has both minimum energy and minimum delay.

V. CONCLUSIONS AND FUTURE WORK

Activities in the sea are expanding, and platforms such as offshore wind farms need innovative robotic technologies such as AUVs and ASVs to operate properly. MUWNs offer promising potential to enhance reliability and efficiency, combining different underwater technologies. Despite recent developments, MUWNs are still in a very initial phase of development, being very little adaptive to the variation of the network scenario conditions.

In this paper we present DURIUS, a novel multimodal approach that considers a set of input parameters, including data size, current AUV battery level, and average bitrate for each technology to estimate the total delay and energy consumption for each available communications technology. DURIUS then makes a final decision on which interface a data chunk should be forwarded to – acoustic, optical or RF – and decides whether it is necessary or not to request the AUV to move in order to use the faster short-range interfaces. The preliminary evaluation shows that the decision to forward the data to a certain interface is affected by several factors. One of the main conclusions is that the power consumption of the vehicle itself can heavily affect the forwarding decision. This is because the energy needed to have AUV thrusters on is not negligible, and this makes RF and Optical technologies only viable to use (in a minimum energy consumption perspective) for considerably larger data sizes.

Future work includes the addition of several external models (e.g. energy consumption, bitrate) to replace the average values we considered, in order to meet a more realistic scenario. For instance, if we had considered a packet loss model, which tends to be very high when using acoustic modems, the results will be different. It is our intention to include such a model in the next version of DURIUS. We also intend to validate DURIUS in freshwater tanks, using RF, acoustic and optical devices.

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