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Underwater Data Muling: Scenarios, Implementation, and Performances

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Abstract—The exploration of the seabed is of strategic importance for various applications, including military, scientific, and commercial purposes. However, underwater communication is limited by the poor propagation of radio waves and the low data rates of acoustic communication. This leads to the topic of retrieving large amounts of data over a long range. To address this challenge, the concept of *data muling*—which involves the use of mobile agents to physically carry data from underwater nodes or Autonomous Underwater Vehicles (AUVs)—seems to be an interesting solution. In this paper, we focus on the scenario of a fixed data *source* and *sink* point separated by a large distance. We propose a relay system that uses mobile agents assigned to specific areas. Each agent can communicate with neighbouring agents and travel within its assigned area to transport data and act as a moving relay.

We evaluate the performance of this data muling solution using three metrics: equivalent throughput, latency, and energy. We compare our solution with a scenario inspired by previous work and show that our relay system can extend the range and data rate of underwater communication. The paper provides a detailed system model and presents experimental results to implement muling along testing scenarios.

I. INTRODUCTION

The exploration of the seabed has become a strategic issue due to military, scientific, or commercial use. With technological progress, these missions are increasingly carried out using Autonomous Underwater Vehicles (AUVs). This represents advantages in terms of area coverage rate and discretion, but also in terms of human resources, thus reducing costs and human risks. However, the use of AUVs for such missions means that the data is not immediately accessible. It is common to carry out long campaigns with long periods below the surface, meaning that a large amount of data is generated but not immediately sent to the surface. Radio waves propagate poorly underwater, and acoustic communication generally has a fairly low data rate. Thus, quickly communicating a large amount of data, over a long distance, is a real problem.

On the one hand, with a range of 100 m up to several hundred kilometres, acoustic communication is the most energy-efficient mode. However, the product data rate (in kb/s) times range (in km) is of the order of one hundred [4] which is

not suitable for the transfer of large amounts of data. On the other hand, Underwater Wireless Optical Communications (UWOCs) can reach up to several hundred megabits in a typical range of the order of ten meters [6][2] depending on the turbidity of the water. Directional UWOC systems using lasers can reach farther, but they require aligning the transmitter and receiver, which adds a layer of complexity. A third approach is the use of Radio Frequency (RF) communications. Such systems have a performance figure capped at 10 Mb/s over a range of a few centimetres for the gigahertz frequency band [6] [4] due to strong attenuation of RF waves in salt water. As a result, wireless underwater transfer of a large amount of data over a range of a few kilometres is not feasible in a reasonable time with existing communication technologies.

To address the problem of retrieving large amounts of data from underwater sensor nodes or AUVs, the interest in data muling solutions is increasing. The key idea is the use of a mobile vector such as an AUV, hereafter called “mule” to physically carry data in its internal memory. A mule is characterized by its ability to move, to relocate other agents (mules or source/sink nodes), and to communicate with a high-bandwidth, short-range communication system that involves docking or not. This idea of using mobile entities within the network was exposed in [11], using random moving entities.

Literature provides several data muling scenarios in the underwater environment. The first considers the case of Underwater Sensors Networks (USNs) where a series of sensing nodes (such as environment monitoring stations) collect data, which is stored locally, and where a mule is periodically sent to visit the nodes and collect the data to bring them to the surface. This is a specific instance of Travelling Salesman Problem (TSP), solved using optimization algorithms (simulated annealing, genetic algorithms, *etc.*) with constraints such as the node coverage or the energy used [3][8][12]. The energy constraints of this problem are addressed by putting a reloading station on the sea floor in the middle of the sensor network or by using a larger ship on the surface that has some means of energy production (solar panels, generators) and a surface docking station to reload AUV [3]. In addition, underwater data gathering problems are also studied with multi-communication regarding the criticality of the data, or spatial layer introduced in the network [1], [7], [14]

A second use case is long range communication in the

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vertical plane (bottom to surface) using one or more mobile agents. Two experimental results presented in [10], [13], tackle the problem of developing a solution where a few AUVs go down to the node, download its data and come back to the surface. Teixeira *et al.* [13] developed a protocol called Underwater Data Muling Protocol (UDMP) protocol to retrieve data from a node or an AUV over a long range. In this protocol, they considered that the node always has a secondary acoustic communication link with the sink point to request data; this is feasible in the vertical plane when the channel depth is not too important (a few hundred meters). They provided a comparison of the impact of the size of the batch of data transported, the number of mules, and the distance travelled by the mule on the overall throughput of the whole system. Then they experimentally showed their solution solves their problem. A limitation of their approach is that mules cannot communicate with each other, but only with the sensor node and the surface ship.

In this paper, we focus on a scenario where one fixed *source* node producing data is separated, by a large distance, to one fixed *sink* node. Our study considers moving mules to transfer information between the source and the sink. These mules travel along a path going from the source to the sink. Each mule in the relay system is assigned to a specific section of the path, which can be fairly large. At the edge of its path section, it can communicate with the agent (another mule or the source/sink nodes) of the neighboring path section. The mule can travel within its assigned path section to physically transport the data and act as a moving relay. To put things into perspective, this is nothing more than a transposition of the short-lived Pony Express mail service (April 3, 1860 – October 26, 1861) to the marine case! We review the pros and cons of this system and compare it with the one inspired from [13]. We will show that, depending on physical parameters such as speed, data transfer rate, *etc.*, this solution improves the data throughput of the system. We believe this is the first time this scenario is formalized in the literature.

To do so we will go through these three different metrics that are interested in building up a data muling solution.

1) *Equivalent throughput*:: To characterise the performance of the model, we use the metric introduced in [13]: the equivalent throughput $R_{b,eq}$ defined as the total amount M of data to transfer over the time, T_{total} , it took to be delivered:

$$R_{b,eq} = \frac{M}{T_{total}} \quad (1)$$

The expression of T_{total} will be detailed for each scenario.

2) *Latency*:: Data muling is known to add latency within networks [11]. Here, latency refers to the span between the moment one data packet is emitted by the source and the moment it arrives at the sink.

3) *Energy*:: Another key performance indicator is energy. In general data muling scenarios, energy is spent to communicate and to move. For this paper, energy will be a function of the number of communications and total travelled distance.

The rest of the paper is organized as follows: in Section II we present a linear and circular data muling scenario. In Section III, we compare their performance. Section IV presents

an implementation of the scenarios and Section V concludes the paper.

II. SYSTEM MODEL

Let the set of agents be designated as $\mathcal{N} = \{n_0, n_1, \dots, n_{N+1}\}$, where agent n_0 and n_{N+1} are the data source (\mathcal{S}) and sink (\mathcal{D}), respectively. The others are the “mules”. The source is the agent producing the data, while the sink is the agent that waits for the data. All agents can communicate in a maximum range d with a data rate R . The mules have a limited memory m .

We assume that the agents move along a polygonal line. The position of agent n_i is uniquely described by a curvilinear abscissa p_i . Without loss of generality, we may consider this polygonal line to be a simple line. We further assume that the source and sink are static, with $p_0 = 0$ and $p_{N+1} = D$. We shall denote by vector $\mathbf{p} = \{p_0, p_1, \dots, p_{N+1}\}$ the positions of all agents at a given time; the dependence on time is implicit and left out for the sake of brevity. We assume that the other agents can move at a speed of modulus v_{mule} and that they are initially evenly distributed between p_0 and p_{N+1} in areas of length L . This length L depends on the scenario. For this paper, to simplify the study, we assume the navigation range and positioning accuracy are not an issue, meaning that the navigation range is infinite and positioning is accurate. Also, we consider that agents never fail and that the environment disturbs neither communication nor navigation.

A. Communication time

We assume all agents can communicate. The communication time with our hypothesis is a combination of the amount m of data to exchange in bits, the data rate R in bits/seconds, and the propagation time $\frac{d}{c}$ in seconds, where c is the celerity of the communication channel in meters per seconds (1500 m/s for underwater acoustics, about 2.25×10^8 m/s in underwater optics) [9]. We add a term T_{rdv} as a penalty to model the initialization time when communication must occur.

If the distance between two agents is d , the range of the modelled communication system is:

$$T_{com} = \frac{m}{R} + \frac{d}{c} + T_{rdv} \quad (2)$$

In the following, we will neglect the channel latency term d/c for convenience and because, in most cases, it is negligible for short-range communication, being small in front of the time to transmit all data.

B. A linear scenario

A first possible scenario could resemble the one presented in Fig. 1. To create a communication link between agents n_0 and n_{N+1} , the mules are distributed in non-overlapping areas of length L . The space between the areas is equal to the communication range d . By dividing distance D in N equal chunks separated by the communication range d , we end up with:

$$L_{lin} = \frac{D - (N + 1)d}{N} \quad (3)$$

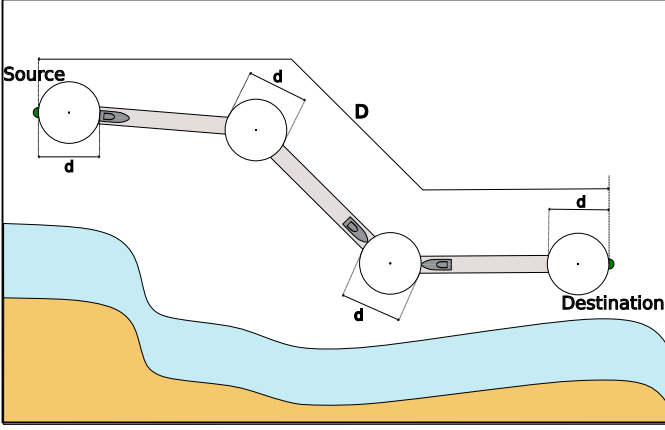


Fig. 1. Linear data muling scenario to transmit data from agent n_0 to n_{N+1} over the distance D

So, for $i \in [1, N]$, the i -th mule lies in interval $[id + (i - 1)L, id + iL]$.

For our study, we consider the following generic operational scenario in which mules are distributed over a straight line that joins the source to the sink:

1) *Situation*:: Let's have an amount M of data in the agent n_0 to send with our data muling protocol. This amount of data is divided into $P \in \mathbb{N}^*$ packets, to be adapted to the memory capacity m of the mules.

2) *Initialisation*: The agent n_0 is placed in the abscissa 0 and the agent n_{N+1} in D . Then we compute the position and the bounds for the roaming area of each mule, as defined in 3. After that, mules are initialized at their lower bound:

$$\forall i \in 1..N, p_i(t = 0) = id + (i - 1)L$$

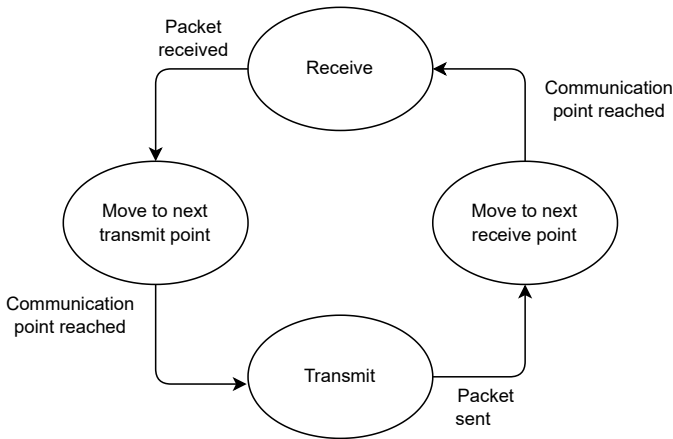


Fig. 2. State machine describing the behavior of a mule

3) *Behavior of a mule*: Each mule follows the state machine shown in figure 2. After initialization, each mule is in the state "Receive", on the lower bound of its area. Once a mule is fully loaded with data, it switches to state "Move to next transmit point" and moves towards the other bound of its area. When the mule reaches the communication point, and when communication is allowed (i.e., the next mule is at a distance $\leq d$), the loaded mule sends all its data loaded to the next

mule. Its state changes to "Move to next receive point". Having done so, it waits for another batch of data. We ensure that we are not locked in the state because of our hypotheses of perfect navigation and communication and by the definition of the areas. This simple state machine fully describes the behavior of a mule in a simulation context. To implement data muling in real life, failure management, a rendezvous solution and communication protocols must be added.

In the above scenario, latency is expressed as the time to send one packet of size m from the source to the sink:

$$T_{latency}^{lin} = (N + 1) \times T_{com} + N \times T_{travel}^{lin} \quad (4)$$

...with T_{com} referring to the communication time, T_{travel} the travel time of a mule over its area L_{lin} i.e $T_{travel}^{lin} = \frac{L_{lin}}{v_{mule}}$. In most cases there is more than one packet to transmit; if P is the total number of packets, the total transmission time becomes:

$$T_{total}^{lin} = T_{latency}^{lin} + (P - 1)(2 \times (T_{com} + 2 \times T_{travel}^{lin})) \quad (5)$$

Here T_{total}^{lin} represents the total time of data transmission fairly well, but it does not express the distance traveled and short-range data transfers. For each mules, those two quantities are equal to:

$$n_{com/mule}^{lin} = 2P \quad (6)$$

$$d_{travel/mule}^{lin} = 2PL_{lin} \quad (7)$$

C. A circular approach

In their paper, Teixeira *et al.* [13] use a circular data muling. In this scenario, the mules can only communicate with the source and the sink but do not communicate with another. Therefore, mules will travel the entire distance, $L_{circ} = D - 2d$ from the source to the sink to carry data. The latency to transmit one packet of size m to the sink is now :

$$T_{latency}^{circ} = 2T_{com} + T_{travel}^{circ} \quad (8)$$

$$(9)$$

And the total time to transmit the data becomes:

$$T_{total}^{circ} = T_{latency}^{circ} + \frac{(P - 1)(2T_{com} + 2T_{travel}^{circ})}{N} \quad (10)$$

both with $T_{travel}^{circ} = \frac{L_{circ}}{v_{mule}}$

The number of communication events and the distance travelled are, respectively, for each mule:

$$n_{com/mule}^{circ} = 2 \frac{P}{N} \quad (11)$$

$$d_{travel/mule}^{circ} = 2 \frac{P}{N} L_{circ} \quad (12)$$

$$(13)$$

III. COMPARISON

We compare in this section the scenarios described above and give some practical considerations. According to the models above, we can estimate the total time needed to send a fixed amount of data, by varying the speed of the mules and the communication interface.

A. Transmission time

The comparison of the two models leads to the following criterion regarding the data transmission latency:

$$T_{latency}^{lin} - T_{latency}^{circ} = (N - 1) \left(T_{com} - \frac{d}{v_{mule}} \right) \quad (14)$$

The total transfer time generalizes this criterion:

$$T_{total}^{lin} - T_{total}^{circ} = K \left(T_{com} - \frac{d}{v_{mule}} \right) \quad (15)$$

where $K = \left(1 + \frac{2(P-1)}{N} \right) (N - 1)$.

The sign of this criterion is driven by a factor $T_{com} - \frac{d}{v_{mule}}$, which is equivalent to comparing the time to send data over the short-range wireless interface to the time for a mule to travel a distance equal to the communication range (the second term). When the criterion is negative, the time to travel distance d at mule speed exceeds the time to communicate over this distance d . If this happens, the linear model is more suitable. Otherwise, it is cheaper for the mules to move, and the circular model is best. However, in an underwater world, T_{com} is generally greater than $\frac{d}{v_{mule}}$. So, with respect to latency, the linear scenario is less suitable than the circular case.

B. Energy

The energy spent by each mule can be approximated by the sum of $n_{com/mule} \cdot P_{com}$ and $d_{travel/mule}$.

Regarding the expressions of the number of communication events, circular muling is more economical. For navigation, the first thing that appears is that in circular muling, the mule will travel over a longer distance at each time. The difference of both total travelled distances is:

$$d_{travel/mule}^{lin} - d_{travel/mule}^{circ} = -2 \frac{P}{N} (N - 1) d \quad (16)$$

This expression is always negative: a mule in the linear approach travels less than a mule in the circular approach, by a factor $-2 \frac{P}{N} (N - 1) d$.

IV. IMPLEMENTING DATA MULING

To illustrate data muling, we performed an experiment at Lake Guerlédan (Brittany, France) in April 2023. A sink was located 78 meters away from the source, at coordinates (64, 46) meters using the source as the origin. The parameters are provided in the table I. Two small Unmanned Surface Vehicles (USVs) acted as mules. In the following, we detail their architecture and the algorithms they ran.

A. DDBoats

The USV are DDBoats (Fig. 3) which are toy remote-controlled boats modified at ENSTA Bretagne to run autonomously, initially as teaching aids, but also used to experiment with robotic swarms and multi-robot missions (up to twenty). All DDBoats have the same architecture. They integrate a 9 Degrees of freedom (DoF) Inertial Measure Unit (IMU) with a magnetometer, and a Global Navigation Satellite System (GNSS) receiver, all integrated using

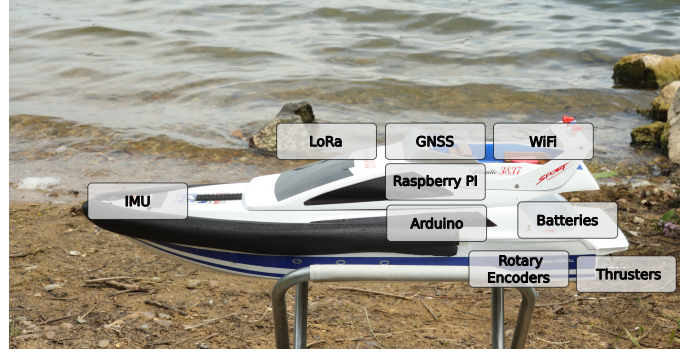


Fig. 3. A “DDBoat” with its electronic architecture

a Raspberry Pi+Arduino setup using the ROS middleware (www.ros.org). The DDBoats communicate using a WiFi antenna. They have also a LoRa antenna which is unused here. The only actuators are two independent propellers whose rotation speed is controlled.

This section describes the different steps to implement data muling and the basic steps to make it work. A generalized, simple model for a mule is a collection of times spent to receive data, times spent to reach a sending point, times to relay the collected data, and times to reach the next agent. The state machine represented in Fig. 2 summarizes this behavior. To implement data muling is to find a technical solution for:

- A communication interface that can be connected/disconnected when agents to communicate with are within range
- A path planning algorithm to provide the next rendezvous point
- Commands to allow the mule to reach the rendezvous points

B. Communication

Because the DDBoats share a single WiFi network with an actual communication range exceeding the total distance between the source and sink, we used a software emulation to simulate a communication interface with a shorter range d and specific throughput. Each mule runs a custom-designed client to send data and a server to receive data from another mule client. Each client periodically sends its estimated position over the network, and the server enables communication only when they are in a predefined range d . The source and the sink are virtual: when the vehicles are within a range d of these points, they instead communicate with the control computer put ashore. Using this setup allows to simplify the experiment: rendezvous is made because GNSS-measured positions are robust and always available and communication using WiFi is simple. In real life, using underwater agents, that would be much harder to experiment.

C. Rendezvous point

Because our scenarios have predefined reference rendezvous points, we implemented them as parameters of the mission at the start.

D. Command and control

DDboats are differential controlled boats, meaning the difference of thrust between the two actuators controls the speed and heading. To compute the desired thrusts, we built up a waypoint follower algorithm based on a proportional controller computing the Rotation per Minute (RPM) instructions for actuators. Algorithm 1 explains how the error between the desired heading ϕ and the measured heading $\hat{\theta}$ is a feedback to compute the RPM control. Value RPM_{median} is the nominal RPM value used when the vehicle should advance without turning; it compromises between a decent speed, while limiting motor overheating and preserving control in the current. Factor k is a gain empirically set to 40. \mathbf{p} is the mule position, and \mathbf{w} is the position of the desired destination [5].

Algorithm 1 Waypoint Follower

- 1: **procedure** WAYPOINT($\hat{\theta}$, \mathbf{p} , \mathbf{w})
 - 2: $\phi = \arctan 2(\mathbf{p} - \mathbf{w})$
 - 3: $e = \text{sawtooth}(\phi - \hat{\theta})$
 - 4: $\text{cmdLeft} = RPM_{median} - k * e$
 - 5: $\text{cmdRight} = RPM_{median} + k * e$
 - 6: **end procedure**
-

The *sawtooth* function is used to avoid a problem of $2k\pi$ modulus. It can be taken as:

$$\text{sawtooth}(\theta) = \arctan(\tan(\frac{\theta}{2})) = \text{mod}(\theta + \pi, 2\pi) - \pi \quad (17)$$

E. Positioning

For the sake of our communications and navigation, the position is computed by the GNSS coordinate projected in a local Cartesian plane using the spherical Earth approximation, where x denote the eastings and y the northings. LAT_REF , LON_REF correspond respectively to the origin of the map, set at the source. Value ρ refers as the earth radius, while lat , lon are the latitude and longitude measured by the GNSS receiver.

$$x = \rho \cdot \cos\left(lon \cdot \frac{\pi}{180}\right) \cdot (lat - LAT_REF) \cdot \frac{\pi}{180} \quad (18)$$

$$y = \rho \cdot (lon - LON_REF) \cdot \frac{\pi}{180} \quad (19)$$

F. Results

Figure 4 and 5 expose the trace of the mules and their state. Firstly, compared to our model, the path of the mules is not a straight line: this is due to our control algorithm and some wind and current during the navigation. This effect is well represented in the distance travelled reported in table I, where mules in the linear scenario travel more than in the circular scenario. This discrepancy can explain the factor 12 between the theoretical apparent data rate and the experimental result. In addition, the short range data rate R shown in the table, is the average over all the communication events; but logs show the data rates are not constant as our formula state. The second point is that when evaluating energy consumption, we assumed

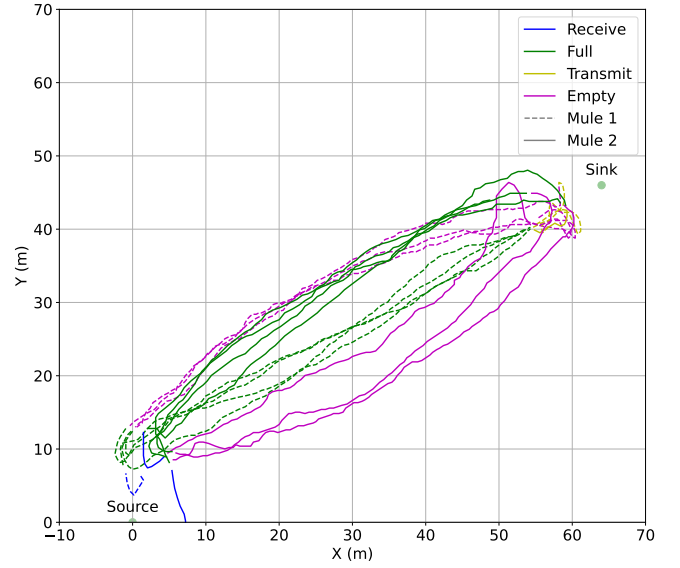


Fig. 4. Mule trajectories for a circular scenario

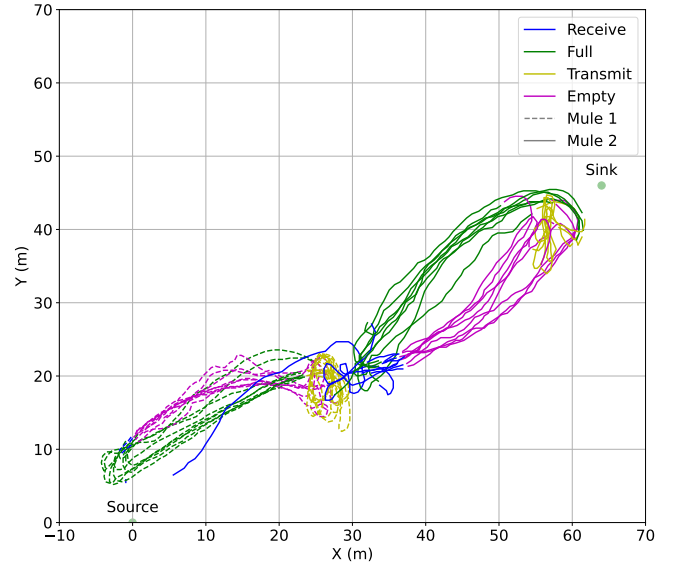


Fig. 5. Mule trajectories for a linear scenario

that mules had two behaviours: either they were mobile to travel between communication points or they were static when communicating. In our implementation, to do station keeping, mule needed to spend some additional energy to resist wind and current, which piles up as the number of communication events increases. Finally, our experiment could not validate the criteria comparing the circular to the linear scenario with respect to latency and total communication time. Due to the experimental parameters, the actual value of the criteria are not significant enough to be compared to theory. In fact, even if the latency criterion is negative, circular muling appears to be still better. This can be explained mostly by the fact that in the circular scenario, all mules communicate over the same network, leading to saturation, whereas in the linear scenario, one mule gathers data from the source and the other

	Symbols	Linear	Circular
Apparent data rate from equations	$R_{b,eq}$	90 kb/s	103 kb/s
Apparent data rate field experimentation	$R_{b,eq}$	73.6 kb/s	89.3 kb/s
Mission duration	T_{total}	916 s	755 s
Short range data rates	R	812 kb/s	814 kb/s
Communication time for one packet	T_{com}	14 s	9 s
Communication range	d	10 m	10 m
Rendezvous Time	T_{rdv}	0 s	0 s
Speed	v_{mule}	0.9 m/s	0.8 m/s
Packet Size	m	1.06 MB	1.06 MB
Number of packets sent	P	8	8
Distance zone	L	28 m	68 m
Distance travelled by mule	$d_{travel/mule}$	563 m — 598 m	501 m — 485 m
Total travel time	T_{total}	669 s — 596 s	662 s — 587 s
Criteria		-0.66	-2.9

TABLE I
PARAMETERS AND RESULT OF THE EXPERIMENTATION

communicates with the sink. Another experiment would be welcome to better compare theory with practice.

V. CONCLUSIONS, FUTURE WORK

Long range, high data rate communication is a key topic for future years. Because of limitation of wireless communication in the underwater environment, there is no such communication system today. This paper exposes data muling, exposing two variants (linear and circular), modeling them functionally and mathematically. The models are valid whatever the environment (underwater, surface, aerial) and whatever the communication system, even if our first motivation was underwater communication. This makes the model suitable for very high-level simulation.

We then exposed a simple data muling experiment using surface vehicles. We showed that, for underwater communication, circular muling is the best variant in terms of data rates, while the linear variant can have its advantages too, especially in the case where communication paradigm could change (environment change, another communication system...).

We believe data muling is a worthy approach to consider to get data in near real-time from highly data-producing sources, instead of awaiting for these sources to come back to surface or back to the harbour to unload them.

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