AUVs Telemetry Range Extension through a Multimodal Underwater Acoustic Network

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***Abstract*—In this paper, we describe an underwater multi-hop network scenario based only on acoustic modems operating at different frequencies. The idea is to remotely control an Autonomous Underwater Vehicle (`AUV`) and verify whether it is able to follow the path sent by a control station (`CTR`) in the form of consecutive waypoints. The `AUV` sends back packets that can be monitoring or control information. We tested by simulation different MAC layer protocols to compare their performance in terms of throughput and packet delivery delay, in particular focusing on both contention-free (TDMA-based) and contention-based (CSMA-based) protocols, to analyze which solution performs better in different network conditions varying the amount of traffic generated by the `AUV` during its mission.**

***Index Terms*—Underwater acoustic networks, AUV, DESERT Underwater simulator, multimodal networks, multi-hop networks, MAC protocol simulations**

I. Introduction and Related Work

Underwater networks combined with modern vehicles and sensors are an enabling technology for ocean exploration and monitoring [1]. These types of networks can be used to monitor underwater oil pipelines, to control water conditions in emergency situations and to explore the coastal ocean environment, but also to explore new underwater resources. Both coastal exploration and pipeline monitoring activities can be carried out through Autonomous Underwater Vehicles (`AUV`s) and Remotely Operate Vehicles (`ROV`s) [2], controlled wirelessly using acoustic [3], optical [4] or radio-frequency (RF) technologies [5]. Although the absence of a direct connection between the controller (`CTR`) and the vehicle reduces the available data rates, removes the possibility of a real-time communication and increases the power requirements, it also allows more freedom from the mobility point of view [6]. The `AUV` can also have multiple operational modes depending on the type of technology: for example, simple mandatory and control movements for acoustic connections and full control capabilities with high-definition image streaming when an optical transmission is available.

Wireless communications in the underwater environment are affected by some constraints, for example, radio-frequency (RF) and optical technologies can be used only for very short distances since their signal attenuates very rapidly [7]. On the other hand, although acoustic transmissions can be used for long-range communications, they suffer from limited bandwidth, low propagation speed or equivalently large propagation delay, and rapid time-varying channel [1]. From these considerations, it appears that a multimodal system that combines different communication technologies can be useful to improve network performance and flexibility, in terms of scenario heterogeneity. The multimodal paradigm has been firstly introduced in [6], where the authors discuss the bandwidth requirements to provide some operational modes during a monitoring mission as a function of the distance. They show that for short-range communications the best solution is the optical technology, which allows very high throughput of the order of Mbit/s, while the acoustic channel offers long-range transmissions, up to several kilometers, at the cost of a higher transmission delay (order of seconds) and a lower bitrate, of the order of kbit/s or less. Similarly, in [7], the authors present an accurate simulation of a master-slave multimodal scenario where acoustic and optical technologies are employed. The technology switching mechanism is based on the power received by the controller during the `AUV` transmission and they compare two different approaches. The first quantizes the time into slots and the metric evaluation is done at the end of each slot while the other proposes an explicit signaling mechanism to guarantee a faster reaction. In [8], a data delivery system for a submarine surveillance scenario is described. Sensor nodes upload data to an Autonomous Underwater Vehicle (`AUV`) via optical technology and coordinate with each other using acoustic communications. The `AUV`, in the end, transmits the data to a collection point using an RF channel. Another interesting solution is reported in [9], where the authors propose a protocol with multi-band acoustic modems that change the transmission frequency to overcome the presence of noise sources. In that case, sensors monitor periodically the noise level and the migration of a portion of the network to a different frequency is organized when the level goes above a certain threshold.

When dealing with these networks, it is also important to define the path followed by the `AUV` during the mission. Specifically, the trajectory can either be predefined, i.e., computed using a path planning algorithm [10], or transmitted as a sequence of waypoints in the three-dimensional space (x, y, z), where z is the depth with respect to the sea level.

For our simulations, we choose the second strategy and more precisely the waypoints are sent at a constant rate based on the speed of the vehicle and the distance we need to cover.

In this paper, we analyze a multimodal multi-hop network scenario, where both medium frequency (MF) and low frequency (LF) acoustic modems are employed in the same network, used to remotely control an AUV that moves inside a certain area. The AUV follows the path sent by a control station (CTR) and sends back monitoring packets to the CTR. In our analysis, we compare the performance in terms of throughput, packet delivery delay (PDD) and packet error rate (PER), of two different multi-hop networks with a linear topology that cover more or less the same distance between AUV and CTR. First, we analyze a multi-hop single technology (ST) network, similar to the one described in [11], where all the nodes are equipped with the same MF acoustic modem. Then, we propose a multimodal (MM) network solution with two acoustic modems, operating at different frequencies, where both contention-free (TDMA-based) and contention-based (CSMA-based) MAC protocols are evaluated. The ST network is used as a benchmark to evaluate the performance of the proposed solution.

The rest of the paper is organized as follows: in Section II-A and Section II-B we describe topologies and MAC layer solutions of the ST and MM networks, respectively. In Section III we talk about the protocol stack designed for the DESERT (DEsign, Simulate, Emulate and Realize Test-beds) underwater network simulator [12], freely available at [13], and used in our simulations. Section IV introduces the simulation scenario and the system parameters. In Section V we depict the results of the simulations and compare the performance of the proposed MM scenario with respect to the ST configuration. Finally, in Section VI we draw some conclusions.

II. AUV Control Range Extension Approaches

The main purpose of this paper is a performance-oriented comparison of different acoustic networks configured to extend the working range of an AUV during a patrol mission of a certain area. This coverage problem is typically solved through the deployment of multiple intermediate single technology (ST) acoustic relays that forward the packets coming from the CTR and destined to the AUV and vice-versa. This first approach, presented in Section II-A, is used as a benchmark for a more advanced solution, that requires the use of a two-hop hybrid multimodal network (MM) that combines different acoustic modems. This second approach is presented in Section II-B.

A. Range Extension via Single Technology Multi-Hop Networks

The ST network topology used in this paper for extending the AUV control range is presented in Fig. 1. In this case, all the nodes are equipped with the same acoustic modem and, therefore, use the same bandwidth for packet transmission. The MAC layer strategy employed in this scenario is an advanced TDMA-based protocol, similar to the one presented in [14],

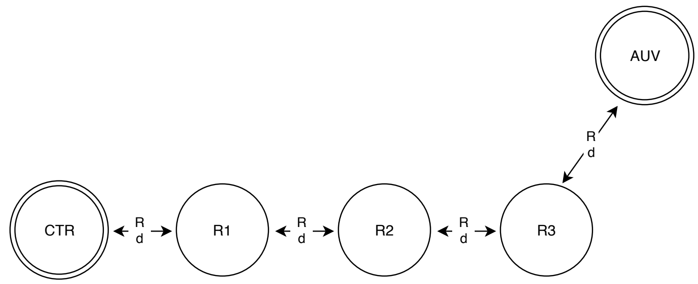

Fig. 1. ST network topology.

that implements a customized time division multiple access where it is possible to control the frame duration (number of slots in each frame) and also the slots assignment. For example, it is possible to schedule more than one slot to the same node within a single frame. Moreover, in the case of multi-hop networks with a sufficient number of nodes, this configuration presents the possibility of using both the pipeline mechanism and the near-far effect, exploiting the high propagation delays, and scheduling simultaneous transmissions in different parts of the network [15]. Using the near-far effect, two adjacent nodes can transmit simultaneously without interfering with each other if the propagation delay is larger than the time needed to transmit a packet. Therefore, once the distance between consecutive nodes is fixed, we have implicitly imposed also the maximum packet length that can be successfully transmitted. This protocol is included in the DESERT Underwater simulator as a MAC layer module, called TDMA_FRAME.

The frame of the TDMA scheme needs to be specifically designed in order to ensure network stability and avoid traffic congestion. Indeed, the nodes generating traffic, i.e., CTR and AUV, must have a total cumulative number of transmission opportunities smaller than or equal to that of each relay. Thus, if in a time frame T_{Frame} both CTR and AUV transmit once, each relay must transmit at least twice within T_{Frame}. The frame allocation used in our simulations is reported in Table I. It can be noticed that both pipeline mechanism and near-far effect are exploited. Indeed, R_1 and AUV can transmit in the same slots, since they are sufficiently separated in space to not interfere with each other. Moreover, R_2 and R_3 transmit simultaneously exploiting the near-far effect. Each node can transmit up to one packet in each assigned time slot. It might be argued that in slot 1, when both R_1 and AUV

TABLE I
Frame of the ST scenario.

Slot N°	1	2	3	4
Node	CTR R_1 AUV	R_1	R_2 R_3	R_2 R_3

are transmitting, they may collide at R_2, as AUV is moving around the coverage area of R_3. In Table II we prove that the presented frame avoids this issue as during slot 1 R_1 transmits only packets for CTR, while it transmits the packets for R_2 in slot 2, where the transmission is not parallelized and, therefore, the collision cannot occur. This Table shows the node queues evolution in three consecutive time frames, where CXX is a control packet generated from CTR to AUV, and MYY is a monitoring packet generated from AUV to CTR, with XX and YY the sequence number of the C and M packets, respectively.

TABLE II
TIME FRAME EVOLUTION ANALYSIS OF THE NODE QUEUES IN THE ST SCENARIO.

Slot N°	CTR	$R1$	$R2$	$R3$	AUV
1	C1				M1
2		C1		M1	
3			C1	M1	
4			M1	C1	
5	C2	M1			M2 **C1**
6	**M1**	C2		M2	
7			C2	M2	
8			M2	C2	
9	C3	M2			M3 **C2**
10	**M3**	C3		M3	**C2**
11			C3	M3	
12			M3	C3	

Although this MAC configuration is very efficient when the AUV moves around R_3, it does not work in the case where the AUV patrols all the area spanning from CTR to R_3. This is a different scenario, where the network topology changes in time, and static routing cannot be employed. Such situation has already been addressed in [11], where a different time frame is used and a specific routing protocol is presented. Such routing protocol, called Estimate-Position Based Routing (EPBR), uses information related to the AUV position to decide the next hop. In this paper we only consider a static topology with the goal to extend the control range of an AUV through a predefined route, thus, in this case a static routing can be employed, because the vehicle always moves near R_3, the farthest relay from the control station.

B. *Range Extension via Multimodal Networks*

The MM network topology used in this paper to extend the AUV control range is depicted in Fig. 2. In this scenario only one intermediate relay is used, equipped with two different acoustic modems. Specifically, the relay is a multimodal node equipped with two technologies working on non-overlapped bands, e.g., one operating at low frequency (LF), and the other at middle frequency (MF). CTR, instead, is equipped with

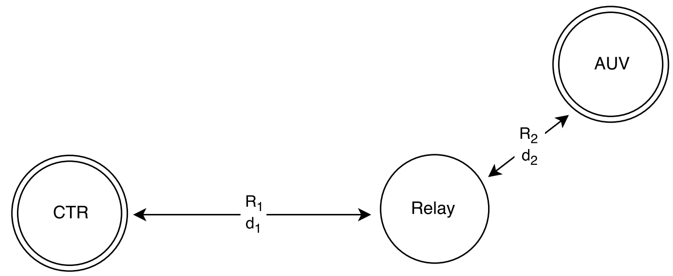

Fig. 2. MM network topology

only an acoustic LF modem, and AUV with acoustic MF. This smart design choice provides an interesting degree of freedom from the channel access point of view. In fact, the relay can communicate at the same time with both CTR and AUV without dealing with any interference problems. In particular, we can consider this network as the composition of two very simple independent networks, one composed by CTR and the relay connected through the LF modem, the other composed by the relay and AUV connected through the MF modem. In this paper we refer to the former network as NET_LF and to the latter as NET_MF.

This channel access freedom significantly simplifies the MAC layer design and opens the possibilities for hybrid MAC solutions such as a contention-based protocol for nodes transmitting with LF, and a contention-free MAC for nodes transmitting with MF. In the following we describe the four different MAC combinations that will be analyzed in Section V.

*1) **TDMA - TDMA**:* This is the simplest case, in fact, it is our starting point for the evaluation of the proposed scenario. Here, both subnetworks use a standard TDMA strategy, the only difference between NET_LF and NET_MF is the length of the time slots t_{slot}. Indeed, in NET_LF the distance between the nodes is twice that in NET_MF, hence, the propagation delay in NET_LF is two times that experienced in NET_MF. Moreover, also the transmission time changes because the bitrate of the two networks is not the same. Details on the frame size and the parameter configuration are presented in Section IV.

In each subnetwork we choose to implement a TDMA MAC layer with only two time slots: the structure of these basic frames is reported in Table III. In our configuration, only one packet per slot can be sent, like in the ST scenario.

TABLE III
SLOT ASSIGNMENTS IN NET_LF AND NET_MF

Slot N°	1	2
Node	CTR	Relay

Slot N°	1	2
Node	AUV	Relay

*2) **CSMA - TDMA**:* Moving to a slightly more complicated solution, we have a hybrid configuration that combines a contention-based and a contention-free protocol. The contention-based protocol selected for this analysis is CSMA 1-persistent [16], available in the DESERT Underwater simulator as a MAC module, called `CSMA_ALOHA`. This module is adopted in `NET_LF` while in `NET_MF` we use again standard TDMA with two slots. The frame structure is presented in Table IV.

TABLE IV
SLOT ASSIGNMENTS IN NET_MF

Slot N°	1	2
Node	AUV	Relay

*3) **TDMA Frame - TDMA**:* In this configuration, we adopt two contention-free protocols. More precisely, in `NET_LF` we use the `TDMA_FRAME` module already presented in Sec II-A, while for `NET_MF` we choose a standard TDMA protocol with only 2 time slots. During the simulations of the simplest case with two independent TDMA described in Sec. II-B1, we observed that many slots reserved for the `CTR` are not actually used. This situation happens because the control station sends a packet containing the waypoint every T_{CTR} seconds while a reserved slot is available every T_{FRAME} seconds, with $T_{FRAME} < T_{CTR}$. A smarter solution, that aims to manage this inefficiency, consists in the design of a suitable frame with $T_{FRAME} \simeq T_{CTR}$. For instance, this requirement can be achieved with a frame where only one slot is reserved for the `CTR` and all the remaining slots are assigned to the relay. The frame structure considered in this paper is reported in Table V.

This particular mechanism greatly increases the number of packets per frame generated by the `AUV`, that can be received by the `CTR`. This happens because the relay has more transmission opportunities to transfer the monitoring packets received from the `AUV`.

TABLE V
SLOT ASSIGNMENTS IN NET_LF

Slot N°	1	2	3	4	5	6	7
Node	CTR	Relay	Relay	Relay	Relay	Relay	Relay

*4) **TDMA Frame-CSMA**:* We close the overview of the proposed solutions describing this last configuration. Again, we have a hybrid solution like in Section II-B3. In this case, in `NET_LF` we use a `TDMA_FRAME` module with the time frame described in Table V, while in `NET_MF` we adopt the CSMA 1-persistent MAC presented in Section II-B2.

*5) **Excluded MAC configurations**:* Also other MAC combinations could be inspected, such as employing CSMA in both `NET_LF` and `NET_MF`, or `TDMA_FRAME` in both `NET_LF` and `NET_MF`. The former solution has been excluded due to the high probability of deafness in long range low frequency networks, such as `NET_LF`, while the former solution provides benefits only if the TDMA frames of both technologies are synchronized. This is in general not easy (or not even possible), as the time slots duration differ per technology according to packet size and distance between nodes.

III. DESERT UNDERWATER SIMULATOR

All the simulation results described in this paper are obtained using a set of C/C++ libraries that reproduce underwater communications through different transmission technologies. In this case we have used only acoustic modems, but also optical and radio-frequency physical layers are available for testing. In principle, the simulator allows the definition of customized network scenarios in terms of number, location and mobility of the nodes, MAC addresses and, more importantly, the protocol stack implemented in every single node.

As an example, in Table VI we report the protocol stack used for the simulation of the multimodal relay described in Section IV-B.

TABLE VI
MULTIMODAL PROTOCOL STACK.

UW APPLICATION LAYER	
UW STATIC ROUTING	
UW MULTI_DESTINATION	
UW MAC 1	UW MAC 2
ACOUSTIC PHY 1	ACOUSTIC PHY 2

In the relay the application layer does not generate traffic as the relay only forwards packets to extend the transmission range of the control station, while `CTR` transmits periodic control packets and `AUV` generates monitoring packets according to a Poisson process. Given the relatively simple topology, we choose a static routing approach. The most important part of the `MM` relay communication stack starts with the `MULTI_DESTINATION` layer, presented in Section III-A. More precisely, we can observe that the lower layers (`MAC` and `PHY`) are duplicated. In general we will have as many copies as the number of different physical layers we want to simulate. Using this particular structure, it is possible to have simultaneous transmissions on the two physical layers. Finally, for each acoustic physical layer we can define transmission frequency, bandwidth, transmission power, transmission bitrate and interference model. The implemented acoustic propagation and noise models are presented in [17].

A. Implementation of the `MULTI_DESTINATION` module

In order to implement the behavior of the multimodal relay, we developed a new module in the DESERT Underwater simulator, called `MULTI_DESTINATION`. The basic idea is a switching mechanism that performs the following operations. For each packet ready to be transmitted, it first checks the IP address of the packet destination, and then chooses the right physical layer technology to use for the transmission.

The selection is performed through a technology per node map, where the `MULTI_DESTINATION` stores the list of physical layers available in each node, and selects the best performing one within range. In our case this list is assumed to be known at network deployment, however, a periodic topology discovery mechanism [18] might be employed to update this list periodically. For example, in the MM network with the three nodes used for our simulations, we defined an address map where CTR, relay and AUV have IP address 1, 2 and 3, respectively. The relay hence has two possibilities: if the destination address is 1, it chooses the LF technology to reach the CTR, while if the destination is 3, it chooses the MF technology. The complete protocol stack is described in Table VI.

IV. System Scenario and Simulation Settings

In our simulations, we analyze a scenario where the control station (CTR) commands at distance the AUV sending waypoints at a constant rate, one packet every T_{CTR} = 50 seconds. On the other side, the AUV moves at a fixed speed (v_{AUV} = 1 m/s) towards the last received waypoint, and sends back monitoring packets generated according to a Poisson process with average generation time equal to T_{AUV} seconds. In Section V, the network performance will be evaluated in different traffic conditions, varying T_{AUV} within a suitable range.

In all the TDMA-based configurations, the length of each slot t_{slot} is computed from Eq. (1):

$$t_{slot} = \frac{d_{max}}{c} + \frac{8 \cdot L_{max}}{R} \quad (1)$$

where the first term is the propagation delay, computed as the ratio between the maximum distance between two adjacent nodes (d_{max}) and the sound speed underwater ($c = 1500$ m/s), while the second term is the time needed to send a packet of L_{max} bytes at bitrate R. This slot duration guarantees that each single packet has enough time to reach the intended destination and takes into account that acoustic underwater communications are affected by very high propagation delays. Moreover, in each slot, we identify a guard time exactly equal to the propagation delay during which the node can not transmit, to avoid collision between transmissions in consecutive slots. In our simulation we assume nodes to be perfectly synchronized. This assumption can be relaxed by adding an additional guard time, however, modern atomic clocks can be employed in the submerged nodes to ensure an almost perfect synchronization between them [19]. Since we want a fair comparison, the length of the packets (L_{CTR} and L_{AUV} respectively), T_{CTR} and the range of possible values for T_{AUV} are the same in both the considered scenarios. The parameters are listed in Table VII.

All the node positions are defined in the three-dimensional space using three coordinates (x, y, z) where z is the depth with respect to the sea level and by definition is always negative, i.e., $z = -1000$ m. In a similar way, also the waypoint consists of a triplet (x, y, z) that defines the next position where the AUV needs to go to continue its mission. The control station and the relays are fixed nodes anchored to the sea-floor to maintain a stable position.

TABLE VII
Simulation parameters.

Parameter	Value
L_{CTR}	1000 byte
T_{CTR}	50 s
L_{AUV}	1000 byte
T_{AUV}	[4, 60] s
v_{AUV}	1 m/s
f_{LF}	12 kHz
BW_{LF}	5 kHz
P_{LF}	187.8 dB Re μPa
R_{LF}	3500 bit/s
$d_{max,LF}$	7000 m
t_{LF}	7 s
f_{MF}	26 kHz
BW_{MF}	8 kHz
P_{MF}	184 dB Re μPa
R_{MF}	4800 bit/s
$d_{max,MF}$	3500 m
d_{ST}	3000 m
t_{MF}	4 s

A. Single Technology (ST) Scenario

The ST scenario has a linear topology, depicted in Fig. 1, with five nodes: CTR, AUV and three intermediate relays (R_i with $i = 1, 2, 3$). In this case, the AUV moves around the last relay (R_3). The distance between consecutive nodes is $d_{ST} =$ 3 km, while the number of relays is set to 3 and the AUV moves around an area 1.5 km apart from R_3, thus, the maximum distance between CTR and AUV is 10.5 km. Each node is equipped with the same MF acoustic physical layer, used to simulate the behavior of real acoustic modems, such as the Evologics S2CR 18/34 [20]. It transmits at a frequency f_{MF} 26 kHz with bandwidth BW_{MF} = 8 kHz, transmission power P_{MF} = 184 dB Re 1μPa at 1 m, bitrate R_{MF} = 4800 bit/s, and maximum transmission range of $d_{max,MF}$ = 3.5 km. The slot duration, obtained with Eq. (1), is set to t_{MF} = 4 s. The parameters are summarized in Table VII.

B. Multimodal (MM) Scenario

The MM scenario, designed to evaluate all the MAC layer protocols proposed in this paper, is reported in Fig. 2. The topology is again linear but this time we have only 3 nodes: the control station (CTR), a single intermediate relay R and

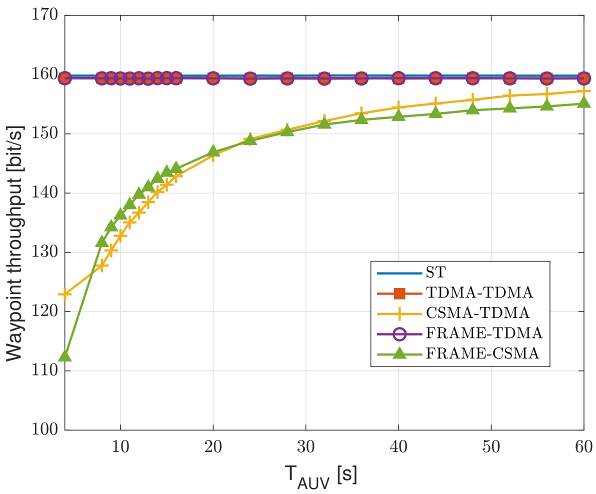

Fig. 3. Average throughput received by the AUV.

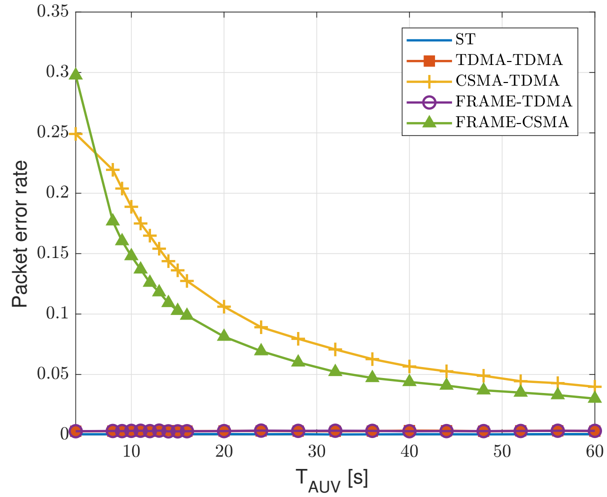

Fig. 4. Packet error rate of the waypoints.

the AUV. This new layout is possible thanks to the longer transmission range of the LF modem.
The total distance covered by this network is the same as in the ST network, i.e., 10.5 km, in order to have a similar use-case scenario. The distance between CTR and relay is equal to $d_{max,LF}$ = 7 km while the AUV moves around the relay within a maximum distance of $d_{max,LF}$ = 3.5 km. In this case we have two different types of transmission technologies: an MF acoustic physical layer, used to simulate the behavior of an Evologics S2CR 18/34 (already presented in Section IV-A), and an LF acoustic physical layer, used to simulate the behavior of an Evologics S2CR 7/17 [20]. This second physical layer is set to transmit at a frequency f_{LF} = 12 kHz, with bandwidth BW_{LF} = 5 kHz, transmission power P_{LF} = 187.8 dB Re 1μPa at 1 m and bitrate R_{LF} = 3500 bit/s (see Table VII).

In this scenario, not all the nodes have the same equipment. Specifically, the CTR is equipped only with LF, the AUV only with MF and, finally, the relay is a multimodal node equipped with both LF and MF, in order to communicate with both the CTR and the AUV. The two transmission bands BW_{LF} and BW_{MF}, centered in f_{LF} and f_{MF} respectively, do not overlap.

V. Results and Performance Comparison

All the results presented in this section are obtained by averaging over 35 independent simulation runs, where every single run simulates an AUV mission of 50 hours.

The results analysis is divided in two parts: the first part, presented in Section V-A, focuses on the network performance considering 6 different metrics, i.e., AUV delay, AUV throughput, AUV packet error rate, CTR delay, CTR throughput and CTR packet error rate; the second part, instead, analyzes the power consumption of the two networks.

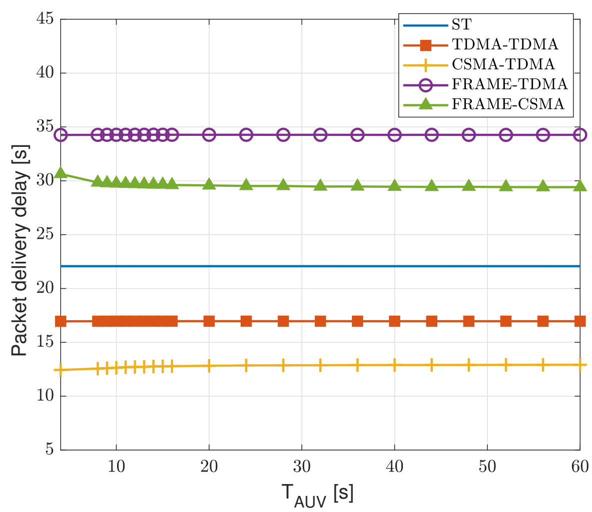

Fig. 5. Average packet delivery delay of the waypoints.

A. Network performance

Fig. 3 depicts the throughput received by the AUV, i.e., the throughput related to the waypoints sent by the control station. We can observe that in the two configurations with the CSMA-based protocol the throughput is lower than in the other cases. In particular, the throughput decreases as the monitoring traffic generated by the AUV increases. That is because in contention-based protocols deafness can occur and, therefore, some packets may be lost. Indeed, as reported in Fig. 4, in the configurations with the CSMA-based protocol, the packet error rate (PER) for the waypoints is non-negligible and increases as the generation of the monitoring traffic increases. Fig. 5 reports the average packet delivery delay (PDD) for the waypoints sent by the CTR to the AUV. The highest PDD has been obtained in the two configurations of the MM network that use the TDMA_FRAME reported in Table V.

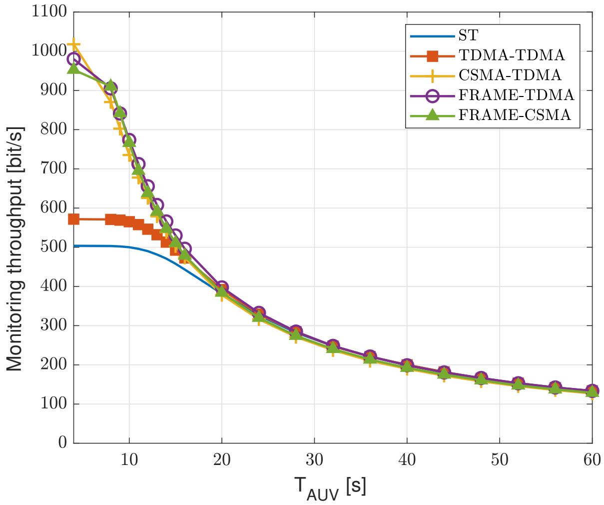

Fig. 6. Average throughput received by the control station.

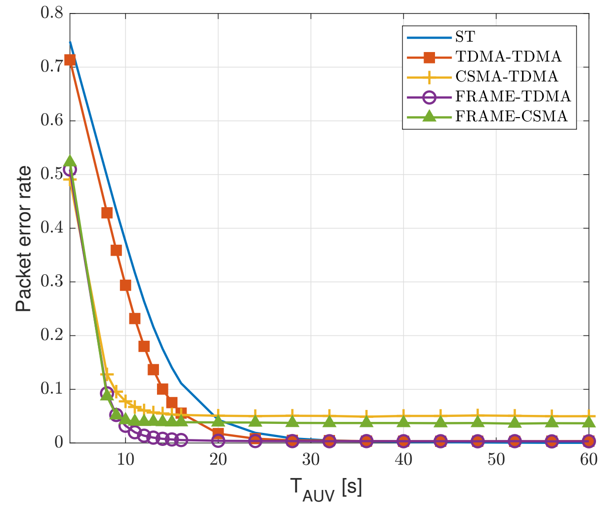

Fig. 7. Packet error rate of monitoring packets.

That is because with this configuration the control station has fewer transmission opportunities than in the other cases and the packets sent by the `CTR` wait, on average, more time for their transmission slot. Moreover, we highlight that the `PDD` is almost independent of the average generation time of the monitoring packets, T_{AUV}.

In general, for all the configurations based on a contention-free MAC protocol, we can observe that the value of T_{AUV} does not affect the performance related to the transmission of the waypoints. Differently, for contention-based protocols, a higher monitoring traffic also affects the transmission of the waypoints, because deafness can cause packet loss.

The monitoring throughput received by the control station is presented in Fig. 6. For values of $T_{AUV} \geq 20$ s, the throughput is similar in all the configurations. For $T_{AUV} < 20$ s, the `ST` solution has the worst results in terms of throughput with respect to all the other configurations of the `MM` scenario. The highest throughput is achieved using the TDMA Frame-TDMA configuration or using the two configurations with the CSMA protocol combined with TDMA or TDMA Frame. However, as reported in Fig 7, we can observe that the CSMA-based configurations have a higher `PER` with respect to the TDMA Frame-TDMA configuration. The `PER` is computed at the application layer, i.e., it takes into account also the packets lost due to buffer overflow. In the `ST` scenario, the `PER` starts to increase for values of $T_{AUV} < 30$ s. This means that the network is not able to support an average packet generation time lower than 30 s. In the TDMA Frame-TDMA configuration, the network is able to support a minimum value of T_{AUV} equal to 15 s. Fig. 8 reports the `PDD` of the monitoring traffic. The `ST` configuration has the biggest `PDD` for all the values of $T_{AUV} > 7$ s. For smaller values of T_{AUV} only the TDMA-TDMA and the TDMA Frame-CSMA configurations have a higher delay than the `ST`.

In general, we can observe that the TDMA Frame-TDMA

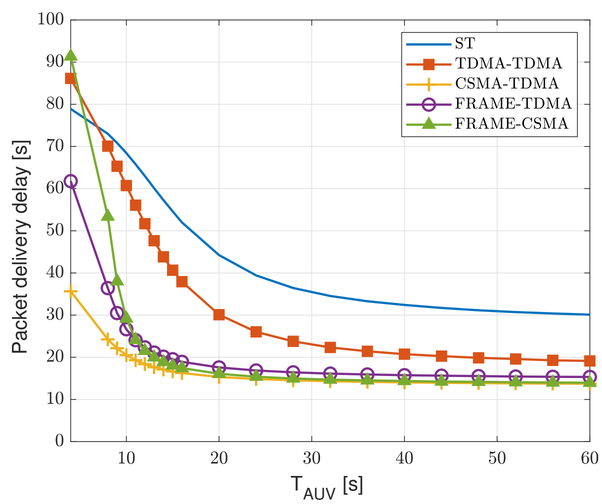

Fig. 8. Average packet delivery delay of the monitoring traffic.

configuration is the best solution in terms of monitoring packet throughput, `PER` and `PDD`. Moreover, this configuration is able to support the highest monitoring traffic without making the network unstable. The drawback of this configuration is that it experiences the highest control packet `PDD`.

B. Power Budget

In this section we compute the overall energy consumption of the `ST` approach and the `MM` approach. The `MM` scenario is analyzed considering the TDMA Frame-TDMA configuration. In both cases we considered an average generation period for the monitoring traffic equal to $T_{AUV} = 20$ s. We supposed to use the EvoLogics S2CR 18/34 as the `MF` modem and the EvoLogics S2CR 7/17 as the `LF` modem. In particular, for the `MF` modem we considered a power consumption equal to $P_{MF} = 35$ W [20] and for the `LF` modem equal to $P_{LF} =$

65 W [20]. During the full mission the overall number of packets sent in the ST and MM scenarios is equal to $N_{ST} = 11883$ and $N_{MM} = 12093$, respectively.

In the ST scenario each packet needs to be transmitted $N_{tx}^{ST} = 4$ times to reach the destination. Each transmission has a duration t_{tx}^{MF} equal to

$$t_{tx}^{MF} = \frac{\textit{packet length}}{R_{MF}} = \frac{8000}{4800} = 1.67 \text{ s.} \quad (2)$$

The overall amount of time each modem is involved in the transmission is equal to

$$t_{totTx}^{ST} = N_{ST} \cdot t_{tx}^{MF} = 19844.61 \text{ s.} \quad (3)$$

The overall energy consumed by a single node for packet transmission during the AUV mission is equal to

$$E_{modem}^{ST} = P_{MF} \cdot t_{totTx}^{ST} = 192.93 \text{ Wh.} \quad (4)$$

Therefore, the energy consumption of the ST network is given by

$$E_{ST} = E_{modem}^{ST} \cdot N_{tx}^{ST} = 771.73 \text{ Wh.} \quad (5)$$

In the MM scenario each packet is transmitted 2 times before it reaches the destination: one time with the LF modem and one time with the MF modem. The transmission time for a packet with the LF modem is equal to

$$t_{tx}^{LF} = \frac{\textit{packet length}}{R_{LF}} = \frac{8000}{3500} = 2.29 \text{ s.} \quad (6)$$

Since in this scenario the number of transmitted packets is equal to N_{MM}, the overall energy consumption of the network is given by

$$E_{MM} = (t_{tx}^{LF} \cdot N_{MM}) P_{LF} + (t_{tx}^{MF} \cdot N_{MM}) P_{MF} = 696.36 \text{ Wh,} \quad (7)$$

where the first term of the sum is the overall energy consumption for the LF modem and the second term is the overall energy consumption for the MF modem.

From this analysis, we can observe that the energy consumption of the MM scenario is lower than in the ST scenario, even if the number of packets sent in the MM network is slightly higher than in the ST network.

VI. Conclusions

In this paper we presented a comparison of the performance of different networks employed to extend the range in which an AUV can be driven during a patrol mission. The performance of different MAC protocols employed in a multimodal and multi-hop network has been compared with the performance of a single technology multi-hop network used as benchmark. The different configurations have been simulated with the DESERT Underwater network simulator. The MULTI_DESTINATION module has been implemented in the network simulator to deal with the multimodal network scenario. Simulation results showed that the ST scenario is outperformed by some configurations of the MM network. Moreover, an ad hoc solution for the MM scenario can greatly improve the performance in terms of monitoring throughput when the network load increases, while in low traffic conditions there are not large differences between the configurations, as expected

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