



HAL
open science

Underwater acoustic sensor network to monitor floating offshore wind: SEM-REV sea trials

Benoît Parrein, Fekher Khelifi, François Babin, Thierry Grousset, Jean-Marc Rousset, Loïc Helloco

► To cite this version:

Benoît Parrein, Fekher Khelifi, François Babin, Thierry Grousset, Jean-Marc Rousset, et al.. Underwater acoustic sensor network to monitor floating offshore wind: SEM-REV sea trials. IEEE OCEANS, Jun 2023, Limerick, Ireland. hal-04190985

HAL Id: hal-04190985

<https://hal.science/hal-04190985v1>

Submitted on 30 Aug 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Underwater acoustic sensor network to monitor floating offshore wind: SEM-REV sea trials

Benoît Parrein
Nantes Université, Polytech Nantes
CNRS, LS2N, UMR 6004
F-44000 Nantes, France
benoit.parrein@univ-nantes.fr

Fekher Khelifi
Nantes Université, Polytech Nantes
CNRS, LS2N, UMR 6004
F-44000 Nantes, France

François Babin
Kopadia
Nantes, France
contact@kopadia.com

Thierry Grousset
Kopadia
Nantes, France
contact@kopadia.com

Jean-Marc Rousset
Nantes Université, École Centrale Nantes
CNRS, LHEEA, UMR 6598
F-44000 Nantes, France

Loïc Helloco
NEREIS Environnement
Nantes, France

Abstract—This paper presents 2 sets of sea experiments on underwater acoustic sensor networks based on the TDA-MAC protocol that were carried out in May and June 2022 around the SEM-REV test field site. Since 2018 SEM-REV hosts the first offshore floating turbine prototype in France. A key conclusion from the sea trials is that the synchronisation between the assets must be carefully executed to succeed in the sensing data collection, especially in bad sea conditions. Packet Delivery Ratios (PDR) below 60% were observed, in particular, if no prior reliable handshake was recorded between the different assets. The paper lists several lessons learnt during those 2 sets of offshore experiments.

Index Terms—underwater acoustic sensor network; TDA-MAC protocol; offshore floating wind; sea trials; SEM-REV;

I. INTRODUCTION

Offshore Marine Renewable Energy (MRE) is crucial for the energy autonomy and for the zero-emission plan of the European Union. With sixteen offshore wind farm projects on its mainland coasts, France is following in the footsteps of its German and Dutch neighbours. The European Commission, for its part, aims to multiply the production capacity by a factor of five in ten years, in part thanks to floating wind power in deep waters. By 2050, a production of 450 GW is thus envisaged along the European coasts. In that context, the Internet of Things (IoT) and more precisely the Internet of Underwater Things (IoUT) is needed to support this unprecedented development in the Industry 4.0's era.

In this paper, we present the results of sea trials of an Underwater Acoustic Sensor Network (UASN) based on the TDA-MAC protocol [1] to monitor offshore floating wind farms. The experiments have been conducted in May and June 2022, over 3 days around the SEM-REV offshore test site. The

The Blue IoT Eolia project has been funded by the Région Pays de la Loire, France in 2020 (2020-04967-04968-04969). This project was lead by Kopadia and had Nantes Université as main partner. Centrale Nantes and Nereis Environnement have actively participated to the sea trials. Authors would like to special thank the captain of the Reborn and his crew from Celtic Marine. Dr Fekher Khelifi is now at EDF, Nantes, France.

SEM-REV offshore test site was created by École Centrale de Nantes 15 years ago to accelerate the development of marine renewables and to facilitate access to the sea for all sectors of MRE, including academic and industrial components. The site has been hosting the first floating offshore wind turbine prototype in France since 2018, and will soon host several other floating technologies from 2023.

The paper is organised as follows. Section II presents the offshore floating wind use case with critical components to monitor. Section III gives the technical background of the TDA-MAC (Time Delay Allocation Medium Access Control) protocol. Section IV describes the material and methods for the experiments. Section V details the results of the experiments and the lessons learnt. Section VI concludes the paper.

II. THE OFFSHORE FLOATING WIND USE CASE

In this section, we describe what is monitored and how on an offshore floating wind farm, in order to establish the requirements for the underwater acoustic network.

A. Monitoring what and how

The critical components of an offshore wind turbine are the dynamic cable and the mooring lines. Some environmental measurements (as temperature, turbidity, pressure...) have to be monitored and transmitted up to the surface as well. We can add fauna tracking on the equipment e.g. dedicated hydrophones to listen for marine mammals in particular. A simplified depiction in Fig. 1 summarises all of these communicating assets. Because the infrastructure around floating wind turbine is very dynamic, the relevant choice to communicate data up to the surface is by using acoustic wireless links. With the propagation speed of typically around $1500m/s$, underwater acoustic communication is 200.10^3 times slower than radio. As an example, it takes around $600ms$ in a usual $1km$ squared area of a single wind turbine to propagate a data packet from the seabed to the surface. If you add to this the data rate of a commodity acoustic modem (around

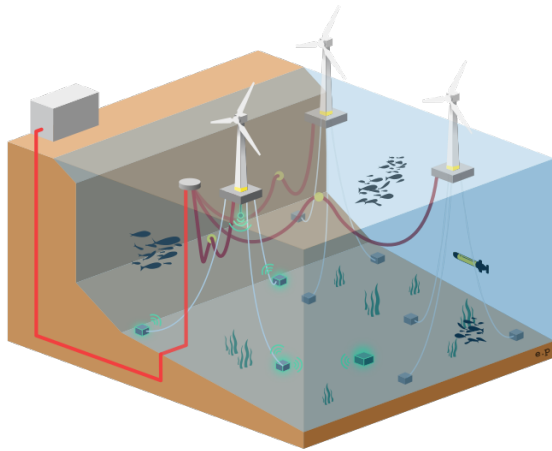


Fig. 1. Prospective representation of an offshore wind farm and corresponding wireless underwater sensor network. Dynamic cables (in red) and only one network (with green communicating nodes) are represented.

50bps in our case), collecting the sensor data is a lengthy task (560ms is the duration of 28bits packet at the nominal rate of 50bps). In a real long term deployment, the data plane (the sequence of data transmissions) must be considered with care with possible compression, piggy-bagging or local processing (namely extreme edge computing). In this work, we used a very simple data plane with 4 types of data (see section IV-C) in the most complex scenario with limited local computation resource to focus the experiments on the acoustic network itself.

B. General requirements of the sensor network

The first discussions with offshore wind farm stakeholders state that 5 to 10 static communicating nodes (each equipped with many sensors) per turbine might be sufficient. Those nodes (equipped with acoustic modems) could be organised in a star topology where the main modem plays the role of a gateway and the other modems located on the seabed are tasked with sensing and communicating the data to the gateway. All the nodes are assumed static most of the time even if they can move slightly when they are fixed on a mobile structure (such as mooring lines or dynamic cables). A mobile node such as an Autonomous Underwater Vehicle (AUV) is not considered in this work but could complete the topology of the network in the foreseeable future. Regarding the energy, the gateway is attached to the main platform and can easily be connected to a power supply (as we can see in Fig. 1); however, the sensing and communicating nodes must be autonomous in energy. The aim of this system which includes sensing, edge processing and communicating is to work for a long period of time (at least 6 months) by avoiding diver intervention as much as possible. For our first experimentation, we do not consider fully this energy requirement. The system requirement we focus on is about scheduling transmissions from the underwater nodes which is the task of the Medium Access Control (MAC) layer in the Open System Intercon-

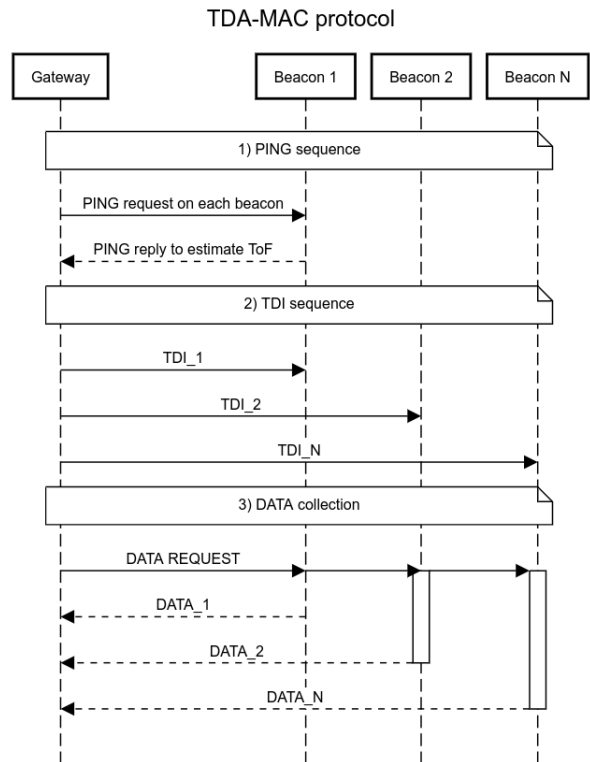


Fig. 2. Sequence diagram of the TDA-MAC protocol in 3 phases: 1) PING request/reply, 2) TDI transmission and 3) Data collection. ToF stands for Time of Flight; TDI for Time Delay Instruction.

tion (OSI) model. As the sensing is performed periodically (except potential asynchronous alarms), we choose a Time Division Multiple Access (TDMA) based protocol explained in the next section.

III. TDA-MAC PROTOCOL OVERVIEW

In our use case, we are especially interested in the Time Division Multiple Access (TDMA) category of MAC protocols, which is well-suited to supporting regular uploads of the sensing data. In this context, we chose the TDA-MAC protocol [1] (e.g. as opposed to a contention based protocol [2] or a more conventional underwater TDMA approach [3]). The main focus of TDA-MAC is to provide a TDMA channel without the need for clock synchronisation of each modem. Moreover, the protocol is very simple to understand and to implement. In a short summary, the protocol works in 3 distinct phases: *i*) a PING phase to estimate distance and Time of Flight (ToF) between each beacon and the gateway, *ii*) a TDI transmission phase where the Time Delay Instruction (TDI) are sent from the gateway to each beacon and *iii*) a data collection phase that consists in uploading data from the beacons after a broadcast gateway request. In this paper, the term *beacon* is used to describe the seabed nodes tasked with sensing and transmitting the data. These 3 phases are summarised in the sequence diagram in Fig. 2. The very simple idea is that each beacon waits a certain amount of time (given through the TDI) to avoid temporal packet collision at the

gateway. More complete details of the protocol can be found in [1]. TDA-MAC has in fact 4 critical parameters: 1) the TDI calculated from the PING sequence 2) the interval guard time T_g that separates each data packet (DATA_x in Fig. 2) to avoid overlapping, 3) the time of the entire frame including all the data collection T_{frame} and 4) the T_{req} , the period between 2 gateway's requests (must be greater than T_{frame} to avoid overlapping and collision).

IV. MATERIAL AND METHODS

In the following, we describe how we implemented the gateway and the beacons. In the last subsection we detail the data plane we used to upload data from the seabed.

A. Gateway and beacons setup

For all the experiments in the Blue IoT Eolia project, we used the MATS-LT acoustic modem, a professional product from the Sercel company. The main characteristics of the MATS-LT are: 3000m of maximal range, bandwidth between 40 and 42kHz, linear frequency modulation (LFM) based on a chirp signal, a bit rate of 50bps and a payload from 8 to 32 bits. MATS-LT can be used both for communication and positioning. It is quite robust to the Doppler effect up to 3m/s in differential speed (manufacturer's information). To drive the gateway on the boat we used the Raspberry Pi3 (model B) connected in USB. An LCD Touch screen and a keyboard completed the setup. For the implementation of the beacons, we used the OEM version of the MATS-LT driven by an STM32 Micro Controller Unit (MCU). Both MCU and modem are powered by a 15V Lithium-Ion battery with a total capacity of 10.4Ah. A yellow waterproof cylinder embeds all the components. A summary of the full setup is given in Fig. 3. The beacon is then weighted using a concrete weight of 200Kg to be immersed and stabilised on the seabed.

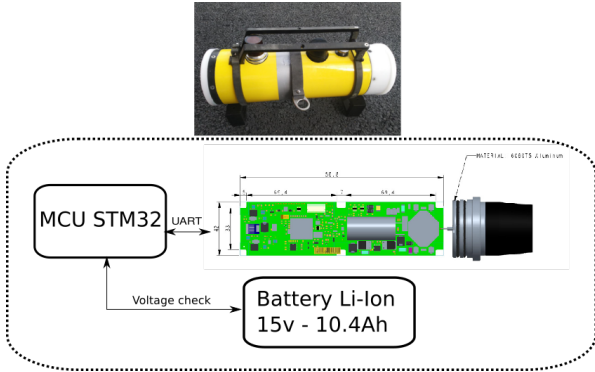


Fig. 3. Autonomous beacon's setup including MATS-LT OEM, MCU STM32 and Li-Ion's battery.

B. TDA-MAC implementation

The TDA-MAC protocol is implemented in C/C++ in the beacons and in Python at the gateway. We used a Python script to set all the parameters and to build the scenarios of the test. To setup the exchanges between gateway and beacon we used

the Source-Destination mode of the MATS-LT. In that mode each packet has a Source (S) and Destination (D) address, a length of the payload and an acoustic Cyclic Redundancy Check (CRC) to detect possible errors after demodulation. From the gateway's point of view, we manage two types of packet: TRA packet that carries the request and RCV packet for the beacon's reply. Fig. 4 and Fig. 5 show each packet's structure. The TRA packet has a total size of 20 bits for a payload of 8 bits and the RCV packet has a total size of 28 bits for a payload of 16 bits. The acoustic CRC is 4 bits long. ERR1 signal is produced when an acoustic error is detected at the reception. All the gateway events (synchronisation, TDI transmission and data collection) are written in a centralised events journal. At the time of the experiment, we do not have such corresponding journals recorded on the MCU at each beacon.

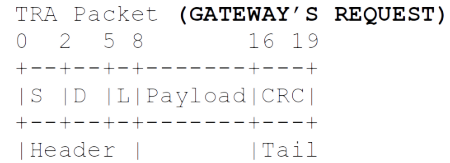


Fig. 4. TRA packet (20 bits long).

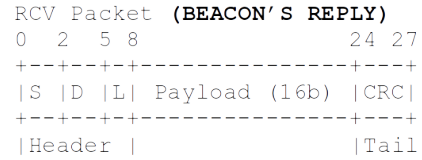


Fig. 5. RCV packet (28 bits long).

C. Data and control planes

In terms of sensing data, we limited the acquisition to beacon's internal measurements such as the battery voltage and precinct internal temperature. The external sensors were not necessary for our proof of concept. For external sensing, acoustic measurements through the MAT-LT transducer were performed. A simple counter ("artificial data") completes the data acquisition with 3 consecutive measurements. Fig. 6 sums up the sequence of data acquisition starting from the artificial data (type 4 in our coding) to acoustic noise (of type 3). We used respectively the S field in the TRA message and D field in RCV message to set the type requested or replied. The sensing value is then simply coded in ASCII format using 2 bytes. Requests (TRA packet) are originally emitted each 5 seconds that leads to a total of 30s for a full data collection. We will see in the following that we have modified slightly this value across different experiments.

In terms of network's quality of service (QoS), we focused our measurements on the propagation delay (and its standard

deviation), the Packet Delivery Ratio (PDR) that is simply the ratio between the RCV packet and the TRA packet for a given beacon and the overall goodput (in packets per minute) that concerns only the useful data packets transmitted by the beacons.

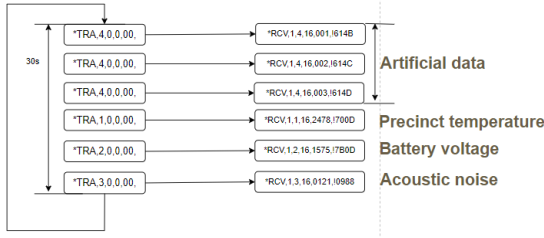


Fig. 6. Data collection's representation including requests (TRA packet) and replies (RCV packet) here from the beacon 1 (B1) for the 4 types of data: the counter (type 4), precinct temperature (1), battery voltage (2) and acoustic noise (3).

V. EXPERIMENTS AT-SEA

The main result of the Blue IoT Eolia project is to have conducted experiments at-sea of TDA-MAC protocol (after initial experiments done in the lab, river and lake [4]) to identify limitations of the protocol and to draw new directions in the underwater supervision of offshore industrial installation. We did 2 sets of experiments in two different areas around the SEM-REV sea experiment site.

A. Preliminary experiments

1) *Specific configurations:* The first set of experiments was done close to the shore for the duration of two consecutive days to demonstrate the functionality of restarting the sensor network after a period of time (overnight in our case). The networks were composed of one gateway and 3 beacons (so 4 nodes in total in the network) positioned in a line on the seabed. The Table I summarises the network's parameters including TDA-MAC parameters: T_{req} , the period of request, T_g , the guard interval, T_{frame} , the total duration of the 3 data packets coming from each beacon. The TRA and RCV packet duration are computed using their respective sizes (20 and 28 bits) and the nominal data rate of the MATS-LT modem (50bps). The nodes were firmly attached to heavy frames to avoid unwanted motions (due to waves, tidal currents, fishing nets,...). The full set was deployed underwater with the crane on a workboat. Two professional hydrophones have been used to record acoustic signals for the two days. One hydrophone was dropped close to the beacons (around 100m away). The second one was under the boat to monitor particularly the gateway. We tested up to 5 positions for the gateway during those two days with a distance to the beacons from 100m to more than 1km. The gateway was firmly fastened at the bottom end of a rigid pole (attached to starboard) and held at a depth of 5m during the experiments. The workboat was anchored to keep a constant station. The sea depth was around 15m at these locations. The sea conditions at that time were very good with an extraordinarily flat sea surface with no perceptible

vertical movement. The tide coefficient was very low (between 31 and 45 during the two days). Acoustic triggers were used to retrieve all the equipment on the last day (beacons and remote hydrophone) to avoid any buoy on the surface during the night.

TABLE I
NETWORK PARAMETERS FOR THE PRELIMINARY EXPERIMENTS

Parameters	Values
Number of nodes	4 (with the gateway)
Tested topology	Linear
T_{req} (ms)	5000
T_g (ms)	50
T_{frame} (ms)	1830
TRA duration (ms)	400
RCV duration (ms)	560

2) *Experiment results:* Results are given in the Tab. II for the 3 better gateway locations turning around the line topology for a distance to the beacons around 400m (location 1) to 100m (locations 2 and 3), for a significant time under test (more than 30min) and number of requests. The table shows that a good packet delivery ratio was achieved from 49.9% (location 3, Beacon 3) to 78.4% (location 1, Beacon 1) when the connection was established between the beacon and the gateway. Unfortunately, no location gave stable links for all the 3 beacons at the same time. We had no connection with Beacon 2 on location 1 and no connection with Beacon 1 on location 3 (the day after). Only location 2 gave replies from the 3 beacons but with bad initial propagation time estimation. Beacon 3 experienced very low PDR (13.2%). The overall goodput (only the correct RCV messages are taken into account) is then given in packets per minute. Last lines of each run give the rate of ERR1 acoustic messages at the gateway which reach more than 10% at the location 2.

The two hydrophones give interesting results to explain more deeply what happens in the full sequence. One example of a spectral acoustic image is given on Fig. 7 for a succession of 3 good sequences of 1 request and 3 replies. The time frequency representation shows also the carrier frequency of 42KHz for the reply packet of 560ms. In this Fig. 7, we see clearly the broadcast request of the gateway first then the train of data packets from 3 different beacons, as expected for the TDA-MAC protocol. We see also that the T_g parameter (guard interval time) is very short (set too low at 50ms here) which caused some collisions at the gateway. We increased this guard interval in the second experiment to allow more time between 2 successive data packets from each beacon.

B. Final experiment

1) *Specific configurations:* The second set of experiments was done on a single day in the end of June 2022 on the SEM-REV experiment site hosting FLOATGEN. The site is located around 12 nautical miles (nm) from the shore at an average depth of 40m (at high tide). As shown on the map in Fig. 8, this unique infrastructure of research is ideally located close to the offshore wind farms of Saint-Nazaire (in production since end of 2022) and Yeu-Noirmoutier (scheduled in 2025).

TABLE II
PERFORMANCE ASSESSMENT FOR 3 GATEWAY'S LOCATIONS ON THE
PRELIMINARY EXPERIMENTS

Metrics	Beacon set		
	Beacon 1	Beacon 2	Beacon 3
Local time	2022-05-10 13:41		
Location id (for the day)	1		
Time under test (min.)	49		
Number of requests (#TRA)	542		
Propagation delay (ms)	287	nc	392
Est. Distance (m)	415	∞	567
Packet Delivery Ratio (%)	78.4	0	75.7
Goodput (pkt per min)	17.04		
ERR1 message rate (%)	1.9		
Local time	2022-05-10 15:47		
Location id (for the day)	2		
Time under test (min.)	45		
Number of requests (#TRA)	501		
Propagation delay (ms)	126	86	513 ^a
Est. Distance (m)	182	124	743 ^a
Packet Delivery Ratio (%)	51.7	58.3	13.2
Goodput (pkt per min)	13.80		
ERR1 message rate (%)	10.6		
Local time	2022-05-11 09:45		
Location id (for the day)	3		
Time under test (min.)	60		
Number of requests (#TRA)	665		
Propagation delay (ms)	nc	108	235
Est. Distance (m)	∞	156	341
Packet delivery ratio (%)	0	64.7	49.9
Goodput (pkt per min)	12.75		
ERR1 message rate (%)	6.3		

^aSomething wrong happens here in the PING phase
'nc' stands for 'no connection'

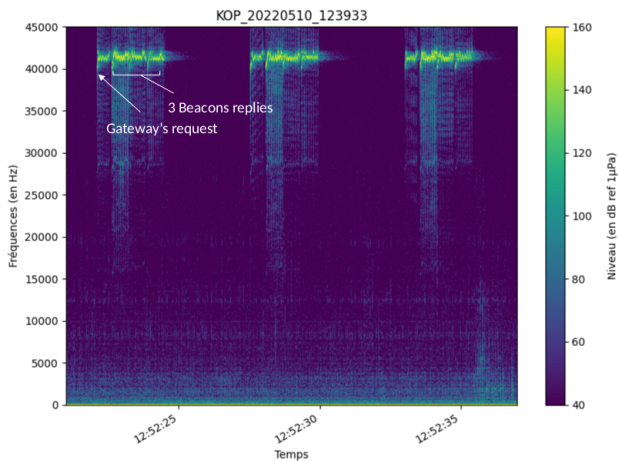


Fig. 7. Observed acoustic image for around 17 sec inside the gateway's location 2 (in a time-frequency space): the gateway's request and 3 beacon's replies are clearly visible.

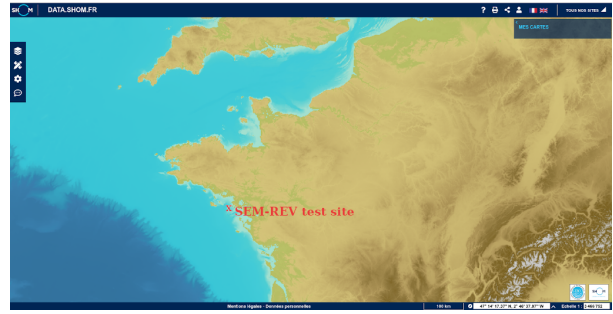


Fig. 8. SEM-REV localisation (credits: SHOM.fr).

As depicted in Fig. 10, the tested sensor network features 1 gateway and 4 beacons in a star topology (illustrated in red on the Figure). Actually we used a second location of the gateway (very close to $B3$ on location id 2) to get a fully connected network. On the day of the test the sea conditions were more severe compared to the first experiment in section V-A. We recorded the Significant Wave Height on the experiment site. On this day, we did not deploy additional hydrophones like in the preliminary experiments but a full acoustic modelisation of the SEM-REV's experiment site was done in a previous study. Main network parameters are given in Table III. The recorded depth was around $35m$ at this place. For this experiment in a star topology, we increase drastically the T_g parameter to $900ms$ to be sure that all acoustic waves are gone from the area before starting a new request/reply sequence (and also to avoid the acoustic overlapping between successive data packets observed in the previous experiment). This leads to the increase in T_{frame} and T_{req} respectively to $5.84s$ and $8.3s$. The format and duration of TRA and RCV packets remain the same.

TABLE III
NETWORK'S PARAMETERS FOR THE FINAL EXPERIMENT

Parameters	Values
Number of nodes	5 (with the gateway)
Tested topology	Star
T_{req} (ms)	8300
T_g (ms)	900
T_{frame} (ms)	5840
TRA duration (ms)	400
RCV duration (ms)	560

2) *Experiments results*: The results of the experiment are given in Table IV for each beacon $B1$, $B2$, $B3$ and $B4$ located as shown in Fig.10. We used the day 2 locations for the gateway (id 1 and id 2: very close to $B3$ as depicted on Fig.10). As we experienced a few connection problems between beacons and the gateway, we reduced the time under test for each run (to relaunch each time the synchronisation process). As mentioned before, the sea conditions were more severe that day with decreasing waves from $1m$ to 0.8 along the day. For the location id 1, we never succeeded to reach $B3$ that led to moving the boat and the gateway to the location id 2 where we succeeded to reach all of the beacons but at very

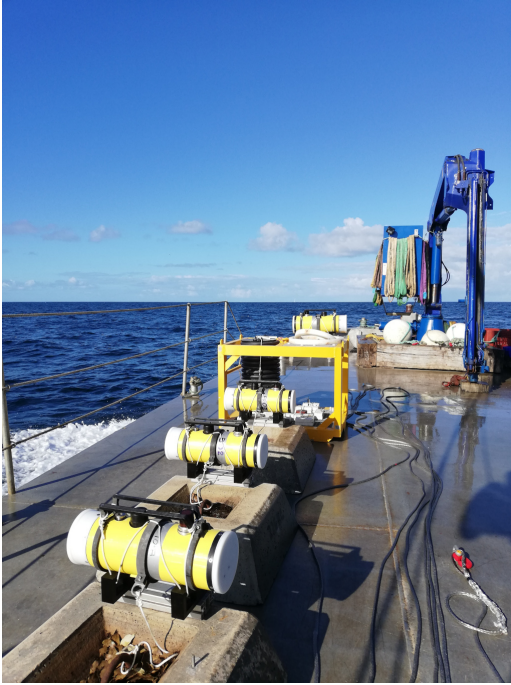


Fig. 9. The 4 beacons on board for the final experiment.

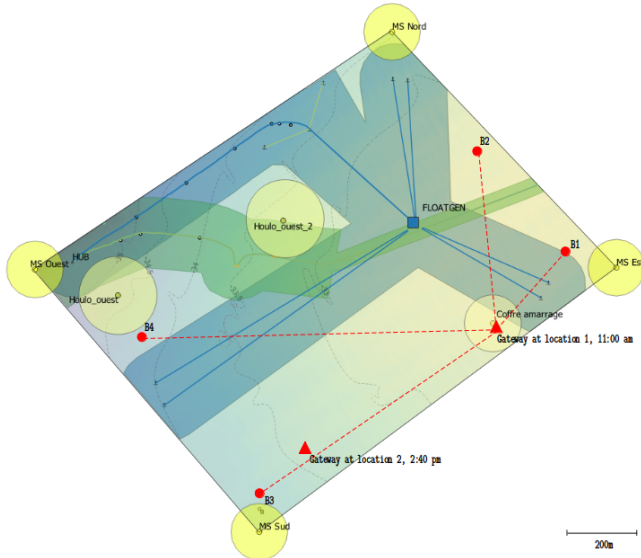


Fig. 10. Network topology including 1 gateway (at 2 locations) and 4 beacons (in red) on SEM-REV field test site. The floating turbine (FLOATGEN) and mooring lines are appearing in blue. Green area stands for the dynamic cable exclusion area.

TABLE IV
PERFORMANCE ASSESSMENT FOR 2 GATEWAY'S LOCATION ON THE FINAL EXPERIMENTS

Metrics	Beacon's set			
	B1	B2	B3	B4
Local time	2022-06-27 11:24			
Location id	1			
Time under test (min.)	12			
Significant Wave Height (m)	0.82			
Distance (m)	240	460	850	1040
Propagation delay (ms)	174	315	na	717
Packet delivery ratio (%)	36.1	12.0	0	25.0
Overall goodput (pkt per min)	2.58			
Local time	2022-06-27 12:16			
Location id	1			
Time under test (min.)	12			
Significant Wave Height (m)	0.86			
Distance (m)	240	460	850	1040
Propagation delay (ms)	174	315	na	717
Packet delivery ratio (%)	63.80	20.0	0	26.7
Overall goodput (pkt per min)	4.5			
Local time	2022-06-27 14:40			
Location id	2			
Time under test (min.)	20			
Significant Wave Height (m)	0.82			
Distance (m)	850	890	240	570
Propagation delay (ms)	683	712	83	409
Packet delivery ratio (%)	46.5	2.9	89.4	10.0
Overall goodput (pkt per min)	12.65			

variable PDR. At this location we achieved a similar overall goodput as measured in the preliminary experiment.

After a dive into the logs (not into the sea), we confirm the difficulty to reach B2 and B4 on the 2 locations with the consequence of bad handshakes between the beacons and the gateway at the synchronisation phase. No TDI command can be received at the 2 beacons in such condition. We see clearly in Fig 11 the several attempts to reach B2 then B4 in the PING sequence (highlighted in orange on the Figure) and the only one failed attempt to transmit TDI command for each beacon in the TDI sequence (highlighted in red on the Figure). After a double check in the source, it appears that when no TDI command is correctly received, the beacon sets its delay to 0 and transmits as soon as the gateway's request arrives leading to possible collisions. From all previous experiences (on sea and on a lake [4]) we did not detect this implementation problem because each time the connectivity was relatively good or masked by another parameter (as T_g in the preliminary experiment).

C. Lessons from the sea trials

We learnt many lessons from the sea trials. The very first one is sea trials are really hard to conduct (much more complicated than in a river or in a lake). It seems obvious to say that but always useful to keep in mind. For the second experiment, we have reported it 3 times in June before doing the final one. Even there, the conditions were not so good with two people sea sick on board. The key is to have very good sailors that conduct all the nautical operations that we really did for the two sets of experiments (we thank again here the

PING SEQUENCE						
2022-06-27 14:38:45.193463	#=SRC-DEST					
2022-06-27 14:38:46.632602	TRA	0	1	0	0	>
2022-06-27 14:38:51.649620	TRA	0	1	0	0	>
2022-06-27 14:38:53.447014	RCV	1	1	8	0	ID98A
2022-06-27 14:38:56.666950	TRA	0	2	0	0	>
2022-06-27 14:39:01.683893	TRA	0	2	0	0	>
2022-06-27 14:39:06.701051	TRA	0	2	0	0	>
2022-06-27 14:39:11.718044	TRA	0	2	0	0	>
2022-06-27 14:39:16.735253	TRA	0	2	0	0	>
2022-06-27 14:39:18.589493	RCV	2	2	8	0	IDC4C
2022-06-27 14:39:21.738498	TRA	0	3	0	0	>
2022-06-27 14:39:22.342594	RCV	3	3	8	0	ID7FOE
2022-06-27 14:39:26.741599	TRA	0	3	0	0	>
2022-06-27 14:39:27.343913	RCV	3	3	8	0	ID7FOE
2022-06-27 14:39:31.748742	TRA	0	4	0	0	>
2022-06-27 14:39:36.765223	TRA	0	4	0	0	>
2022-06-27 14:39:38.161348	ERR1					
2022-06-27 14:39:41.782283	TRA	0	4	0	0	>
2022-06-27 14:39:46.799364	TRA	0	4	0	0	>
2022-06-27 14:39:48.041662	RCV	4	4	8	0	ID7E1
TDI SEQUENCE						
2022-06-27 14:39:51.807026	*TRA	0	3	0	32	>
2022-06-27 14:39:52.493997	*RCV	3	3	12	32	I2E78
2022-06-27 14:40:01.681580	*TRA	0	4	1	968	>
NO ACK						
2022-06-27 14:40:06.618343	*TRA	0	1	1	429	>
2022-06-27 14:40:08.488025	*RCV	1	1	12	D29	I2BE2
2022-06-27 14:40:11.836341	*TRA	0	2	2	12x0	>
2022-06-27 14:40:13.644826	ERR1					

Fig. 11. Crop of the log for PING and TDI sequences for one of the test at 14:40 pm. Orange lines in the PING sequence stand for the trials to ping two of the beacons (B2 and B4 here) including one ERR signal. Green lines (dark and light) are for normal handshakes (TRA then RCV signals). Red lines are for the lack of answers or received incorrectly (through ERR1 signal) respectively from B2 and B4 here.

captain of the Reborn and his crew). The second reason why the sea trials are so difficult is because you have to manage several different scientific and technical aspects: 1) mechanic, 2) acoustic communication, 3) embedded electronic, and 4) computer network.

On the mechanical side, the sealing and the weight are very important even if we did not investigate that part in this study. Actually, we tested 3 types of assembly and we observed some differences. A dedicated metallic rectangular structure of around $1m^3$ with the beacon sealed on the top seems to be the better option (visible on the picture in Fig. 9). Acoustic triggers releasing a buoy and a lifting rope are commonly used in deep and shallow waters. It can nevertheless be affected by troubles such as power shutoff or blocked rope. In our case divers were requested to search and retrieve two items of the underwater equipment in very turbid waters.

In terms of acoustic communication, the use of professional hydrophones on the first experiment was very useful and helps a lot to set the network parameters on the second experiment. A perfect knowledge and modelisation of the SEM-REV experimental site allowed to post-analyse and to confirm acoustic shadows for some beacon locations. This precise acoustic monitoring is a preliminary study to measure impact on the ecosystem (fauna in particular [5]). This is the purpose of our current study. About the acoustic modem, some parameters need to fit better the target use case of offshore floating wind farm. First, we do not need a $3000m$ range of propagation for a typical $1km^2$ area. This can lead to a reduction in the required electrical power and the noise between the different possible subnets. For a better flexibility in the data plane, a payload of 32 or 64Bytes is recommended to piggy-back floating point data transmissions. The data rate increase is required (to 500bps) to avoid an extensive acoustic trace on the physical layer. In experiments like the ones discussed here, building

your own modems based on the open specification proposed by the Technical University of Hamburg [6] would work well.

From the network point of view, it is necessary to take into account the acoustic physical layer properties by giving up the conventional approaches of terrestrial radio communication. The request period needs to be reduced drastically (each 5 seconds or more) and the guard interval time needs to be set especially carefully in the star topology to avoid echoes on the different locations. You have to keep in mind that in many modems the reception is blocking the possibility of transmission. Such echoes can produce collision but also delay in the transmission with a negative impact on the TDA-MAC protocol. Last but not least, as shown in Fig. 11 the synchronisation (PING and TDI phases) phase must be carefully executed with reliable handshakes between the gateway and the beacons before starting the data collection. It is covered in [7] (not available at the date of the experiment).

VI. CONCLUSION

This paper summarises the 2 sets of experiments on underwater acoustic sensor networks based on the TDA-MAC protocol that were carried out in May and June 2022 around the SEM-REV field test site hosting the first offshore floating wind turbine prototype in France. The 2 sets of results show some difficulties to have all the beacons connected at the same time to constitute a full network. This leads naturally to low Packet Delivery Ratios (PDR) at some point (below 50 %). A deep study of the logs shows that we did not spend enough time in poor sea conditions to synchronise each asset of the network, which led to packet loss and collision in the data collection phase. In future work, we plan to use an open system modem to better adapt the communication system to our industrial use case. The frugality of the communications is also on the road map to increase the network time and to prevent the possible impacts on the underwater life.

REFERENCES

- [1] N. Morozs, P. Mitchell, and Y. V. Zakharov, "TDA-MAC: TDMA without clock synchronization in underwater acoustic networks," *IEEE Access*, vol. 6, pp. 1091–1108, 2018.
- [2] A. A. Syed, W. Ye, and J. Heidemann, "T-lohi: A new class of mac protocols for underwater acoustic sensor networks," in *IEEE INFOCOM 2008-The 27th Conference on Computer Communications*, pp. 231–235, IEEE, 2008.
- [3] K. Kredo II, P. Djukic, and P. Mohapatra, "Stump: Exploiting position diversity in the staggered tdma underwater mac protocol," in *IEEE INFOCOM 2009*, pp. 2961–2965, IEEE, 2009.
- [4] F. Khelifi and B. Parrein, "An Experimental Testbed for Underwater Acoustic Sensor Network Protocol Dedicated to Offshore Wind Turbines," in *The 15th International Conference on Underwater Networks & Systems*, (Shenzhen, Guangdong, China), Nov. 2021.
- [5] B. L. Southall, J. J. Finneran, C. Reichmuth, P. E. Nachtigall, D. R. Ketten, A. E. Bowles, W. T. Ellison, D. P. Nowacek, and P. L. Tyack, "Marine mammal noise exposure criteria: Updated scientific recommendations for residual hearing effects," *Aquatic Mammals*, vol. 45, no. 2, pp. 125–232, 2019.
- [6] B.-C. Renner, J. Heitmann, and F. Steinmetz, "Ahoi: Inexpensive, low-power communication and localization for underwater sensor networks and μ AUVs," *ACM Trans. Sen. Netw.*, vol. 16, jan 2020.
- [7] N. Morozs, B. Sherlock, B. T. Henson, J. A. Neasham, P. D. Mitchell, and Y. Zakharov, "Data gathering in uwa sensor networks: Practical considerations and lessons from sea trials," *Journal of Marine Science and Engineering*, vol. 10, no. 9, 2022.