DATA COLLECTION IN SHALLOW FRESH WATER SCENARIOS WITH LOW-COST UNDERWATER ACOUSTIC MODEMS

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Abstract: The Robotic Vessels as-a-Service (RoboVaaS) project intends to exploit the most advanced communication and marine vehicle technologies to revolutionise shipping and near-shore operations, offering on-demand and cost-effective robotic-aided services. In particular, the RoboVaaS vision includes a ship hull inspection service, a quay walls inspection service, an antigrounding service, and an environmental and bathymetry data collection service. In this paper, we present a study of the underwater environmental data collection service, performed by a low-cost autonomous vehicle equipped with a very low-cost acoustic modem and moving within a network of submerged acoustic sensor nodes. To this end, an underwater acoustic network composed by both static and moving nodes has been implemented and simulated with the DESERT Underwater Framework, where the performance of the smartPORT Acoustic Underwater Modem have been mapped in the form of lookup tables. The performance of the modem has been measured near the Port of Hamburg, where the RoboVaaS concept will be demonstrated with a real field evaluation.

Keywords: Underwater acoustic network simulations, DESERT Underwater, AHOI modem.

1 INTRODUCTION

Today, 90% of transported goods are waterborne [1]: the Robotic Vessels as-a-Service (RoboVaaS) project [2] intends to reorganize this sector by exploiting the most advanced communication technologies to interconnect unmanned vessels (UVs), such as autonomous surface vessels (ASVs), and autonomous underwater vehicles (AUVs). The main goal of this project is to offer on-demand robotic-aided services, requiring the capabilities of both Internet of Things (IoT) and Internet of Underwater Things (IoUT) [3,4] devices. The RoboVaas project intends to identify those services, beneficial for near-shore maritime operations, that have a strong positive impact on automation and digitization. These include, among others, a data collection service with a wide range of applications, such as measuring environmental data with an underwater sensor network. In this paper we refer to this service, which requires the deployment of a low-cost underwater sensor network (UWSN). In this application, an AUV patrols the area and collects data from the UWSN, equipped with a low cost underwater acoustic modem, the smartPORT Acoustic Underwater Modem (AHOI) [5] (presented in Section 2). In order to retrieve the data from such network, we design a polling-based Medium Access Control (MAC) protocol (Section 3), tailored to the needs of an UWSN [6]. In Section 4, we evaluate the proposed solution via simulations based on field measurements, and, finally, in Section 5, we draw our concluding remarks.

2 SMARTPORT ACOUSTIC UNDERWATER MODEM

This section presents the smartPORT Acoustic Underwater Modem (AHOI) [5].

The AHOI modem is a small, low-power and low-cost acoustic underwater modem (see Fig. 1), developed to be integrated into micro AUVs or UWSNs. The modem consists of three stacked Printed Circuit Boards (PCB) with an overall size of 50x50x25 mm³ and a component cost of about €200. The first PCB includes a CortexM4 microcontroller, power supply and external connections. In addition, the second PCB works as the receiver and involves amplifiers, a bandpass filter and an analog-to-digital converter. To receive acoustic signals with different signal strength, the amplifier gains are software adjustable (overall amplification between 40-96 dB). In the default setup, a software-based automatic gain control is used to adjust the amplifier gains. Finally, the third PCB is the transmission board including a digital-to-analog converter and a power amplifier. The power consumption in idle and receive mode is around 300 mW and 2.1 W during data transmission with highest amplification. For the acoustic signal reception and transmission, the AHOI modem uses an Aquarian Scientific AS-1 broadband measurement hydrophone with a price of about €400. In the case of the highest power amplifier level and a transmission in the 50-75 kHz range, the transmission source level is between 150-160 $\mathrm{dBre1\mu Pa^2@1m}$ with an AS-1 hydrophone.

Fig. 1: AHOI acoustic underwater modem with hydrophone.

Signal processing is realized in software on the microcontroller, which allows a fast reconfiguration of frequency and coding setups. In the default setup, the modem uses an orthogonal binary frequency shift keying (BFSK) with 2.56 ms symbol duration and a 781.25 kHz frequency spacing. Each symbol consists of four superimposed sinusoidal waveforms. To counter frequency cancellations caused by multi-path propagation, each bit is repeated on three different carriers, and frequency hopping (FHSS) is applied to avoid inter-symbol interference. All in all, the modem has 25 kHz of bandwidth around a central frequency of 62.5 kHz. The default setup in combination with a Hamming coding leads to a net data rate of 260 bps (up to 4.7 kbps are feasible).

2.1 Modem's performance in very shallow water

A real-world evaluation was performed in a marina in southern Hamburg. The marina is located in a branch of the river Elbe, where depth ranges from 3.5 m to 7.5 m depending on the tide. The experiments were performed on Nov. 11, 2018. In total six AHOI modems were deployed on a jetty, one modem acted as the sender and the other five as the receivers. All hydrophones were submerged 1.5 m under the water surface and each modem was connected to a laptop to record the received packets.

During the evaluation, packets with different payload lengths were transmitted. In each setup the sender sent 200 packets with randomly generated payload. Table 1 contains the packet delivery rate (PDR) of the five receivers for 16, 32, and 96 bytes payloads. In this test, the node deployed 99 m far from the transmitter received more packets than the node at 24 m due to the effects of multipath and automatic gain control (the receiver at 99 m used a higher gain than the receiver at 24 m, as the latter had to employ a low gain to avoid saturation).

Size [Bytes]	*PDR@12 m*	*PDR@24 m*	*PDR@46 m*	*PDR@99 m*	*PDR@152 m*
16	96.5%	75.0%	89.5%	88.0%	84.5%
32	95.0%	70.0%	88.5%	99.0%	51.5%
96	77.0%	92.0%	83.0%	100.0%	n.a.

Table 1: Packet delivery rate achieved during the real-world evaluation in a marina in Hamburg.

2.2 Modem's reaction to shipping noise

The typical range of applications of UWSN include marinas, ports and rivers with high shipping activity. Each vessel produces acoustic noise, caused by propellers, machineries and other effects [7]. For this reason, in order to provide a stable communication link, the AHOI modem must be robust against vessel noise. The acoustic noise emitted by ships and vessels has highest power spectral density (PSD) below 10 kHz, which is smaller than the communication frequency range. In addition, the AHOI modem receiver involves a bandpass filter between 50 kHz and 75 kHz. Furthermore, a simulation was performed to prove the stability against vessel noise. The noise was generated offline and added to different recorded packets. A single AHOI modem was used to receive the signal, which was generated with an arbitrary signal generator (TiePie Handyscope HS5, 200 kHz sampling). The signal generator simulated the received hydrophone voltage for different PSDs. During the simulations a constant receiving sensitivity of -208 dBV re 1 μPa for frequencies up to 100 kHz was assumed. Fig. 2 shows the PSDs of received packets at the receiver side. At first, the packets were transmitted without additional vessel noise. In the following simulations, different noise profiles were added to the packets.

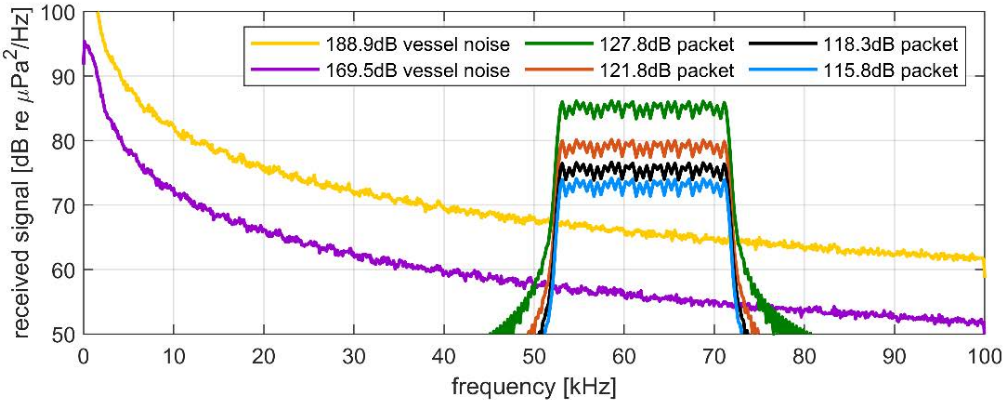

Fig. 2: Power spectral density at the receiver side.

The noise profiles were generated according to [7] and are shown in Fig. 2. For each combination of vessel noise level and communication signal strength, 100 packets (with 32 B payload) were transmitted. In all cases, the AHOI modem received all packets.

2.3 Modem's reaction to interference

In addition to the vessel noise discussed in Section 2.2, other underwater modems in a network could disturb the transmission. To evaluate the effect of packet interference and the resulting PDR, the described hardware setup in Section 2.2 was used. Instead of additional simulated vessel noise, a second recorded packet was added to the generator samples. All packets carried 32B payload and had a signal duration of 1.311 s, including the synchronization symbols. Fig. 2 displays PSDs of the different transmitted packets. Three different interference situations were simulated, for different degrees of overlap between the intended packet and the interfering packet, based on the time displacement between the two: (i) 0 s delay (100% overlap), (ii) 0.5 s delay (61.9% overlap), and (iii) 1 s delay (23.7% overlap). In addition, reception without any interference was also simulated (0% overlap). For each combination of communication signal strength and delay, 100 packets were transmitted.

The PDR has been measured by varying the interference component and its performance mapped in the simulator. Specifically, the Signal to interference Ratio (SIR) component has been calculated by employing the mean power model, computed as $SIR = Pr/(Pi \cdot ovr)$, where *Pr* is the power received by the signal carrying the data packet, *Pi* the power of the interfering signal and *ovr* the overlap percentage of the two signals, calculated as the portion of time the two signals are interfering divided by the total packet duration. The measurements are reported in Table 2.

Rx power [dB re μPa²@1m]	*Interf Rx power [dB re μPa²@1m]*	*Overlap*	*SIR [dB] (mean power)*	*PDR*	*average PDR*
127.8, 121.8, 118.3, 115.8	Same as Rx power	100.0%	0	0%	0.0%
121.8	127.8	23.7%	0.248	0%	0.0%
127.8, 121.8, 118.3, 115.8	Same as Rx power	61.9%	2.086	12%, 36%, 46%, 40%	33.5%
118.3	115.8	100%	≥2.5	100%	100%

Table 2: AHOI modem's reaction to interference.

In order to extend the measurements and model them in the simulator, we interpolated the samples by employing the Piecewise Cubic Hermite Interpolating Polynomial (PCHIP) with Matlab, obtaining the line depicted in Fig. 3.

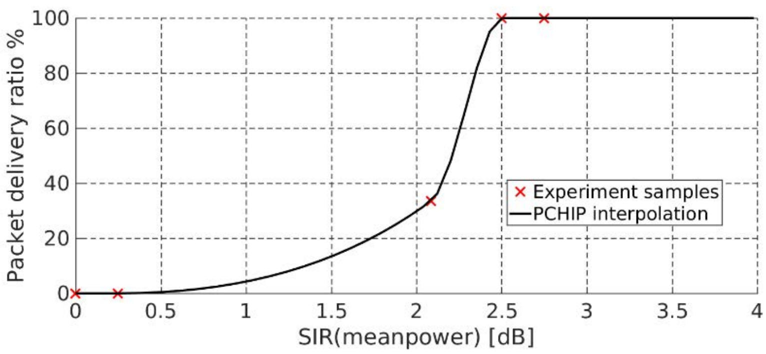

Fig. 3: Packet delivery ratio vs Signal to Interference Ratio, with PCHIP interpolation.

The AHOI modem performance figures have been included in the form of lookup-tables (LUTs). In particular, the PDR vs distance has been mapped to obtain the modem's behaviour in case of absence of interference. In addition, the PDR vs SIR LUT sampled by the PCHIP interpolation line presented in Fig. 3 has been included in the simulator, to obtain the penalty introduced by the interference. The resulting packet delivery ratio is approximated as $PDR = PDR(d) \cdot PDR(SIR)$, where $PDR(d)$ is the packet delivery ratio obtained at a distance *d*, while $PDR(SIR)$ is the packet delivery ratio obtained in ideal conditions with signal to interference ratio equals to SIR.

3 POLLING MAC PROTOCOL

Both [8] and [9] demonstrated that a polling-based MAC layer suits well underwater data-muling scenarios: in the uwpolling protocol [8], the AUV first triggers the channel and then waits for the static nodes to answer with a probe, that contains information on how much data the static node needs to transmit to the AUV. Before probing the channel, the static nodes wait for a back-off time randomly generated within a maximum interval *TbMax*. Then, the AUV sends a poll packet to assigns each static node the time interval within which that node can transmit its own data packets. In [9] the authors demonstrated that if the propagation delay is bigger than the packet duration and the distances from the AUV to the static nodes span a wide range, *TbMax* can be set to 0 to maximize the throughput, without increasing the probability of packet collisions. This result is not applicable in our scenario, where the packet duration can be bigger than the propagation delay, since many nodes are deployed within a range of 100 m, and the modem bit rate is 260 bps.

The protocol employed in our simulations is an enhanced version of uwpolling. In this protocol, the AUV first wakes up the surrounding nodes with a Trigger packet (*TrP*). Then each node *i* that received *TrP* and has data to transmit sends back a Probe packet (*PrP*) to the AUV containing the number of packets it needs to transmit ($P_{EXP,i}$). The transmission of *PrPs* is contention-based: each node waits for a random back-off period, up to a Maximum Backoff Time (*TbMax*), before transmitting its own *PrP*. After this first phase, the AUV selects the nodes to be polled in order, according to a fair policy: for each node *i* that successfully probed the channel, the AUV computes the weight $wgt_i = P_{EXP,i} / P_{RX,i}$, with $P_{RX,i}$ equal to the total number of packets received by the AUV from node *i* at that moment, and orders the nodes according to *wgt*. If no *PrP* has been received by the AUV within a Maximum Trigger Timeout (*MTT*) bigger than *TbMax* + *RTT*, or after the AUV finishes to poll all nodes of the list, the AUV transmits a new *TrP*.

The uwpolling protocol provides also the possibility to use a sink node different from the AUV, to which to upload the data collected by the AUV [10]. To use this feature with the AHOI modem, data compression techniques should be investigated in order to forward all the data collected from the AUV when the sink is in the range of the vehicle. This solution will be part of our future work.

4 SIMULATIONS

In Section 4.1 we describe the simulation settings and the simulation scenario, while in Section 4.2 we present the simulation results.

4.1 Simulation settings and scenario description

In our scenario the water conditions are the same as in the experiment presented in Section 2.1: the water column between 3 and 7 meters deep, and the nodes are deployed 1.5 meters below the sea surface. Each node is equipped with an AHOI modem with carrier frequency 65.2 kHz, bandwidth 25 kHz, payload data rate (computed as the packet size, in bits, divided by the total packet duration, including the preamble, in seconds) of 200 bps, and transmission power 156 dB re μPa^2@1m. The packet size is set to 256 bits, and each polled node transmits 5 data packets. The protocol is evaluated in different working conditions, where the AUV speed (*v*) is varied from 0.1 m/s to 4 m/s, and the node density (*N*), defined as the number of nodes within the coverage area of the AUV (circular area, with a radius of 110 meters), is varied from 3 to 30 nodes. A realization of the scenario with $N = 6$ is depicted in Fig. 4. The nodes position (blue dots) is set randomly, along the AUV path (red line). The AUV performs 7 laps of the same path, 1.6 km long, moving at a constant speed during each simulation run. The system is simulated with the DESERT Underwater framework.

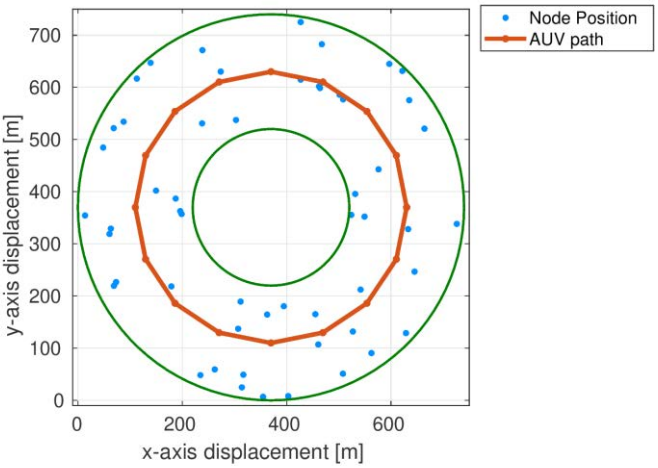

Fig. 4: Network scenario. The AUV path is described by the solid red line. The solid green lines define the area in which nodes are randomly placed

4.2 Simulation results

In this section we present the simulation results obtained by varying the node density and the AUV speed. The results are obtained averaging over 20 independent simulation runs. All the simulations are performed considering that each node always transmits 5 data packets when it is polled by the AUV. The analysed performance metrics are the throughput (*THR*) and Jain's Fairness Index (*JFI*), computed as

$$THR = \sum_{i}^{n} x(i) \cdot sz \cdot T^{-1}, \quad \text{and} \quad JFI = \left(\sum_{i}^{n} x(i) \right)^{2} \cdot \left(n \sum_{i}^{n} x(i)^{2} \right)^{-1}, \tag{1}$$

where *x(i)* is the number of packets received by the AUV from node *i*, *n* is the total number of nodes in the whole network, *sz* is the packet size, in bits, and *T* is the total simulation time, in seconds.

In Fig. 5 (a) the overall throughput of the network is reported as a function of the maximum backoff time *TbMax* for different values of the node density *N*. For $N = 6$, the throughput first increases as *TbMax* increases by reaching a maximum peak value of 58 bps for *TbMax* = *TbOp(6)*=8 s. With *TbMax* lower than 8 s the collision of probe packets at the AUV is very likely, thus many probe packets will not be received, and in turn a lower number of nodes will be polled in the subsequent polling round. When *TbMax* is greater than 8 s the throughput starts to decrease as well, since some of the triggered nodes may get out of the transmission range of the AUV after waiting *TbMax* seconds. A similar behavior occurs also for $N = 3$ and $N = 10$, where $TbOp(3) = 6$ s and $TbOp(10) = 14$ s, respectively. For $N = 30$, $TbOp(30) = 28$ s, but the maximum throughput becomes 16% lower than with $N = 6$, because 28 s is enough to avoid collisions, but in that amount of time the AUV already moved 56 m away from the position in which it sent the trigger, leading to a large number of triggered nodes out of range.

With $N = 3$, $N = 6$ and $N = 10$, a $TbMax = TbOp(N)$ provides a *JFI* of 0.89, 0.85 and 0.8, respectively, that is close to the maximum *JFI* reachable with those densities (Fig. 5 (b)). Therefore, in these cases the choice $TbMax = TbOp(N)$ provides a good fairness as well. On the other hand, with $N = 30$, the AUV is not able to serve in a fair way all the nodes in the network, indeed the maximum *JFI* value obtained is equal to 0.58.

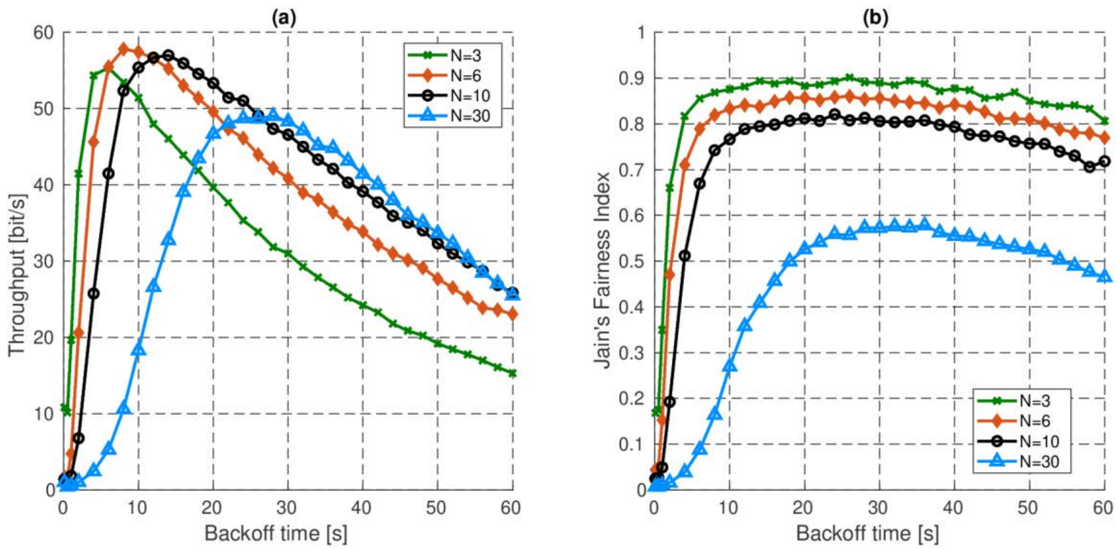

Fig. 5: Throughput of the network (a) and JFI (b) vs backoff time, for different values of the node density N.

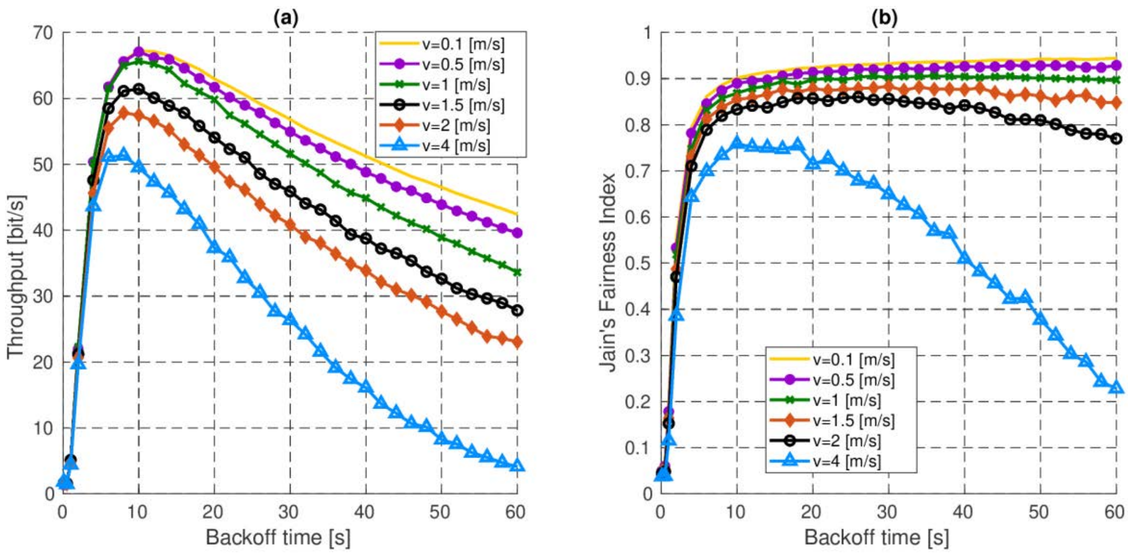

Fig. 6: Throughput of the network (a) and JFI (b) vs backoff time, for different values of the AUV speed v.

Fig. 6 (a) depicts the overall throughput of the network as a function of the maximum backoff time with $N = 6$, by varying the AUV speed v between 0.1 m/s and 4 m/s. The peak for the overall throughput is reached, on average, around *TbMax* = *TbV* = 10 s, with small differences in the peak positions when varying the AUV speed. When *TbMax=TbV, JFI* is almost maximized for $v \leq 2$ m/s (see Fig. 6 (b)). On the other hand, with a speed of 4 m/s, the nodes are not served in a fair way because the AUV moves too fast, and many triggered nodes become out of range due to the new AUV position.

5 CONCLUSIONS

In this paper, we proved the feasibility of a data-muling application with the very low-cost AHOI modem, via simulations based on real field measurements. The proposed polling protocol ensures fairness to all nodes for AUV speeds up to 2 m/s. This encourages us tu pursue further developments, aimed at the optimization of the protocol and at the evaluation of the system in a real field test.

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