A Software-Defined Underwater Acoustic Modem for Everyone: Design and Evaluation

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***Abstract*—The development of small low-cost autonomous underwater and surface vehicles has increased the need for underwater wireless communication and ranging to support swarm operations for collaborative data collection efforts. Specifically, newly available low-cost underwater and surface vehicles make the realization of swarm formation cost effective. However, their mission coordination involves the use of expensive acoustic modems whose price may be higher than that of the vehicle itself. In this paper, we describe and evaluate a low-cost software-defined acoustic modem developed with only off-the-shelf components, able to perform one-way travel-time ranging. The modem is specifically designed for dense mobile networks deployed in shallow water environments, such as rivers, lagoons and lakes. The modular software design of the modem allows us to easily configure parameters such as modulation and coding schemes, scheduling algorithm, source power, carrier frequency and bandwidth. In this paper we evaluate, in a shallow environment, the modem performance in terms of packet detection ratio, packet delivery ratio, and one-way travel-time ranging.**

***Index Terms*—Underwater communication networks; underwater acoustic communications; one-way travel-time ranging.**

I. INTRODUCTION

Underwater acoustic communication is the enabler of several types of submerged operations. Submarines, human divers, buoys and devices like autonomous underwater vehicles (AUVs), remotely operated vehicles (ROVs), autonomous surface vessels (ASVs), and seagliders, are often equipped with underwater modems [1]–[3]. This has progressively led to the formation of underwater networks, where devices transmit their location, share their measured data, and collaborate with other sensors. Traditionally, acoustic modems were designed for deep water deployments and long range communications, as they were mainly used in large scale military and off-shore operations [3].

In contrast, the recent development of low-cost unmanned vehicles [4], [5] called for inexpensive low-power underwater acoustic modems [1], [6], [7]. The modem developed by the Newcastle University [1], for instance, has been installed in several low-cost unmanned vehicles [5], while the *ahoi* modem developed by the Technical University of Hamburg [6] was designed to be installed in micro AUVs, and so is the modem developed by the joint effort of the Georgia Institute of Technology, the Xiamen University, and The University of Alabama [8]. The commercial modems manufactured by Waterlinked [9] can be installed in the BlueROV [4] to provide this 5000 EUR vehicle with an underwater acoustic and positioning systems that costs less than half the price of the ROV. All the aforementioned modems are capable of ranging and of achieving a bitrate of hundreds of bits per second up to a range of a few hundred meters in a shallow water environment. For a more complete review of both low-cost and expensive acoustic software-defined modems we refer the interested reader to [10] and [11].

More recently, the University of Padova and Wireless and More srl engaged in a joint effort to develop a low-cost modem completely composed of commercial off-the-shelf equipment [7] for the MOrphing Distributed Autonomous Underwater Vehicle (MODA) national project. In addition to the abilities of the other low-cost modems mentioned in this section, the MODA modem is able to perform one-way travel-time (OWTT) ranging thanks to precise oscillators. The oscillator can either be an atomic clock, that has a high cost (i.e., a few thousand EUR) but ensures a ranging error of less than one meter for missions that last up to one year, or an oven controlled crystal oscillator (OCXO), that ensures the same error in missions that last up to one week, and has a cost that is 10 times lower than atomic clocks. While atomic clocks should be employed in long term or resident offshore installations, OCXO suits well temporary low-cost deployments of AUV swarms and dense underwater networks. The simple hardware design, low cost of the components and low complexity of the hardware integration, as well as the high level of maturity of the software components, make this modem platform suitable not only for universities and research institutes that want to bring students near to acoustic communication experimentation via laboratories and tutorials, but also for do-it-yourself (DIY) practitioners that want to explore the underwater acoustic communication topic, moving one step further in the field of underwater acoustic communication and positioning systems. Indeed, the hardware platform consists of just a Linux (embedded) machine able to receive and transmit acoustic signals through a high quality sound card. A complete guide for the hardware integration and the software manual are available at https://www.wirelessandmore.it/sdm.html, where the user can ask for support and for the latest version of the modem software. This material makes it possible even to relatively inexperienced users (e.g., students) to successfully build and configure the modem with limited effort. The same system can be optionally used, for instance, to play previously created signals or as an underwater acoustic recorder. For this prototype, the main development focuses on the software framework, which includes an actual real-time software-

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defined modem completely written in C and C++ programming languages and able to perform all signal processing in the Linux embedded platform.

In this paper we first describe the MODA modem hardware and software components (Section II), then we describe the observed metrics and the experiments setup (Section III) used to evaluate the modem performance with tests performed in the Piovego river in Padua (IT) (Section IV). Finally, we draw our concluding remarks (Section V).

II. MODA ACOUSTIC MODEM

In this section we describe the MODA acoustic modem developed by the University of Padova and Wireless and More srl, highlighting its main novelty. The main characteristics that differentiate the MODA acoustic modem from the current state of the art are:

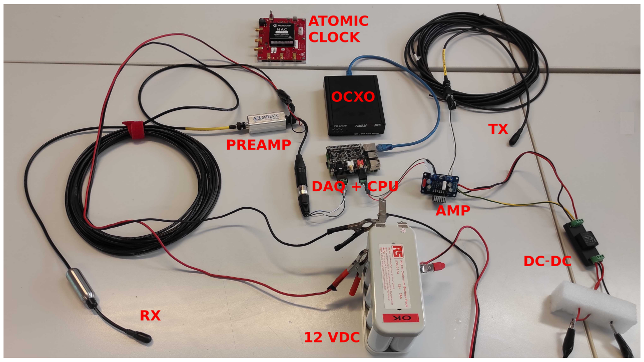
- low cost of the components;
- low power consumption;
- all components are available off-the-shelf;
- ability to perform OWTT ranging without the need for an expensive atomic clock.

Compared to legacy acoustic modems designed for open sea deployments and able to cover tens [3] or hundreds of kilometers [12] with a transmission power of tens or hundreds of watts, respectively, this modem uses a transmission power of less than 1.5 W and is able to transmit up to a distance of 100 m. In fact, the modem is tailored to internal water deployments, such as rivers, ports and lagoons, where the water is very shallow and the reflections caused by the irregular shape of the canals, that present many bends and are affected by strong sedimentation, make the correct reception of the acoustic signal impossible at distance of more than a few hundred meters, even with high power transmitters. When compared to other low-cost acoustic modems [1], [6], [9], the peculiarities of this platform are that i) all components are available off-the-shelf, making it easy to build for students and DIY practitioners that want to explore the world of underwater acoustic communication, and ii) it is able to perform OWTT ranging, thanks to the use of a high precision oscillator, such as an OCXO or an atomic clock.

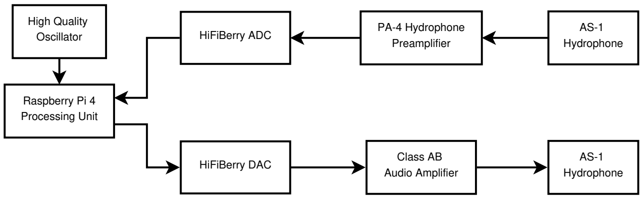
In the rest of this section we present the hardware components of the modem (Section II-A) and its modular software architecture (Section II-B).

A. Hardware Components

The MODA acoustic modem, presented in Figure 1, is composed of a Raspberry Pi 4 B processing unit, a data acquisition (DAQ) system composed of a HiFiBerry DAC/ADC+ with 192 kHz sampling rate (depicted in the center of the figure), and two AS-1 transducers. These transducers have a flat reception sensitivity from 10 Hz to 100 kHz, and can transmit signals from 35 kHz to 100 kHz: given the limitations of the DAQ, we never transmitted signals with a frequency higher than 90 kHz. The first transducer, depicted in the top-right corner of Figure 1a, is connected to the DAC output and used to transmit the signal; the second transducer, depicted in the bottom-left corner of the figure, is connected to the ADC input and used to receive the acoustic signal. In addition, an LM3886TF-based class AB audio amplifier is used to amplify the signal transmitted with the first transducer, while a PA-4 Hydrophone Preamplifier amplifies the signal received with the second transducer before it reaches the ADC. Although audio amplifiers are not designed to operate outside the 20 Hz-20 kHz bandwidth, most class AB amplifiers do not have any low-pass filters[1] to cut high frequencies, and from our test the LM3886TF class AB audio amplifier turned out to be a good choice to amplify all signals below 90 kHz.



(a) Hardware components.



(b) Hardware block diagram.

Fig. 1: MODA modem hardware components (Figure 1a) and diagram depicting how all components are connected (Figure 1b).

Thanks to a DC-DC converter, all components are powered with a single 12 VDC battery. Given that the output peak-to-peak voltage V_{pp} was set to 40 VDC (i.e., the peak voltage $V_{pk} = V_{pp}/2$ of the sine wave was 20 VDC), and that the transducer impedance at 50 kHz is $R_{50kHz} = 357\ \Omega$, the transmission power, computed as $P_{50kHz} = V_{pk}^2/R_{50kHz}$, is approximately equal to 1.12 W (or 0.55 W_{RMS}). Figure 1b summarizes how all the aforementioned components are connected. The total cost of the components of the current version of the modem is slightly below 1000 EUR: in the next version only one transducer will be used together with a TX/RX switch, with a reduction of the components cost of approximately 400 EUR. In principle, given the software nature of the modem, all the hardware components can be replaced with other parts. The first version of the modem [7], for instance, was developed using a laptop as processing unit, its internal sound card as DAQ, and simple audio amplifiers. This design makes the modem easy to upgrade as better hardware components become available.

Optionally, OCXO or Atomic clocks can be used to perform

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[1] Class D audio amplifiers are more efficient than class AB audio amplifiers, but they all have a low-pass filter that prevents their use outside the 20 Hz-20 kHz bandwidth.

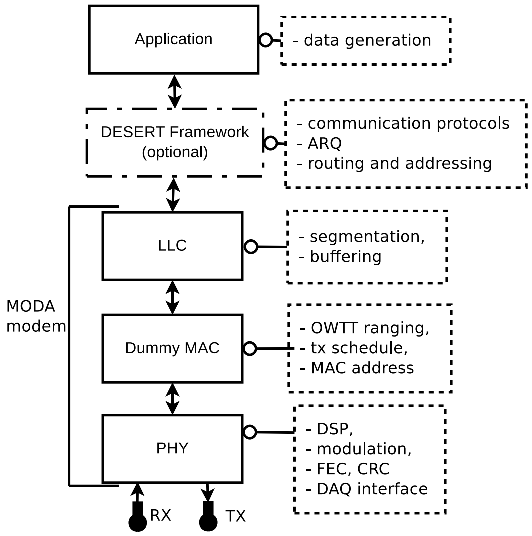


Fig. 2: MODA modem protocol stack.

one way travel time ranging, with the former suitable for low-cost short- and medium-term deployments and the latter to be preferred for long-term deployments of expensive equipment. In Figure 1 the TM2000 OCXO-based miniaturized NTP server is connected to the processing unit via Ethernet, while the 1PPS output of the atomic clock depicted at the top of the figure can be plugged to the Raspberry Pi GPIO for a more precise clock accuracy, using a 1PPS client: in fact while the clock drift of the TM2000 in 5 days is approximately 0.67 ms (that corresponds to 1 m of ranging error), the same clock drift with the miniaturized atomic clock SA.55s occurs after 1 year. On the other hand, while the cost of an OCXO is a few hundred Euros, the price of an atomic clock is, on average, 10 times higher. An extensive overview of precise clock oscillators is presented in [7].

B. *Software Architecture*

The modular software design of the modem is shown in Figure 2. Specifically, the modem is composed of logical link control (LLC), multiple access control (MAC) and physical (PHY) layers, the last using digital signal processing (DSP) libraries and the DAQ software interface. Given the modular design, different LLC, MAC and PHY modules can be interconnected together, and the PHY can use different DSP libraries and DAQs. Many modem parameters can be configured via software, specifically: sampling rate, carrier frequency, modulation scheme, internal and external forward error correction (FEC) schemes, transmission power, interpolation factor, cyclic redundancy check (CRC) size and address of the node. In the current version, the modulation schemes can be selected among (differential and non differential) phase shift keying (PSK), on-off keying (OOK), and direct sequence spread spectrum (DSSS). Other modulations, such as Gaussian minimum-shift keying (GMSK) and frequency-shift keying (FSK) will be supported in the near future. The FEC schemes available are a large set of Hamming, repetition, convolutional and Reed-Solomon codes.

Any external application generating payload data can be connected to the modem via socket programming: the LLC performs data segmentation, including each segment in a packet that is forwarded to the MAC through a shared buffer. The MAC can then issue the PHY to perform modulation and data transmission through two different callback functions.

The default framing structure, built using the open source liquid-dsp library [13], is composed of three parts, namely:

1) a pseudo-noise sequence preamble for packet detection and synchronization;
2) an 8-byte packet header, containing information on the size and the modulation and coding schemes used in the payload, protected with two levels of FEC;
3) a variable size payload, that can be coded with different modulation and coding schemes.

The correct reception of header and payload is checked with two different CRCs. As the receiver must first detect the packet, and then decode the packet header to finally be able to decode the payload, the packet preamble detection probability is obviously higher than the header reception probability, that, in turn, is higher than the probability of correctly receiving the payload. Moreover, when the OWTT ranging feature is activated, the MAC modulates the signal in advance and transmits it at a precise moment. The transmission time is saved in the form of a 16-bit timestamp with millisecond precision in the packet header: 10 bits for milliseconds and 6 bits for seconds, assuming that we can never experience a propagation time larger than 60 s. This mechanism allows to perform precise ranging excluding the modulation time from the processing time, at the cost of a small throughput reduction. In fact, the receiving node can compute the time of flight just observing the instance when the packet preamble was detected, and subtracting the packet transmission time and the detection processing time, that is computed experimentally. The packet header, in addition to the 16 bits used for the timestamp, uses 5 bits to store the source address and 5 bits for the destination address, hence all nodes that receive a packet can infer the range from the source node computing the time of flight. In its current form, the destination address is always set to the broadcast address (that in our modem is address 0), leaving other tools, such as the DESERT Underwater network simulation and experimentation framework [14], to perform routing and advanced MAC features. Both the software of the modem and DESERT can be installed in embedded systems like a Raspberry PI, that can then be added to the payload of underwater nodes and AUVs.

III. TEST SETUP AND EVALUATED METRICS

In this section we present the test configuration and the methodology used to evaluate the performance of the modem. After presenting the experiment setup (Section III-A), we describe the evaluated metrics (Section III-B) used for the system evaluation (Section IV).

A. *Test Setup*

The test was performed in the Piovego river (Padua, Italy) between March and May 2022, using the Portello bridge, located two hundred meters from our laboratory, to deploy the transmitting unit, and a service jetty to deploy the receiving

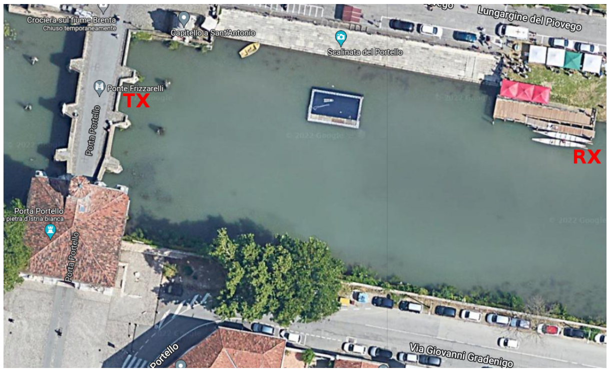


Fig. 3: Picture of the testing area. The transmitter (left) was deployed from the Portello bridge, while the receiver (right) was deployed from a service jetty. The distance between transmitter and receiver was 80 m.

unit. The distance between receiver and transmitter was approximately 80 m: during the experiment the position varied by about one meter due to water current and wind. Both modems were placed 1 m below the water surface, hence very close to the river bottom, given that the river depth was, on average, 1.5 m. A picture of the testing area is shown in Figure 3. The modulation schemes tested were BPSK (March 2022) and DSSS (May 2022), while we compared the case when no FEC was used with the cases when Hamming(7,4) and, finally, two levels of FEC, called inner and outer FEC, were used. Specifically, the latter is composed of a convolutional code with code rate 1/2 and constraint length 9, and a Reed-Solomon code with block length 255, message length 223, and alphabet size 256. We tested two configurations of packet size, i.e., 5 and 32 bytes, in order to test the transmission of short control packets and data packets, respectively. We used a carrier frequency of 50 kHz and, for DSSS, a bandwidth of 30 kHz. When no FEC was used, the raw bitrate at the physical layer was 1.5 kbps with BPSK, and 240 bps for DSSS.

In order to keep the transmitter and the receiver synchronized for the whole test, we connected each node to a TM2000 OCXO-based NTP server. This device uses a GPS to get the absolute time, and an OCXO to maintain the clock synchronized when the GPS signal becomes unavailable (such as when the device is deployed underwater). For the ranging analysis we assumed a sound speed equal to 1480 m/s: even though we did not have a precise measure of the sound speed in the test location (that usually in fresh water varies between 1440 and 1490 m/s), given the range of less than 100 m the variations on this parameter induce an error on the OWTT estimate that is almost negligible, i.e., less than the position fluctuation due to water current (that has been observed to be approximately one meter).

B. Evaluated Metrics

During the experiments we tested different configurations of modulation and coding schemes, transmitting at least 300 packets per configuration. We observed the number of packets correctly detected, the number of packets whose header was successfully demodulated and the number of packets correctly received (i.e., whose payload was correctly demodulated). We then computed:

- the packet detection ratio ρ_D, i.e., the ratio between the number of packets correctly detected and the number of packets transmitted;
- the correct header demodulation ratio ρ_H, i.e., the ratio of the number of packets whose header was successfully demodulated and the number of packets transmitted;
- the packet delivery ratio ρ_P, i.e., the ratio between the number of packets correctly received and the number of packets transmitted.

Given that the header can be demodulated only when the packet is successfully detected, and that the payload can be demodulated only if the header is correctly demodulated, we remark that ρ_P is always less than or equal to ρ_H, that is always less than or equal to ρ_D.

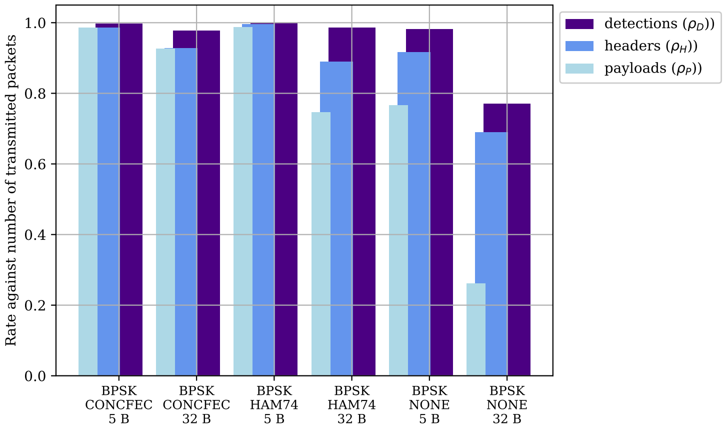
In addition, we analyzed the signal strength indicator (RSSI), in dB, computed at the physical layer as $RSSI = 20\log_{10}(g)$, with g the estimated channel gain, that is always less than or equal to 1. Finally, for each transmission we observed the ranging value provided by the modem, and compared it with the ground truth.

IV. RESULTS

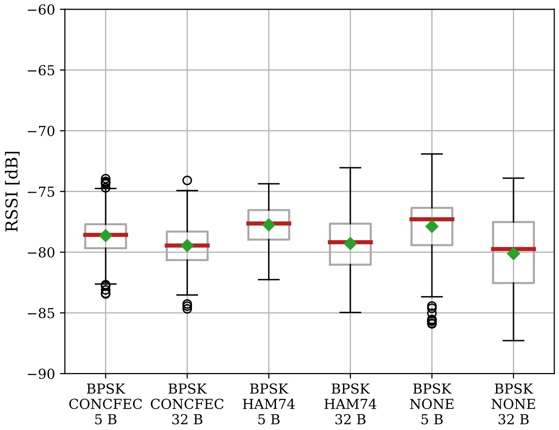
In this section we evaluate the performance of the modem, in terms of transmission robustness and OWTT ranging abilities. Specifically, we present the results of the test described in Section III, highlighting strengths and limitations of the proposed system.

With Binary PSK (BPSK) modulation, the modem was able to reach, almost always, a ρ_D of 100% (the average among all configurations being 95.3%), as can be inferred observing the dark purple bars depicted in Fig. 4a. The average ρ_H, instead, is 90.1% (blue bars) and the average ρ_P is 77.9% (cyan bars). Fig. 4a clearly highlights how the use of FEC allows to reach performance that cannot be matched by simple direct transmissions without any FEC. While a strong FEC does not provide significant advantages compared to a simple Hamming(7,4) in the case of a 5-byte payload, as the latter is already enough to ensure the correct reception of almost all packets, the application of a strong FEC is more effective for long packets. In fact, the ρ_P of 32-byte packets for the cases when no FEC, Hamming(7,4) and a concatenation of two schemes are applied are, respectively, 26.2%, 74.6% and 92.6%. This implies that, at the cost of a reduced datarate (by 43% in case of Hamming(7,4) and by 50% in the case of the concatenated FEC), the ρ_P increases up to 3.6 times when applying FEC encoding.

Considering the DSSS modulation, whose results are depicted in Fig. 5a, the average ρ_D is 84.6%, while the average ρ_H and ρ_P are, respectively, 70.6% and 59.8%. In contrast to the results obtained with BPSK, with DSSS a higher reception rate was experienced when FEC was not used: this happened due to a combination of factors caused by an intrinsic behavior of the modem, the properties of the acoustic channel, and some external factors. Specifically, DSSS is already quite robust due to the large bandwidth used and the low bitrate, leading to a packet duration (i.e., the size of the signal containing

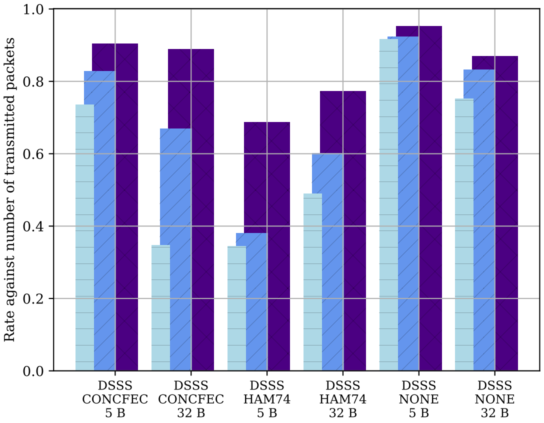


(a) ρ_D, ρ_H and ρ_P for BPSK packets.

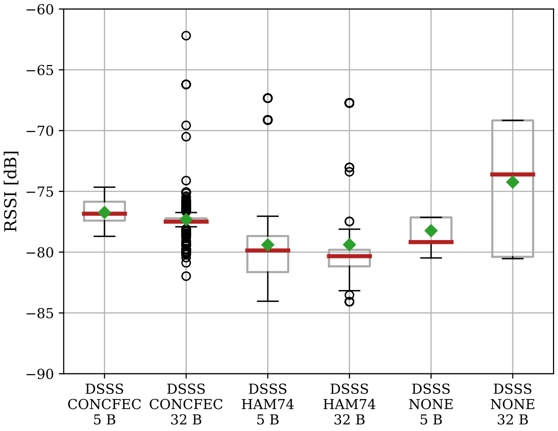


(b) RSSI values for BPSK packets.

Fig. 4: Performance for BPSK packet transmissions: rate of the number of detections, headers decoded and payloads decoded (Figure 4a), and Boxplots of the RSSI values for each packet (Figure 4b).



(a) ρ_D, ρ_H and ρ_P for DSSS packets.



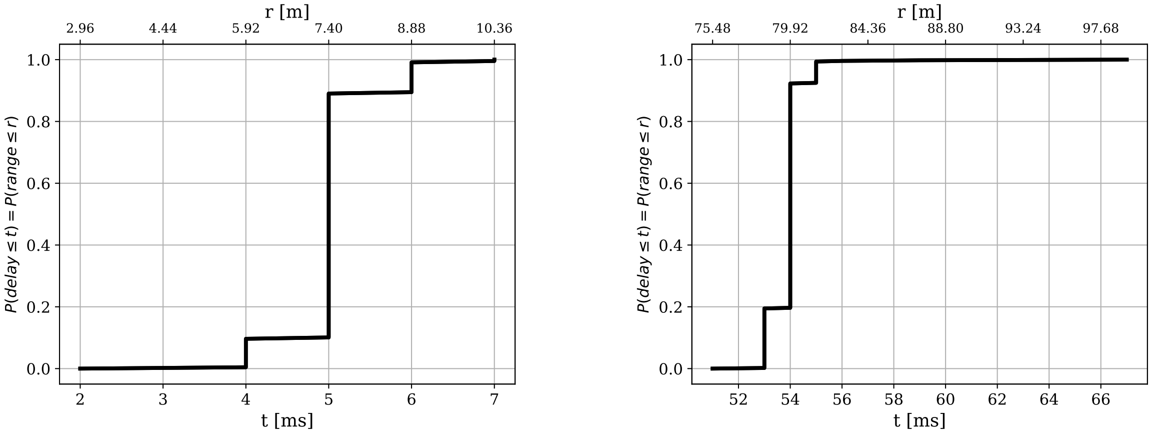
(b) RSSI values for DSSS packets.

Fig. 5: Performance for DSSS packet transmissions: rate of the number of detections, headers decoded and payloads decoded (Figure 5a), and Boxplots of the RSSI values for each packet (Figure 5b).

the modulated packet) of more than 1.5 s for a payload size of 32 bytes. Furthermore, adding redundancy bits the resulting packet duration can easily exceed 3 s. This has two consequences. First, the acoustic channel being a medium with short channel coherence time, defined as the amount of time the channel impulse response does not change by more than 5%, the channel impairments estimated during the reception of the packet preamble and used to tune the reception filters change in time and can differ from the beginning to the end of the packet. Second, the audio amplifier has an automatic system to prevent damages in case the temperature exceeds 70° C: during the transmission of such long packets during days when the external average temperature was about 30° C, it was not rare that such threshold was exceeded and the triggered protections gave a signal with a smaller amplitude. To mitigate in part this issue we applied a heatsink to the modem's amplifier.

In addition to these intrinsic issues, in the days when we tested the DSSS modulation (26th and 27th of May 2022) we had witnessed many disturbances, including many passing boats and ships that made the channel much more unstable compared to when we tested BPSK modulation (March 2022, when the weather was still not warm enough to encourage tourists to visit the river with guided trips): this caused a high standard deviation of the received RSSI that reached 4.92 dB, more than double compared to the BPSK case. These effects can be observed in Fig. 5b that shows that the RSSI values are mostly sparse with a large number of outliers, in particular when compared to the BPSK transmissions (Fig. 4b). The three worst cases are the Hamming(7,4) with a 5-byte packet and with a 32-byte packet, and with no FEC applied using a 32-byte packet, with a standard deviation of, respectively, 3.58, 3.86 and 4.92 dB. Using the DSSS modulation, with an average of the expected values of the RSSI equal to -77.55 dB, and an average standard deviation equal to 2.73 dB, the modem was able to reach an average ρ_P of 59.9%.

We also tested the OWTT ranging capability of the modem by including the timestamp of the transmission time in the payload. Given that both units (transmitter and receiver) were kept synchronized with OCXOs, the receiver was able to infer the distance once the sound speed had been set. We performed a test at the two sides of the bridge (approximately 7 m in length) and a test with the receiver at the service jetty, i.e., using the configuration presented in Fig. 3. Assuming the



(a) 7 m.

(b) 80 m.

Fig. 6: Cumulative distribution function for the delay received at 7 m (Figure 6a) and 80 m (Figure 6b).

speed of sound in the fresh water of the canal to be around 1480 m/s, we have a propagation time of 4.73 ms for the 7 m range test and 54 ms for the 80 m range test. The cumulative distribution functions of the actual values, in ms, are presented in Fig. 6, where it can also be observed that the expected values, for the two sets of measurements are, respectively, 5 ms and 54 ms, while the standard deviations are, respectively, 0.52 ms and 0.82 ms which translates to 77 cm for the former and 1.2 m for the latter.

The test results are in line with the current technology and validated the core design of the modem.

V. CONCLUSIONS

In this paper we detailed the structure of the high frequency acoustic modem developed for the MODA project. We also presented and discussed the results of the experiments performed using this modem in the Piovego river (Padua, IT) in a very shallow water scenario. The tests demonstrated the ability of the modem to perform both robust communication at a range of 80 m with a very low transmission power, and OWTT ranging. The detection rate is around 96% for BPSK modulation and around 85% for DSSS modulation, while the ρ_P strongly depends on the packet size and the applied FEC: some configurations allowed to reach a ρ_P greater than 90% even with large packets. The ranging error was less than one meter most of the times for a range of 7 m and 80 m. We stress the fact that the modem was assembled from available off-the-shelf components and that its price is below 1000 EUR, making it a suitable device for inexpensive lightweight underwater drones for swarm missions.

Future work will focus on improving both hardware and software components, by including in the modem a TX/RX switch that will allow to receive and transmit the signal with a single transducer, an impedance matching circuit that will maximize the power transmission, the possibility to introduce other modulation and coding schemes, such as Orthogonal Frequency-Division Multiplexing (OFDM), and to interface the modem with the DESERT Underwater Framework in order to extend the capability of the modem with routing and advanced MAC features.

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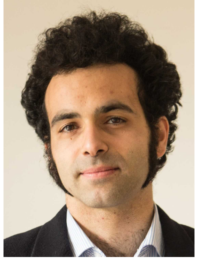

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