Affordable underwater acoustic modems and their application in everyday life: a complete overview

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ABSTRACT

In the past, underwater acoustic modems were mainly used in Oil & Gas and military scenarios, that need long range transmissions with high power emitters often deployed in deep water. For this reason, the development of low-cost acoustic modems was limited to academic activities and experimentation. Recently, the new developments of low-cost unmanned vehicles suitable for shallow-water shore and coastal missions, and the need for sensors networks for measuring water quality and studying the effect of climate change in littoral areas, highlighted the need for low-cost and low-power acoustic modems. These communication systems can enable a wide set of applications, often based on low-cost underwater and surface unmanned vehicle swarm formations, where an acoustic link between the vessels is required to coordinate the mission and maintain the formation. In fact, these low-cost modems can be used for small-scale applications thanks to their low price at the cost of a low transmission range and throughput, when compared with the performance achievable with legacy acoustic modems. In this paper, we review the recent developments of low-cost and low-power acoustic communication, identifying advantages and limitations of these devices, and describe potential new applications that can be enabled by these systems.

KEYWORDS

Underwater acoustic networks; low-cost acoustic modems.

ACM Reference Format:

Filippo Campagnaro, Fabian Steinmetz, Bernd-Christian Renner, and Michele Zorzi. 2023. Affordable underwater acoustic modems and their application in everyday life: a complete overview. In *The 17th International Conference on Underwater Networks & Systems (WUWNet'23), November 24–26, 2023, Shenzhen, Guangdong, China.* ACM, New York, NY, USA, 8 pages. https://doi.org/10.1145/3567600.3568156

WUWNet'23, November 24–26, 2023, Shenzhen, Guangdong, China

ACM ISBN 978-1-4503-9952-4/22/11…$15.00
https://doi.org/10.1145/3567600.3568156

1 INTRODUCTION

The high attenuation of electromagnetic signals underwater makes WiFi, cellular and satellite transmissions not suitable for long range communication links in this environment [25]. Magneto-inductive modems can reach a distance up to a few tens of meters and a bitrate of a few kbps [45], although they can cross the water-to-air boundary, their high transmission power may affect marine life. Underwater optical modems, instead, can cover the same distance and provide a higher rate of a few Mbps, and are the best communication devices for underwater broadband short-range links [13]. Finally, acoustic modems are the only devices able to establish long range underwater links, up to a distance of tens of kilometers [3] using a power of less then 100 W, with bitrate of a few kilobits per second: for this reason acoustic is the mostly used communication technology, with several industrial and research devices being developed in the last decades.

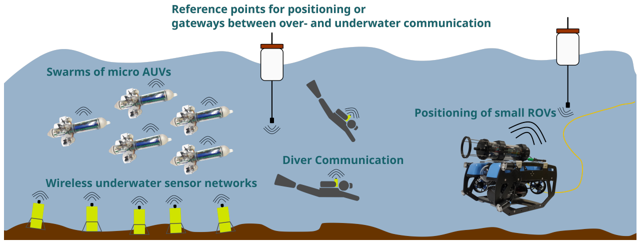


Figure 1: New concepts enabled by low-cost underwater modems.

The use of traditional commercial acoustic modems [1–3] is typically restricted to military and offshore deep water deployments, due to the high power consumption and the high cost of these devices, making them not usable in many civil applications, where a dense underwater internet of things (IoT) sensor network can be used to predict floods and monitor the water quality of port, coastal areas and biodiversity hotspots. Moreover, their price is often higher than low-cost remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs), such as the BlueROV [4], and the use of traditional acoustic modems in small low-cost underwater vehicle, often equipped with small batteries, will dramatically shorten the vehicle range. In fact, the recent availability of low-cost unmanned vehicles [4, 9, 36] and the introduction of new sensor technologies for aquaculture sites [28], highlighted the need for low-cost and low-power acoustic modems able to cover a range of a few hundred meters with a low datarate. In addition, the maximum depth of the deployment in the aforementioned applications is typically a few tens of meters, instead of several hundreds of meters like in offshore applications: this allows the use of low-depth rated casing, hence reducing the cost of development and materials. In fact, these new coastal civil applications (Figure 1) require simple and affordable devices that can be powered with small batteries. Thanks to the effort performed in the last five years by both industries [19] and research institutes [46] to fill this gap, new low-cost and low-power acoustic modems have been developed and are now available in the market. Most of them have similar performance and satisfy the requirements of having a cost of less than 2000 EUR, a maximum power consumption of approximately 1 W in transmission and 100 mW in reception,[1] a range of at least 100 m and a datarate of at least 40 bps.

This paper presents an overview of low-cost acoustic modems, identifying potential applications that can be enabled by these affordable devices providing benefits for civil applications. By the authors' best knowledge, this work, together with its extended version in [26] is the first paper which focuses on underwater low-cost acoustic modems and their recent developments. This paper, compared to the work in [26], provides a more updated, corrected and complete survey of low-cost underwater acoustic modems and their applications, while the latter is a more general overview that also presents low-cost acoustic positioning systems. The remainder of this paper is structured as follows. Section 2 presents a complete and detailed review of low-cost underwater acoustic modems, including both commercial devices and research prototypes. Section 3 presents the applications enabled by these new types of devices and, finally, Section 4 concludes the paper.

2 LOW-COST ACOUSTIC MODEMS

In this section we present the state-of-the-art of low-cost acoustic modems, first presenting the research prototypes in chronological order, reviewing both pioneer (Section 2.1) and recent studies and research developments (Section 2.2), and then providing a complete overview of what is available in the market (Section 2.3).

2.1 Early studies

In 2006 the authors in [22] presented the design of one of the first low-cost acoustic modems for moored oceanographic applications. Frequency shift keying (FSK) modulation was used to achieve 80 bps up to 7 m. A 50 EUR fish finder transducer with resonant frequency of 50 kHz and 2 kHz bandwidth was used to keep the development price extremely low (less than 100 EUR overall). In the same year, the authors in [55] highlight the compelling need to develop low-cost and low-power acoustic modems for short-range communications, presenting the ongoing development of a 100 EUR modem prototype equipped with a wake-up receiver to lower the power consumption. In 2007 the authors in [41] presented the design a low-cost acoustic modems where all data processing was computed with a PC. The microphone and the speakers of the PC were used as receiver and transmitter, respectively. The components were waterproofed with elastic membranes and the modem prototype was able to transmit 24 bps with FSK up to a distance of 17 m using the frequencies between 1000 Hz and 2000 Hz. A few years later (2010), the FPGA-based acoustic modem developed by the University of California San Diego (UCSD) [23] achieved a bitrate of 200 bps up to a range of 350 m transmitting in the 32-38 kHz band with a transmission power of 40 W. In this modem the authors managed to avoid purchasing expensive underwater transducers by encapsulating in a potting compound a simple and low-cost piezoelectric transducer: even if this modem uses a high power transmitter, its design inspired more recent works where other scientists developed their own underwater transducer. The ITACA modem [48] developed in 2012, provides transmission of digital data using coherent

[1] With exception of software defined modems, that require a computing unit that may consume up to 5 W.

FSK at rates of 1 kbps with an 85 kHz carrier frequency: the authors managed to transmit up to 240 m with a transmission power consumption of only 0.1 W. It uses a precise real-time-clock to perform coherent demodulation and to use a TDMA MAC scheme. It uses low-cost transducers (with a cost of about 100 EUR each) usually employed in low-cost echosounder applications, hence significantly reducing the hardware cost. In 2013, the authors in [21] developed an FSK modem performing all signal processing in a PC with GNU RADIO. The hydrophone was built in-house with eight car-audio piezoelectric-tweeters (with a cost of 0.50 EUR each) waterproofed with a plastic container filled with vegetable oil. They managed to transmit with a bitrate of a few hundred bits per second at a distance of 6 m. One year later, the micro-modem developed by the Gangneung-Wonju National University (South Korea) [42] achieved a maximum distance of a few hundred meters and a transmission rate that ranges between 200 bps and 5 kbps using a BPSK signal, with a maximum power consumption of 8 W and using a frequency of 70 kHz. In the same year, the authors in [56] developed an On Off Keying (OOK) transceiver with carrier frequency 40 kHz, able to reach a communication range of 60 m with a bitrate of 333 bps in a lake trial.

2.2 Recent research developments

Despite the aforementioned works, that can be considered as pioneer studies in the world of affordable underwater communication, most developments in low-cost acoustic modems have happened in the last five-to eight years. In 2018, a very small low-frequency modem specifically developed for micro AUVs was presented in [54]. This modem uses direct sequence spread spectrum (DSSS) modulation with a central frequency of 12.5 kHz and a bandwidth of 3 kHz, obtaining a bitrate of 55 bps up to a distance of 200 m. Using a carrier frequency of 40 kHz, the FSK ultrasonic modem [40] presented in the same year uses a very low-cost waterproof ultrasonic transducer typically used in the automotive industry for measuring the distance from the car and the closest obstacle. All processing is performed with an Arduino, and from a pool test the authors managed to perform error-free transmissions with a bitrate of 1.2 kbps up to a range of 1.5 m. In the meantime, the authors in [49] introduced the concept of a surface receiver consisting of a hydrophone plugged into a standard sound card of a mobile device such as a smart phone or tablet. They prove the possibility to transmit up to a range of 100 m transmitting with very low power and with a bitrate between 25 and 375 bps in the 8-16 kHz band, using a very low-cost hydrophone and comparing different M-ary Orthogonal Signalling (MOS) schemes using up/down chirps in one scheme, and bandlimited m-ary PN sequences in others. Using a chirp waveform, the low-power Nanomodem V2, presented by the University of Newcastle in 2018 [43] operates in the 24-28 kHz band, achieving a datarate of 40 bps within a surprising range of 2 km, despite the very low transmission power (168 dB re 1μPa @ 1 m). The recently released new version of the Nanomodem (V3) [50], instead, uses MOS with a BPSK modulated orthogonal PN sequences over an 24 kHz-32 kHz band with a raw data rate of 640 bps and a range of up to 2.3 km in sea. The same research group previously developed the Seatrac miniature acoustic modem [44], that uses DSSS and operates in the ultrasonic 24-32 kHz band, achieving a throughput up to 1.4 kbps at a range of 1.5 km, with a transmission power of 176 dB re 1μPa @ 1 m. It is designed to support communication between divers and ROVs and, although it is a more complex system and uses a higher transmission power than the other modems discussed so far, its deserves to be mentioned in this context as its licence has been provided to Blueprint Subsea, that commercializes the modem as it is. The Nanomodem V3 technology, instead, is licenced to Succorfish, that developed the SC4X portable integrated acoustic, iridium and GSM diver communications system [17], a low-power (only 168 dB re 1μPa @ 1 m) modem used to enable diver to diver and diver to surface communication with a datarate of 463 bps.

The very small ahoi modem, that was started to be developed in 2014 [47] and whose first stable version used in a complete network was developed in 2020 [46], has a total component costs of less than 600 EUR, including an off-the-shelf transducer (400 EUR), microprocessor and the transceiver board developed in house (200 EUR). It uses a very low transmission power of 160 dB re 1μPa @ 1 m and the frequency band of 50 kHz to 75 kHz, achieving a throughput of 260 bps (default net rate, that can be increased up to 4.7 kbps in good channel conditions) and a range up to 200 m in very shallow water, thanks to a robust frequency hopping (FH) FSK modulation. The ahoi modem is an open source project[2], which allows other researchers to reproduce and understand hardware and software. At the moment, a chirp spread spectrum (CSS) modulation scheme is under development [52]. In 2021 a low-cost modem developed by the Tianjin and the Guilin Universities, China, based on the embedded system STM32H743 that uses single and multi carrier MFSK schemes, has been presented in [53]. The modem can achieve a distance of 5 km with a bitrate of 125 bps, and of 2.5 km with a bitrate of 1 kbps, and operates in the 20-30 kHz band. The low-cost modem developed in 2022 by the Xiamen University, China, [29] operates in the 35–45 kHz frequency band, and is able to achieve 500 m with a bitrate of a few hundred bits per second using FH-MFSK. The total cost of components is approximately 500 EUR and the maximum power consumption, when transmitting, less than 6 W.

[2] http://ahoi-modem.de/

Table 1: Performance figures of affordable acoustic modems ordered by transmission range

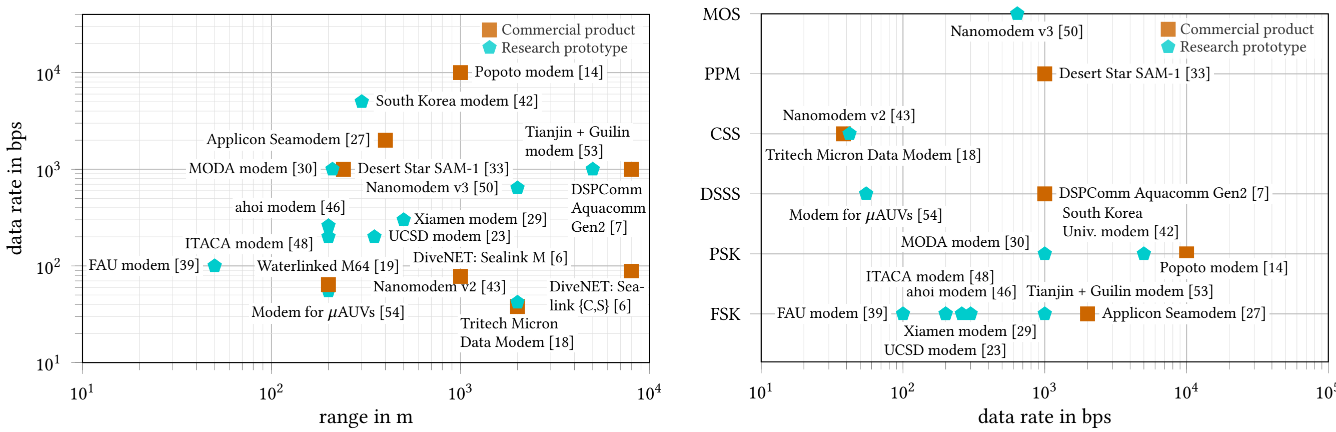
Manufacturer and model	Developer	Max Range	Bit Rate	Freq. Range	Modulation	Price[1]
FAU modem [39]	research	50 m	100 bps	100-164 kHz	FH-BFSK	—
MODA modem [30]	research	300 m	1 kbps	50-70 kHz	BPSK, DSSS, FH-BFSK	1000 EUR
Waterlinked M64 [19]	commercial	200 m	64 bps	31-250 kHz	—	2200 EUR
ITACA modem prototype [48]	research	200 m	200 bps	85-200 kHz	FSK	100s EUR
Modem prototype for μAUVs [54]	research	200 m	55 bps	11-14 kHz	DSSS	800 EUR
ahoi modem [46]	research	200 m	260 bps	50-75 kHz	FH-BFSK (OFDM)	600 EUR
AppliCon SeaModem [27]	commercial	400 m	{0.75, 2} kbps	25-35 kHz	MFSK	—
South Korea Univ. modem [42]	research	{100-300} m	{0.2-5} kbps	70 kHz	BPSK	—
Desert Star SAM-1 [33]	commercial	240 m	1 kbps	34-48 kHz or 65-75 kHz	16-PPM	800 EUR
UCSD prototype [23]	research	350 m	200 bps	32-38 kHz	BFSK	300 EUR
Xiamen Uni. modem [29]	research	500 m	200-300 bps	35-45 kHz	FH-MFSK	500 EUR
Waterlinked M16 [20]	commercial	1 km	16 bps	58.5 kHz	—	2200 EUR
DiveNET: Sealink M [6]	commercial	1 km	78 bps	15-30 kHz	—	1500 EUR
Popoto low-power modem [14]	commercial	1 km	10 kbps	20-40 kHz	PSK, FH-BFSK	3000 EUR
Tritech Micron Data Modem [18]	commercial	2 km	40 bps	24-28 kHz	CSS	—
Nanomodem prototype V2 [43], V3 [50]	research	2 km	40 bps, 640 bps	24-28 kHz, 24-32 kHz	CSS, MOS	100 EUR
Tianjin + Guilin modem [53]	research	{2.5-5} km	{0.125-1} kbps	20-30 kHz	MFSK (OFDM)	—
DiveNET: Sealink {C,S} [6]	commercial	8 km	80 bps	5-15 kHz	—	2000 EUR
DSPComm Aquacomm Gen2 [7]	commercial	8 km	{0.1, 1} kbps	16-30 kHz	DSSS (OFDM)	1000 EUR

[1] Overall price of all modem components, included the transducer.

The recently-developed MODA modem [30] uses all off-the-shelf hardware components, including a Raspberry PI4 as a processing unit, a high quality 192 kHz audio DAQ Raspberry HAT, an audio amplifier for transmission, a hydrophone preamplifier in reception and two transducers, one for transmitting and one for receiving. The cost of all the components is 1000 EUR per modem: this price can be lowered significantly (by about 400 EUR) if a tx/rx switch is used instead of a second transducer. Optionally, the modem is designed to perform one way time travel ranging by relying on precise clocks such as oven-controlled crystal oscillator, that are more affordable than atomic clocks. The modem uses a carrier frequency of 50 kHz and a bandwidth of 20 kHz, and is still under evaluation. For this reason the performance figures are not available at the moment: preliminary results have shown that it can perform reliable transmissions with a bitrate of 1 kbps at a distance of 80 m, while recent test demonstrate its capability to reach a few hundred meters (300:400 m). The researchers from the Florida Altantic University (FAU) [39] recently developed a low-cost FH-FSK modem prototype with a transmission power of 5 W that is able to reach 50 m with a bitrate of 100 bps in the 100-164 kHz frequency band.

2.3 Commercial devices

Commercial low-cost acoustic modems are also available off-the-shelf. For instance, the modem launched by DSP-Comm [7] costs about 1000 EUR, uses the 16–30 kHz band, has a maximum transmission rate of 100 bps, and a nominal range of 500 m. With the same range, the Micron Data Modem developed by Tritech [18] is a low-power compact modem with a maximum data rate of 40 bps and operates in the 20-28 kHz band. Its transmission power is up to 169 dB re 1μPa @ 1 m and weighs less than 250 g. This modem is a commercial version of the aforementioned Nanomodem V2 [43] designed by Newcastle University, that gave Tritech its licence to produce the Micron Modem. DiveNET, a company that mainly produces communication and localization equipment for divers, supplies Sealink [6], an affordable and low-power acoustic modem that provides either a range up to 8 km at a datarate of 80 bps using the 5-15 kHz band (models C and S) or, with a more compact design and a lower transmission power, a range of 1 km at a datarate of 78 bps using the 15-30 kHz band. Subnero [16], in addition to its high power and high depth-rated devices for industrial applications, supplied a research edition software-defined-modem (WNC-M25MRS3) operating in the 20-32 kHz band and able to transmit up to 10 kbps at a maximum range of 1 km, with a source level of 175 dB re 1μPa @ 1 m. Based on our



(a) Range vs. data rate **(b) Data rate vs. modulation**

Figure 2: Comparison between recent low-cost acoustic underwater modems.

knowledge, its price exceeded the one of the other low-cost commercial modems listed in this section, but is still less than half the cost of the modems used in offshore applications. In 2023, Subnero and Popoto Modem [14] started a partnership, developing a common research modem named S1000-N and able to achieve a datarate up to 10 kbps up to a range of 1 to 4 km: we believe that this modem, that costs more than 6000 EUR, have substituted the WNC-M25MRS3, given that the WNC-M25MRS3 in not present anymore in the Subnero website.

Popoto Modem [14], in addition to solutions for offshore applications, also provides a series of low-rated and low-power modems with an affordable price of less than 3000 EUR. These modems use the 20-40 kHz band and achieve datarates up to 10 kbps at a typical range between 1 and 2 km. The AppliCon SeaModem [27] is commercially available as well: the modem uses FSK to transmit up to 2 kbps within a range up to 400 m. The modem uses a central frequency of 30 kHz and a bandwidth of 10 kHz.

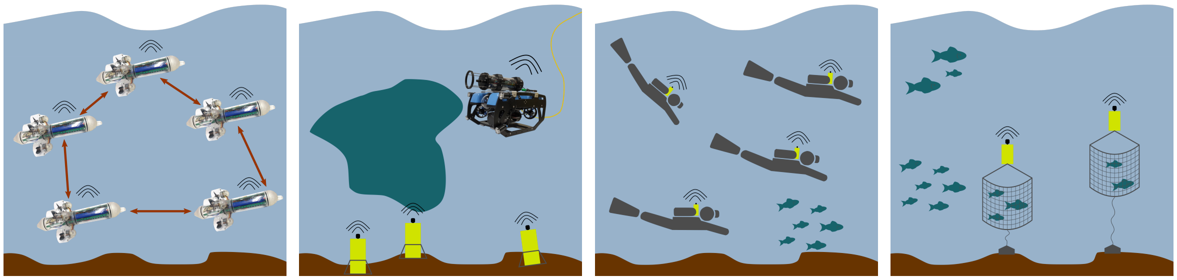
The low-cost Desert Star SAM-1 modem [33] uses either the 34-48 kHz band or the 65-75 kHz band, has a bitrate of a few tens of bits per second and a typical range of 250 m. Compared to the other low-cost acoustic modems described so far, it has a higher transmission power (up to 189 dB re 1μPa @ 1 m) and uses pulse position modulation (PPM) instead of spread spectrum techniques such as DSSS or chirp-based modulations. Waterlinked [19], instead, supplies the M64 acoustic modem, able to achieve a range up to 200 m and a bitrate of 64 bps. This low-power modems can be easily integrated in a BlueROV, and operates in the frequencies between 31 and 250 kHz. Moreover, the recently released Waterlinked M16 modem [20] is able to reach a larger distance (up to 1000 m) with a bitrate of 16 bps. The price of both modems is approximately 2000 EUR and they consume approximately 2 W.

The most representative low-cost underwater acoustic modems discussed in this section are summarized in Table 1, whereas Fig. 2 compares range, data rate, modulation scheme and carrier frequency, highlighting which modems are commercial product (orange square) and which are research prototypes (light blue hexagon). Thanks to the fact that low-cost acoustic modems are now available, many new applications for civil use can be enabled, paving the way for a large use of these devices in Underwater Internet of Things applications. In the next section we discuss these applications, the benefits they can provide and what is still limiting their extended use in everyday life.

3 APPLICATIONS

In the past, acoustic underwater networks were mainly used for large-scale military and industrial operations such as Oil and Gas pipes inspections [25], coastal erosion and tsunami prevention [34], distributed coastal surveillance and monitoring, intelligence gathering, surveillance and reconnaissance, mine countermeasure, rapid environmental assessment, and anti-submarine warfare systems [35]. In all of these applications the use of both sophisticated high-power acoustic modems and multiple AUVs is needed to achieve the stringent system requirements, such as deep water deployment, long range transmissions, bitrate of a few kbps, etc.

Fixed and distributed subsea dense sensor deployments allow to measure the marine environment with high spatial resolution and a high temporal update rate. They are driven by the increasing interest in studying water quality and presence of pollutants in the water, as well as the effect of climate change to coastal areas and biodiversity. In fact, in [32] the authors demonstrate that surface measurements



(a) Swarm coordination **(b) Pollution detection** **(c) Diver coordination** **(d) Rope-less fish traps**

Figure 3: Example applications for low-cost acoustic modems.

are not enough to characterize the presence of pollutants in the water, given that plastic debris have been found up to a depth of several hundreds of meters. For dense wireless sensor networks low-cost acoustic underwater modems are a key enabling technology and a requirement for the Internet of Underwater Things and its applications. Figure 3 depicts selected examples. In this context, miniature autonomous platforms for cost-effective oceanographic sensing have been developed by commercial and research organisations. For instance, ecoSUB Robotics [8] supplies a line of small low-cost AUVs for acquiring water measurements. H20 Robotics developed a line of low-cost surface vehicles [11]. Furthermore, the BlueROV2 [4], a small, low-cost, and open-source remotely operated vehicle, can be equipped with sensors and can perform some simple autonomous tasks. The WaterLinked acoustic underwater modem can be ordered with a BlueROV2 integration kit. In fact, the BlueROV2 is used by many researchers to develop localization and navigation algorithms, e. g., [37]. Three types of robotic agents were built during the EU H2020 subCULTron project to measure sensors data in a swarm formation. The newly-developed surface vehicles, AUVs and bottom nodes were deployed to perform long-term marine monitoring and exploration in the Venice Lagoon [15]. All of them were equipped with low-cost acoustic modems. The University of Washington and PMEC have developed the μFloat [12], a simple low-cost underwater robot for distributed sensing in coastal waters. The μFloat is a trackable drifting sensor package specifically tailored to be deployed in swarms to perform simultaneous, distributed measurements in strong tidal currents. In both projects, subCULTron and μFloat, the low-cost acoustic modem developed by Newcastle University was used. Similarly, the ahoi acoustic modems and the DESERT Underwater communication stack [38] were used in the RoboVaas project for underwater data collection. The use case was demonstrated, using autonomous surface vessels (ASVs) and AUVs to retrieve data from a dense underwater acoustic sensor network [51]. The discussed sensor platforms are not designed for open sea deployments. They can be used in scenarios with less challenging weather conditions, for example inland waters, such as rivers, lakes and lagoons, where assertion of water quality and inspection of the effect of climate changes on biodiversity is still very important.

Furthermore, low-cost acoustic devices help to solve the entanglement of marine mammals in crab trap lines set during the commercial crab fishery operations. In addition to the loss of the traps for fishermen, entangled traps and buoys interfere with the breathing of the mammal and restrict its feeding, up to starvation [5]. Acoustically-activated rope-less gear systems can solve this problem. As the cost of each traps is a few hundreds of Euros, the price of the acoustic system must be in the same order, while commercial solutions, such as the Desert Star ropeless fishing system (that uses the SAM-1 modem) have a price that starts from 5000 USD [33].

All commercial modems presented in Table 1 (expect the Popoto modem that is designed for offshore application) can be used in robotic swarms and ropeless fishing system and low-cost sensors for water monitoring. Same for the ahoi modem and the Nanomodem, while the other research prototypes are either at a initial stage (e.g., the prototype recently developed by FAU), or have a idle power consumption that is still too high, like the MODA modem. The latter, in fact, is a software-defined modem where all signal processing is performed on a Raspberry (that is the most power-hungry component), making it a valuable open-source platform for research experimentation. Also the ahoi modem is an open-source project, and uses a low-power microprocessor to demodulate the signal.

The use of acoustic underwater modems is still very limited to a few applications. The lack of availability of low-cost buoys and bottom nodes equipped with batteries that are easy to deploy and maintain is one of the main reasons. The Hamburg University of Technology developed their own small buoys using waterproof containers mainly used for kayaking and other water sports for the final RoboVaaS demonstration [31]. They are developed for testing purposes and are sufficient for academic demonstrations, and cannot be used in long-term applications. These nodes can be built with a cost of less than 150 EUR, but their development requires a non-negligible human effort. Commercial systems are still too expensive for usage in dense deployments. The data buoys developed by Fondriest [10] have a price starting from 1500 EUR. The price is similar to the cost of H2Orbit, the low-cost surface vehicle developed by H20 robotics [11]. The lack of availability of low-cost systems for medium term deployments in controlled environments and inland waters decelerate the opportunity to bring acoustic underwater communication to the mainstream. Indeed, new companies started to conquer the market and sell less expensive underwater equipment and components. Blue Trail Engineering offers low-cost connectors and cables [24], with a 600 m depth rating. Blue Robotic [4] provides watertight enclosures with different diameters and lengths. Moreover, 3D printers allow research institutes to manufacture their components and connectors. H20 Robotics [11] develop low-cost equipment to support water monitoring and divers' mission coordination. Presumably, more manufactures will develop and launch new low-cost underwater components and platforms during the next months and years such as the BlueBoat, a low-cost ASV recently announced by Blue Robotic that will become commercially available from this autumn, and the low-cost smart-buoy this summer by H20 Robotics at the Oceans Conference and Exhibition.

4 CONCLUSIONS

In this paper we presented an extensive review of low-cost acoustic modems, describing the main applications in which they can provide a significant benefit. Although legacy acoustic modems can provide very long range communication, their cost and power consumption are prohibitive for civil applications, indeed they are mostly used by military and Oil and Gas industries. Conversely, low-cost acoustic devices can support several civil applications, such as diver-to-diver communication, data retrieval from environmental sensors, and micro AUV swarms, with the trade-off of a lower bitrate and transmission range. While in the past, these affordable modems were mainly developed by universities for research purposes, the recent development of low-cost AUVs and ROVs highlighted the need for these devices in the market, that have become finally available off the shelves. We believe that this paper can be used for decision-making of research groups or product developers for new underwater projects and applications.

ACKNOWLEDGMENTS

This work has been partially supported by the European Union - FSE REACT EU, PON Research and Innovation 2014-2020 (DM 1062/2021).

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