Experimenting Various JANUS Frequency Bands with the Subsea Software-Defined Acoustic Modem

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***Abstract*—The use of traditional commercial acoustic modems is typically confined to Oil & Gas and military scenarios, as their high power consumption and steep cost make them inaccessible for many other applications, such as aquaculture, diver communication and low-cost underwater vehicle swarm. While low-cost acoustic modems are gradually entering the market, flexible research platforms like software-defined acoustic modems (SDAMs) remain prohibitively expensive for small research groups and startup companies, who, on the other hand, often drive innovation and generate new ideas. As a result, the development of these technologies, which currently find application in a few specialized contexts, remains constrained.**

When considering experimentation, what has empowered do-it-yourself practitioners and students approaching circuits and embedded systems is the availability of user-friendly and affordable prototyping boards like Arduino and Raspberry Pi. Following this paradigm, we developed the first Raspberry Pi HAT acoustic frontend for underwater acoustic testing and experimentation, and hence realized the low-cost Subsea software-defined acoustic Modem (SuM). In this paper we present its evaluation when used with the JANUS waveform at different frequencies bands, in both salt and fresh water. Given that we succeeded in proving its technological maturity in sea trials, we believe this modem can be both a valuable platform for industrial applications and a game changer to encourage other research institutes to experiment underwater communications.

***Index Terms*—Underwater acoustic modem, software defined modem, sea-trial, tests, low-cost underwater modem.**

I. Introduction and Motivation

Experimentation in underwater wireless communication is hindered by the high cost of components [1], [2] and the lack of open and easy to use research platforms affordable by small research groups and startup companies that often drive innovation and generate new ideas. Low-cost acoustic modems start to be available on the market, but are often close platforms for a specific application, such as diver to diver communication [3] or rope-less fish traps [4], rather than open platforms which researchers can use to experiment new waveforms, error correction schemes or adaptive algorithms for underwater networks. An effort in this direction was the Ahoi acoustic modem [5], whose processing unit is composed by a very low-power micro-controller able to perform only very low-computation tasks. Moreover, developing demodulators in micro-controllers may not be trivial: usually, researchers prefer a more flexible platform to experiment different waveforms and transmission configurations before selecting the one to be developed in hardware, be it a micro-controller or a Field Programmable Gate Array (FPGA). Such research platforms are often referred to as software-defined acoustic modems (SDAMs), that so far have always been very expensive to purchase or realize. Despite the existence of affordable platforms for testing channel access and routing schemes for underwater networks [6]–[8], low-cost SDAMs are not available on the market: this is a gap that needs to be filled to help democratize underwater communication research and make it an attracting subject for a wider audience. Our research group faced the same challenge when experimenting on the physical layer aspects of the protocol stack, and decided to develop its own SDAM. We first experimented different solutions using off-the-shelf audio components in the context of the Italian PNRM MODA project [9], [10] discovering that, while the developed software was mature enough to support various modulation and coding schemes in real-time transmissions, the hardware components had to be significantly refined to achieve good performance. Therefore, after carefully reviewing the state of the art of low-cost acoustic modems developed by research institutes and universities [5], [11]–[14], we designed our new acoustic frontend. A few proof-of-concept prototypes have been developed to validate our idea, to then end up with the final analog frontend for the acoustic modem as a Raspberry Pi HAT add-on, making it what we believe is not only a valuable platform to approach underwater communication, but also a mature device able to be customized for several applications. When coupled with a high quality 192 kHz Data Acquisition system and a Raspberry Pi, it allows to transmit waveforms of any type and to support a frequency range from 2 Hz to 70 kHz, depending on the selected transducer. This allows, for instance, to perform channel sounding and transmit with various waveforms, including the one used in JANUS [15], the first

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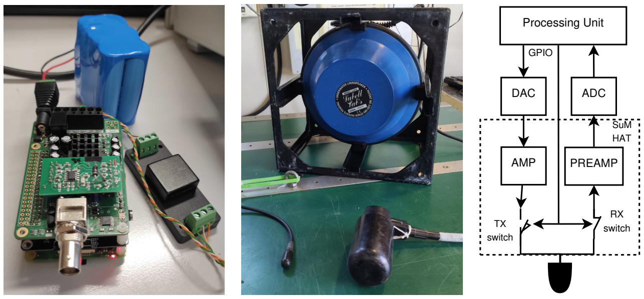
digital underwater communication standard.[1] More important, when used with our software framework to perform physical layer tasks, it becomes the Subsea software-defined acoustic Modem (SuM), a complete user-friendly and affordable platform for professionals and enthusiasts of all backgrounds. SuM's capabilities can be further extended by using it with the DESERT Underwater protocol stack [6], hence enabling the use of SuM in multi-hop networks. Finally, if precise clock oscillators are used, SuM natively allows one-way travel-time (OWTT) ranging. By design, it is not only a research platform, but also a complete modem able to change several parameters according to the channel and network conditions. This paper briefly presents the SuM modem developed by the University of Padova and SubSeaPulse SRL and its performance when used to transmit the JANUS waveform with various frequency bands in fresh and salt water. A full description of the new version of the modem and its abilities is instead provided in [16], where its communication and ranging performance are evaluated when transmitting PSK signals.

II. HARDWARE COMPONENTS

The design of our revised modem consists of three main hardware blocks described as follows.

1) A Raspberry Pi, used as the processing unit, performs all the tasks of the protocol stack, including routing, channel access, forward error correction and digital signal processing (filtering, preamble synchronization, modulation and demodulation).
2) A HiFiBerry DAC+ADC Pro HAT [17] serves as the 192 kHz 24 bit analog to digital and digital to analog converter.
3) An amplification and switch module is used to i) switch the modem from reception to transmission, ii) preamplify the received signal, iii) amplify the output signal to be transmitted.

From the hardware perspective, a great step forward has been made compared to the modem prototype presented in [9]: in contrast with the previous design, all components of the analog frontend have been moved on a single Printed Circuit Board (PCB) which has the footprint of a standard Raspberry Pi HAT and is called from here onward the SuM HAT. In this way, the complete modem is a stack composed of three layers (Figure 1a): the Raspberry Pi, the HiFiBerry, and the SuM HAT. The modem can run with any Raspberry Pi: for power constrained applications the Raspberry Pi 0 can be used, while for more power-demanding applications the Rasperry Pi 4B is recommended, although for general use a Rasperry Pi 3B may be the best trade-off between power consumption and processing power. While in [9] two transducers were used, one for transmitting and one for receiving, a GPIO-controlled transmission and reception switch has been added to the SuM HAT, allowing the use of the same acoustic transducer for both transmitting and receiving. This is an important design change, as it allows to significantly reduce the cost of the components at the price of giving up the full-duplex ability of the original design.



(a) (b) (c)

Fig. 1: The SuM HAT on top of a Raspberry Pi 4B and a HiFiBerry DAC+ ADC Pro (a) has been used with several transducers (b): the large Lubell LL916C underwater speaker (top), the small Aquarian AS-1 hydrophone (bottom left) and the Btech-2RCL transducer (bottom right). The SuM block diagram is depicted in (c).

The modem can be used with several underwater acoustic transducers (Figure 1b), and its main limitation in terms of frequency band is given by the HiFiBerry, that allows to transmit from 2 Hz up to a maximum frequency of 70 kHz. The maximum transmission power depends on the impedance and Transmitting Voltage Response (TVR) of the used transducers: for instance, given the 30 dB of gain provided by our output amplifier, when used with the low-cost Aquarian AS-1 hydrophone [18] (the small hydrophone in Figure 1b), that has low-power transmission abilities, we managed to transmit around 155 dB re 1 μPa at 40 kHz. With the high quality Btech-2RCL transducer [19] (the transducer on the bottom right hand side of Figure 1b), instead, we could transmit up to 180 dB re 1 μPa at 28 kHz due to its higher TVR. While the former can be directly connected to the modem, to perform impedance adaptation with the latter an inductance of 2 mH has been added in series to the transducer. The aforementioned maximum acoustic source levels, estimated observing the specifications provided by the manufacturers, are imposed by the transducers and the low-power components of our modem chosen to maintain a low production cost and a low power consumption. It is worth mentioning that for more demanding off-shore applications such power can be significantly increased when an additional external amplifier is added in series to our modem. In a recent test where an external amplifier was applied to the modem, we managed to transmit 186 dB re 1 μPa at 28 kHz with Btech-2RCL and 180 dB re 1 μPa at 10 kHz with a Lubell Labs LL916C [20] piezoelectric underwater speaker (the blue large projector in Figure 1b) adapted with an AC205C Lubell transformer box, reaching a significantly longer range than the one presented in this paper, at the price of a higher power consumption.

III. TESTS SETUP AND LOCATIONS

The setup employed in the tests was composed by two SuM equipped with AS-1 hydrophones: one of the modems was transmitting and the other was receiving. The modems were powered by 11.1 V Li-Ion batteries. The hardware components

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[1] JANUS, that uses a Frequency-Hopped (FH) Binary Frequency Shift Keying (BFSK) with 13 different sub-carriers, is simple and lightweight enough to be opportunistically implemented on several hardware platforms, including SuM.

were kept protected from water splash and rain through an IP67 electrical box. The modems were running on a Raspberry Pi 4B and were controlled via SSH connection from a laptop via WiFi, as the two IP67 boxes with the modems were placed outside the water. In one of the experiments the Btech-2RCL and the Lubell LL916C were used as well to test various frequency bands.

The tests were performed in 3 different locations and environmental conditions, namely:

1) the Bacchiglione River, in Padova, a freshwater 50 m-wide river with maximum depth of 6 meters;
2) the port of Chioggia, close to Venice, in a shallow water (3-5 m) area affected by the noise caused by ships and ferries passing quite frequently in front of our deployment (we counted, on average, one boat per minute);
3) in La Spezia Gulf (also known as the Gulf of the Poets) in a controlled area, where the shipping activity, compared to Chioggia, was quite low.

The test in Padova was performed on the 22^{nd} of April 2024 during a rainy day: the transmitter was deployed from the pedestrian Bassanello Bridge (Figure 2a) and the receiver from a typical Venetian Mascareta boat (Figure 2b) kindly provided by the “Amissi del Piovego” rowing association.

The test in Chioggia was performed on the 5^{th} of May 2024: this time the receiver was deployed from a jetty in front of Fort San Felice (Figure 3a) and the transmitter from a working boat owned by the Hydrobiological Station Umberto D’Ancona of the University of Padova.

The tests in La Spezia were performed on the 15^{th}, the 16^{th}, the 24^{th}, and the 25^{th} of May 2024: the transmitter was deployed from shore in front of the Italian Polo Nazionale della dimensione Subacquea (PNS) (Figure 3b) and the receiver from a working boat owned by the Centro di Supporto e Sperimentazione Navale (CSSN) (Figure 3c), close to the LOON testdbed, one of the facilities of the NATO Centre for Maritime Research and Experimentation (CMRE) [21]. The maximum water depth of the area is 15 m.

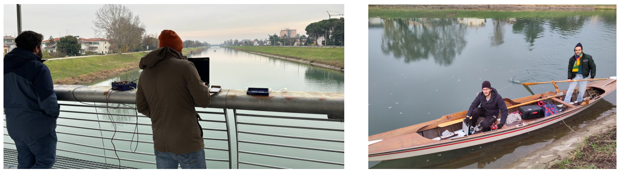
(a) (b)

Fig. 2: Test in the Bacchiglione River (Padova) from the Bassanello Bridge (a) and a Venetian Mascareta (b).

In all tests we tried to achieve the maximum range of the modem transmitting the JANUS waveform with a center frequency of 40 kHz. In addition, in La Spezia the same task was performed when transmitting with a center frequency of 28 kHz and the Btech-2RCL transducer, and with a center frequency of 9.7 kHz and 11.52 kHz with a Lubell LL916C underwater speaker. The tests were performed by sending packets of fixed length from the transmitter to the receiver: the packet size was set to 8 bytes at the application level. The subsequent levels, MAC and PHY, add 4 bytes in total. The payload was sent as a JANUS cargo packet. 100 packets were transmitted in each position. The analyzed metric is the Packet Delivery Ratio (PDR), computed as the ratio between the received packets and the transmitted packets. A simple receiver akin to the one provided by the JANUS reference implementation [22] was used in the modem: although better performance might have been obtained by including equalizers, we remark that the goal of this work was to evaluate the effectiveness of SuM as an experimentation platform by using it with a well-established communication standard rather than proposing an optimal receiver.

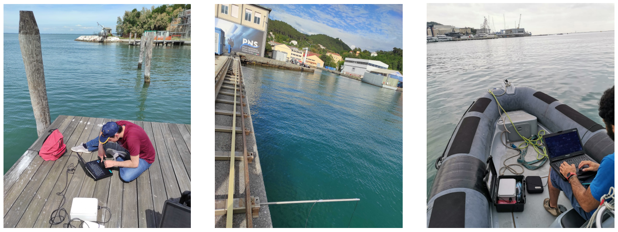
(a) (b) (c)

Fig. 3: Fixed location of the test in Chioggia (a) and at CSSN (b). In both tests the mobile node was deployed from a working boat (the one used in La Spezia is depicted in (c)).

IV. TESTS RESULTS

In this section we present the results of the tests performed in the three locations presented in Section III. We both tested some JANUS bands and some arbitrary bands imposed by one of our transducers (i.e., using a carrier frequency of 40 kHz).

A. *Results in Padova, Bacchiglione River*

The performance of the test performed in the Bacchiglione River are depicted in Figure 4. The modem was configured with the AS-1 hydrophones transmitting with a source level of 155 dB re 1 μPa with i) a center frequency of 40 kHz and a bandwidth of 4.16 kHz (blue line) and ii) a center frequency of 28 kHz and a bandwidth of 6.5 kHz (red line), according to the standard JANUS band E. The symbol duration in the two cases is, respectively, 6.25 ms and 4 ms and the JANUS standard FEC rate of 1/2 is applied.

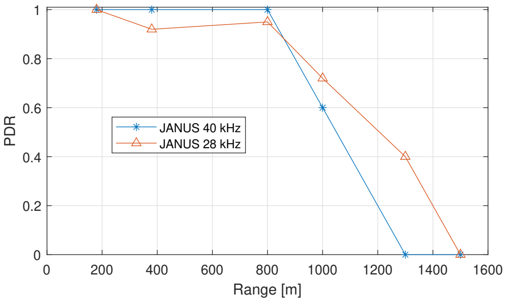

Fig. 4: PDR versus range obtained in the Bacchiglione River using a center frequency of 40 kHz (blue line) and a center frequency of 28 kHz (red line).

The test performed in the Bacchiglione River faced quite variable working conditions. At the beginning of the test the weather was cloudy with no rain, then it suddenly started raining for the remainder of the test, significantly increasing the acoustic noise. This is also reflected in the performance, as in the distances between 400 and 800 meters we received 100% of the packets, while for longer range we lost a large fraction of packets due to a combination of both the stronger attenuation of the signal (caused by the longer distance) and the higher noise (caused by the rain). Surprisingly, although the transducer TVR increases and the rain-induced noise decreases with frequency [23], slightly better performance was observed with the JANUS band E than at 40 kHz.

B. Results in Chioggia, Venice Lagoon

The results obtained in Chioggia are depicted in Figure 5. A center frequency of 40 kHz was used during all tests, where the modems were used with the AS-1 hydrophones transmitting with a source level of 155 dB re 1 μPa. Despite the high shipping activity observed during the test, we managed to obtain quite a stable link using 5 kHz of bandwidth up to 500 m (blue line), where we received all the transmitted packets. Between 700 and 800 meters the link started to be unstable, and the PDR was oscillating between 40% and 50%. At a distance of 1 km, instead, no packet was received. With a wider bandwidth of 10 kHz (red line), which corresponds to a symbol duration of 2.6 ms, the PDR was higher than 60% up to a range of 600 m. For longer range it immediately dropped to less than 40%, while at 1 km we did not receive any packet.

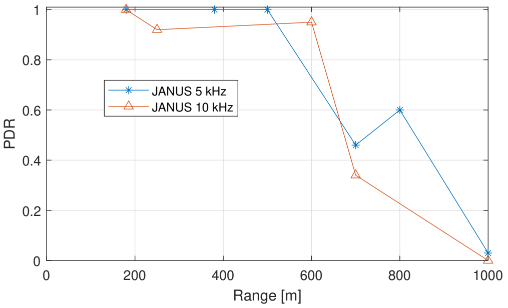

Fig. 5: PDR versus range obtained in the port of Chioggia using a center frequency of 40 kHz and a bandwidth of 5 kHz (blue line) and 10 kHz (red line).

C. Test in La Spezia

The tests in La Spezia were significantly different from the experiments in Chioggia and Padova. In fact, thanks to the equipment provided by CSSN and CMRE, more configurations have been tested. Specifically:

1) JANUS in high frequency (non standard, center frequency 40 kHz) with 5 kHz and 10 kHz of bandwidth using the Aquarian AS-1 hydrophones;
2) the NATO Standard JANUS band A with center frequency 11.52 kHz and bandwidth 4.16 kHz using a Lubell LL916C underwater speaker for transmitting and an Aquarian AS-1 hydrophone for receiving;
3) the NATO Standard JANUS band C with center frequency 9.7 kHz and bandwidth 2.6 kHz using a Lubell LL916C underwater speaker for transmitting and an Aquarian AS-1 hydrophone for receiving;
4) the NATO Standard JANUS band E with center frequency 28 kHz and bandwidth 6.5 kHz using the Btech-2RCL transducers.

While Aquarian AS-1 and Btech-2RCL were directly piloted by the modem's amplifiers (transmitting 155 dB re 1μPa and 180 dB re 1μPa, respectively), an external amplifier and an isolation box were used with the Lubell LL916C (transmitting 180 dB re 1μPa). Figure 6 presents the results of JANUS at high frequency with a band of 5 kHz (blue line) and 10 kHz (red line). The communication link was very stable and we managed to achieve a maximum distance of 1 km with almost 100% PDR. No packets were received at a longer distance. These results are significantly better than those observed in Chioggia (Figure 5), in our opinion due to the lower shipping noise.

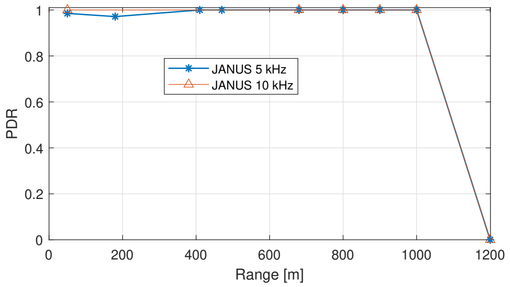

Fig. 6: PDR versus range obtained in La Spezia using a center frequency of 40 kHz and a bandwidth of 5 kHz (blue line) and 10 kHz (red line).

Figure 7 presents the results obtained with the JANUS bands A, C and E. Due to the constraint of the La Spezia Gulf we did not manage to test a distance of more than 2.8 km, as we would have reached the land on the other side of the gulf. The communication link was very stable and we managed to achieve a PDR of almost 100% at any tested transmission range up to 2.8 km.

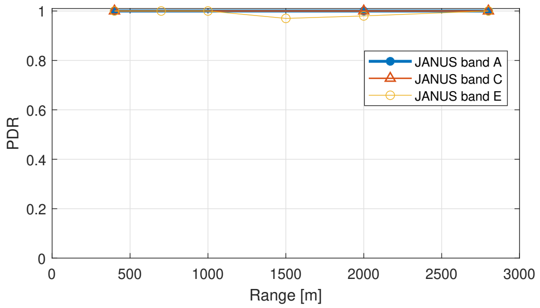

Fig. 7: PDR versus range obtained in La Spezia using the NATO Standard JANUS band A (blue line), C (red line) and E.

V. CONCLUSION

In this paper we reported the tests performed to evaluate the SuM modem when used to transmit the JANUS waveform. These tests were performed in different locations and water conditions, including fresh and salt water, and with different frequency bands. Results demonstrate how SuM can be used to communicate to up to several hundreds of meters with a low-cost high frequency transducer, or up to a few kilometers with medium and low frequency transducers, despite the low cost of its components and the low power consumption. The evaluation proved its effectiveness and readiness for use in sea trials as a valuable platform for research and experimentation of underwater acoustic networks.

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