The Subsea Software-Defined Acoustic Modem v2: Extended Capabilities and Sea Test

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***Abstract*—The variety of technological applications that can benefit underwater missions—such as diver coordination and surveillance of critical areas with Autonomous Underwater Vehicles (AUVs)—calls for the development of a flexible underwater communication platform that can be customized according to the user needs. Building on the architecture of the low-cost SuM software-defined acoustic modem [1] developed for research purposes, we introduce SuM2, a new and more sophisticated acoustic device designed for operational conditions. SuM2, while maintaining interoperability with JANUS digital communication, enhances both the hardware and software architecture of the original SuM modem by introducing higher transmission power, an improved analog front-end, support for Single-Sideband (SSB) analog voice and advanced digital transmission features including multiplexed data streams and optional CSMA-like medium access. Sea trials demonstrate interoperability with commercial communication devices, reliable communication at ranges up to 3.3 km, and bit rates up to 19.2 kbps at short range. The results confirm that SuM2 achieves a significantly extended communication range compared to its predecessor while retaining full software-defined flexibility and compatibility with commercial SSB devices and NATO standards. The presented architecture establishes SuM2 as a versatile and affordable acoustic modem suitable for both research and operational deployments.**

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

I. Introduction and Motivation

Software-defined acoustic modems [2]–[4] are flexible platforms that let users customize waveforms, routing, and media access control (MAC) protocols for research and experimentation and for specific application needs. Nevertheless, the high cost of such devices prevents the development of low-cost solutions for professional diving and fishing, which often require adaptation to different environmental conditions and to the specific data patterns that must be transmitted. These patterns are typically tightly bound to the application itself—for example, the type of task being performed by divers (welding, inspection, rescue, etc.) or the fishing technique adopted, each requiring different communication ranges, data rates, robustness levels, or message formats. As a result, affordable systems capable of being tailored to mission-specific requirements remain largely unavailable, despite the clear operational need. Focusing on the first application, professional scuba divers performing welding, maintenance, or rescue operations are often exposed to the risks and hazards of the underwater environment. These activities typically require reliable communication channels to ensure safety, coordination, and situational awareness, especially when divers operate in low-visibility conditions, strong currents, or confined spaces. In such scenarios, the availability of robust voice and data links becomes essential for task execution, emergency response, and overall mission effectiveness. Essential for interoperability with diver voice communication devices and digital data transmission apparatus, such system should be compliant with underwater communication standards, such as Single-Sideband (SSB) analog voice transmissions–which provides continuous speech even when digital links cannot sustain reliable packet delivery and is used in the standard STANAG 1074 and STANAG 1475—and digital communication through the JANUS NATO standard (STANAG 4748) [5]. Moreover, high speed (in the order of a few kbps) data transmission with customized modulation schemes should also be made available. To date, to the best of the authors' knowledge, all commercial off-the-shelf modems— except for the high-power PopotoModem PMM5544 and the bulky underwater telephones used onboard submarines and ships—are designed either exclusively for digital data transmission [2], [6], [7] or solely for analog voice communication [8], [9].

Using the paradigm introduced by the low-cost Subsea Modem (SuM)—whose initial concept was developed by the University of Padova within the Italian PNRM MODA project [1], [10] and subsequently improved and engineered into a commercial device by its spin-off company SubSea-Pulse—we developed a communication device that satisfies all these needs, also thanks to DRASS Galeazzi, which provided operational end-user requirements. By significantly enhancing the SuM modem, we created the first prototype of SuM2, an affordable acoustic modem capable of meeting the aforementioned requirements in operational scenarios and achieving communication ranges up to 3.3 km—more than sufficient for most diver-related missions—in sea state 1, for both voice and digital communication.

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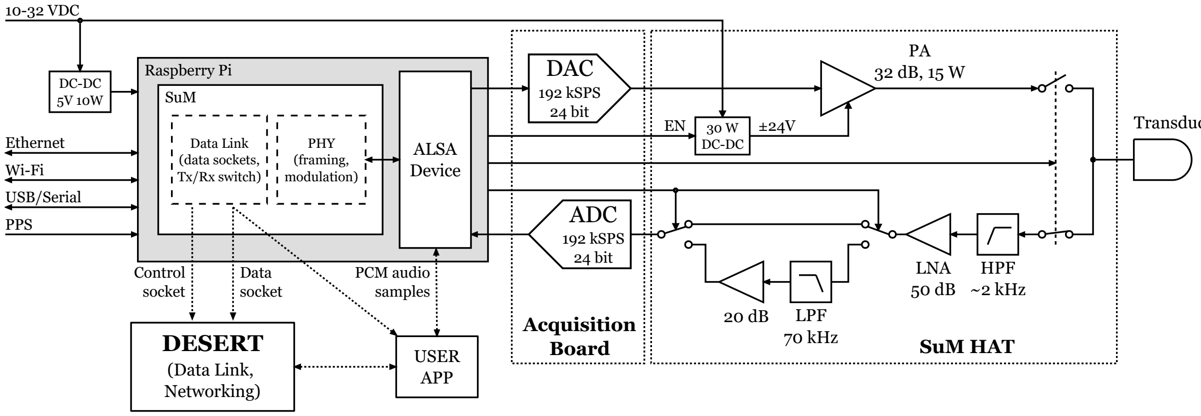

Fig. 1: Hardware block diagram.

II. MODEM ARCHITECTURE

A. Hardware Architecture

The SuM2 hardware components have been significantly improved compared to [11], while still maintaining its three-board structure composed of a processing board, a data acquisition (DAQ) board, and an analog front-end. The complete hardware block diagram is depicted in Figure 1 and described as follows.

1) The Raspberry Pi 4B originally used as the processing board has been replaced with a minimalist carrier board for a Raspberry Compute Module 4 unit (CM4), with significant advantages in power consumption and robustness, thanks to the onboard EEPROM memory replacing the SD card and the presence of less input/output ports.
2) A modified HiFiBerry DAC2ADC Pro HAT [12] currently serves as the 192 kHz 24 bit analog-to-digital (ADC) and digital-to-analog (DAC) converter, although it is in the process of being substituted with a self-made 192 kHz DAQ board.
3) A new amplification and switch module (the SuM2 HAT), enables transmission with an output power of 15 W, three times higher than the original SuM modem. In reception, the amplification module allows—after the initial 50 dB preamplifier—the use of an optional secondary amplifier providing an additional 20 dB of gain while filtering noise above 70 kHz.

Through the CM4 GPIO pins, it is possible to enable or disable the secondary amplification stage, switch between transmission and reception, and power the DC-DC converter supplying the transmitter on or off. In analog voice transmission mode, a GPIO pin is also used to read a push-to-talk (PTT) button that manually toggles between transmission and reception. The output amplifier can directly drive medium-impedance piezoelectric transducers with a maximum differential voltage of ±44 V peak, up to a maximum average power of 15 W.

An impedance matching network can also be introduced between the transmitter output and the transducer to increase the active power delivery to the acoustic medium, and thus the Transmission Voltage Response (TVR) of the transducer, and to remove the reactive impedance component, which causes increased heating of the amplifiers. A simple series-tuning inductor L_s can be inserted into the circuit to improve the transmission performance while not affecting the receiving sensitivity. The value of the inductor can be computed knowing the conductance G and susceptance B of the transducer at the working frequency f using the following equation:

$$L_s = \frac{B}{2\pi f(G^2 + B^2)}. \tag{1}$$

With series tuning, the TVR will increase by an amount ΔTVR computed using the following equation:

$$\Delta TVR = 10 \log_{10} \frac{G^2 + B^2}{G^2} [dB]. \tag{2}$$

For the transducers used in our tests, a series-tuning inductor L_s = 1.8 mH was sufficient to reduce the reactive impedance component to acceptable values. For example, with the BTECH BT-2RCL transducer [13], the addition of L_s increases the TVR from 143 to 152 dB re 1 μPa/V@1 m at frequency 28 kHz. Using instead a self-made transducer [14], the inductor allowed us to increase the TVR from 136 to 145 dB re 1 μPa/V@1 m at frequency 32.5 kHz.

Following the design choice of allowing the user to change not only the modulation scheme but also the transducer and central frequency while maintaining consistent output quality, we adopted two class-AB power amplifiers. This solution enables high-quality transmissions across a wide frequency range (2-70 kHz), provided that the transducer is properly matched, at an efficiency of approximately 70%. Higher efficiency could be achieved with class-D amplifiers, but at the cost of increased design complexity and more complex impedance matching network to avoid frequency-dependent variations in transmission quality, which is incompatible with the requirements of a fully-fledged software-defined acoustic modem. Future versions will adopt a modular architecture, allowing users to select whether to operate with two or four power amplifiers in parallel, reaching an output power of up to 40 W when heat is properly dissipated. Lower-power modules can also be selected to create an inexpensive variant for do-it-yourself practitioners and recreational divers.

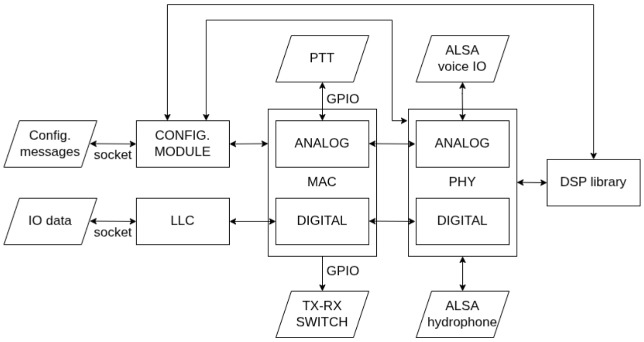

Fig. 2: Software architecture.

B. Software Architecture

The software architecture of the original SuM modem [11] is organized into three main components: the Logical Link Control (LLC), the MAC, and the physical layer (PHY). The LLC segments the data received from a socket connected to an external application into fixed-size chunks, forwards these chunks to the MAC, and delivers to the application the chunks received from the MAC. The MAC appends the 8-byte SuM MAC header—containing source and destination MAC addresses and a timestamp—to the chunks received from the LLC, and instructs the PHY to transmit them. The PHY modulates the chunks and transmits the resulting waveform through the DAQ driving the transducer; in reception, it demodulates the chunks from the signal acquired by the DAQ and forwards them to the MAC. When high-quality oscillators are available, the MAC timestamp can be used to perform One-Way Travel Time (OWTT) ranging.

In SuM2, the software architecture has been significantly enhanced through the inclusion of several new components, as illustrated in Figure 2 and described as follows.

- Support for analog voice transmission and reception, which requires a dedicated MAC layer that reads the GPIO pin connected to the PTT button used by the operator to switch from reception to transmission, as well as a dedicated physical layer capable of: i) capturing input audio from a microphone through a dedicated audio interface; ii) modulating the audio signal using SSB; iii) transmitting the modulated signal through the underwater channel via the DAQ driving the transducer; iv) performing the inverse processing chain during reception when the PTT is released. To improve the reception of analog voice reception, the SSB receiver was equipped with a 3 kHz pass-band filter, a squelch filter based on WebRTC [15] voice activity detector, and Automatic Gain Control (AGC) in order to provide to the user an audio signal with the same magnitude independently of the distance between transmitter and receiver.
- Inclusion of data-stream multiplexing: if digital transmission is selected, multiple data sockets can be opened, each carrying a specific traffic type (e.g., images or SMS). These streams are prioritized according to user requirements, enabling automatic multiplexing and demultiplexing of heterogeneous data flows.
- Inclusion of a CSMA-like MAC layer which uses a random backoff to monitor packet receptions: if no packet is received during the backoff interval, the modem transmits; otherwise, it defers again. This optional MAC protocol improves channel access efficiency by reducing the probability of collisions. It can be used in place of the simpler MAC available in the original SuM modem.
- Inclusion of a real-time configuration utility: this tool allows the user to change the transmission mode, inspect modem status, reset the device, clear transmission queues, adjust transmission power, select the MAC protocol, configure reception gain, set central frequency and bandwidth, and choose forward-error-control schemes.
- Inclusion of a band-pass filter adapted to the bandwidth chosen by the user.

While the current digital communication preamble enables correct processing of the selected modulation and coding schemes, future improvements will allow analog and digital demodulators to operate simultaneously on the same ADC-acquired samples, without the need to manually switch between them.

III. Tests Results

Before the tank tests and the sea trial, a set of channel-replay simulations was performed to optimize all transmission parameters. Specifically, a 1 km SSB transmission—recorded with the low-power SuM—was used to repeatedly replay the decoder chain. In the first SSB implementation, the absence of pass-band filtering, AGC, and squelch resulted in very low-volume reception and unintelligible speech. By adding and tuning these filters through the replay-based testing framework, we developed a high-quality receiver capable of operating at very long range. Similarly, digital communication, in particular the SuM BPSK framing structure, was optimized in all its components, including the detection threshold, the number of equalizer coefficients and adaptation speed, and the modulation and coding schemes that perform best across diverse channel conditions. These parameters were optimized using both the synthetic channel built from the sea-trial data in [16] and the replay channels in [17]. The detection threshold was empirically lowered to enable packet detection even under very weak received-signal conditions, while keeping the false-detection rate bounded. In parallel, the step size of the adaptive linear equalizer was increased up to the maximum value that preserves stability. Without this optimization, in shallow-water scenarios the equalizer required up to ten packets to converge before enabling clean reception. Among the FEC schemes available in the SuM software suite [18], an interleaved convolutional code with constraint length 9 and rate 1/3 proved to be the most robust across all tested conditions.

A. Results in Water Tank

A first batch of tests was conducted in the small water tank (60 cm × 70 cm × 75 cm) [19] available at the SIGNET laboratory of the University of Padova. Two in-house–developed transducers, with TVR similar to those presented in [14] and a resonant frequency of 25 kHz, were deployed 40 cm apart at a depth of approximately 20 cm. The Packet Delivery Ratio

TABLE I: Tank test results

Modulation	Bandwidth	Payload Size	Period	PDR
BPSK	1.2 kHz	8 byte	2	146/150
BPSK	1.2 kHz	8 byte	1	149/150
BPSK	1.2 kHz	64 byte	5	97/100
QPSK	5 kHz	64 byte	5	73/100
JANUS Band E	6.5 kHz	8 byte	2	94/100
JANUS Band E	6.5 kHz	8 byte	1	100/100
JANUS Band E	6.5 kHz	32 byte	5	93/100

(PDR)—computed as the ratio between received and transmitted packets—and the voice quality (i.e., intelligibility of the speech signal) were evaluated while varying the transmission pattern and the external acoustic conditions. In particular, different tones were injected into the tank using an external source to assess how the presence of other acoustic signals affects the performance. The results of the digital communication tests are reported in Table I, confirming the maturity of the developed modem and its readiness for subsequent sea-trial experiments. . For SSB analog voice communication, the speech signal remained intelligible in all tested configurations, even in the presence of strong out-of-band noise. This confirms the effectiveness of the applied filtering stages, as previous tests without such filters showed that out-of-band noise could prevent successful communication. When in-band noise was introduced, the communication quality degraded, but the voice remained intelligible. SSB interoperability was also evaluated by exchanging voice messages among SuM2 and the OTS, Divelink, Popoto Modem, and the ELAC UT2200 devices made available by DRASS Galeazzi for the test campaign, confirming successful bidirectional communication between the different devices.

B. Sea Trial Results in La Spezia

A harbor test was performed on March 16, 2026 in La Spezia, Italy, thanks to the support of the Centro di Supporto e Sperimentazione Navale (CSSN) of the Italian Navy. In the test area the water column was between 8 and 12 meters, and the two transducers were deployed at a depth of approximately 4 meters. The weather conditions were quite favorable, as it was a sunny day with no rain, temperature between 14°C and 20°C, low wind (10-14 Km/h) until 11 a.m., and strong wind (18-23 km/h) afterwards, with sound speed measured at 1506–1507 m/s over the full depth. Shipping activity was quite low before 11 a.m., then increased significantly due to the presence of large cargo ships passing in the deployment area. The setup consisted of two nodes equipped with BTECH 2RCL transducers and SuM2 modems configured as follows:

- Node TX was deployed from a pier, and impedance matching was applied to obtain the maximum transmission power;
- Node RX was deployed from a work boat, and impedance matching was not applied to observe the benefits of impedance matching at node TX.

TX acted as the transmitter and RX as the receiver in digital communication, while for analog voice transmission the nodes were used in both directions. Due to time constraints in digital communication only small packets were transmitted (8 bytes of payload, PSK with 1.2 kbps gross rate, at central frequency 28 kHz). At least 100 packets were transmitted in

Fig. 3: Node RX deployed from a work boat (left) and Node TX deployed from a pier (right).

TABLE II: Sea trial results

Time	Distance	Modulation	PDR/Voice Quality
10:00	260 m	BPSK	100/100
10:15	260 m	SSB	TX⟶RX very good quality
10:20	260 m	SSB	RX⟶TX good quality (medium volume)
10:30	1150 m	BPSK	100/100
10:40	1150 m	SSB	TX⟶RX very good quality
10:45	1150 m	SSB	RX⟶TX good quality (low volume)
11:00	2000 m	BPSK	92/100
11:15	2000 m	SSB	TX⟶RX very good quality;
11:20	2000 m	SSB	RX⟶TX very low volume
11:40	3334 m	BPSK	81/200
11:55	3334 m	SSB	TX⟶RX good quality with some noise
12:00	3334 m	SSB	RX⟶TX no reception

each run. The main observed metrics were PDR and voice quality. At a distance of 3334 m, we enabled the secondary preamplifier thus obtaining 20 dB of additional reception gain. Reception was almost ideal up to a distance of 2000 m and at a distance of 3334 m we still managed to receive some data packets while SSB voice from TX to RX was still intelligible, although with a strong background noise. SSB voice from RX to TX was instead intelligible (with very low quality) up to a maximum distance of 2 km, highlighting the positive impact of impedance matching. Voice quality was verified by two DRASS experienced operators of SSB devices, who provided a subjective assessment of intelligibility, perceived volume, and background noise. Voice tests consisted of one operator reading a series of numbers plus some generic sentences.

In the afternoon we tested the maximum achievable transmission rate at a range of 520 meters. The test was performed by transmitting 64-byte packets using BPSK and enlarging the bandwidth up to the maximum achievable with the employed transducer. Results proved we could reach a bitrate of up to 19.2 kbps with a PDR of approximately 70% at such a range.

IV. Conclusion

This paper presented the SuM2 modem in all its components, detailing its design choices and sea-trial performance. Tank tests demonstrated its interoperability with the NATO JANUS standard and with several commercial analog voice-communication devices. Hardware and signal-processing improvements enabled SuM2 to achieve a higher and more stable PDR and a significantly longer communication range than that of the original SuM modem presented in [11], while fully preserving its modular, software-defined architecture. Future work will focus on increasing the transmission power and developing more powerful FEC such as LDPC and Polar codes. Moreover, implementing multicarrier modulations suited for doubly dispersive channels can extend the applicability of the SuM2 modem to high-mobility scenarios.

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