PSK modulation for Underwater Communication and One-Way Travel-Time Ranging with the Low-Cost Subsea Software-Defined Acoustic Modem

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ABSTRACT

What limits most the use of low-cost underwater unmanned vehicles is the lack of affordable and low-power acoustic modems and positioning systems able to provide satisfactory performance, such as accurate distance measurement, a transmission range of at least several hundred meters, and a data rate of a few kilobits per second. In fact, although low-cost modems are now available in the market, they usually provide a data rate of only a few hundred bits per second and may not be able to adapt their communication parameters such as modulation and coding schemes nor perform complex tasks such as One-Way Travel-Time (OWTT) ranging or online data collection and processing from attached sensors. In contrast, the Subsea underwater acoustic software-defined Modem (SuM), recently developed by the University of Padova and SubSeaPulse SRL, is a low-cost platform composed of a newly developed Raspberry Pi HAT analog frontend, which brings underwater acoustic data transmission and positioning capabilities over the widely used Raspberry Pi platform, thus exploiting its great flexibility. In this paper we present its inaugural sea trial campaign in fresh and salt water, where its ranging and communication abilities have been significantly tested. Results prove that the developed system is mature enough to be used in sea trials and provides good performance up to a range of several hundred meters when equipped with low-cost transducers, and of a few kilometers when used with professional transducers.

KEYWORDS

Underwater acoustic communications, PSK, acoustic modem, low-cost acoustic modem, one-way travel-time ranging.

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1 INTRODUCTION

The wireless underwater channel is recognised as one of the most challenging communication media [15]. The strong attenuation of the electromagnetic signal makes radio-frequency transmissions impractical, while wireless optical communication tipically works only up to a few tens of meters [14]. Acoustic signals, instead, can propagate up to several kilometers [18]: for this reason, acoustic modems are the most widely used communication devices for underwater wireless transmissions. However, this communication medium offers limited communication performance, due to the low bandwidth of the acoustic channel and the long propagation delay. Additionally, communication can be frequently disrupted by multipath effects, shadow zones, and environmental noise from ships, wind, rain, and marine life. In addition, acoustic modems [7, 9]

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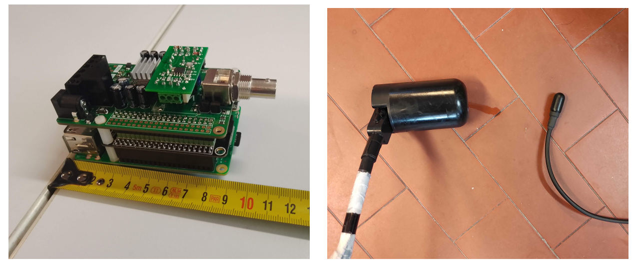
are typically designed for offshore applications, that require high power transmission and deep-water rated components, resulting in very expensive devices that have a price of tens of thousands of USD, allow to cover a range of several kilometers, and have a maximum bitrate of a few kilobits per second.

A new trend in technology development and experimentation of underwater acoustic modems is the development of low-cost modems for civil applications [4], such as diver-to-diver communication, smart-ports, low-cost vehicle telemetry and positioning, and research. All these modems are characterized by a production cost below 1'000 USD (and, for the commercial modems, a selling price of about 2'000 USD), a maximum power consumption less than 5 W, a communication rate up to a few hundred bits per second, and a range between a few hundred meters and one kilometer. Therefore, when compared with the modems used in offshore applications, the low price comes at the cost of significantly lower performance. Moreover, given that for lowering the production cost and the power consumption most of these modems are based on microcontrollers [16, 17], they have low computation abilities and are not easy to reprogram to, for instance, change Medium Access Control (MAC) protocols or Modulation and Coding Schemes (MCS), which on the other hand is possible using software defined acoustic modems (SDMs) [5, 8, 9]. However, low-cost SDMs are currently not available in the market, slowing down new developments in MCS for the underwater environment.

In fact, while spread spectrum techniques such as Direct Sequence Spread Spectrum (DSSS), Frequency Hopping Spread Spectrum (FHSS), and Chirp Spread Spectrum (CSS), may ensure a high reception rate even in shallow water conditions, their band utilization is very inefficient and can be used only for low-rate transmissions. The JANUS NATO standard, for instance, uses FHSS to ensure a robust link even in challenging conditions. However, its data rate is less than 100 bps. Orthogonal Frequency-Division Multiplexing (OFDM) [18], instead, can provide a higher data rate and is proven to be robust to multipath, but suffers from Doppler shift. Moreover, it requires a wide bandwidth and, therefore, a high center frequency. Given that the higher the frequency the stronger the channel attenuation, OFDM suits better short range transmissions [20]. Single carrier PSK modulations, instead, might not be the best choice in a reverberating channel, but in good conditions they can provide a higher rate than spread spectrum techniques.

Although the Subsea underwater Modem (SuM) presented in this paper can be classified as a low-cost acoustic modem, it supports different MCS including PSK (BPSK, QPSK, 8PSK and 16PSK), FHSS (using the JANUS waveform) and DSSS. Developed in the context of the Italian PNRM MODA project [6], SuM proved to be a flexible and mature enough platform for research and experimentation of underwater acoustic data transmission. When equipped with a precise clock oscillator, it can also perform One-Way Travel-Time ranging. In this paper we present the extensive test campaign performed to evaluate the modem when transmitting PSK signals at various frequencies, and discuss how the modem changes its scope from a low-cost research platform to a proper acoustic modem just changing a few components of the system.

The rest of the paper is organized as follows. Section 2 presents the SuM modem and its features, Section 3 describes the setup used in our tests, and Section 4 presents the results of the field measurements. Finally, Section 5 draws our concluding remarks.



(a) (b)

Figure 1: Picture of the SuM modem (a) and the MF and HF transducers used during the tests (b).

2 SuM MODEM DESCRIPTION

The SuM modem (Figure 1a) is a low-cost software-defined acoustic modem for research and experimentation. It is equipped with a complete software suite and a hardware platform able to process and amplify the transmitted and received audio signal. The description of both hardware and software will be given in the following sections.

2.1 SuM Hardware description

The hardware, as represented in Figure 2, is composed of three main boards, namely:

(1) a Raspberry Pi processing board;
(2) a HiFiBerry DAC+ADC Pro 192 kHz analog/digital converter;
(3) the SuM analog frontend.

While the first two components are available off-the-shelf, the SuM analog frontend has been custom-developed by the University of Padova and SubSeaPulse SRL. The SuM board main components are:

(1) a DC-DC step down converter and filter circuits for 5V supply to the Raspberry board;
(2) a low noise input amplifier with a gain of 50 dB connected to the Analog-to-Digital Converter (ADC) input;
(3) a class AB power amplifier in bridge configuration, which receives its input signal from the HiFiBerry Digital-to-Analog converter (DAC) and is able to directly drive a medium impedance transducer like the AS-1 (which offers an impedance of 430 Ω at 40 kHz) with an output signal of 30 V RMS;
(4) a solid state switch, controlled by a General-Purpose Input/Output (GPIO) signal from the Raspberry that connects the transducer alternatively to the output or to the input amplifier when the modem is respectively in transmit or receive state. Another GPIO signal can be used to shut down the output amplifier DC supply, to avoid unneeded power consumption and heating.

The SuM board is to be connected to an 8-15 V DC source and provides the power to the other boards via the standard Raspberry HAT connector, as well as to an external DC-DC booster which

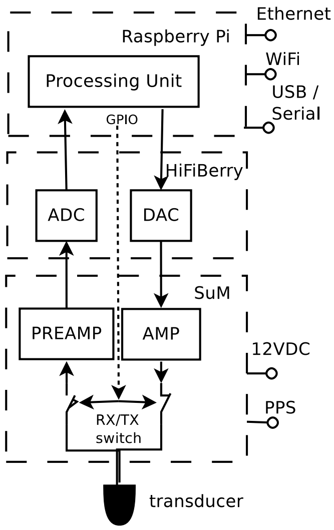


Figure 2: SuM modem schematic.

feeds the output power amplifier with a dual voltage of ±24 V DC. It also offers a connector for receiving a Pulse Per Second (PPS) signal from an external GPS or precision clock. This input is routed to a GPIO port of the Raspberry and can be used to synchronize and discipline its system clock for performing One-Way Travel-Time (OWTT) ranging. As to the frequency band and the transducers to be used, there are different options that result in completely different systems. In fact, the software defined nature of the modem allows it to use whatever transmission frequency up to 70 kHz depending on the selected transducer. For research and budget applications, the low-cost (less than 400 USD) Aquarian AS-1 transducer [1] (the small transducer in the right side of Figure 1b) can be used to transmit 155 dB re 1 μPa with a center frequency of 40 kHz. If the AS-1 is still too expensive, a do-it-yourself (DIY) transducer can be built in-house using the indications in [11]. On the other hand, for demanding applications, the same modem can be used with a professional transducer, that in this case would become the most expensive component of the modem. For instance, with the Btech BT-2RCL [2] (the transducer in the left side of Figure 1b) it can provide significantly better performance, transmitting up to 180 dB re 1 μPa at 28 kHz when connected to the SuM modem with just a series inductance to offset the high capacitive reactance of the transducer. When greater output power is required, or when a low impedance transducer needs to be used, SuM can also serve as a signal generator to drive more powerful linear amplifiers that can exceed the thermal and current limitations of the SuM, as we already successfully tested with a 20 Ω LL916C transducer [12] and a Bruel&Kjaer 2713 amplifier.

2.2 SuM Software Description

Although in some modems [20] the signal processing is offloaded to a FPGA for better performance and efficiency, the SuM performs all the processing in the Raspberry Pi. This choice is to allow the users, even without specific knowledge in the FPGA domain, to easily write and run their own DSP code as well as any other routine that the user wants to run beside the modem software. In fact, running on a full-fledged Linux operating system, SuM offers great flexibility for executing any third-party program to process the audio data coming from the hydrophone or data from any external sensor or device which may be connected via serial ports, Ethernet or WiFi. Third-party software can record or transmit custom audio waveforms on the underwater channel by directly accessing the HiFiberry ADC and DAC via Advanced Linux Sound Architecture (ALSA) API. The modem software is launched via a script where the user can set the MCS parameters (carrier frequency, Forward Error Correction (FEC), symbol duration, modulation). The modulations tested so far include PSK, OFDM-PSK, FH-BFSK (NATO JANUS standard) and DSSS. When running the modem software, the user can connect to TCP socket for sending and receiving the data, which is handled by a very simple MAC module that takes care of forming the data frames adding a header with source and destination addresses. A second TCP socket is used by the modem to exchange control information and allows to use the modem in conjunction with the DESERT Underwater Framework [3], which supports various routing and MAC schemes for multihop and multimodal data transmission in complex underwater networks.

3 TEST SETUP AND KEY PERFORMANCE INDICES

Two SuM modems, each enclosed in an IP67 electrical box, were utilized, with one configured as a transmitter and the other as a receiver. Three tests were performed in three different locations and water conditions, namely: in the Bacchiglione River (Section 3.1), in Chioggia (Section 3.2) and in La Spezia (Section 3.3). All three locations are in Northern Italy. During these experiments, BPSK modulation combined with a convolutional code with code rate 1/2 and constraint length 9, followed by an outer Reed-Solomon code with block length 255, message length 223 and alphabet size 256, was tested. At each location, 200 packets with a user payload of 32 bytes were transmitted and the Packet Delivery Ratio (PDR), computed as the number of received packets divided by the number of transmitted packets, was observed. In addition, the Received Signal Strength Indicator (RSSI), that is an estimate of the received signal strength in dB, and the Error Vector Magnitude (EVM) after demodulation, were analyzed. The Error Vector is computed as the difference between the received symbol and the ideal symbol of the constellation. The root mean square (RMS) average amplitude of the error vector, normalized to an ideal signal amplitude reference, is the EVM. The EVM, often expressed in dB, is an indication of the signal-to-noise ratio (SNR) at the receiver (the higher the EVM the lower the SNR). RSSI and EVM are computed with the liquid-dsp C library [13].

3.1 Freshwater Tests

The first test campaign was performed in the Piovego Canal and in the Bacchiglione River in Padova, Italy. In these fresh water experiments the receiver node was deployed from a typical venetian "mascareta" (Figure 3a), a boat kindly provided by the "Amissi del Piovego" rowing association, while the transmitter was deployed

(a) (b) (c)

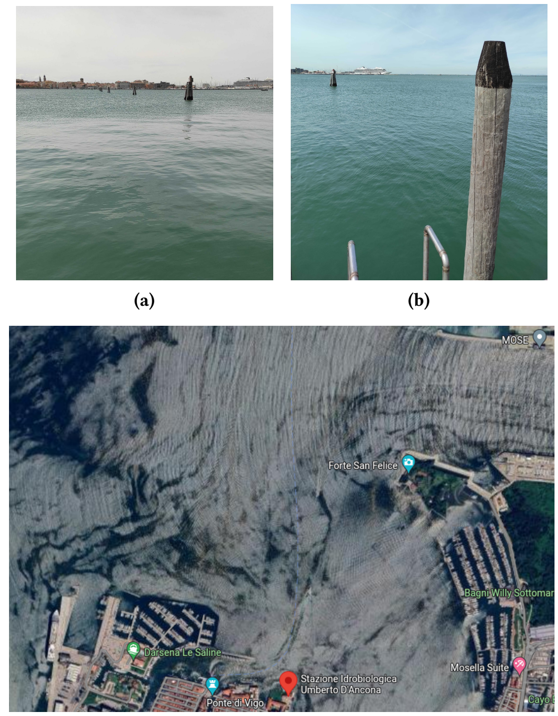
Figure 3: The "mascareta" (a) and the rubber boat (b) used in the test in the Bacchiglione river. Most of the tests were performed in an area known as the Scaricatore Canal (c).

either from a rubber boat (Figure 3b) of the Department of Information Engineering (DEI), or from the Bassanello Bridge. The Piovego Canal is very shallow, as its maximum depth of 2 m is reached only in the center of the canal, in an area 6 m wide, while in the rest of the canal the water depth is less than 1 m. In contrast, the area of the Bacchiglione River where we performed the other freshwater tests (called Scaricatore Canal) is 40 m wide and 6 m deep in its center, and it is straight for almost 3 km without any river bend, making it a perfect area for testing underwater transmissions. The only obstacles found along the path are the pillars of three bridges located at the beginning of the Scaricatore, 1 km far from the first bridge, and at the end of the Canal. During the freshwater tests a carrier frequency of 40 kHz was used in conjunction with the Aquarian AS-1 transducers. Three tests were performed:

(1) a test from 100 m up to 400 m was performed in the Piovego Canal, in front of DEI on the 25^{th} of October 2023;
(2) a test was performed on the 20^{th} of December 2024 in an area of the Bacchiglione river called Scaricatore Canal (Figure 3c), testing a distance between 400 m and 650 m;
(3) one last test was performed in the Bacchiglione river on the 9^{th} of March 2024, testing a distance between 900 m and 1 km.

3.2 Chioggia Port

The second test campaign was performed on the 5^{th} of May 2024 in Chioggia (Figure 4), in the Venice Lagoon, in front of the Hydrobiological Station Umberto D'Ancona of the University of Padova, that provided the working boat used for the test. The transmitter was deployed from the working boat, while the receiver from a jetty in front of Fort San Felice, close to the MOSE dam. Both transmitter and receiver were placed at a depth of 1.5 m, while the maximum depth was 3 m. The scenario was challenging, not only due to the extremely shallow water and closed geometry of the water body that result in severe multipath effects, but also due to the strong noise caused by boats and ferries frequently passing in the deployment area. During the test a center frequency (`fc`) of 40 kHz was used in conjunction with the Aquarian AS-1 transducers transmitting with a source level (SL) of 155 dB re 1μPa. Given the poor results obtained in this test, we decided to further investigate the performance of the modem in salt water in a more favorable area.



(a) (b) (c)

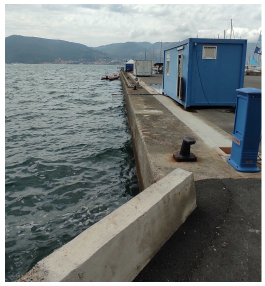
Figure 4: View from the working boat (a) and Fort San Felice (b) where the nodes were deployed in Chioggia. The deployment area is shown in (c).

3.3 La Spezia

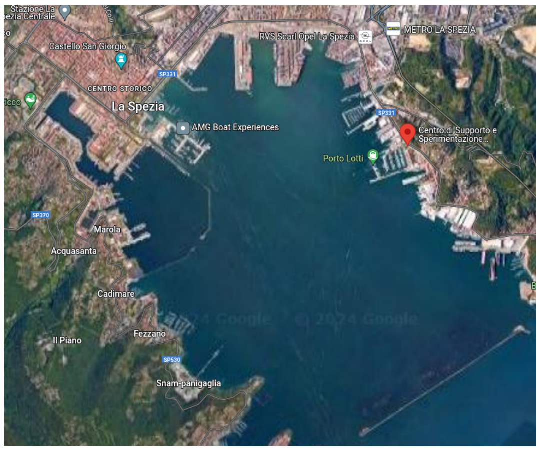
The last group of tests were performed in the second half of May 2024 in the Gulf of the Poets in La Spezia, Italy (Figure 5c), in front of the Italian Polo Nazionale della dimensione Subacquea (PNS). The facilities used for this test were provided by the Centro di Supporto e Sperimentazione Navale (CSSN), and include a working boat (Figure 5a) and some container laboratories (Figure 5b). We tested two different setups, specifically:

- `fc` = 40 kHz with the Aquarian AS-1 transducers transmitting with SL = 155 dB re 1μPa;
- `fc` = 28 kHz with the Btech BT-2RCL transmitting with SL = 180 dB re 1μPa.

(a)



(b)



(c)

Figure 5: The working boat (a) and container laboratories (b) used in the test in La Spezia. The tests were performed in an area known as the Gulf of the Poets (c).

4 RESULTS

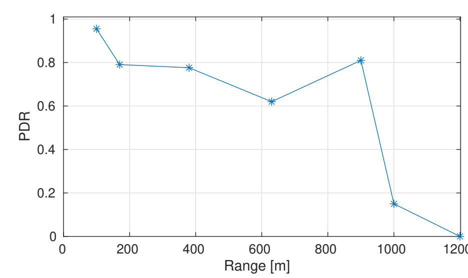
In this section we present the experimental results. Results are discussed hereafter, observing average values, confidence intervals and box-plots of the analyzed metrics for each location.

4.1 BPSK Performance in Freshwater

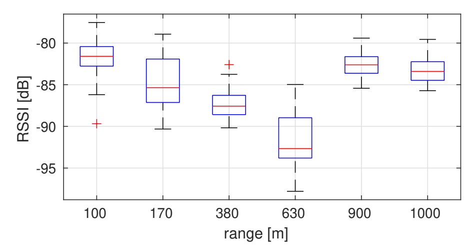
Figure 6 presents the performance of the modem obtained from the freshwater test campaign in the Bacchiglione River and the Piovego Canal in Padova.

The PDR vs range performance results (Figure 6a) obtained from the tests show how the SuM modem achieved a PDR of 0.8 up to 900 m. The PDR then drops to 0.15 at a range of 1 km, and to 0 for a range of 1.2 km. The only exception was encountered at a range of 630 m, where the PDR was 0.62. The EVM, as expected, monotonically increases with the distance (Figure 6c). The RSSI instead, while supposed to have a monotonic trend decreasing with the distance, presents an anomaly as the values at 900 m and 1000 m are very similar to 100 m (Figure 6b). While a satisfactory explanation to this cannot yet be provided, it should however be noted that, due to logistic limitations, the tests at different distances had to be performed in different periods of the year. As a consequence, the results might have been affected by a number of variable factors such as the amount of solid suspension in the river, temperature, factory tolerances between different samples of modems and transducers used, human error in the setup of the test, hidden irregularities in the river floor and banks. While the RSSI is provided for all packets correctly detected, the EVM is provided only for the packets that are correctly received, and for the few packets received at 1 km the two metrics are similar to the ones observed at 900 m, despite the huge difference in terms of PDR.

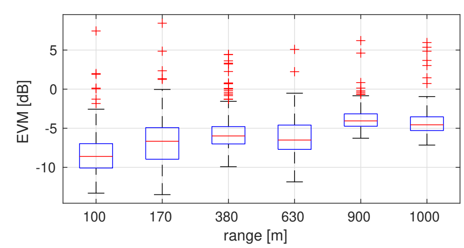
In these tests a previous version of the modem was used, able to transmit at 149 dB re 1μPa, that is 6 dB less than the maximum power of the current version of the modem with the AS-1 transducers. In a recent test performed on the 22^{nd} of April 2024 with the new version of SuM, that transmitted with SL = 155 dB re 1μPa, we reached a PDR of 96% at a distance of 1 km (with an average RSSI of -73 dB and and EVM of -8 dB). Given such a good performance enhancement we were encouraged to do some tests in salt water where, according to the Francois–Garrison formula [10], the acoustic absorption at 40 kHz is about 11 dB per km higher than in freshwater.



(a) PDR in freshwater.



(b) RSSI in freshwater.

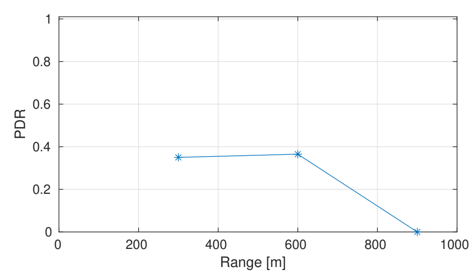


(c) EVM in freshwater.

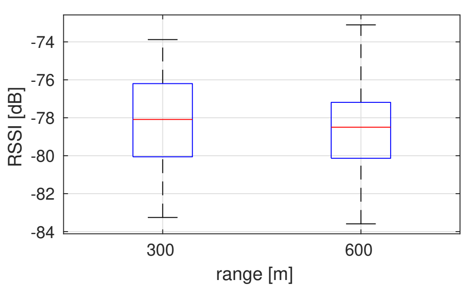
Figure 6: Performance in freshwater transmitting with fc = 40 kHz and SL = 149 dB re 1μPa.

4.2 BPSK Performance in the Chioggia Port

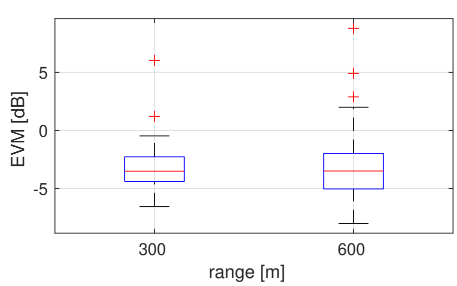
The first test in salt water of SuM took place on the 9^{th} of May 2024 in Chioggia. Poor performance was obtained (Figure 7a) despite the higher source level and the higher RSSI than in the tests in freshwater (Figure 7b), as we recorder a PDR of less than 0.4 for a range between 300 m and 600 m, while no packets where received at 900 m. Also, the observed EVM was quite high (Figure 7c), and so were the multipath and the noise caused by the high shipping activity. Specifically, the water was very shallow (depth between 2 m and 3 m) and we counted more than two ships and ferries per minute passing between the transmitter and the receiver. Other tests with frequency hopping spread spectrum provided better results at a lower rate, hence we decided to go for further investigation and test the modem in other locations with better propagation conditions.



(a) PDR in Chioggia Port.



(b) RSSI in Chioggia Port.

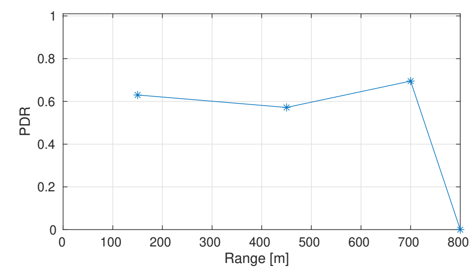


(c) EVM in Chioggia Port.

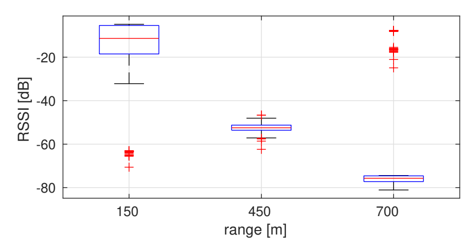
Figure 7: Performance of the modem in the Chioggia Port transmitting with `fc` = 40 kHz and `SL` = 155 dB re 1μPa.

4.3 BPSK Performance in La Spezia

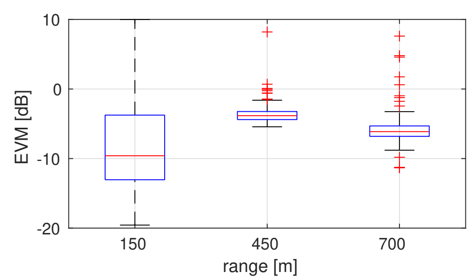
On the 15^{th} and on the 16^{th} of May 2024 we performed a test in La Spezia to inspect the maximum transmission range of the modem. The PDR obtained with `fc` = 40 kHz and `SL` = 155 dB re 1μPa is presented in Figure 8a, where more than 60% of the packets were received up to a distance of 700 m. For longer distances no packets were delivered to the destination, indicating that 700 m is the maximum range achievable with the SuM modem transmitting with PSK in this setup. The RSSI decreased linearly with the distance (Figure 8b), while the EVM (Figure 8c) had a quite sparse distribution at 150 m, indicating periods of extremely good channel conditions (with EVM < -10 dB) and a few moments of very bad channel conditions (with EVM > 0 dB), while for a range of 450 m and 700 m the distribution is more concentrated to the median of -3.8 dB and -6.1 dB.



(a) PDR in La Spezia with `fc` = 40 kHz.



(b) RSSI in La Spezia with `fc` = 40 kHz.



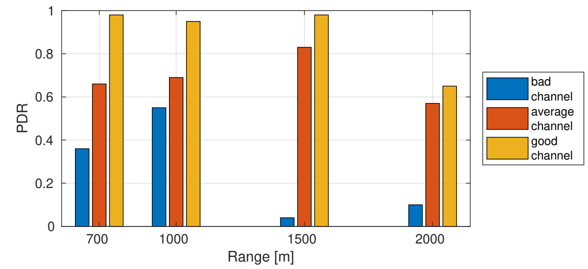
(c) EVM in La Spezia with `fc` = 40 kHz.

Figure 8: Performance of the modem in La Spezia transmitting with `fc` = 40 kHz and `SL` = 155 dB re 1μPa.

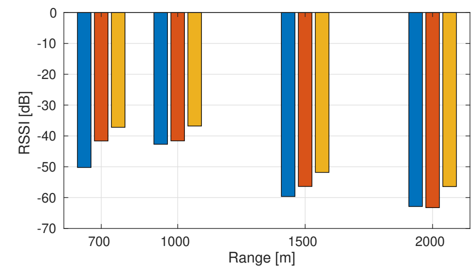
Another quick test performed on the 16^{th} of May 2024 indicated that using a better transducer, such as the Btech BT-2RCL that allows to transmit with `fc` = 28 kHz and `SL` = 180 dB re 1μPa, the modem could reach a significantly longer distance as at a range of 2 km, that was the maximum distance we could test in the Gulf of the Poets, we received more than 60% of the packets. We therefore came back to La Spezia on the 24^{th} of May 2024 to perform another test using this last setup. In contrast to the test performed the week before, less stable conditions were encountered, as there was a higher shipping activity, with some yachts docked in the port with echo-sounder switched on almost all the time, and some other boats moving around in the testing area. Given the instability of the testing conditions, for each tested distance we performed 3 transmissions of 200 packets. Given the high variability of the three measurements, instead of providing the overall mean PDR we decided to plot the three measures of PDR ordered from the worst to the best as a bar plot in Figure 9a. To prove that the encountered channel conditions ordered in the correct way, in Figures 9b and 9c we depict RSSI and EVM for the respective channels. In good channel conditions (the yellow bar), more than 90% of the packets were received up to a range of 1500 m, and more than 60% of the packets were received at a range of 2000 m. In the presence of high shipping activity and strong echo-sounders (the blue bar), instead, the performance drops significantly. In average channel conditions (red bar), that we believe is the most usual working condition for the modem, we managed to receive with a PDR of 60% or higher for all the tested ranges.

4.4 One-Way Travel-Time ranging

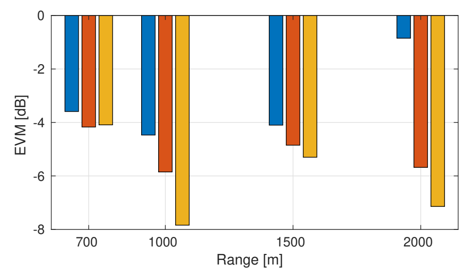
As mentioned in the introduction, the SuM modem can perform OWTT ranging. To achieve this, the system clocks of the involved devices must be synchronized either via Network Time Protocol (NTP) or using the PPS input present on the board. In addition to this, on the software side, the "premodulation" option shall be activated on the sender: it consists in scheduling the instant of transmission Tx with sufficient advance to ensure that by that time the modulation process is concluded and the signal samples are ready to be handed to the DAC. The transmission timestamp Tx is as well premodulated in a 24-bit field of the packet header to let the receiver know the exact transmission time. Since the focus of the conducted trials was on evaluating the communication rather than the ranging performance, we did not deploy the rigid setup that would have been needed for obtaining accurate ranging measurements since such a deployment would have required additional equipment and would have slowed down considerably the execution of the trials. In fact neither of the transducers were firmly fixed, but both were subject to drifts due to swell and currents and, for the one on the boat, to the variable effect of wind. Also, we did not have access to precise ground truth so the boat anchor was each time dropped when the approximate desired range was reached according to the GPS fix provided by a smartphone. Given these premises, we collected the ranging measurements from the same runs of 200 packets used for PDR estimation to assess the ranging variance. In Fig. 10 we show the measurements taken by the modem at the approximate distances of respectively 700 m and 1500 m. Each modem was connected to a GPS-based NTP server with a 1 ms precision [19] which, considering the sound speed in water of 1522 m/s measured with a Conductivity, Temperature, and Depth (CTD) probe before the trials, translates into a precision of 1.52 m.



(a) PDR in La Spezia with fc = 28 kHz.



(b) RSSI in La Spezia with fc = 28 kHz.



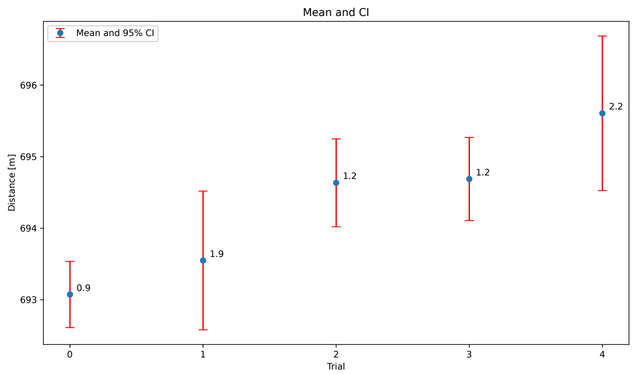
(c) EVM in La Spezia with fc = 28 kHz.

Figure 9: Performance of the modem in La Spezia transmitting with fc = 28 kHz and SL = 180 dB re 1μPa.

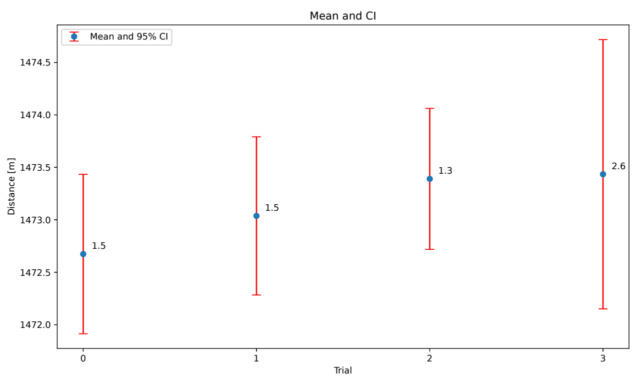
The results in Fig. 10 show a confidence interval of less than 2 meters around the average for most measurements, showing how the modem can provide useful OWTT ranging information whenever the scenario requires a precision of a few meters. Although these results were expected, given the aforementioned NTP precision and unavoidability of drifts, further work is underway to try to estimate and reduce the jitter introduced by the software itself, which is caused by the jitter of the system timers and the size of the ALSA audio buffer.

5 CONCLUSIONS

In this paper we reported the results of the evaluation of the SuM modem using the BPSK modulation by plotting the PDR, RSSI and EVM values during the trials that were performed in both fresh and salt water, using the center frequencies of 28 kHz and 40 kHz. The tests showed the ability of SuM to perform one-way ranging and to communicate up to several hundred meters with a low-cost high frequency transducer, or up to a few kilometers with a medium frequency transducer. The trials overall showed how SuM



(a) Ranging measures around 700 m.



(b) Ranging measures around 1500 m.

Figure 10: Ranging performance with mean and confidence interval.

represents a practical low-cost but capable tool for research on underwater acoustic communications.

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