Comparative Analysis of Throughput Maximization Strategies in Underwater Acoustic Networks: Results from At-Sea Experiments

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***Abstract*—This study explores the performance of different modulation schemes for underwater acoustic communications, which are crucial for efficient data exchange in Uncrewed Underwater Vehicles (UUV) used in various maritime applications. We conducted sea trials in the Venetian Lagoon and the Gulf of La Spezia using a low cost software-defined acoustic modem developed by the University of Padua and SubSeaPulse SRL. Our analysis compares the performance obtained using the JANUS waveform with that recorded using Binary Phase Shift Keying (BPSK). While JANUS ensures superior Packet Delivery Ratio (PDR), BPSK achieves greater throughput over shorter distances. Specifically, JANUS consistently provides high PDR across different environmental conditions, making its use ideal for scenarios where reliable communication is required. Conversely, BPSK modulation provides significantly higher data rates, even though with a lower PDR. This makes BPSK suitable for applications where throughput is more critical. These findings highlight the trade-offs between communication reliability and data rate, guiding the selection of modulation techniques for specific underwater scenarios. This research contributes to the ongoing development of efficient underwater communication networks, which are essential for the advancement of autonomous marine technologies.**

***Index Terms*—Underwater communications, acoustic modem, software defined modem, JANUS, MPSK, sea-trial.**

I. INTRODUCTION

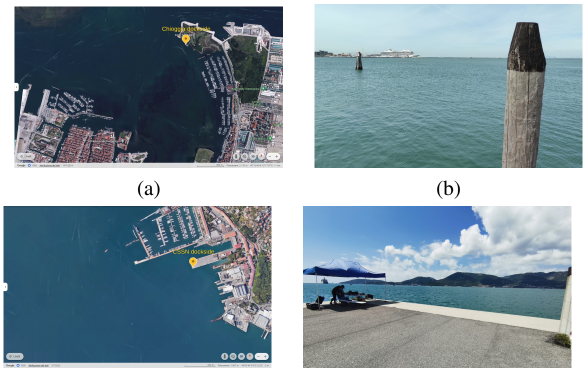
Nowadays we are facing an increasing use of uncrewed vehicles for underwater applications, such as underwater surveillance, as well as assisting human operations in observing marine flora and fauna [1] and underwater archaeology [2]. UUVs can support underwater operations without the need for a ship or a human diver, and their use helps to keep the overall costs low and substantially reduces the risks faced by operators. A significant portion of various applications in underwater environments that can now be performed by autonomous vehicles requires cooperation among different and heterogeneous assets. This highlights the need for efficient communication systems, information exchange, and advanced sensors and algorithms that can achieve various outcomes. These technologies should contribute to improving the required autonomy for underwater assets [3], thereby minimizing the involvement of human operators. In this context, one of the most challenging objectives is to find efficient solutions for underwater communications. This involves connecting various heterogeneous and autonomous vehicles to each other, while also enabling underwater assets to communicate with a Command and Control station that may be located far from the operational area. Although various communication technologies exist, such as optics or magneto-inductive, acoustic communication is the most widely used for applications involving nodes separated by distances greater than tens of meters. This preference is due to the superior ability of acoustic signals to propagate over long distances underwater, where other methods like radio frequency or optical communication are less effective due to rapid signal attenuation and environmental interference [4] [5]. Conversely, underwater communications are highly dependent on environmental conditions which cause the quality of the channel to vary significantly over time, space and frequency [6]. Factors such as water temperature, salinity, and the possible movements of the nodes may greatly influence signal propagation, leading to fluctuating communication performance. The strong discontinuities between the water and the sea floor, as well as between the water and the sea surface, generate significant multipath effects, especially in very shallow water scenarios. For these reasons, establishing a high-performance network for underwater nodes remains a key challenge [7].

Our research is focused on investigating potential technological solutions for digital communication networks applicable to swarms of drones operating in specific scenarios. Unlike in the surface environment, there are no established standards yet for underwater communications. The only exception is JANUS, an underwater communication protocol developed by the NATO Centre for Maritime Research and Experimentation (CMRE) [8] [9], based in La Spezia, Italy. The modulation used in the JANUS physical layer is known as Frequency-Hopped (FH) Binary Frequency Shift Keying (BFSK). The implementation of 13 different sub-carriers prevents the signal from being affected by multipath effects and minimize the intersymbol interference (ISI) as adjacent symbols are on different subcarriers, hence guaranteeing a very robust link under different environmental conditions at the cost of a reduced bitrate and a lower bandwidth efficiency. In the case of JANUS, the maximum achievable net data rate is 125 bps, with the highest frequency band, known as band E, which has a carrier frequency of 28 kHz and a bandwidth of 6.5 kHz. Although the JANUS standard defines 5 operational bands ranging from 4.960 kHz to 31.250 kHz, it is accepted, for experimental research purposes, to implement the same protocol also in non standardized frequency bands. This allows researchers to compare the performance of this modulation with other potential solutions, providing a valuable benchmark. Other modulations that are already widely used for digital acoustic communications, such as M-Phase Shift Keying (M-PSK), can typically achieve higher data rates despite a reduced communication reliability. It is therefore necessary to evaluate which situations and operational contexts warrant the preference for reliable communication with a low bitrate over faster, yet less reliable communication. In this work we present data collected in different sea trials using a software defined acoustic modem developed by the researchers of the University of Padua and SubSeaPulse SRL. In particular, we propose a comparison between the JANUS waveform and BPSK, evaluating their performance in terms of data rate, communication reliability and energy efficiency.

The paper is organized as follows: Section 2 describes the materials and setup used to conduct the sea trial; Section 3 reports an analysis of the collected data; Section 4 summarizes the main experimental results with considerations of the authors.

II. Environmental Conditions and Experimental Setup

The experimental sea trials were conducted in shallow water scenarios, in two different locations in Italy: in the Venetian Lagoon, in the vicinity of Forte San Felice in Chioggia, and in the waters adjacent to the Naval Support and Experimentation Centre in La Spezia. Each scenario involved significant levels of ambient noise caused by the presence of maritime vessels. In the Chioggia scenario the maximum water depth reaches 10 meters in correspondence with the navigable channel, while the average depth across the area is typical of a very shallow water environment, not exceeding 6 meters. The Gulf of La Spezia has a maximum depth of 15 meters, although the tests conducted were carried out in waters not exceeding 6 meters.



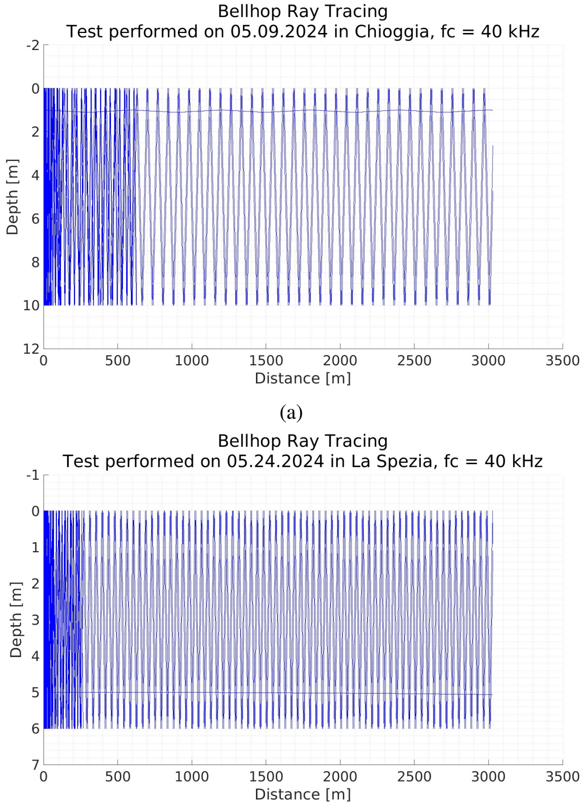
(a) (b)

(c) (d)

Fig. 1: Experimental locations for tests in the Venice Lagoon and the Gulf of La Spezia. Panels (a) and (c) show site maps, while panels (b) and (d) depict Chioggia's dockside and the wharf at the Naval Support and Experimentation Centre where transmitting modems were deployed.

Using the environmental data collected for the Chioggia and La Spezia shallow water scenarios, we applied the Bellhop ray tracing method to generate the graphs shown in Fig. 2. These graphs provide a qualitative overview of the ray trajectories, revealing the acoustic propagation patterns in each environment. As expected in shallow water conditions, both scenarios exhibit significant multipath effects, which play a crucial role in shaping the sound transmission behavior.

In order to better contextualize the performance observed in the different scenarios, we conducted a spectral analysis of the ambient noise. This examination was crucial for understanding the noise environment in which the modem operates, as well as the potential impact of this noise on signal quality and



(a)

(b)

Fig. 2: Ray tracing results for the Chioggia (a) and La Spezia (b) shallow water scenarios using the Bellhop model, showing qualitative ray trajectories and highlighting multipath effects typical of shallow water environments.

communication efficiency. For the Chioggia tests, we used the Aquarian AS-1 hydrophone from the SubSeaPulse acoustic Modem (SuM) described later to record audio clips during periods with no intentional transmissions. In La Spezia, instead, we utilized an icListen HF hydrophone on the receiving side, independent of the SuM, throughout the entire duration of the tests. In light of these considerations, it is important to note that the graphs presented in Fig. 3 and Fig. 4 are not directly comparable. This is due to differences in the hydrophones' sensitivity and gain of the recording equipment used in each scenario. However, it is possible to observe some distinctive features: in Chioggia there was a significant low-frequency noise component, primarily attributed to maritime traffic in the area. On the other hand, in La Spezia, a constant interference at 50 kHz was detected, likely caused by a nearby yacht equipped with an echo sounder and this could have had a significant impact on the receiving performance, as will be described later. As will be shown in the following section, the difference in results for these scenarios was primarily influenced by the presence of ambient noise rather than by propagation conditions, which, although not optimal, played a secondary role.

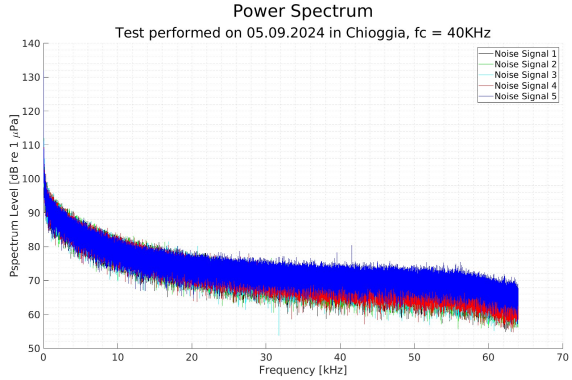


Fig. 3: Power spectrum of five ambient noise signals recorded in the Chioggia scenario.

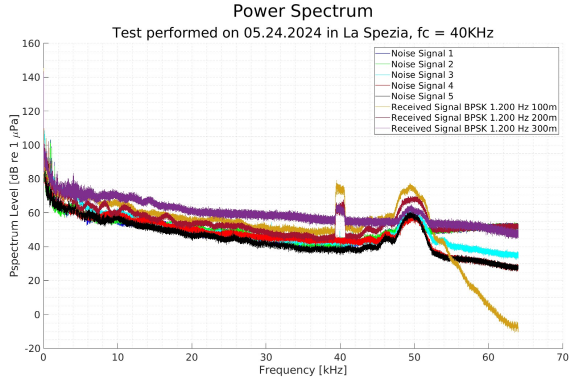


Fig. 4: Power spectrum of five ambient noise and BPSK signals with 1200 kHz bandwidth at various distances, recorded in the La Spezia scenario.

The tests were carried out using a transmitting modem positioned dockside and a receiving modem on a boat maintained at a distance as constant as possible. The transmitter's transducer was set to a depth of about 1 m in the Chioggia scenario and 5 m in the La Spezia scenario. Reception tests were performed at different ranges by moving the boat to different locations. The modems used for the sea trials are the SuMs, developed by the researchers of the University of Padua within the context of the Italian National Project for Military Research (PNRM) MODA [10] [11], with a renewed electronic design. They are equipped with a Raspberry Pi, working as a processing unit, and a HiFiBerry DAC/ADC pro HAT, operating at 192 kHz sample rate.

The SuMs can work with a wide range of underwater acoustic transducers operating in different frequency ranges between 2 Hz to 70 kHz. For the sea trials presented in this paper we used the low-cost Aquarian AS-1 hydrophone that allows it to operate around the center frequency of 40 kHz. The source level for the acoustic modem in this configuration is around 155 dB re 1 μPa @1m. We tested the JANUS waveform at a central frequency of 40 kHz, using various possible bandwidths: 4160 Hz, 6500 Hz (corresponding to band A and band E of the JANUS standard, respectively),

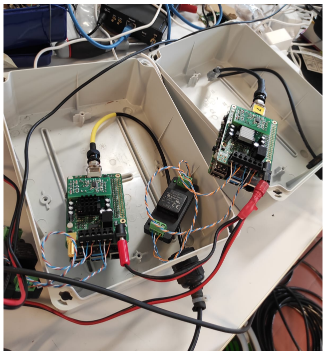


Fig. 5: Two SubSeaPulse acoustic modems used for the ranging tests.

as well as 5000 Hz, 10000 Hz and 10400 Hz. For comparison with a widely used modulation for underwater applications, we also tested BPSK with various possible frequency bandwidths. Each modulation uses a 2:1 redundancy encoding for the Forward Error Correction (FEC). For each test, a minimum of 50 packets were transmitted, and the number of packets received was counted. This method was used to measure the Packet Delivery Ratio (PDR) and the throughput as follows:

$$PDR[\%] = 100 \times \frac{\text{no. Packets received}}{\text{no. Packets sent}} \tag{1}$$

$$Throughput[bit/s] = \text{Data rate} \times \text{PDR} \tag{2}$$

III. TEST RESULTS

In this section, we present the test results conducted at the two locations described in the previous section.

A. *Test in Chioggia*

Fig. 6 and Fig. 7 show the performance results measured during the tests performed in Chioggia. Three different modem configurations were tested using a center frequency of 40 kHz:

1) BPSK with a 1200 Hz bandwidth;
2) The JANUS waveform with a 10000 Hz bandwidth;
3) The JANUS waveform with a 5000 Hz bandwidth.

The results demonstrate that JANUS modulation consistently proves to be highly reliable, always ensuring PDR values higher than those of BPSK. Although BPSK modulation provides a lower PDR, it ensures a higher throughput up to a distance of 600 meters.

B. *Test in La Spezia*

The performance measured during the tests conducted in La Spezia is shown in Fig. 8 and Fig. 9. For all the tests we used a central frequency of 40 kHz, testing the following modulations:

1) BPSK with a 1200 Hz bandwidth;
2) BPSK with a 2400 Hz bandwidth;
3) BPSK with a 4800 Hz bandwidth;
4) The JANUS waveform with a 4160 Hz bandwidth;
5) The JANUS waveform with a 6500 Hz bandwidth;
6) The JANUS waveform with a 10400 Hz bandwidth.

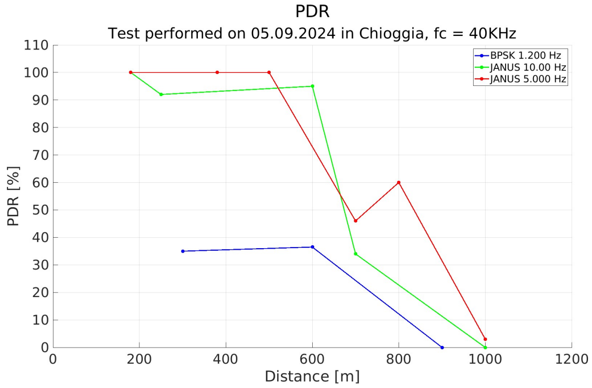


Fig. 6: PDR versus range obtained in the port of Chioggia using a center frequency of 40 kHz.

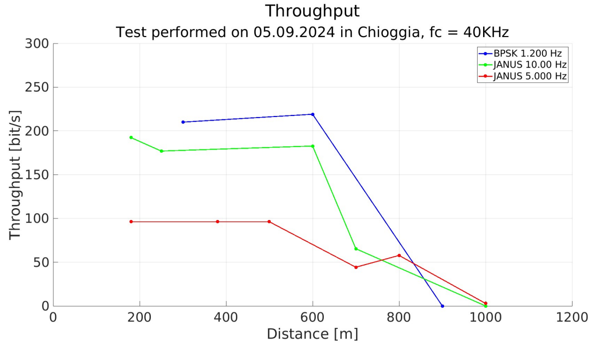


Fig. 7: Throughput versus range measured in Chioggia tests for JANUS and BPSK modulations.

In this scenario, we tested shorter ranges compared to the tests conducted in Chioggia, as higher distance transmissions were tested with a lower central frequency. In tests conducted in La Spezia as well, JANUS modulation generally proved to be more reliable, achieving a 100% PDR in most instances. Regarding BPSK modulations, the data collected at a distance of 100 meters likely experienced the effects of ambient noise present at the time, which disrupted communication and resulted in poorer performance compared to the data collected at greater distances. The BPSK modulation with a 4800 Hz bandwidth proved to be overly ambitious in this scenario, resulting in no packets being received across all tests conducted. Similarly to the findings from the tests conducted in Chioggia, we can note that, overall, with the exception of BPSK modulation with a 4800 Hz bandwidth, BPSK modulations achieved better results in terms of throughput. It is plausible that the 50 kHz noise emission described in the previous section, being close to the modem's pass-band filter bandwidth, negatively impacted the observed performance, especially for BPSK. To confirm this, additional tests were conducted in the same area on nearby days, showing significantly better results and allowing us to achieve good performance up to 600 m with BPSK and up to 900 m with JANUS, as reported in [12] and [13] respectively.

Fig. 8: PDR versus range obtained in the Gulf of La Spezia using a center frequency of 40 kHz, in the presence of strong interference at 50 kHz.

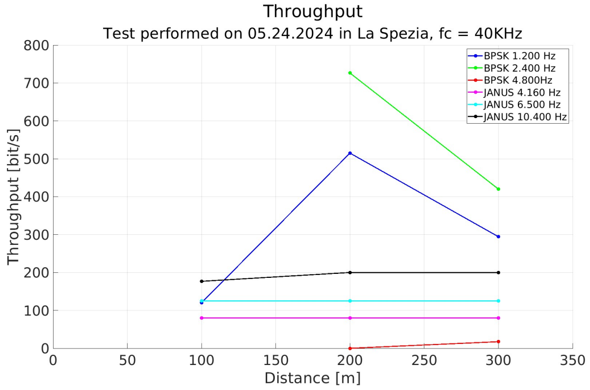


Fig. 9: Throughput versus range measured in La Spezia tests for JANUS and BPSK modulations, in the presence of strong interference at 50 kHz.

C. *Energy Efficiency Analysis*

The graph presented in Fig. 10 provides a detailed visualization of the energy expenditure per bit for the transmitting modem across various tested modulation techniques. The dataset takes into account the bits used for the FEC. It is noteworthy that JANUS transmissions exhibit a substantial energy consumption ranging from 3 to 30 times that of BPSK modulation. This significant difference underscores the diverse energy efficiency implications of different modulation schemes in practical communication systems, particularly for Autonomous Underwater Vehicles or sensors powered by batteries. Significant insights can be gained by examining these parameters in relation to the PDR. By analyzing the average PDR over the tested distances, we can derive the graphs shown in Fig. 11, which illustrate the mean amount of energy expended by the transmitting modem per received bit. In this analysis, the energy efficiency values of BPSK and JANUS modulation tend to converge. When the PDR is extremely low, such as with BPSK at a 4800 Hz bandwidth, the modulation proves to be highly inefficient. It is also important to note that in adverse channel conditions, JANUS modulation gains efficiency, becoming comparable to BPSK. This is evident in the Chioggia scenario, where the energy per received bit for BPSK is quite similar to that of JANUS with a 5000 Hz bandwidth.

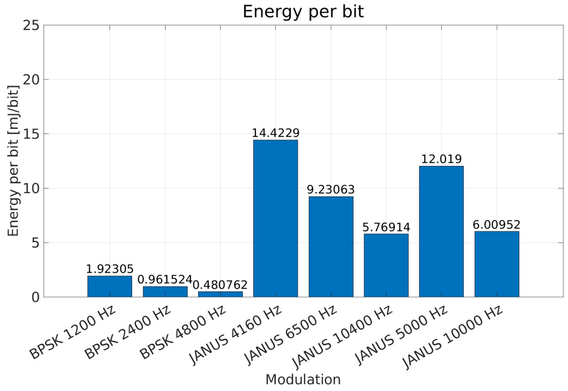
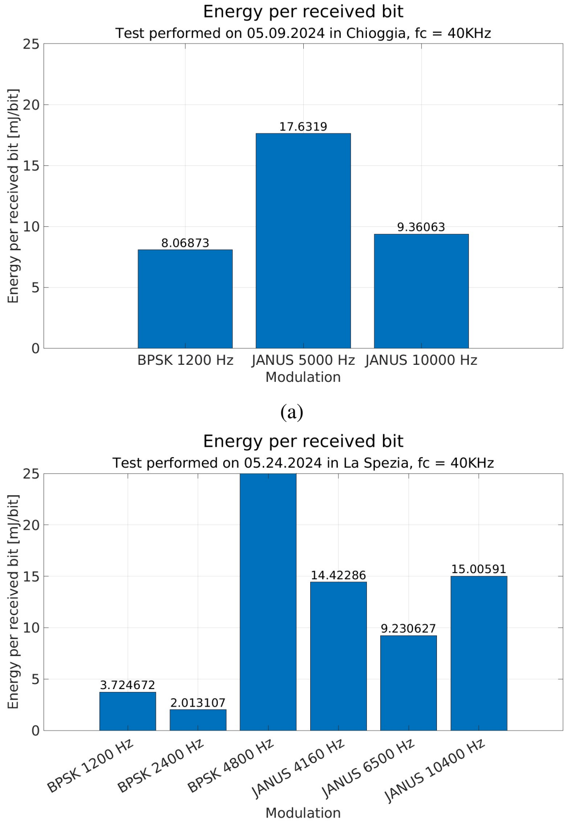


Fig. 10: Energy efficiency per bit transmitted by the modem using BPSK and JANUS modulations.



(a)

(b)

Fig. 11: Energy expended per received bit by the transmitting modem during the test conducted in Chioggia (a) and La Spezia (b).

IV. CONCLUSIONS

In this paper, we presented the performance results of the tests performed in different locations and environmental conditions employing a low-cost software-defined acoustic modem developed by the research team at the University of Padua and SubSeaPulse SRL. One of the aims of the report is to propose a comparison between the BPSK and JANUS modulations. In most scenarios, JANUS emerges as a highly reliable modulation scheme, consistently achieving high PDR. In contrast, BPSK generally exhibits lower reliability, but often achieves higher throughput in the presented scenarios.

Although different bandwidth sizes are not directly comparable, the aim of this analysis is to highlight the variations in the quality of service when using modems with the same transducers but different available modulations. Based on the presented results, data transmission is overall generally faster using BPSK modulation compared to JANUS. However, it remains to be investigated how this behavior changes as the network complexity increases and more nodes are added to the scenario. Other modulations, such as Orthogonal Frequency-Division Multiplexing (OFDM) and Frequency Shift Keying (FSK), can be implemented in the SuM to increase the transmission rate. The results obtained from these initial experimental tests can lay the foundation for designing an underwater network for autonomous vehicles or underwater sensors. This effort aims to develop increasingly efficient and autonomous systems for marine exploration and the sharing of data collected from the underwater environment.

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