4-FSK High-Speed Underwater Acoustic Communication System

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Abstract— **Oceans all over the world are an important way of sustainability in the lives of many people and have a high impact on the economy of most of the coastal countries. With the growth of underwater activity provided by the development of autonomous and remotely controlled vehicles and with the appearance of new underwater sensors, there is also a need to develop and design more robust underwater wireless networks to provide better and faster communications among the devices connected to the network. Nowadays several technologies provide wireless underwater communications. In this work, we address acoustic technology and the implementation of an acoustic communication system which applies a version of frequency modulation. The main goal of this work is to study the 4-FSK modulation technique and verify the efficiency of the communication system according to variables such as communication distance and baud rate. This implementation uses FPGA systems and Xilinx Vitis Model Composer software and MATLAB Simulink software for simulation. The developed communication system was tested in a controlled environment at two stages: aquarium and pool. The tests were carried out transmitting at 3 different baud rates (40, 100 and 200 kbps) in a distance of 100 cm in the aquarium and 5 meters in the pool.**

Keywords— Underwater Communications, High-frequency Acoustic, QFSK Acoustic Communication.

I. INTRODUCTION

Underwater wireless communications systems are becoming a priority in terms of research and technological development, due to the increasing demand for a better understanding of the complex sea dynamics and exploring the oceans' potential. This demand has been increasing exponentially the need for high baud rates and near real-time communications between submerged mobile and static agents in diverse scientific fields like pharmaceutical, geology, oceanography and ecology. In addition, the sapiens' curiosity for the unknown has been pushing those operations into increasingly deeper waters.

The existing wireless communications technologies, using electromagnetic waves, are not suitable in the aquatic environment beyond a few tens of meters, especially in the ocean's saltwater, due to the strong attenuation of the radio-frequency signals. Acoustic signals exhibit a much lower attenuation and thus sound waves, particularly in the ultrasonic range, have been used for underwater long-distance communications, being able to transmit a few kilobits per second. However, the underwater acoustic medium is one of the less reliable and most complex communications channels, bringing up major challenges for underwater communications. Moreover, there are relevant non-homogeneous, non-linear and time-variant phenomena that must be considered when communicating through the water. In deep water, those problems are magnified due to the long length of the channel.

The existing acoustic communication technology is optimized to communicate over long distances (a few tens of km), which leaves a gap in high-speed and medium-range communications. Long-distance communications require an acoustic transducer with low frequency and high output power, which leads to an available narrow frequency band. Therefore, to achieve the high-speed communications objective, it is necessary to go beyond the state-of-the-art of acoustic transducers and enable operational bitrates above 100 kbps for ranges above 1 km.

This work presents the development of an acoustic communication system whose purpose is the transmission of data in the underwater environment at speeds in the order of kilobits per second, always considering energy consumption.

II. STATE OF THE ART

In order to increase the baud rate, bandwidth-efficient modulations have been proposed, such as OFDM [1], or multiple transmitters and coding [2]. As in underwater acoustic communication the performance of a system, at a given time and location, does not guarantee a similar performance at different times and locations, this has motivated the emergence of reconfigurable systems [3] able to adapt to varying operating conditions. The use of higher frequencies (above 100 kHz) has also been proposed, together with the development of new transducers with larger bandwidths. In [4] the authors presented an FPGA-based acoustic modem operating at frequencies between 0.1 and 1 MHz. Using a Binary Phase Shift Keying modulation with 800 kHz carrier frequency, the system achieved 80 kbps baud rate in a laboratory tank with a 1 m distance range. In [5] a polymer-based directional transducer was developed with a bandwidth between 0.5 and 1 MHz, and pool-experimental results have shown a data rate of 1 Mbps with a simple modulation scheme as OOK at 12 m.

Several works have addressed communication systems using wideband, wide beam and high-frequency transducers. For example, [6] presented the development of a piston transducer with two resonance points between 90 and 220 kHz, referred to as the Transverse Resonance Orthogonal Beam mode, where the active material is set in resonance in the half-wavelength mode in the transverse direction and the acoustic beam is generated in the conventional transverse width beam direction and latter being orthogonal to the resonating transverse direction.

A more recent work [7] describes the development of a broadband and omnidirectional emitter transducer. A cylindrical transducer was developed using piezoelectric ceramic elements alternating with a flexible polymer and a matching layer for multimode coupling. After testing, the working frequency range of the transducer was between 230–380 kHz.

Another work [8] describes an evaluation of the signal quality of ultrasonic transducers using digital modulations. Two types of transducers were tested: PZT-5H ceramic transducers and PVDF polymers. The study includes MATLAB/Simulink simulations and experimental validations for BASK, OOK, BFSK and BPSK modulations with a 1 MHz carrier at a transmission rate of 125 kbps. In conclusion, the BPSK modulation presented the worst signal quality for demodulation in both transducers at 1 MHz carrier.

Despite the recent developments in acoustic transducers, there is no reliable solution that meets all the needs of underwater broadband wireless communications for a distance coverage range of up to 100 m.

III. System Description

A frequency-based modulation technique (FSK) was developed for communications using four frequencies to transmit two-bit symbols (QFSK or 4-FSK modulation). In this way, it is possible to duplicate the bandwidth compared to the normal FSK modulation technique that uses one frequency per bit.

The process for choosing the four frequencies considered oceanic bio-environment characteristics (above 200kHz, range of frequency used by several marine animals) and transducer operation limitations (up to 1.5MHz). The frequencies chosen were 700kHz, 865kHz, 1035kHz and 1.2MHz (symbols ‘00’, ‘01’, ‘10’ and ‘11’, respectively).

The hardware system is composed by two modules that were previously developed [8]. The emitter module contains a computer or terminal, an acoustic emitter module and an acoustic emitter acoustic transducer. The receiver is composed of another terminal, an acoustic receiver module and a hydrophone. The acoustic emitter module block is composed by an FPGA, a Digital Analog Converter (DAC) and a power amplifier. The acoustic receiver module is composed by another FPGA, an Analog Digital Converter (ADC) and a band-pass filter. The DAC selected was an AD9708 from Analog Devices, with 8-bit resolution that generates an analogue current signal between -20 mA and +20 mA to a maximum of 125 MSPS. This system was developed specifically to be applied in the areas of communications, signal reconstruction and instrumentation.

For the ADC it was chosen an IC AD9057 by Analog Devices. This device has 8-bit resolution, with three performance grades (40 MSPS, 60 MSPS and 80 MSPS) and has an important requirement: the input signal must be at most 1 Vpp centred at the reference of 2.5 V.

Between the Hydrophone and the ADC, a filter was implemented to remove the ambient noise. It was designed as a 1st-order bandpass filter to disregard frequencies below 5 kHz and above 2 MHz.

The power amplifier is crucial in the acoustic emitter module since the signal at the DAC output has a low amplitude (1 Vpp). To be able to increase the communication distance, it is necessary to increase the signal power, so it was necessary to introduce a power amplifier to amplify the output signal. The ADA4870 Operational Amplifier from Analog Devices was selected, which can amplify a signal up to 40 Vpp with a maximum output current of 1 A for signals with frequencies up to 52 MHz. However, for all the tests performed it was operated with an output voltage of 12Vpp with an effective power of 5W.

A PTZ-5H piston transducer with 1.1MHz resonance frequency, home-made and built for high-frequency underwater communications, with a 1.9 mm thickness and a divergence angle of 10 degrees was used. For the acoustic receiver, it was used the commercial transducer with pre-amplifier BII-7187 from Benthowave Instrument INC., with a 1Hz to 1.6MHz range.

The FPGA used was the Neso – Artix™ 7 FPGA Development Board. This board was chosen because it is easy to use, low cost compared to other options and it was specially designed for the development and integration of accelerated features based on FPGA [40]. This board contains the IC XC7A100T from Xilinx, have 2 Gb of RAM DDR3 memory, one micro-USB gate and a JTAG gate which are used to program the device and a 3.5 mm Jack port to power the board. This board also has 140 input/output ports. The MATLAB Simulink add-on Vitis Model Composer by Xilinx Inc was used to program both the emitter and receiver FPGAs. The developed software includes electrical signal generation (transmitted data modulation), hardware control (DAC, Amplifier and ADC) and received signal digital filtering and demodulation. Fig. 1 shows the acoustic module system in the aquarium experimental set-up.

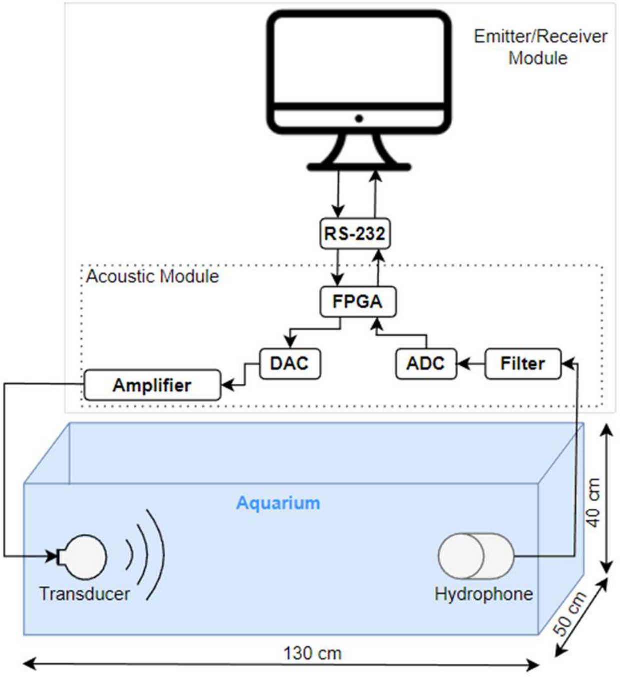


Fig. 1. Acoustic communication module experimental set-up.

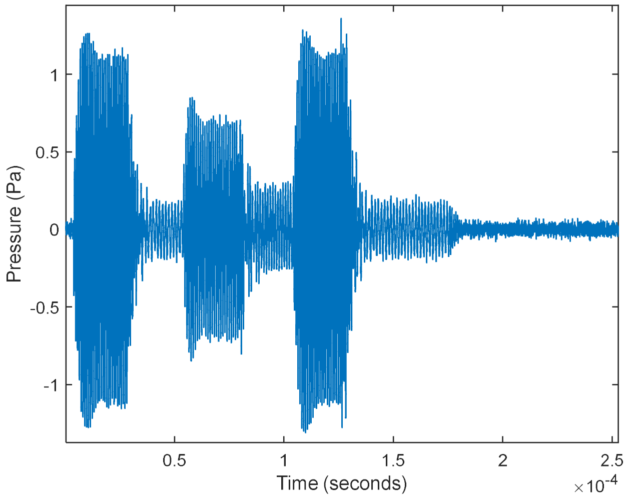
IV. SIMULATION AND LABORATORY VALIDATION

The simulation of acoustic signals modulated in MATLAB Simulink allows for the validation of the modulation scheme. The Simulink simulator integrates a model of the transducer and an aquatic medium model that includes attenuation, noise, echoes, and propagation delay. This simulator allows for a more comprehensive understanding of the effects of the aquatic environment on the modulated signals. By simulating the modulation and demodulation of signals in an underwater environment, we can analyse and optimize the performance of the communication system. Therefore, the simulated modulation scheme with good performance was implemented and tested in the laboratory aquarium and the results were evaluated.

For the simulation and the laboratory validations, the emitter and the hydrophone were placed approximately 100cm apart as presented in Fig. 1. The simulation was configured with the conditions observed in the experimental tests, with fresh water at a temperature of 13 ºC and 7.2 pH. In this simulation with 4FSK modulation, 3 different bit rates were used, namely 40kbps, 100kbps and 200kbps.

To compare the simulation with the laboratory test in the aquarium, the following sequence of bits "1100100111" were selected, where the first bit is the start bit and the last two bits are the stop bits. It also included a set of "0000" at the end of the sequence to help detect the end of transmission. The bit sequence results in a modulation signal with the following frequencies pattern (11 – 200 kHz, 00 – 700 kHz, 10 – 1035 kHz, 01 – 865 kHz, 11 – 1200 kHz, 00 – 700 kHz and 00 – 700 kHz). All results from the test laboratory present 3 signals, the yellow signal is the input bit stream, the blue signal is the hydrophone signal and the purple signal is the demodulated bit stream.

Fig. 2 presents the results of the simulation and the laboratory tests with a 40 kbps baud rate.

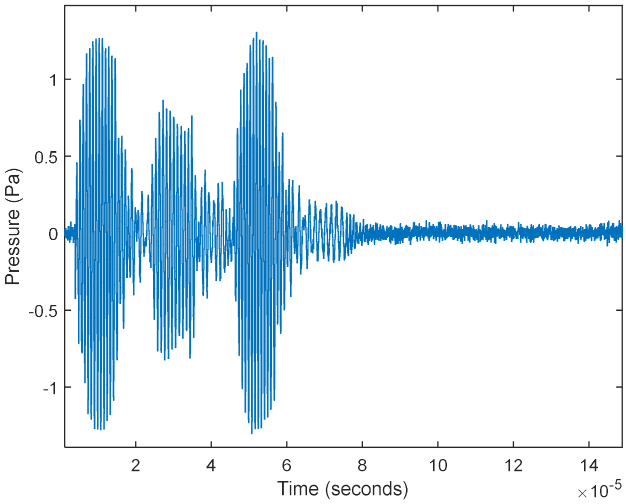


a)

b)

Fig. 2. a) Simulation of the transmission with a 40kbps baud rate. b) Laboratory test for the same transmission conditions.

Fig. 3 presents the results of the simulation and the laboratory tests with a 100 kbps baud rate.

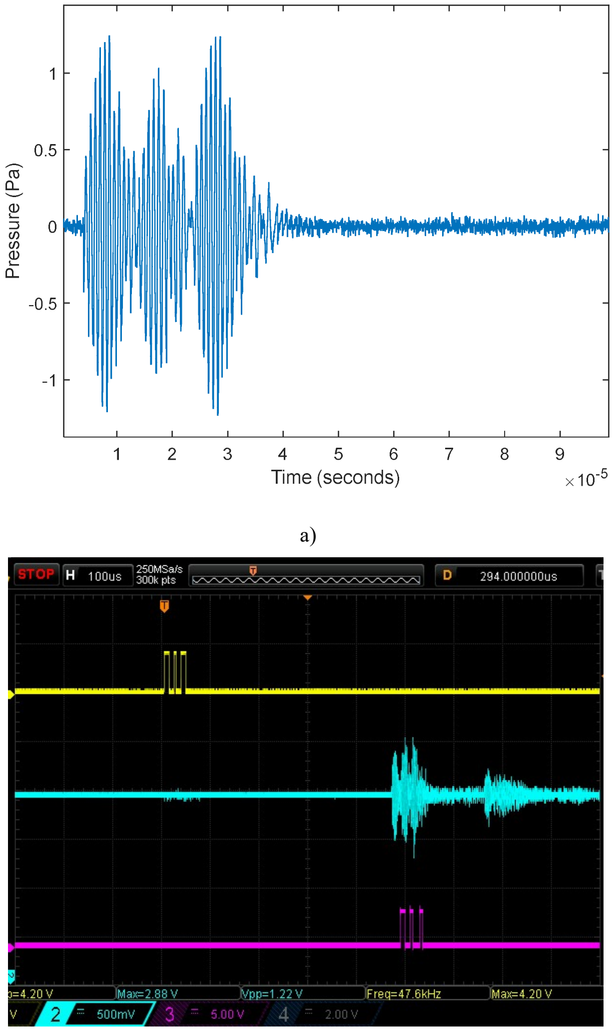


a)

b)

Fig. 3. a) Simulation of the transmission with a 100kbps baud rate. b) Laboratory test for the same transmission conditions.

Fig. 4 presents the results of the simulation and the laboratory tests with a 200 kbps baud rate.



a)

b)

Fig. 4. a) Simulation of the transmission with a 200kbps baud rate. b) Laboratory test for the same transmission conditions.

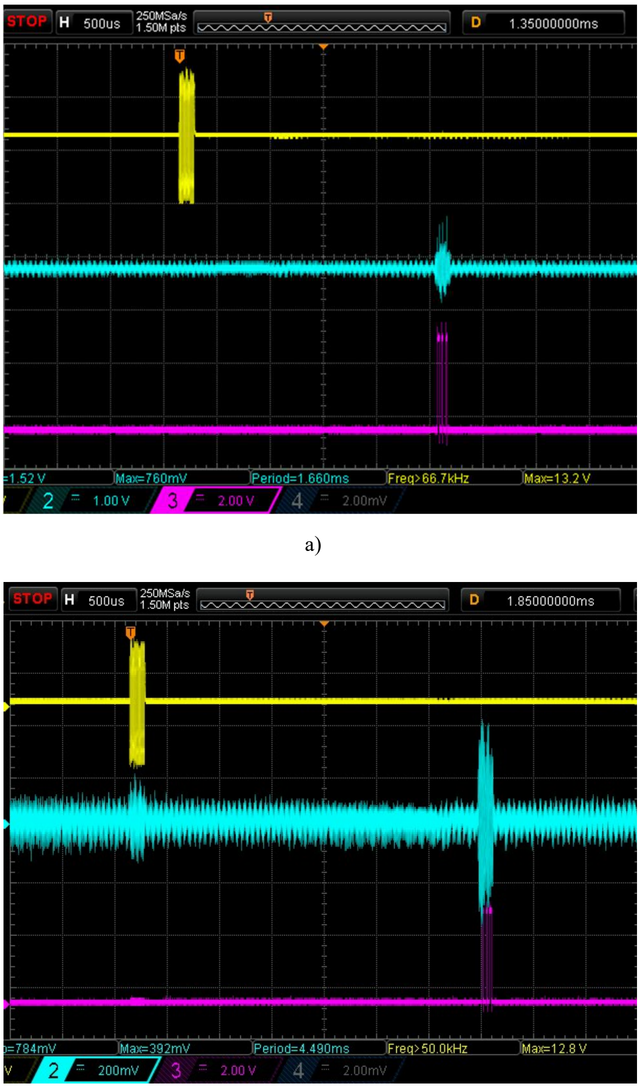
The results presented in Fig. 2, 3 and 4 demonstrate that the communication system simulation model results were validated by laboratory tests and can be used in the evaluation of new modulation schemes.

In Fig. 2 it is perceptible that the lower frequencies (700 kHz and 865 kHz) have lower amplitude compared to the higher frequencies (1035 kHz and 1200 kHz). This phenomenon happens for two reasons: the first is that the acoustic performance is directly proportional to the frequency of the electrical signal, within the operating frequency of the transducer [8] and ignoring the interference of the underwater channel. The second reason has to do with resonance, the transducer has a resonant frequency of 1.1 MHz and the closer the carrier frequency is to the resonant frequency, the greater the amplitude. However, the resonance of a transducer can be a problem in digital communications, since resonance works on energy accumulation and the carrier frequency variation is not immediate in the transducer, which can lead to problems at higher baud rates as it is presented in the next results. This phenomenon is observed in Fig. 3 and 4, as the lower frequencies are less noticeable as the baud rate increases. However, as we can observe in Fig. 3.b and 4.b the demodulator is able to identify the correct frequencies.

V. ACOUSTIC COMMUNICATION TEST IN POOL

Tests were also carried out in a swimming pool, knowing that this type of environment does not represent a real ecosystem. This is the environment that most closely resembles real conditions, since it has larger dimensions than the aquarium used in the previous tests. In addition, it is an environment that is exposed to natural phenomena such as wind. The objective of these tests were to verify the behaviour of the communication system over longer distances. The tests were conducted in the pool at different distances (2, 5 and 8 meters) and using baud rates of 100 and 200 kbps. Two distinct systems were used: one module to transmit and another to receive, and both are electrically separated.

Fig.5 presents an example of a transmission at 5 and 8 meters at 200 kbps.



b)

Fig. 5. Examples of a transmission at a) 5 and b) 8 meters at 200 kbps.

Fig. 5 shows that the system is able to communicate in a distance up to 8 meter. However, the system presented several errors. To measure the errors, a small packet of 100 bytes was sent several times for each distance and baud rate. The average results are in Table I.

TABLE I. POOL TEST ERROR COUNT

	100 kbps	**200 kbps**
2 m	86/100	42/100
5 m	76/100	41/100
8 m	74/100	25/100

The emitter transducer operates in a directional pattern with a divergence angle of 10 degrees and, as the distance increase it is difficult to keep aligned. Therefore, it was not possible to keep a line of communication for long periods without the need to re-align.

VI. CONCLUSIONS

An underwater acoustic communication system was presented and a 4-FSK modulation technique was implemented to verify the efficiency of the communication system according to variables such as communication distance and baud rate. A simulation model of the communication system was implemented and tested with 4FSK modulation at 3 different bit rates, namely 40kbps, 100kbps and 200kbps. The results show that the model is capable of generating modulated acoustic signals similar to those of the laboratory, allowing for an evaluation of the performance of modulation schemes before implemented in hardware.

The pool tests were conducted at different distances (2, 5 and 8 meters) and using baud rates of 100 and 200 kbps. The implemented 4FSK scheme was able to successively communicate at 8 m at 200kHz. With the increasing distance and baud rate, the system presented increasing errors. However, whenever transducer alignment was guaranteed, isolating the system from external interference, errors were substantially reduced.

The system has a very low energy consumption, below 10W, which also made longer-range communications difficult. Therefore, for future work, the communication system will be implemented and tested in a higher-power system with more powerful transducers.

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