High Data Rate Acoustic Modem for Underwater Aplications

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Abstract—**The development of an underwater wireless communication systems is becoming a research and a technological priority due to the increasing demand for exploring the potential of oceans in fields such as pharmaceutics, oil, minerals, environmental and biodiversity. However, underwater wireless communications still fail to ensure high data-rate connections which support real time applications.**
In this work a low power high data-rate acoustic modem is presented, based on a piezoelectric poly (vinylidene fluoride) polymer as a transducer and a Xilinx Field Programmable Gate Array (FPGA) that can be programmed to work with different types of modulations.
The system has been validated by the implementation of a full duplex point-to-point communication at 1 Mbps using On-Off Keying (OOK) modulation with a 1 MHz single carrier and it represents a major advance in the state of the art and a breakthrough in underwater acoustic communications, being the first to show the possibility to achieve data rates up to 1Mbps.
It was successfully tested with a 1 Mbps rate, achieving a $3x10^{-3}$ Bit Error Rate (BER) using just 1.4 µW of power consumption per bit.

Keywords—Reprogrammable Acoustic Modems, High Data-Rate Acoustic Modem, Underwater Communications, Low Power Acoustic Modem.

I. INTRODUCTION

The need for reliable and efficient underwater wireless communication technologies is increasing due to the increasing demand on systems for ocean exploration, research and economic exploitation [1] [2] [3] [4].

There are three main forms to communicate through water: acoustic, radio frequency and optical based communications [5]. Radio frequency is limited by the high level of absorption in water [6]. Optical systems suffer from the same limitation as well as the disadvantages associated to the high levels of ambient light close to the water's surface and scattering due to suspended particles [7]. As a result, acoustic communication systems are the preferential form of wireless underwater communications, since they show low sound attenuation in water [5]. Acoustic communications have been used for long distance communications, up to 20 km, and in deep waters with stable thermal conditions. But, despite underwater wireless communications having shown strong advances in recent years, there are still many limitations concerning data rates and robustness for real-time applications [8].

There are works showing that it is possible to use frequencies up to 1 MHz to achieve high data rate acoustic communications [9] [10] [11] [12]. For example, in [10] the authors presented an acoustic FPGA based modem operating at frequencies between 100 kHz and 1 MHz for distances ranging between 50 m and 100 m. Using a BPSK modulation with a 800 kHz carrier frequency, the system archived a 80 kbps data rate.

High communication frequencies also raise strong problems related to attenuation. Being directly related to the frequency, the acoustic absorption at 1 MHz can reach 280 dB/km [13]. Consequently, the maximum communication range decreases dramatically to a few hundred meters or less with increasing frequency [14]. On the other hand, real time acoustic communications are not supported at long distances, since acoustic waves propagate at around 1500 m/s, resulting in high propagation delays and disabling, therefore, any real time connection [13]. Summarizing, a high data rate and real time acoustic communication only can be applied at medium range, meeting therefore the needs of applications such as costal sensor networks, underwater unmanned vehicle control, equipment monitoring on offshore platforms and docks, among others.

There are also several commercial acoustic modems available [12] [15] [16] [17], which are not reliable solutions for data rates above 100kbps. For instance, EvoLogics [15] offers acoustic modems that can reach 2000 meters deep with an operational range of 1000 meters that can reach up to 2000 meters under specific water conditions. A maximum transmitting power of 60W can achieve 31.2 kbps in an omnidirectional pattern with a BER less than 10^{-10}. Another very interesting acoustic modem is the SAM1 by AppliedOcean System [12] that can reach 1 km in distance with a maximum data rate of 100 kbps.

The best choice for long distances is the LinkQuest Inc. [17]. Their powerful modem with a 40W transmitting power consumption offers a 10 km distance range and a 7 km maximum depth, and can achieve 5 Kbps in a omnidirectional pattern with a BER less than 10^{-9}.

In this work an underwater acoustic modem that allows communications over several meters, achieving a maximum data rate of 1 Mbps, using 1.4 µW of power consumption per bit with a 1 MHz carrier is presented. This solution allows for reprogramming the digital signal processing block and the implementation of different types of digital modulations in

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order to improve the modem's performance. The system is based on a poly(vinylidene fluoride) PVDF ultrasonic emitter transducer which is capable of sending high quality and clean signals needed for digital modulations with high symbol rates per carrier period [18] [19] [20]. However, the PVDF transducer cannot reach the same acoustic pressure level as other transducers such as piezoceramic transducers [20], reducing the effective distance range of the acoustic waves.

II. MODEM DESIGN

In order to design an acoustic modem capable of performing several types of digital modulations, a highly adaptable system was developed. Fig. 1 shows the block diagram of the system hardware.

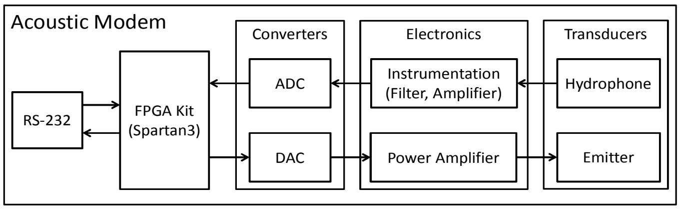


Fig 1: Block diagram of the acoustic modem system.

FPGA Spartan3 is responsible for the modem processing and control functions. The main task is to process digital signals by implementing the modulator and demodulator. It is also responsible for controlling the electronic circuits, the analog to digital converter (ADC) and the digital to analog converter (DAC). In section 3 the details of the modulator/demodulator process are presented. The selected A/D converter is an AD9244 capable of converting 65 Mega samples per second with 14 bits [21], and the D/A converter is a DAC904 with a current output and 14 bit resolution that supports update rates in excess of 165 Mega samples per second [22].

To carry out the A/D conversion it is necessary to handle the electrical signal from the hydrophone. For this purpose a filter, an amplifier and a signal conditioning system were implemented. The filter is an active 2nd order band-pass between 1 and 2000 kHz with a 12 dB gain. After amplification the signal cannot overcome the 3.3 V (peak-to-peak) because in order to obtain accurate measurements in the ADC input the signal must have a voltage between 1.65 V and 4.95 V centered at 3.3 V.

The DAC has a current output so it was necessary to implement a current to voltage converter using an operational amplifier, resulting in a 3 V peak-to-peak voltage output. The Power Amplifier block amplifies the modulated signal before being sent to the ultrasound transducer and consists of a Push-Pull symmetric amplifier with a 12 dB gain.

The ultrasound transducers are the most important part of the acoustic modem since, at high frequencies and high symbol rate per carrier period, the transducer must project and receive accurate modulated signals. At 1 Mbps communications with 1 MHz carrier frequency, the most used ceramic piezoelectric transducers operating at the resonance frequency [23] [24] are not a suitable solution since the acoustic energy within the transducer creates a deformation on the modulated signal. Therefore, an emitter transducer based on the piezopolymer PVDF was developed [20]. This material has a much lower piezoelectric coefficient d33 ~ $3.40x10^{-11}$ C/N [25] than the most used piezoceramics such as Lead Zirconate Titanate, PZT, ~ $5.10x10^{-10}$ C/N [26], leading to a weaker acoustic signal. On the other hand, the acoustic impedance (~$3.3x10^6$ kg/m²s) is close to the acoustic impedance of water (~$1.5x10^6$ kg/m²s) when compared to the acoustic impedance of piezoceramics (~$34x10^6$ kg/m²s) [20]. The acoustic impedances matching between transducer and communication medium allows for an improved acoustic energy transfer from the transducer to the medium, reducing energy losses within the transducer and resulting in a more perfect acoustic signal [18]. The ultrasonic projector active element was constructed with two layers of PVDF with a thickness of 110 µm each in a piston configuration with 2 cm diameter. Specific details on the transducer construction and characteristics can be found in [20]. The ultrasonic receptor was a Cetacean ResearchTM C304XR hydrophone with an effective sensibility of -181 dB, 1 V/µPa, a linear frequency range (±3dB) between 0.012 and 1000 kHz and a frequency range (+3/-12dB) between 0.005 and 2000 kHz.

III. DIGITAL SIGNAL PROCESSING

An OOK modulator and demodulator was implemented in the Xillinx Spartan3A using the Xillinx System Generator Toolbox for MatLab. The modulator and demodulator logic circuits were optimized to reduce the consumption of resources in order to be able to include more functions in the future.
The modulator and demodulator logic circuits were implemented in parallel without any interconnection between each other. In this way it is possible to ensure the optimal functioning for full-duplex communication without any interference and/or delays.

A) Modulator

Using a DDS Compiler block it is possible to generate a 1 MHz sine wave for the carrier frequency. The signal from the RS232 port controls the sine wave generator, sending the sine wave in the case of a logic level '1 ' or a null value in the case of a logic level '0'. At the beginning of each transmission the reset of the DDS Compiler block is carried out, restoring the sine wave phase to 0º in order to synchronize the data stream with the carrier frequency. The DDS Compiler block was set to generate a sine wave with amplitude values between 0 and 16384 with an 8192 offset. These values have a direct current output correspondence in the DAC [22]. After the current/voltage converter, the signal shows an amplitude between 3 and -3 V. A clock output of 25 MHz was also implemented to the DAC with 25 samples per period. In this way, it is possible to ensure the best quality of the 1 MHz modulated signal avoiding the early deformation.

B) Demodulator

The ADC amplitude ranges were between -8192 and 8192 which corresponds to an input voltage between -1 and 1 Volt. Since digital filters require too many resources, it was necessary to reduce the sampling frequency to 6.25 MHz. Before filtering the signal, an absolute value function, converting all samples into positive values was implemented. Thus, the signal appears to have twice the frequency and an offset. Then, the filter allows for the lower frequency to be isolated which corresponds to the digital information. The filter consists of a FIR Equiripple with an order of 90 and a density factor of 16. The filter was configured to a 6.25 MHz frequency sample, a pass frequency of 250 kHz and a stop frequency of 500 kHz. After filtering it is necessary to select what is a ‘1’ and what is a ‘0’. Therefore, an adaptive threshold function, where the signal amplitude is measured each 20 milliseconds, was implemented. Then the optimal threshold function measures the filtered signal amplitude and sets the threshold with half of the measured value only if the period is higher than 1 bit, in order to avoid narrow noise peaks. Finally, the resulting signal is a bit stream sent to the RS232 port.

IV. Experimental Results

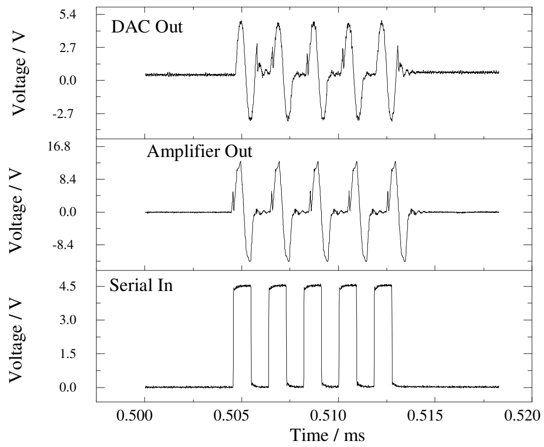
The performance of the communication system was evaluated by implementing an experimental set-up for the measurement and recording of the acoustic signals with several baud-rates. With the collected data it was possible to measure the transmission BER.

A. *Experimental setup*

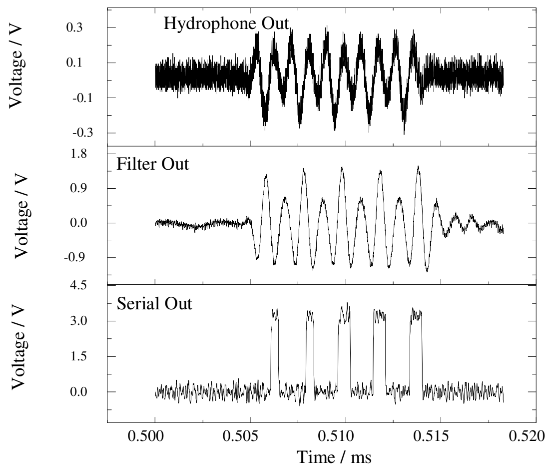
The experimental tests were performed in a swimming pool with 10 meters in length, 5 meters width and 1.5 meters deep. The receiver and emitter transducers were placed in the swimming pool 6 meters away from each other, with 2.5 meters from each side wall, 2 meters from the back wall and 50 centimeters deep. The distances were selected in order to avoid sidewall echo interferences.

B. *Results*

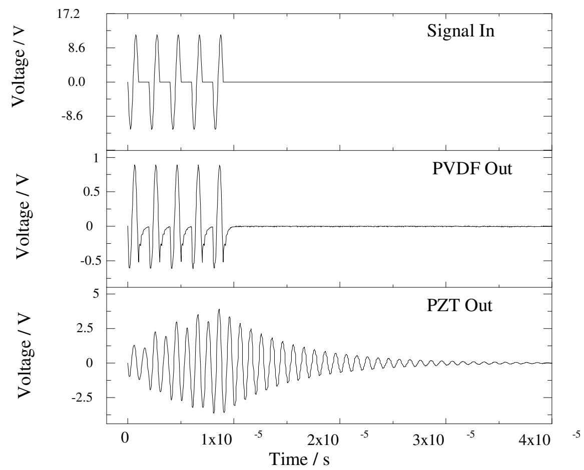
The initial test consisted in sending the ASCII char 'U' in a continuous mode. The code bits of this character has the particularity to toggle between ‘1’ and ‘0’, resulting in a ‘01010101’ binary sequence. This is one of the most difficult sets of bits to demodulate, due to the constant change of state. Fig. 2 shows the signals from the emitter and receiver acoustic modem as well as the transducer simulations.



a)



b)



c)

Fig. 2: a) Signals from the emitter; b), signals from the receiver; c) PVDF and piezoceramic PZT transducer performance simulation [20].

The emitter side shows (Fig. 2a) the input serial stream bits from the PC, the modulated signal in the DAC output and the signal sent to the emitter transducer. In the receiver side (Fig. 2b) it is shown the signal coming from the hydrophone, the signal at the filter output and the serial bit stream at the modem output. In Fig. 2c a simulation of the expected performance of the PVDF and PZT transducers is shown [18] [20].

This test was performed using an OOK 1 Mbps transmission with a 1 MHz single carrier, resulting in a sine period to each bit length. In the emitter side it is possible to observe that each high logic state is converted to a 1 MHz sine wave. It is noteworthy that the serial port is operating with inverted logic, meaning that a high logic state corresponds to a '0' bit and low logic state to a '1' bit.

The simulation was obtained through a transducer simulation model developed in Matlab Simulink [18]. The simulation was carried out under the same swimming pool setup conditions, the PVDF characteristics being the same as the one used in the experimental measurements and the PZT transducer being a 1 MHz resonator piston type with 2 mm thickness and 2 cm diameter [12].

The simulation results show a large difference between the PZT and PVDF signal amplitude. The PZT shows an amplitude ~ 4 times higher than PVDF, however the PZT transducer shows high levels of signal deformation, disabling any attempt to recover the digital information.

The PVDF transducer simulations are consistent with the results obtained experimentally. Analyzing the signals at the receiver modem it can be observed that the signal never reaches the zero value, having residual signal at the end of each sine wave. This is due to part of the acoustic energy that is retained and dissipated within the transducer. Despite this setback, it is still possible to clearly distinguish the high logic level with higher amplitude, enabling the signal demodulation. The signal at the hydrophone presents a SNR of 7 dB. Since the distance between emitter and receiver could not be increased due to experimental restrictions, it was performed an experimental tests using lower transmission powers were the signal demodulation was still possible under a minimum SNR of -1.74 dB, Interpolating these values leads to the conclusion that the system will be operational up to the 16 m range. Another aspect regarding the maximum distance range was the low excitation voltage tension (12 V) applied to the transduced. This value can be increased by at least an order of 10 times limited only by the piezoelectric material maximum operating voltage [27], enabling the system to reach further distances.

The BER was also measured for the baud rates of 1 Mbps, 512 kbps and 256 kbps. The measurements were performed at two RS232 ports, allowing for sending and receiving the file on the same computer for comparison. The file size is 2 MB and no type of error detection or correction mechanisms were implemented. The results registered were $3x10^{-3}$ BER with 1 Mbps, $2.3x10^{-5}$ with 512 kbps and $1x10^{-8}$ with 256 kbps.

Most of the errors were caused by a false start bit that initialized the demodulation process. These false start bits were caused by noise peaks. When the baud rate is reduced the noise peaks were no longer detected by the receiver modem. However, there are several ways to reduce this occurrence by improving the filter quality or implementing a function that detects and distinguish a real data transmission from a demodulated peak noise. Subsequently, an error control coding can be also implemented to reduce the BER.

Consequently, it is possible to conclude that the developed solution achieves data rate speeds 10 times higher than one of the fastest acoustic modems available: the SAM1 by AppliedOcean System [12], but in proper water conditions and with external power supply this system can reach over 160 times further. When compared to the EvoLogics [15] the developed system is 32 times faster in terms of data rate and consumes 1370 times less energy to send 1 MB. On the other hand, their solution is able to communicate over 300 times further. Nevertheless, it is important to take into account that the present prototype still has room for improvement and optimization before the development of a commercial product.

V. CONCLUSIONS

A Low Power Acoustic Modem for underwater wireless communications capable of reaching a maximum data rate of 1 Mbps was presented.

The measured BER using an OOK 1 MHz single carrier modulation was $3x10^{-3}$ BER at 1 Mbps, $2.3x10^{-5}$ at 512 kbps and $1x10^{-8}$ in 256 kbps. These characteristics allow for the implementation of unmanned underwater vehicles (UUV) in real time remote control with compressed video and sound or access to internet from a submarine.

Future work will consist of increasing emitter transducer power output to reach long distances, implement other digital modulations with higher bit rates per symbol and optimizing the corresponding electronic circuits and digital filters.

ACKNOWLEDGMENT

M. S. Martins thanks the FCT– Fundação para a Ciência e Tecnologia for the grant SFRH/BD/60713/2009.

This work has been supported by FCT – Fundação para a Ciência e Tecnologia within the Project Scope: Pest-OE/EEI/UI0319/2014.

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