Low cost adaptive underwater acoustic modem for the Black Sea environment

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ABSTRACT

The success of terrestrial wireless sensor networks in monitoring various phenomena caused an increased interest to develop underwater sensor networks by the underwater acoustics community. These networks are based on underwater acoustic modems for real-time data transmission. The high cost and fixed architecture of these devises makes it impossible to implement dense wireless sensor networks adapted to the environment.

We propose an adaptive architecture for a low cost underwater acoustic modem. Designing such a modem with adaptable parameters is determined by the zonal variability of the underwater channel. This article presents the results of a frequency dependent simulation for a particular underwater channel in the Black Sea for which we determined the distance dependent impulse response. The simulation results reinforce the idea of variability of the transmission channel and support the idea of designing an adaptive underwater acoustic modem.

Underwater acoustic modem, frequency dependent simulation, underwater wireless sensor network, underwater acoustic channel.

1. INTRODUCTION

Research in experimental underwater acoustics requires fairly large technical equipment: at least one ship and marine platforms equipped with a variety of projectors, hydrophones and sensors for measuring the parameters of interest in the marine environment. Thus we can say that experimental marine expeditions are expensive and do not permit long-time monitoring of phenomena of interest.

These shortcomings have determined the increase of the research efforts in the field of sensor networks[1-5]. Currently there are two types of underwater sensor networks. In the first case nodes communicate the data taken from the environment through optical fiber[6]. Although the speed at which data is transmitted is comparable to terrestrial fiber networks, the installation and maintenance of underwater fiber networks is quite expensive. In the second case the nodes communicate the data wirelessly using acoustic waves. In this case a network node consists of an underwater acoustic modem[7-10] and a sensor module.

Underwater wireless sensor networks (UWSN) have a lower cost than underwater fiber networks because they use less equipment for monitoring. However the cost is not sufficiently lower to allow the implementation of UWSN with hundreds of nodes spread over tens of kilometers as it is possible in terrestrial sensor networks. The implementation cost is still high because the price of an underwater acoustic modem is quite high.

Another shortcoming is represented by the energy consumption. Each node has finite energy for transmission of data over distances of tens, hundreds or even thousands of meters. This energy is often used inefficiently. An effective way to use this energy is that the modem can transmit adapted to the underwater sound channel. This requires knowledge of the mean properties of the transmission channel.

Minimizing energy consumption and lowering the implementation costs are two research directions needed to streamline existing underwater acoustic modems.

Most commercial underwater acoustic modems were created in order to send information at distances of a few kilometers. The cost of such a modem is at least several thousand dollars. These aspects prevent the implementation of dense underwater sensor networks for monitoring areas of interest. On the other hand the architecture of these modems is fixed. The modem's parameters can not be modified to satisfy user specific requirements[11-14].

The development of research modems focuses on increasing the system throughput for long transmission distances (2-6 km). This increase is based on transmitting signals with small period, which enhance the inter-symbol interference at the receiver. For the data to be correctly received the use of an equalizer is mandatory. Using an equalizer in conjunction with the underwater acoustic modem determines the increase of acquisition cost and energy consumption[15, 16].

Given the tragic events that occurred recently in Japan, it is necessary to implement cheap underwater sensor networks, spread over thousands of kilometers, to monitor the pollution. In the case of terrestrial sensor networks the data from the environment were used in taking decisions that have favored the development of the monitored area. These networks have been successfully used in detection of forest fires[17], seismic monitoring[18, 19], flood detection[20] or habitat monitoring[21].

It is necessary to create an underwater acoustic modem whose parameters can be adapted depending on the application and location. Implementing such a modem will cause a reduction in energy consumption and cost of the underwater acoustic network. The proposed modem will be used to monitor the pollution in the Danube Delta and Black Sea, for tsunami and seismic monitoring, for early detection of algal bloom and for monitoring the physical, chemical or biological properties of the sea water.

Next we present the design of the proposed modem. In Section 2 we highlight the characterization of the underwater acoustic channel for a particular region in the Black Sea. In Section 3 we present the proposed modem architecture. The design of analog front-end is presented in Section 4. The digital front-end is presented in Section 5. In Section 6 we propose the architecture for an adaptive sensor module. In Section 7 we present the conclusions of this article.

2. BLACK SEA UNDERWATER CHANNEL SIMULATION

To implement an underwater acoustic modem first is necessary to know the characteristics of the transmission channel through which it will send the data acquired by sensors. The modem presented in this article is designed to operate in the shallow waters of the Black Sea continental shelf.

We will consider the Danube Delta as our region of interest. An underwater sensor network could be installed at the mouth of the Danube Delta in the Black Sea in order to monitor the silt composition, the pollution from vessel traffic and many other properties of sea water. This area has an average depth of about 40 meters. In figure 1 we show the average sound speed profile over a period between February 1890 and September 1998.

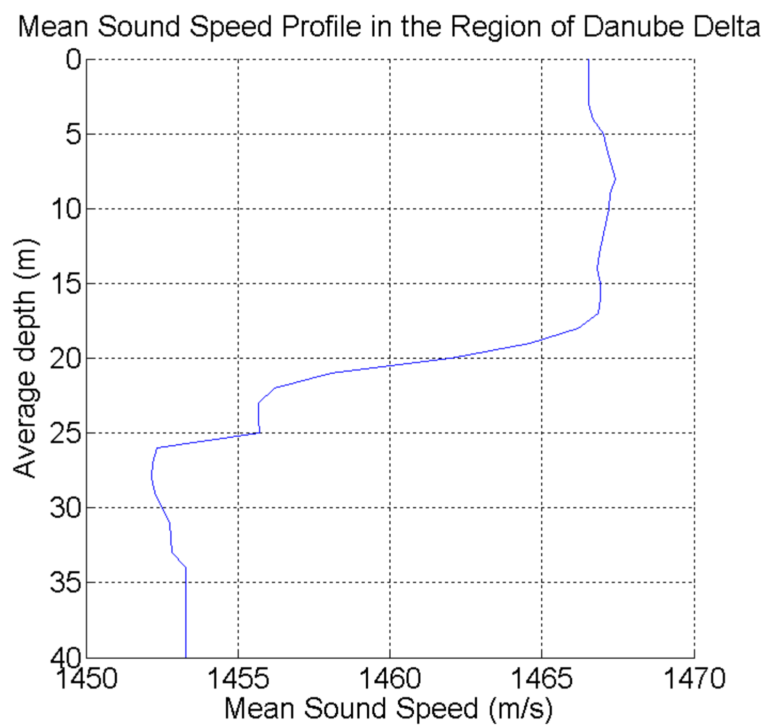

Figure 1. Mean sound speed profile in the region of Danube Delta.

Using the AcTUP simulation software[22-24] we simulated the Danube Delta transmission channel. We set up an environment as shown in Figure 2. In the process of creating the environment we used the sound speed profile shown in Figure 1, the sea bed was considered flat and the transmitter and receiver transducers were positioned very close to the sea bottom. We considered five distances of interest 500, 1000, 1500, 2000, 2500 meters. For each distance we obtained the frequency response of the Danube Delta underwater acoustic channel.

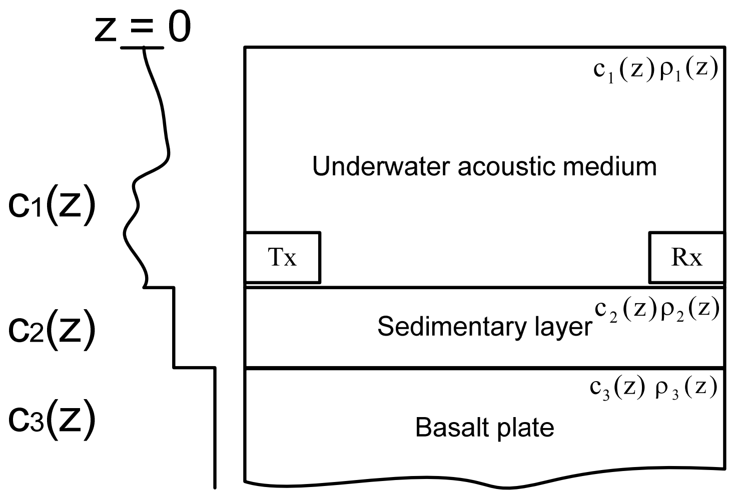

Figure 2. AcTUP simulation software environment setup.

These profiles are shown in Figure 3.1. In Figure 3.2 we present the global mean frequency response of the underwater acoustic channel. As in [25] we obtained, for each considered distance, an optimal transmission frequency, where the summed effect of noise and attenuation is lowest, around which we could choose a frequency band according to certain criteria: channel capacity maximization, as in [25, 26], or transmission power decrease. We observe that the levels of the Danube Delta frequency responses are lower than the global mean frequency responses in average with 5 dB. This fact means that the underwater acoustic channel will attenuate the transmitted signals more so the transmitter mode of the analog front-end must be design to take into account this shortcoming.

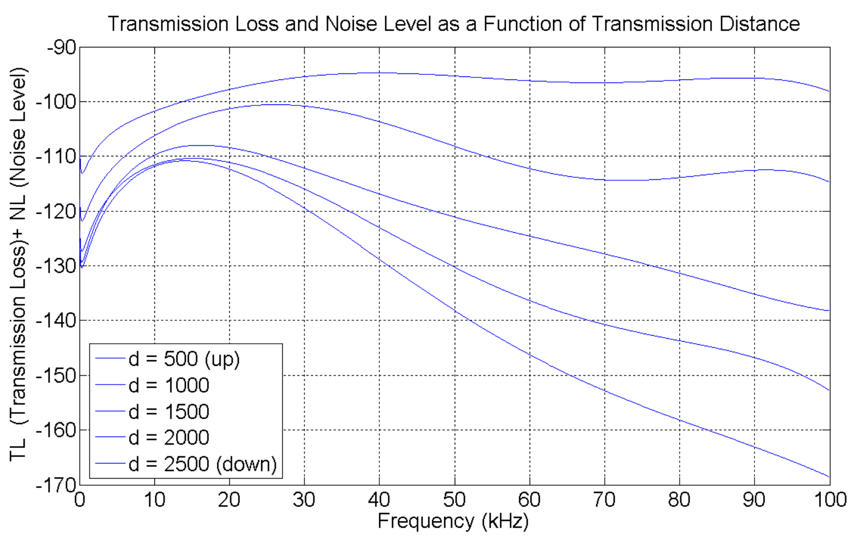

Figure 3.1. The frequency response of the Danube Delta underwater acoustic channel as a function of distance.

We chose two transmission frequencies, $f = 40\ kHz$ for the distance of 500 meters and $f = 20\ kHz$ for the distance of 2000 meters. The bandwidth was chosen to be equal to 10 kHz, but it can be increased to 20 kHz. If we want to transmit at distances smaller than 500 meters we will reduce the output power. If we want to transmit at distances greater than 2000 meters then the analog transmitter module will increase the transmission power. In Figure 4 we show the impulse responses for the chosen frequencies.

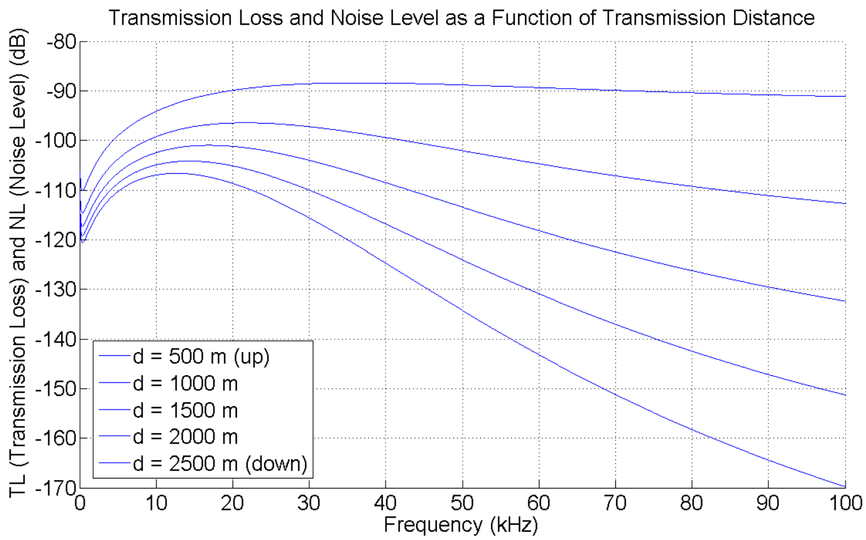

Figure 3.2. The global mean frequency response as a function of distance.

3. UNDERWATER MODEM ARCHITECTURE

The underwater acoustic modem's architecture is represented in figure 5. As shown, the modem has two transducers to transmit underwater signals, so it can be used in full-duplex mode. The analog receiver consists of four band pass filters with center frequency of 20 kHz and 40 kHz. The system can choose the filters with 10 kHz bandwidth or the ones with 20 kHz bandwidth. The analog transmitter will take into account the frequency response of the projector and the passive sonar equation to provide the necessary amplification so that the transmitted signals reach the required distance with the desired signal-to-noise ratio (SNR). The digital front-end is implemented in an Altera FPGA. The FPGA is part of a development kit called DE0-nano[27]. Using a hardware description language we have also implemented in FPGA the interface and the architecture of the sensor module and the controller of the analog-to-digital-digital-to-analog (AD-DA) converter. After we performed the simulations in which we used the impulse responses shown in Figure 4, we chose the symbol duration and the time guard interval values so that the effect of intersymbol interference is minimized. In Table 1 we show these values and the minimum bit rate.

We chose the sampling frequency to be 200 kHz. This value is approximately 3.5 times higher than the maximum frequency the receiving part of the analog front-end could process. This maximum frequency is 60 kHz.

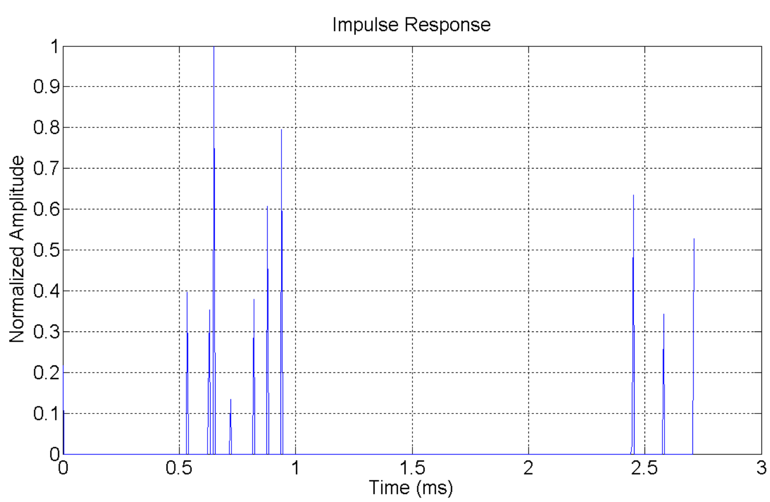

Figure 4.1. Danube Delta channel impulse response at 40 kHz.

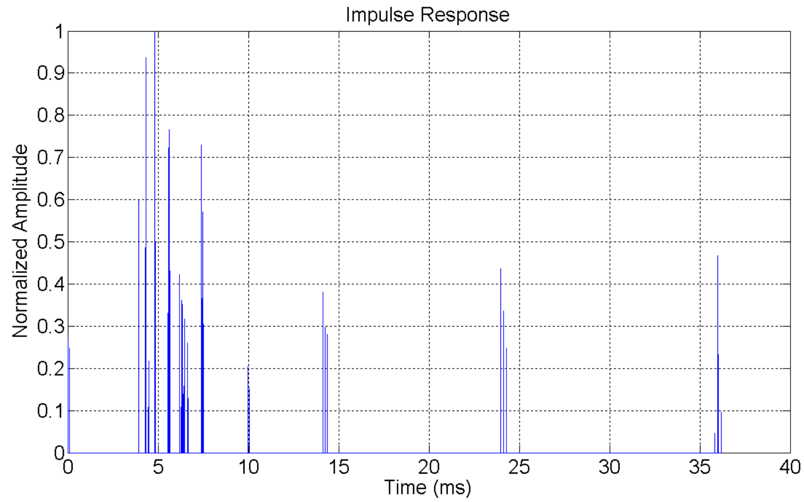

Figure 4.2. Danube Delta channel impulse response at 20 kHz.

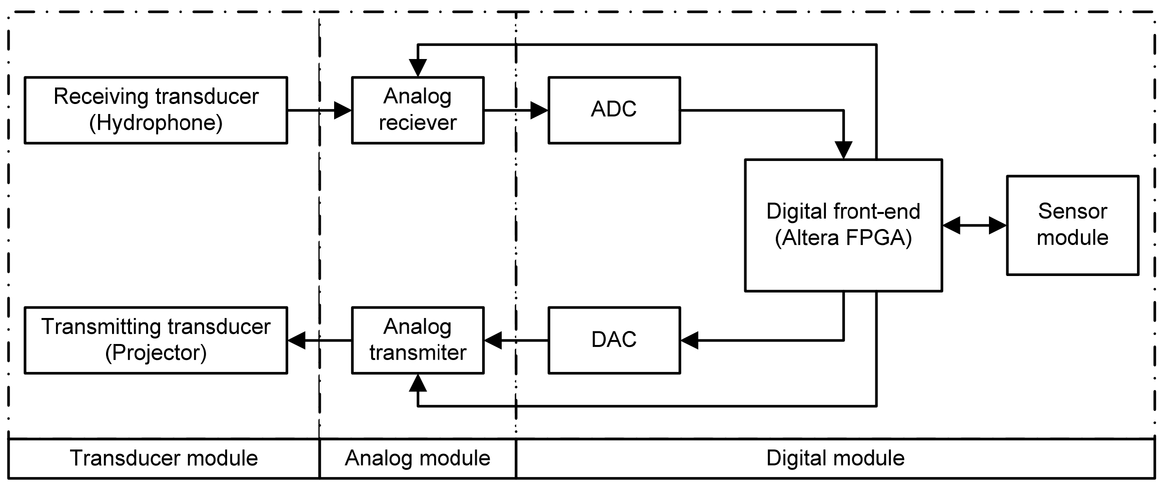

Figure 5. Proposed underwater modem architecture.

Transmission Distance (km)	Central Frequency (kHz)	Symbol Duration (ms)	Time Guard Interval (ms)	Minimum Bit Rate (bps)
0.5	40	2	3	250
2	20	2	38	25

Tabel 1. Underwater acoustic modem's signal parameters.

4. ANALOG FRONT-END

4.1. Transmitter module

We designed the transmitter part of the analog front-end using the following equation.

$$\mathrm{SNR} = \mathrm{TVR} + 20 \cdot \log_{10}(\mathrm{K} \cdot \mathrm{V_{rms}}) - \mathrm{TL} - \mathrm{NL} - 10 \cdot \log_{10}(\Delta\mathrm{B}) \quad (1)$$

We took into account the frequency response of the projector represented by the Transmitting Voltage Response (TVR), the underwater channel properties represented by the Transmission Loss (TL) and Noise Level (NL) and the signal properties represented by the rms voltage amplitude (V_{rms}) and the transmission bandwidth (ΔB). For a SNR equal to 20 dB we computed the amplification K knowing that $V_{rms} = 1.16\ V$. The results are represented in Table 2.

This module consists of four band pass filters: two filters with a central frequency of 20 kHz and an adjustable bandwidth from 10 to 20 kHz and two filters with a central frequency of 40 kHz with the same adjustable bandwidth. The analog front-end can use only two filters at the same time for a given frequency band.

SNR (dB)	20			
Frequency (kHz)	40		20	
ΔB (kHz)	10	20	10	20
TL+NL (dB re 1uPa)	95	95	110	110
TVR (dB re 1uPa/V @ 1m)	138	138	154	154
K (V/V)	**9**	**12**	**8**	**11**

Table 2. Filter amplification K computed using the properties of the transducer, underwater channel and input signal amplitude.

4.2. Receiver module

The receiver part of the analog front-end is also composed of four band pass filters, but these filters are design to have higher amplification to compensate the losses due to conversion of acoustic signals into electrical signals.

5. DIGITAL FRONT-END

5.1. Transmitter module

This module runs a MFSK modulation scheme. Table 3 highlights the modulation parameters. This module has a replaceable architecture. If we want to implement a different modulation scheme we can replace the current algorithm with a new algorithm, created with the purpose of increasing the transmission throughput. In conclusion the transmitter part of the digital front-end is designed to be modular and scalable.

Modulation		4-FSK	
Carrier Frequency		40 kHz	20 kHz
Transmitted bits	00	1 kHz	
	01	2 kHz	
	10	3 kHz	
	11	4 kHz	

Table 3. The 4-FSK parameters of the transmitter part of the digital front-end.

5.2. Receiver module

In figure 6 we show the block diagram of the receiver module which consists of three blocks. The first block is designed to synchronize the data stream. The syncronization method uses the good correlation properties of the chirp signals. In Table 4 we present the chirp signal parameters.

Chirp Signal Parameters		
Transmission Frequency (kHz)	40	20
Sweep mode	up-chirp	
Initial frequency (kHz)	35	15
Maximum frequency (kHz)	55	25
Sweep duration (ms)	2	2

Table 4. Chirp signal parameters.

The second block will demodulate the acquired signal and will offer a baseband signal. This block uses the classical method of amplitude demodulation of the processed signals.

In the third block we implemented a MFSK demodulation algorithm, the parameters of which are highlighted in Table 3. This module has a replaceable architecure. As in the case of the transmitter module, we can replace the current demodulation scheme with a different one.

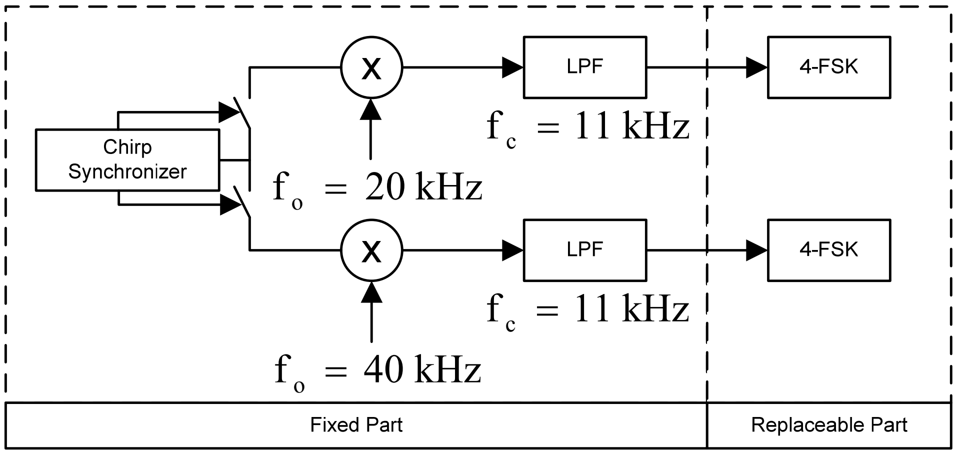

Figure 6. Block diagram of the receiver part of the analog front-end. The module has a fixed part composed of syncronization and demodulation blocks and a replaceable part where we transform the acquired signals in bits.

6. SENSOR MODULE

In figure 7 we present the architecture of the sensor module. The analog to digital converter (ADC) offers the possibility to connect up to six sensors. The minimum sampling frequency the ADC can handle is equal to 50 kHz, which means that the data are acquired at intervals of 20 μs.

The values of the physical, chemical or biological properties we want to monitor, such as temperature, salinity, pH, usually does not change very rapidly, which means that we ca sample them more slowly. Because of the fact that the development board does not allow us to sample at smaller rates, we chose to downsample the data. The adaptive downsampler is placed after the ADC module and will enable the acquisition of slow varying signals but also the transient ones. This will be possible by changing the downsampling factor in a controlled way. The acquired values are then stored in a buffer. When we change the value of the downsampling factor the buffer will be emptied and then we acquire new signals at a different sampling rate.

The adaptive acquisition of data is possible due to the way the control unit was implemented. This unit has two modes of operation: the algorithm control mode and the user control mode.

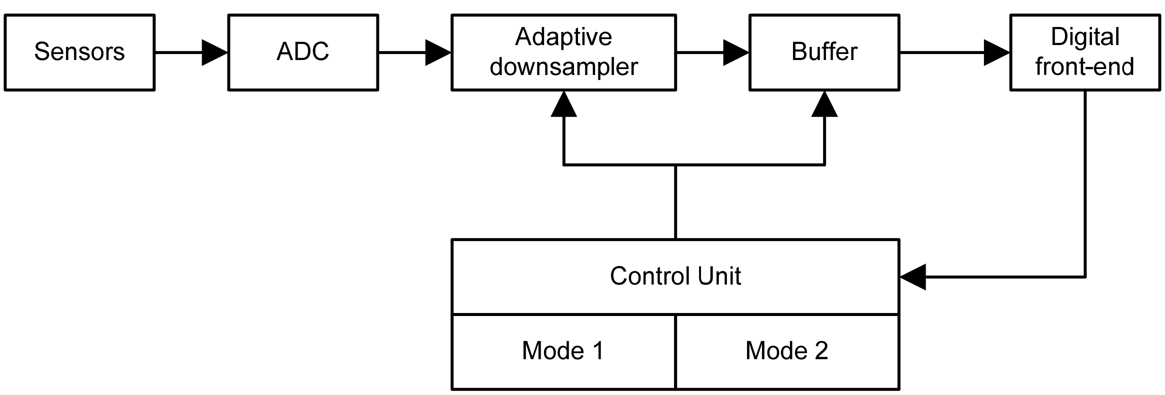

Figure 7. Block diagram of the adaptive sensor module. Mode 1 is the algorithm control mode and Mode 2 is the user control mode.

Using the algorithm control mode the data will be acquired after a certain algorithm This algorithm is stored in the flash memory of the FPGA just when the modem is implemented. The user control mode is a more sophisticated acquisition scheme and allows the user to create different acquisition scenarios and to remotely control the sampling process. The scenarios will be created based on weather forecasts, previous periodic events or different periods of the day.

7. CONCLUSIONS

This article presents an underwater acoustic modem architecture whose design is based on the underwater acoustic channel properties. For an underwater modem to transmit efficiently it must be adapted to the transmission channel. In this way the underwater modem will consume minim energy when data is transmitted through medium.

The frequency response and the weighted function are the most important properties of underwater acoustic channel. Using sound speed profiles acquired from 1890 to 1998 from the region of the Black Sea continental shelf we were able to obtain the mean sound speed profile. Then we obtained the properties of the underwater acoustic channel using the AcTUP simulation software. Based on these results and using the passive sonar equation and the frequency response of the projector and hydrophone we design the analog front-end. The digital front-end is based on the M-FSK modulation-demodulation scheme.

In this article we proposed an adaptive architecture for the sensor module. The architecture has two modes of operation: algorithm control and user control. The sensor module will permit the acquisition of information about steady and transient phenomena. In conclusion sampling adaptively will lower even more the energy consumption.

In Table 5 we summarize the cost of the proposed underwater acoustic modem. We didn’t include in the estimated cost the housing and the power supply costs.

Modem Parts	Cost (€)
Projector & Hydrophone	370 + 120
Analog Front-End	30
Digital Front-End and Sensor Module	60
Total Cost	580

Tabel 5. The estimated cost of the proposed underwater acoustic modem.

In the near future we plan to test the underwater acoustic modem in a test tank and then into the Black Sea.

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