Advanced monitoring systems for biological applications in marine environments

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ABSTRACT

The increasing need to manage complex environmental problems demands a new approach and new technologies to provide the information required at a spatial and temporal resolution appropriate to the scales at which the biological processes occur. In particular sensor networks, now quite popular on land, still poses many difficult problems in underwater environments. In this context, it is necessary to develop an autonomous monitoring system that can be remotely interrogated and directed to address unforeseen or expected changes in such environmental conditions . This system, at the highest level, aims to provide a framework for combining observations from a wide range of different in-situ sensors and remote sensing instruments, with a long-term plan for how the network of sensing modalities will continue to evolve in terms of sensing modality, geographic location, and spatial and temporal density. The advances in sensor technology and digital electronics have made it possible to produce large amount of small tag-like sensors which integrate sensing, processing, and communication capabilities together and form an autonomous entity. To successfully use this kind of systems in under water environments[2] , it becomes necessary to optimize the network lifetime and face the relative hindrances that such a field imposes, especially in terms of underwater information exchange.

Keywords: Advanced monitoring, wireless sensor networks, underwater applications

1. INTRODUCTION

To date, monitoring systems in the environment have been very limited in their temporal and spatial resolution with the exceptions being few but extremely expensive short-term undertakings. The multidisciplinary area of such a project brings together concepts of wireless communications and ad hoc networking, low-power hardware design, signal processing, distributed computing, and embedded software design, and needs to develop technologies for sensing, in-situ sensor configuration, data capture and storage, data collection and transmission, data storage, multi-sensor data fusion, data presentation and visualization, and for analytical mode checking[3] . The established system is intended to cover a range of issues in environmental sustainability, including those related to phenomena such as climate change, as well as more specific areas such as water quality and elements of marine ecology. They should also cover a range of locations including waterways, coastal waters, reefs, and oceanic sites. The network seeks to operate at multiple scales so that its data collection, analysis, and synthesis are consummate with the nature of the environmental management and research questions of concern. The system is designed to incorporate existing technologies, but will also include new indigenous ICT and sensor technologies such as RF underwater transmission and communication systems, micro- and nano-sensors, and interactive user defined data analysis models and testing platforms. Current research focuses on the development of efficient signal processing algorithms, multi-user communications in the presence of interference, and design of efficient modulation and coding schemes.

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2. MONITORING SYSTEM

The growing attention from the scientific community to the environment and its safety requires always better instruments to collect and analyze environmental data. In this work we focus onto a particular case, the Great Barrier Reef health research. A measurement system to easily retrieve physical and chemical data from underwater sensors is needed. Up to now these data are obtained from single data loggers deployed and wired according to the particular necessities, and finally collected from the sea floor. This method presents three main drawbacks. At first, deploying and collecting the devices takes a not negligible amount of boat time. On second place, is needed to act directly on each device to change the data acquisition mode. At last, underwater wirings are a weak link, because they are most likely to undergo corrosion, water infiltrations, and damages due to wildlife, and because they need complex maintenance. The solution to these problems is a measurement system which is permanently deployable, capable to communicate with a base station on mainland, and which requires a few wirings: in other words, a wireless system. An underwater communication technology based on ultrasound transmission is feasible[4] , but its cost is high, and its efficiency is strongly dependent upon the geometry of the sea floor, on the environmental acoustic noise level, and on the presence of rocky and reflecting obstacles. In order to overcome these problems, which are most likely to occur on the Great Barrier Reef, we conclude that the use of radio frequency communication can represent a better option in this context. The propagation is not strongly influenced by obstacles, and the cost of a radio frequency transceiver is much lower than the acoustic modem one. Thus in this work, starting from general observations, calculations of attenuation for EM waves through seawater are performed. The results will be compared with seawater field tests.

3. ULTRASOUND UNDERWATER COMMUNICATION TECHNIQUE: PROBLEMS AND HINDRANCES

Ultrasonic underwater communication devices are already off the shelf, and are successfully employed in several applications such as seafloor to surface communication and open sea ship to submerged device data exchange. The transmitter emits, through an ultrasonic transducer, a modulated sound wave, and the receiver transforms the sound wave into an electric signal through a similar device[5] . Even if ultrasonic modems can be successfully used in open sea applications to communicate over distances that may reach 10 km, their performance is tremendously reduced while operating in shallow water and coastal environments, as shown in figures 1-2. This happens because of sound wave multiple sea floor and surface reflection which produces multipath propagation and consequent inter-symbol interference. These phenomena increase their effects in shallow water environments, where the need of performing underwater communication for sensor networks is greatest. Together with echoing and multipath

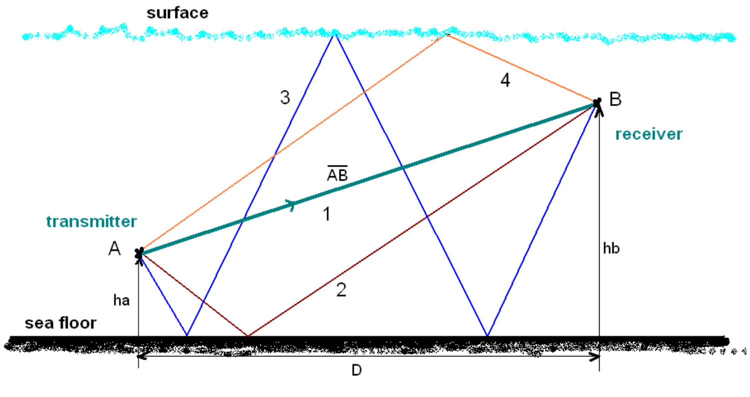

Figure 1. Multipath scheme in underwater communication

propagation, high levels of surface and snapping shrimps wideband noise are found, thus increasing ultrasonic communication difficulties and sometimes making a link quite impossible to obtain, because of solid obstacles such as rocks or coral reefs interfering with the sound wave path. Due to all these aspects, ultrasonic modems become difficult and sometimes impossible to operate in a shallow water environment. The attempt to cancel transmission errors through sophisticated modulation algorithms makes the devices cost to rise and both their software and hardware structures to grow in complexity and power consumption, thus asking for a suitable and cost effective alternative for shallow water short distance communication applications. This alternative can be offered by radio frequency communication, which shows to be competitive in this application branch as reported in the next sections.

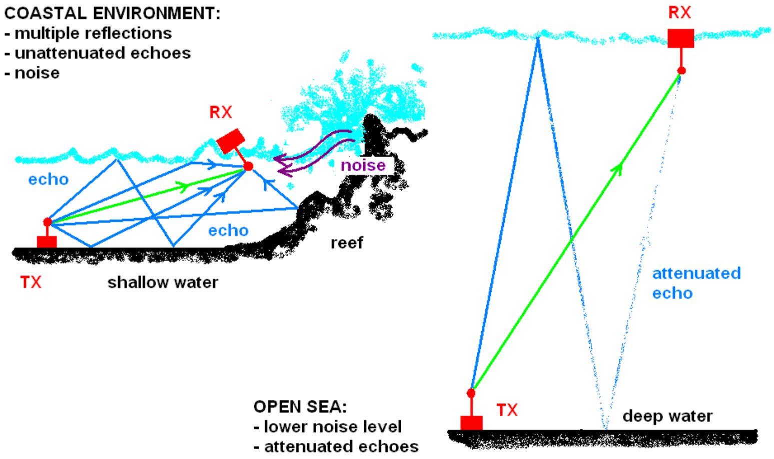

Figure 2. Example of multipath in both shallow and deep water

4. RF UNDERWATER COMMUNICATION: THEORETICAL ANALYSIS

This novel underwater communication technique is based on the propagation of an electromagnetic wave. Since water (and sea water in particular) is a conductive medium, the attenuation due to eddy currents must be considered in order to find out the maximum distance between transmitter and receiver that keeps the signal still intelligible. The source of the electromagnetic wave is an alternate voltage applied to an antenna submerged in the water. The electromagnetic field generates eddy currents in the water, therefore causing an attenuation that is variable with both frequency and conductivity. Providing a frequency lower than approximately 1 MHz for fresh water and 100 MHz for sea water we can calculate[6] the attenuation α due to eddy currents by means of this approximated formula:

$$\alpha = 0.544 \cdot \sqrt{f \cdot \sigma} \tag{1}$$

where f is the frequency, expressed in kHz, and σ is the water conductivity, expressed in S/m (note that for sea water we assume a $\bar{\sigma} = 5$ S/m, and for fresh water $\bar{\sigma} = 0.06$ S/m). The attenuations for both fresh and sea water are shown in the figure 3.

Off the shelf RF RSSI (Received Signal Strength Indicator) ICs provide a sensitivity that can reach approximately 1 to 10 μV, therefore we can assume in the present discussion this voltage to be the lower threshold for a received signal to be detected. This value range corresponds to a level placed between -120 and -100 dBV. Assuming an average signal level of -110 dBV, it is possible to state that, for 0.1 V on the transmitter electrodes, that corresponds to -20 dBV, the threshold attenuation is 90 dB. Given this particular attenuation, it is possible to plot the maximum linkable distance as a function of transmission frequency in both fresh and sea water.

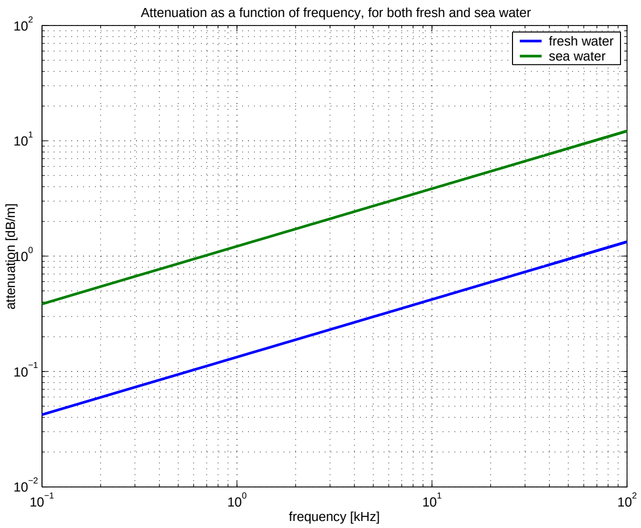

Figure 3. Attenuation as a function of frequency for both fresh and sea water.

The whole attenuation that the electromagnetic signal undergoes, including the path loss term, is:

$$attenuation = 0.544 \cdot d \cdot \sqrt{f \cdot \sigma} + 20 \log \frac{4\pi \cdot d \cdot \sqrt{f \cdot \sigma}}{100} \qquad [\mathrm{dB}] \tag{2}$$

since the wavelength λ in a conductive medium is:

$$\lambda = \frac{100}{\sqrt{f \cdot \sigma}} \qquad [\mathrm{m}] \tag{3}$$

where the units and the limit frequencies are the same as before. To obtain the 90 dB signal attenuation distance, that is the estimated maximum linkable distance, it is sufficient to pose:

$$0.544 \cdot d \cdot \sqrt{f \cdot \sigma} + 20 \log \frac{4\pi \cdot d \cdot \sqrt{f \cdot \sigma}}{100} = 90 \qquad [\mathrm{dB}] \tag{4}$$

and to solve for the distance d as a function of both frequency f and conductivity σ. The result can be seen in figure 4.

Although the maximum linkable distance in seawater is between about 10 and 100 meters depending on the frequency, it has been regarded as feasible for shallow water monitoring networks. In the following section higher frequencies (840 kHz) have been analyzed in order to verify the accordance between experimental results and the above reported equations.

5. EXPERIMENTAL RESULTS

Experiments have been conducted to test the theoretical results given in Section 4. These experiments consisted in measuring the voltage on an antenna submerged in the water, located at a variable distance from another one that was fed with an alternate voltage at the frequency of 0.84 MHz. The purpose of this experiment was to compare the voltage on the receiving device to the theoretical prediction. In particular, the calculated attenuation was compared to the measured signal strength decay, and the shown results correspond to the theoretical predictions.

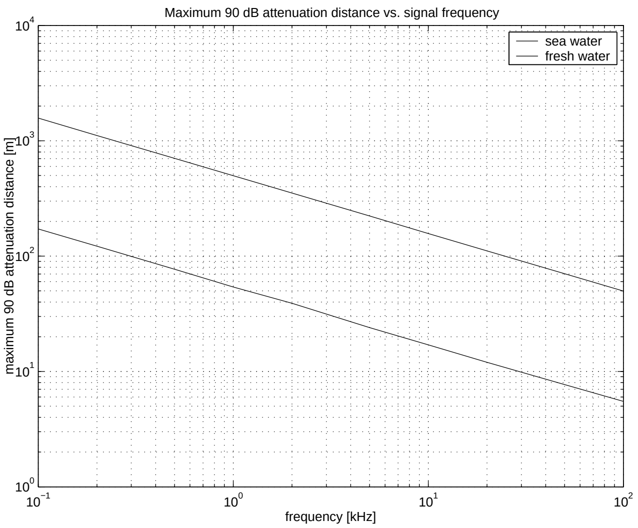

Figure 4. 90 dB attenuation distance over different frequencies

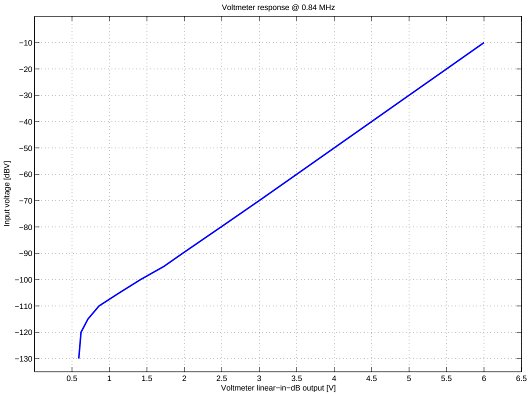

Figure 5. Voltmeter characteristic curve

5.1. Experimental setup

As explained above, an alternate voltage generator and an RF logarithmic voltmeter were needed. The generator consisted of a kHz to MHz range oscillator, capable to drive 1 W power. As stated above, seawater has an average conductivity $\bar{\sigma} = 5$ S/m. This value may vary according to temperature, location, depth and weather conditions, but has been previously verified that a change of ± 30% does not affect the reliability of the experiments. The voltmeter was capable, as shown in figure 5, to give an output signal exactly proportional to the dBV level of the input signal, provided its amplitude was greater than about -110 dBV, equivalent to a voltage of 3.2 μV. This limit is imposed by the noise figure of the circuitry employed and the graph reported in figure 5 is the result of a laboratory characterization of the instrument.

This performance has shown to be widely satisfactory for the experiments conducted. We want to remark that at the moment an off-the-shelf measurement system cannot be used due to its size, to the difficulties risen in finding a suitable and safely sealed container and in obtaining a power grid connection in an off-the-field situation.

5.2. Sea water experiments

The trials have been conducted in a sea water environment. The generator output power was 1 W and the results of the experiment are shown in figure 6. As can be seen, the theoretical attenuation (calculated by means of the previously obtained formulas) is in good accordance with experimental data. We can calculate the per-unit attenuation, the wavelength and the 90 dB attenuation distance by using the following equations:

$$attenuation = 0.544 \cdot d \cdot \sqrt{f \cdot \sigma} + 20 \log \frac{4\pi \cdot d \cdot \sqrt{f \cdot \sigma}}{100} = 35.3 \cdot d + 20 \log d + 18.2 \text{ [dB/m]} \quad (5)$$

$$wavelenght = \frac{100}{\sqrt{f \cdot \sigma}} = 1.54 \quad \text{[m]} \quad (6)$$

$$0.544 \cdot \bar{d} \cdot \sqrt{f \cdot \sigma} + 20 \log \frac{4\pi \cdot \bar{d} \cdot \sqrt{f \cdot \sigma}}{100} = 90 \quad \text{[dB]} \quad \Leftrightarrow \quad \bar{d} = 1.9 \quad \text{[m]} \quad (7)$$

where $f = 840\ [kHz]$ and $\sigma = 5\ [S/m]$.

The slight difference in the steepness is due to a difference between the real and assumed salinity of the water site the experiment was conducted in. Since the experiment was performed in a dock area, the conductivity could have been greater than in open sea either because of greater salinity due to greater evaporation, or because of a higher concentration of pollutants. In fact, it is possible to see in the diagram reported in figure 6 that the theoretical curve is less steep than the experimental ones, thus proving that the measured attenuation was slightly higher than the theoretical one, probably because of the higher concentration of solutes in the dock water.

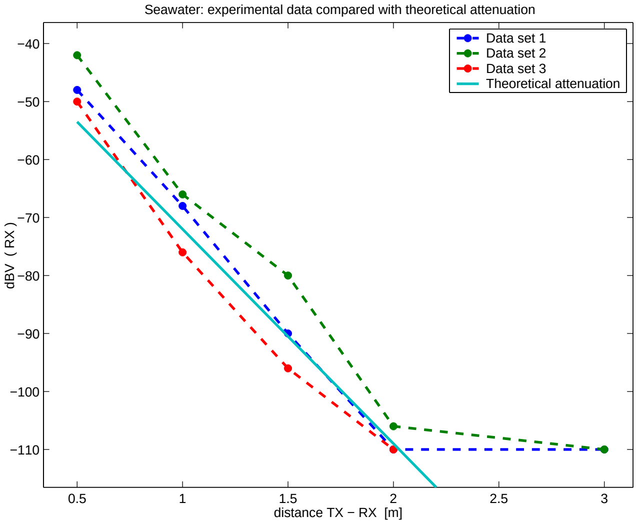

Figure 6. Conductivity tests for different experimental environments

6. UNDERWATER COMMUNICATION TECHNIQUE: FURTHER DEVELOPMENTS

As can be stated by the analysis of the theoretical analysis and experimental results, underwater radio frequency communication can be successfully used if the frequency of the employed signal is chosen accordingly to the maximum distance needed for the communication to be operated. The maximum linkable distance and the operation frequency are inversely proportional, as it is shown by the graph in figure 4. In order to develop an underwater sensor network, this must be taken into account, because a lower frequency allows a greater distance between nodes to be chosen, that means a lower node density, but forces the data rate to be lower. On the other hand, a higher frequency gives the possibility to achieve a higher data rate, but the node density is forced to be higher. Node density is also affected by the required measurement spatial accuracy, and by the presence of physical obstacles on the link path, that force for example two clusters of sensors to be more distant. Another challenging issue regarding underwater sensor networks is the power consumption. Data transmission and collection time affect the *on status* time of each node. Therefore, for a given data volume to be exchanged throughout the network, a higher data rate means a lower *on status* for each node, but also a higher frequency and therefore a lower maximum transmission distance. This means that for a message to be forwarded along a fixed distance, a greater number of nodes must be employed because they are closer, and therefore on average each node in the network must handle a greater number of packets.

7. CONCLUSION

Wireless sensor networks are a class of distributed communication and computing systems that provide network connectivity for a variety of sensing devices. This emerging field is a multidisciplinary area that brings together concepts of wireless communications, ad hoc networking, low-power hardware design and signal processing. Today advances in sensor technology, wireless communications, and digital electronics make it possible to produce large amount of small-size, low-cost sensors which integrate sensing, processing, and communication capabilities together and form an autonomous entity. The advantages are evident not only in the reduction of size, but also in the increase of functional performance and reliability, and a unit-cost reduction in high-volume batch processing. Such wireless sensor networks can be used in many new applications, ranging from industrial sensing to environmental monitoring, performing an automated continual or discrete monitoring. While sensor networks have now become very popular on land, the underwater environment still poses some difficult problems. This paper presents a review of recent results and research problems in underwater communications and several fundamental key aspects of RF channel are investigated. We described the challenges posed by the peculiarities of the underwater communications with particular reference to monitoring applications for the marine environment and in this direction possible solution approaches are outlined.

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