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Abstract—Conventional wireless sensor networks (WSNs) are increasing in use; however, not all environments can support the typical wireless sensor model, which utilizes RF as a communication medium. Hostile sensing and communication environments, such as underwater and subterranean, require the practical use of other methods. In particular, the underwater domain has necessitated the use of acoustics to enable communication in underwater WSNs. Previous work in this area consists of sensor nodes built with bulky, costly acoustic modems. In contrast, we present the low cost, small form factor CORAL testbed, which consists of piezo-transducers, a microcontroller-based architecture and interface circuitry. We illustrate the operation of a prototype, show the performance in various environments, and explain its integration into a micronode for underwater WSNs. We conclude with a discussion on the results, limitations, and challenges, as well as a discussion on potential applications.

I. INTRODUCTION AND BACKGROUND

The objective of wireless sensor networks is to gather data about the state of an environment and of the interaction of its components remotely and efficiently [1]. To that end, a group of individual, distributed sensor nodes is deployed and connected, often in an ad-hoc fashion. Each of these nodes typically consists of five subsystems: control and timing, communication, networking, sensing, and power. Each subsystem is often designed and implemented in parallel with others due to the degree of interdependence between subsystems, as well as overall engineering and economic constraints.

Most sensor nodes, and therefore most sensor networks, are tailored to a specific application [2]. Consequently, each of the five subsystems has to be designed for a particular task. The power subsystem, for example, has to be fabricated with certain longevity and reliability specifications in mind. Similarly, the communication subsystem must be designed for a particular application given specifications for range, signal strength, antenna type and length, frequency band, and underlying media.

In an underwater environment, a typical RF-based communication subsystem would not be appropriate due to the fact that antennas (of a fairly large length) would be needed to communicate efficiently at Kilohertz frequencies. Furthermore, these antennas would be power-intensive. In a sensor network world, where nodes are miniaturized, both size and power are at a premium.

Therefore, to communicate effectively underwater, another medium must be considered. Acoustic communication is a particularly good candidate since it closely mirrors standard RF communication. Previous research done in this area has shown that, while there are significant challenges, acoustic communication is fairly suitable for this task [3].

II. CORAL DESIGN

CORAL stands for Common Object Remote Acoustic Link, and it is specifically designed to be the communication subsystem for a node and a base in a hostile environment sensor network paradigm. The “Common Object” segment of CORAL signifies that CORAL is not designed for a particular sensor. Rather, it is a prototype designed to show that a modular acoustic communication subsystem could easily be integrated with other subsystems in an application-centered, underwater WSN.

CORAL essentially consists of two components: a transmitter and a receiver. Normally, one would want communication to be bi-directional – the node should be able to listen as well as talk (and vice-versa for the base). However, within an acoustic frame of reference, difficulties arise with ensuring that both components do not transmit and receive at the same time. This is partially due to the modulation of a digital or near-digital signal into an analog one, as will be shown later. Because of this, the first implementation of CORAL simply features the node as a continuous transmission mechanism and the base as a continuous receiving mechanism (Fig. 1).

Figure 1. Overall Schematic of CORAL.
A. Acoustic Transducers

The heart of CORAL lies in the acoustic transducers used to achieve the basic communication. These comprise the underlying “physical layer” that any communication channel must have [4]. The acoustic transducers were of an ex-USN (US Navy) design and specification. Due to the nature of these components, most of the operating specifications were found experimentally rather than in a component data sheet. The characterization of the transducers will be described in the Results section along with the performance of the system.

B. Transmitter Circuitry

One of the core requirements for CORAL, as mentioned above, was that it should be able to interface seamlessly with other subsystems as part of an integrated node. With this mind, the only required condition for CORAL was that the input be modulated digitally, in order to accurately simulate input or timing signals from other subsystems of a wireless sensor node. The transmission interface circuit consisted of a microcontroller, a power MOSFET, an amplification gain stage and an acoustic transducer.

This interface circuit was constructed on a prototype board and was shown to transmit effectively within a certain distance. Fig. 2 shows the transmission of a clock pulse, as sensed by a receiver underwater at a frequency of 1.5 Hz.

C. Receiver Circuitry

As Fig. 2 shows, when a transmitted signal was received, an interesting phenomenon was noted. The digital signal was modulated into analog waveform – the result of harmonic loss in the channel caused by interference in the environment as well as the frequency response of the transducers.

Because of this modulating effect, the receiving circuit had to be specialized. However, in this, there were two options – a quasi-digital receiver, as well as an ADC dependent receiver. The first type of circuit consisted of a variable gain stage, a rectifier and a filter stage, and a secondary conditioning gain stage. In the second circuit, an ADC was connected after an initial gain stage and with an optional rectifier stage. The schematic of the quasi-digital interface receiver is shown in Fig. 3.

The goal of the quasi-digital receiver was to “recover” a digital signal from a near-analog waveform, thereby insulating the subsystem from environmental effects and showing that the node could operate in low power (ADC and microcontroller both unpowered) conditions.

Figure 3. Schematic of Quasi-Digital Receiver Circuit.

The alternate ADC dependent circuit was microcontroller based much like the transmission circuitry. The receiving transducer was connected to a gain stage, a filter stage, and then to a microcontroller-based sample-and-hold ADC (TI MSP430 was the microcontroller used).

III. ENVIRONMENT SPECIFIC RESULTS

In wireless sensor networks, tailoring the communication subsystem implies maximizing the signal and the transmitted distance while minimizing noise, power, and frequency range (for sensitive uses). In order to verify the performance of the prototype, the transducers and corresponding circuitry were tested in air (for benchmarking) and under water.

A. Atmospheric Results

The optimum operating frequency of the transducers in air was found empirically to be approximately 25 kHz. The maximum reception distance (as denoted by a recognizable waveform at the frequency of transmission) was found to be approximately 155 cm at the optimum frequency. This distance is short, due to limitations of sensor node power output (5 Volt, 1 Watt limitation) and impedance mismatch between the piezo-element and air medium, as well as limitations in the testing facilities available.

The noise floor in air was 25 to 30 dB below the signal level, thereby limiting efficiency of communication. The signal to noise ratio (SNR) at the optimal frequency of 25 kHz was found to be approximately 20.2. The SNR changed drastically with the frequency the transducers were operated at, verifying that the system does indeed have an optimal operating point (Fig. 4).

Figure 4. SNR v. Frequency Plot in Air.
As shown by Fig. 2 previously, harmonic loss meant that the signal transmitted in the air looked distinctly different than the intended digital pulses, which consisted of clock signals or discrete ASCII characters (simulation of microcontroller produced output in a real sensor node).

The frequency response of the transducers constrained the effective bandwidth to a very narrow range, from 23 to 25 kHz – the region where a high SNR made effective transmission and reception possible.

**B. Underwater Results**

1) **Test Setup**

The testing of the CORAL prototypes and the individual transducers underwater was conducted in a shallow water tunnel (Fig. 5), with the interface circuitry, power sources, measurement and automation devices off to the side.

![Figure 5. Underwater Testing Setup.](image)

2) **Performance**

An optimal operating frequency of 1.7 kHz was found for the operation of transducers in shallow water. The noise floor in water was 50 dB below the signal level thereby allowing for more efficient reception than in air.

At 20 cm., the transmission efficiency (in percent signal received) was approximately the same efficiency observed at very short distances (1-2 cm). By simple extrapolation, one could theorize that the attenuation of the transmitted signal in shallow water is very low over large distances. However, as the testing distance is increased, near-field attenuation models do not hold. Therefore, finding the exact range of the transducers underwater would require an enlarged test facility. However, under power and signal constraints, and considering the efficiency decay and the $1/r^2$ decay in acoustic field strength, we estimate that a range of 5-10m. is not unreasonable from the CORAL subsystem.

The frequency response of the transducers is significant underwater since the communication efficiency (measured in terms of SNR) improves dramatically when operating near the optimal frequency (Fig. 6).

![Figure 6. SNR v. Frequency Plot Underwater.](image)

**IV. DISCUSSION**

A. **Environment Comparison**

As mentioned previously, acoustic communication is thought to be especially suitable for underwater environment. This fact was verified by testing CORAL in both environments, and comparing the performance of CORAL underwater to CORAL in air (Fig. 4 and Fig. 6 respectively).

The difference in SNR for the two environments is significant, with the peak SNR differing by a factor of 10. This difference is due to impedance differences in the medium. A large mismatch between the air and piezo interface causes reflection into the piezo element, while a smaller mismatch between water and the piezo interface allows more energy to be transferred into the water medium, thereby allowing greater range and higher SNR at a given power.

B. **Power Consumption**

The power consumption is a function of the signal voltage applied, with the overall response being nonlinear and shown in Fig. 7.

![Figure 7. Power v. Signal Voltage.](image)
In order to demonstrate a low power system, a signal voltage of 5 V was used. In atmosphere, an effective range of 155 cm. was achieved at the optimal frequency (SNR ~ 20). Underwater, at the optimal frequency, an SNR of near 250 is possible. Using constant power and SNR as a means of estimation rather than the decay of transmission efficiency as used before, the estimated effective range increases from 5-10 m. predicted before to 20 meters. Of course, a formal experiment would be needed to ascertain the range conclusively, but an effective low-power underwater range on the order of 5-20 meters would make CORAL an invaluable component in many underwater WSNs.

V. APPLICATIONS

A. Lateral Line and Flow Sensing

One of the primary applications of CORAL being researched is the integration of CORAL with MEMS flow sensors [5] to form a lateral line configuration. A lateral line is a sensory organ found in many aquatic animals that allows the organisms to perform flow sensing in the near-field [6]. This information is then used to make vital decisions on catching prey, avoiding predators, navigation, etc. Mimicry by artificial sensors would enable many applications such as UUV (Unmanned Underwater Vehicle) guidance, flow calibration, and advanced submarine sensing.

However, for this to be effective, an artificial lateral line must consist of an array of sensors. In fact, multiple artificial arrays may be needed for an accurate flow-imaging scenario. In such an array, the arrays (which would have on-chip control and processing circuitry) would need a communication subsystem robust enough to handle small streams of data without consuming much power or producing a large footprint. CORAL would be an ideal subsystem for a “lateral-line” micronode – which is actively being researched. A schematic of the possible integration between CORAL and artificial lateral line is depicted in Fig. 8.

![Figure 8. Potential Integration of CORAL with Lateral Line Sensors.](image)

B. Undersea Environment Monitoring

Another potential application of CORAL lies in the creation of portable acoustic devices that can be used to communicate with stationary acoustic beacons placed underwater. This would allow the monitoring of large environments (lakes, seas, and possibly ocean sections) with relatively small amounts of hardware. Data collected in this fashion could be used to predict natural disasters such as undersea earthquakes, tsunamis, and volcanoes, as well as perform environmental or military measurements.

VI. CONCLUSION

The prototype CORAL system was designed to demonstrate that construction of a miniature acoustic communication system for underwater WSN applications is possible. CORAL has its limitations but also its successes. It was shown to transmit in air and underwater at various optimal frequencies, and to take data to be transmitted from a microcontroller. Power consumption, signal strength, and noise were effectively measured at the reception point, showing that WSN node operation underwater is feasible. Conversion of the signal to relevant data at the receiving point was attempted by two low-power receiver interface circuits, but more work is required to increase communication accuracy and efficiency. Various characteristics of the environment such as harmonic loss, acoustic reflections, and medium noise limited the performance of the interface circuitry and pose a fundamental challenge. These are issues that need to be solved before CORAL can be practically deployed. However, considering that existing underwater nodes are large and expensive, and one of the priorities is to develop miniature and inexpensive systems [7], CORAL is very promising.

ACKNOWLEDGMENTS

The authors would like to acknowledge the support of colleagues in the MASS Group as well as the support of their families. The authors would also like to thank the project sponsors and various funding sources.

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