Software Acoustic Modems for Short Range Mote-based Underwater Sensor Networks

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Abstract— **Most recent work in underwater network development has relied on using expensive commercial acoustic modems or on building custom transceivers for each application to establish acoustic communication links among the sensors. Using commercial modems or designing custom hardware may require prohibitive monetary or time investment for many applications. Our work proposes the design of software acoustic modems that can utilize built-in microphones and speakers on the relatively cheap Tmote Invent platforms. The built-in Tmote hardware and the software modem enable acoustic communication in a short range shallow water network. In this paper, we present the initial design and architecture of our acoustic communication system which targets environmental monitoring applications. Our experiments with generic acoustic hardware to profile this underwater communication channel reveal that the channel favors frequencies below 3Khz, a result which guides the design choices for our FSK software modem. We perform experiments with our software modem/generic hardware system to explore the system's data transfer capability. The data communications experiments confirm the system's capability of transferring information in the order of tens of bits per second for a communications range of up to 10 meters.**

I. INTRODUCTION

Recent improvements in the processing power, memory size, form factor, and battery consumption of sensor modules have fueled increased interest in the development and deployment of underwater acoustic sensor networks. The diversity in the potential application space for underwater sensor networks has led to related projects with a wide range of design requirements. For example, Vasilescu et al. [1] propose a network that combines acoustic and optical communications, stationary nodes and AUV's for monitoring coral reefs and fisheries with ranges in the order of hundreds of meters. In another project, Heidemann et al. [2] propose the use of stationary Stargate modules for applications such as seismic monitoring and equipment monitoring with ranges of about 500m.

Most underwater acoustic sensor network efforts rely on specialized hardware for modulating, transmitting, receiving and demodulating acoustic signals. The specialized modulation hardware ranges from expensive commercially available acoustic modems [3, 4] to dedicated integrated circuits [1] and dedicated DSP boards [5, 6]. The communication hardware ranges from specialized underwater acoustic transducers and hydrophones [2] to off-the-shelf speakers and microphones [1]. The use of specialized hardware for establishing acoustic communications underwater typically increases the network cost, the design time and effort spent in interfacing node hardware components, and the size and weight of individual network nodes.

In the past, low processing speeds dictated the use of specialized hardware for underwater acoustic modulation. An alternative approach to hardware modems is the implementation of acoustic modulation and demodulation in software, as suggested in [7] for aerial acoustics. Recent advances in miniaturization and circuit integration have yielded smaller and more powerful processors that are capable of efficiently running acoustic modulation and demodulation software. The transmission and reception of the software modulated acoustic signal can also avoid using specialized hardware by exploiting generic speakers and microphones.

Eliminating the need for specialized hardware for acoustic communication greatly reduces the cost of network nodes, facilitating the dense deployment of motes to form underwater acoustic sensor networks. Within this context, the work described in this article is part of a project to deploy a short range shallow water network to monitor pollution indicators in Newport Bay, CA [8] and to provide the data to environmental engineers in near real time. We expect the network to consist of general purpose sensor modules that use software modems and generic hardware to communicate acoustically and send the data to the base station.

For our application, we have selected mote-class computers, which are powerful enough to perform the limited in-network processing and are affordable enough to enable the deployment of a dense network at reasonable cost. In particular, we have selected the Tmote Invent module, from Moteiv Corp. [9], which has an on-board SSM2167 microphone from Analog Devices sensitive to 100Hz to 20kHz, and an on-board TPA0233 speaker amplifier from TI with an 8 ohm speaker that has a range of 400Hz to 20kHz. We intend to exploit the on-board microphone and speaker to establish short range acoustic links among Invent modules.

In this paper, we explore the fundamentals of underwater acoustics in order to profile the channel and to design software acoustic modems that can run on a general purpose mote

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modules, such as the Tmote Invent unit. We also investigate the acoustic communication capability of the system consisting of the software modems and the generic speakers and microphones in the underwater environment.

The remainder of this paper is organized as follows. Section II discusses the related work on both hardware and software acoustic underwater modems. Section III presents the basic principles and relationships governing acoustic signal propagation in water. Section IV addresses our experiments to evaluate the underwater performance of the communication system, consisting of the generic acoustic hardware and the software modems. Our initial medium profile experiments enable the design of a simple FSK modem, which we subsequently use to evaluate the data transfer characteristics of our acoustic underwater communication system. Section V concludes the paper.

II. RELATED WORK

Acoustic underwater communication is a mature field and there are several commercially available underwater acoustic modems [3, 4]. The commercially available acoustic modems provide data rates ranging from 100 bps to about 40 Kbps, and they have an operating range of up to a few km and an operating depth in the range of thousands of meters. The cost of a single commercial underwater acoustic modem is at least a few thousand US dollars. The prohibitive cost of commercial underwater modems has been an obstacle to the wide deployment of dense underwater networks, until the recent development of research versions of hardware acoustic modems.

Researchers at the Woods Hole Oceanographic Institution are developing a Utility Acoustic Modem (UAM) as a completely self-contained, autonomous acoustic modem capable of moderate communication rates with low power consumption [6]. This modem uses a single specialized DSP board with on board memory and batteries. The purpose of developing the UAM is to make a more affordable acoustic modem available for the research community. Researchers at UC, Santa Barbara are also developing a hardware acoustic underwater telemetry modem [5] for ecological research applications, using a DSP board with custom amplifiers, matching networks, and transducers. Their modem is intended for interfacing to nodes in an underwater ad hoc network, and it achieves a 133 bps data rate. Whereas both of the efforts reported in [6] and [5] aim at making underwater acoustic modems cheaper and more accessible by developing specialized affordable hardware, our work aims at driving the cost even lower and at making acoustic underwater communications even more accessible through the development of software acoustic modems that can operate on generic hardware platforms.

The work in [1] uses generic microphones and speakers along with a specialized integrated circuit that generates ASK or FSK modulated sound signals in order to demonstrate the acoustic communication capability underwater. Vasilescu et al. achieve a bit rate in the order of tens of bits per second up to about 10 to 15 meters. Our work resembles their work in the use of generic microphones and speakers for acoustic communications, but our work differs in its implementation of software modems with a generic platform rather than a specialized integrated circuit.

With the rapid increase in processor speeds, the idea of implementing acoustic modems in software became feasible. Coupling software acoustic modems with the use of microphones and speakers for transmission and reception can eliminate the need for specialized hardware for acoustic communication, trading off increased processing activity for reduced node cost. The cost of software acoustic modems is limited to the development cost. Because of these attractive features, researchers have started exploring software acoustic modems for aerial acoustic communications. Lopes and Aguiar [7, 10] have investigated using software modems for aerial acoustic communications in ubiquitous computing applications. Building on their results, our work here proposes software acoustic modems for underwater communication in order to eliminate the need for specialized hardware in underwater communications, thereby encouraging wider deployment of underwater sensor networks.

III. UNDERWATER ACOUSTICS

A. The Passive Sonar Equation

The passive sonar equation [11] characterizes the signal to noise ratio (SNR) of an emitted underwater signal at the receiver:

$$SNR = SL - TL - NL + DI \tag{1}$$

where SL is the source level, TL is the underwater transmission loss, NL is the noise level, and DI is the directivity index. All the quantities in Equation 1 are typically in $dB\ re\ \mu Pa$, where the reference value of 1 μPa amounts to $0.67 \times 10^{-22}\ Watts/cm^2$ [11]. However, we will use the threshold of human hearing at $10^{-12}\ Watts/m^2$ as the reference power density level, in order to put the results in perspective relative to the typical aerial response of our generic hardware. In the rest of the paper, we use the shorthand notation of dB to signify $dB\ re\ 10^{-12}$, unless otherwise mentioned.

The directivity index DI for our network is zero because the generic speakers we use are omnidirectional. Note that establishing a certain mechanism for directing the acoustic energy emitted from the speakers could significantly improve signal quality, as described in [12] for directive hydrophones.

B. Transmission Loss

The transmitted signal pattern has been modelled in various ways, ranging from a cylindrical pattern to a spherical one. The following expression governs acoustic signal propagation in shallow water [11]:

$$TL = 10 \times \mu \log d + \alpha d \times 10^{-3} \tag{2}$$

where d is the distance between source and receiver in meters, α is the frequency dependent medium absorption coefficient in dB/km, and TL is in dB. The variable μ depends on the signal spreading pattern. If the acoustic signal spreads in all directions from the sound source, then μ is equal to 2. If the acoustic signal signal spreads in a cylindrical pattern from the source (as is the case signals propagating along the surface or ocean floor), then μ equals to 1. In shallow water cases, the value of μ lies somewhere between 1 and 2, depending on the depth.

Equation 2 indicates that the transmitted acoustic signal loses energy as it travels through the underwater medium, mainly due to distance dependent attenuation and frequency dependent medium absorbtion. Fisher and Simmons [13] conducted measurements of medium absorbtion in shallow seawater at temperatures of 4^oC and 20^oC. We derive the average of the two measurements in Equation 3, which expresses the average medium absorption at temperatures between 4^oC and 20^oC:

$$\alpha = \begin{cases} 0.0601 \times f^{0.8552} & 1 \le f \le 6 \\ 9.7888 \times f^{1.7885} \times 10^{-3} & 7 \le f \le 20 \\ 0.3026 \times f - 3.7933 & 20 \le f \le 35 \\ 0.504 \times f - 11.2 & 35 \le f \le 50 \end{cases} \tag{3}$$

where f is in Khz, and α is in dB/Km.

Through Equation 3, we can compute medium absorbtion for any frequency range of interest. We use this value for determining the transmission loss at various internode distances through Equation 2.

C. Source Level

The transmitter source level (SL) of underwater sound relates to signal intensity I_t, which in turn depends on the transmission power. Given the transmission power P_t, the transmitted intensity of an underwater signal at 1 m from the source can be obtained through the following expression [11]:

$$I_t = \frac{P_t}{2\pi \times 1m \times H} \tag{4}$$

in $Watts/m^2$, where H is the water depth in m.

The source level SL of the underwater acoustic signal indicates the relative amplitude of the signal to the reference. Thus, we have the following equation for obtaining the source level relative to the threshold level of human hearing:

$$SL = 10\ log(\frac{I_t}{10^{-12}}) \tag{5}$$

D. Noise Level

Factors contributing to the noise level NL in shallow water networks include waves, shipping traffic, wind level, biological noise, seaquakes and volcanic activity, and the impact of each of these factors on NL depends on the particular setting. For instance, shipping activity may dominate noise figures in bays or ports, while water currents are the primary noise source in rivers. In a swimming pool environment, the main sources of underwater noise are swimmers, vibrations from people walking near the pool, and water pumps.

IV. PERFORMANCE EVALUATION

This section describes our experiments to explore the underwater acoustic communication capability of generic desktop PC speakers [1]. We have selected Sony SRS-P7 [14] PC speakers and Labtec PC microphone [15], both of which are cheap off-the-shelf components. In order to waterproof the speakers and microphones and still maintain most of their acoustic properties, we have placed each of them inside vinyl membrane containers. We sealed the vinyl containers around the wires of the components with electric tape to prevent water leakages into the components.

For our experiments, we used two laptops, with one laptop attached to the speakers acting as a sender, and another attached to the microphone acting as a receiver. The microphone and speakers are placed inside a controlled water environment at a depth of about 50 cm, while the wires and the laptops remained outside the water. To test our design for simple FSK modulation and demodulation, we conducted two sets of underwater experiments: (A) experiments to profile the medium's frequency response; and (B) experiments to evaluate data transmission capability.

A. Medium Profiling

Our application has unique channel characteristics that differ from underwater channels that appear in the related literature [11, 16–18]. First, our channel is not limited to the underwater medium. Our channel also includes the generic speakers and microphone, whose response and coupling with the underwater environment is unknown. In addition, our channel includes the vinyl membranes which may amplify or attenuate certain frequencies.

In an earlier study on aerial acoustic communications [19], we had determined that PC speakers and microphones have the best response at frequencies up to about 7 KHz. Building on that result, we have limited our analysis of the underwater channel profile to the frequency range from 400 Hz to 6700 Hz at 100 Hz increments. Each frequency tone is sent in a square signal for a duration of 1 second, and the full signal consists of a sequence of the square signals separated by guard times.

To obtain the signal quality of each frequency f_i of a signal received from distance d_j meters away, we apply a 100 Hz Equiripple [20] band pass filter centered at f_i to the received signal. The filtered signal shape includes the transmitted tone at f_i along with all the background noise within the frequency range $f_i - 50$ to $f_i + 50$. The background noise is distinguishable in all the temporal components of the signal during which the tone at f_i is not transmitted. Through this filtering process, we can obtain the signal to noise ratio $SNR(f_i, d_j)$ of the channel for each frequency f_i and distance d_j.

We have performed experiments to assess the frequency profile of the channel. We use SNR as the quality indicator of

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[1] The Tmote Invent units are currently still in production, so we have chosen speakers and microphones of comparable specifications to the the Tmote speakers.

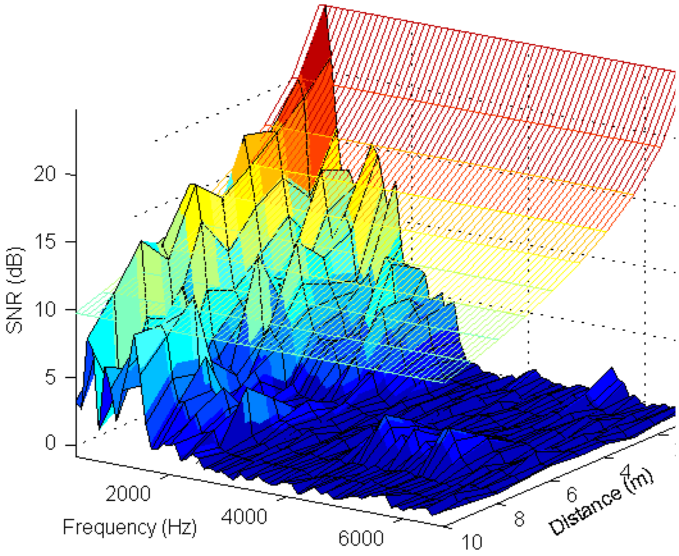

Fig. 1. Profile of the underwater channel: The solid plot represents the measured SNR and the transparent plot represents the expected SNR

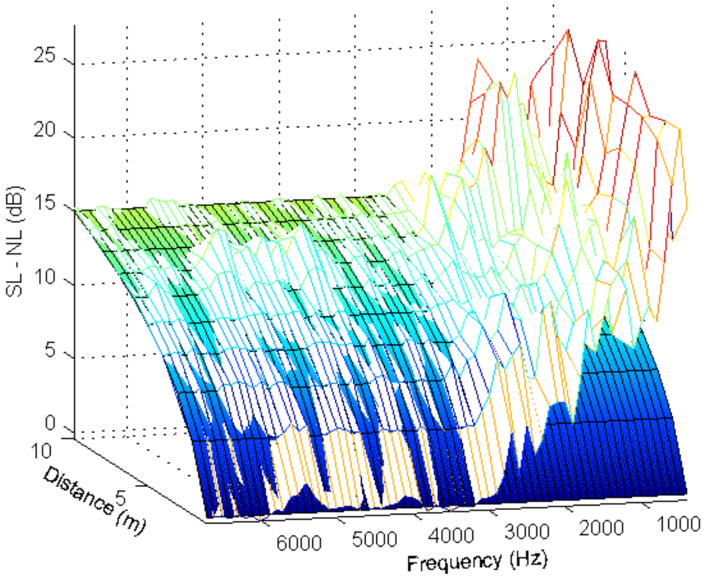

Fig. 2. Difference between source level and noise level for each frequency and distance pair. The solid graph indicates the difference the points at which the difference yields an SNR of 0 dB. The white graph shows the measured values.

the received signal to profile the medium. We have conducted the underwater experiments for distances d_j ranging from 1m to 10m at 1m increments. At each distance d_j, we conducted the measurements three times and obtained the average $SNR(f_i, d_j)$ of the three samples for f_i using Matlab.

Figure 1 shows the $SNR(f_i, d_j)$ results for each frequency f_i at each distance d_j. The solid plot in Figure 1 represents the measured SNR. In order to better understand the signal interaction, we also computed the expected SNR through the following method. We can use the transmission power P_t of the speakers, which is 0.8 Watts, to obtain I_t through equation 4. We can then compute the source level SL through equation 5. Let (f_m, d_n) be the frequency and distance pair with the highest received SNR_{max}. We can also get the transmission loss $TL(f_m, d_n)$ through equation 2 with a value of μ equals to 1.5, which is the recommended value for a shallow water setting. Finally, we can obtain the noise level $NL(f_m, d_n)$ through equation 1. To determine the expected SNR, we assume that NL for all frequencies and distances is uniform and equal to $NL(f_m, d_n)$ [2]. We can then obtain the expected $SNR(f_i, d_j)$ for all frequencies by simply using equation 1. The transparent plot in Figure 1 represents the expected SNR.

It is obvious from the figure that low frequency signals have a similar SNR value as the expected case, whereas there is an increasing gap between the expected and measure SNR values as the frequency increases. Along the distance axis, the SNR of lower frequency signals closely follows the TL model with a μ value of 1.5, whereas this trend also becomes less evident at higher frequencies. To explore these interactions further, we focus our discussion on the measured SNR plot.

The first observation is that for all distances, lower frequencies in general had a higher signal quality than higher frequencies. In particular, SNR is too low to distinguish the signals from noise for frequencies above 3Khz. Our earlier study on aerial acoustics [19] indicates that the generic speakers do not exhibit degraded performance within the frequency range from 3 Khz to 7 Khz. As such, we can rule out the speaker hardware as a cause for the low quality of the received signal in this frequency range. The two other possible causes for this signal quality degradation are: the presence of higher background noise in the frequency range between 3 and 7 Khz; and the poor vibration properties of the encompassing vinyl membrane for these frequencies (yielding a lower SL).

Another interesting observation is the frequency selectivity of this particular channel. For example, the experiments for most distances yielded a higher SNR for the frequency of 1400 Hz than at 1100 Hz. This is probably due to the speaker and microphone design, to higher ambient noise at certain frequencies, or to the vinyl membranes, which might resonate at some frequencies better than others.

The above discussion strongly suggests that the vinyl membrane creates unknown frequency-specific variations for SL. It also suggests that the noise level in our shallow water setting has unknown frequency-specific patterns NL. We can rewrite equation 1 to place all unknowns on one side of the equation:

$$SL(f_i) - NL(f_i, d_j) = SNR(f_i, d_j) + TL(f_i, d_j) \qquad (6)$$

Through equation 6, we can obtain the difference $SL(f_i) - NL(f_i, d_j)$ since we have measured $SNR(f_i, d_j)$ and we can easily compute $TL(f_i, d_j)$ from equation 2.

Figure 2 plots the difference of the two unknowns, SL and

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[2] Although this assumption may seem simplistic, the purpose is simply estimating the expected trend of the SNR at the receiver. In the subsequent discussion, we drop this assumption and explore the noise level for every frequency and distance.

NL. The solid graph represents the difference between SL and NL for each frequency f_i that yields a 0 SNR at a receiver d_j meters away. The white graph shows the difference between SL and NL obtained from the measured SNR values and equation 6. For most distances at frequencies above 3 Khz, the difference of SL and NL is almost the same as the 0 SNR plot, and the shape of both plots follows the trend of TL [3], rising with increasing distance in a logarithmical trend from 0 to 15 dB. For lower frequencies, the gap between the two plots widens, corresponding to a higher SNR and a larger measured value for $SL - NL$.

In addition to profiling the channel frequency response, the results in Figures 1 and 2 also provide insight into the software modem design. Based on the medium profiling results, we determine that designing an FSK software modem can make use of 8 frequencies, since using more frequencies would severely limit the communication range.

B. Data Transmission

The sensor nodes in our application send small amounts of data, consisting of sensor readings, once every several minutes. Thus, the data rate requirement of this application is small, so the transmission of tens of bits per second is sufficient. The relaxed requirement on bit rate enables us to maximize the communication range of our network by using only 8 frequencies for FSK modulation. We choose the 8 frequencies with the highest SNR from Figure 1 for our FSK software modem: 400; 500; 600; 700; 800; 900; 1300; and 1400 Hz. Each frequency in our modem encodes 3 bits.

Prior to conducting data communication experiments, we can compute the achievable error-free bit rate C for each communication distance using the Shannon-Hartley expression [21]:

$$C = Blog_2(1 + SNR)\ bps \tag{7}$$

where B is the bandwidth of the channel. In our case, the digital channel bandwidth is 8 discrete frequencies, so B is equal to 8. By plugging in the measured SNR for the lowest quality frequency of our software modem, we can compute the expected channel capacity for each distance d_i, shown in Figure 3. The expected error-free channel capacity drops steadily from about 30 bps at 1m to 10 bps at 10m. The expected channel capacity seems to be lowest for distances of 6m and 7m, which is most likely due to the specific conditions and environment in which the profiling experiments were performed. In our software modem design and experiments, we choose to explore bit rates that exceed the expected channel capacity within a system that is tolerant of some communication errors.

Our software modem is based on a structure of time slots. Each time slot of length T milliseconds contains one FSK symbol, which has a duration of $T/2$ milliseconds, in addition to a guard time of $T/2$ milliseconds. Guard times between adjacent FSK symbols are necessary to avoid inter-symbol interference which may arise as a result of multi-path propagation effects. To evaluate the impact of the length of the time slot on the data reception capability at different distances, we consider 4 cases for the time slot lengths: (1) 250 ms; (2) 125 ms; (3) 62.5 ms; and (4) 31.25 ms. The above time slot lengths correspond to data bit rates of 12, 24, 48, and 96 bits per second respectively.

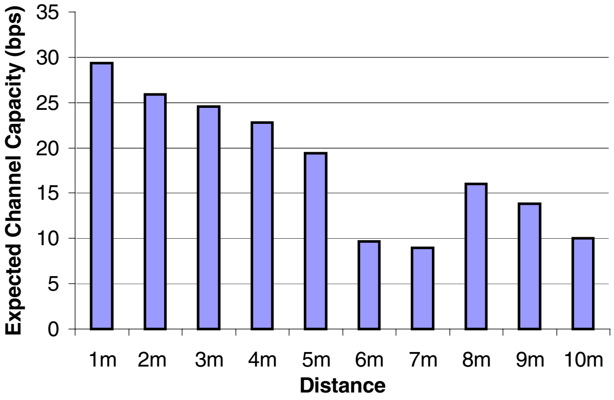

Fig. 3. The channel capacity computed from the measured SNR, as a function of distance

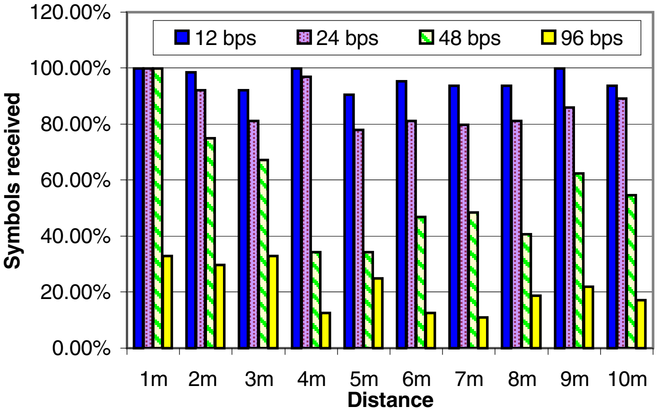

Fig. 4. Observed data reception capability at different distances and bit rates

Figure 4 plots the percentage of correctly received FSK symbols at different distances and bit rates. The experiments for a separation distance of 1m between the transmitter and receiver serve as a benchmark for other experiments, since most of the transmitted energy is captured by the receiver. For a distance of 1m, all the transmitted symbols are correctly decoded at the receiver for bit rates of 12, 24, and 48 bits per second. The perfect decoding of the 48bps stream exceeds the expected channel capacity at 1m. For the higher bit rate of 96bps, the receiver could not decode a significant portion signal. The 1m experiments indicate that the generic speaker and microphone pair may be capable of supporting a software modem with a bit rate of up to 48 bps.

The experiment results for larger separation distances exhibit distinct patterns for each bit rate. The successful symbol decoding rate for the 12bps modem ranges between 90% and

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[3] When a signal is not received, the SNR is 0 and equation 6 reduces to $SL - NL = TL$.

100% for distances up to 10m. There is no apparent effect of distance on the successful symbol reception and demodulation rate for the 12bps modem. This confirms the expected channel capacity results, in which the achievable bit rate is above 12bps for most distance and slightly lower than 12bps for other distances.

For the 24bps modem, the successful symbol decoding rate drops to about 92% at 2m, and it ranges between 78% and 97% for distance between 3m and 10m. The variation in successful decoding rate for different distance seems to be random rather than distant-dependant, and it possibly depends on the experiment setup. Medium profile results from section IV-A help justify the lack of dependance of the decoding success rate on distance. Because the 8 frequencies used in the FSK have SNR above 5 dB for distances up to 9m, this SNR is sufficiently high for the reception and decoding of 12bps and 24bps signals. Higher bit rate modems require a higher SNR at the receiver to successfully decode all symbols.

The successful decoding rate at the receiver for the 48bps modem degrades significantly for distance above 1m. The decoding rate is 75% for 2m, 67% for 3m, and much lower for 4m and higher distances. Because the threshold SNR for successful decoding is higher for this modem, the decoding ability, like the SNR results in section IV-A, is highly dependent on distance up until 3m, after which no significant portion of the signal can be decoded.

In sum, the 12bps and 24bps software modems exhibit successful decoding rates of 90% and 80% respectively for distances up to 10m. The 48bps modem has a highly distance dependent decoding ability within its usable range of 3m.

V. CONCLUSION

In this paper, we have proposed the use of software acoustic modems running on generic speakers and microphones to establish acoustic communications for underwater sensor networks. The capability of running software modems on generic hardware has the potential of significantly reducing hardware cost of underwater sensor networks, thereby promoting their wide deployment.

We have presented the fundamentals of acoustic underwater communications, and we have used these concepts as a model to conduct performance evaluation experiments for the software acoustic modem. Our experiments have employed generic hardware of comparable capabilities to the on-board hardware on the upcoming Tmote Invent module. The experiments have explored the frequency profile of the medium as a means for designing the software modem for distances up to 10m. Subsequently, we have designed and experimented with a family of simple software FSK acoustic modems on the generic hardware. The bit rates of our software modems range from 12bps to 96bps. The results have shown that 12bps and 24bps can be used within a 10m range with a constant decoding capability. The experiments have also indicated that the 48bps modem is usable for distance up to 3m in error-tolerant applications.

Most existing underwater modems and transceivers are expensive and they are intended for deep long-range communication links. The high cost of existing underwater communication hardware imposes having underwater networks with few nodes and thus a low spatial density. In contrast, the communication system described in this paper advocates the use of short multi-hop links for deploying dense underwater sensor networks. Because the cost of our system is limited to the relatively cheap sensor module, we expect the system to promote wider deployments of underwater sensor networks.

Another advantage of our system is that the low transmission power is less likely to adversely affect the marine wildlife. In general, sending sound waves underwater also has implications for the marine wildlife, such as whales and dolphins. Recently, there have been 13 incidents in which whales or dolphins were disoriented and stranded because of marine sound emitting devices such as sonar, oil exploration, and shipping [22]. Avoiding adverse effects on marine biology is a major consideration for our project, especially since our ultimate goal is environmental preservation. Because our network relies on multi-hop short range low power links between sensor nodes, our network minimizes sound interference with the marine life.

We plan to capitalize on the results obtained here to implement a software acoustic modem on Tmote Invent units and to deploy the units in Newport Bay, CA. The field deployment will allow us to better evaluate the acoustic modem in a practical application scenario.

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