Software Modems for Underwater Sensor Networks

Raja Jurdak*, Pedro Aguiar‡, Pierre Baldi†, and Cristina Videira Lopes†

* University College Dublin
raja.jurdak@ucd.ie

†University of California, Irvine CA 92697 U.S.A
{pfbaldi, lopes} @ics.uci.edu

‡Institute for Systems and Robotics / IST, Lisboa, Portugal
aguiar@isr.ist.utl.pt

Abstract— **The prohibitive monetary cost and high power consumption of existing acoustic hardware represent an obstacle for underwater sensor network deployment efforts. To address this issue, we propose underwater networks that rely on widely available speakers and microphones in electronic devices, coupled with software modems, to establish acoustic communication links. In this paper, we analytically and empirically explore the potential of this acoustic communication system for the underwater environment with a generic PC microphone as a receiver and with the Tmote Invent sensor module speaker as a transmitter. After waterproofing the components with elastic membranes that provide suitable coupling with the water, our experiments profile the hardware communication capability in a controlled aquatic environment. The medium profiling results expose the favorable frequencies of operation for the hardware, enabling us to design a software FSK modem. The experiments to evaluate the data transfer capability of our 8-frequency FSK software modem in the underwater channel yield an error-free channel capacity of 24 bps, and they also demonstrate that the system supports data rates up to at least 48 bps within a transmission range of 17 m.**

I. INTRODUCTION

The predicted scientific, economic, and social benefits of wider access to the marine environment have fueled interest in the development of sensing and communication systems for water monitoring. One of the more prominent technological developments that facilitate aquatic monitoring is sensor networks. Although sensor networks have had significant success for terrestrial applications, adapting this technology for the marine environment is impeded by the need to use acoustic communications, for which the specialized hardware is prohibitively expensive.

Most underwater communication solutions rely on specialized hardware for modulating, transmitting, receiving and demodulating acoustic signals. Current solutions for modulation and demodulation range from expensive commercial acoustic modems [7, 8] to dedicated integrated circuits [4] and dedicated DSP boards [9–11]. The communication hardware ranges from specialized underwater acoustic transducers and hydrophones [5] to generic speakers and microphones [4]. The use of specialized hardware for establishing acoustic communications underwater typically increases the network cost, the design time spent in interfacing node hardware components, and the size and weight of individual network nodes.

The focus so far on hardware acoustic modulation has stemmed from low processing speeds that did not allow the modulation of acoustic signals in software. Software modulation and demodulation [2, 3] is an alternative approach which overcomes most of the drawbacks of hardware modems. 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. Software modulation also provides a higher level of flexibility for on-the-fly tuning of modulation parameters, such as the data transfer rate and symbol duration, to suit the deployment environment's variability.

Coupling software modems with generic microphones and speakers that are built-in to sensor modules eliminates the need for specialized communication hardware and reduces system cost, facilitating the dense deployment of motes to form underwater acoustic sensor networks. This paper proposes the use of software modems, coupled with widely available speakers and microphones in electronic devices, to establish acoustic communication links as an affordable and easily deployable solution for underwater sensor networks. We analytically and empirically explore the potential of this acoustic communication system for underwater environments with the generic PC microphone as a receiver and with the Tmote Invent sensor module speakers as a transmitter. Our experimental approach profiles the hardware communication capability in the water after waterproofing the components with elastic membranes. The medium profiling results expose the favorable frequencies of operation for the hardware, enabling us to design a software FSK modem. Subsequently, our experiments evaluate the data transfer capability of the underwater channel with 8-frequency FSK software modems. The experiments within a 17x8 m controlled underwater environment yield an error-free channel capacity of 24 bps, and they also demonstrate that the system supports date rates between 6 and 48 bps with adaptive fidelity.

The remainder of the paper is structured as follows. Section II surveys related projects, most of which focus on

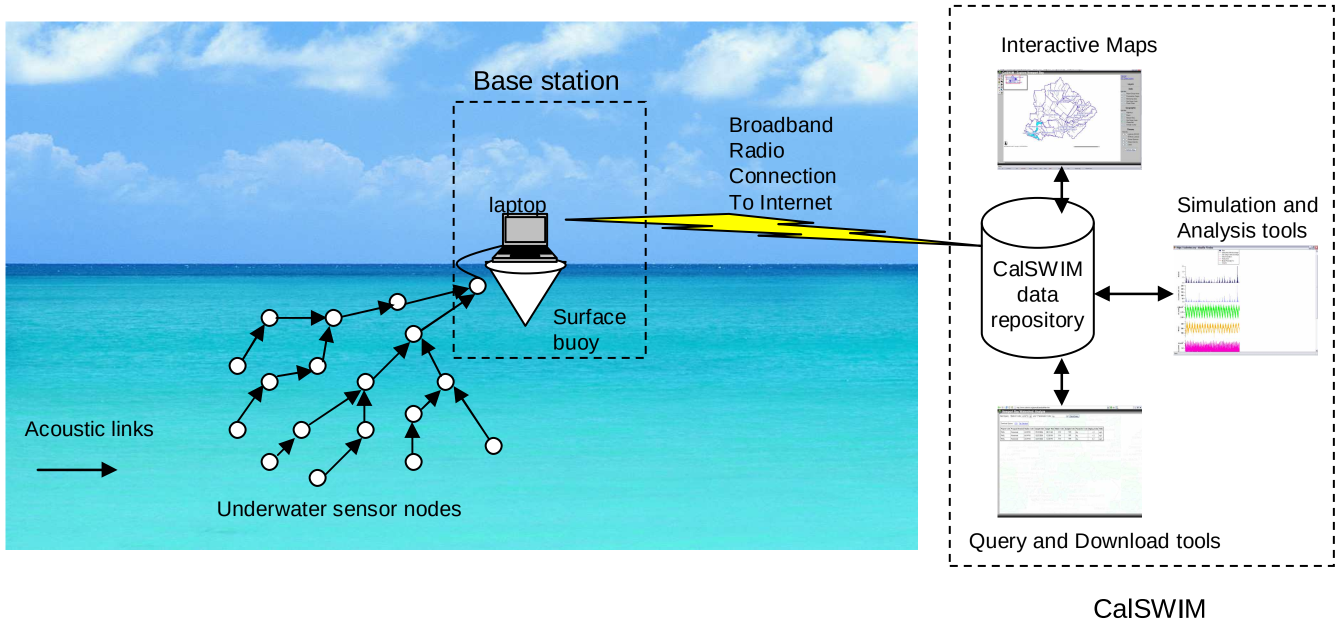

Fig. 1. Target Network Application

specialized communication hardware. Section III provides a topological overview of the proposed monitoring system. Section IV presents the fundamental issues that characterize the underwater acoustic channel, defining the modeling parameters of interest for our empirical experiments. Section V presents our performance evaluation of the system in a controlled water environment. Section VI discusses the empirical results and concludes the paper.

II. RELATED WORK

Acoustic underwater communication is a mature field and there are several commercially available underwater acoustic modems [7, 8]. 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 [10]. 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 [9] 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 [10] and [9] 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.

In a more recent article, Wills et al. [11] propose their design for an inexpensive hardware modem for dense short-range underwater sensor networks. Their work aims at borrowing communication concepts, such as wake-up radio, from terrestrial sensor networks. Although we share the same end goal as Wills et al. (inexpensive acoustic modems for dense short-range wireless networks), our approach differs in its emphasis on modulation through software rather than through specialized hardware..

One of the few attempts to deal with generic microphones and speakers is Vasilescu et al. [4]. These authors 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. The work in [4] uses generic microphones and speakers along with a specialized integrated circuit that generates ASK or FSK modulated sound signal 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. Although our work resembles their work in the use of generic microphones and speakers for acoustic communications, it differs in its proposal and implementation of software modems with a generic platform rather than the use of specialized integrated circuits for communication.

Lopes and Aguiar [2] have investigated the use of *software modems* for aerial acoustic communications in ubiquitous computing applications. Software acoustic modems can also eliminate the need for specialized hardware in underwater acoustic communications, thereby encouraging wider deployment of underwater sensor networks. In preliminary experiments, we started profiling the underwater acoustic spectrum and data communications capabilities with software acoustic modems [3], using waterproofed generic microphones and speakers as receivers and transmitters. The achieved bit rates were in the order of tens of bits per second for distances up to 10 m. Our work here extends the earlier work by coupling software modems with Tmote Invent module hardware. Since the experiments in [3] used similar microphones and speakers to the on-board Tmote Invent hardware, we expect the Tmote hardware to support comparable data rates to the generic hardware.

III. SYSTEM OVERVIEW

The work described in this article is part of a project to develop a prototype short range shallow water network to monitor pollution indicators in Newport Bay, CA [1] 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. Figure 1 sheds more light on the target network application. We expect to deploy a network consisting of tens to hundreds of sensor modules in a shallow water environment. The sensor modules can communicate acoustically through multi-hop links. The modules periodically sample their sensors, collecting physical indicator data such as temperature and salinity data, which influence pollution levels in the water. After sampling their sensors, the nodes report their data to a surface node nearby. The surface node, known as the base station, consists of a laptop with a water-immersed acoustic transceiver that communicates with the underwater nodes. The laptop computer is also equipped with a long range wireless broadband communication card that uses the cellular phone network. The laptop streams the network data towards a central database at UCI, that acts as the main data repository.

The collected data will feed into the existing CalSWIM project [12]. CalSWIM is a watershed management web site designed both for public service and for professional use. CalSWIM's goal is to develop protocols and standards related to the management of watershed information that can be applied to any watershed, facilitating coordinated and informed decisions for water resource management professionals. Currently, the CalSWIM prototype provides historical data from the Newport Bay watershed of Orange County in southern California. The proposed network deployment will stream near-real time data from Newport Bay into CalSWIM, providing professionals in the water management and research communities with access to sizeable and timely marine data.

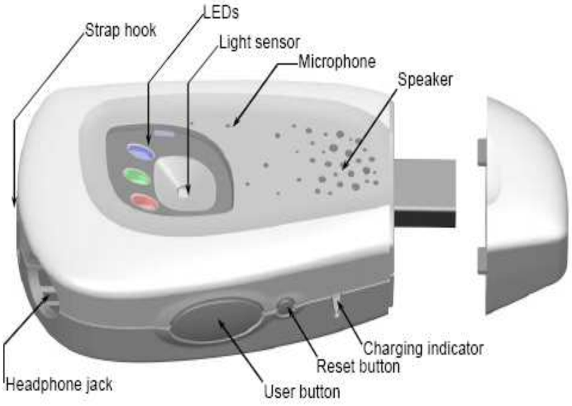

Fig. 2. The Tmote Invent module

For our application, we have selected mote-class computers, which are powerful enough to perform sufficient 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 (shown in Figure 2), from Moteiv Corp. [13], which has an on-board SSM2167 microphone from Analog Devices sensitive to frequencies from 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. The Tmote Invent on-board speaker and microphone serve as an acoustic transmitter and receiver respectively.

Establishing acoustic communication links between the speaker and microphone requires modulation of the acoustic signal at the sender and demodulation of the signal at the receiver. This work proposes and explores *software modulation* techniques that provide high flexibility low cost alternatives to hardware modems. The next section exposes the fundamental issues of underwater acoustic signal propagation that lay the groundwork for the design of our software acoustic modems.

IV. FUNDAMENTALS OF UNDERWATER ACOUSTICS

The passive sonar equation [14] characterizes the signal to noise ratio (SNR_u) of an emitted underwater signal at the receiver:

$$SNR_u = SL - TL_u - NL_u + DI \tag{1}$$

where SL is the source level, TL_u is the underwater transmission loss, NL_u 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 $0.67 \times 10^{-22}\ Watts/cm^2$ [14]. Without loss of generality, we use the threshold of human hearing, at $10^{-12}\ Watts/m^2$, as the reference level for the underwater signal since the Tmote speaker are originally designed for audio applications. 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 we assume omnidirectional hydrophones. Note that this is another conservative assumption, since the use of a directive hydrophone [17] reduces power consumption.

1) Source Level: Typically, the specifications of audio speakers indicate the speaker's maximum emitted signal power. 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 [14]:

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

in $Watts/m^2$, where H is the water depth in m. The following equation determines the source level SL relative to the threshold level of human hearing:

$$SL = 10\ log(\frac{I_t}{10^{-12}}) \tag{3}$$

2) 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 signals propagation in shallow water [14]:

$$TL_u = 10 \times \mu \log d + \alpha d \times 10^{-3} \tag{4}$$

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 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 4 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 [18] 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 5, which expresses the average medium absorption at temperatures between 4^oC and 20^oC:

$$\alpha = \begin{cases} 0.0601 \times f^{0.8552} & 1 \le f \le 6 \\ 9.7888 \times f^{1.7885} \times 10^{-3} & 7 \le f \le 20 \\ 0.3026 \times f - 3.7933 & 20 \le f \le 35 \\ 0.504 \times f - 11.2 & 35 \le f \le 50 \end{cases} \tag{5}$$

where f is in Khz, and α is in dB/Km.

Through Equation 5, 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 4 which enables us to compute the source level in Equation 3 and subsequently to compute the power needed at the transmitter.

3) Noise Level: Factors contributing to the noise level NL_u in shallow water networks include waves, shipping traffic, wind level, biological noise, seaquakes, volcanic activity, and rain, and the impact of each of these factors on NL_u 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, where we conducted our experiments, the main sources of underwater noise are swimmers, vibrations from people walking near the pool, water pumps, and drains.

V. PERFORMANCE EVALUATION

Building on our earlier experiments for generic acoustic hardware [3], our experiments here first profile the Tmote Invent speakers for underwater acoustic communication, using SNR as the quality indicator of the received signal. We waterproof the Tmote Invent modules with thin latex membranes.

Our application has unique channel characteristics that differ from underwater channels that appear in the related literature [14, 15]. Our channel is a complex channel that includes several components: the underwater medium; the generic speakers and microphone (whose response and coupling with the underwater environment is unknown); the waterproofing membranes (which may amplify or attenuate certain frequencies).

The signal to noise ratio SNR_u is the main quality indicator of the received signal. 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 [16] 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 $SNR_u(f_i, d_j)$ of the channel for each frequency f_i and distance d_j. The underwater profiling experiments cover transmission distances d_j from 1 m to 13 m at 1m increments, and frequencies f_i between 400 Hz and 3500 Hz at 100 Hz increments. The selected range of frequencies is the most favorable spectrum for this channel according to our earlier generic hardware experiments [3]. At each distance d_j, we conducted the measurements three times and obtained the average $SNR_u(f_i, d_j)$ of the three samples for f_i.

Figure 4 illustrates the Tmote Invent measured SNR (solid plot) and theoretical SNR (transparent plot) values versus frequency and distance. In order to better understand the signal interaction, we obtain the expected SNR through the following method. Let the (f_m, d_n) be the frequency and distance pair with the highest received SNR. We can use the transmission power P_t of the speakers to obtain I_t through Equation 2. We can then compute the source level SL through Equation 3. We can also get the transmission loss $TL_u(f_m, d_n)$ through Equation 4 with a value of μ equals to 1.5, which is suitable 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 $NL(f_m, d_n)$. We can then obtain the

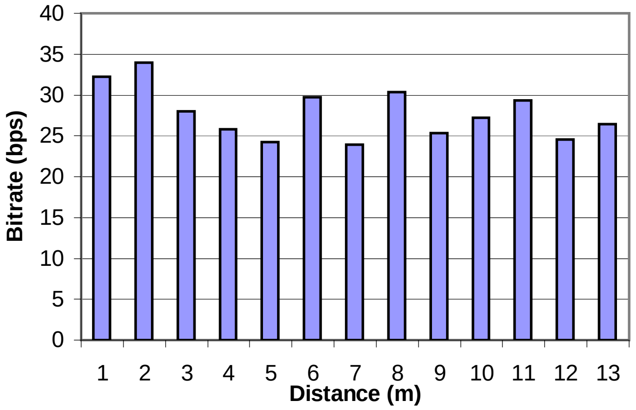

Fig. 3. Error-free bitrate of Tmote Invent Speakers in the underwater environment

expected $SNR_u(f_i, d_j)$ for all frequencies by simply using Equation 1.

Close observation of Figure 4 reveals that the measured SNR for certain frequencies between 1000 and 2000 Hz, such as 1300 Hz and 1500 Hz, is higher than the projected SNR for those frequencies. This effect is a reflection of the choice of 1.5 for the μ variable for the computation of the transmission loss. The higher values of the measured SNR indicate that the signal spreading for these particular frequencies is closer to the cylindrical model than the spherical model, highlighting favorable multi-path and reflection effects for these frequencies in the closed testing environment.

Another observation on Figure 4 is the frequency-selective behavior of the channel (consisting of the Tmote Invent speaker, latex membranes, underwater medium, and PC microphone). The channel's frequency selectivity emphasizes the importance of choosing the frequencies with the highest received signal quality for the software modem.

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 [20]:

$$C = Blog_2(1 + SNR)\ bps \tag{6}$$

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. Based on the measured SNR of the selected frequencies for the software modem, we can project the achievable error-free bitrate of the Tmote Invent speakers Figure 3 illustrates the projected error-free bitrate of the Tmote Invent speakers. For all distances up to 13 m, the measured SNR indicates that the speakers can support an error-free bitrate of at least 24 bps.

Based on the channel's frequency selectivity, we design an FSK software acoustic modem with the following 8 frequencies that exhibit the highest signal quality at all distances: 1000, 1200, 1300, 1500, 1600, 1700, 1800, and 2000 Hz. The minimum SNR for all of these frequencies within a range of 13 m is 6.95 dB, yielding an estimate of 24 bps for the error-free channel capacity.

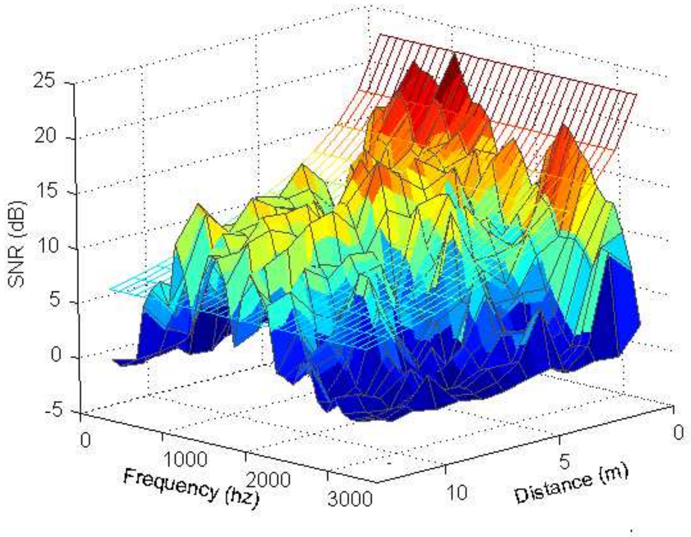

Fig. 4. Profile of the underwater channel with the Tmote Invent speakers

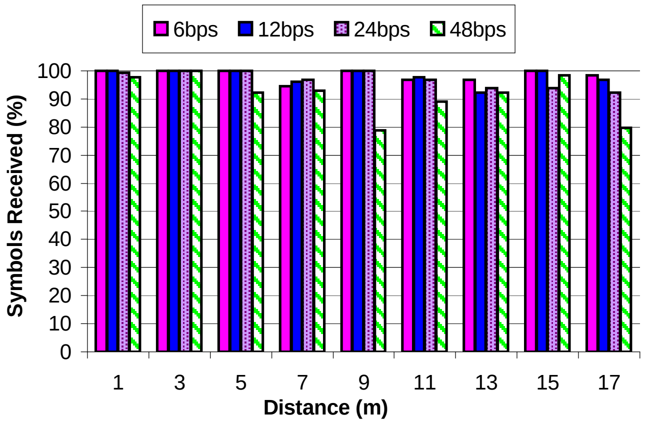

Fig. 5. Percentage of symbols correctly received for the Tmote Invent

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. Because 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) 500 ms; (2) 250 ms; (3) 125 ms; and (4) 62.5 ms. The above time slot lengths correspond to data bit rates of 6, 12, 24, and 48 bits per second respectively.

Figure 5 shows the percentage of symbols correctly received with the Tmote Invent speakers. For all bit rates in the experiments, the receiver could decode at least 79% of the transmitted symbols, even when transferring data at double the channel capacity. At bit rates of up to 12bps, the percentage of correctly received symbols stands at more than 90%. Using these results as guidelines, the development of the software modem should provide adaptive fidelity data transmission that supports lower bit rates for high noise scenarios (such as during a storm) or higher bit rates for low noise scenario (such as for calm water in a like). For all supported bit rates, forward error correction (FEC) techniques can detect and correct erroneous symbols with no need for data retransmission.

VI. DISCUSSION

The empirical results from the study serve as a proof-of-concept for underwater communication through generic acoustic hardware and software modems with data rates in the order of tens of bits per second. It is worth noting that the communication range of 17 m in this study is a limitation of the available physical space and not a technical communication limitation. An interesting direction for future work is to push the technology further to evaluate the maximum achievable communication and detection ranges, and the associated data transfer rates. In fact, an extrapolation of the experimental results reveals that the theoretical channel capacity at 50 m still remains above 16 bps.

Deploying our communication system within an unattended underwater sensor network involves several open research challenges, such as the design of Medium Access Control (MAC) and routing mechanisms. For instance, the underwater nodes should ensure that their data packets do not collide, which requires the use of carrier sensing or handshake messaging prior to data transmission. Such collision avoidance mechanisms include either energy overhead or delay overhead or both. Energy efficiency is always a major concern for in-situ sensor networks because recharging or replacing node batteries is difficult, especially in hard-to-access areas such as the underwater environment. Any MAC or routing layer mechanisms for ensuring proper data delivery must also provide energy-efficient behavior. The main challenge is therefore the design of higher layer communication mechanisms that serve the needs of the user application while balancing the energy-throughput-delay tradeoff. A prominent trend for managing this tradeoff in ad hoc and sensor networks is the design of cross-layer mechanisms that cut across traditional layer boundaries to achieve fine-grained optimizations [22].

The communication system described in this paper advocates the use of short multi-hop links for deploying dense underwater sensor networks. The multi-hop topology of our network aims at limiting disruption to marine wildlife. Sending sound waves underwater has implications for the marine wildlife, such as whales and dolphins. Recently, there have been several incidents in which whales or dolphins were disoriented and stranded because of human noise pollution resulting from sonar, oil exploration, and shipping [21]. Avoiding adverse effects on marine biology is a major consideration for environmental preservation. Because our network relies on multi-hop short range low power links between sensor nodes, it minimizes sound interference with the marine wildlife.

Our proposed network's multi-hop topology also reduces the network deployment cost. 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. Because the cost of our system is limited to the relatively cheap sensor module, we expect the system to promote wider and denser deployments of underwater sensor networks.

ACKNOWLEDGEMENT

The authors would like to thank Aude Bernard for her instrumental role in assisting with the underwater experiments. The work of R. Jurdak is supported by the Irish Research Council for Science, Engineering & Technology (IRCSET).

REFERENCES

[1] R. Jurdak, C. V. Lopes and P. Baldi. "Battery Lifetime Estimation and Optimization for Underwater Sensor Networks," *Sensor Network Operations*, Wiley-IEEE Press, pp. 397-420. May, 2006.

[2] C. V. Lopes and P. Aguiar. "Acoustic Modems for Ubiquitous Computing," *IEEE Pervasive Computing, Mobile and Ubiquitous Systems,* Summer 2003.

[3] R. Jurdak, C.V. Lopes, and P. Baldi. "Software Acoustic Modems for Short Range Mote-based Underwater Sensor Networks," In Proc. of *IEEE Oceans Asia Pacific*. Singapore. May, 2006.

[4] I. Vasilescu, K. Kotay, D. Rus, M. Dunbabin and P. Corke. "Data Collection, Storage, and Retrieval with an Underwater Sensor Network," In Proc. *Sensys' 05*, San Diego, CA, 2005.

[5] J. Heidemann, Y. Li, A. Syed, J. Wills, and W. Ye. "Underwater Sensor Networking: Research Challenges and Potential Applications," USC/ISI Technical Report ISI-TR-2005-603, 2005.

[6] X. Yang et al. Design of a Wireless Sensor Network for Longterm, In-Situ Monitoring of an Aqueous Environment. Sensors, 2:455-472, 2002.

[7] Linkquest Inc. available at: www.link-quest.com

[8] DSPComm. available at: www.dspcomm.com

[9] R. A. Iltis, H. Lee, R. Kastner, D. Doonan, T. Fu, R. Moore and M. Chin. "An Underwater Acoustic Telemetry Modem for Eco-Sensing," In proc. *MTS/IEEE Oceans'05*, September 2005.

[10] Utility Acoustic Modem available at: auvlab.mit.edu

[11] J. Wills, W. Ye, and J. Heidemann. "Low Power Acoustic Modem for Dense Underwater Sensor Networks," In Proc. *IEEE Workshop on Wireless Underwater Networks (WUWNet06)*, September, 2006.

[12] California Sustainable Wetland/Watershed Information Manager. available at: www.calswim.org

[13] MoteIV Corporation available at: www.moteiv.com

[14] R. J. Urick. *Principles of Underwater Sound*. Mcgraw-Hill, 1983.

[15] M. Stojanovic. Recent advances in high speed underwater acoustic communications. *Oceanic Engineering*, 21(4):125–36, 1996.

[16] Cetin, A.E. Gerek, O.N. Yardimci, Y. "Equiripple FIR filter design by the FFT algorithm," In *IEEE Signal Processing Magazine*, 14(2):60–64, 1997.

[17] N. Fruehauf and J.A. Rice. System design aspects of a steerable directional acoustic communications transducer for autonomous undersea systems. In *OCEANS*, volume 1, pages 565 –573. IEEE, 2000.

[18] F. H. Fisher and V. P. Simmons. "Sound Absorption in Sea Water," *Journal of Acoustical Society of America,* 62:558, 1977.

[19] S. A. L. Glegg, R. Pirie, and A. LaVigne. A study of ambient noise in shallow water, available:http://www.oe.fau.edu/ acoustics/.

[20] C. E. Shannon. "A mathematical theory of communication," *Bell System Technical Journal*, volume 27, pp. 379-423 and 623-656, 1948.

[21] R. Black. "Research Needed on Marine Sound," *BBC News* article, available: news.bbc.co.uk/2/hi/science/nature/4706670.stm

[22] R. Jurdak. *Wireless Ad Hoc and Sensor Networks: A Cross-Layer Design Perspective*. Springer-Verlag, 2007.