

A Comparative Analysis and Experimental Study on Wireless Aerial and Underwater Acoustic Communications

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Abstract—Widely available speakers and microphones in electronic devices motivate the use of generic audio hardware to establish acoustic communication links. Acoustic communication with generic hardware requires software modems for data modulation and demodulation. The resulting acoustic communications system paves the way for cheap and easily deployable underwater acoustic sensor networks through the use of audio hardware built in to the sensor modules. In this paper, we explore the potential of the acoustic communication system for both aerial and underwater environments. Our experiments profile both media with generic microphones and speakers. An initial test of the channel’s underwater data communication capability has revealed that the channel can transfer data at 12bps and 24bps, with respective error rates of 10% and 20%, up to a distance of 10m.

I. INTRODUCTION

Recent increases in the processing power and in the availability of speakers and microphones in embedded and mobile devices have fueled interest in designing software acoustic modems for audio communications. Many current electronic devices already includes audio speakers and microphones, which can support data communications through a low bit rate modulated audio signal. Supporting audio wireless communications through existing acoustic hardware enables cheap and easily deployable solutions for several emerging applications, such as ubiquitous computing and sensor networks.

Reliable communications through audio signals are already established for telephone modems. Acoustic signals have also been the top choice for wireless underwater communications, with applications that include oil prospecting, marine biology research, and environmental monitoring.

Most existing wired and wireless audio communication techniques rely on specialized hardware. In particular, wireless underwater acoustic communications often rely on specialized and expensive acoustic modems, as well as acoustic transducers and hydrophones to send and receive the signals underwater. Requiring the use of specialized hardware limits the pervasive use of acoustic communications, since it typically

reduces system portability, increases the system cost, and requires more time and effort for installing and interfacing hardware components.

In the past, low processing speeds dictated the use of specialized hardware for acoustic modulation. An alternative approach which overcomes the compatibility, cost, and portability drawbacks of hardware modems is the implementation of acoustic modulation and demodulation in software, as suggested in [1] for wireless aerial acoustic communications. 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 through generic speakers and microphones.

Eliminating the need for specialized hardware for acoustic communication greatly reduces the system cost, enabling the networking of any devices with speakers and microphones. Within this context, our study here is part of a project to deploy a short range shallow water network to monitor pollution indicators in Newport Bay, CA [2] 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 built-in 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. [3], which has an on-board microphone sensitive to 100Hz to 20kHz, and an on-board speaker 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 aerial and underwater acoustics in order to profile these channels and to

design software acoustic modems that can run on a general purpose mote 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 underwater experiments. The experiments reveal that the aerial channel favors frequencies above 1Khz because of high ambient noise at low frequencies. In contrast, the underwater channel favors lower frequencies as a result of the vinyl membrane that we use for speaker waterproofing which seems to resonate better at lower frequencies.

The remainder of this paper is organized as follows. Section II discusses the recent work on both hardware and software acoustic modems. Section III presents the basic principles of acoustic signal propagation in both air and water. Section IV addresses our performance evaluation of generic acoustic hardware for profiling the aerial and underwater media. We use also an FSK modem to evaluate the data transfer characteristics of our acoustic underwater communication system. Finally, section V concludes the paper

II. ACOUSTIC COMMUNICATIONS AND MODEMS

Many applications can benefit from acoustic communications, so several works have considered the modulation of sound in order to transmit information. These works can be broadly classified into 2 categories: (A) hardware modems; and (B) software modems.

A. Hardware Modems

Earlier efforts in acoustic communication have focused on using specialized and dedicated hardware for sound modulation and demodulation. There are 2 main applications for hardware acoustic modems: (1) phone line modems; and (2) underwater acoustic modems.

1) *Phone line modems*: Modems originally allowed long-distance point-to-point communication using the voice band in ordinary telephone networks. Early acoustically coupled modems, which required an external connection with the telephone receiver, transmitted at 300 bits per second. Direct-connect modems, which interface directly with the telephone line, have replaced these acoustic modems. They are less bulky, give a better connection, and avoid the background noise problems of acoustic modems. Modern telephone line modems transmit at bit rates of up to 56 Kbps.

2) *Underwater Acoustic Modems*: Acoustic underwater communication is a mature field and there are several commercially available underwater acoustic modems [4, 5]. 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.

Both of the efforts reported in [6] and [7] aim at making underwater acoustic modems more affordable and accessible to the research community 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 [8] uses generic microphones and speakers along with a specialized integrated circuit that generates an 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. 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.

B. Software Modems

With the rapid increase in processor speeds, the idea of implementing acoustic modems in software became feasible. The cost of software acoustic modems is limited to the development cost. Researchers have started exploring software acoustic modems for aerial acoustic communications. Lopes and Aguiar have investigated using software modems for aerial acoustic communications [1] in ubiquitous computing applications. Many ubiquitous computing applications can make use of generic microphones and speakers available on computing devices to communicate through sound. Sound communication in aerial environments promotes privacy in indoor environments (since it does not penetrate walls) and requires no line-of-sight for communication. The only limitation of using aerial acoustic communications is the low bit rate [1]. As in ubiquitous computing applications, underwater sensor networks can also benefit from low bit rate software acoustic modems that can be easily deployed, which is why our study here explores the communication potential of generic hardware coupled with software modems in both aerial and underwater environments.

III. FUNDAMENTALS OF ACOUSTICS

A. Aerial Acoustics

The signal-to-noise ratio (SNR) quality metric at the receiver of an emitted aerial acoustic signal is governed by the following equation:

$$SNR_a = SL_a - TL_a - NL_a \quad (1)$$

where SL_a is the source level, TL_a is the transmission loss, NL_a is the noise level. All quantities in Equation 1 are in dB relative to the power density level of the threshold of human hearing, which is $10^{-12} Watts/m^2$.

1) *Source Level*: Typically, the specifications of audio speakers indicate the speaker's maximum emitted signal power. To obtain the source level SL_a of the speaker, we first obtain the signal intensity at 1m from the speaker, assuming that the signal spreading is cylindrical with a unity radius within a distance of 1m from the source:

$$I_t = \frac{P_t}{2 \times \pi \times 1^2} \quad (2)$$

where I_t is expressed in $Watts/m^2$, and P_t is the transmission power in $Watts$. The following equation determines the

source level SL_a relative to the threshold level of human hearing:

$$SL_a = 10 \log\left(\frac{I_t}{10^{-12}}\right) \quad (3)$$

2) *Transmission Loss*: The transmission loss of the aerial acoustic signal depends on the surroundings. For example, in an indoor environment, the signal reflects on objects and walls, and the signal is approximated to spread in a cylinder between source and receiver. It is particularly for this reason that the same sound or music heard indoors seems *louder* than it does outdoors.

The signal transmission loss in an indoor environment is expressed as [9]:

$$TL_a = 10 \log(d) \quad (4)$$

where d is the distance in meters between the sender and receiver, and TL_a is expressed in dB.

3) *Noise Level*: The noise level for aerial indoor acoustic environments results from many factors, including movement of people and objects, vibration and sounds from machines, and occasional noise impulses from the surroundings such as cell phones. In typical indoor environments, the noise sources typically add to the background noise at lower frequencies, suggesting a higher noise level for these frequencies.

B. Underwater Acoustics

1) *The Passive Sonar Equation*: The passive sonar equation [10] characterizes the signal to noise ratio (SNR_u) of an emitted underwater signal at the receiver:

$$SNR_u = SL - TL_u - NL_u + DI \quad (5)$$

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. We use the same reference for the underwater signal as for the aerial acoustic signal (i.e. the threshold of human hearing at $10^{-12} \text{ Watts}/m^2$) in order to compare results more effectively. In the rest of the paper, we use the shorthand notation of dB to signify $dB \text{ re } 10^{-12}$, unless otherwise mentioned¹. For simplicity we assume omnidirectional hydrophones, although using a directive hydrophone as described in [12] reduces power consumption. Thus, $DI = 0$ for the remainder of this discussion.

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 [10]:

$$TL_u = 10 \times \mu \log d + \alpha d \times 10^{-3} \quad (6)$$

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 . Equation 6 contains two components: a distance dependent attenuation component; and a component representing medium absorption that depends on both distance and frequency. 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 for signals propagating along the surface or ocean floor), then μ equals to 1, which renders equation 6 identical to equation 4 for indoor aerial acoustic signals. In shallow water cases, the value of μ lies somewhere between 1 and 2, depending on the depth.

Equation 6 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 absorption [13].

3) *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 [10]:

$$I_t = \frac{P_t}{2\pi \times 1m \times H} \quad (7)$$

in $Watts/m^2$, where H is the water depth in m. We can then use I_t in equation 3 in order to solve for SL .

4) *Noise Level*: Factors contributing to the noise level NL_u in shallow water networks include waves and shipping traffic. 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, the main sources of underwater noise are swimmers, vibrations from people walking near the pool, and water pumps.

IV. EXPERIMENTS

A. Aerial Channel Profiling

The first set of experiments profile the aerial acoustic channel. In these experiments, we use an IPAQ 5550, with a built-in audio speaker, as the transmitter of the acoustic signal. The signal is then captured by a microphone attached to a desktop PC, where the signal is recorded into a file for analysis. We conducted the experiments in a typical office environment with distances ranging from 1 to 7 meters at 2 meter increments.

We had determined in an earlier study on aerial acoustic communications [14] that PC speakers and microphones have the best response at frequencies up to about 7 KHz. Building on that result, we limit our analysis of the aerial channel profile here to the frequency range from 400 Hz to 6700 Hz at 100 Hz increments. Each frequency tone is sent for a duration of 1 second, and the full signal consists of a sequence of the signals separated by guard times.

Figure 1(a) shows an example of a captured signal, and Figure 1(b) shows the corresponding filtered 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 band pass filter centered at f_i to the received signal. The filtered signal shape includes the transmitted tone at f_i ,

¹The notation dB re X indicates the decibel level of a signal relative to a reference value X.

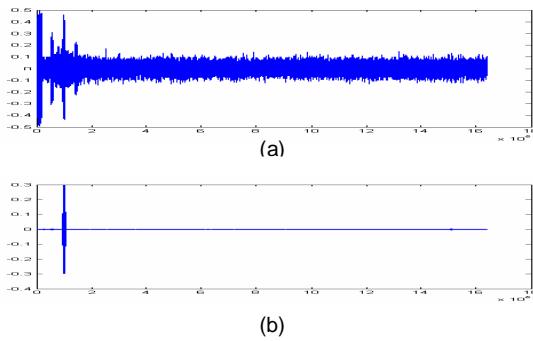


Fig. 1. (a) Captured signal plot (b) Filtered signal.

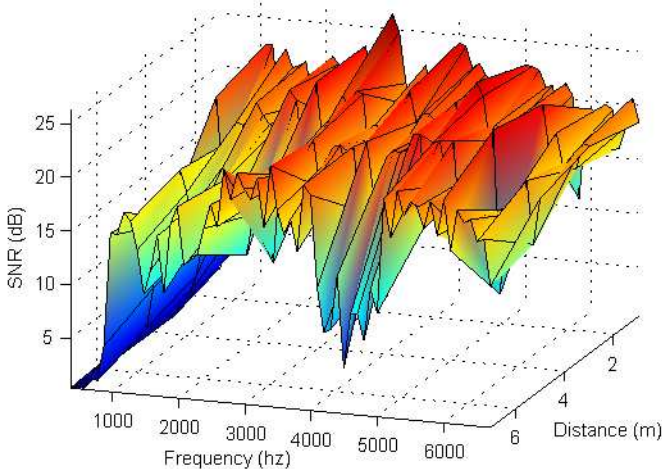


Fig. 2. Received signal quality in the indoor aerial channel

whose average amplitude we indicate as S , 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, and we indicate the average amplitude of the noise as N . Through this filtering process, we can obtain the signal to noise ratio $SNR_a(f_i, d_j)$ of the channel for each frequency f_i and distance d_j as:

$$SNR_a(f_i, d_j) = 10 \log \frac{S(f_i, d_j)}{N(f_i, d_j)} \quad (8)$$

Figure 2 illustrates the measured $SNR_a(f_i, d_j)$ for the various frequencies f_i and distances d_j in our experiments to profile the aerial channel. The most prominent trend in Figure 2 is that the received signal quality for low frequency tones below 1 KHz is considerably lower than for higher frequencies. In fact, the received signal quality gradually increases with increasing frequency from 400 Hz to 1000 Hz. For frequencies between 1 KHz and 2.5 KHz, the signal quality is generally stable with minor variations among frequencies. The signal quality is highest for frequencies above 2.5 KHz, which confirms the earlier results in [14]. In regards to distance, the signal quality degrades with a trend following the expected signal attenuation in most cases. The cases in which

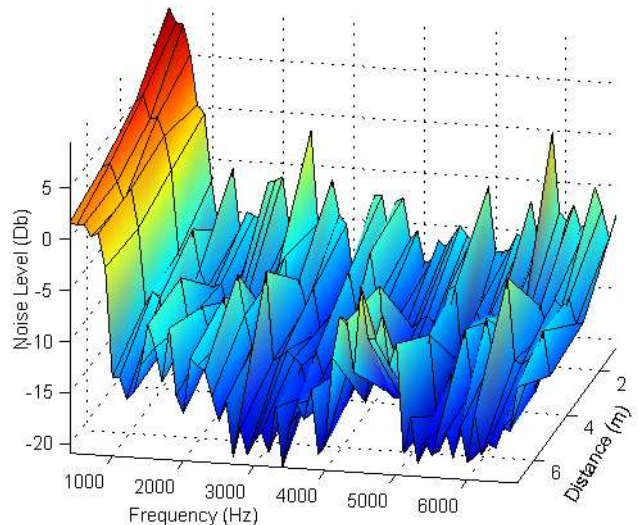


Fig. 3. Apparent noise level in the indoor aerial environment

the received signal quality does not adhere to the attenuation can be attributed to multi-path effects (such as reverberation) and varying exposure to noise sources at the positions within our experiment area.

We can use the measured $SNR_a(f_i, d_j)$ values to obtain the observed $NL_a(f_i, d_j)$ values for each frequency f_i and distance d_j in the indoor aerial acoustic channel. The audio speakers of the IPAQ 5550 have a maximum audio transmission power P_t of 2 Watts. Through equations 2 and 3, the corresponding source level SL_a of the IPAQ acoustic signal is 10.5029 dB. For the remainder of this analysis, we assume that SL_a is uniform at 10.5029 dB across frequencies in our spectrum from 400 Hz to 6700 Hz. Having determined SL_a and $SNR_a(f_i, d_j)$ for each (f_i, d_j) pair, we can obtain the transmission loss for $TL_a(f_i, d_j)$ for each distance d_j from equation 4 in order to compute $NL(f_i, d_j)$, which is shown in Figure 3.

According to Figure 3, the apparent noise level in the indoor acoustic channel is higher for frequencies between 400 Hz and 1000 KHz. The higher apparent noise level at low frequencies is due to interference from electronic devices, such as computers, monitors, printers in the form of white noise. Also, the movement of people and objects creates transient noise impulses at low frequencies.

B. Underwater Medium Profiling

The second set of experiments explores the underwater acoustic communication capability of generic desktop PC speakers². We have selected Sony SRS-P7 PC speakers and Labtec PC microphone, 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

²The Tmote Invent units were still in production at the time of this study, so we have chosen speakers and microphones of comparable specifications to the the Tmote speakers and microphones.

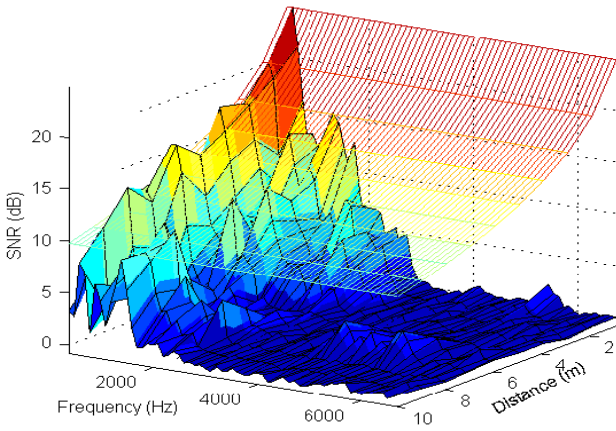


Fig. 4. Profile of the underwater channel: The solid plot represents the measured SNR and the transparent plot represents the expected SNR

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. We conducted two sets of underwater experiments: (1) experiments to profile the medium's frequency response; and (2) experiments to evaluate data transmission capability.

Our application has unique channel characteristics that differ from underwater channels that appear in the related literature [10, 15]. 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.

We have performed experiments to assess the frequency profile of the channel. As in the aerial acoustic experiments above, we use SNR_u as the quality indicator of the received signal, and we profile the medium through the same signal and SNR calculation method. We performed 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 $SNR_u(f_i, d_j)$ of the three samples for f_i .

Figure 4 shows the $SNR_u(f_i, d_j)$ results for each frequency f_i at each distance d_j . The solid plot in Figure 4 represents the measured SNR. In order to better understand the signal interaction, we also computed 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 speaker transmission power P_t of 0.8 Watts [11] to obtain the source level SL through equations 7 and 3. We can also get the transmission loss $TL_u(f_m, d_n)$ through equation 6 with

a value of μ equals to 1.5, which is suitable for a shallow water setting [10]. Finally, we can obtain the noise level $NL(f_m, d_n)$ through equation 5. 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 expected $SNR(f_i, d_j)$ for all frequencies by simply using equation 5. The transparent plot in Figure 4 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_u 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_u is too low to distinguish the signals from noise for frequencies above 3Khz. Through the analysis in section IV-A, we know that speakers of this size do not exhibit degraded performance with 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 NL in our shallow water setting has unknown frequency-specific patterns. We can rewrite equation 5 to place all unknowns on one side of the equation:

$$SL_u(f_i) - NL_u(f_i, d_j) = SNR_u(f_i, d_j) + TL_u(f_i, d_j) \quad (9)$$

Through equation 9, we can obtain the difference $SL_u(f_i) - NL_u(f_i, d_j)$ since we have measured $SNR_u(f_i, d_j)$ and we can easily compute $TL_u(f_i, d_j)$ from equation 6.

Figure 5 plots the difference of the two unknowns, SL and NL . The dark graph represents the difference between SL and NL for each frequency f_i that yields a 0 SNR at a receiver d_j . The white graph shows the difference between SL and NL obtained from the measured SNR values and equation 9. 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 , rising with increasing distance in a logarithmical trend from 0 to 15 dB.

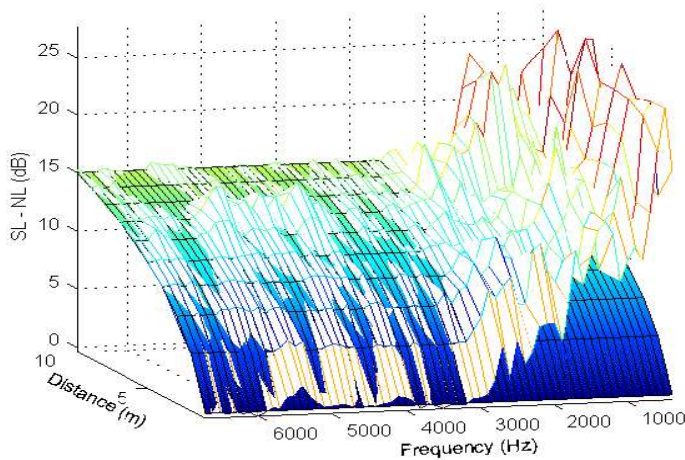


Fig. 5. Difference between source level and noise level.

For lower frequencies, the gap between the two plots widens, corresponding to higher values for both SNR and $SL - NL$.

In addition to profiling the channel frequency response, the results in Figures 4 and 5 also provide insight into the software modem design. Depending on our target SNR ratio for the network, we can determine the number of frequencies that can be used for reliable communication. For instance, for a target SNR of 5 dB, the plot for all distances up to 9 m have at least 8 frequencies with an SNR of more than 5 dB, so the software modem can use an 8-frequency FSK scheme for data transmission for distances of up to 9m without violating the signal quality requirement. This insight has proved valuable for developing the data modulation scheme.

C. Underwater 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 4 for our FSK software modem: 400; 500; 600; 700; 800; 900; 1300; and 1400 Hz. Each frequency in our modem encodes 3 bits. To evaluate the impact of the FSK symbol length on the data reception capability at different distance, we consider 4 modems with the following data bit rates: 12; 24; 48 and 96.

Figure 6 plots the percentage of correctly received FSK symbols at different distances and bit rates using the generic hardware. The receiver could successfully receive and demodulate more than 90% of symbols at 12 bps, and about 80% at 24 bps. The demodulation capability does not appear to diminish with increased distance for these lower bit rates. For the higher data rates, the receiver could not demodulate a significant portion of the signal beyond 3m for 48 bps rates, and at 96 bps, the demodulation capability is even lower.

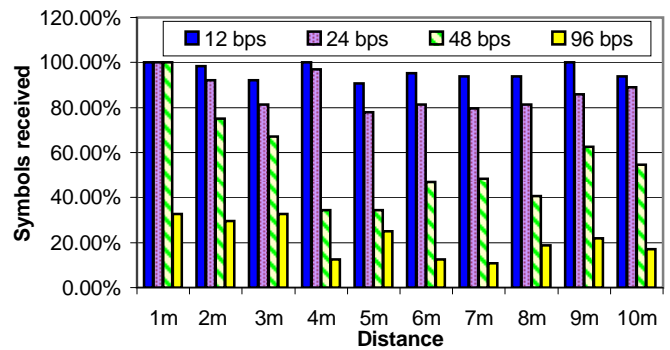


Fig. 6. Data reception capability at different distances and bitrates

V. CONCLUSION

In this paper, we have provided a comparative analysis and experimental study on the channel profile of generic acoustic hardware with software modems for acoustic communications in air and in water. The aerial channel favors frequencies above 1Khz because of high ambient noise at low frequencies. In contrast, the underwater channel favors lower frequencies as a result of the vinyl membrane for speaker waterproofing which seems to resonate better at lower frequencies. An initial test of the channels's underwater data communication capability has revealed that the channel can transfer data at 12bps and 24bps, with respective error rates of 10% and 20%, up to a distance of 10m. We plan to capitalize on the results obtained here to implement a software acoustic modem on Tmote Invent units and deploy the units in Newport Bay, CA. The longer term field deployment will allow us to better evaluate the acoustic modem in a practical application scenario.

REFERENCES

- [1] C. V. Lopes and P. Aguiar. "Acoustic Modems for Ubiquitous Computing." *IEEE Perv. Comp., Mobile and Ubiquitous Sys.*, Summer 2003.
- [2] R. Jurdak, C. V. Lopes and P. Baldi. Battery Lifetime Estimation and Optimization for Underwater Sensor Networks. *Sensor Network Operations*, IEEE Press. May, 2006.
- [3] MoteIV Corporation www.moteiv.com
- [4] Linkquest Inc. available: www.link-quest.com
- [5] DSPComm. available: www.dspcomm.com
- [6] 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.
- [7] Utility Acoustic Modem available: auvlab.mit.edu
- [8] 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.
- [9] Blauert, Jens (Ed.) *Communication Acoustics*. Springer, 2005, ISBN: 3-540-22162-X
- [10] R. J. Urlick. *Principles of Underwater Sound*. McGraw-Hill, 1983.
- [11] Sony SRS-P7 PC speakers. available: www.sony.com
- [12] 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.
- [13] F. H. Fisher and V. P. Simmons. "Sound Absorption in Sea Water," *Journal of Acoustical Society of America*, 62:558, 1977.
- [14] R. Jurdak, C.V. Lopes, and P. Baldi. "An Acoustic Identification Scheme of Location Systems," In Proc. *ICPS'04*, Beirut, Lebanon. 2004.
- [15] M. Stojanovic. Recent advances in high speed underwater acoustic communications. *Oceanic Engineering*, 21(4):125-36, 1996.