Designing an Adaptive Acoustic Modem for Underwater Sensor Networks

Lingjuan Wu, Jennifer Trezzo, Diba Mirza, Paul Roberts, Jules Jaffe, Yangyuan Wang, *Fellow IEEE,*
and Ryan Kastner, *Member IEEE*

Abstract—There is a growing interest in using underwater networked systems for oceanographic applications. These networks often rely on acoustic communication, which poses a number of challenges for reliable data transmission. The underwater acoustic channel is highly variable; each link can experience a vastly conditions, which change according to environmental factors as well as the locations of the communicating nodes. This makes it difficult to ensure reliable communication. Furthermore, due to the high transmit power, the energy consumed in transmitting data is substantial which is exacerbated at lower data rates. The main challenge that we address in this article is how to build a system that provides reliable and energy efficient communication in underwater sensor networks. To this end, we propose an adaptive underwater acoustic modem which changes its parameters according to the situation. We present the design of such a modem and provide supporting results from simulations and experiments.

Index Terms—acoustic modem, underwater sensor networks, wireless communication.

I. INTRODUCTION

UNDERWATER sensor networks have a wide range of oceanographic applications including marine exploration, environmental monitoring and coastal surveillance. The preferred mode of wireless communication in these networks is based on acoustic signals. This is due to the fact that radio frequencies suffer high attenuation underwater. Optical communication is possible but only in clear water at relatively short distances. Unfortunately, acoustic communication is challenging due to large and variable multipath delay spread, Doppler shifts and long propagation delays [1].

Underwater networks are envisioned to consist of tens to hundreds of nodes that are deployed in 3-dimensional space, in different configurations [2]. A concrete example is a sensor network consisting of freely floating autonomous drifters for underwater exploration [3]. In such scenarios, the acoustic channel can vary considerably between different transmitter-receiver pairs. This is due to the significant variation in the nodes' positions, the extent of motion between them, and the topography of the ocean environment. For example, in moored oceanographic applications, where nodes are deployed at different depths in a static configuration, the channel experienced by nodes closer to the bottom of the ocean is different from those near the surface due to variations in signal reflection and refraction across different water layers. In networks consisting of mobile vehicles, additional variability is introduced due to the dynamics of the ocean environment and the relative motion between the vehicles.

To ensure reliable communication, we must choose the modem parameters for worst case channel conditions. Unfortunately, this often leads to communicating at lower data rates than are practically possible. Moreover, due to the high transmit power of acoustic modems (often tens of watts), a lower data rate results in a substantial increase in the energy consumed per bit. Since devices in an underwater sensor network are generally battery operated, energy efficient communication is crucial. The essential challenge that we address in this paper is how to provide reliable and energy efficient acoustic communication for underwater networks by designing an adaptive physical layer.

To this end, we propose an underwater acoustic modem that adapts its data rate and modulation scheme to the channel conditions. This idea is also motivated by previous observations that adaptive modulation is key to maximizing both channel capacity and channel efficiency at the physical and MAC layers [4]. As a result of such adaptations nodes that experience a more favorable channel can communicate at a faster rate, thereby saving energy. Alternatively, if the channel multipath increases, a node automatically chooses a lower rate to avoid intersymbol interference. These adaptations are performed on a link by link basis. The major contribution of this article is an adaptive modem architecture. We describe its main signal processing and control components and motivate our design via simulations and actual ocean experiments.

Prior work on acoustic modem design also recognizes the fact that communication performance underwater has a strong dependence on the deployment environment. Consequently, modems with adaptable features have been previously proposed. For example, in order to deal with different channels, the Woods Hole Micro-Modem, which is widely used in the research community, has two operation modes: a low data rate FSK mode and a high data rate PSK mode [5]. Other examples include a dual-mode acoustic modem [6] and a software modem [7]. The dual mode modem can switch between two modulation schemes - FH and DSSS according to channel

L. Wu is with the Institute of Microelectronics, Peking University, Beijing 100871, China, and also with the Computer Science and Engineering Department, University of California San Diego, La Jolla, CA 92037 USA. (e-mail: wljuan17503@gmail.com).

P. Roberts and J. Jaffe are with the Scripps Institution of Oceanography, University of California San Diego, La Jolla, CA 92037 USA. (e-mail: paulr@mpl.ucsd.edu; jules@mpl.ucsd.edu).

Y. Wang is with the Institute of Microelectronics, Peking University, Beijing 100871, China (e-mail: yywang@pku.edu.cn).

J. Trezzo, D. Mirza and R. Kastner are with the Computer Science and Engineering Department, University of California San Diego, La Jolla, CA 92037 USA. (e-mail: jtrezzo@ucsd.edu; diba.mirza@gmail.com; kastner@cs.ucsd.edu).

signal to noise ratio (SNR) [6]. The software modem allows the user to select a desired modulation technique, data-rate and frame length [7]. These modems require the user to set certain communication parameters prior to deployment and they are not designed to adapt to a variable channels in real-time, after the network is deployed. We aim to design a modem architecture that can be dynamically changed either before deployment or during its operation.

The rest of this article is organized as follows. In Section II, we describe our adaptive modem architecture focusing on the major components: channel estimation, symbol synchronization and modulation. Section III provides simulation and experimental results. We conclude the paper and present future work in Section VI.

II. ADAPTIVE ACOUSTIC MODEM DESIGN

Underwater acoustic modems consist of three fundamental components as shown in Fig. 1: a transducer, an analog transceiver and a digital hardware platform for signal processing and control. This article focuses on the design of the physical layer on the digital platform.
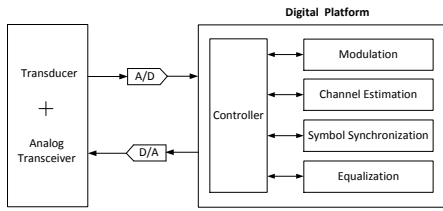

Fig. 1. An example adaptive acoustic modem design

In the following we provide details about the major parts of the digital hardware platform. In each case, we give a general description of its function, discuss the parameters that can be adapted, and describe options that we studied in our experiments.

Controller: The controller orchestrates the digital platform. This includes moving data to and from the analog transceiver, setting the parameters for the various parts of the digital hardware, and ultimately interfacing with higher level network stack.

Modulation: There are many different types of signals used for underwater communication. These include FSK [5], PSK [8], OFDM [9], DSSS [6], [10]. While an adaptive modem can ideally switch between any modulation scheme, we studied FSK and DSSS in our experiments. FSK is a fairly simple and widely used modulation scheme in underwater communication due to its intrinsic robustness to time and frequency spreading. Our receiver uses a non coherent energy detection demodulation method [11]. In DSSS, symbols are spread in frequency domain by multiplying with a spreading code. We used a DSSS waveform based on Walsh and m-sequence [10].

Channel Estimation: A major component of an adaptive modem is the ability to change aspects of the modem including selecting a modulation scheme, the data rate, the transmit power and other configurable portions of the design. Many of these depend upon current and future characteristics of the acoustic channel. Therefore channel estimation is an important part of any adaptive modem.

The Doppler shift, channel path gains and SNR are some of the important channel state information that must be measured and predicted. Prediction is particularly important since sound travels slowly (1500 m/s) and some channel characteristics vary on the order of seconds or faster. Ideally, the receiver will measure the channel characteristics and feed it back to the transmitter. This requires estimation at least one transmission in advance. Some work has been done such as a channel prediction scheme is proposed for adaptive modulation in [12].

Our experiments use a chirp signal for estimating the channel due to its good autocorrelation properties. Using a chirp signal, the Doppler shift, multipath delay spread and SNR are computed as follows.

Doppler shift is induced by the relative motion between the transmitter and receiver as well as by the motion of the medium. The Doppler scaling factor is calculated as $\Delta = T_{rp}/T_{tp} - 1$, where T_{tp} and T_{rp} are the duration of transmitted and received data packets respectively. The packet structure designed to calculate Δ is shown in Fig. 2. The received signal correlates with the original chirp and the time duration between two correlation peaks, T_{rp} is computed. After that, we calculate Doppler shift $\widehat{f} = \Delta \times f$ where f is the carrier frequency.
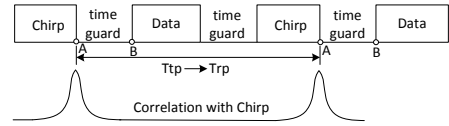

Fig. 2. Packet length measurement using chirp signal

Multipath is a cause of intersymbol interference (ISI), which is a limiting factor for robust high speed underwater communication. The multipath intensity profile can be calculated using a form of the Matching Pursuits algorithm [10]. In our experiments, we calculate the multipath delay spread using the previously discussed chirp signal. The received chirp is correlated with the original chirp to generate the amplitude delay profile. The RMS of the amplitude delay profile is used as a threshold and the delay spread is computed as the time difference between the path with maximum amplitude and the last path whose amplitude is greater than the RMS value.

Our experiments determine the SNR as the ratio of signal's variance to that of the ambient noise. As shown in Fig. 2, the time guard after the chirp is used to calculate the noise power.

Symbol Synchronization: It is critical that the receiver correctly determine the beginning of the incoming data. This is an important part of any digital communication and there are many techniques for symbol synchronization. We perform synchronization by correlating the received signal with a known preamble. We studied two different signals for candidate preambles, namely a Gold code and a chirp signal.

We used a Gold Code of length fifteen as the preamble, and an orthogonal Gold code to estimate the noise variance. Based on the noise variance a dynamic threshold was generated. The

start of the packet was determined to be when the received signal has a maximum correlation with the known preamble and exceeds the noise threshold [13].

We also tested a chirp signal as the preamble for synchronization due to its autocorrelation properties. We can also use the same chirp for synchronization and channel estimation to minimize the amount of data transmitted. As shown in Fig. 2, a correlation peak is detected at point A, and after a time guard of length T, the receiver starts to demodulate at point B which is the expected start of the data sequence.

Equalization: Long multipath delay spreads in the underwater channel make channel equalization significantly more difficult than radio channels and thus play an important role in the modem design. A significant number of equalization techniques have been proposed [14]. These are not a direct focus of this article, but must be mentioned in the design of a modem due to their importance in achieving low BER.

III. Simulation and Sea Test Results

To evaluate the proposed adaptive modem, we did both simulations and sea tests. We executed a set of simulations to find the best data rates for different links in a network and to understand the potential benefits of modifying the data rates on a per link basis. We also performed sea tests to evaluate the performance of the major components of the proposed adaptive modem in a real environment.

The parameters for the chirp, FSK and DSSS modulation schemes used in our simulations and sea tests are given in Table I.

TABLE I
CHIRP, FSK AND DSSS SIGNAL PARAMETERS

CHIRP SIGNAL PARAMETERS	
Sweep mode	up-chirp
Initial frequency	8 kHz
Maximum frequency	12 kHz
Sweep duration	50 ms
FSK & DSSS SIGNAL PARAMETERS	
FSK/DSSS carrier frequency	9 kHz
FSK/DSSS sampling frequency	192 kHz
FSK space frequency	10 kHz
FSK mark frequency	11 kHz

A. Simulation Results

We performed simulations using the Actup underwater acoustic propagation modeling software [15]. It generates the amplitude and delay profile of the received signal. The Actup simulations require that we set environmental parameters such as the communication range, water depth and the sound speed profile, and specify the location of the transmitters and receivers. We generated the underwater acoustic channel for five different transmitter and receiver pairs which were placed at different locations in the water column as shown in Fig. 3. The amplitude and delay profiles for links 1 and 5 are shown in Fig. 4. We observe that the two links have fairly different profiles which supports the fact that nodes in the underwater sensor network are likely to experience different channels.
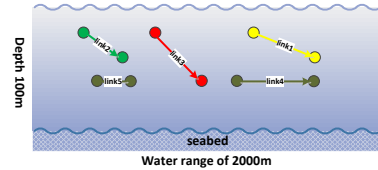

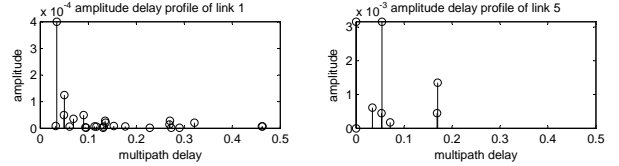Fig. 3. Underwater environment and the sensor nodes in Actup simulation

Fig. 4. Multipath amplitude and delay profile of link 1 and link 5

For this network scenario, we found the best data rate for each link in simulations using the channels generated in Actup. The simulations were performed for the FSK and DSSS modulation schemes. For each modulation scheme, the BER was computed over a range of data rates by demodulating 10 packets each containing 102 bits. The maximum data rate whose BER was smaller than 10^{-2} was considered as the best rate for any specific link. The simulation parameters for the described network scenario for each link and the corresponding best data rate are given in Table II.

TABLE II
BEST DATA RATES FOR DIFFERENT CHANNEL LINKS

	Actup Setup Parameters (m)			Data Rate (bps)	
Link	Tx depth	Rx depth	Distance	FSK	DSSS
link1	20	40	200	200	1900
link2	20	40	150	400	1900
link3	20	60	200	100	1900
link4	60	60	200	300	600
link5	60	60	50	40	800

The results show that the best data rate varies for different links in a network; it changes from 40 bps to 400 bps for FSK, and from 600 bps to 1900 bps for DSSS. Our results also show that rate adaptation can save considerable energy. For example in the case of FSK modulated transmissions, if we consider the best fixed data rate that allows reliable communication under the worst channel condition, all the links must communicate at 40 bps. The total energy consumed for each link transmitting one symbol is $0.125 * P_t$, where P_t is the transmitting power. Alternatively if the nodes perform rate adaptation and communicate at their best data rate, the total energy consumed is $0.0458 * P_t$. Therefore, rate adaptation gives an energy saving of 63.4%. In the same way, an energy saving of 45.8% is possible for DSSS. Moreover, faster data rates decrease the probability of collisions between different links, which in turn causes fewer retransmission and therefore costs less power. These results motivate the idea of an adaptive modem for underwater sensor networks.

B. Sea Tests

To evaluate the performance of the major components of our adaptive modem we performed experiments in the Pacific

Ocean in May 2011. The deployment setup is shown in Fig. 5. The transmitter was located at UC San Diego Scripps Pier, 20 feet below the water surface and the receiver was attached to the bottom hull of a boat residing at different locations. Data was collected at two sites at distances of 265m and 638m from the transmitter. For each site, FSK and DSSS data was transmitted at six different data rates. At each data rate, 20 packets containing 2040 symbols were transmitted.
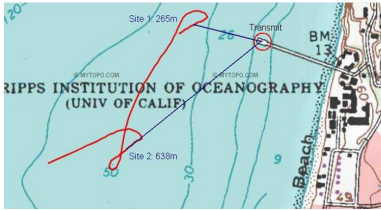

Fig. 5.   Sea test setup (the red line is the route of the boat)

The results showed that the chirp signal had a better synchronization performance compared to the Gold code. While the chirp was able to successfully synchronize to the start of the data sequence for all data packets, the Gold code could only successfully synchronize 68% of the packets at Site 1 and 70% of the packets at Site 2. This indicates that the chirp is a good candidate for channel estimation as well as symbol synchronization.

We computed the BER for FSK and DSSS modulated data when the chirp signal was used for packet synchronization. The results are summarized in Table III. We observe that the BER increases with data rate likely due to intersymbol interference. Further, the results show that DSSS modulation outperforms FSK. Finally, we observe that the average BER at Site 2 is higher than that at Site 1. To explain this, we estimated the channel for both sites as shown in Fig. 6. The figure shows that the Doppler shift and the multipath delay spread are both higher for Site 2 compared to Site 1. These sea test results correspond with our Actup simulation results in the sense that BER varies significantly with the data rates and channel between the sender and receiver.

TABLE III
SEA TESTS BER FOR SITE1/SITE2

Data Rate	BER of FSK (%)	BER of DSSS (%)
50	9.67 / 7.99	0.22 / 2.36
100	19.33 / 16.62	1.47 / 1.86
200	12.58 / 27.39	1.53 / 6.40
300	21.86 / 27.78	0.78 / 7.07
400	21.67 / 31.75	3.56 / 13.58
500	35.26 / 40.60	16.97 / 32.30

IV. CONCLUSION

This article makes a case for an adaptive acoustic modem in underwater sensor networks. We describe the potential benefits of the adaptive modem and describe a general digital hardware platform architecture. We perform a set of experiments and sea tests that quantify the benefit of different modulations, types of channel estimation and symbol synchronization. The results show that rate adaptation can lead to substantial energy
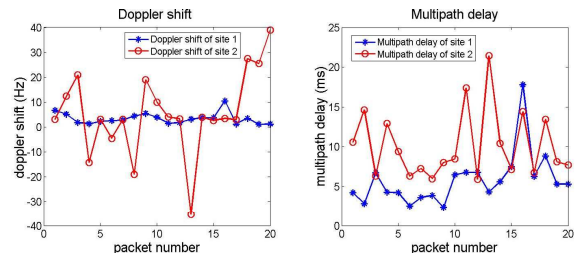

Fig. 6.   Doppler shift and multipath delay estimate for sea test.

savings while ensuring reliable communication. Furthermore, they show that a chirp signal is a good candidate for symbol synchronization and channel estimation. The simulations and sea tests indicate that DSSS modulation consistently outperforms FSK. Currently, we have finished the design of the major components and are building our system using hardware and software co-design implementation on an FPGA platform. Eventually our proposed adaptive modem will be able to change its modulation scheme and data rate automatically according to channel conditions in real-time.

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