Physical Layer Sensing Using Long Pseudo Noise Codes

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ABSTRACT
As research into building underwater sensor networks proceeds, researchers are focusing on using these networks to solve applicable problems. In particular we have found that underwater sensor networks are capable of performing acoustic tomography, even at very small scales. As sensor networks consist of a network of power constrained devices, researchers must also look for efficient ways to perform the required tasks.

In our work we are developing an acoustic tomography system implemented in an underwater sensor network. Traditionally, acoustic signals used for tomography would be followed by acoustic signals carrying data about the previous operations. In this paper we present an acoustic network physical layer that provides for simultaneous data transmission and sensing using the same acoustic signal. By combining data and sensing transmissions we conserve energy. We describe the physical layer followed by experimental data that shows our system can perform as desired.

1. INTRODUCTION
Underwater sensor networks are an attractive solution to the underwater sensing problem because they use low cost, networked nodes with on board sensors allowing researchers to deploy a multitude of nodes throughout bodies of water under study. Due to favorable propagation properties, most underwater sensor networks will use acoustic communications to create the network. Since the speed of sound for an acoustic signal in water is dependent on several physical properties (most significantly temperature and current flow), the time-of-flight for acoustic signal can be used for sensing. Thus the physical layer of an underwater sensor network can be used for sensing.

Deploying spatially distributed sensor nodes across an area increases the spatial resolution of the data collected, however there is almost always a limit (either financial or technical) to the number of nodes that can be deployed. Therefore, to further increase the spatial resolution of data collected for certain water properties (e.g. temperature), we are developing a small scale acoustic tomography system that can sense the properties of the water between nodes by leveraging the physical layer of the sensor network itself.

In general, water temperature is a critical piece of data that is collected by virtually every marine experiment. High resolution water temperature sensing in small to medium sized bodies of water has both ecological and national security applications. For example, harmful algal blooms are often triggered by the upwelling of colder, nutrient rich water. However, the upwelling is often only monitored in one location in a given coastal area, typically at a pier or buoy [13]. Since the spatial resolution of this data is very sparse, detailed analysis of the coastal dynamics that lead to the upwelling is difficult to study. By deploying several low-cost buoys (perhaps at different depths) and then performing acoustic tomography between the nodes, a greatly increased 2D or 3D image of the water temperature dynamics can be obtained.

As a national security application, sensor network acoustic tomography can be used to detect smaller submarines. Such submarines are quiet and with the development of materials that render boats acoustically transparent, they can be difficult to impossible to detect with active SONAR [17]. However, all submarines, diesel or nuclear, must dissipate heat into the water. A sensor network that performs acoustic tomography between the nodes can be used as a virtual submarine net across waterways of critical importance by detecting the thermal signature of a submarine.

Acoustic tomography is typically deployed at the scale of 100’s to 1000’s of kilometers. By using the calculated times-of-flight for acoustic signals through the water, tomographic inversion techniques create a water temperature map that includes reconstructed data points that are located between the transmitter/receiver pairs. While working with acoustic communications for underwater sensor networks, we conjectured that the acoustic communications channel could also perform this function, however at a much smaller scale (50 m to 1 km).

Therefore, we set out to develop a small scale acoustic topography system capable of providing increased spatial resolution and accurate temperature resolution. A key component of any acoustic tomography system is the acoustic signal (chirp) sent and received by the nodes to measure the time-of-flight. Chirps must provide for robust detection in the noisy underwater environment, while also providing sufficient time resolution, as the time resolution determines the limit of temperature resolution. We are targeting our
system to low power sensor network nodes, and thus cannot expect high-power transmissions. Hence we must develop a chirp signal that can be detected at our targeted distance with a minimum of transmit power.

We also observed that typical signals used for transmitting data underwater, do not necessarily provide the required attributes to be suitable as a tomography signal. This is before the cost of commercial underwater modems is considered. On the other hand, the signals used for chirps in SONAR and other underwater ranging techniques are not generally appropriate for use in a sensor network.

In this paper we describe our effort at building an underwater sensor network that can use the acoustic physical layer to sense and communicate. We present the details of our technique that provides for a large set of chirps that meets the requirements described above: robust detection in a noisy environment, sufficient time resolution and the ability to carry data transmissions. The technique uses long pseudo noise sequences modulated with binary phase-shift keying to generate large sets of orthogonal codes. A key contribution of this paper is the identification of an algorithm using Legendre sequences that can generate arbitrary length codes that are especially suited to this application. These long codes can be used to obtain large amounts of detection gain as required when transmitting in a very noisy environment. We describe and show results from real-world experiments carried out in our underwater testbed. These results show that our system performs as desired in a extremely noisy environment.

2. RELATED WORK

2.1 Ocean Acoustic Tomography

Ocean acoustic tomography is a technique to measure ocean temperatures by exploiting the relationship between water temperature and speed of sound in water. The technique was first proposed in 1978, and since then several experiments have been carried out[9, 16, 2]. These experiments have been conducted in open ocean locations such as the Norwegian Sea, Mediterranean Sea and Mid-Atlantic Ocean. Distances between nodes are on the order of 100's to 1000's of kilometers. Sound propagating over such distances in the ocean is bent along predictable paths ('rays') and thus ocean acoustic tomography can yield temperature data about the ocean at different depths, while time-of-flight for the acoustic signal is measured in minutes.

We have drawn inspiration from ocean acoustic tomography, however we must take into account two important differences. First we are able to simplify the tomographic inversions because at distances of less than 5 km we can assume that sound is taking a direct path between transmitter and receiver[12]. On the other hand we must develop a highly precise time-of-flight measurement system because the travel time for an acoustic signal at short distances is measured on the order of 10's of milliseconds with changes due to temperature on the order of 10's to 100's of microseconds.

2.2 Underwater Acoustics: Sensing, Ranging, and Communications

Performing specialized acoustic tomography, an inverted echo sounder (IES) is a device that measures the average temperature of a water column at a point location in the ocean. The device is placed on the sea floor and transmits a ping to the surface. This ping is reflected off the surface of the water and when received back, the round-trip-time is calculated. Given the depth of the water at the IES, the average temperature of the water column can be calculated. This technique operates at the same distances as our system, however we envision a sensor network of active transmitters and receivers at different depths which can provide 2D or 3D temperature maps.

Underwater positioning systems such as long or short baseline navigation systems use a set of fixed location transponders that reply with fixed delay to interrogation signals. Given the round-trip time and fixed delay, the acoustic propagation time and thus distance to the transponder can be calculated. With adaptation, such a system could be used to perform tomography. However, existing systems are designed for a specific positional accuracy which dictates the required time-of-flight accuracy. Thus, the time-of-flight accuracy required to obtain the positional accuracy specified by current underwater ranging systems is typically insufficient for use as a tomography system.

Underwater acoustic communications is a well studied field with a plethora of academic papers published on modems, modulation techniques and media access control schemes[14, 1, 3, 15]. These academic researchers offer details on how to construct specific components from the transducers to DSP or FPGA based modems. There are also several commercial underwater modems systems that offer varying bit rates and modulation schemes. Two modulation methods are worth discussing here, frequency shift keying (FSK) and direct sequence spread spectrum (DSSS).

Frequency-shift keying has been shown to have good properties under a wide range of conditions in underwater communications and is therefore offered as a modulation technique on most underwater modems. FSK offers reliable communication and simple modulator/demodulator design, however it does not perform well in the presence of multi-path interference, and is thus most suited to open or deep waters. We are specifically targeting (but not limited to) shallow coastal waters, or even lakes, and thus need a system that performs well in the presence of multi-path interference and low signal to noise ratio.

Direct sequence spread spectrum communications systems draw on the advantageous mathematical properties of long pseudo-noise codes to improve noise immunity (spreading gain) and resistance to multi-path interference. DSSS systems include a synchronization method that can be used for precise time-of-flight mechanisms, however the spreading gain may not be enough to overcome a noisy channel with very low transmit powers.

A well cited example modem is the WHOI MicroModem. The feature most similar to our system is the wide-band REMUS compatible navigation system. This system use a coded PSK signal to interrogate transponders. Using the known locations of the transponders and the round-trip-times, the modems can perform ranging. If the locations of the nodes in a sensor network is known and fixed, ranging is equivalent to performing tomography, however due to system design the WHOI MicroModem allows for $125\mu s$ in temporal resolution. Our system is capable of delivering approximately 10 times the temporal resolution.
families of pseudo-noise codes have been used in spread spectrum techniques because they provide signal-to-noise ratio gain by spreading the signal out in time. These code families are also constructed such that the cross correlation function (CCF) of any two codes has a maximum of some small magnitude, while the auto correlation function (ACF) for any one code is large (near or at the Welch bound). The length of a code determines the spreading gain, if \( P \) is the length then spreading gain \( G \) is \( 10 \log_{10}(P) \). Thus in our underwater sensor network adjusting the spreading gain is the primary ‘knob’ by which we can tune the system to overcome a noisy channel.

Gold, Bent or No \([5, 11, 10]\) codes are common families used in DSSS (and therefore CDMA) systems for RF or underwater communications. However, by their construction \( P = 2^n - 1 \) with \( n \) increasing by a minimum of two when increasing the code length. This results in a minimum increase in code length of a factor of 4. For example, if we were using a code length \( P = 511 \) and required more spreading gain, the next two code lengths are of \( P = 2047 \) and \( P = 8191 \).

Therefore we select a code family constructed by Guohua and Quan \([7]\) based on Legendre sequences where the length \( P = 3 \mod 4 \), i.e. the length is a prime number where \( P + 1 \) is a multiple of 4. These sequences have several desirable properties: good CCF and ACF properties, good balance properties and flexible code length. See section 6 for a summary of the construction method.

To build our set of orthogonal chirps we choose the length \( P = 3 \mod 4 \), and some decimation \( d \). When then choose a number of \( k \)'s to give us the desired number of codes. These parameters are used as shown in section 6 and will generate a set of orthogonal binary sequences from set \( M \) or \( N \) that have the desired ACF and CCF properties.

Finally, we use binary phase shift keying to modulate a carrier of appropriate frequency (we use 12 kHz or 18 kHz) with the orthogonal codes. This gives us a (potentially large) set of codes that can be used for sensing and communications at low signal to noise ratios in the underwater environment.

4. UNDERWATER EXPERIMENTS

4.1 Marina Del Rey Testbed

As sensor network research at its core is about sensing the environment, we endeavor to focus our research on solutions that perform in the real world. To provide a real-world environment for underwater acoustic sensor network research, we have constructed a five node underwater testbed at a small boat marina located in Marina Del Rey, California. Each node consists of a standard small-form-factor PC, GPS receiver, receive hydrophone and transmit hydrophone with a power amplifier. The computers are networked to our offices across the street using inexpensive 5GHz Wi-Fi equipment. The nodes are placed in various locations around the marina, with internode distances varying from 60 m to 200 m. As discussed in \([6]\) our novel use of the GPS pulse-per-second signal allows for acoustic time-of-flight measurements accurate to approximately 10\( \mu s \). For deep underwater applications we show similar accuracy, but without the need for GPS.

Figure 1(a) shows the locations of the nodes in the MDR testbed. Figure 1(b) is a schematic diagram indicating the node names used for the experiments discussed in this paper. The remainder of this section describes several experiments...
4.2 Orthogonal Data Transmissions

For this experiment a set of BPSK modulated codes of length 3067 were created (referred to as 'q1', 'q2', 'q3'). The modulation frequency was set to 12 kHz, thus at a sampling rate of 96 kHz the signals are approximately 255 ms in duration. The code 'q1' was transmitted from node C, while the code 'q3' was transmitted from node D. The signals were received at node A. The transmissions were co-ordinated so as to arrive overlapping. Figure 2(a) shows the audio from the marina at the time of transmission. Figures 2(b) and 2(c) show the overlapping, yet successful detection of the orthogonal signals. With this simple experiment we show that our system has sufficient spreading gain to overcome the noisy marina environment, while also showing that the generated codes are orthogonal and do not interfere with each other.

4.3 Physical Layer Sensing

To show that we can perform sensing with our system we sent the tomography signal between nodes C and D. Each node transmitted their assigned signal at the start of each minute over one week. Additionally, a USB temperature sensor was used to record the water temperature at each node. Figure 3(a) shows time-of-flight recorded between these nodes and figure 3(b) shows the USB temperature data. The strong correlation between these signals shows that we can measure the arrival time of an acoustic signal accurately enough to detect time-of-flight changes caused by changes in water temperature. Further, to show that our system can yield useful information about the water temperature between the nodes, we can test the following hypothesis. Since the heating of the marina is mostly due to exposure to the Sun, we expect the water along the paths with fewer covering docks to heat up faster. We use three nodes (A, C and D) for this experiment. In our experimental arrangement the two paths originating from node D (paths AD and CD) are primarily through uncovered water. Additionally, the marina is shallower at the eastern end (near node A), so we also expect path AD to heat up faster than path CD. As it is mostly covered by docks, we expect the path between nodes A and C (path AC) to heat up slowest.

With the time-of-flight measured between the nodes we can use the MacKenzie Equation [8] to calculate the average water temperature between the nodes. We use the data collected at various times over one day, and calculate the temperature change starting at 10am. The data is shown in figure 4. The data nicely confirms our hypothesis, showing that the shallow uncovered path AD heats up faster as the Sun comes out, whereas the mostly covered path AC heats up slower and experiences less temperature rise overall. Path CD is in the middle, it starts to heat up a little after path AD, but eventually heating approximately the same amount.

5. CONCLUSION AND FUTURE WORK

In this paper we have presented an underwater acoustic communications system that can also be used for acoustic tomography. Based on a class of codes derived from Legendre sequences, the flexible code length enables the system to be tuned for low power transmissions as are required by underwater sensor networks. The system allows for simultaneous data and sensing transmissions, a key contribution that conserves energy. We present results from a set of experiments that show our system does indeed have the required properties to perform correctly in a noisy, real-world environment. We believe the presentation of our microtomography results
represents the first 2D acoustic tomography performed at such a small scale.Going forward we are looking to design embedded, real-time underwater sensor network nodes that will implement the physical layer presented here to enable the ecological, commercial and defense applications described in our introduction.

6. APPENDIX A: CONSTRUCTION OF GUOHUA AND QUAN SEQUENCES

This section is a summary of the construction method found in [7]. Arithmetic operations on the sequences below are performed position-wise modulo 2. First we define a number \( q \in \mathbb{Z} \) to be a quadratic residue if 1 does not hold, and we denote the set as \( QNR \).

A Legendre sequence \( L(t) \) of period \( P \), \( P \) prime is defined as:

\[ L(0) = 0, \forall t < P \quad QNR \]

\[ L(t) = 1, \forall t \in QNR \]

If \( L_d \) is the decimation by \( d \) of the sequence \( L(t) \) (i.e. taking every \( d \)th element of \( L(t) \)), Guohua and Quan show that for Legendre sequences, \( L_d(t) \) takes only one of two forms:

\[ L_d(t) = L(t), d \in QRP \]

or

\[ L_d(t) = 1 + L(t), d \in QNR \]

Finally we define the operator \( T^k \) as a cyclic left shift by \( k \) positions. Given the above equations Guohua and Quan construct the following sets:

\[ M = \{T^k L_d(t) + L(t), t = 0, 1, \ldots, P-1\}, k = 1, 2, \ldots, (P-1)/2 \]

\[ N' = \{T^k L_d(t) + L(t), t = 0, 1, \ldots, P-1\}, k = (P+1)/2, \ldots, P-1 \]

\[ N = N' \cup L \]

7. REFERENCES


