ON THE MUTUAL INFORMATION OF THE MOVING TARGETS IN UNDERWATER WIRELSS COMMUNICATION

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Abstract**—** In this paper, we analyze the mutual information of moving target in underwater wireless communication system by placing the acoustic sensor nodes at optimal location to achieve optimum mutual information. The performance of acoustic sensors nodes are observed and analyzed by placing the sensors in collaborative and parallel channel network system. Different numerical calculations and experimental observations for both network systems focusing on probability of error, entropy of message signal, information loss, bit error rate, cross correlation, and a minimum mean square error, are presented. The use of fundamental information theoretic tools in calculating the mutual information between input and the output of a channel has given an interesting insight and in order to find the channel capacity.

Index Terms**—**mutual information, channel capacity, maximum rate of information, acoustic wireless, underwater sensor communication, acoustic channel, collaborative network channel, parallel network channel.

I. INTRODUCTION

This paper basically explores the experimental evaluation and simulation result of mutual information between transmitted signal and received signal via different channel in underwater communication, yielding maximum data rate and minimum loss of information. The result contributes to a more thorough understanding between the amount of information one random variable contains about another for our domain of interest in underwater communication system. We address optimal estimation of correlation between input and output digital signals. We generated the 1024 code length of pseudo random sequence using the 10^{th} order polynomial in Matlab simulation tool box as an input to the channel. We also find covariance and information loss in transmission of data in collaborative channel using the principle of data process inequality and parallel channel. The major factors we will consider is the study the mutual information of input and output signals are cross correlation, joint entropy, minimum mean square error, signal to noise ratio, and probability error.

Communication in underwater is difficult since radio waves do not travel well in salt water. Very low frequency radio waves i.e. 3-30 KHZ can penetrate sea water to a depth of approximately 20 meters and it is highly affected by noise. Similarly, optical communication in underwater can carry significantly more information but limited in distance to a few hundred meters. Acoustic communication is the most versatile and widely used technique in underwater environments due to the low attenuation (signal reduction) of sound in water. This is especially true in thermally stable, deep water settings. On the other hand, the use of acoustic waves in shallow water can be adversely affected by temperature gradients, surface ambient noise, and multipath propagation due to reflection and refraction.

The much slower speed of acoustic propagation in water, about 1500 m/s (meters per second), compared with that of electromagnetic and optical waves is another limiting factor for efficient communication and networking [1]. Therefore, acoustic waves are practical for underwater acoustic sensor networks from the physics and communication point of view but also a tremendous amount of work is demanded from the networking perspective.

Multiple sensors deploying in underwater can monitor and detect more environmental parameters. Underwater wireless sensor networks provide better sensing and surveillance technology to acquire better data and information. Our approach is to investigate an underwater distributed sensor networks and analyze how the communication of transmitting sensor message signal is correlated to receiving sensors. Underwater Wireless Communications (UWC) is affected by transmission loss depending upon the signal attenuation, interference, distance between transmitter and receiver, multipath and geometric spreading of sound energy,

Path loss in an acoustic channel over a distance d is given by, $PL = \mathrm{dk}\alpha(f)$, where k is the path loss exponent whose value is between 1 and 2, and $\alpha(f)$ is the absorption factor that depends on the frequency f. Path loss is an energy loss along each propagation due to geometric spreading, absorptive loss, and scattering loss. The effect of the noise is another factor that causes challenges in UWC. Noise could be two types—man made noise and ambient noise. Man-made noise is caused by machinery noise and shipping activity while Ambient noise is related to hydrodynamics, seismic and biological phenomena.

The multi-path geometry depends on the link configuration. Vertical channels are characterized by little time dispersion; whereas horizontal channels may have extremely long multi-path spreads, whose value depends on the water depth [2]. For number of distinct paths between the source and the receiver, we also observe a propagation delay. Similarly, there will also be a channel delay spread which is a time difference between the first and last arrivals of multipath propagation. When there is a large channel delay spread, it introduces time dispersion of a signal which causes inter symbol interference.

The Doppler frequency spread is also significant in underwater wireless acoustic channel, causing degradation in the performance of digital communication. Motion of the transmitter or receiver contributes additionally to the changes in channel response causing frequency shifting as well as additional frequency spreading. We assume that the following factors will cause the significant role in variation of cross correlation between input-output signals and thus affect the mutual information of transmitted and received signals.

II. CHANNEL CAPACITY MEASUREMENT

Acoustic communication channel capacity determines the maximum data rate that can be supported by an acoustic channel. Finding the maximum data rate has important practical implications. In order to obtain the upper bound on the channel capacity, we will assume that both the transmitter and receiver know the channel transfer function exactly for each transmission, and that the channel function doesn't vary during each transmission [3].

According to Shannon's theorem, a given communications system has a maximum rate of information C known as channel capacity. If the information rate R = rH, where r=rate at which message are generated (message/second) and H=Entropy for message in bits/message.

$$\text{Maximum rate of information (R)} \leq \text{Channel capacity(C)}$$

If the information rate R is less than C, one can approach small error probabilities by using intelligent coding techniques. Increasing rate of information will increase SNR.

Shannon theorem states that the channel capacity is given by

$$C = Blog_2(1 + \frac{S}{N})$$

where C is the capacity in bits/second, B is the bandwidth of the channel in Hertz, and S/N is the signal to noise ratio. According to information theory, the channel capacity is the maximum average information that can be sent per channel use. Mutual information is the function of probability distribution of transmitted signal. By changing the probability distribution of transmitted signal, we receive different I(X; Y).

A maximum mutual information achieved for a given transition probability matrix (a fixed channel characteristics) is the channel capacity.

$$C_x = \max_{p_x} I(X;Y)$$

The mutual information I(X; Y) is the relative entropy between the joint distribution and the product distribution.

$$I(X;Y) = \sum_x \sum_y p(x,y) \log \frac{p(x,y)}{p(x)p(y)}$$

To understand the mutual information, we need to understand entropy and conditional entropy. According to Shannon, entropy is a measure of uncertainty- the higher the entropy, the more uncertain one is about a random variable.

$$H(X) = -\sum_x P_X(x) log P_X(x)$$

The conditional entropy is the average uncertainty about X after observing a second random variable Y, and is given by,

$$H(X|Y) = \sum_y P_Y(y) \; \left[-\sum_x P_{X|Y}(x|y) \log(P_{X|Y}(x|y))\right]$$

where,

$$P_{X|Y}(x|y) = \frac{P_{XY}(x,y)}{P_Y(y)}$$

Therefore,

$$I(X;Y) = H(X) - H(X|Y) = H(Y) - H(Y|X)$$

it is also a one way among many of measuring how related two random variables are. However, it is measure ideally suited for analyzing communication channels. Communication channel can be visualized as a transmission medium which receives an input X and produces output Y. If the channel is noiseless, the output will be equal to input. However, in general the transmission medium is noisy and an input x ix converted to y with probability $P_{Y|X}(y|x)$.

$$x_1x_2x_3 \dots \dots . x_n \dashrightarrow [noisy\ channel\colon\ P_{Y|X}(y|x)] \dashrightarrow y_1y_2y_3 \dots \dots . y_n$$

The maximum number of messages that can be transmitted almost error free is a function of the mutual information between X and Y. If a communication channel is considered that transmits 0's and 1's, and transmit correctly with probability q.

$$P_{Y|X}(1,1) = P_{Y|X}(0,0) = q$$

Since binary bits 0 and 1 are used in transmitting messages, $P_X(0) = P_X(1) = 1/2$

The probability of making error or the probability particular message to occur is given by,

$$P_n = \left[(\frac{1}{2})^{n/2} \frac{\left(\frac{n}{2}\right)!}{\left(\frac{qn}{2}\right)!\,((1-q)n/2)!} \right] \text{^}2$$

$(\frac{1}{2})^{n/2}$ is the probability of a particular message occurring and rest computes all the ways to arrange symbols.

III. BIT ERROR RATE AND INFORMATION LOSS

Bit error rate is the change in received bots of data stream due to noise, interference, distortion, and bit synchronization errors. Each time we run a bit-error-rate simulation; we transmit and receive a fixed number of bits. We determine how many of the received bits are in error, and then compute the bit-error-rate as the number of bit errors divided by the total number of bits in the transmitted signal.

The transmission loss or information loss in underwater wireless communication is accompanied by various physical and technical factors which we discussed in an introduction. Besides being channel noisy, underwater wireless communication is affected by surface duct, surface reflection, sound propagation characteristics, bottom bounce etc.

Information loss is induced by passing signals via a noisy channel. In our work, conditional entropy is used to quantify the information loss induced by passing pseudorandom sequences through an underwater channel system. Information loss can mostly be expressed as the difference of mutual information. The information loss rate for input X and output Y for any transmitting channel is given by,

$$\bar{L}(X \longrightarrow Y) \coloneqq \lim_{n\to\infty} \frac{1}{n} L(X_1^n \longrightarrow Y_1^n) = \lim_{n\to\infty} \frac{1}{n} H(X_1^n\,|Y_1^n)$$

This is the average of the block information loss. The information loss in the systems can be computed as:

$$L(X \longrightarrow Y) = H(X|Y)$$

IV. EXPERIMENTAL MODEL AND PROCEDURE

In order to compensate the information loss in UWC we implemented pseudo random sequences as our input signals. M-sequences are the nearest approximation to random sequences. M-sequence code mimics the second order statistical behavior of a white noise. Pseudo random sequence is generated by employing several linear feedback shift registers. A PN sequence generated by a linear feedback shift register must eventually become periodic with period at most $2^m - 1$, where m is the number of shift register. A PN sequence whose period reaches its maximum value is named the maximal- length sequence or simply m-sequence.

PN sequences generated from linear shift register satisfy following three properties. First, balance property i.e. the number of 1's is one more than that of 0's. Second, run property i.e. the total number of runs $=2^m - 1$. And third, correlation property i.e. the periodic autocorrelation function is mathematically expressed as:

$$\theta_b(k) = \begin{cases} 1 & for\ k = lN \\ -\frac{1}{N} & for\ k \neq lN \end{cases}$$

where, l is any integer and N is the sequence period.

We used the 10[th] order polynomial in Matlab simulation tool box to generate the 1024 code length of pseudo random sequences. Therefore, in our experimental work we will transmit these 52 m-sequence of length 1023 bit. The output will be correlated with input m-sequences, evaluate mutual information, find covariance and information loss in transmission.

We are trying to optimize the mutual information and see the correlation between transmitted signals and received signal. Since, UWC is band limited; we examined different modulation techniques that would increase the waveform bandwidth while maintaining pulse duration. We focused on linear frequency modulation (LFM) and spread spectrum techniques. Specifically, we modulate the transmitted signal using LFM and maximal length sequence, also called m-sequence. The idea behind is to increase the pulse bandwidth and signal resolution.

Let X and Y be the two binary sequences of period T. The cross correlation function between these two sequences at shift n, where for each n $0 \leq n \leq T$, is defined by

$$C(n) = \sum_{i=0}^{T-1} (-1)^{X_i + Y_i + n}$$

Besides, we use the data collected from collaborative sensors and give a maximum likelihood formulation in concordance with relation between mutual information and the minimum mean square error (MMSE) on Gaussian channel.

$$\frac{d}{dsnr} I(snr) = \frac{1}{2} MMSE(snr)$$

Mutual Information *I(snr)* tells how much coded information can be transmitted through a channel reliable given a minimum probability error P_e . The MMSE estimates the input given output or represents how accurately each sample can be recovered using the channel output.

V. SIMULATION RESULTS AND CONCLUSION

The simulation result of transmitted and received signal in an ideal channel plus real environment using a MATLAB software and its Simulink library is found by plotting various results for correlation among two signals, coherence, autocorrelation, and mutual information. **Figure 1** represents the cross correlation between the received signal and transmitted signal of the real data from underwater wireless channel in swimming pool. The **Figure 1** plot shows the variation in the coherence of input and output data due to system noise, multipath, and propagation loss. **Figure 2** is the autocorrelation of one pseudo random sequences (also called one m-sequence of 1023 bits length), which is perfectly 1. Similarly, **Figure 4** and **Figure 5** represent the autocorrelation and cross correlation of the input and output signals in an ideal channel designed in MATLAB Simulink. The plots for both simulations are quite identical which tell that in an ideal channel there is no noise loss and propagation loss. Therefore, we will study the result obtained from simulation of cross correlation which will help us to find the maximum mutual information that leads to the channel capacity of the given system.

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REFERENCE

[1] **Liu Lanbo, Zhou Shengli, Cui Jun-Hong, *"Prospects and problems of Wireless Communication for Underwater sensor networks"*** Special Issue: Underwater Sensor networks: Architecture and Protocols, Volume 8, Issue 8, pages 977-994, October 2008.

[2] **Ian F. Akyildiz, Dario Pompili, Tommaso Melodia, *"Challenges for efficient communication in underwater acoustic sensor networks"*** Special issue on embedded sensor networks and wireless computing, Volume 1 Issue 2, July 2004, pp. 3-8.

[3] **Thomas J. Hayward and T.C. Yang, *"Underwater Acoustic Communication channel capacity: A simulation study"*** Naval Research Laboratory, Washington, DC, AIP Conf. Proc. 728, pp. 114-121.

[4] **Geir Jarle Ness and Tor Helleseth, *"Cross correlation of m-sequences of different lengths"*** Information Theory, IEEE Transactions on Volume: 52, April 2006, pp. 1637-1648.

[5] **Ning Han, SungHwan shon, Jae Hak Chung, Jae Moung Kim *"Spectral Correlation Based Signal Detection in IEEE 802.22 WRAN systems"***. Advanced Communication Technology, 8th International Conference.

[6] **Daniel P. Palomar and Sergio Verdu, *"Representation of Mutual Information via Input Estimates"*** IEEE Transactions on Information theory, vol. 53, No. 2, February 2007.

[7] **V. Sharma and S. K. Singh, *"Entropy and channel capacity in the regenerative setup with applications to Markov channels,"*** in Proc. IEEE Int. Symp. Information Theory (ISIT 2001), Washington, DC, Jun. 2001, p. 283.

FIGURES:

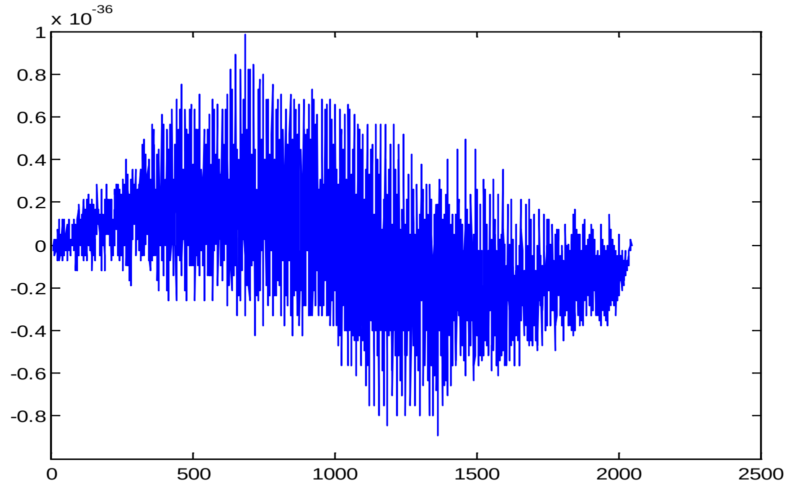

Figure 1 Cross correlation between Transmitted signal and Received signal for UWC channel

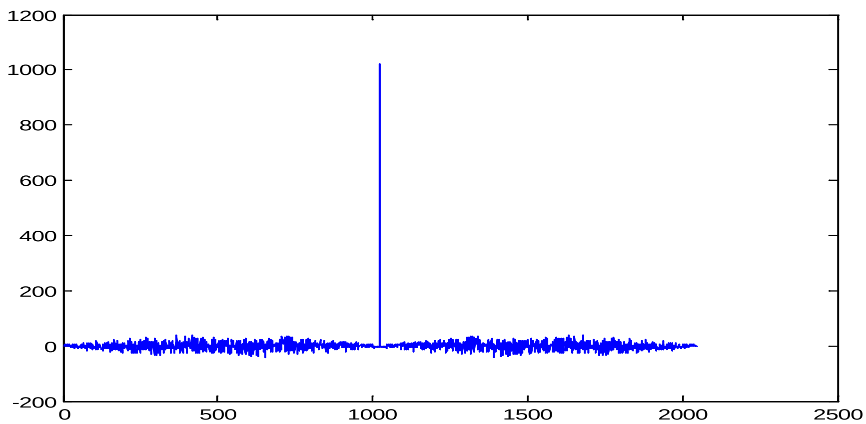

Figure 2 Autocorrelation of single transmitted m-sequence

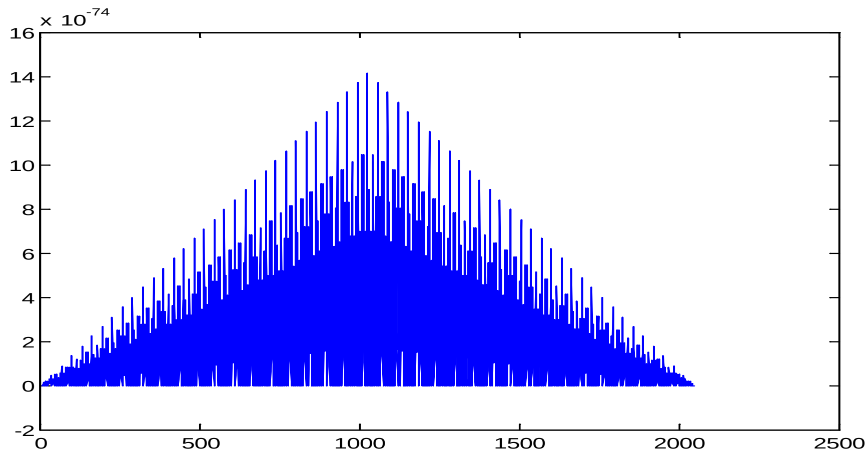

Figure 3 Autocorrelation of Received signal in UWC channel

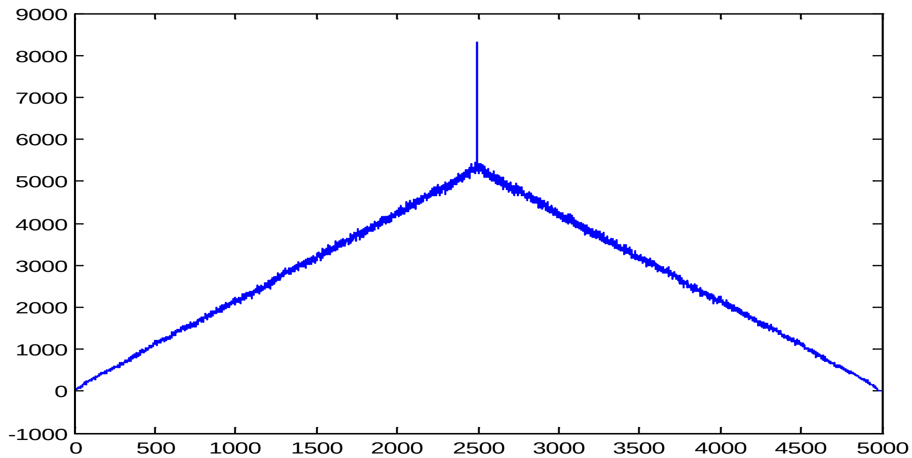

Figure 4 Simulation result for autocorrelation of random integers transmitted in ideal channel

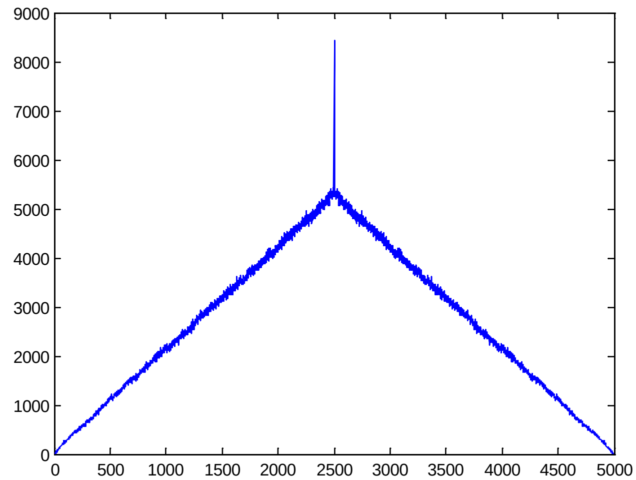

Figure 5 Simulated result for cross correlation of transmitted and received signal for ideal channel