On the Mutual Information of Sensor Networks in Underwater Wireless Communication: An Experimental Approach

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Abstract— **In this paper, we analyze the mutual information of sensor networks in an underwater wireless communication system by placing the acoustic sensor nodes at different location in order to achieve optimum mutual information. The performances of acoustic sensors nodes are observed and analyzed by placing the sensors in collaborative and parallel channel network system. Different numerical calculation and experimental observation for both network systems such as information loss, bit error rate, mutual information, and channel capacity are considered.**

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

I. INTRODUCTION

Underwater wireless sensor networks provide better sensing and surveillance technology to acquire better data and information by deploying multiple sensor nodes. Our approach is to investigate a distributed underwater sensor networks and analyze the communication channel between transmitting sensor and receiving sensor nodes. After the wide development in wireless digital communication for the underwater environment, it is important to improve the performance of existing system such as data rate, channel capacity, information loss, probability of error etc. Underwater Wireless Communication (UWC) impose many constraints that affect the design of wireless network such as path loss, transmission distance, energy absorption by water, long propagation delays, channel dispersion, Doppler effects, and interference [1].

In this paper we focused on the underwater wireless sensors (UWS) in collaborative and parallel network model. We used the SAM-1 miniature acoustic modem set in order to transmit and to receive sensor data by placing them at different location and depth. In this sensors network networks we focused on:

1. Bit error rate between input and output signal in an underwater wireless communication. Bit loss is given by transmitting binary sequence of maximal length, also called *m*-sequences and observing the received bits at receiver side.
2. Channel noise for underwater acoustic communication transmission medium that transmits, input data sequences and produces output *Y* of data sequences . If the channel is noiseless, the output will be equal to input. However, in practical situations, the transmission medium is noisy and an input is converted to the output *Y* with probability .

(1)

3. Analyzing the Information loss *(L)* between two different sensors network models using the knowledge of entropy. Information loss is calculated from conditional entropy of input and output data.

(2)

(3)

4. Evaluating the maximum number of messages that can be transmitted almost error free, which gives the mutual information between *X* and *Y*.

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

For this experimental approach, we used information theoretic tools such as the entropy, conditional entropy, mutual information, probability mass function, and joint probability mass function of each input data signal and output data.

The average mutual information between the transmitted and received sequences *X* and *Y* is given by

—

where $I(X; Y)$ is the mutual information between the random vectors X and Y and M is block length. The channel capacity is the maximum value assumed by the average mutual information over all possible probability distribution of the transmitted signals consistent with some input constraints such as transmitted power, frequency, and bandwidth.

In this paper, we performed a comparative analysis of the influence of various acoustic transmission loss models for optimum placement and location of sensor network in underwater to reduce effect of loss and thus increase the rate of data transmission with lesser probability of error [2]. At first, we investigated the noise itself in an underwater communication channel, distance between transmitter and receiver, multipath and geometric spreading of sound energy.

The rest of the paper is organized as follows. In Section II we introduce the experimental system model setup for collaborative and parallel network system and we discuss mathematical evaluation procedure for both system networks. In Section III, we approximate the models to improve the existing performance of UWC system. Section IV gives numerical and simulation results for different sensor network model. Conclusions are summarized in the last section which includes related work in similar field and future work.

II. CHANNEL MODEL

The transmission loss in underwater wireless communication is accompanied by various physical and technical factors which we discussed in an introduction. In UWC, transmission loss is due to absorption, spreading, propagation, surface reflection, and channel noise. In our work, conditional entropy is used to quantify the information loss induced by passing pseudorandom (PN) sequences through an underwater channel system. PN sequences are deterministically generated but yet they are almost like random sequence of 0's and 1's with equal probability of occurrence. Information loss can mostly be expressed as the difference of mutual information and entropy of transmitted signal:

(6)

A. Collaborative Sensor Network System

In UWC, acoustic links and their propagation characteristic differ in terms of distance, time, and multipath spreads. Collaborative sensor network model influences the acoustic communication in order to state the challenges posed by path loss, geometric spreading, multi-path, and Doppler spread.

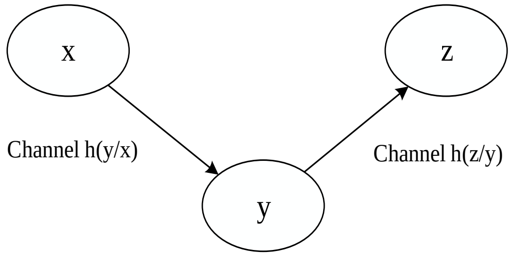

Fig. 1. Cascaded channel model.

The Fig 1 shows that the use of multiple sensor nodes in underwater to form a collaborative network system can increase the information contained in signal Y about signal X [3]. We use the data processing inequality to show that information loss can be reduced forming the sensor nodes as a Markov chain. For data transmitted through , the conditional distribution of Z depends only on Y and is conditionally independent of X. Specifically, the join probability function of for X, Y and Z can be written as:

(7)

Therefore, the mutual information between random variable X and Z will be improved with addition of another sensor node Y in between the propagating distance of X and Z. This approach of creating n cascaded channels to transmit data from one node to another will effect in the information loss, mutual information, and channel capacity of the system.

Each sensor node in the network becomes a primary transmitter with its own probability density function and new energy level. The objective of our work is to organize the sensors in cascade system to maximize the transmitted signal power along large distance of propagation in an underwater communication [4].

In this sensors network model, we wish to retransmit the received signal to another sensor node exactly as they are received. Thus, in order to obtain the input-output statistics of the cascade, we need only to consider the signal as one sample at a time. Let the sample X of the first transmitter has its corresponding probability $p(x)$. The signal X will transmit down the first channel and will be received as Y_1 by the first receiver sensor node, Y_2 by the second receiver sensor node, and finally as Y_i by the last receiver sensor node. During the observation of downstream transmission of signal data from X to Y_i , each channel will have different conditional probability distribution since the channel state is changing with time i.e. for the i^{th} channel gives the probability distribution of the samples Y_i .

In terms of distance of propagation and energy of wireless sensor node in an underwater, the use of multiple nodes forming a cascade channel will help to reduce the information loss and increase the signal to noise ratio (SNR), thus increasing the channel capacity of the signal [5].

The channel capacity for discrete time Gaussian channel with signal power *'S'* and the noise power "*N*" is given by, However, for bandwidth limited performance,

It can be easily seen form (9) that, for a source with constant power and limited bandwidth, the capacity of a channel is highly dependent on the noise in the channel. The effect of signal power, bandwidth, and distance in capacity of channel is discussed in [8]. But in this paper, we assume the transmitted signal power and bandwidth is limited during our experiment. We see the effect of acoustic sensors network in terms of bit error and mutual information for different network model.

For , we know the channel capacity is equal to

(10)

However, by cascading and by using the data processing inequality we have for :

(11)

We can find the of both sides:

(12)

In order to find the capacity of the product channel of Markov chain [4] we will obtain in succession:

(13)

Therefore,

(14)

Similarly, to calculate the information loss in between the cascaded channel system, we individually estimate the conditional entropy for each channel communication.

Intuitively, in cascaded channel, output *Y* of input data *X* is directly used as input to transmit to *Z*. This will show us

(15)

B. Parallel Sensor Network System

Let us consider the power of signal *X* be *P*. Assuming additive white Gaussian noises, Z_1 and Z_2 with zero mean and variance as in Fig.2, we will obtain

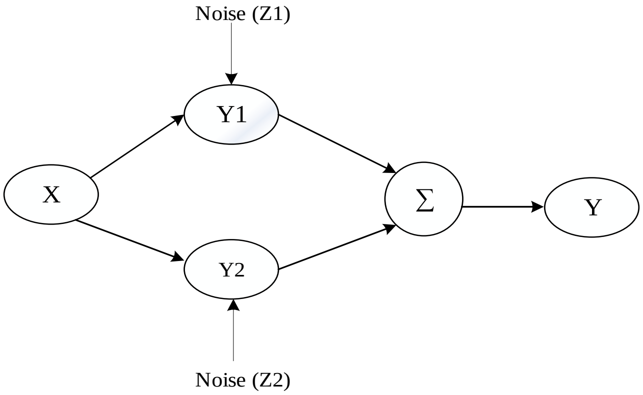

Fig. 2. Parallel sensor network system

(16)

The channel can be reduced to,

(17)

By using the equation (14) and (15), the channel capacity formula is:

When we have cost constraint on the power, we need to optimize the total capacity of the two parallel channels,

Let the two outputs Y_1 and Y_2 be conditionally independent and conditionally identically distributed given *X*. Thus,

(20)

Therefore,

(21)

Hence, the capacity of channel is

(22)

Similarly, information loss in our discrete data communication can be calculated from conditional entropy estimation for between input and output data. Comparing the best output result from parallel channel, we estimate the conditional entropy to obtain the information loss rate [6].

where is marginal pmf for output Y and is the channel error estimation.

In parallel channel network system,

(23)

III. EXPERIMENTAL MODEL

Our experimental model consisted of an indoor swimming pool, two pairs of SAM-1 acoustic transducers provided by Desert Star Systems, four portable computers all of them equipped with MATLAB software, signal processing toolbox, and communication toolbox, a hydrophone to measure sound underwater, and an acoustic speaker to generate noise. The data was transferred using transducers and was processed in MATLAB. Figure 3 and Figure 4 illustrates our prototype environment.

The maximum distances between two communicating sensors were 15 meters. The sensors were positioned such that they could float in water and move freely. We are optimizing the sensors locations and sensitivity analysis to increase the mutual information and channel capacity [7].

The modems can operate in the range of 250 meters. The transmitting power of sensors depends on the voltage supply (ranging from 183dB at 8V to 189dB at 16V).The modems were configurable to specific data rate. However, increase in data rate decreased the range of transmission. Therefore, we configured the sensors to operate in 13 bits per second. The main problem in our experiment was the limited storage of the modems. The buffer memory size was only 32 bytes and each bits sent via serial port were codded as 8 bits. As a result, we were only able to send maximum of 32 bits at a time from the m-sequences of length 1023. So practically the length of the sequence could be considered 32 for one transmission.

The acoustic modems transfer serial data at 4800 baud, 8 data bits, no parity, and 1 stop bit. Flow control should be set to software handshaking. However, we observe that software handshaking would affect data rate. It is worth mentioning that serial communication using, 'fprintf' 'fscanf' and 'fwrite' functions in MATLAB does not populate the data every time it gets. Instead data is exported to workspace after a certain period. We used Simulink to transmit the whole 1023 length sequence.

To perform serial communication from MATLAB software, we first define the serial port object and then configured device parameters for communication. Values sent, received, transfer status and bytes available were recorded in MATLAB for tracking purpose.

A. *Collaborative sensor network experimental setup*

In cascaded sensor network we transmitted data from sensor 1 and received the output data in sensor 2. Then we transmit the received data from sensor 2 exactly as it was received to sensor 3. And same process was repeated to send data from sensor 3 to sensor 4. The output at sensor 4 was compared with input data at sensor 3 and then we calculated mutual information.

Besides, bit error rate, probability error, and information loss is calculated at each communication channel. The results obtained are presented in next Section of experimental results.

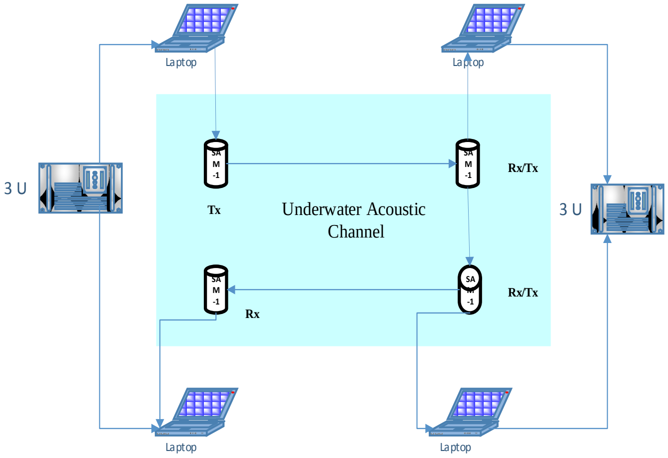

Fig. 3. Cascaded underwater wireless sensor network

B. *Paralle Sensor Network Experimental Setup*

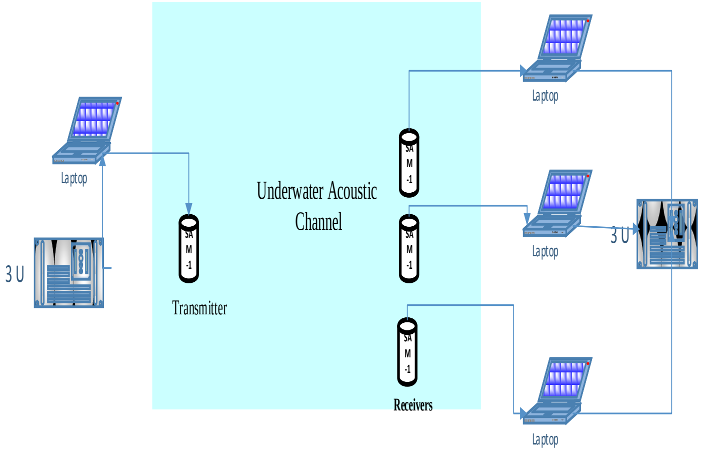

Fig. 4. Parallel underwater wireless sensor network

A similar experiment was performed in parallel sensor network system. In this system, we have one transmitter and 3 receiver, acting system as Single Input Multiple Output (SIMO) system. The optimum output was recorded each time and the experiment was carried out several times for *m* sequences of length 1023 bits. The result obtained for probability of error, BER, mutual information, entropy estimation is displayed in numerical results of Section IV.

IV. EXPERIMENTAL RESULT

First, we obtained the experimental result for cascaded wireless sensor network in an underwater acoustic communication for four sensors.

The bit loss and bit error were computed in an underwater channel sending 1023 bits of 1's and 0's alternately for couple of times for different location of sensors.

Table 1: Bit loss test for different distance of sensors

Distance between sensors	No. of bits transmitted	Received no. of bits	Bit loss	Bit error rate
5 m	1023	1015	8	0.007
7 m	1023	1011	12	0.011
10 m	1023	1011	12	0.011

In Table 2, we transmitted 1023 bits of binary sequences data to the receiver sensor node at a distance of 5 m. This channel transmitted all 1023 bits; however it has bit error of 8 bits in average.

Table 2: Result analysis for Tx_1 and Rx_1 (d=5 m)

Bits transmitted	Bits received	BER	*I(X;Y)*	Information loss $H(X\|Y)$
1023	1023	0.0078	1.00	0.0
1023	1023	0.0087	1.00	0.00
1023	1023	0.0078	1.00	0.00

In Table 3, the transmitted data were exactly the received data from first senor node; however we filtered the error bits that were incurred in first channel. This channel was also set for distance of 5 m between transmitter and receiver. We saw a full communication of data between sensor nodes with bit error of 7 -8 bits in average.

Table 3: Result analysis for Tx_2 and Rx_2 (d=5 m)

Bits transmitted	Bits received	BER	*I(X;Y)*	Information loss $H(X\|Y)$
1015	1015	0.0068	1	0
1014	1014	0.0078	1	0
1015	1015	0.0088	1	0

In Table 4, we load the received data from sensor node 3 and transmitted exactly to another sensor node in cascaded network. This receiver was at a distance of 5 m. The channel had full communication of data with bit error of approximately 7-8 bits.

Table 4: Result analysis for Tx_3 and Rx_3 (d=5 m)

Bits transmitted	Bits received	BER	*I(X;Y)*	Information loss $H(X\|Y)$
1008	1008	0.0079	1	0
1007	1007	0.0079	1	0
1006	1006	0.0089	1	0

Table 5 shows our improvement regarding drop in bit loss and bit error compare to direct transmission between two senor nodes and cascaded network. The channel distance was approx. 15 m. The output result shows that the channel has bit error along with bit loss. This proves that transmission loss in underwater acoustic communication depends on distance.

Table 5: Result analysis for Tx_1 and Rx_4 (d=15 m)

Bits transmitted	Bits received	BER	*I(X;Y)*	Information loss $H(X\|Y)$
1023	1012	0.0185	0.9156	0.0844
1023	1015	0.0156	0.9419	0.0581
1023	1009	0.0215	0.8952	0.1048

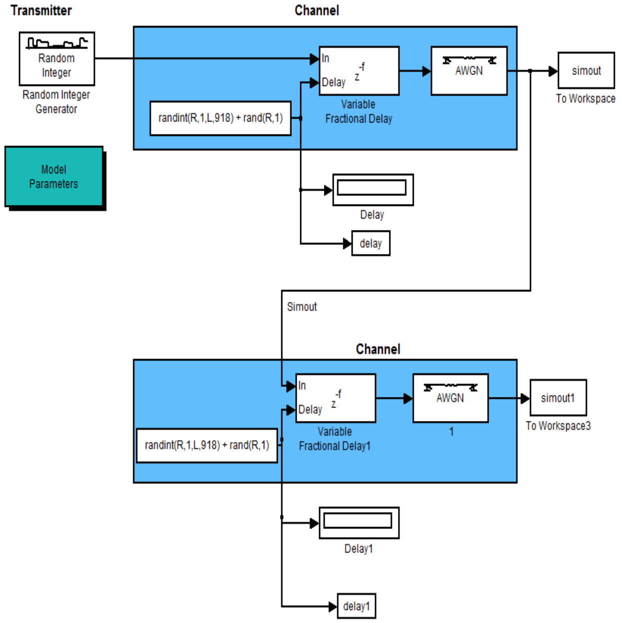

Fig. 5. Simulink design for cascaded network system.

Table 6 shows that underwater acoustic communication (UAC) capacity is strongly dependent on transmission distance. Using more than one sensor in cascaded network system will increase in the mutual information and rate of data transmission with minimum bit error probability.

Table 6: Result analysis for cascaded sensors network

S.N	Case study	$I(X:Y)$	BER	Information loss $H(X\|Y)$
1	Tx_1 and Rx_1	1	0.0081	0
2	Tx_2 and Rx_2	1	0.0078	0
3	Tx_3 and Rx_3	1	0.0082	0
5	Tx_1 and Rx_4	0.9054	0.1853	0.0824

Similarly, an experimental result for parallel sensor network model shows the following outcomes shown in Table 7. This channel network is more effective than cascaded sensors network channel; however cascaded network can transmit data to larger distance for available sensor nodes. In parallel sensor network channel, bit error rate is significantly low compared to cascaded sensor networks. This tells us that data transmission in parallel sensor network has low probability error. The bit loss and bit error in data transmission between X and Y_1 might be fixed during data transmission with second or third sensor node.

Table 7: Result analysis for Tx_1 and Rx_1

Bits transmitted	Bits received	BER	$I(X;Y)$	Information loss $H(X\|Y)$
1023	1019	0.0039	0.9804	0.0196
1023	1016	0.0068	0.9645	0.0355
1023	1017	0.0058	0.9700	0.0300

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V. CONCLUSION AND FUTURE WORK

The primary aim of this research was to quantify and predict the gain in mutual information and channel capacity reducing the bit loss and bit error. We investigated the bit loss, bit error, and mutual information calculation for two different underwater wireless sensor network models for the transmission of m-sequences. Our results show that the placement of multiple sensors nodes over a long range of communication will improve the channel capacity rather than using one single node of communication. Forming a cascaded system network with multiple sensor nodes at different distance will reduce the propagation loss, information loss, multipath fading etc. Similarly, placing the senor in an underwater forming a SIMO channel will also increase in the channel capacity of network system. The result obtained from two different underwater wireless sensor network model improves the communication system by optimizing the data rates that can be transmitted with minimum probability of error. For the future work, we will focus on obtaining the result for movable sensors to address the issues with Doppler spread.

ACKNOWLEDGMENT

The authors thank for support received from the Department of Defense (DoD) Grant W911NE-11-1-0144.

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