Evaluation of Underwater Optical-Acoustic Hybrid Network

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Abstract: The deployment of underwater networks allows researchers to collect explorative and monitoring data on underwater ecosystems. The acoustic medium has been widely adopted in current research and commercial uses, while the optical medium remains experimental only. According to our survey onthe properties of acoustic and optical communicationsand preliminary simulation results have shown significant trade-offs between bandwidth, propagation delay, power consumption, and effective communication range. We propose a hybrid solution that combines the use of acoustic and optical communication in order to overcome the bandwidth limitation of the acoustic channel by enabling optical communicationwith the help of acoustic-assisted alignment between optical transmitters and receivers.

Key words: optical communication, acoustic communication, underwater

I. INTRODUCTION

According to statistics collected by National Oceanic and Atmospheric Administration, the ocean covers more than 70 percent of the Earth's surface, yet over 95 percent of the underwater world remains unexplored. Researchers have studied various alternatives by building underwater networks to facilitate monitoring and exploration of underwater ecosystem. The deployment of underwater sensor networks provides valuable data, including water temperature, salinity, fish population, the ebb and flow of the tide;the information helps in addressing issues such as the effect of human activities on underwater ecosystem and the impact of pollutants on the marine environment. Another promising application of underwater networks is to launch unmanned robotics to record real-time videos of unexplored underwater environments, and send back the live video stream via underwater network. These applications require a high bandwidth, scalable and energy-efficient network; thus, researchers have studied the feasibility of acoustic and optical communication in underwater environment.

When using acoustic communications, devicescan transmit at longer ranges compared to optical communications, butoperate under the constraints of limited bandwidth and high energy consumption for transmissions and receptions. On the other hand, optical communicationscan provide higher bandwidth with lower energy consumption, but suffer from highly limitedcommunication range (i.e., lesser than 50m).The rest of the paper is organized as follows.In Sections 2 and 3, we present our survey on underwater acoustic and optical communications, respectively. In Section 4, we discuss the tradeoff between acoustic and optical communications and further provide further preliminary simulation results. In Section 5, we propose a hybrid solution; combining acoustic and optical communications in order toobtain high enough bandwidth for video transmission and reduce energyconsumption.In Section 6, we conduct extensive simulations to validate the performance of the proposed solution. Finally, we conclude the paper in Section 7.

II. ACOUSTIC COMMUNICATIONS

This section covers the basic properties of acoustic communications, an evaluation of using acoustic network, and the attenuation of acoustic signals.

2.1 Overview of acoustic communications

Existing radio wave communications(e.g., Wi-Fi, Zigbee) are unsuitable for underwater communications because water severely absorbs electromagnetic waves and causes radio wave signal strengthto drop dramatically within centimeters of the transmitter. Thus, acoustic communication is commonly adopted in underwater communications for research and commercial uses. Underwater acousticnetworking is popular due to several reasons: first of all, acoustic signals can be propagated over long distances in magnitudes of several kilometers, providing a notably large effective-range for transmission. Moreover, acoustic signals are broadcasted sound wavesso that they have a wide field-of-view, often spread omnidirectionally. In the event of an obstacle is present in the line-of-sight between sender and receiver, sound waves may simply travel through non-absorbing materials, or go around the obstacle via a wide field-of-view. Therefore, acoustic communication does not strictly require line-of-sight.

Acoustic communications, however, have several drawbacks: the speed of sound is relatively slower than electro-magnetic waves, resulting in a slow propagation delay between sender and receiver (around 1513.74m/s). Such propagation delay slows down thedata rate; thus, acoustic communications result in highly limited bandwidth. We may potentially increase the frequency at which the acoustic signal is broadcasted, but increasing the frequency will result in larger attenuation and higher energy consumption, which will be discussed in section 2.3.

2.2 Using acoustic communications in networking

When using acoustic signals for networking, we have sender nodes capable of broadcasting signals to receiver nodes, so the network characteristics are very similar to existing wireless networks like Wi-Fi. Acoustic networking thus will have similar issues as terrestrial wireless networks, such as the hidden terminal effect, interference, and signal collisions. Moreover, since the speed of sound in water is much slower than the speed of electromagnetic waves in air, interference issues are even worse.

Qadri and Shah [1] have evaluated the performance of applying existing routing protocols (DSR, AODV, DSDV, and OLSR) in underwater acoustic sensor networks. They conclude that DSR is not suitable because of low packet delivery ratio and throughput, and OLSR is not suitable due to its high energy-consumption. AODV and DSDV have better performance but different trade-offs. AODV is suitable for denser network of less traffic, while DSDV is suitable for high traffic of regular network.

2.3 Acoustic signal attenuation

When evaluating the general performance of wireless communications, one important factor to consider is the attenuation of signals under different conditions. According to the work by Stefanov*et al.*in [2], the attenuation of acoustic signals can be modeled by the following equation:

$$A(d, f) = A_0\, d^k\, a(f)^d$$

Equation 1: Attenuation of Acoustic Signals in Water

where $A(d, f)$ represents the amount of attenuation over distance d and frequency f, and the normalizing constant A_0 and spreading factor k = 1.5 are fixed values. According to this

In this paper, we explored the properties of both underwater acoustic and optical communications. From our simulations, we determined that acoustic communications were well suited for transmitting small amounts of data over long distances, or for aligning nodes to prepare for optical communications.

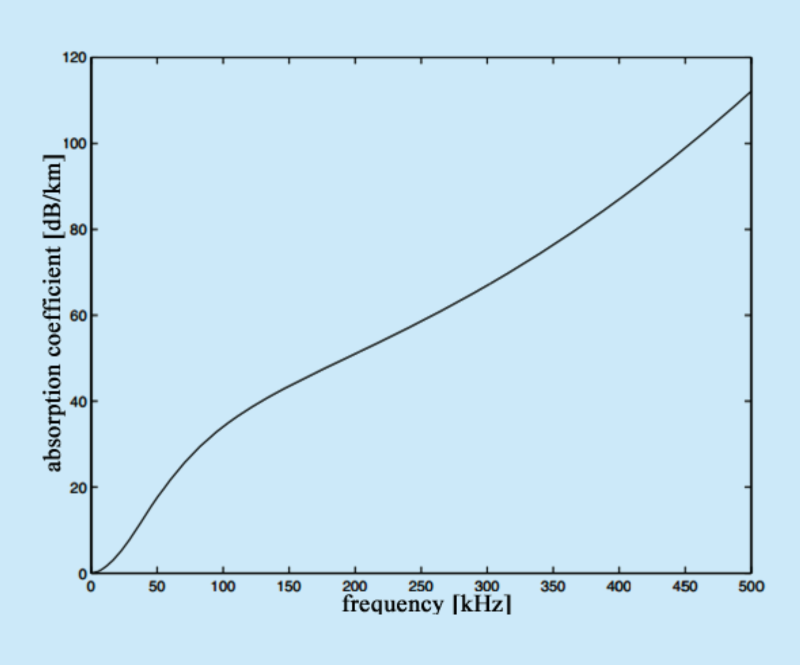

Fig.1 *Absorption coefficient versus frequency*

equation, the amount of attenuation A increases as distance d increases. This equation shows that the further the receiver node is away from the sender node, the more difficult it is for a signal can be transmitted to the receiver. We observe that the absorption coefficient $a(f)$ described by the Thorp's formula [3]shows the directly proportional relationship between absorption coefficient and frequency. In other words, acoustic signals attenuate faster at higher frequency. Table 1 shows two commercial acoustic modems' data from [4], and we observe that while the EvoLogics modem is operating at 48-78 kHz, it only hasan effective range up to 6 km, whereas the Aquatec modem has a much higher range up to 20 km, but operating at lower frequency of 8-16 kHz.

A node can theoretically transfer more data per second by using a higher frequency. However, higher frequencies not only yield higher attenuation, as discussed before, but also require higher power consumption. In Table 1, we observe that the EvoLogics modem has a higher data rate, but it consumes much more power over transmission compared to the Aquatec modem.

Table I *Existing Acoustic Modems*

Modem Name	AquaModem	S2C seriecs
Manufacturer	Aquatec	EvoLogics
Frequency band	8-16 kHz	48-78 kHz
Data rate	300-2000 bps	Up to 20 kbps
Transmission Power	20 W	100 W
Range	Up to 20 km	Up to 6 km

III. OPTICAL COMMUNICATIONS

This section covers an overview of optical communications, an evaluation of using optical networks, and the attenuation model for optical signals.

3.1 Overview of optical communications

From acoustic modem specifications in Table 1 and [4], we observe that acoustic communication supports a limited data rate, up to 20 kbps. A video streaming service requires much larger bandwidth than 20kbps, so we consider the use of optical communications as a communication medium. Optical communications are currently experimental in underwater networks, and existing research includes[5], [6], [7] and [17]. Optical communications generally benefit from much higher bandwidth at lower energy consumption rate, as well as a lower propagation delay because the speed of light is much faster than the speed of sound.

Despite higher throughput at lower power, optical communications suffer from larger attenuation over distance, an issue that will be addressed in section 3.2. Moreover, optical communication has a much narrower field of view and requires line-of-sight between sender and receiver, which will be further discussed in section 3.3.

3.2 Optical signal attenuation

Optical signals have more restricted range due to higher attenuation. Anguita*et al.*[8] modeled the power of optical signals at receiver node in the following formula:

$$P = \frac{2P_0A_r\cos\beta}{\pi L^2(1-\cos\theta)+2A_t}\cdot e^{-cd}$$

Equation 2: Power of Optical Signals in Water

area of receiver (A_r), inclination angle to receiver (β), distance to receiver (L), transmitter light beam diverge angle (θ), area of transmitter (A_t), attenuation coefficient (c), and distance to sender (d). The relationships of β and θ are illustrated in Figure 2.

The inclination angle β denotes how far off a receiver node B is from the center of sender node A's signal, and the transmitter light beam diverge angle θ denotes one half of the field-of-view of sender A's signal. According to Equation 2,the power decreases as β increases up to 90 degrees. In other words, thesignal attenuation increases as the receiver node B moves away from the center of the light beam. Thus, a line-of-sight (i.e., alignment between the sender and receiver) is a significant factor to maximizing the receiving power. Also, the receiving power attenuates over a larger transmitter light beam diverge angle θ. Therefore, we can observe that a larger field-of-view also results in higher attenuation. In conclusion, for optimized receiving power, the optical communications requires both a narrower field-of-view and direct line-of-sight.

Equation 2 can be transformed tothe following simpler model presented by Giles and Bankman in [9]:

$$I = I_0 e^{-cd}$$

Equation 3: Attenuation of Optical Signals in Water

In Equation 3, the transmitted intensity I_0attenuates over distance d. Different water types have a different attenuation coefficient c, as shown in Table 2 from [9]. Simulation shows that water with a higher attenuation coefficient suffers from quicker attenuation over shorter distance. In Figure 3, we observe that turbid harbor water with c = 2.19 has an effective range of less than 5 meters. In normal oceans, we have an effective range less than 20 meters. In optimal pure seawater, we finally have a possible range of up to 100 meters under optical communications. We conclude that optical communications suffer from large attenuation, with an effective range of less than 100 meters

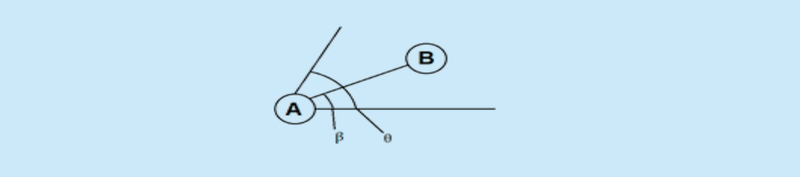

Fig.2 *Inclination angle β and transmitter light-beam diverge angle θ*

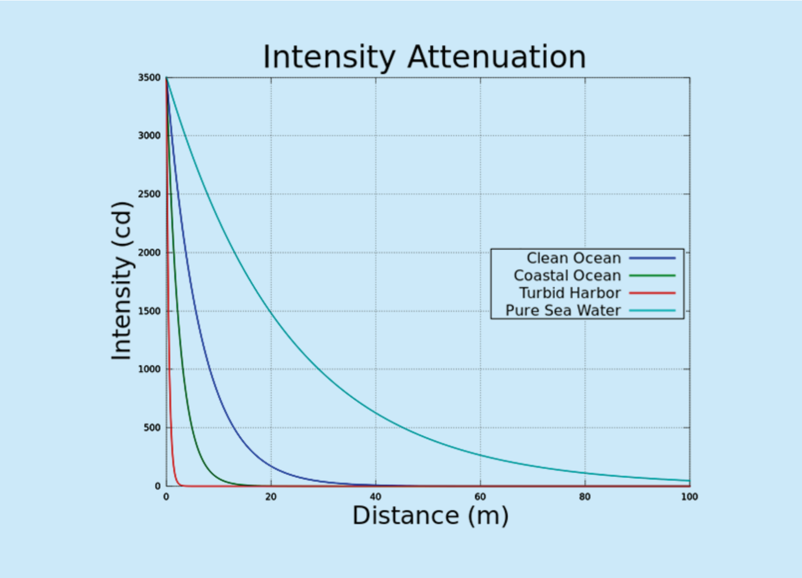

Fig.3 *Optical intensity over distance in different water types*

Table II *Attenuation Coefficient of Different Water Conditions*

Water Type	Attenuation Coefficient (m^{-1})
Pure Seawater	0.043
Clean Ocean	0.141
Coastal Ocean	0.398
Turbid Harbor	2.190

3.3 Using optical communications in networking

Arnon et al. [16] proposed a novel approach to overcome the environment without a line-of-sight by using a reflective communication link. However, a line-of-sight(i.e., alignment between the sender and receiver) is generally a strict requirement for optical communications. Thus, sender and receiver nodes need to establish a direct link before initiating data transmission. In other words, the optical modems on sender and receiver nodes need to be aligned before any packets can be transferred. Despite the fact that optical communications is performed without wires, this point-to-point link topology makes optical networking similar to wired networking. Such transmission is characterized as more targeted and localized. Unlike acoustic signals, optical signals are not omnidirectional. Optical communications thus benefit from less interference issues and negligible propagation delay.

IV. ACOUSTIC VS. OPTICAL DISCUSSION

In order to determine the correct transmission medium to use and balance the tradeoffs between optical and acoustic communications, the differences between the two mediums must be explored.

The primary difference between the two communication methods is the speed of propagation. When in water, the propagation speed of sound is roughly 1500 m/s. The propagation speed of light in water is 2.55 * 10^8 m/s, slightly slower than the 3.00 * 10^8 m/s of air. Inother words, the propagation speed of light is five orders of magnitude slower than the propagation speed of sound.

The tradeoff between transmission range and bitrate must also be considered when comparing the two methods of transmissions. Figure 4 is a chart showing the different acoustic and optical modems currently available. The optical modems are concentrated in the top left corner, meaning that their bitrates are orders of magnitude higher than the acoustic modems, and are measured in terms of megabits. However, their ranges are also much more limited than the acoustic modems, and are measured in terms of meters. The acoustic modems are spread out along the bottom half of the graph, with a wide range of bitrates and distances. The bitrates for the modems are measured from bits to kilobits, and the ranges are measured on the order of magnitudes.

Table III *Acoustic vs. Optical*

Telemetry Method	Range	Data Rate	Efficiency
Acoustic	Several km	1 kbps	100 bits/Joule
Optical	100 meters	1 Mbps	30,000 bits/Joule

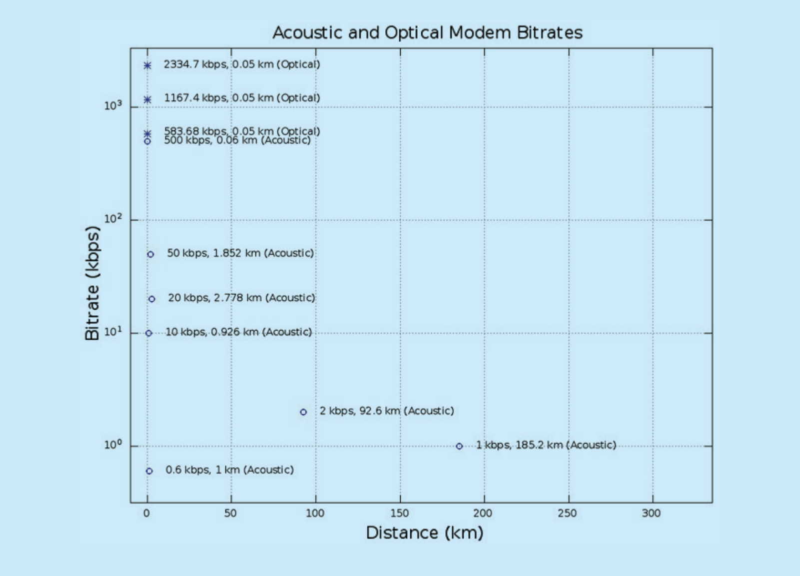

Fig.4 *Acoustic and optical modem bitrates*

In Table 3 below, we see the conclusions drawn previously summarized by Farr, *et al*. [10]. The power efficiency of optical communications is significantly higher than the power efficiency of acoustic communications.

Another differing aspect between optical and acoustic communications is the field of view required by the modems. Acoustic communications can be made to be omnidirectional, and do not require direct line of sight between sender and receiver as the waves are able to make their way around obstacles. However, optical communications require direct line of sight between sender and receiver.

In Figure 5, the experiments done by Schul, *et al*. [11]demonstrate the possible fields of view of an optical transmitter. From their results, it is shown that optical transmitters can transmit up to about 120 degrees. However, as the receiver is placed further and further off from the center of the beam, the effective distance decreases. This effect is explained by the equation for the power of optical communications defined in Section 3.3, where the power of the transmission is dependent both on the inclination angle to the receiver and the light beam divergence angle. By forcing the transmitter to have a wide field of view, both of these angles are set to larger values, resulting in lower power.

V. Hybrid Solution

5.1 Objectives of hybrid solution

As seen in the previous sections, the acoustic and optical communications have their tradeoffs in terms of power, range, and bitrate. These tradeoffs must be balanced on a case-by-case basis in order to better tradeoff between acoustic and optical communications. Section 4 showed that optical communications had a higher bitrate and lower energy consumption, but a much shorter range compared to acoustic. Acoustic communications, on the other hand, had a slower bitrate and higher power consumption, but also a much longer range. In order to properly take advantage of the benefits of both solutions, a hybrid solution is necessary.

In Figure 6, a possible example of a hybrid solution is shown. In the hybrid solution, an Autonomous Underwater Vehicle (AUV) is equipped with both acoustic and optical modems. The AUV contains three acoustic receivers, an acoustic transmitter, an optical transmitter, and an optical receiver. The optical transmitter and receiver can be used to communicate with other nodes when within optical communication range and aligned. The acoustic receivers and transmitters will serve a dual purpose of transmitting small bits of information over long ranges, and helping with the alignment of the optical communication components.

5.2 Acoustic source localization

Node alignment is essential in optical communications to achieve expected bandwidth performance. In this section, we present an acoustic source localization technique that maneuvers the time-difference-of-arrival (TDoA) calculation. Combination use of TDoA with a depth sensor then allows a node to locate the relative three-dimensional positions of other nodes, which will be used for the alignment between the sender and receiver.

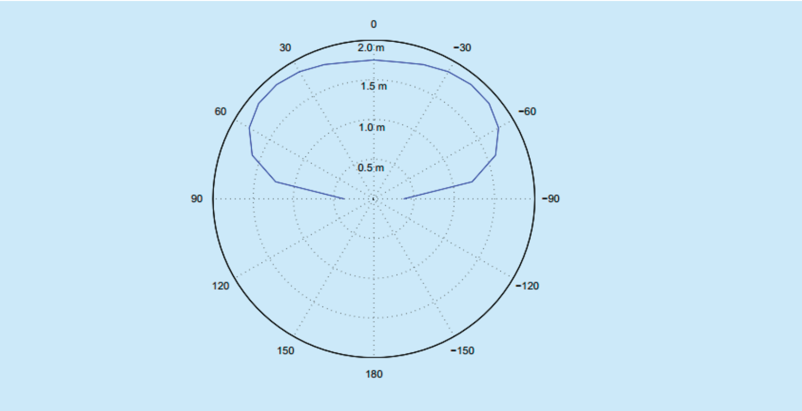

Fig.5 *Field of view of optical transmissions*

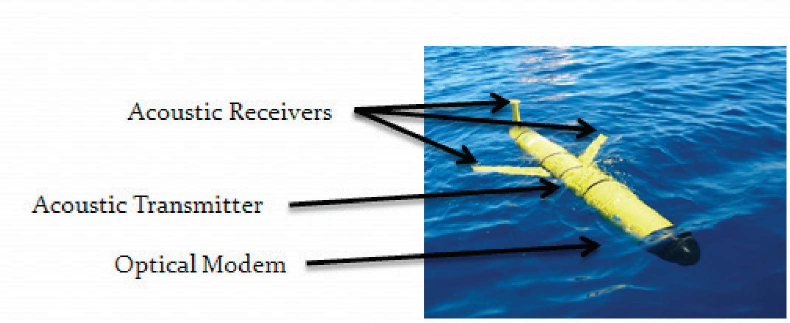

Fig.6 *Example of Hybrid Solution*

5.2.1 Time-difference-of-arrival

Work by Liu *et al.*[12] presents a high-level explanation of acoustic source localization via the time-difference-of-arrival measurements. Assuming there is a receiver node B that wants to locate the position of sender node A, the TDoA technique requires a minimum of three acoustic receivers located at different points on the receiver B. Then, sender node A will broadcast an acoustic signal, which will arrive at the three acoustic receivers at different time. Using the time-difference-of-arrival of two points, we can anticipate all thepossiblepoints of the sound source in the form of a hyperbola. Then, we choose a different pair of nodes, and draw out another hyperbola. The location of the sound source can then be estimated by calculating the intersection of two hyperbolas, as shown in Figure 7.

5.2.2 Estimating relative 3D position

For three-dimensional underwater space, we design our triangular plane formed by three

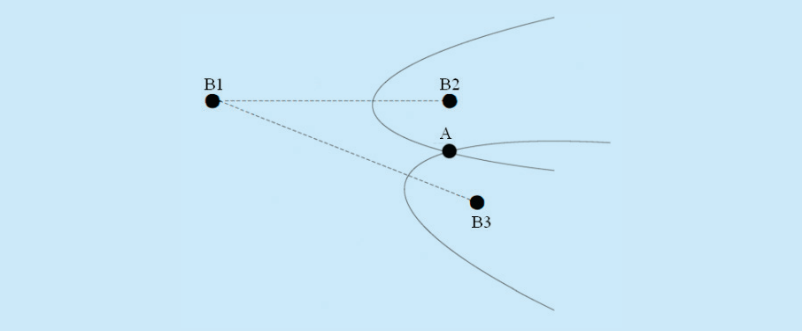

Fig.7 *Time difference of arrival*

acoustic receivers to be orthogonal to z-axis. Each node will contain a depth sensor, such as a pressure sensor, to correctly calculate the absolute z position (i.e., depth) from water surface(avg. error < 1m [13]). The z-position data is transferred from sender A to receiver B, so that the receiver can calculate the relative z-position. Then, the receiver uses the z-position data to project the speed of sound in xy plane, and usesTDoA to estimate x-position and y-position. Once all relative x-, y-, and z-positions are calculated, the node B can use this position data for sender-receiver alignment and routing.

5.2.3 Selecting a node to communicate with

Using the previously described alignment methods, an AUV can align its optical receiver with the sender’s transmitter using an onboard acoustic transmitter. However, if there is more than one source node present, it must be able to identifyeach node among the nodes. This requires a different method of alignment, and a preliminary version of this alignment protocol is described in the following.

We use the TDoA to triangulate the position of the other node. This assumes that the nodes are equipped with at least 3 acoustic antennas and a depth sensor, and that the nodes are within line-of-sight.

On a successful connection request, Node A requests a connection to Node B using the Communication_Request packet. Node A waits for Node B to generate its own Communication_Request. This continues while the nodes move closer and closer into alignment, at which point the periodiccommunication request stops.

If Node B is busy, Node A determines this when it receives a Node_Busy message from Node B, which is currently involved with another transmission to Node C. Node A will then wait for the specific time requested by Node B, while Node C continues the transmission and discards the Node_Busy message that it also receives. Once Node A is done waiting, after a random interval, Node A sends another Communication_Request and begins the process again.

If Node B is unreachable, then Node A determines this when a predetermined period of time expires. Node A then resends the Communication_Request message with an updated timestamp and waits for the same amount of time. After 4 attempts at retransmission, Node A declares Node B unreachable and stops attempting to communicate with Node B.

There are several considerations to be taken when implementing this alignment algorithm. We account for the multipath effect by adding a timestamp to each packet. Since the multipath effect will result in a delay for other messages, the packet sent over the most direct path will arrive at the destination first. The timestamp messages with previous sequence number are discarded once the first message arrives with newer sequence number. Nodes must deal with synchronization issues, and must wait a random interval (i.e., random jitter) before submitting a Communication_Request instead. To achieve this alignment, acoustic conversations are highly necessary due to long communication ranges and omnidirectional spreads so that optical modem can initiate its communications after the alignment between the sender and receiver.

5.3 Hybrid rransmission

To properly utilize both types of communication possible, the following algorithm is proposed when node A wants to transmit to node B:

1) Node A sends an acoustic invite to Node B

2) Node B uses the information to triangulate the position of Node A and turns to align to Node A

3) Node B sends an acoustic response to Node A

4) Node A uses the acoustic response from Node B to triangulate the position of Node B and align to Node B

5) If Node A is currently out of optical communication range, it proceeds to move into range to transmit while using the acoustic modem to transmit data

6) Once Node A is in optical communication range, it either switches to using the optical modem exclusively for transmissions, or uses a combination of both the acoustic and optical modems to transmit data.

In the algorithm above, a node uses an acoustic modem when the intended receiver is located out of optical communication range. If the distance isclose enough for optical communication range, then it will use optical communications after alignment. In the cases where the distance between the two nodes is long (i.e., out of optical communication range), or the amount of data that needs to be sent is small, then using acoustic communications will be optimal as it does not require alignment.

VI. SIMULATION

6.1 Simulation setup

The existing acoustic and proposed hybrid approaches are evaluated via QualNet simulator using actual modem properties. The setup is as follows:

The optical modem setting used is the AquaOptical II modem from Doniec, *et al.* [6]. The maximum range was set to be 50 meters and the maximum bitrate is 2.28 Mbps.For the acoustic modem setting,we used the S2CR 18/34 modem from Evologics with a range of 3.5 kilometers and a maximum bitrate of 13.9 kbps. The specifications of this modem were obtained from the Evologics web site [14].Unless otherwise stated, the transmission power is 105 dB re μ Pa.

In the simulations, four source nodes were placed in a cube as shown in Figure **8**.The dimensions of the cube were 1 km on each edge, with the source nodes at the bottom corners, equally distant from the sink node. The sink node was placed at the top of the cube like a surface buoy.The sources generated packets based on CBR with predefined packet generation rates, and M-FAMA [15]was used for an underwater MAC protocol. For the optical communications, an AUV travels to each source node at a speed of 3m/s, and stops 50 meters away for 600 seconds at each source node to receive the data from the node.

The data packet sizeused by the acoustic modem was set to be 1.75kB, and the data packet size used by the optical modem was set to be 50kB.Unless otherwise specified, the average value of 50 runs with the 95% confidence interval is reported.

6.2 Simulation results

In Figure 9, the average throughput of hybrid (i.e. combining acoustic and optical modems) and acoustic onlyapproachesare plotted against the offered load. For the throughput of acoustic modem only case, it shows that the acoustic channel gradually saturated as the offered load increases.For the hybrid case, acoustic modem is used for long distance and optical modem is opportunistically used for short distance after alignment assisted by acoustic communications. To our surprise, the result reports thatthe

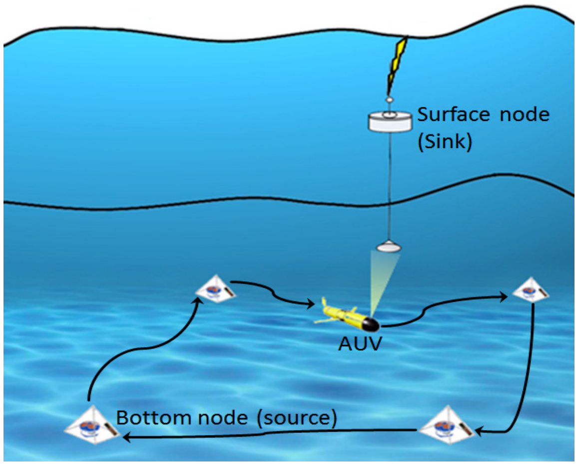

Fig.8 *Mobile source to sink setup*

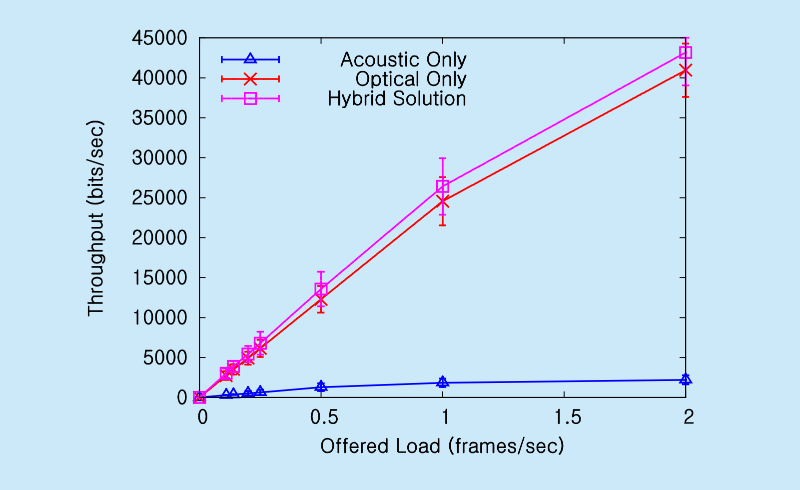

Fig.9 *Throughput as a function of offered load*

proposed hybrid solution outperforms average throughput ofthe acoustic modem only caseup to more than twenty times. The careful reader may notice that there is no huge gain in terms of the throughput between optical only and hybrid solution. However, it is noteworthy that the acoustic modem not only delivers data but also enables the optical communication by being guidance of AUV's optical modem alignment. Less obviously butof equally importance, the acoustic modem can be used in cases of challenged environments for the optical communications namely long range communications, non-line-of-sight, and poor water quality. In reality, the acoustic modem is still essential part for the underwater acoustic sensor networks.

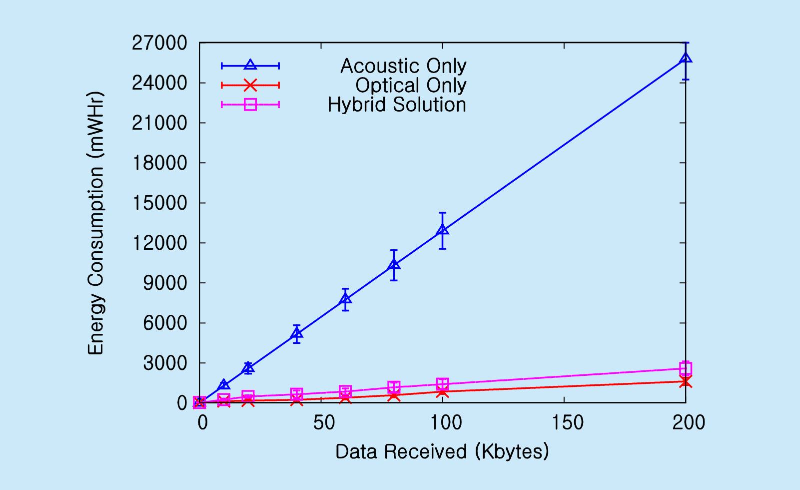

Fig.10 *Energy consumption with varying data size*

The proposed hybrid approach also has a significant advantage in terms of the energy efficiency. In Figure 10, the energy consumptions of the modems were plottedagainst the amount of data received. It is shown that there is no significant energy consumption gap between the acoustic only and hybrid casesfor the small amount of received data. However, the gap becomes distinct as the received data increase. Note that equipping a node with both modems provided it with the freedom to select the optimal transmission method with the lowest transmission time, but that using a combination of optical and acoustic transmissions while two nodes are within optical transmission range yielded negligible time savings gains that were probably not worth the extra power expended to utilize both modems.

VII. CONCLUSIONS

In this paper, we explored the properties of both underwater acoustic and optical communications. From our simulations, we determined that acoustic communications were well suited for transmitting small amounts of data over long distances, or for aligning nodes to prepare for optical communications. We proposed the concept of a hybrid system where a node is equipped with both acoustic and optical modems. From our extensive simulations, the proposed hybrid solution outperforms the case in which only the acoustic modem is used from both throughput and energy consumption perspectives. The performance gain from the acoustic modem is seemingly negligible in some cases. However, the importance of acoustic communications is still not to be disregarded. As seen in Table 2 and Figure 3, the attenuation of the optical modem depends greatly on the water conditions. In the case of a turbid harbor, the attenuation may be so severe that transmitting data via optical modem would be virtually impossible. In such cases, despite the high energy consumption and slow data rates, the acoustic modem would still be necessary to ensure that the data is still transmitted.

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Biographies

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Dr. Mario Gerla, is a Professor in the Computer Science at UCLA. He holds an Engineering degree from Politecnico di Milano, Italy and the Ph.D. degree from UCLA. He became IEEE Fellow in 2002. At UCLA, he was part of the team that developed the early ARPANET protocols under the guidance of Prof. Leonard Kleinrock. At Network Analysis Corporation, New York, from 1973 to 1976, he helped transfer ARPANET technology to Government and Commercial Networks. He joined the UCLA Faculty in 1976. (see www.cs.ucla.edu/NRL for recent publications).