Evaluating the Feasibility of Establishing Full-Duplex Underwater Acoustic Channels[*]

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Abstract—**Multipath fading, severe bandwidth limitation, non-Gaussian noise, and large propagation delays combine to make an underwater acoustic network (UAN) one of the more challenging ad hoc networking environments. It is important to refine the traditional networking protocols to optimize their performance for the given physical layer constraints of UANs [5]. One such refinement, the use of full-duplex channels, has been proposed for mitigating the performance penalties induced by large signal propagation delays that are inherent with UANs. Some full-duplex aerial acoustic communication capabilities were demonstrated recently [7]. However, due to the harsher physical environment in the ocean, the underwater acoustic research community in general was not convinced that the same level of performance would be attainable underwater. Furthermore, because of the scarcity of underwater acoustic bandwidth, bandwidth efficiency should not be sacrificed for the sake of full-duplex. This paper presents for the first time positive evidences that it is feasible to establish bandwidth efficient full-duplex underwater acoustic channels using Code Division Multiplex Access (CDMA) techniques.**

Index Terms— ***Underwater Acoustic Network, Full-Duplex Communication, CDMA, Frequency Hopping, Pulse Postion Moulation***

I. INTRODUCTION

The potential benefits of ad hoc networking are not limited to the aerial wireless environment. Much effort has been focused on developing effective ad hoc networks to support data collection and autonomous vehicle control within the aquatic environment [1-3, 5]. For example, the U.S. Naval Postgraduate School's Center for Autonomous Underwater Vehicle (AUV) Research and several other institutes around the world are conducting experimentation into the use of ad-hoc network techniques to provide command and control support to AUV operations. Such operations may include the command of multiple AUVs acting in concert. The goal is to allow such AUV swarms to self-organize, as well as, distribute remote command directives among the vehicles or collect onboard system status information or gathered sensor data and relay that information back to the remote command facility. Other potential applications for ad hoc underwater networks include harbor monitoring, fisheries monitoring, off-shore facilities monitoring, and sport diving.

Underwater ad hoc networks primarily use acoustics to communicate between nodes. Three major challenges are inherent with encoding data with underwater acoustic signals. The first challenge is *multipath fading* that occurs as a result of destructive interference. Reflections off the sea bottom and the sea surface, as well as scattering from non homogeneities in the water column, result in multiple receipts of the same signal at the receiver. These multiple arrivals superimpose on each other and deform the signal in amplitude and phase. Similarly, the motions of the source, the receiver, and the medium itself result in Doppler shifts and Doppler spreading, which further distort the signal. The second challenge is *severe bandwidth limitation*. High frequency acoustic signals are strongly attenuated in the ocean, which results in relatively small transmission bandwidths, in the range of several kHz, and relatively low data rates compared to those achievable in radio frequency (RF) communications. The last challenge is the ocean noise that is *non-Gaussian* and results from many systems including biologics, weather, surface wave action, shipping, and industrial noise near the coastline. The ocean noise level varies greatly over time and geographic location, and different sources dominate in different bands. Experimental observations [4] show that at the lower frequencies (below 10 Hz) ambient noise is dominated by ocean turbulence. Noise between 50 Hz and 500 Hz is dominated by distant shipping and depends on the geographic location. At higher frequencies, 500 Hz to 50 kHz, the roughness of the sea surface dominates the noise spectrum. Sea surface

roughness is directly related to the wind speeds at the sea surface and is therefore weather dependent. Lastly, at high frequencies above 50 kHz, the thermal noise, due to the motion of the molecules of the sea itself, is the dominant source of ambient noise. Given the great variation, developing good statistical representations of the ocean noise is very difficult.

Moreover, the propagation speed of acoustic signals is *five orders of magnitude slower* than that of airborne radio signals. The water temperature, salinity, and pressure dictate how fast sound will travel. It is unlikely that some fundamental advances will happen in the foreseeable future to address this and other physical layer acoustic signal problems. It is up to the upper layer network protocols to ensure sustained data throughput and control end-to-end message transfer delays [4, 5].

However, the networking protocols used in current underwater acoustic networks (UANs) by and large are not optimized for the given physical layer constraints. A prime example is that the preponderance of existing acoustic modems operate in half-duplex mode with contention-based media access control. Half-duplex communication exacerbates the negative effects of signal propagation delay on data transfer latency by requiring the exchange of several control packets to establish media access. Establishing an exclusive full-duplex channel [1] between each pair of nodes assures access to the media without the exchange of access requests prior to each traffic exchange session. Therefore, using full-duplex connection should reduce the negative effect of large propagation delays on channel use [5]. The benefit of full-duplex communications, and its potential impact on underwater networking, can be appreciated by its influence on satellite communications. In satellite communications, the uplink and the downlink channels use different frequencies to realize full-duplex communication in order to mitigate the large propagation delays caused by the long propagation distances. This implementation allows the source to send multiple frames, using the uplink and downlink as a virtual buffer. The destination is able to throttle the source transmission rate using sliding window flow control mechanisms. Without full-duplex communications, the source must either send the

traffic with no guarantee of its receipt by the destination, or wait for the destination to acknowledge each frame. If the frame size is small compared to the propagation time then the source spends a large portion of its time idle even though it has data to send. If the frame size is large, then rejected frames result in significant wasted transmission time. Full-duplex communications allows smaller frames to be sent without suffering the penalty imposed by waiting for acknowledgments between frames.

Some full-duplex aerial acoustic communication capabilities have recently been demonstrated [7]. However, due to the harsher physical environment in the ocean, the underwater acoustic research community in general was not convinced that the same level of performance would be attainable underwater. A successful trial of full-duplex underwater acoustic telemetry is briefly reported in [9]. A simple frequency division multiple access (FDMA) scheme was used to create the concurrent channels for the trial. More bandwidth efficient channelization schemes were not considered. In light of the scarcity of underwater acoustic bandwidth, bandwidth efficiency must not be sacrificed for the sake of full-duplex operations. While FDMA provides a straight forward means of channelizing the available bandwidth, unless the supported nodes each provide a persistent data stream, some of the generated channels will be inactive, thus leading to poor utilization of the bandwidth. Furthermore, as *frequency selective fading* in the shallow underwater acoustic channel varies with time, channels that are serviced by a fixed frequency band may suffer higher levels of data loss than other channels. Both of these issues are mitigated by the use of Code Division Multiple Access (CDMA), which has been shown to be more bandwidth efficient in many circumstances and provides mitigation for frequency selective fading. This paper presents for the first time positive evidences that it is feasible to establish bandwidth efficient full-duplex underwater acoustic channels using CDMA techniques. The results are obtained from in-water experiments using a test bed based on four inexpensive commercial underwater acoustic modems.

The rest of the paper is organized as follows. Section II provides more background to make the case for full-duplex communication in underwater acoustic networks. Section III describes our evaluation methodology, particularly the design of a test bed for investigating full-duplex underwater acoustic communication. In Section IV, the details of a complete test bed implementation using commercial acoustic modems is presented. Section

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[1] There are different ways of implementing the full-duplex channel. One possibility is to assign each node a private transmission channel, i.e., one that is unique in the neighborhood of every potential receiving node, with the assumption that a node is able to receive from multiple such channels [5, 7].

V describes the test results. Finally in Section VI, the paper provides conclusions based on experimental observations.

II. BENEFITS OF FULL-DUPLEX COMMUNICATION

A full-duplex UAN uses a data transmission mode that allows data to be transmitted in both directions at the same time. This type of network is analogous to a two-lane road where traffic can go in opposite directions at the same time. The data being transferred will be split between the network channels and must fully load the channels to ensure that the use of the network does not decrease. In order to ensure that the channels can carry concurrent data streams, the UAN will have to use a time division multiple access (TDMA), frequency division multiple access (FDMA), or a code division multiple access (CDMA) scheme.

Compared to a half-duplex configuration, the full-duplex network may provide a much better networking environment under certain conditions. Half-duplex connections compound the effects of the propagation delay on data transfer latency by requiring the exchange of several control packets to establish media access. The establishment of an exclusive full-duplex channel between each pair of nodes provides a means of assured access to the media without exchanging access requests prior to each traffic exchange session [5]. Using a simple half-duplex network with three nodes, A, B and C, a message transmission will be initiated when Node A sends a ready-to-send message (RTS) to Node B. When Node B receives the RTS, it will then send a clear-to-send message (CTS). After Node A receives the CTS, it will start sending its data. The same operation happens between Node B and C. Therefore, the total effect of the propagation delay will be three times greater than the propagation delay between Node A and B (d_1) plus Node B and C (d_2). Fig. 1 (a) is a visual diagram of this protocol. With a half-duplex configuration, when a node is transmitting, it uses the entire bandwidth of the channel. When using a full-duplex network, the bandwidth is split and communication channels are assigned to receive and to transmit data. Each node has at least one channel for transmitting and one channel for receiving data. With dedicated channels there will be no collisions and the overhead associated with the half-duplex contention based protocol is eliminated. By using TDMA or FDMA these dedicated channels will reduce the efficiency of the data transfer because the bandwidth has been split. However, by using CDMA, this problem may be minimized and the full-duplex network will be able to use the entire bandwidth just like a half-duplex
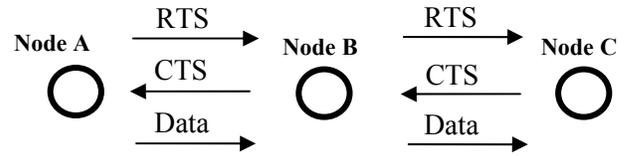
Delay $\geq 3(d_1 + d_2)$, where d1 and d2 are respectively the propagation delay between Nodes A and B and that between Nodes B and C. [half-duplex protocol]

(a)
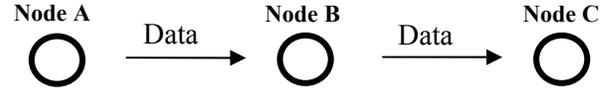
Delay $\approx (d_1 + d_2)$ [full-duplex protocol]

(b)

Fig. 1. Comparison of Message Delays [5]

network. As can be seen from the Fig. 1 (b), the total propagation delay of the full-duplex protocol will be equal to the delay between node A and B (d_1) plus the delay between node B and C (d_2).

A full-duplex network will provide a smaller total data transfer time as long as the transmission time of the data is constant between the two configurations. But, even if the transmission rate is lower, the full-duplex configuration may still have a more responsive data delivery. In both guided media and traditional wireless settings, the propagation time is normally negligible and is often ignored. "However, propagation delays in water are significant and play a dominant role in the speed that the data is transferred [5]."

Another crucial benefit of implementing a full-duplex capability in UANs is the resultant opportunity to implement a sliding-window based flow control mechanism rather than the stop-and-wait mechanism used for half duplex communications. These mechanisms are used whenever reliable data transfer is required and it is possible for the source to send data to the destination faster than the destination can process it. With stop-and-wait, the source must wait for explicit acknowledgment of each frame before transmitting the next. Sliding window mechanisms allow multiple frames to be sent, constrained by the capacity of the receiver's buffer, while waiting for acknowledgments for previous frames. Sliding window protocols are particularly useful for networks where the transmission delay is small compared to the propagation delay and

thus several frames may be "buffered" by the medium. UANs are such networks.

III. EVALUATION METHODOLOGY

A. Test Bed Design

An underwater acoustic modem uses a water-proof electro-acoustic transducer to transmit and receive acoustic signals. Just like an RF antenna, the transducer cannot operate in the transmit mode and receive mode at the same time. Therefore, four transducers must be used to implement a point-to-point full-duplex acoustic channel.

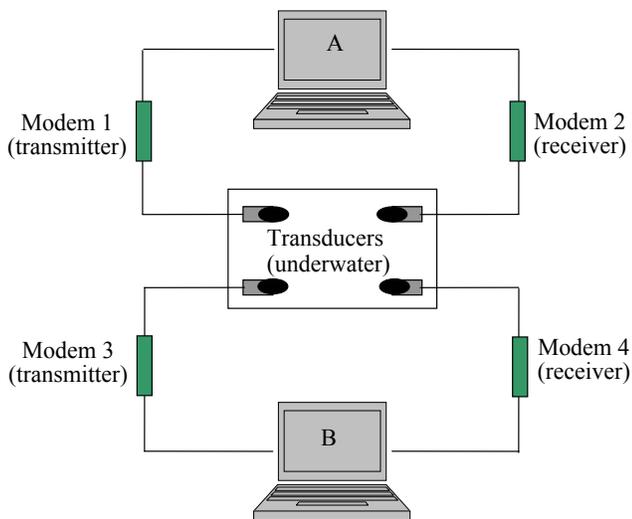All existing acoustic modems come with a single

Fig. 2. Full-Duplex Test Bed Design

transducer because they are built with only half-duplex communications in mind. Instead of developing a full-duplex acoustic modem from scratch, we opted to use a pair of commercial half-duplex modems to emulate a full-duplex modem. A simple test bed following this approach is shown in Fig. 2. There are two computers (labeled A and B) representing two UAN nodes. Each computer connects via the serial interface to a pair of half-duplex acoustic modems operating as the message transmitter and the message receiver, respectively, for the node. The exact placement of the four transducers may vary according to the target water environment and test objectives. It is desirable to have access to the source code of the modems so that various full-duplex channelization schemes can be implemented and evaluated using the same test bed. To evaluate the performance of a particular channelization scheme,

simply install the corresponding version of modem software to all four modems and then transfer two sets of ASCII messages simultaneously, one set from Node A to Node B and the other from B to A.

The metric we use to measure the performance of a message transfer is its *success rate*, i.e., the ratio of the number of the characters received correctly by the receiving application to the number of characters transmitted from the sending application[2]. Using the test bed, we sought to determine if there exists a bandwidth efficient channelization scheme that can achieve high success rates with full-duplex underwater message transfers.

B. Test Environments

For this work, the tests were conducted in two different water environments. The first test environment was a 20 inch by 14 inch bucket and the second one was a small lake (the "Frog Pond") in the city of Del Rey Oaks, California, USA.

There is a significant performance impact, due to the limited signal attenuation when the system in operated in a bucket because of the proximity of the transducers. While signal attenuation is normally detrimental to communications, too little attenuation results in crosstalk between channels as a result of the receiver's frequency selectivity design characteristics.

During the lake test, the transducers from Modems 1 and 2 were placed in the water on one side of the dock with the units spaced approximately one foot apart. Transducers from Modems 3 and 4 were placed in the water on the opposite side of the dock. The two transducer pairs were spaced 15 feet apart. All four transducers were inserted two inches into the water. Fig. 3 illustrates this layout. While the shallow lake provides a more suitable test environment than does a small container, it does not have as good a performance characteristic as does the open ocean. This is due to the increased multi-path fading induced by reflections of the signal from the bottom and surface of the lake [10]. The impact of obstructions, such as rocks and vegetation can also reduce the signal quality. For these reasons, we believe the shallow pond provides a lower bound for the expected performance of acoustic communications in the shallow ocean region.

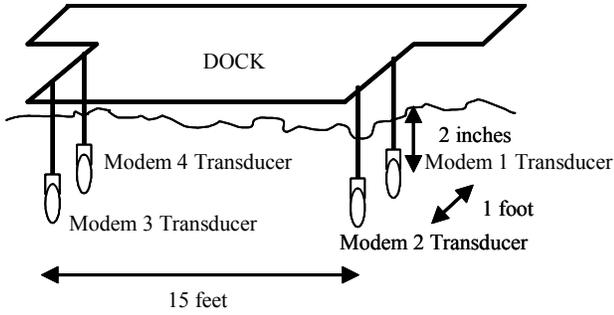[2] Serial terminal application (e.g., HyperTerminal bundled with Microsoft Windows)

Fig. 3. Placement of Transducers in Lake Test

C. Target Full-duplex Channelization Schemes

As full-duplex communications requires two separate channels between the communicating hosts, the water channel requires subdivision. This may be done physically, using various multiplexing techniques, or logically, using code division techniques. The operational characteristics of some modems offer frequency division as a physical means of subdividing the link. FDMA is straightforward to implement with these modems.

Traditional time division is problematic due to a lack of a universal timing reference – the modems do not incorporate a GPS reference, a feature not likely to be present in a typical underwater acoustic network host. Possible logical techniques include frequency hopping code division multiple access and direct sequence multiple access. A third logical technique, coined herein as timing hopping, may be suitable for modems that use time domain data modulation techniques like pulse position modulation (PPM). Timing hopping is designed to minimize the chance of signal collisions by varying the modulation window period of each transmitter in a certain way. Frequency division and timing hopping are straight forward to implement in modems that employ frequency hopping as a means of mitigating selective frequency fading and pulse position modulation, provided the source code of the modem software is available. Code division effectively reduces the data rate as each character is spread over several bytes, allowing orthogonal codes to be used to simultaneously support multiple data streams.

Each of these physical and logical mechanisms may be combined to form a hybrid technique which may either compound the advantages of the underlying schemes such as efficiency, insensitivity to multipath fading, or simplicity, or mitigate some of their disadvantages such as complexity, frequency selective fading, or reverberations. Various combinations that are evaluated in this work are shown in Table 1.

TABLE I. TESTED CHANNELIZATION SCHEMES

FDMA
Frequency Hopping CDMA (FH-CDMA)
Direct Sequence CDMA (DS-CDMA)
Timing Hopping CDMA (TH-CDMA)
Combination of FDMA and FH-CDMA
Combination of FDMA and DS-CDMA
Combination of FDMA and TH-CDMA
Hybrid CDMA (Combining DS- and TH-CDMA)
Combination of FDMA and Hybrid CDMA

Table II contains the test sequences (text messages) used by this work to evaluate the various channelization schemes in the lake and bucket experiments.

TABLE II. TEST MESSAGES

Test Sequence 1	1234567890
Test Sequence 2	Qwertyuiopasdfghjklzxcvbnm
Test Sequence 3	QWERTYUIOPASDFGHJKLZXCVBNM
Test Sequence 4	This is a test sentence.
Test Sequence 5	Aaaassssddddffffgggghjhjhj
Test Sequence 6	Zzzzxxxxccccvvvvbbbbnmnmnm
Test Sequence 7	Qqqqqqqqqq

IV. TEST BED IMPLEMENTATION

The test bed design may be realized with any acoustic modem platform that allows access to the source code of the modem system software. Specifically, the test bed used by this work consists of four Desert Star RBS-1 acoustic modems [8]. The data communication features of these modems and our full-duplex driven enhancements to the modem software are described next.

A. Communication Features of Desert Star Modem

The data communication features of the RBS-1 modems are implemented in a Desert Star proprietary software system called AModem. AModem is mostly C based and runs on a Motorola 68HC11E1FN microprocessor for RBS-1 modems.

To transmit a message, AModem first segments the message into 2-character blocks, and then transmits the blocks in sequence. Next, we explain the detail of the
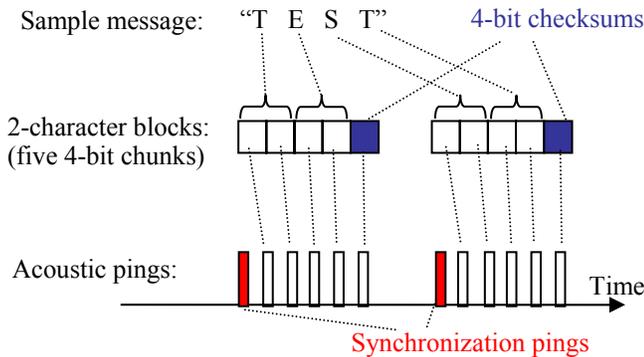

Fig. 4. Message Transission Schema of RBS-1 Modem

AModem transmission schema using an example as illustrated in Fig. 4. Suppose AModem is called upon to send the message "TEST". It first breaks the message into two 2-character blocks: "TE" and "ST". Each message block is appended with a 4-bit checksum, resulting in a new data block with five 4-bit chunks. AModem encodes each new data block with an independent group of 6 acoustic pings. The first ping does not represent any data and serves as a synchronization beacon for the receiver to get ready. Each of the remaining five pings represents a 4-bit chunk in the data block.

More specifically, AModem converts a data block to acoustic signals using the Pulse Position Modulation (PPM) method. PPM is a time domain method. The 20 bits of the data block are encoded by six "ping" pulses contained in a pulse window as shown in Fig. 5. The first ping (synchronization ping) establishes the time frame reference for the pulse window. The remaining five pings, which carry four bits of information each, are "pulse position coded." Pulse position coding was chosen for the AModem system because it is a very energy efficient way of coding [8]. This means that there is a specific window of fixed duration in which each of the data pings must occur. As illustrated in Fig. 5, a PPM time frame for AModem contains five fixed duration data ping windows sandwiched with recovery periods. The recovery periods are inserted to allow

sufficient time for reverberations of an acoustic pulse signal to die down before the next ping. Each data ping window is evenly divided into 16 subwindows. One ping will be transmitted during one of these subwindows. Which subwindow the ping is in determines the four-bit value that the ping represents. In other words, the value
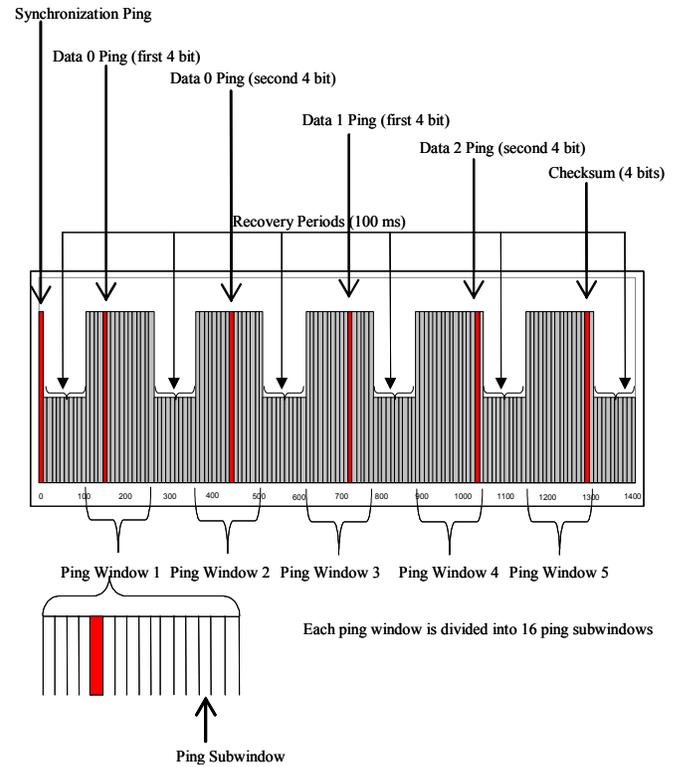

Fig. 5. Pulse Position Modulation of 2-Character Message Block

of 0000 is associated with the first subwindow, 0001 with the second, and so on.

To combat frequency selective fading, AModem utilizes multi-channel transmission. There are a total of four channels, numbered 0 to 3, each with a distinct transmission frequency. AModem uses a fixed channel hopping schedule as shown in Table III to transmit each group of six pings representing a 2-character message block.

TABLE III.
MULTI CHANNEL TRANSMISSION SCHEDULE

Ping 1	Ping 2	Ping 3	Ping 4	Ping 5	Ping 6
CH-0 33.9 kHz	CH-1 36.4 kHz	CH-2 38.5 kHz	CH-3 40.8 kHz	CH-1 36.4 kHz	CH-2 38.5 kHz

It should be noted that in the test environments of this work, only two of four channels were reliably

distinguishable. The modems' receive filters were unable to completely isolate Channels 0 and 2, possibly due to the proximity of the modems to each other. This limitation is especially significant with respect to the synchronization pings, as a bleed-over may cause the impacted receiver to lose its pulse position reference.

At the receiving end, AModem detects the start of an incoming message block upon receiving a synchronization ping. The processing of the synchronization ping also establishes the time reference for decoding the data pings (including the checksum ping). If the software detects a bad checksum on an incoming message block, it will forward "##" to the application program via the serial data link.

B. *Enhancements to Desert Star Modem Software*

The original AModem code already included a frequency-hopping implementation. While the purpose of this implementation is to mitigate multipath fading, it provided a reasonable means by which to manipulate the data signaling method of the modems. While hardware modifications to the modem may provide a more robust production version of the channelization mechanisms, especially the DS-CDMA based approaches, for test purposes, the software modifications proved sufficient.

The software modification necessary for FDMA is changing the designed channel hopping scheme such that the hops are either entirely eliminated or are confined to a specific frequency range for the hybrid implementations. Since the channel hopping pattern is defined by a character string in the source code (default value = "0,1,2,3,1,2"), simply modifying the character string such that it contains an appropriate sequence of identical channel numbers, or an appropriate pattern of channel numbers suffices. For the baseline FDMA implementation, two of the modems are modified to send and to receive only with the "Channel 1" frequency and the other two are modified to send and to receive only with the "Channel 3" frequency. Therefore, the transmitter sends each of its six-ping windows on "Channel 1," while the other transmitter sends its six-ping blocks on "Channel 3." One problem that had to be overcome for both FDMA and frequency hopping modifications was that the original modem design always transmitted the synchronization pulse on the same channel. This limitation was addressed by allowing the synchronization pulse to be sent on a specific channel as determined by the channeling technique employed.

With this change, FH-CDMA is also straight-forward to implement with the AModem software.

Implementation simply requires the hopping sequence to be placed in the respective AModem character string, as noted for FDMA. The sequences "1,2,0,2,2,0" and "3,0,2,0,0,2" are used to establish an appropriate orthogonal frequency hop sequence for each logical channel, respectively. Note that the sequence represents a single PPM frame and that the frame begins with the synchronization ping being sent on either Channel 1 or Channel 3. Unfortunately, no data could be signaled on either Channel 1 or 3, as doing so could cause the other channel to lose its synchronization reference. While it might be possible to modify the AModem code such that a synchronization pulse is rejected if it falls within the time bounds of a given pulse window, thereby allowing both sequences to be used by both channels, this was not done for this set of experiments.

Combining the FDMA and FH-CDMA mechanisms into a hybrid that provides both hopping and bandwidth separation, was done by replacing the hopping sequence in each modem's software with either of the sequences, "1,0,1,1,0,0" and "3,2,2,3,3,2.". Two of the modems are modified to use the first sequence, resulting in one transmit/receive pair. The other two modems are modified to use the second sequence thereby providing the second modem transmit/receive pair.

The Timing Hop Code Division Multiple Access (TH-CDMA) modification is based on manipulating the data ping window duration. The timing hops are determined by a timing-hop sequence. Two sequences are used, "0,1,0,1,1" and "1,1,1,0,0." A given sequence is assigned to a transmit/receive pair. No change is made to the frequency hopping sequence of the original modem code. Rather, the duration of the subwindows between the pings are driven by the timing-hop sequence.

To combine the timing-hop and FDMA mechanisms, the bandwidth allocated to the two logical channels is constrained to the use of the two distinguishable channels, Channels 1 and 3. The same timing hop sequences are applied as with the TH-CDMA alone.

A bandwidth-efficient implementation of DS-CDMA would require a hardware upgrade to use a different modulation technique. For this work, DS-CDMA is emulated at the application layer using software. Specifically, each 2-character message block is spread across four PPM frames, with each character being signaled within two of those windows. Each original data bit is expanded according to the assigned 4-bit chip sequence. The two orthogonal chip sequences selected for DS-CDMA modification are "1111" and "1010,"

according to the Walsh Code. Two of the modems are modified to use a "1111" chip sequence for transmitting data bit "1" and "0000" for transmitting data bit "0." The other two modems are modified to use a "1010" chip sequence for transmitting data bit "1" and "0101" for transmitting data bit "0." These chip sequences are short, but sufficient to demonstrate the utility of CDMA. The disadvantage of this modification is the impact on data transmission speed. It is four times slower than the original modem's code speed-option parameters as each application bit is encoded by four signal bits.

FDMA and DS-CDMA techniques are combined by modifying the frequency sequence to isolate the two channels. Instead of the frequency sequence "0,1,2,3,1,2", the two distinguishable channels are used. Channel 1 is used for all pings with a "1,0,1,0" chip sequence and Channel 3 is used for all pings with a "1,1,1,1" chip sequence.

For the hybrid CDMA (DS/TH) two of the modems use a "0,1,0,1,1" timing-hopping sequence with the chip sequence "1,0,1,0" and the other two use a "1,1,1,0,0" timing-hopping sequence with the chip sequence "1,1,1,1". Thus, the first pair of modems use a "1,0,1,0" chip sequence and speed 0 parameters between the first ping and the second ping, speed 1 parameters between the second ping and the third ping, speed 0 parameters between the third and the fourth ping, speed 1 parameters between the fourth and the fifth ping and speed 1 parameters between the fifth and the sixth ping. Likewise the second pair use a "1,1,1,1" chip sequence applied across the ping windows, internally spaced by the "1,1,1,0,0" timing-hop sequence.

The FDMA and Hybrid CDMA design combination further separates the channels by limiting the frequency use of each transmitter to exactly one of the two distinguishable channels (Channel 1 and Channel 3). In each of the cases where FDMA is used to isolate the two channels, a reduction in the modems' resistance to multi-path fading and channel reverberation is induced. While this would be significant if the primary focus of the experiment was preserving throughput, it is less of an issue when the focus remains the demonstration of the full-duplex capability. Improving the resulting throughput remains an area for further research.

V. TEST RESULTS

All full-duplex channelization schemes were tested in the bucket as well as in the lake. FH-CDMA performs the best in the lake environment. For brevity, we only show the FH-CDMA results here.

Each technique was tested in two parts. The first part consisted of a couple of simplex transmissions which verified that the modems were operational and only the designated receivers received the data, while the unintended receivers correctly discarded the transmitted signals. All four test sequences were exchanged by each transmitter/receiver pair. The second part of each test involved a simultaneous transmission from Modem 1 and Modem 3 to Modem 4 and Modem 2, respectively.

A. FH-CDMA Bucket Test

Tables IV and V present the results of the simplex transmissions in the bucket. Recall that Modem 2 is the designated receiver for messages transmitted from Modem 3 and Modem 4 the receiver for Modem 1. In the tables, the "β" character represents a blank and the character "¥" represents one of the non-alphanumeric ASCII codes. The reception of blanks at the unintended receiver indicates that sufficient acoustic energy was detected to exceed the recognition threshold, but the value of the character could not be determined. This is the artifact of the RBS-1 modem software which can be revised to report no characters at all in such cases. It should be noted that the success rates at the designated receivers are not 100%. The errors are most likely caused by the close proximity of the transducers as discussed in Section III B. It should be noted that each test was repeated many times. The average performance (in terms of success rate) is very similar to the numbers reported here. We have chosen to show results of individual test runs in order to give some sense of the typical transmission error patterns.

TABLE IV.
TRANSMIT ONLY FROM MODEM 1 (BUCKET, MODEM 3 IS SILENT)

Test Sequence	Received by Modem 4	Success Rate
1	12ββ567890	80%
2	Qwertyuiopasdfghjkββxcvbnm	92.31%
3	QWERTYUIOPASDFGHJKββXCVBββ	84.62%
4	This is a test sentence.	100%
Test Sequence	Received by Modem 2	Success Rate
1	β	0%
2	ββββββββββββ	0%
3	βββββββββ	0%
4	ββββββββββββ	0%

TABLE V.
TRANSMIT ONLY FROM MODEM 3 (BUCKET, MODEM 1 IS SILENT)

Test Sequence	Received by Modem 2	Success Rate
1	1234567890	100%
2	Qwertyuiopasdfghjklzxcvbββ	92.31%
3	QWERTYUIOPASDFGHJKLZXCββNM	92.31%
4	This is a test sentence.	100%

Test Sequence	Received by Modem 4	Success Rate
1		0%
2	ββββββββββ	0%
3	ββββββββ	0%
4	ββββββββββββββ	0%

Table VI shows the results of the simultaneous transmissions in the bucket. While the unintended receivers detected elevated acoustic energy during the simplex transmissions, the simultaneous test results indicate that the modems are able to detect and recover a significant portion of the transmitted data streams even in the presence of another active channel. This test demonstrates that simultaneous transmission can be achieved with FH-CDMA in the bucket, although some errors occur. Again, most of the errors are likely artificial due to the close proximity of the transducers in the bucket test.

TABLE VI.
RESULTS OF SIMULATAENOUS TRANSMISSIONS (BUCKET)

Test Sequence Sent from Modem 1	Test Sequence Sent from Modem 3	Message Received by Modem 4	Message Received by Modem 2	Total Success Rate
5	6	aaββ ssss dddd ffff ggββ ββββhj	zzzz xxxx cccc vvvv bbββ ββnmnm	76.92%
6	5	zzzz xxββ cccc ββββ bbbb nmnmnm	aaaa ssββ ββββ ffff ββββ hjhjhj	69.23%
1	7	1234567890	ββqqqqqqββ	80%
7	1	ββββqqqqqq	1234ββββββ	50%

B. FH-CDMA Lake Test

Tables VII and VIII present the results of the two simplex transmissions in the "Frog Pond." It is clear that the performance of FH-CDMA is much better in the lake environment, which validates our claim that most of the transmission errors observed in the bucket are the consequence of the artificial bucket environment.

TABLE VII.
TRANSMIT ONLY FROM MODEM 1 (LAKE, MODEM 3 IS SILENT)

Test Sequence	Received by Modem 4	Success Rate
1	1234567890	100%
2	Qwertyuiopasdfghjklzxcvbnm	100%
3	QWERTYUIOPASDFGHJKLZXCVBNM	100%
4	This is a test sentence.	100%

Test Sequence	Received by Modem 2	Success Rate
1	ββββ	0%
2	ββββββββββββ	0%
3	ββββββββββββ	0%
4	ββββββββββββ	0%

TABLE VIII.
TRANSMIT ONLY FROM MODEM 3 (LAKE, MODEM 1 IS SILENT)

Test Sequence	Received by Modem 2	Success Rate
1	1234567890	100%
2	Qwertyuiopasdfghjklzxcvbnm	100%
3	QWERTYUIOPASDFGHJKLZXCVBNM	100%
4	This is a test sentence.	100%

Test Sequence	Received by Modem 4	Success Rate
1	ββββ	0%
2	ββββββββββββ	0%
3	ββββββββββββ	0%
4	ββββββββββββββββββββββββ	0%

Table IX reports the results of the simultaneous transmissions. The success rate is 100% in three of four transmissions. Even the imperfect transmission has a success rate above 80%.

TABLE IX.
RESULTS OF SIMULTANEOUS TRANSMISSIONS (LAKE)

Test Sequence Sent from Modem 1	Test Sequence Sent from Modem 3	Message Received by Modem 4	Message Received by Modem 2	Total Success Rate
5	6	aaaa ssss dddd ffff gggg hjhjhj	zzzz xxxx cccc vvvv bbbb nmnmnm	100%
6	5	zzzz xxββ ββββ vvvv bbbb nmnmββ	aaaa ssss dddd ffff gggg hjhjhj	84.62%
1	7	1234567890	qqqqqqqqqq	100%
7	1	qqqqqqqqqq	1234567890	100%

VI. CONCLUSIONS

After several tests in the bucket and the lake with the four Desert Star RBS-1 underwater acoustic modems, we conclude that bandwidth-efficient full-duplex communication is feasible in underwater acoustic networks using CDMA techniques. In particular, the FH-CDMA method performs extremely well.

This research also confirms it is possible to achieve full-duplex underwater acoustic communication using FDMA techniques. However, FDMA techniques are not as bandwidth-efficient as CDMA techniques. The total underwater acoustic bandwidth is typically limited to several kilohertz, which imposes a very low data transfer rate, unlike aerial wireless communications. Therefore, the protocol must use the available transmission bandwidth as efficiently as possible. Another drawback of FDMA systems is that they do not handle frequency selective fading well, which could impact the acoustic link reliability.

Finally, this work has several limitations which require further study. First, the potential of DS-CDMA and other more elaborate forms of CDMA were not fully realized due to the hardware limitation of the RBS-1 acoustic modems used in this work. Second, only two transmitters at a fixed distance were used in simultaneous transmission tests. In a real UAN, the number of interfering transmissions may be more than one and the positions of the transmitters may vary over time.

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