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***Abstract* — Acoustic signals offer a means of establishing wireless networks in shallow water regions. These networks may provide command and control for autonomous underwater vehicles, forward reporting by arrays of sensor grids, ad hoc communications links to covert forces, or positive control of unmanned, forward-deployed weapons systems. However, the capacity limitations and extreme propagation delays of acoustic communications must be addressed to ensure timely, predictable message delivery.**

This paper presents the status of current experimentation at the Naval Postgraduate School regarding the viability of full-duplex underwater acoustic communications. As implementation of full-duplex links requires partitioning the total capacity into distinct sub-channels, the paper presents a top-level description and specification of a capacity allocation protocol to mitigate the adverse impacts of such a partitioning when system load is light.

I. Introduction

Channel capacity and propagation delay are fundamental characteristics of a given transmission medium. For guided or aerial connections of limited length, system capacity continues to grow, as evidenced by the proliferation of Digital Subscriber Lines, digital cable service, and satellite downlinks to private residences. With the exception of satellite links, propagation delay is often considered negligible. However, for extremely long or slow connections, such as interplanetary or satellite links (as previously noted), transcontinental or transoceanic cables, or acoustic links of more than a few meters, the propagation delay becomes substantial, in the range of hundreds of milliseconds to a few seconds.

For systems with large propagation delays, collision avoidance protocols requiring the exchange of either tokens or access request and approval messages between communicating parties prior to the transmission of data, further exacerbate the impact of propagation delay, resulting in poor predictability in message delivery times. Collision detection techniques allow users to access the media whenever they determine that, locally, it is not in use by another user. Collisions are inherent, however, due to the propagation delay of the signals through the system and the reliance on local monitoring to determine channel availability. The limited ability to determine channel activity based on local monitoring is amplified for long-propagation links. As traffic loads increase, so does the probability of collisions. Either collision-avoidance or collision-detection techniques are applicable where two or more users rely on the same channel to send information. In both cases the channel is half-duplex, that is, a given user cannot send and receive simultaneously [Forouzan, 2001]. The preponderance of current acoustic networks relies on half-duplex links, which require the exchange of handshake messages to coordinate exclusive access to the shared channel [Xie, 2001]. Full duplex links would provide each user a dedicated transmit channel and the ability to listen on the transmit channels of its neighbors, thereby alleviating the need for

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access control once the network topology is established and allowing more effective flow control mechanisms to be employed to increase the overall network utilization and throughput.

However, implementing full-duplex links requires the total system data capacity be divided between the generated channels, which can lead to a net decrease in utilization should the offered traffic load of each network node be less than sufficient to fully load its assigned channel. Multiple access techniques available to generate the channels include time division (TDMA), frequency division (FDMA), and code division (CDMA). Due to the limited bandwidth, long propagation delays affecting timing control, and the selective frequency fading characteristics of the underwater channel, CDMA holds the greatest promise. A decrease in channel utilization is especially detrimental to low capacity systems, as the acoustic bandwidth is very limited, typically less than 25 kHz [Sozer, 2000]. Thus, implementation of full duplex connections for acoustic networks must consider the projected traffic load and mitigate the impact of under loaded channels on system throughput and traffic delay.

While not generally employed, the feasibility of implementing full-duplex, underwater acoustic links has been acknowledged. This capability comes at the expense of added complexity in terms of the number of required transceivers at each node as well as the reduced capacity per channel [Proakis, 2002]. This paper presents the results of experiments that model full-duplex acoustic communications. These experiments, conducted in an acoustic chamber, suggest that it is feasible to receive acoustic signals while simultaneously transmitting on another channel. Further, the paper discusses the impact of subdividing the system capacity into discrete, mutually exclusive channels to take advantage of full-duplex communications, the impact of various traffic loads on utilization, and considerations for mitigating the impact of implementing full duplex links on message delivery time when traffic loading is light.

The remainder of the paper is organized as follows: Section II provides a description of a generic underwater acoustic network (UAN) and gives an overview of an operational concept which depends upon the implementation of a reliable acoustic network, and addresses the expected traffic load; Section III provides a discussion of the full-duplex experiments performed at the Naval Postgraduate School; Section IV describes the impact of traffic load on system utilization and throughput; Section V presents a mechanism for reclaiming unused or unallocated channel capacity when a network member has traffic loads which exceed the capacity of its assigned channel while its neighboring nodes do not have sufficient traffic to fully load their allocated channels.

II. Description of a Nominal Military Underwater Acoustic Network System

The current envisioned implementation of underwater acoustic networks in support of the U.S. Navy involve one or more gateways between the acoustic network and the manned command and control facilities utilizing it. [Rice, 2000] The underwater network is expected to be self-configuring following ad hoc deployment, where the topology of the network is discovered autonomously by an orderly exchange of initialization messages between the fixed and mobile network members (nodes). The configuration task may be repeated or updated periodically to track changes in node status or location.

The network may be composed of outlying sensor nodes, which report information of interest to the command facility, and surveying or reconnaissance vehicles, which gather environmental observation data. Each of these devices is connected to the command facility though a network of acoustic repeaters, each responsible for forwarding command information to the mission nodes and relaying collected data back to the command facility. The collected data may be fused or concatenated at the intervening routers to reduce the overhead associated with forwarding individual mission data packets.

The topology of the network is generally a tree, resulting in a concentration of mission data traffic flow near the gateway. The concentration at the gateway may be significant, depending upon the number of mission nodes served by the gateway. [Rice, et al, 2001]

Present acoustic networks implement half-duplex links because of several compelling cost constraints:

First, low-cost modems typically use a common electro-acoustic transducer for both receive and transmit modes of operation, thereby preventing full-duplex operation for purely physical reasons.

Second, the available acoustic spectrum is often needed to provide some degree of frequency diversity for purposes of immunity to frequency-dependent fading (i.e., destructive interference), narrowband noise and jamming.

Third, spread-spectrum signaling over the widest practical range of frequencies is adopted for many military implementations for reasons of transmission security, CDMA soft-capacity limits, and the aforementioned inherent frequency diversity.

Fourth, the process of sub-channel allocation could be a costly process in terms of the associated overhead communications required to assign and maintain channel assignments, particularly for transient nodes such as unmanned undersea vehicles (UUVs) and submarines. An innovative coding scheme may be required to mitigate the overhead.

Fifth, the limited spectral bandwidth is precious, and FDMA techniques necessarily restrict the bit-rate associated with so-divided links. Moreover, the need for guard bands between adjacent sub-channels imposes a significant overhead cost on the link budget. Therefore, FDMA may not be a viable candidate for sub-channel generation.

Sixth, network layer protocols for underwater acoustic networks are in their infancy, and a premium is placed on simplicity in order to achieve reliable network implementations. For this reason, existing and planned networks generally involve scheduled TDMA, asynchronous TDMA, polled TDMA, or CDMA protocols. An exception to this pattern was one of the first undersea acoustic networks, Seaweb ’98, which successfully implemented a 3-cluster FDMA strategy with 3 interleaved frequency sets. [Green, et al, 1998]. However, a significant conclusion of that experiment was that the desired decrease in probability of collision was not realized because of the attendant 3-fold reduction in bit-rate, and hence the longer transmit durations. Thus FDMA was abandoned in subsequent Seaweb implementations in favor of TDMA and hybrid TDMA/CDMA.

Seventh, underwater acoustic networks can exhibit variable quality of service (QoS) because of degraded channel conditions caused by phenomena such as elevated noise levels or roughened sea surface. So network protocols relying on frequent upkeep mechanisms may collapse during such channel outages. These impairments may be sudden, as in the event of a strong interfering noise source such as a

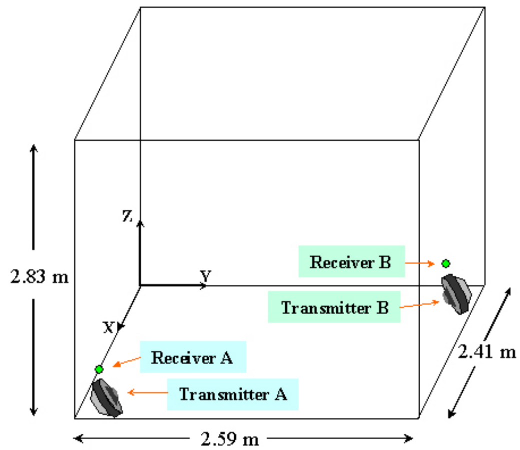

Figure 1. Full-duplex geometry in a reverberant chamber. The chamber is 2.59 m long, 2.41 m wide, and 2.83 m high, with concrete walls covered with thick plaster. The sources are JBL 2445 compression drivers and the receivers are homemade electrets microphones. For the coordinate system shown in the figure Node A is located at (2.41 m, 0, 0), and Node B is at (0 m, 2.59 m, 0).

passing ship. Moreover, a highly complex network layer may not recover from such outages as gracefully as a simpler system might.

So, the potential benefits of full-duplex communications must be weighed carefully against the costs. Care must be taken to minimize protocol complexity and limit the impact of the control traffic overhead on channel availability.

III. Full-Duplex Acoustic Communications Experiments

We conducted our experiments in a reverberation chamber 2.59 m long, 2.41 m wide and 2.83 m high, with concrete walls covered with thick plaster. For the coordinate system shown in Figure 1, transmitter and receiver A, Node A, are located at (2.41,0,0), while transmitter and receiver B, Node B, are located at (0,2.59,0). The distance between Node A and Node B is then 3.54 m. The sources are JBL 2445 compression drivers and the receivers are homemade electrets microphones. The two input and two output channels of a laptop soundcard perform the data acquisition and generation, with built-in amplifiers and preamplifiers for transmitting and recording.

Previous work in this room using a similar configuration has examined applications of time reversal acoustics to room de-reverberation [Heinemann et al., 2002]. In this work, we are interested only in the standard one-way communication between the elements to produce full-duplex communication.

The frequency range used throughout the experiment was between 2 kHz and 9 kHz. This frequency range was equally divided with a fixed frequency spacing of 2 kHz for each node, and four center frequencies. For Node A the frequencies are 3 kHz, 5 kHz, 7 kHz, and 9 kHz while for Node B they are 2 kHz, 4 kHz, 6 kHz, and 8 kHz. Each signal has a time length of 5 msec and a Hanning window envelope. These features for the symbols are followed throughout the experiment.

We will refer to the four center frequency signals for Node A as A_1, B_1, C_1, and D_1, and similarly, for Node B the signals will be designated by A_2, B_2, C_2, and D_2, where signal A_i corresponds to the lowest center frequency of the node and signal D_i corresponds to the highest (Fig 2). For the purposes of examining full-duplex communications, combinations of these

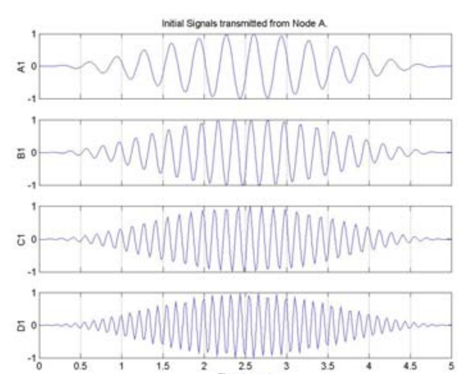

Figure 2. Initial signals transmitted from Node A.

signals will be employed as described later. Ultimately, we will examine the resolution of signals A-D when transmitted and received in full-duplex mode.

The signal processing used in our approach is based on matched-filtering the messages transmitted from the nodes with replicas of the transfer functions for each signal, based on initialization of the signaling scheme. To accomplish this, a sequence of probe signals A_1, B_1, C_1 and D_1 were transmitted separately from Node A with a sufficient time between transmissions that allows Node B to record all the multipath arrivals. And then A_2, B_2, C_2 and D_2 were transmitted separately from Node B with a sufficient time between transmissions that allows Node A to record all the multipath arrivals. These receptions were saved as prototypes that contained the transfer function of the reverberation room. Then the messages, shown in Fig 3, consisting of combinations of probe signals that make the symbols were transmitted from each node simultaneously and the receptions were recorded allowing for multipath arrivals. The recorded messages in memory were first matched-filtered with the corresponding prototypes and the resulting files were then matched-filtered with the initial signals A_1, B_1, C_1 and D_1 for Node A, A_2, B_2, C_2 and D_2 for Node B (Fig 4). This figure clearly illustrates the viability of full-duplex communications of paired acoustic links.

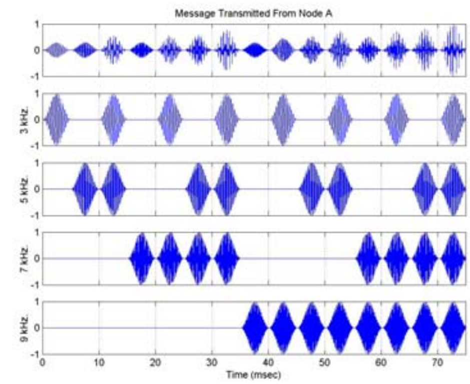

Figure 3. Message transmitted from Node A.

We also investigated the robustness of the technique for digital full-duplex acoustic communication link for different noise levels. The SNR level for each signal, A_1, B_1, C_1, D_1, A_2, B_2, C_2 and D_2, was computed each time. The minimum SNR level for which the message was still resolvable was then determined. Figure 5 corresponds to typical data with low SNRs, where it can be seen that some frequency smearing and increased side lobes occur due to the low relative signal strength. Further study is warranted to determine the overall bit error rate of the recovered signal and whether the signal strength can be increased sufficiently to lower the demonstrated error

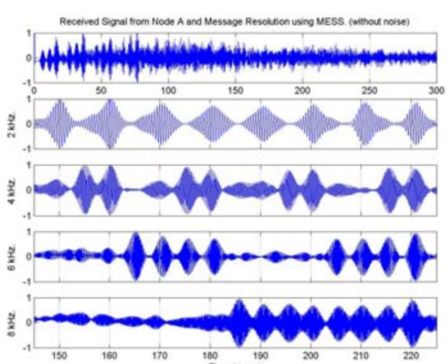

Figure 4. Message received at Node A (top), and match-filtered with the prototype signals.

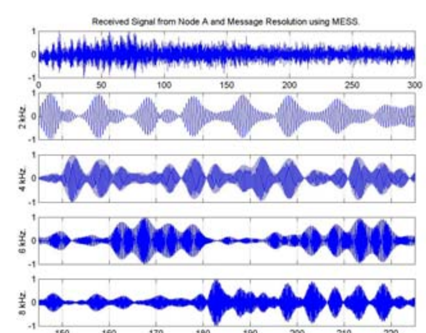

Figure 5. Received Message at node A and Message Resolution. SNR_{A2}=3.37 dB, SNR_{B2}=4.9 dB, SNR_{C2}=6.67 dB and SNR_{D2}=8.81 dB.

rate without impacting the background noise level.

IV. Traffic Load Considerations

Dividing system capacity into sub-channels may result in increased message delay if the sub-channels are insufficiently loaded. [Tannenbaum, 1988] This occurs because the effective transmission rate is decreased as the channel capacity is reduced. If any of the sub-channels are idle their capacity is wasted and nodes which have traffic to send may have been able to send the traffic at higher transmission rates had the system capacity not been divided.

Very heavy traffic loads, roughly equally presented by each of the network members, stand to benefit by full duplex communications. The reduction in control overhead, by elimination of request and authorization messages for channel access, minimizes the propagation delay imposed on each message. Further, more efficient flow control methods, necessary for coordinating the delivery and acknowledgement of data packets, can be implemented over full-duplex links than over half duplex links.

On the other hand, light traffic loads, where the probability of more than one station attempting to transmit simultaneously is very low or negligible, may suffer from the division of the system capacity into discrete channels, as the reduction in capacity reduces the maximum transmission rate, as described above. The total delay is a function of the transmission rate, the aggregate propagation delay, and the internal node processing and queuing delays. If the likelihood of packet collision is negligible, then an Aloha-protocol based access scheme provides near 100% utilization for a finitely populated network [Tannenbaum, 1988]. In such cases the network members may transmit whenever they have traffic to send without concern as to whether another member is transmitting. If a collision occurs, the intended recipient would not acknowledge receipt of the data and the transmitting node would retransmit the frame after a suitable time-out period. Since the chance of a collision is very small, retransmissions due to simultaneous access by two or more nodes is rare and the delay induced by the protocol is marginalized. While the light traffic load may result in less collisions thus permit operating the network without collision avoidance or detection techniques at the media access control layer, a separate low capacity back channel may still improve the performance of the network by allowing more capable flow control mechanisms to be employed at higher protocol levels.

While these two scenarios describe the extremes of traffic load patterns, it is necessary to also consider systems whose traffic patterns fluctuate between the extremes, varying over time. The Transmission Control Protocol (TCP) addresses this by implementing a *slow-start* approach to congestion control [Feit, 1999]. When a network member initializes transmission the receiving node throttles the sender's transfer rate, as measured by the number of packets the sender may submit before waiting for acknowledgements. If the network is able to absorb the traffic flow the recipient increases the number of packets the sender may send between acknowledgements. This mechanism prevents members from degrading or denying the service provided to other users by over loading the system. It assumes that more than one user is utilizing the capacity at one time, otherwise congestion would not occur, assuming intervening nodes (routers) have sufficient capacity to process and forward any load presented within the channel capacity of the network.

Limited Contention Protocols provide for a *fast start* capability, where it is assumed that most frames will not collide, but should collisions occur the collision domain is recursively restricted until the collision is eliminated. Tannenbaum provides a discussion of two such protocols, the Adaptive Tree Walk and the Urn Protocols. [Tannenbaum, 1988] In each case, contentions are eliminated by systematically reducing the number of stations authorized to transmit until either the contention is eliminated or only one station is authorized to send traffic [Tannenbaum, 1988].

Either the *slow start* or *fast start* methods may be implemented in an acoustic network, depending upon the known characteristics of the network's traffic. For networks where the traffic is best characterized by arrival in bursts and the overall system load is light, the fast start mechanism may be most appropriate. On the other hand, where traffic is more continuous in nature, the slow start mechanism provides a better likelihood of lower delays due to initial collisions while the network adapts.

If, however, the traffic arrival is sporadic and unpredictable, another approach may be warranted. We propose an approach where each node is allocated a dedicated channel if it has at least one child node, otherwise it contends with its sibling nodes for a common express channel. Note that a node will be both a child and a parent if it is not on a logical extremity of the network and would have a dedicated parent-channel. All other channels not assigned within the two-hop neighborhood of the parent are collectively pooled as a source of dynamic capacity to be allocated on demand by the parent node. No node is delayed pending collision management, and the parent is able to allocate the dynamic capacity based on observed traffic loads. When a node notifies the parent that it has traffic to send the remaining capacity is allocated to that node. If other nodes are currently transmitting, then the total capacity, excluding the express and parent-channels, is equally divided among the transmitting nodes. This mechanism ensures collisions only occur on the express channel. To limit the number of sequential collisions, the parent may de-allocate the dynamic capacity such that each node is provided a dedicated channel if the number of collisions exceeds an arbitrary threshold. Upon successful access by the child nodes, the parent can determine which children have traffic to send and re-allocate the capacity accordingly.

Recognizing that dividing the total system capacity into discrete sub-channels in order to implement full-duplex links may lead to decreased capacity utilization, the following section describes a method of implementing an adaptive capacity allocation so as to mitigate that impact and allow the effective utilization to be restored, while providing users with higher traffic submission requirements to access to increased transmission rates via multiple sub-channel access.

V. Reclaiming Unused System Capacity

Our approach adapts the allocation of capacity to the dynamic traffic load, providing each node a dedicated portion of the local capacity after it successfully communicates the first frame to its parent. This strategy makes use of the low likelihood of collisions due to the sporadic nature of the traffic. Within a one-hop sub-tree, child nodes contend for access to a single express channel, without collision avoidance measures. If a child has traffic to send it sends the first frame with a flag to indicate whether additional frames follow. If two or more frames arrive at the parent node simultaneously, the parent sends a collision notification to all its children. Those children in the process of sending a frame over the express channel or are awaiting acknowledgement for a frame sent over the express channel attempt to resend the frame after waiting a random period of time. If no collision occurs and the frame indicates that the source has more data to send, the parent allocates the dynamic allocation pool to the source. However, if any other node is currently allocated the dynamic pool, then the parent must distribute the dynamic capacity among those nodes as well as the new source.

Following is a high level specification of the protocol described above, constrained by these key assumptions:

- The network is configured as a tree topology [Xie, 2001]
- Each node is aware of its two-hop neighborhood
- All nodes can transmit and receive simultaneously (full-duplex capable)
- The node density may be affected by adjusting the transmit levels
- Each parent (local sub-tree root) can communicate to its children without prior coordination
- Nodes can detect collisions and determine which channels are involved
- Communications link characteristics, while dynamic, change slowly over time as compared to the node configuration interval.
- Communications links are symmetric within their change period, that is, if Node a can communicate directly with Node B, then Node B can communicate directly with Node A
- Each node is able to configure its transmit and receive channels dynamically and autonomously
- Transmission rates may be dynamically changed by controlling the number of sub-channels a given node transmits on simultaneously

Following are objects, variables, and procedures used to manage the channel allocation within a parent's local neighborhood as well as to track the status of each node's communications. The channels are unidirectional, thus both a send and a receive channel must be established between nodes to support full-duplex links. The procedures describe the actions taken by a child node to send traffic and by the parent node to allocate capacity to active children. Note that if the parent has more than a single frame to send to any of the children it may allocate a portion of the dynamic capacity to itself for the duration of the transmission. In this case the active children must be advised of the re-allocation by the parent so that they terminate use of those channels until the parent releases them.

- *F*, boolean flag (bit) indicating whether or not the current frame is the first frame of the message
- *E*, boolean flag (bit) indicating whether or not the current frame is the last frame of the message
- *C*, boolean flag (bit) set when the parent detects a collision on the express channel; initially set to false
- *Active*, the number of nodes currently transmitting data; initially set to zero
- *p*, parent node's channel
- *x*, express channel contended for by child nodes to initiate data transmission
- *S(i),* set of channels allocated to node *i*; initially empty

Procedure ChildTransmission ()
// called by child node when it has traffic queued
// to send to its parent

```
Begin
   if (received collision notice from parent)
      then    wait random time;
   end-if

   if (previously idle)
      then    set F = true;
   end-if

   if (last frame)
      then    set E = true;
              // determination of last frame
              // status is application specific
   end-if

   if  (S(i) is empty)
      then    send frame on channel x;
      else    send frame on S(i)
   end-if
End

Procedure ParentReceipt ()
// called by parent when it received traffic
// from a child
Begin
   read in frame;

   if (collision detected)
      then
          if (C = true)
             then
                allocate each child one channel;
                SendReallocationNotice ();
             else
                send collision notice on channel p;
                set C = true;
          end-if
      else
          extract the F and E bits;
          set C = false;
          if (F = true and E = false)
             then      Active = Active + 1;
             else if (F = false and E = true)
                  then     Active = Active - 1;
                  end-if
         end-if
   end-if

   if (Active changed)
      then
        Partition channel set equally among
           active nodes, avoiding neighbor conflicts;

           BroadcastReallocationNotice ();
   end-if
End

Procedure BroadcastReallocationNotice()
// called by parent when it needs to change
// allocations sent to its children
Begin
   append S(i) for each active node to message;
   send message on channel p;
End

Procedure ReceiveReallocationMessage ()
// called by child node when it receives a new
// allocation message from its parent
Begin
  extract S(i), where i is this node's ID;
  if (S(i) is not empty)
     then    configure channels accordingly;
  end-if
End
```

VI. RELATED WORK

Much effort has been put forth to provide effective schemes to control access to the shared medium in wireless ad hoc networks. As indicated earlier, one of the fundamental differences between wireless ad hoc networks and underwater acoustic networks is the significant propagation delays experienced in the aquatic medium. This difference, on the order of five magnitudes, severely limits the adaptation of Time Division Multiple Access (TDMA) schemes often employed in the tradition wireless environment. In particular, the requirement for precise timely in TDMA schemes, normally as measured in relation to the propagation time between the two most distant nodes, makes it difficult to control time slot access. The Five-Phase Reservation Protocol proposed by Zhu requires precise timing at each node [Zhu, 1998]. This predicates access to a global clock, not necessarily available in an underwater acoustic network. Additionally, nodes must exchange several handshake exchanges before access to the media is established. While each handshake message is only on the order of several bits each, the added propagation delay induced, negligible in an air-based network, is significant in an underwater environment.

Code Division Multiple Access (CDMA) provides a key alternative to TDMA for sub-channel creation. J.J. Garcia provides a thorough discussion of its utility, as well as a distributed approach to allocating channels in an ad hoc network based on the use of CDMA [Garcia-Luna-Aceves, 1997]. Like Zhu's discussion, Garcia focuses on air-based wireless networks where the propagation delay is s\mall compared to the data transmission time. His algorithm also addresses a more general network topology, whereas the underwater acoustic networks discussed in this paper are tree-based. A significant finding of Garcia, however, is that the number of codes necessary to fully connect a network, where each node has its own code and thereby a dedicated transmit/receive link, thus eliminating contention for the shared media, is strictly less than the square of the largest number of nodes within a one-hop radius. Thus, the maximum number of channels necessary to support an underwater acoustic network can be determined based on the number of nodes deployed and their respective transmission ranges, which determines the one-hop neighbor radius.

VII. Conclusions

The feasibility of full-duplex acoustic communications and, by analogy, full-duplex underwater links, has been demonstrated. Further, the paper explored a mechanism for mitigating the adverse impact on traffic transmission delays induced by dividing the total channel capacity into sub-channels. Bounding the accumulated propagation delay is critical to providing predictable message delivery across underwater acoustic networks. The implementation of innovative protocols, which adapt advances being made in ad hoc air-based wireless networks to acoustic networks, is essential to improving the performance characteristics, as measured by delay and transmission rates, of underwater acoustic networks.

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