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Full Duplex Underwater Acoustic Networking

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ABSTRACT

We investigate the benefits of in-band full duplex (FD) communication for underwater acoustic network (UAN) protocol development. In the case of a point-to-point link, FD communication allows simultaneous transmission in both directions, thus doubling the maximum throughput. However, in UANs the interference from other nodes must be managed using a Medium Access Control (MAC) protocol. In this study, we evaluate the throughput gains afforded by FD communication for ALOHA random access and schedule-based MAC protocols, in particular, proposing a spatial reuse scheduling algorithm that exploits FD communication. Further work includes the development and hardware implementation of UAN protocols that exploit the two-element FD transducer developed at York.

KEYWORDS

Full Duplex, Medium Access Control, Underwater Network

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1 INTRODUCTION

In-band full-duplex (FD) communication [4] enables simultaneous transmission and reception of acoustic signals between two underwater nodes. For example, this can be achieved by equipping each node with a two-element transducer such as that shown in Figure 1, and performing *self-interference cancellation (SIC)*, i.e. cancellation of the transmitted signal at the hydrophone. The throughput gain of FD on a point-to-point link is clear: the maximum channel throughput is doubled. However, in underwater acoustic networks (UANs) the performance benefit of FD is less straightforward. It depends on the traffic flow and interference from other nodes managed by the Medium Access Control (MAC) protocol. The problem of inter-node interference (illustrated in Figure 2) exists regardless whether the nodes are equipped with half-duplex (HD) or FD acoustic modems.

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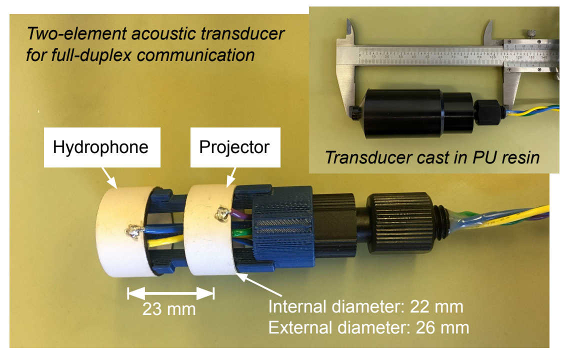

Figure 1: Two-element transducer prototype developed at University of York for FD communication [2].

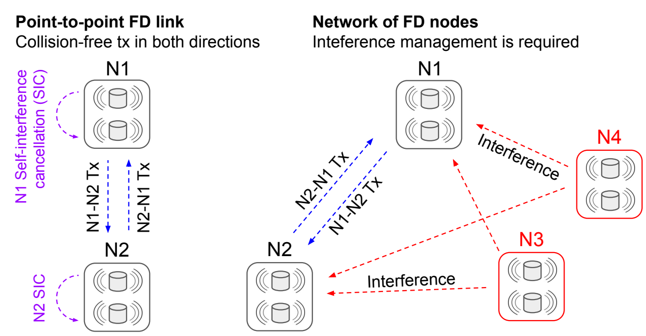

Figure 2: To gain the benefit of FD in networks, inter-node interference must be managed.

In this study, we investigate the throughput gains afforded by FD using ALOHA [1] and Spatial Reuse Time Division Multiple Access (STDMA) [3] protocols. We discuss the modified constraints of the STDMA slot assignment problem for FD-enabled nodes and compare the throughput of STDMA in HD- vs FD-enabled networks.

2 ALOHA NETWORKS

ALOHA [1] is a straightforward random access MAC protocol, which is still widely used in both UANs and terrestrial networks due to its simplicity and lack of control overhead. It is based on the principle of random access: if a node has a packet to transmit, it transmits it immediately, unless it is currently busy transmitting a previous packet, in which case it waits until it finishes before transmitting the new packet. We simulated ALOHA in two equivalent sets of UAN scenarios: one with HD-enabled nodes and one with FD-enabled nodes. In each scenario, the nodes were uniformly randomly placed within a 2×2×0.5 km space and generated packets

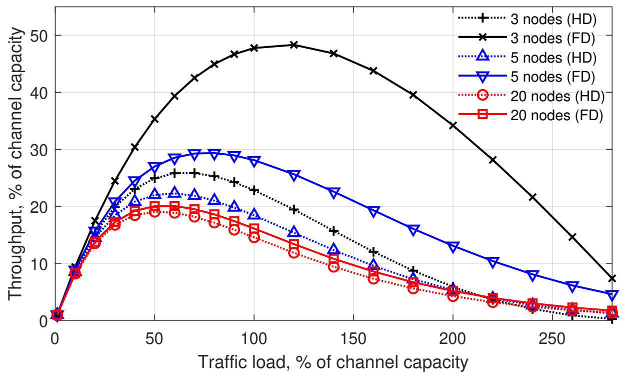

Figure 3: ALOHA throughput in HD- vs FD-enabled UANs.

to a random destination, at random times following the Poisson traffic model. The simulations assumed 1,500 m/s propagation speed, single-collision domain, and lasted 1,000,000 transmissions each.

Figure 3 plots the ALOHA network throughput against traffic load at different network sizes. The benefit of FD is pronounced in small networks, because Tx-Rx collisions (i.e. transmitting a packet while receiving another one) are a significant source of packet loss in the HD case, but are eliminated by the FD capability. In the case of 3-node networks, the increase in the maximum network throughput is 87%, which is approaching a factor of two: the maximum throughput increase on a point-to-point link. However, in larger networks, the likelihood of Rx-Rx collisions (inter-node interference) is far greater than that of Tx-Rx collisions (at an equivalent traffic load). Therefore, the performance improvement afforded by FD is much smaller, e.g. 5% in 20-node networks.

3 STDMA SCHEDULING IN FD NETWORKS

TDMA is another class of MAC protocols widely used in UANs. There, every node is assigned a dedicated time slot for transmission. The throughput of TDMA in UANs can be increased by exploiting topology sparsity and scheduling multiple transmissions in the same slot (spatial reuse), thus upgrading TDMA to STDMA [3].

Figure 4 depicts an example where FD capability at the network nodes is beneficial for STDMA. There, a 6-node network can operate using a 3-slot frame, by allowing N1&N2, N3&N4 and N5&N6 to transmit in parallel and avoid collisions. In comparison, the shortest possible STDMA frame in the HD case is 4 slots, where nodes can reuse the same time slots only if they are separated by more than 2 hops (i.e. they have no common neighbours). Deriving an STDMA schedule that minimises the number of time slots (i.e. maximises the throughput) is NP-Complete [3]. In the traditional HD case, the

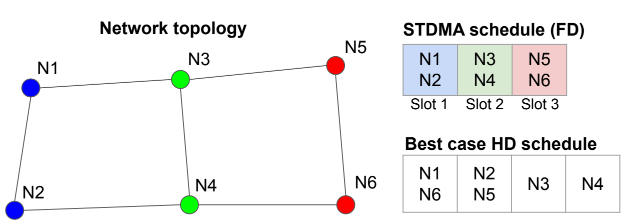

Figure 4: FD enables more efficient spatial reuse in STDMA.

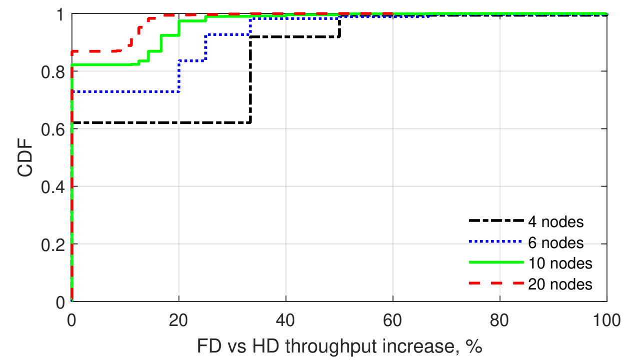

Figure 5: STDMA throughput enhancement afforded by FD.

optimisation constraint can be described as follows: *nodes can reuse the same slot only if they are separated by more than 2 hops*, i.e. if they have no common neighbours. In this paper, we propose a relaxed constraint for the STDMA scheduling problem which exploits the use of FD communication. *In addition to nodes separated by more than 2 hops, a pair of direct neighbours can reuse the same slot, but only if they do not have a common neighbour.* The difference between the HD and FD constraints on the STDMA scheduling problem is exemplified in Figure 4: two different solutions are produced, with the FD solution exploiting the ability of two nodes communicating with each other simultaneously. In this case the throughput increase afforded by FD is 33%: 6 packets in 3 slots (FD) vs 4 slots (HD).

Figure 5 compares the throughput of FD- vs HD- enabled STDMA networks for a range of network sizes, with 100,000 randomly generated UAN topologies for each size. The results suggest that the upper limit on the throughout increase achievable by FD is 100% (factor of two). However, such a large increase was achieved in a small proportion of cases, with topologies particularly suitable to take advantage of FD. In the majority of simulations, there was little to no benefit in having the FD capability in an STDMA network.

4 CONCLUSIONS AND FURTHER WORK

This study empirically demonstrated that in-band FD capability can provide up to a 100% throughout gain in a UAN. However, simulations of ALOHA showed that the throughput gain is significant only in very small networks; and simulations of STDMA showed that, although a high throughput increase can be provided in particular network topologies, FD provides little to no benefit for network throughput. Future work includes the development of novel MAC protocols that approach the empirically observed 100% throughout gain limit, and their hardware implementation using the two-element FD transducer developed at York.

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