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FULL-DUPLEX UNDERWATER ACOUSTIC NETWORKING: THE IMPACT OF RESIDUAL SELF-INTERFERENCE ON THE MAC LAYER PERFORMANCE

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ABSTRACT

In-band full-duplex (FD) communication enables simultaneous transmission and reception of acoustic signals between two underwater nodes. This can be achieved by performing self-interference cancellation (SIC) at the physical (PHY) layer. In this paper, we investigate the benefits of FD in underwater acoustic networks (UANs), in particular, focusing on the Medium Access Control (MAC) layer. In practice, SIC produces residual self-interference (RSI) which reduces the received signal quality. We evaluate the performance of ALOHA and Spatial TDMA (STDMA) MAC protocols at a range of practical RSI levels observed in previous lake experiments. Simulation studies show that RSI has a negative impact on the throughput and packet loss in small UANs; however, this performance degradation is typically negligible in larger networks. Comparing the performance of FD-STDMA networks with equivalent half-duplex networks shows that there are specific network geometries where FD can substantially enhance the throughput – by up to 100%; however, in most simulated topologies the throughput gain of FD is small. Further work is required to jointly optimise the PHY and MAC layers and produce topology-specific solutions to extract bigger performance gains from FD.

Keywords: *full duplex, medium access control, self-interference cancellation, underwater acoustic network*

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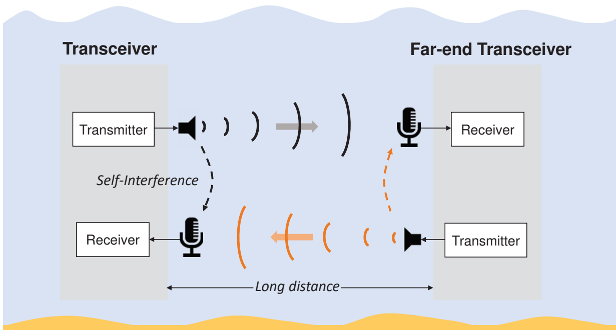


Figure 1. Illustration of a point-to-point FD underwater acoustic link [3].

1. INTRODUCTION

In-band full-duplex (FD) communication [1] 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 [2], 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 highly variable. 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 exists regardless of whether the nodes are equipped with half-duplex (HD) or FD modems, as depicted in Figure 2.

MAC protocol design is especially challenging in

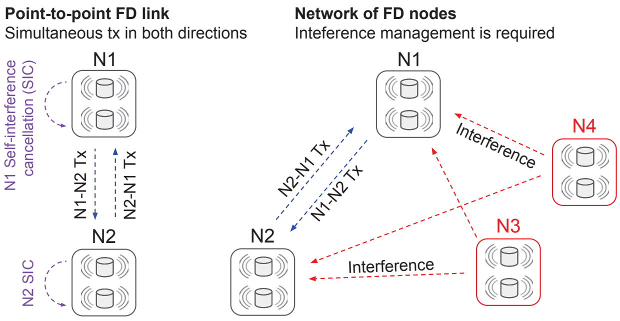


Figure 2. For point-to-point acoustic links, FD enables simultaneous transmission in both directions; however, in FD networks the interference from other nodes must be managed to enable FD [4].

the underwater acoustic domain due to the extremely slow propagation of acoustic waves (typically between 1450–1550 m/s) and low available bandwidth (typically in the order of several kHz) [5]. Existing single channel MAC protocols can be primarily categorised as follows: (1) *Random access* — the nodes are allowed to transmit at random times, when they have a packet to send (the ALOHA principle [6]); (2) *Carrier sensing* – a node must "listen" for the presence of other transmissions on the shared channel and only transmit a packet if the channel is idle [7]; (3) *Channel reservation* (related to CSMA) – before transmitting a packet, a node must reserve channel access via dedicated control signals, typically involving a Request-to-Send (RTS), Clear-to-Send (CTS) exchange between the sender and the receiver [8]; (4) *Packet scheduling (Time Division Multiple Access – TDMA)* – the nodes are scheduled to transmit their data packets in particular time slots such that the packets arrive at the intended receivers without collisions.

There have been multiple efforts to design MAC protocols specifically for FD UANs, e.g. [1, 9–12]; however, they largely focus on increasing the robustness and efficiency of the RTS/CTS channel reservation process, where the FD capability was shown to improve the carrier sensing performance (nodes can "listen" on the channel even when transmitting), thereby increasing the network throughput and reducing the latency compared with equivalent half-duplex (HD) protocols. In this paper, we investigate the impact of FD capability on the performance of ALOHA and Spatial reuse TDMA (STDMA) protocols, and in particular evaluate the impact of *residual self-interference (RSI)* on the performance of these protocols, which to our knowledge has not been considered in the FD UAN protocol literature. The RSI was modelled based on the results of deploying a hardware prototype of a two-element FD transducer [2] in lake experiments.

The rest of the paper is organised as follows: Section 2 discusses the challenges of FD communication at the physical (PHY) layer; Section 3 considers the MAC layer in FD networks and our proposed solution to Full Duplex STDMA (FD-STDMA) packet scheduling; Section 4 presents the results of the simulation study; finally, Section 5 concludes the paper.

2. FD COMMUNICATION AT THE PHY LAYER

The main PHY layer challenge of FD communication is to cancel the strong self-interference (SI) from the near-end transducer. Any residual SI (RSI) would reduce the signal-to-noise ratio of the far-end desired signal thus degrading the system throughput. A combination of analogue and digital cancellation is normally used in terrestrial radio communications [13, 14]. Analogue cancellation is applied before digital cancellation to avoid the saturation in the analogue-to-digital converter (ADC) [15]. For underwater acoustic (UWA) systems, in general, significantly lower frequencies are used than that in terrestrial radio communications. High-resolution ADCs up to 24 bits or higher can be used [3]. Therefore, digital cancellation up to 100 dB is feasible. One of the main factors limiting the digital cancellation performance comes from the non-linearities of the hardware instruments, including the power amplifier (PA) used for near-end transmission, the hydrophone pre-amplifier and the transducer itself [16]. The non-linearities introduced by the PA can be mostly addressed by using the PA output as the reference signal for digital cancellation [3, 17]. An adaptive linear equalizer is proposed in [18] to address the non-linearities introduced by the hydrophone pre-amplifier. However, there is no obvious solution on how to address the non-linearities of the transducers. Another limiting factor of the digital cancellation performance is the fast variation of the SI channels, which is mainly caused by the moving sea surface [19, 20]. Many algorithms have been proposed to provide a better tracking performance of the SI channels in FD UWA communications [19, 21, 22].

As shown in [21, 22], a good digital SI cancellation (SIC) performance can be achieved when the far-end signal is absent. However, the SI channel estimation performance is limited in FD scenarios with the presence of the far-end signal. In [23], a two-iteration FD UWA system which alternates between the near-end SIC and far-end data demodulation is proposed. In the first iteration, the SI channel is estimated, treating the far-end signal as an extra noise. In the second iteration, the far-end signal is removed from the received signal based on the tentative data estimates in the previous iteration. Experimental results from lake trials in [23] showed that a residual SI level of about 0 to 5 dB higher than the background noise level can be achieved using this scheme.

To achieve more reliable SIC performance, it is useful to combine digital cancellation with other cancellation techniques. The use of wide-band signals in UWA systems does not allow us to perform antenna cancellation as suggested in [15], but we can perform SIC in the spatial and acoustic domains. In [24], a spatial SI cancellation technique was proposed to reduce the SI in a desired direction using a UWA vector sensor and a phased array transducer. An acoustic domain SIC scheme with two projectors was proposed in [25]. This scheme requires real-time adaptation and generation of the cancellation signal on the secondary projector. A higher level of SIC performance can be potentially achieved by applying spatial/acoustic cancellation on top of the digital cancellation.

3. MAC IN FD NETWORKS

In this section we discuss the benefits of introducing FD capabilities for different types of MAC protocols.

3.1 ALOHA in FD networks

ALOHA [6] is a straightforward 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 busy transmitting a previous packet, in which case it waits until it finishes before transmitting the new packet.

The main benefit of FD in ALOHA is that it enables packet reception even when the transmitter is busy. In this way, the probability of collision between a received packet and a transmitted packet at the same node is eliminated, assuming hypothetical "perfect" FD with zero RSI. However, in practice there will be a non-negligible level of RSI which will reduce the Signal-to-Noise Ratio (SNR) of a received packet, thus increasing the probability of frame error (and therefore the probability of packet loss). In Section 4 we investigate the impact of a variable level of RSI on the ALOHA network performance.

3.2 CSMA-based FD Networks

The key benefit of FD in CSMA-based networks is that the nodes are able to sense the channel continuously, even when they are transmitting, thus improving their collision detection performance and thereby reducing the probability of packet loss. In particular, the existing literature focuses on the RTS/CTS version of CSMA in FD networks, where the nodes have to reserve the channel using an RTS/CTS handshake before transmitting their data. The RTS/CTS handshake alleviates the hidden terminal and exposed terminal problems, which are encountered in standard CSMA or CSMA-CA (CSMA with collision avoidance). For example, Zhang et al. [9] and Li et al. [11] propose protocols which aim to facilitate parallel RTS/CTS handshakes afforded by the FD capability of the nodes, thus reducing the channel reservation delay and increasing the network throughput. Kang et al. [10] propose a bidirectional FD MAC protocol where, upon reserving the channel using a standard RTS/CTS handshake, both the initiating node and the receiving node can transmit packets to each other simultaneously. This has a clear benefit over an equivalent half-duplex scenario; however, it is only relevant if the receiving node also happens to have a packet which needs to be sent to the node that reserved the channel for transmission.

3.3 STDMA Scheduling in FD Networks

In TDMA, all nodes have a synchronised clock reference and time is divided into frames and slots, such that every node is assigned a dedicated time slot in a frame for collision-free transmission. The throughput of TDMA can be increased by exploiting topology sparsity, often encountered in ad hoc UANs, and scheduling multiple transmissions in the same slot (spatial reuse), thus upgrading TDMA to STDMA [26].

Figure 3 gives an illustrative example of spatial reuse

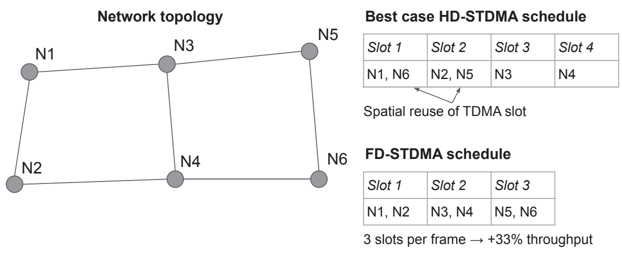


Figure 3. Example of spatial reuse in FD-STDMA.

of time slots and how it can be enhanced by FD. The given 6-node network can operate using a 4-slot STDMA frame in the standard HD case. In comparison, FD-STDMA can operate with a 3-slot frame, where N1&N2, N3&N4 and N5&N6 can transmit in parallel with each other and avoid collisions (not taking into account the impact of RSI), since they do not have any common single-hop neighbours. Deriving an STDMA schedule that minimises the number of time slots (i.e. maximises the throughput) is NP-Hard [26]. In the traditional HD case, the 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 [4] we proposed 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 3: 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).

However, the above analysis assumes perfect FD (zero RSI), which enables collision-free spatial reuse of time slots in the manner depicted in Figure 3. In a practical FD communication system, the RSI will effectively reduce the SNR of a received packet if a transmission is taking place at that node, thus increasing the probability of packet loss due to self-interference.

4. SIMULATION STUDY

In this section the performance gains provided by FD are evaluated in simulations of ALOHA and STDMA networks at a range of RSI values: from perfect FD (-∞ dB) to 20 dB RSI relative to the noise floor. For each experiment, we compare the performance of FD networks with an equivalent HD protocol. The details of the simulation model are given in the next subsection.

Table 1 lists the key parameters of the simulation model. The nodes are uniformly randomly distributed in a 5×5×0.5 km underwater space with a minimum distance of 700 m between any two nodes. This minimum distance was set to ensure that the nodes are distributed across the whole area and form sparsely connected ad hoc networks for STDMA simulations, such as that depicted in Figure 3. In the ALOHA simulations, the acoustic transmit power was set to 170 dB re 1 μPa @ 1m, which was empirically found to result in all nodes being within communication range of each other. The Urick propagation loss model was used [27,28], which comprises the spreading loss (exponent k=1.5) and Thorp absorption loss. In practice, such transmit power is unlikely to provide full coverage across a 5×5 km area, e.g. due to higher propagation loss, multipath fading etc., but in this simulation model this transmit power was empirically found to provide realistic SNR levels at the receivers. In STDMA simulations, the transmit power was reduced to 145 dB re 1 μPa @ 1m to provide partial network connectivity and to enable spatial reuse of the channel in different parts of the network.

Table 1. Simulation parameters.

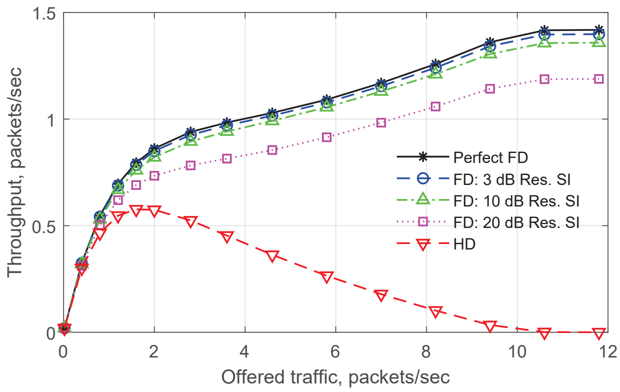
Parameter	Value
Network area	5×5 km
Sea depth	500 m
Number of nodes	4–20
Acoustic Tx power	145–170 dB re 1 μPa @ 1m
Centre frequency	24 kHz
Bandwidth	7.2 kHz
Fixed sound speed	1,500 m/s
Acoustic noise	Ambient noise model [27]: 10 m/s wind, 0.5 shipping activity factor
Propagation model	Urick model [27]: spreading loss (exp. k=1.5) + Thorp absorption loss
Traffic model	Poisson, unicast, random dest. addr.
Channel bitrate	1 kbit/s
Packet size	500 bits
RSI for FD	{-∞, 3, 10, 20} dB above noise floor

4.1 Modelling the Impact of RSI

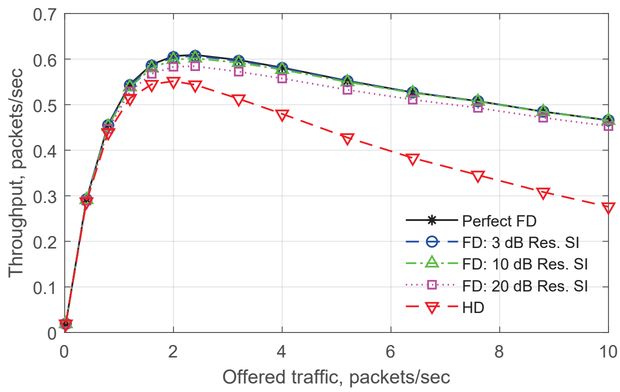
The receiver performance is modelled based on computing the Signal-to-Interference-plus-Noise Ratio (SINR) for every received packet as follows:

$$\mathrm{SINR_{lin}} = \frac{P_{\mathrm{rx}}}{P_{\mathrm{noise}} + P_{\mathrm{rsi}} + P_{\mathrm{intf}}}, \quad (1)$$

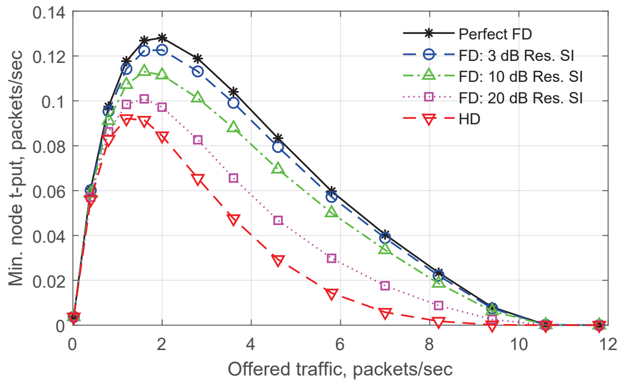
where $\mathrm{SINR_{lin}}$ is the SINR in linear scale; P_{rx} is the received signal power; P_{noise} is the noise power calculated by integrating the ambient noise power spectral density (modelled as stated in Table 1) across the frequency band of the signal; P_{rsi} is the RSI power (only included if the receiving node is also transmitting at the same time); and



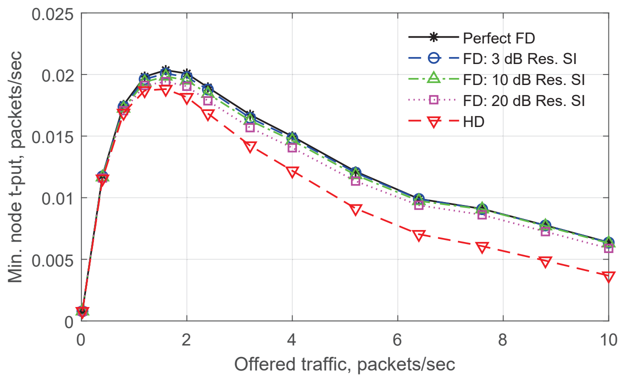
(a) Network throughput, 5 nodes



(b) Network throughput, 20 nodes



(c) Minimum node throughput, 5 nodes



(d) Minimum node throughput, 20 nodes

Figure 4. ALOHA throughput in 5- and 20-node networks.

P_{intf} is the total interference power, i.e. total received power of unwanted packets from other nodes, if any. We define $\text{SINR}_{\text{min}} = 3$ dB as the minimum SINR at which the packets are decoded correctly; if $\text{SINR} < \text{SINR}_{\text{min}}$ during the reception, the packet is dropped.

We model the RSI as an additional noise source that reduces the SINR when there is a transmission taking place at the given node. Our previous lake experiments in [23] have shown that it is possible to achieve RSI close to the noise level using effective SIC at the receiver. The RSI levels used in this simulation study range from 3 to 20 dB above the noise floor, representing relatively good and poor SIC at the receiver, respectively. We also include results for RSI$= -\infty$ dB, i.e. "perfect FD".

4.2 Performance of ALOHA in FD Networks

Figure 4 shows the results of simulating ALOHA in 5-node and 20-node networks with and without FD. Figure 4a shows an interesting effect of FD on the throughput performance of very small networks. The throughput was calculated as the average number of packets successfully received *by the intended receivers* per second. There, the FD network throughput kept increasing with the traffic load to the point where it became full buffer traffic (all nodes constantly transmitting packets). A closer inspection of the simulation results revealed that the network had effectively split into two isolated point-to-point FD links, where two pairs of nodes located significantly closer to each other were able to communicate at a sufficiently high SINR, but were not able to communicate with any other nodes. This effect is demonstrated in Figure 4c; it shows that the minimum node throughput in the network deteriorates with the increase in the traffic load, as expected in ALOHA, until one of the nodes is in complete outage due to the interference from the other nodes. Figure 4c also shows that FD can bring a considerable improvement in the maximum throughput by reducing the packet loss rate in small FD UANs: up to 44% throughput increase in the perfect FD case. However, when RSI is taken into account, this improvement is reduced to 37%, 28% and 11% for RSI levels of 3, 10 and 20 dB, respectively.

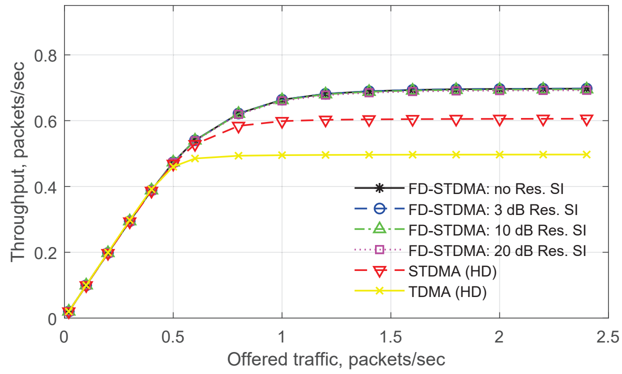
Figure 4b and 4d show the results of the same experiment for 20-node networks. The plots show a much smaller improvement in performance achieved by FD, compared with HD ALOHA. This is because the benefit of FD in ALOHA is that it eliminates Tx-Rx collisions (i.e. transmitting a packet while receiving another one). In very small networks, Tx-Rx collisions are a significant source of packet loss at high traffic loads, whereas 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).

4.3 STDMA in FD Networks

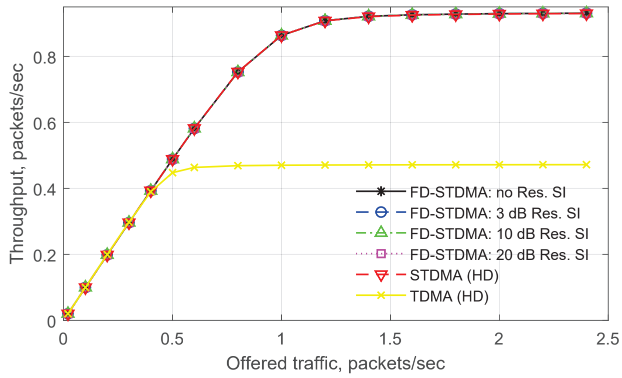
Figure 5 compares the throughput of FD- vs HD- enabled STDMA networks, based on the average performance in 500 randomly generated UAN topologies for each network size. The plots also show the performance of TDMA without spatial reuse for baseline comparison. As stated in Section 4.1, a successful packet reception is assumed if SINR $>$ 3 dB. In the absence of any interference, SINR is equal to the SNR; therefore, the SNR $>$ 3 dB threshold defines the effective communication range of the nodes. The interference range for STDMA scheduling in this study was based on the SNR $>$ 0 dB threshold, i.e. any links with SNR $>$ 0 dB are considered as interfering links; therefore some nodes, that were not able to communicate, still interfered with each other.

Similarly to ALOHA, the largest impact of FD on the performance of STDMA was observed in small networks (6 nodes). This is because they were more likely to form sparsely connected topologies, such as that in Figure 3, by randomly placing nodes in a square coverage area. In theory, similar throughput gains could be observed in much larger networks, if they followed a particular topology pattern (e.g. extending the spatial reuse pattern from Figure 3 to the right or left). However, in our simulations, where nodes were placed randomly in a square coverage area, the performance benefits of FD in larger STDMA networks were negligible, as shown in Figure 5b. This shows that careful consideration of the node placement and transmit power parameters is required to extract benefits from FD communication in UANs.

The impact of RSI on the performance of FD-



(a) 6 nodes



(b) 20 nodes

Figure 5. Network throughput comparison of TDMA, STDMA and FD-STDMA.

STDMA is shown in Figure 6. Here, the cumulative effect of interference from distant nodes reusing the same time slot and the RSI caused by the node's own transmissions slightly increases the probability of packet loss. The higher the RSI, the higher the probability of packet loss; however, this difference is relatively negligible.

Finally, Figure 7 shows the cumulative distribution functions (CDFs) of the throughput increase achieved by FD-STDMA with 10 dB RSI, compared with equivalent HD-STDMA simulations. The results show that the upper limit on the throughout increase is 100%. However, such a large increase was achieved in a small proportion of cases, with topologies which were particularly suitable to take advantage of FD, in particular, networks with linear segments, i.e. multiple nodes connected in a chain topology. However, for larger randomly generated networks the performance improvements were typically negligible, if any. In fact, in a small proportion of cases a decrease in per-

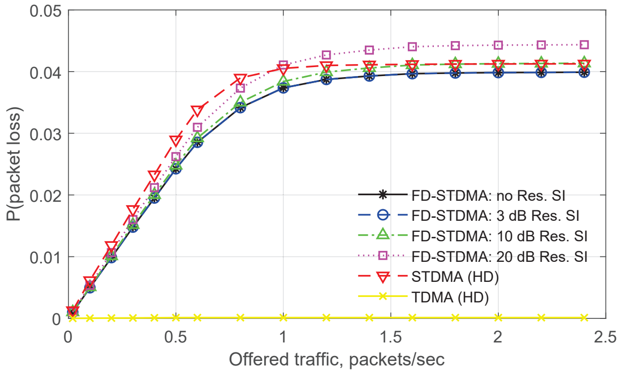


Figure 6. Probability of packet loss using TDMA, STDMA and FD-STDMA in 6 node networks.

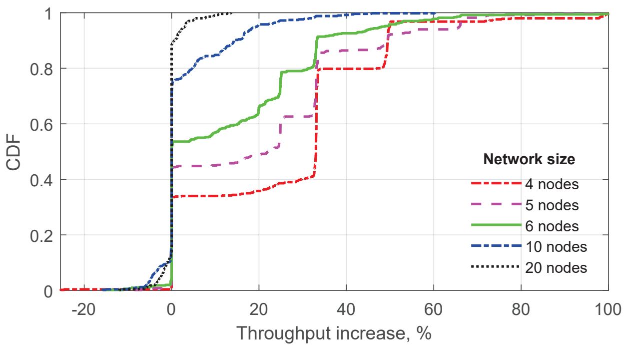


Figure 7. Throughput increase achieved by FD-STDMA (10 dB RSI) compared with HD-STDMA.

formance was observed; this was due to an increase in the packet loss due to interference and RSI.

5. CONCLUSIONS AND FURTHER WORK

In-band FD communication is based on SIC at the receiver to cancel the transmitted signal during the reception of a far-end signal. In practice, this produces RSI which effectively reduces the SINR of the received signal. In this paper, we evaluated the performance of ALOHA and STDMA in FD networks at a range of practical RSI levels based on our previous lake experiments. The simulation experiments showed that RSI can have a visible impact on the network performance in small ALOHA networks, where self-interference from the nodes' own transmissions are a relatively significant factor. However, in larger ALOHA networks, a much smaller impact on the throughput performance was observed. In FD-STDMA networks, RSI had a negligible impact on the overall network throughput performance, but a slight increase in the probability of packet loss was observed at higher RSI.

Generally, FD did not provide significant throughput gains in the majority of randomly generated topologies. However, there are specific network geometries where FD can provide a considerable throughput enhancement: up to 100%. Further work is required to jointly optimise the PHY and MAC layers for specific types of network, e.g. sensor networks with a centralised data sink, and produce topology-specific solutions to extract significant gains from FD in UANs.

6. ACKNOWLEDGMENTS

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