Empowering Full-Duplex Wireless Communication by Exploiting Directional Diversity

Evan Everett, Melissa Duarte, Chris Dick, and Ashutosh Sabharwal

***Abstract*—The use of directional antennas in wireless networks has been widely studied with two main motivations: 1) decreasing interference and 2) improving power efficiency. We identify a third motivation for utilizing directional antennas: empowering full-duplex (FD) wireless communication. We evaluate FD operation in two scenarios that possess *directional diversity*: 1) multi-hop communication and 2) access-points with simultaneous uplink/downlink. It is shown that in both scenarios, using off-the-shelf WiFi directional antennas, FD operation significantly outperforms HD operation without requiring the FD terminals to use extra hardware for canceling the self-interference in the analog domain, as has been required in the previous work.**

I. Introduction

Current wireless devices operate in half-duplex (HD) mode – they do not transmit and receive simultaneously in the same band – which results in inefficient use of the resources available for communication. The hurdle to full-duplex (FD) operation is self-interference: a FD terminal's transmit signal appears at its receiver with very high power, potentially overwhelming the signal it is trying to receive. Recent results [1], [2] demonstrate the feasibility of FD wireless communication by suppressing the self-interference via a combination of analog and digital cancellation. Analog cancellation is usually necessary since digital cancellation alone would require the ADC to capture the entire dynamic range of the self-interference, resulting in debilitating quantization distortion in the much weaker signal-of-interest. Unfortunately, analog cancellation is also costly in that it requires extra hardware resources that HD terminals do not need.

The conclusion drawn from our experiments is that FD communication can be extremely successful in scenarios in which *directional diversity* can be exploited. If a FD terminal T_{FD} wishes to receive from terminal T_1 and simultaneously transmit to terminal T_2, and if T_1 and T_2 are located in different directions from T_{FD}, then T_{FD} can *passively* suppress its self-interference by directing its transmit energy towards T_2 and away from its own receive antenna. We show that in such cases, FD operation can achieve significant rate improvements over HD *without resorting to the use of extra hardware for analog cancellation*: the passive self-interference suppression obtained by having directional Tx and Rx antennas pointed away from one another is sufficient for satisfactory reduction of quantization distortion. Thus the self-interference suppression can be performed entirely digitally using preexisting resources.

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We study two scenarios in which directional diversity can be exploited to empower FD operation: 1) multi-hop communication and 2) multi-user access points with simultaneous uplink/downlink. The performance of FD operation in both of these scenarios is assessed using a common experiment setup as described below.

II. Experiment Configuration

A. Experiment Setup

As is illustrated in Figure 1, two WARP nodes, T_1 and T_2 were placed in separate rooms, and a FD enabled WARP node, T_{FD}, was placed at the door between the two rooms such that T_{FD} had a line-of-sight path to both T_1 and T_2. T_{FD} was equipped with 5 dB gain standard WiFi directional patch antennas – one pointed at T_1 and the other at T_2 – as is depicted in Figure 2. Omnidirectional antennas were used at T_1 and T_2.

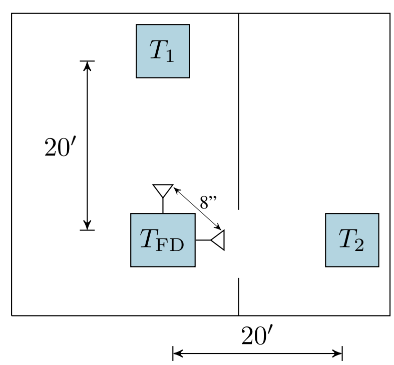

Fig. 1: Full-duplex experiment setup

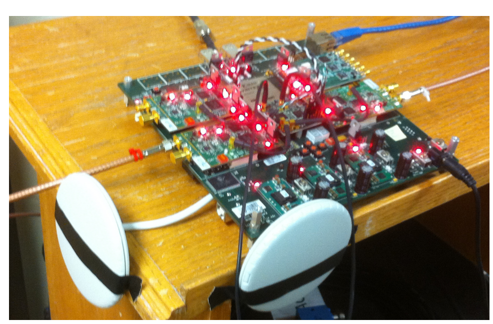

Fig. 2: Full-duplex WARP node with 5 dB directional patch antennas – one pointed towards T_1 and the other towards T_2.

B. Performance Metric

To compare FD performance vs. HD performance, we compute the average error vector magnitude squared (AEVMS) for each frame transmitted, from which the effective SNR per frame is obtained using $\texttt{SNR} = 1/(\texttt{AEVMS})$ [3]. For HD mode, only one link is active at a time[1], and the effective SNR per frame for each link, $\texttt{SNR}^{\text{HD}}$, is measured as shown in Figure 3. For FD mode, both links are simultaneously active, and the effective SINR's are measured as shown in Figure 4. From these SNR/SINR measurements, achievable rates per frame can be computed using the expressions described in the following two sections.

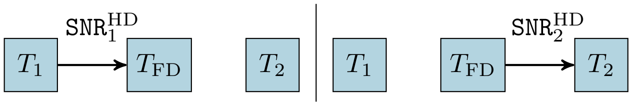

Fig. 3: HD mode AEVMS-based SNR measurements.

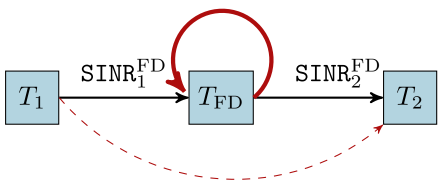

Fig. 4: FD mode AEVMS-based SINR measurements: FD operation introduces self-interference at T_{FD} and, to a lesser extent, interference from T_1 at T_2.

III. First Scenario: Multi-hop Communication

A. Motivation for full-duplex

Consider the two-hop network shown in Figure 5. In this topology, T_{FD} serves as a relay, R, whose job is to route T_1's frames to T_2 using the store-and-forward protocol.

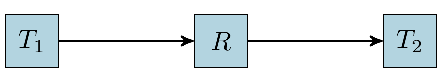

Fig. 5: Two-hop network.

In HD mode, the R may not listen to the source while forwarding to the destination, thus the source must be silent in every-other time slot. However, in FD mode, the R may forward to the destination while simultaneously receiving the next frame from the source, ideally doubling the HD rate.

B. Results

For HD relay operation, we compute the achievable end-to-end rate for each frame according to

$$R_{HD} = \frac{1}{2}\log_2(1 + \min\{\texttt{SNR}_1^{\text{HD}}, \texttt{SNR}_2^{\text{HD}}\}), \tag{1}$$

[1]Since in HD mode each terminal transmits half as often, HD terminals transmit at twice the power as FD for fair average power comparison.

where the $\frac{1}{2}$ pre-log factor is due the HD constraint. For FD operation, we compute the achievable end-to-end rate for each frame according to

$$R_{FD} = \log_2(1 + \min\{\texttt{SINR}_1^{\text{FD}}, \texttt{SINR}_2^{\text{FD}}\}). \tag{2}$$

In Table I the measured end-to-end achievable rates, averaged over 250 frames, are shown. We see that that even without analog cancellation (i.e. only digital cancellation), exploiting directional diversity enables FD operation to provide a 62% end-to-end rate improvement over HD.

TABLE I: Two-Hop Network Achievable Rates.

	End-to-end Achievable Rate	Rate Improvement over HD
Half-Duplex	4.76 bits/s/Hz	–
FD w/o Analog Canc.	7.70 bits/s/Hz	62 %
FD w/ Analog Canc.	8.27 bits/s/Hz	74 %

IV. Second Scenario: Multi-user Access Point with Simultaneous Uplink/Downlink

A. Motivation for full-duplex

Consider now the topology shown in Figure 6. Here T_{FD} is serving as an access point (AP) to which T_1 is uploading data and from which T_2 to downloading data. In HD mode, the AP must time-share between T_1's uplink and T_2's downlink. However, in FD mode, the AP can have uplink and downlink active simultaneously.

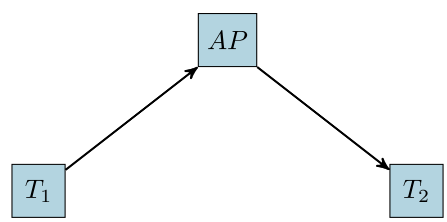

Fig. 6: Multi-user access point.

B. Results

The experimentally determined rate region for the AP network is shown in Figure 7. The end-points of the HD curve are the rate pairs $(R_1, R_2) = (\log[1+\texttt{SNR}_1^{\text{HD}}], 0)$ and $(R_1, R_2) = (0, \log[1+\texttt{SNR}_2^{\text{HD}}])$. Other rate pairs along the HD curve can be achieved via TDMA. For FD operation, the corner point is the rate pair $(R_1, R_2) = (\log[1+\texttt{SINR}_1^{\text{FD}}], \log[1+\texttt{SINR}_2^{\text{FD}}])$, which is the rate pair achieved when uplink and downlink are both always active. Rate pairs to the right of the corner can be achieved by "turning off" T_2's downlink for some portion of time, during which T_1's uplink will get the HD rate, and visa versa for points to the left of the corner.

We see in Figure 7 that by exploiting directional diversity, FD AP operation enables a significantly expanded rate region. Even without the AP performing analog cancellation, uplink

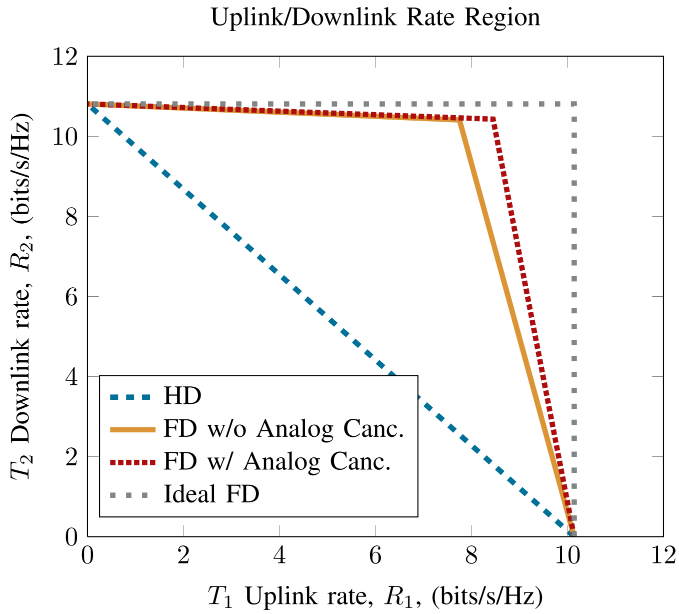

Fig. 7: Rate regions for the multiuser AP.

and downlink can be active simultaneously with the uplink at only 24% less rate than would be the case if the AP allocated all time to the uplink.

V. Next Steps

We have shown that the use of directional antennas is a cheap and very effective solution for enabling full-duplex communication. The next question to answer is "Can we exploit directional diversity in mobile networks?" The experiment setup presented above is most applicable for fixed terminals such as backhaul links. However, by merging the current FD architecture with the multiple-passive-antenna switching system and antenna selection algorithms described in [4], we believe that we can exploit the full-duplexing benefits of directional diversity even when terminals are highly mobile. Extending this work to mobile scenarios will be the next step in our research.

References

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