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 between devices and 2) improving power efficiency. We identify a third motivation for utilizing directional antennas: pushing the range limitations of full-duplex wireless communication. A characterization of full-duplex performance in the context of a base station transmitting to one device while receiving from another is presented. In this scenario, the base station can exploit "directional diversity" by using directional antennas to achieve additional passive suppression of the self-interference. The characterization shows that at 10 m distance and with 12 dBm transmit power the gains over half-duplex are as high as 90% and no lower than 60% as long as the directional antennas at the base station are separated by 45° or more. At 15 m distance the gains are no lower than 40% for separations of 90° and larger. Passive suppression via directional antennas also allows full-duplex to achieve significant gains over half-duplex even without resorting to the use of extra hardware for performing RF cancellation 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 operation is self-interference: the signal transmitted by a full-duplex terminal appears at its own receiver with very high power, potentially overwhelming the signal it is trying to receive. Recent results [1]–[3] demonstrate the feasibility of full-duplex wireless communication by suppressing the self-interference via a combination of RF and digital cancellation. RF cancellation is used to suppress the self-interference before it can impinge on the receiver front end and cause receiver desense. Moreover, digital cancellation alone would require the analog-to-digital converter to capture the entire dynamic range of the self-interference, resulting in unrecoverable quantization distortion in the low signal-of-interest regime. RF cancellation therefore also serves to suppress the self-interference prior to A/D conversion so that the signal-of-interest can be captured with sufficient precision. Unfortunately, RF cancellation is also costly in that it requires extra hardware resources (such as an RF combiner and an extra RF front end).

Even with RF and digital cancellation mechanisms, full-duplex wireless communication is inherently range-limited. It is the high ratio of the self-interference power to the signal-of-interest power that makes full-duplex challenging, and as range increases, path loss in the signal-of-interest makes this ratio even larger. The state-of-the-art *active suppression* mechanisms described in [1]–[3], namely RF cancellation and digital cancellation, have been shown to enable full-duplex communication at ranges around 6 m and at transmit powers typical of WiFi devices. In order to extend full-duplex to longer ranges, we need to also look to *passive suppression* mechanisms at the electromagnetic level to attenuate the self-interference in proportion to the path loss.

In this paper we explore the use of directional antennas to achieve *passive suppression* of the self-interference, and quantify the gains attained by presenting a performance characterization using a full-duplex prototype. The conclusion drawn from the characterization is that full-duplex communication can be extremely successful in scenarios in which *directional diversity* can be exploited.

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A. Topology and Motivation

As mentioned previously, the challenge to full-duplex operation is the high *ratio* of the self-interference power to the signal-of-interest power. Spatial separation of the receive antenna(s) from the transmit antenna(s) can be employed to reduce the self-coupling, but the amount of antenna separation is obviously constrained by the device size. Therefore, the "early adopters" of full-duplex technology will likely be infrastructure nodes where the overhead of adding the extra RF hardware is insignificant and where spatial isolation of antennas can be employed. The question then becomes how to leverage the benefits of full-duplex when infrastructure nodes are full-duplex but end-user devices are half-duplex.

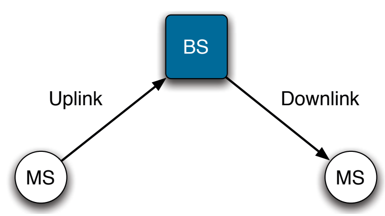

Fig. 1: A full-duplex base station can receive and uplink signal from one device while transmitting a downlink signal to another.

One common scenario in which full-duplex can be leveraged with half-duplex devices is depicted in Figure 1: a base station (BS) communicating to two half-duplex mobile stations simultaneously. Full-duplex operation allows the base station to receive an uplink signal from one mobile station (MS) while simultaneously transmitting a downlink signal to another mobile in the same frequency band, ideally doubling

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the network spectral efficiency of a time-division-duplex or frequency-division-duplex approach. This scenario is the focus of the paper.

B. *Directional Diversity*

The topology of figure 1 is an example of a scenario in which full-duplex terminals can exploit *directional diversity*. By "directional diversity" we simply mean that the direction in which the base station transmits is (in general) different than the direction from which it receives. In such cases, the full-duplex base station can make use of directional antennas, and by directing its transmit energy towards the downlink mobile and hence away from its own receive antenna (which is directed at the uplink mobile) *passive suppression* of the self-interference is achieved.

The goal of this study is to characterize full-duplex performance as a function of the amount of directional diversity available at the base station. By "amount" we mean the size of the angle in Figure 1 between the uplink and downlink directions. The larger this angle, the more one can isolate the transmitter from the receiver via antenna directionality. However, the extent to which system-level performance will vary with this angle is unknown. This is what we seek to characterize in the experiments described in the paper.

We acknowledge that there are two challenges presented in the topology of figure 1. The first challenge is self-interference at the base station caused by simultaneous transmission and reception. The second challenge is interference from the uplink mobile at the downlink mobile. In the first case the problem is how to communicate in the presence of a high-power interference that is partially known, and in the second case the problem is how to communicate in the presence of a commensurate-power interference that is unknown. Acknowledging that both challenges are significant and need to be addressed, in the characterization that follows we focus only on the first challenge: self-interference. The literature on interference channels is vast, but robust understanding of managing full-duplex self-interference is still being developed.

C. *Outline of the Paper*

In Section II the prototype full-duplex system and experiment procedure are described. The results of the characterization are described in Section III, and Section IV summarizes and concludes the paper.

II. Experiment Description

A. *Full-Duplex Prototype*

The prototype full-duplex base station used in these experiments is a WARPLab [4] implementation of the real-time wideband OFDM full-fuplex physical layer presented in [5]. In the WARPLab framework, waveforms are transmitted over the air using the WARP platform [6], but are crafted and processed off-line in MATLAB. The prototype communicates using 20 MHz, 64-subcarrier OFDM waveforms within a packet structure that mimics 802.11a. The experiments were performed at a center frequency of 2.484 GHz (channel 14 of the 2.4 GHz ISM band) and at a transmit power of 12 dBm.

1) RF Cancellation: The base station implements the wideband RF cancellation[1] mechanism proposed in [5]. The self-interference channel is estimated via special-purpose time-orthogonal pilots at the beginning of each packet. Using these per-subcarrier channel estimates, the full-duplex terminal forms a wideband "cancellation waveform" that is the inverse of the predicted self-interference. A separate RF front end transmits the cancellation waveform simultaneously with the over-the-air data transmission. The cancellation waveform is added to the received signal via an RF power combiner, so that the self-interference is suppressed prior to the receiver RF front end. For a more detailed description on how this wideband RF cancellation is implemented see [5], [7].

2) Digital Cancellation: Estimation of the residual self-interference channel after RF cancellation from the regular channel-equalization pilots allows a second layer of "digital cancellation" at baseband. From the residual self-interference channel estimates, a prediction of the received self-interference is formed (since the transmitted samples are known), and this prediction is subtracted from the received baseband samples. For a better description of digital cancellation see [2], [7]. In the results that follow we will compare performance when RF cancellation and digital cancellation are employed in tandem to performance when RF cancellation is ignored and we try to suppress the self-interference using only digital cancellation at baseband.

B. *Directional Antennas*

The antennas used in the experiment were standard 2.4GHz rectangular patch antennas [8]. These circularly polarized antennas have 5 dBi gain and $85°$ half-power beamwidth. The configuration of the antennas for the experiment is shown in Figure 2(a). One antenna was used for transmission and the other for reception. The antennas were mounted such that they pivot around a common axis. The distance from the axis to the antennas was 18 cm. This mounting apparatus allowed control of the angle between transmit and receive directional antennas, so that performance as a function of the angle between the antennas could be measured. In Figure 2(a) the antennas are at $30°$ separation. Figure 2(b) shows a front view of the prototype full-duplex base station with the directional antennas at $45°$ separation.

C. *Performance Metric*

To quantify performance and compare full-duplex against half-duplex, we compute effective achievable rates from error-vector-magnitude (EVM) statistics. We measure the average error vector magnitude squared (AEVMS) for each frame transmitted, from which the effective signal to noise ratio per frame is obtained via $\texttt{SNR} = 1/(\texttt{AEVMS})$ [9].

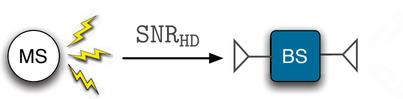
To measure half-duplex SNR, the base station restrains from transmitting while it is receiving from the mobile, and the effective post-processing SNR per frame, $\texttt{SNR}_{\text{HD}}$, is measured

[1] In the previous literature this mechanism is labeled "analog cancellation". We use "RF cancellation" to emphasize that not only is the cancellation perfomed prior to A/D conversion, but also prior to the receiver RF front end.

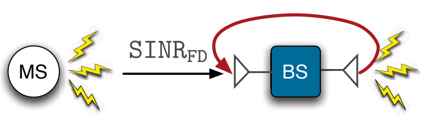
(a) 5dBi directional patch antennas at the prototype full-duplex base station (b) Front view prototype full-duplex base station with directional antennas mounted

Fig. 2: Prototype full-duplex base station with directional antennas

as shown in Figure 3(a). For the full-duplex measurements, the base station transmits frames to a "dummy" downlink mobile, and the effective post-cancellation signal to interference plus noise ratio, $\texttt{SINR}_{\text{FD}}$, is measured from the EVM statistics as shown in Figure 3(b). Since in half-duplex mode the uplink mobile transmits half as often as in full-duplex mode, it transmits with twice the power (15 dBm) as it does in the full-duplex measurements (12 dBm) for fair average power comparison.



(a) Half-duplex: base station is silent while receiving and EVM statistics provide a proxy for post-processing SNR



(b) Full-duplex: base station transmits while receiving and EVM statistics provide a proxy for post-processing SINR

Fig. 3: EVM-based SNR measurements from which achievable rates are computed.

From these EVM-based SNR measurements, we can compute the average achievable rate for the mobile-to-base-station uplink from the SNR measurements using Shannon's formula. Let i be the index for the frame transmitted, and the N be the total number of frames transmitted. The half-duplex average achievable rate R_{HD} and the full-duplex average achievable rate R_{FD} are then computed by

$$R_{\text{HD}} = \sum_{i=1}^{N} \frac{1}{2} \log_2[1 + \texttt{SNR}_{\text{HD}}(i)] \quad (1)$$

$$R_{\text{FD}} = \sum_{i=1}^{N} \log_2[1 + \texttt{SINR}_{\text{FD}}(i)]. \quad (2)$$

Note that in (2) a $\frac{1}{2}$ pre-log factor is added due to the half-duplex constraint. This $\frac{1}{2}$ factor assumes that in half-duplex mode the base station performs a 50/50 time-split between the uplink and downlink. The optimal time-split is in general not 50/50, but since in this experiment we do not incorporate a third node to receive the base station's downlink transmission, we assume that the SNR at the downlink mobile is the same as the SNR for the uplink mobile, in which case the optimal time split would indeed be 50/50.

D. Experiment Procedure

The experiment was carried out in an open hallway in Duncan Hall at Rice University, where long-range line-of-site channels could be obtained. Figure 4 visualizes the experiment setup. At distances of 10 and 15 meters, we varied angle between the transmit and receive antennas from 30 to 180 degrees. From each of the dots shown in Figure 4 the mobile transmitted 150 frames to the base station. The first 50 frames were half-duplex transmissions: the base station was not transmitting while receiving. From these first 50 frames we compute the half-duplex rate R_{HD}. During the second 50 frames the base station transmitted to a dummy downlink mobile while it received the frames form the uplink mobile, and the base station employed both RF cancellation and digital cancellation to suppress the self-interference. From these full-duplex frames we compute $R_{\text{FD}}^{(\text{RF+Dig})}$, the rate achieved when both RF and digital cancellation are employed. Finally, in the last 50 frames the base station did not employ RF cancellation, and only canceled the self-interference digitally at baseband. From these frames we compute the achievable rate for digital cancellation alone, $R_{\text{FD}}^{(\text{Dig})}$.

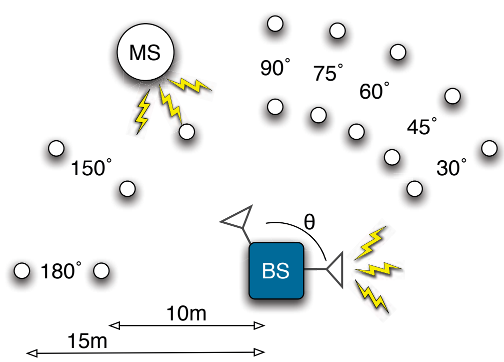


Fig. 4: Procedure for measuring full-duplex performance as a function of range and angle between Tx and Rx antenna at the base station

To quantify the benefits of using directional antennas at the base station, we also collected data for frames transmitted when using omnidirectional antennas. Changing from directional antennas to omnidirectional antennas has two results: (1) the self-interference at the base station will likely be stronger, since the transmit antenna will be radiating directly onto the receive antenna, (2) the power of the received signal from the mobile will be weaker, since the receive omnidirectional antenna has a smaller gain than the directional antenna. The goal of this experiment was to characterize the benefits of directional antennas in mitigating self-interference, not in improving link quality. We therefore wanted to study the first effect in isolation from the second. For this reason, we empirically determined a mobile-to-base-station distance for which the received signal strength (RSS) at the base station with omnidirectional antennas was nearly equal to the RSS when directional antennas were used. We then transmitted 50 frames at each of these effective distances to measure $R_{\mathrm{FD}}^{(\mathrm{Omni})}$. Hence instead of taking measurements at 10 m and 15 m, as in the directional antenna case, measurements were taken at the "effective distances" of 7.0 m and 13.3 m.[2]

III. Results

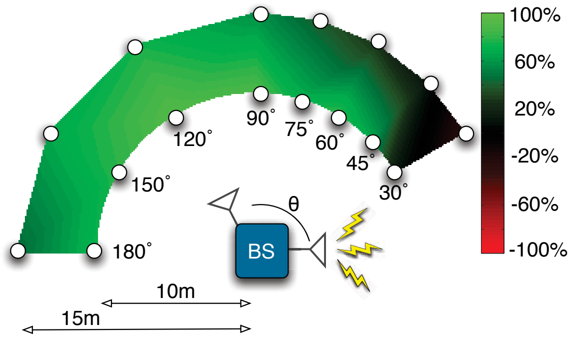
Figure 5 visualizes the measured percentage rate improvement full-duplex achieves over half-duplex. The regions are colored according to percent improvement over the half-duplex achievable rate attained at each angle and distance. The dots represent the coordinates of the actual measurements, and the rest of the region's coloring is obtained via interpolation. Green indicates an improved rate over half-duplex with bright green corresponding to the ideal 100% gain (i.e. doubling of half-duplex rate). Black corresponds to full-duplex being on par with half-duplex and red indicates full-duplex underperforming half-duplex. The top plot is the case of RF and digital cancellation applied in tandem, the second is digital cancellation alone, and the last is when omnidirectional antennas rather than directional antennas are used (in this case both RF and digital cancellation are employed).

1) RF + Digital Cancellation: We see in Figure 5(a) that full-duplex performs quite well when directionality is exploited and both RF and digital cancellation are employed. At 10 m range full-duplex outperforms half-duplex by more than 60% as long as the antennas are separated by at least $45°$, and at 15 m range full-duplex outperforms half-duplex by at least 50% for angles ranging from $90°$ to $150°$. The best performance is achieved at (10 m, $120°$), where a near 95% improvement over half-duplex is achieved; this means we are approaching the ideal doubling of rate that full-duplex promises. However as the angle between antennas gets small, performance degrades. When $45°$ separation is approached, the gains over half-duplex are small, and in the region around (15 m, $30°$) we actually see the color fade from black to dark red: at (15 m, $30°$), full-duplex is underperforming half-duplex. We now turn to the received signal strength values to understand why full-duplex fails in this region.

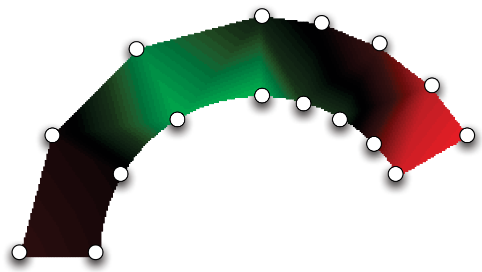
Figure 6 plots the pre-cancellation signal-of-interest to self-interference ratio (SIR) as a function of the angle between antennas for each of the distances evaluated in the experiment. The SIR values are obtained from the radios' average RSSI readings over the frames transmitted. Figure 6 helps us understand why full-duplex is underperforming at small angles. At around $75°$ the pre-cancellation SIR begins to fall off rapidly with decreasing angle due to the coupling between the Tx and Rx antennas becoming stronger as the angle between them gets smaller. At (15 m, $30°$) the self-interference is nearly 20 dB more powerful than the signal-of-interest, and in this regime the cancellation mechanisms do not suppress the self-interference sufficiently for full-duplex to outperform half-duplex.

2) Digital Cancellation Alone: Figure 5(b) shows that when directionality is exploited, full-duplex can achieve significant rate improvements over half-duplex even without employing extra hardware for RF cancellation. At $120°$ the full-duplex rate is around 60% higher than the half-duplex rate, and full-duplex continues to out-performs half-duplex for angles from $60°$ to $150°$ at 10 m and from $90°$ to $130°$ at 15 m. However,

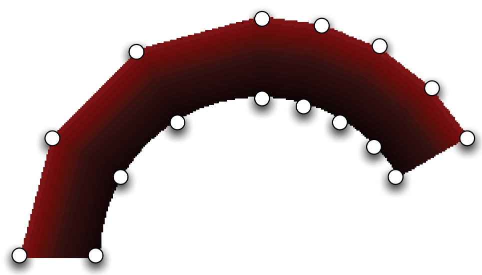
[2]Because the self-interference power will not change significantly with the angle between omnidirectional antennas, only one measurement at each of the two distances is performed, and in the plots that follow we assume that the same values would have been measured at all angles.



(a) RF + Digital Cancellation with Directional Antennas



(b) Digital Cancellation Alone with Directional Antennas



(c) RF + Digital Cancellation with Omni Antennas

Fig. 5: Percent improvement over the half-duplex achievable rate as a function of mobile-to-base-station distance and angle between antennas (a) when directional antennas are employed and both RF and digital cancellation are performed (b) with directional antennas and digital cancellation only, and (c) with omnidirectional antennas and both RF and digital cancellation.

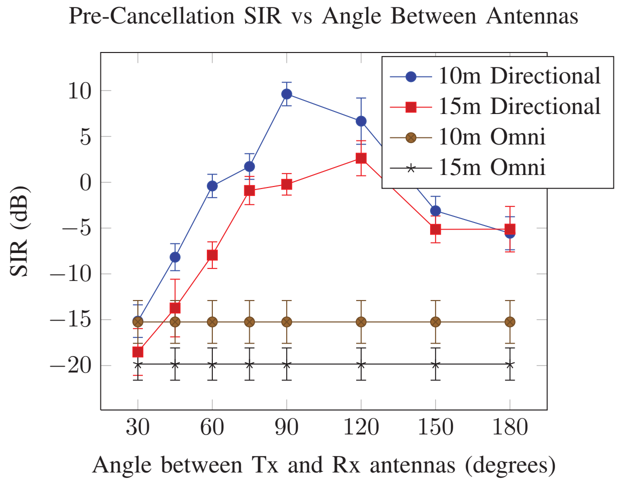


Fig. 6: Pre-cancellation signal to self-interference ratio (SIR) as computed from RSSI readings

at 60° the gains over half-duplex are marginal and as the angle get smaller the self-interference becomes too powerful to be suppressed via digital cancellation alone, and the rate falls below the half-duplex rate. The fact that performance degrades for smaller angles is expected, but it is surprising that performance also degrades for large angles. At 180°, when the antennas are pointed in opposite directions, full-duplex actually underperforms half-duplex when RF cancellation is not employed. Let us look to the pre-cancellation SIR values for an explanation of this decreased performance at large angles.

We see in Figure 6 that SIR starts off small when the angle between the antennas is small, and the direct coupling is strong. As the angle increases the SIR increases, since the self-interference is becoming weaker as the antennas become more isolated. The SIR reaches a maximum somewhere around $90 - 120°$, and then begins to decline as the angle increases further. The self-interference is actually much stronger at 180° than 90°. There are three possible causes for this surprising increased coupling when the antennas are facing opposite directions. One possibility is an antenna back-lobe. The patterns included in the antenna data sheet [8] indicate a small back-lobe, but the back-lobe does not seem strong enough to produce the observed 10 dB swing in SIR. Another possibility is that the increased coupling is an artifact of room-specific reflections – that it is not direct coupling between antennas causing the lower SIR, but a reflected component. This could partially be the case, but when performing a pilot study in a different room, similar effects were observed. The final possibility is that the increased self-interference at large angles is due to a near-field coupling effect that would not be captured in the far-field antenna patterns. A future work is to perform full-wave electromagnetic simulations to determine the exact mechanism causing this observed increase in self-interference when antennas are pointed away from each other.

3) Omnidirectional comparison: Figure 5(c) shows the performance when omnidirectional antennas are employed rather than directional antennas. With omni antennas there is obviously no angular variation in performance. We see that the self-interference is too strong to be suppressed enough for full-duplex to be preferable to half-duplex at the distances evaluated. The distances evaluated here are longer than those evaluated in [2], [5], where full-duplex was shown to effective with omnidirectional antennas. This result shows that as the distance between devices increases, and the signal-of-interest attenuates, *passive suppression* is needed to attenuate the self-interference in order for full-duplex to be effective. Comparing omni vs. directional performance at (15 m, 90°), we see that with directional antennas and RF + digital cancellation full-duplex outperforms half-duplex by $\sim$75%, but when the directional antennas are interchanged with omni antennas the pre-cancellation SIR shifts from a benign ~ 0 dB SIR to a challenging ~ -20 dB SIR, and the full duplex achieved rate is $\sim$75% *less* that what is achieved with half-duplex. Hence achieving passive suppression by exploiting directionality makes a huge impact on system performance.

IV. Conclusion

A characterization of full-duplex communication with directional antennas was presented. The characterization showed that when passive suppression via directional antennas is combined with active suppression via RF and digital cancellation, full-duplex can be extremely successful. At 10 m distance and with 12 dBm transmit power the gains over half-duplex were as high as 90% and no lower than 60% as long as the antennas were separated by 45° or more. At 15 meters the gains were no lower than 50% for angles ranging from 90° to 150°. Passive suppression via directional antennas also allowed full-duplex to achieve significant gains over half-duplex without resorting to the use of extra hardware for performing RF cancellation.

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