An Outdoor Experimental Study of Many Antenna Full-Duplex Wireless

Hadi Hosseini[1], Ahmed Almutairi[1], Syed Muhammad Hashir[2], Ehsan Aryafar[1], and Joseph Camp[2]
[1]Department of Computer Science, Portland State University, Portland, OR, USA
[2]Department of Electrical and Computer Engineering, Southern Methodist University, Dallas, TX, USA

Abstract—**Full-duplex (FD) wireless communication refers to a communication system in which both ends of a wireless link transmit and receive data simultaneously and on the same frequency band. One of the major challenges of FD communication is self-interference (SI), which refers to the interference caused by transmitting elements of a radio to its own receiving elements. Fully digital beamforming is a technique used to conduct beamforming and has been recently repurposed to also reduce SI. However, the cost of fully digital systems (e.g., base stations) dramatically increases with the increase in the number of antennas as these systems use a separate Tx-Rx RF chain for each antenna element. Hybrid beamforming systems use a much smaller number of RF chains to feed the same number of antennas, and hence can significantly reduce the deployment cost. In this paper, we aim to quantify the performance gap between these two radio architectures in terms of SI cancellation and system capacity in FD multi-user MIMO setups. We first obtained over-the-air channel measurement data on two outdoor massive MIMO deployments over the course of three months. We next study two state-of-the-art transmit beamforming based FD systems for fully digital and hybrid architectures. We show that the hybrid beamforming system can achieve 80-97% of the fully digital system capacity, depending on the number of clients.**

I. INTRODUCTION

Global mobile data traffic is estimated by ITU (International Telecommunication Union) to grow at an annual rate of around 55 percent from 2020 to 2030 to reach 607 exabytes (EB) in 2025 and 5016 EB in 2030. Full-Duplex (FD) transmission and massive MIMO (mMIMO) are two candidate technologies to help operators meet this traffic demand. Existing wireless networks operate in half-duplex (HD) mode, which means simultaneous transmission and reception happen on two separate frequency bands. With FD, simultaneous transmission and reception can happen on the same frequency band. The main challenge in FD communication is to overcome the SI problem resulting from strong in-band leakage from the transmitter to the receiver on the same device. Initial work on FD focused on radio designs with a small number of antennas [1]–[8].

On a parallel front, many antenna (e.g., mMIMO) base stations (BSs) have emerged as a key technology to improve the performance and reliability of cellular networks, resulting in a better user experience. With more antennas, base stations can cover a larger area, and support more users simultaneously enabling faster and more reliable data transfer. The high number of antennas dramatically increases the complexity of original FD architectures. However, it also introduces a new degree of freedom to combat SI. For example, beamforming (which is traditionally used to form beams towards intended clients) can now be used to also reduce SI [8], [9].

Our goal in this paper is to quantify the gap between two types of beamforming systems, fully digital and hybrid, in terms of SI and capacity over measured outdoor mMIMO channels. In conventional fully digital beamforming, each antenna element has a dedicated radio frequency (RF) chain, which substantially increases the cost for mMIMO systems. Analog beamforming, which uses phase shifters to connect all antennas to a single RF chain, is the simplest way to overcome hardware costs, but it only supports single-user and single-stream communication, resulting in low spectral efficiency. To balance system performance and hardware complexity, hybrid (analog-digital) beamforming has been introduced. Here, the analog beamforming uses phase shifter networks and several antennas can be connected to one RF chain, which reduces the number of required RF chains compared to the number of antennas. As a result, this scheme is cost-effective and consumes less power. The digital beamforming, on the other hand, can be carried out at each RF chain at the baseband, enabling the hybrid beamforming to support multi-user and multi-stream communications [9]–[13].

Fig. 1 shows the architecture of the two beamforming schemes. In fully digital architecture, the transmit array has precise control over both the amplitude and phase of the signal at each antenna and more flexibility in beamforming. In hybrid beamforming, one RF chain is connected to multiple antennas through phase shifters, which adjust the phase of the signal at each antenna, but the amplitude of the signal is similar among all antennas connected to the same RF chain. Further, hybrid beamforming is often implemented with discrete quantized phase shifters, which limits resolution in terms of the possible phase values they can apply to the signal. For example, for 2 bits phase shifter network the phase of the signal for each antenna can be selected from four possible values: $0°, 90°, 180°$, and $270°$.

In this paper, we explore the performance trade-offs between hybrid and fully digital architectures for FD over outdoor mMIMO BSs. We use real-world channel measurements obtained from two NSF funded platforms: POWDER [14] in Salt Lake City and RENEW [15] in Houston. Both are publicly available, fully programmable, and open-source mMIMO platforms. We consider scenarios involving both single-user and multi-user MIMO communication. We focus on how the performance changes as the number of clients increases. The

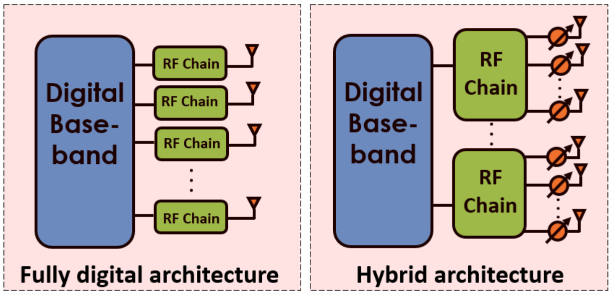

Fig. 1: Illustraion of fully digital and hybrid architectures.

main contributions of our study are summarized as follows:

- **Measurements:** We collected numerous actual channel measurements from two outdoor real-world platforms in three different (Internal, Downlink, Uplink) scenarios. Our measurement campaign lasted about three months.
- **Implementation:** We implemented two SI cancellations algorithms: (i) SotNull [9], which is the state-of-the-art fully digital FD candidate, and (ii) M-HBFD, which we introduced in our previous work [16] and is optimized for hybrid setups. Both schemes only use transmit beamforming to reduce SI and enable FD.
- **Public Release:** We have released all of our data on the project website [17] so that other researchers in the community can build on our work.
- **Performance Evaluation:** We show that with only 5 bits of phase quantization, M-HBFD achieves 80-97% of SoftNull capacity, has 2-30% more SI, and results in 27-33 times increase in per RF chain capacity.

The rest of this paper is organized as follows. Section II describes the FD algorithms studied in this paper. We discuss our measurement campaign in Section III. Section IV presents our performance evaluation results. Finally, we conclude the paper in Section V.

II. FULL-DUPLEX ALGORITHMS

In this section, we briefly describe the system model along with the key components of SoftNull and M-HBFD in terms of SI cancellation. Both solutions only use transmit beamforming to reduce SI.

A. System Model

We assume a BS with M_{Tx} transmit and M_{Rx} receive antennas[1]. The BS simultaneously transmits to K_{down} downlink clients and receives data from K_{up} uplink clients. A transmit array can be divided into N_{Tx} subarrays, where N_{Tx} can be any whole factor of the rows in the Tx array. For example, let $M_{Tx} = 32$, then if $N_{Tx} = 2$, the Tx array is divided into two subsets each with 16 antennas, which by concatenation the original array can be restored (Fig. 2).

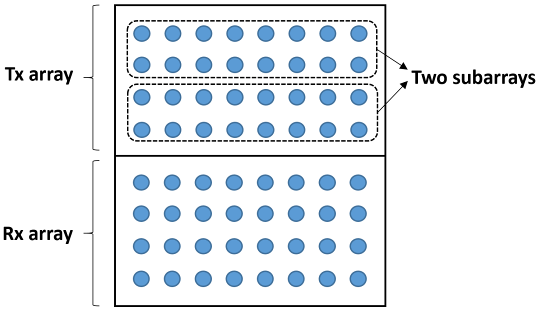

Fig. 2: BS model with $M_{Tx} = 32$, $M_{Rx} = 32$ and $N_{Tx} = 2$.

The self-interference channel matrix is denoted by $\mathbf{H}_{self} \in \mathbb{C}^{M_{Rx} \times M_{Tx}}$. Similarly, the SI channel matrix between a transmit subarray i and the receive array is denoted by $\mathbf{H}_{sub_{i,all}} \in \mathbb{C}^{M_{Rx} \times M_{Tx}/N_{Tx}}$, the uplink channel matrix is denoted by $\mathbf{H}_{up} \in \mathbb{C}^{M_{Rx} \times k_{up}}$, the downlink channel matrix is denoted by $\mathbf{H}_{down} \in \mathbb{C}^{k_{down} \times M_{Tx}}$, and the channel matrix between a transmit subarray i and the downlink clients is denoted by $\mathbf{H}_{down_i} \in \mathbb{C}^{k_{down} \times M_{Tx}/N_{Tx}}$. Then, the signal received by the Rx array can be written as follows:

$$\mathbf{y}_{up} = \mathbf{H}_{up}\mathbf{x}_{up} + \mathbf{H}_{self}\mathbf{x}_{Down} + \mathbf{z}_{up} \tag{1}$$

where $\mathbf{x}_{up} \in \mathbb{C}^{k_{up}}$, $\mathbf{x}_{down} \in \mathbb{C}^{k_{down}}$ are vectors of the transmitted symbols by the uplink clients and the Tx array respectively, and $\mathbf{z}_{up} \in \mathbb{C}^{M_{Rx}}$ captures the noise.

If we ignore the client-to-client interference, downlink clients will receive the signal below:

$$\mathbf{y}_{down} = \mathbf{H}_{down}\mathbf{x}_{down} + \mathbf{z}_{down} \tag{2}$$

where $\mathbf{z}_{down}$ is noise at downlink clients.

B. SoftNull Components

SoftNull is composed of two main stages. The first stage is the standard MU-MIMO precoder (denoted by $\mathbf{P}_{down} \in \mathbb{C}^{D_{Tx} \times K_{down}}$) which precodes signals between D_{Tx} effective antennas and K_{down} clients, and the second stage is the self-interference reduction stage with the SoftNull precoder (denoted as $\mathbf{P}_{self} \in \mathbb{C}^{M_{Tx} \times D_{Tx}}$). Effective antennas capture the set of antennas used for downlink communication. Now, let $\mathbf{s}_{Down} \in \mathbb{C}^{K_{down}}$ denote the vector of symbols that the base station wishes to communicate to each of the K_{down} downlink clients. The signal transmitted from the base station antennas is then $\mathbf{x}_{Down} = \mathbf{P}_{self}\mathbf{P}_{down}\mathbf{s}_{Down}$.

The standard precoder can be selected from standard precoders, such as zero-forcing. The SoftNull precoder specifies D_{Tx} effective antennas that have the least interference on the receive array by taking a singular value decomposition of the SI matrix between all transmit and receive antennas and sets the other highly correlated $(M_{Tx} - D_{Tx})$ antennas, which play the most role in the self-interference, to zero. The dimensionality of the transmit array reduces to D_{Tx} by nulling (soft nulling) these antennas.

---

[1] Unless otherwise stated, we equally divide the total available antennas at the BS into transmit and receive antennas.

C. M-HBFD

M-HBFD [16] is an adaptation of SoftNull for hybrid beamforming architectures[2]. In this study, we implemented M-HBFD only on the Tx array. We divided the Tx array into N_{Tx} subarrays and each subarray uses a single RF chain to communicate with a single downlink client. For example, in the case of $M_{Tx} = 32$ and $N_{Tx} = 2$, we have two subarrays, each with 16 antennas connected to one RF chain and we have two total RF chains that transmit to two clients. SoftNull is calculated separately for each subarray, using the SI matrix $\mathbf{H}_{sub_{i,all}}$, which represents the relationship between subarray i and the receive array. The total number of effective antennas for the transmit array is then divided equally among the subarrays to determine the number of effective antennas used for each subarray's SoftNull calculation. For example, for the above-mentioned scenario, if $D_{Tx} = 20$, then each subarray would use 10 effective antennas for SoftNull calculation, and the singular value decomposition would be taken from $\mathbf{H}_{sub_{i,all}}$. The value of $\mathbf{x}_{down}$ for each physical antenna is approximated to the closest achievable value, depending on the number of quantization bits in the system's architecture.

III. DATA GATHERING

A. Outdoor Many Antenna Platforms

We conducted experiments utilizing two different mMIMO testbeds: University of Utah's POWDER testbed and Rice University's RENEW testbed. Both platforms use Iris software defined radios (SDRs) developed by Skylark wireless, which allowed us to use many similar software modules across the two platforms. For the POWDER setup, we utilized the Merrill Engineering Building (MEB) rooftop setup, which consists of one base station with 64 antennas and three client sites. For the RENEW testbed, we conducted our experiments using a base station with 96 antennas (with only 80 antennas fully working) and four clients which are located inside the Rice University football stadium. The BS is located at the top corner of the stadium. The two systems use different versions of the IRIS hardware and represent two different urban deployments. A brief detailed description of each setup is as follows:

POWDER: The BS is equipped with 8 Remote Radio Head (RRH) units, each containing four 2x2 MIMO Iris SDRs operating in the Citizens Broadband Radio Service (CBRS) band (3540 MHz to 3600 MHz). The three client sites each contain a 2x2 MIMO Iris SDR that acts as a client. For our experiments, we focused on the BS and client site number one and client site number two, which are located at a distance of 20.1 meters and 35.5 meters from the BS, respectively. Client site number three is still under construction.

RENEW: The base station is equipped with 8 Remote Radio Head (RRH) units, each containing six 2x2 MIMO Iris Software Defined Radios (SDRs) operating in the Citizens Broadband Radio Service (CBRS) band (3540 MHz to 3600 MHz). The four clients each contain a 2x2 MIMO Iris SDR that acts as a client. For our experiments, we used 80 antennas of the base station and all four clients.

B. Measurement Campaign

We conducted three main experiments for each setup. In the first set of experiments, we performed uplink measurements by transmitting a pre-defined sequence, such as a Zadoff-Chu sequence, from the client and receiving it at the base station. In the second experiment set, we performed downlink measurements by transmitting a pre-defined sequence from the base station and receiving it at the client. In the third experiment set, we conducted internal measurements, which involved transmitting a pre-defined sequence from one antenna of the base station and receiving it at all other antennas of the BS simultaneously. This was done by iterating over all the base station antennas, with each iteration involving one antenna transmitting and the others receiving. Each experiment set is composed of running experiments at different times (e.g., morning, evening, night) and days to capture channels in a variety of conditions.

To perform an experiment, both POWDER and RENEW setups allow a scheduled remote slot to connect to the servers that are directly connected to the testbeds' hardware (BSs and clients). We initially used the open-source code [18] to run our experiments. Those setups allow user-defined configurations such as specifying the number of antennas at BS and clients, number of frames, number of samples, and frequency. We later further optimized the software for calibration and taking internal channel measurements, among others.

The output of our experiments were captured in the form of IQ samples, which were written into a Hierarchical Data Format 5 (HDF5) file. The dimensions of the HDF5 file were based on the number of frames, cells, pilot slots, base station antennas, and samples in each slot. We finally extract the CSI of the channels for the uplink, downlink, and between BS antennas using measured IQ samples saved in HDF5 files. We finally process the CSI data offline to obtain our desired performance metrics such as SI, SNR, and wireless capacity.

IV. PERFORMANCE EVALUATION

In this section, we present the results of our extensive experiments. We first discuss the impact of hybrid radio accuracy (measured in terms of the number of quantization bits) on system capacity. Next, we investigate the tradeoffs between the two systems in terms of SI, capacity, and capacity per RF chain.

A. Number of Quantization Bits

In hybrid beamforming systems, the number of quantization bits is crucial in determining the system's performance. It is necessary to carefully choose an appropriate quantization bit level to optimize the performance and cost of the overall design. We take the following approach to determine an

---

[2] Our prior work [16], compares the performance of M-HBFD against SoftNull in an indoor environment with a small antenna BS, and clients which are 1-2 meters away from the BS. This work is conducted over two outdoor mMIMO deployments with a much higher number of antennas as well as a planned layout (planned BS/client heights, distances, etc.) that mimic practical cellular deployments.

appropriate number of quantization bits. We first compare the ratio of the capacity between M-HBFD and Softnull in terms of the number of quantization bits to find a proper baseline for our comparisons. Fig. 3 shows the ratio of M-HBFD total capacity to SoftNull total capacity for different numbers of quantization bits in the POWDER setup. Each data point is the total capacity of the FD channel for 4 subarrays (communicating with 4 clients) and is computed by averaging over 1000 measured channel realizations. Error bars show the confidence interval aournd the estimate.

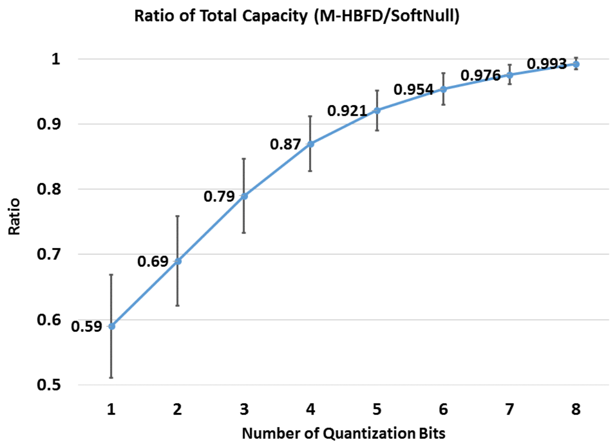

Fig. 3: Capacity ratio with varying quantization bits.

Since five bits of quantization offers a good capacity approximation (93%) of fully digital architecture, we select this level of quantization as a baseline for other evaluations[3] that will be carried out in the following sections.

B. Self-Interference Cancellation

Fig. 4 illustrates the impact of the number of subarrays and effective antennas on the level of SI across the two schemes on the POWDER testbed. We observed similar trend in the RENEW setup but omitted the figure due to the page limitation. Each data point is an average of 1000 channel realizations. The x-axis shows the number of transmit subarrays and clients. For example in the 1 subarray setup, the BS in hybrid setup would be equipped with only a single RF chain. Further, there is only a single client to be served. Similarly, when the number of subarrays is four, the BS in hybrid setup would have 4 RF chains, and there are 4 clients in the network.

We observe that when M-HBFD is employed, SI is higher when compared to SoftNull, across all scenarios studied. SoftNull additional SI cancellation gain to M-HBFD is 2.4% to 29% on the POWDER setup, and 1.8% to 31% on the RENEW setup. The disparity between the two methods was smaller when using more effective antennas, or when communicating with multiple clients concurrently. SoftNull's maximum performance advantage is limited to only about 30% on both setups, indicating that a substantial portion of the SI in the results can be effectively mitigated by both SoftNull and M-HBFD techniques, or may remain unaffected by either method. The inclusion of additional effective antennas reduces the SI cancellation advantage of SoftNull, and depending on the other SI cancellation techniques on the receiver side, the number of effective antennas can be optimally selected. In M-HBFD, as the number of clients increases by augmenting the number of subarrays, the discrepancy in SI between the two algorithms decreases. This suggests that if the mMIMO BS communicates with more clients simultaneously, hybrid and fully digital beamforming systems would have a very narrow performance gap in terms of overall FD SI.

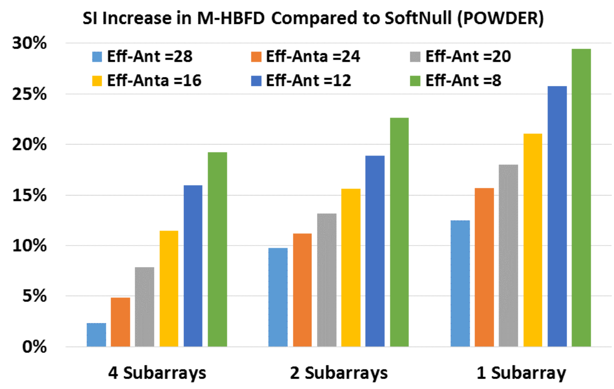

Fig. 4: POWDER SI results.

C. System Capacity

Fig. 5 illustrates the impact of the number of subarrays and effective antennas on the total M-HBFD sum (uplink + downlink) capacity in comparison to SoftNull on the POWDER setups. We observed similar trend in the RENEW setup but omitted the figure due to the page limitation. Each data point represents the average of 1000 channel realizations. In both testbeds, the total capacity of M-HBFD was found to be within about 20% of the SoftNull. In the best case, the total sum capacity of M-HBFD can reach up to 95% and 97% of the SoftNull on POWDER and RENEW setups, respectively. We also observe that with the increase in the number of effective antennas, the gap between the two systems shrinks. Effective antennas capture the number of antennas used for downlink communication. As the number of effective antennas increase, there is less resource for SI cancellation. This shrinks the gap between the two systems in terms of SI (as depicted in Fig. 4) as well as the gap in downlink beamforming, which together manifests itself in shrinking gaps in terms of total capacity.

D. Capacity per RF Chain

Fig. 6 shows the impact of the number of subarrays and effective antennas on the total sum capacity *per RF chain*. Per RF chain capacity can also be considered as a cost saving metric. The error bar on each data point represents

---

[3] Five bits is a reasonable number in modern systems. Each additional increase in the number of bits can make the hardware design much more complex/costly.

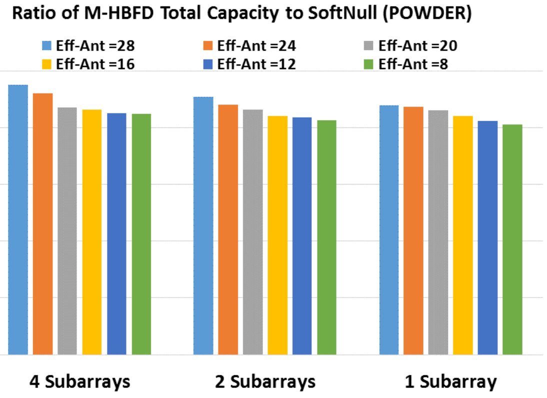

Fig. 5: POWDER capacity results.

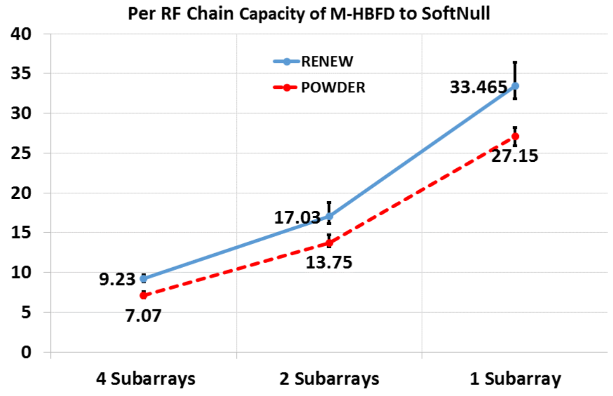

Fig. 6: Per RF chain capacity of M-HBFD to SoftNull as a function of number of subarrays. Error bars capture the varying number of effective antennas.

the variation of the capacity for different numbers of effective antennas. Results indicate that M-HBFD consistently outperforms SoftNull by a factor of at least 7 and 9 on POWDER and RENEW testbeds, respectively, and in the best case, it has 27x and 33x higher capacity with only one RF chain.

The results show that the proposed hybrid architecture and the associated SI cancellation method for mMIMO systems is more advantageous than the fully digital architecture as it deploys far fewer RF chains. Note that in M-HBFD, as the number of clients increases, the required number of RF chains increases. In one extreme, if the total number of simultaneously served clients is equal to the number of antennas, the gap between the two disappears. However, in practical mMIMO systems it is expected that the number of simultaneously served clients to be far smaller than the number of antennas. Thus, we expect in practical deployments, hybrid systems to provide comparable performance to fully digital systems in terms of SI and capacity at a fraction of the cost.

V. Conclusion

In this paper, we carried out experiments on two many antenna testbeds. We measured the CSI in three different scenarios including internal measurements on the base station antennas, downlink, and uplink channels. We then compared the performance of M-HBFD (optimized for hybrid radios) and SoftNull (optimized for fully digital radios). Both methods use transmit beamforming to simultaneously reduce SI and increase the downlink beamforming gain. Our study demonstrated that the hybrid beamforming approach achieves similar SI cancellation and capacity rates as the state-of-the-art fully digital solution, even though it uses fewer RF chains. Furthermore, the hybrid beamforming architecture significantly outperforms fully digital algorithms in terms of performance per RF chain.

VI. Acknowledgements

This research was supported in part by NSF Grants CNS 1910517 and CNS 1909381. We would like to thank Oscar Bejerano and Rahman Doost-Mohammady for their continued support of our measurement campaign, code debugging, and numerous discussions.

References

[1] J.I. Choi, M. Jain, K. Srinivasan, P. Levis, and S. Katti, "Achieving single channel, full duplex wireless communication," in *Proceedings of ACM MOBICOM*, 2010.

[2] M. Duarte and A. Sabharwal, "Full-duplex wireless communications using off-the-shelf radios: Feasibility and first results," in *Proceedings of IEEE Asilomar*, 2010.

[3] M. Duarte, C. Dick, and A. Sabharwal, "Experiment-driven characterization of full-duplex wireless systems," in *IEEE Transactions on Wireless Communications*, 2012.

[4] M. Jain, J.I. Choi, T. Kim, D. Bharadia, S. Seth K. Srinivasan, P. Levis, S. Katti, and P. Sinha, "Practical, real-time, full duplex wireless," in *Proceedings of ACM MOBICOM*, 2011.

[5] D. Bharadia, E. McMilin, and S. Katti, "Full duplex radios," in *Proceedings of ACM SIGCOMM*, 2013.

[6] E. Aryafar and A. Keshavarz-Haddad, "FD2: A Directional Full Duplex Communication System for Indoor Wireless Networks," in *Proceedings of IEEE INFOCOM*, 2015.

[7] E. Aryafar, M. A. Khojastepour, K. Sundaresan, S. Rangarajan, and M. Chiang, "MIDU: Enabling MIMO Full Duplex," in *Proceedings of ACM MOBICOM*, 2012.

[8] E. Aryafar and A. Keshavarz-Haddad, "PAFD: Phased Array Full-Duplex," in *Proceedings of IEEE INFOCOM*, 2018.

[9] E. Everett, C. Shepard, L. Zhong, and A. Sabharwal, "SoftNull: Many-Antenna Full-Duplex Wireless via Digital Beamforming," in *IEEE Transactions on Wireless Communications*, 2016.

[10] T. Chen, M.B. Dastjerdi, H. Krishnaswamy, and G. Zussman, "Wideband Full-Duplex Phased Array With Joint Transmit and Receive Beamforming: Optimization and Rate Gains," in *IEEE/ACM Transactions on Networking*, 2021.

[11] R. López-Valcarce and M. Martínez-Cotelo, "Full-Duplex mmWave Communication with Hybrid Precoding and Combining," in *Proceedings of the 28th European Signal Processing Conference (EUSIPCO)*, 2021.

[12] I.T. Cummings, J.P. Doane, T.J. Schulz, and T.C. Havens, "Aperture-Level Simultaneous Transmit and Receive With Digital Phased Arrays," in *IEEE Transactions on Signal Processing*, 2020.

[13] N.M. Gowda and A. Sabharwal, "JointNull: Combining Partial Analog Cancellation With Transmit Beamforming for Large-Antenna Full-Duplex Wireless Systems," in *IEEE Transactions on Wireless Communication*, 2018.

[14] "Powder," https://powderwireless.net/.

[15] "Renew website," https://renew.rice.edu/.

[16] G. Megson, S. Gupta, S.M. Hashir, E. Aryafar, and J. Camp, "An Experiment-Based Comparison Between Fully Digital and Hybrid Beamforming Radio Architectures for Many-Antenna Full-Duplex Wireless Communication," in *MDPI Electronics Journal*, 2021.

[17] "Code repository," https://guanyin.cs.pdx.edu/repository.html.

[18] "Renew code," https://github.com/renew-wireless/RENEWLab.git.