RENEW: A SOFTWARE-DEFINED MASSIVE MIMO WIRELESS EXPERIMENTATION PLATFORM

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Massive multiple-input multiple-output (mMIMO) technology uses a very large number of antennas at base stations to significantly increase efficient use of the wireless spectrum. Thus, mMIMO is considered an essential part of 5G and beyond.

However, developing a scalable and reliable mMIMO system is an extremely challenging task, significantly hampering the ability of the research community to research next-generation networks. This "research bottleneck" motivated us to develop a deployable experimental mMIMO platform to enable research across many areas. We also envision that this platform could unleash novel collaborations between communications, computing, and machine learning researchers to completely rethink next-generation networks.

In this paper, we present an overview of our more than a decade-long effort in developing an ecosystem consisting of hardware and software innovations and deployment of an experimental mMIMO software-defined platform. This effort has culminated in the NSF-PAWR *RENEW* project, aimed at creating a shared open-source open-access deployed platform that is available for use by anyone in the research community.

We will first describe our efforts to develop a mMIMO hardware that was later commercialized via a Rice University spinoff. We then outline our effort in developing an open-source software ecosystem that leverages this hardware. Additionally, we introduce the POWDER-RENEW testbed, which is a public platform that enables the use of this platform by the broader research community. POWDER testbed provides access to multiple mMIMO base stations and clients as well as computing resources for researchers. RENEW complements that bare-metal platform with an open-source software ecosystem that allows researchers to conduct original research. Lastly, we conclude by providing a sampling of research use cases and challenging problems that can be solved using the RENEW platform.

BENEFITS AND CHALLENGES OF mMIMO

mMIMO achieves significant gains in data throughput and communication range by using a large number of antennas at each base station. By using a technique called *multi-user beamforming*, the antennas jointly and simultaneously transmit and receive multiple data streams to and from multiple user terminals over the same radio frequency band, thereby enabling a high-order spatial multiplexing. Note, mMIMO is an extension of MIMO technology, in which only a small number of antennas (typically 2 or 4) are used for *spatial multiplexing*. The theoretical idea behind mMIMO, as laid out by Thomas Marzetta in his seminal paper [15], is that as the number of antennas M goes to infinity, an arbitrarily large number K of users can be served simultaneously with multi-user beamforming when $M >> K$.

Generally, in cellular systems, the base station and the users communicate within a unit of time called frame. During a frame and based on a well-defined schedule, a series of wireless signals are exchanged between the base station and users. At each end point, through a series of processing steps (blocks) collectively called baseband processing, the signals are converted to bits and vice versa. In mMIMO, during each frame, K users transmit specific time-orthogonal signals, called pilots, to the base station. The base station antennas use the pilot to estimate the effect of the wireless channel, also known as channel state information (CSI). CSI is then used to enable beamforming, i.e., to demultiplex the jointly received signals at M antennas from all K users into K separate data streams (uplink direction), and similarly to beamform K data streams to multiple users through M antennas (downlink direction).

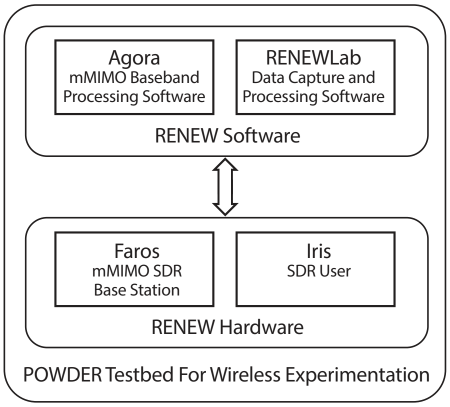


FIGURE 1. Block diagram of the RENEW Hardware and Software on the POWDER testbed.

Despite all the benefits, building a practical mMIMO base station with a large number of antennas is a big challenge. For e.g., to enable beamforming at the base station, all radios must be fully synchronized in time and frequency. As the target number of antennas in the system increases, providing system scalability and reliability become significantly more challenging.[1] Moreover, baseband processing with more antennas and subsequently more users are a big computational challenge. The remainder of this paper describes our multi-year effort

[1] Here we are talking about digital beamforming, in which each antenna is connected to a separate digital transceiver or radio. This is different from phased arrays that are used in mmWave technology where all antennas are driven by a single digital radio.

in developing i) a reliable mMIMO hardware platform, and ii) a scalable mMIMO baseband processing software, all as part of the RENEW project. We also describe how the entire platform is available for use for the research community through the POWDER testbed. Figure 1 outlines all the components covered in the paper.

RENEW HARDWARE

The key criteria in the design of RENEW hardware was to develop an mMIMO platform that was highly reliable, easily programmable, and field deployable. To achieve them, we used the lessons learned from the RENEW predecessor, the Argos platform [20, 21].

Argos mMIMO base station was the first of its kind that demonstrated the practical feasibility of the mMIMO technology. Argos used the WARP [19] software-defined radio (SDR) as its radio block. WARP SDR modules can be used to transmit and process any waveform through a custom FPGA design. Each WARP radio includes four digital transceivers that can be independently programmed to transmit and receive through their respective physical antennas. Using 16 WARP radio modules and a total of 64 antennas, Argos demonstrated the practicality of beamforming and characterized the throughput gains achievable with mMIMO. Later, ArgosV2 [21] used 24 WARP modules to demonstrate a 96-antenna array (see Figure 2). The lessons of Argos were instrumental in the design decisions we made for RENEW. In this section, we will describe these design decisions and how they helped to achieve the design criteria outlined above. RENEW base station is now commercially available from Skylark Wireless, under the commercial name FAROS. A block diagram of the base station architecture is shown in Figure 3.

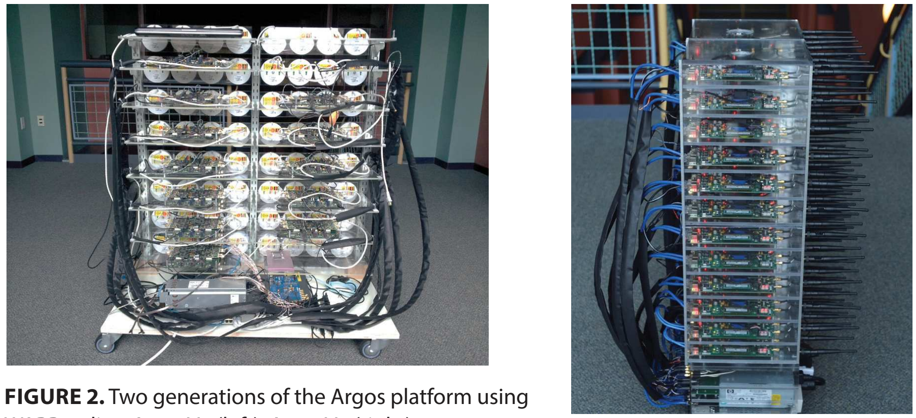


FIGURE 2. Two generations of the Argos platform using WARP radios, ArgosV1 (left), ArgosV2 (right).

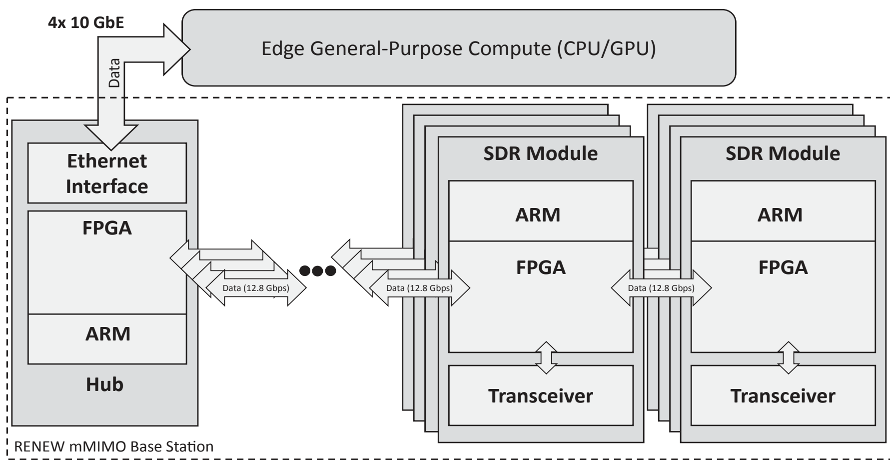


FIGURE 3. RENEW mMIMO base station hardware architecture.

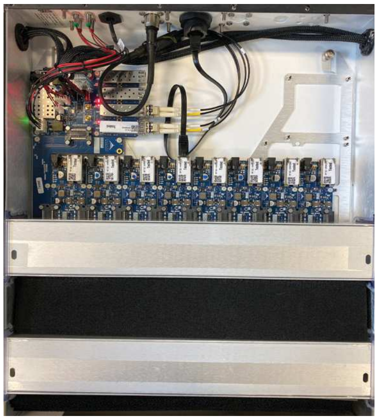
Reliability

To achieve the design goals that we set out for RENEW, we decided early on to develop a new SDR module. The new SDR module, called Iris, would replace the WARP SDR platform used in Argos. A significant bottleneck for most existing mMIMO platforms to this day is the amount of cabling required to interconnect all the radio modules. As an example, in a 96-antenna ArgosV2 base station, each of the 24 WARP modules required four separate wired connections for power, clock, time synchronization trigger, and data (Ethernet). As a result, assembly, reconfiguration, and maintenance of the base station required significant effort, with each cable being a common point of failure. To minimize the cabling, Iris implements a daisy chaining capability so that each Iris can interconnect with others in a LEGO-like fashion without any wiring. Up to eight Irises can be daisy chained together and assembled in a weather-proof enclosure as shown in Figure 4a. When daisy chained, Irises can pass along data and power among each other. In a daisy chain configuration, Irises are automatically synchronized both in time and frequency, thus removing any need for additional cabling among them.

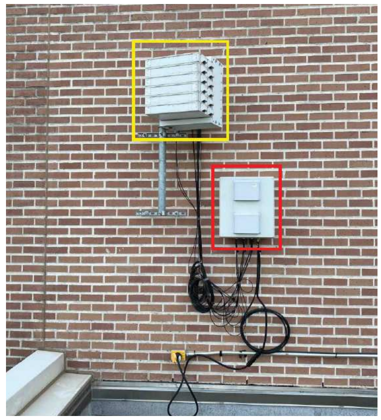
Multiple Iris daisy chains can be interconnected via a central node. RENEW base stations are designed to interconnect up to six Iris daisy chains. A custom FPGA board, known as the *hub*, provides data connectivity to each daisy chain through a dedicated fiber. Through the same fiber cable, the hub provides a common reference clock and reference timestamp. Lastly, through dedicated power *cables* the hub provides power management and sequencing to all daisy chains. Figure 4b shows a 96-antenna RENEW base station deployed on the Rice university campus. Note, in this setup only six power and six fiber cables are used to interconnect radios, a sixfold reduction in the number of cables required for ArgosV2. Additionally, the hub provides data streaming and control message exchange between all Irises in the system and the host server through a 40 Gbps Ethernet fiber.

Programmability

Programmability is an essential characteristic of an SDR device. Depending on the use case, every SDR device uses either FPGAs or general-purpose CPUs for baseband



(a) A daisy chain of 8 Irises assembled within an enclosure. Part of the daisy chain is hiding under a heat sink. The Irises connect to the hub through a power and fiber cable.



(b) A 96-antenna RENEW base station deployed on Rice campus. The yellow box shows 6 stacked daisy chains in weatherproof enclosures. A wall-mounted weatherproof enclosure (red box) contains the hub that powers up the daisy chains and distributes data and common clock to them through dedicated fiber.

FIGURE 4. An inside (a) and outside (b) look at the RENEW base station hardware.

processing. Today, support for many popular *open-source* SDR development platforms such as GNURadio [7] relies on continuous streaming of samples from hardware to the host CPU, where baseband processing software is run. However, WARP adopted an FPGA-centric model [16] where most of the baseband processing logic is implemented in the FPGA. The FPGA-centric model is excellent for real-time latency-sensitive baseband processing,[2] but it also limits how complex the implemented baseband processing logic can be due to the limited number of logic cells in an FPGA. Additionally, FPGAs are much harder to program.

For ease of programmability and the ability to rapidly prototype more complex 5G-like systems, we adopted the CPU-centric model for Iris. Iris is essentially an Ethernet-based device, and it can communicate with PCs through commodity network equipment. Another programmable component of Iris is its digital transceiver. Its operating frequency band can be tuned anywhere from 400 MHz to 3.8 GHz. The radio sampling rate can also be tuned at any rate in 1-40 MHz range allowing the fractional sampling rate used in LTE and 5G-NR.

Field Deployment Capability

Small Form Factor: To enable deployment of the hardware in outdoor sites, we needed a smaller footprint for the base station. The key to accomplishing this goal was designing the Iris such that it would have a significantly smaller form factor compared to WARP. For comparison, a 4-radio WARP module is approximately 8×8 inches and a comparable 4-radio Iris configuration is 3.1 in × 11.2 in. The daisy chaining capability also helped in significantly reducing the size of the RENEW base station. The base station, as shown in Figure 4b, is approximately 0.4 m x 0.4 m x 0.45 m, almost 3x smaller in size than a similar 96-antenna ArgosV2 base station, which is approximately 0.5 m x 1.2 m x 0.35 m.

High Transmit Power: Most existing SDR devices are incapable of transmitting at high power and therefore are not suitable for outdoor long-range deployment. Iris, however, is supported by an amplified and modular RF front-end with a maximum output power of 0.63 W. This transmission power is similar to what the cellular industry uses for small cell base stations [2].

Remotely Manageable: Iris uses the Xilinx Zynq system-on-chip (SoC) [28] as its local processing element. The Xilinx SoC includes an ARM dual-core processor. We leverage the ARM processor to run the Linux operating system on the Iris. Using Linux, a whole suite of services for reconfiguration and monitoring are developed to run on the Linux environment. Additionally, using the Linux networking stack, network device discovery and configuration is implemented, enabling remote management of the RENEW hardware.

RENEW SOFTWARE

To support experimentation on RENEW hardware, we have designed and implemented an open-source software ecosystem to enable various research needs. A real-time mMIMO baseband processing software, called *Agora* [9], is developed to enable physical layer experimentation. To our knowledge, Agora is the first software-based realization of mMIMO baseband processing that is publicly known. Additionally, we have developed RENEWLab, a set of software tools to collect and analyze real-time channel traces.

mMIMO Baseband Processing with Agora

The large number of antennas in mMIMO creates a large computational complexity that grows with the number of base station antennas. As an example, a 64-antenna[3] base station using 20 MHz bandwidth generates roughly 47 Gbps raw sample data that must be processed in real-time. In the 5G standardization community, there is already a big push to softwarize the cellular radio access network (RAN) functions and ultimately move most of these functions to the cloud. This concept is known as cloud-RAN (C-RAN).

In C-RAN, major processing blocks including the PHY layer blocks, are assumed to be running on general-purpose processors. Therefore, one of the big questions in C-RAN standardization groups, such as O-RAN [17], is whether the current processors can handle the large computational cost associated with mMIMO, especially as the number of base station antennas is predicted to reach hundreds of antennas, if not more, in the next decade [6]. Agora is an evolutionary step toward a cloud-native mobile network that meets the computational need of mobile networks with a cloud-like infrastructure, instead of dedicated and specialized computing equipment [1, 27]. While software realizations of baseband

[2] WARP implemented a standard-compliant real-time 802.11 stack.

[3] 64-antenna base stations are the most commonly deployed mMIMO size by cellular operators.

processing have been attempted before, e.g., Sora [23] and BigStation [29], Agora is the first to support mMIMO at a scale required by modern mobile network standards. Specifically, Agora supports many more antennas and users, and more computationally intensive bit error correction schemes like low-density parity-check (LDPC) coding that is used in the 5G New Radio (5G-NR) standard [3].

A Data-Parallel Design

The large numbers of antennas and users in mMIMO bring abundant data parallelism in mMIMO baseband processing. Agora exploits this inherent rich data parallelism to scale the processing to all cores on a single many-core commodity server. To scale the processing to many cores, Agora employs a carefully designed threading model, borrowed from web server design [26, 22], and applies a series of non-trivial cache-aware optimizations to cope with the memory bottleneck. For processing each baseband block, Agora uses the Intel AVX-2 and AVX-512 intrinsics to accelerate the processing. Our experiments show that Agora can support real-time baseband processing for 64 × 16 MIMO with a single 36-core server. Figure 5a shows how Agora scales the processing to the number of cores. Moreover, Agora achieves a processing latency that is well below the 4 ms latency requirement for Enhanced Mobile Broadband (eMBB) use case of 5G-NR.

Earlier works on MIMO baseband processing, e.g., [29, 4], have mostly focused on pipeline-parallel designs. That means each processing block is allocated a carefully chosen number of cores to enable real-time baseband processing. A pipeline-parallel design results in a significantly larger processing latency than data-parallel design as shown in Figure 5b and 5c. For the uplink, Agora's processing time is longer than the frame length, since processing cannot finish before the entire frame data is received. In this case, Agora's average latency is about 180 µs longer than the frame length, which is approximately 3× better than the pipeline-parallel variant. For the downlink, the processing time is not constrained by the frame length, since the data to be processed comes from the higher network layers. Therefore, Agora can achieve a latency shorter than the frame length, while the latency for the pipeline-parallel variant is roughly 1 ms longer than the frame length in average.

Simulation versus Hardware

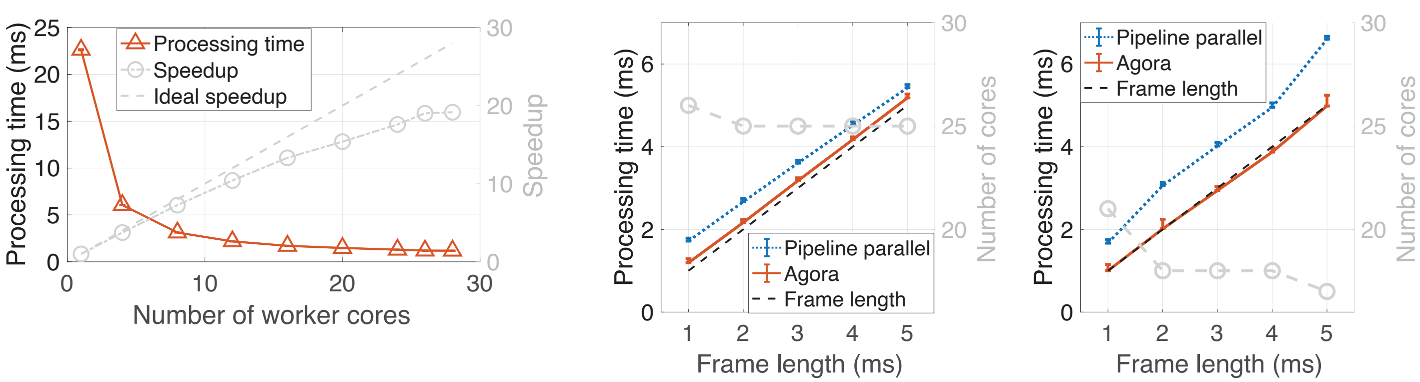
We have performed end-to-end testing with Agora in both simulation and over-the-air mode. We implement a baseband processing software for user terminals that we call the *user software*.

To test Agora in simulation mode, we implement a mMIMO wireless channel simulator. Agora sends frames to the simulator encapsulated as network packets, and the simulator applies the channel effect on the data before forwarding it to the user software instance in the downlink direction and vice versa in the uplink direction. The simulator allows further development and end-to-end testing of Agora before running on actual hardware. It also allows experimentation with Agora in simulated but diverse channel environments when mMIMO hardware is not available.

For over-the-air testing, both Agora and the user software interface with the RENEW hardware and can communicate through the real wireless channel. The software is fully configurable with many operational parameters, including the number of base station antennas, number of users, the frame schedule, the modulation order, and the LDPC code rate. Additionally, many parameters on the base station and user radios can be configured at run-time due to their software-defined nature, including transmission power, and operating frequency band.

Limitations and Future Work in Agora

Agora is an ongoing project that will continue to improve for better performance and additional features. Currently, Agora can support real-time processing in up to 20 MHz bandwidth, the highest bandwidth supported in LTE-advanced standard [14]. However, the signal bandwidth in 5G-NR can be up to 100 MHz. Supporting higher bandwidths and a higher number of antennas and data streams are still big challenges that we need to address in Agora. Additionally, we are moving towards implementing a medium access (MAC) layer for Agora. The MAC will oversee scheduling multiple users per frame based on the quality of their connection to the base station. This will create additional computational complexity to be addressed by Agora.



(a) Agora's uplink processing time and speedup (b) Uplink (c) Downlink

FIGURE 5. a) Effectiveness of Agora in scaling baseband processing load to CPU cores, b) and c) Number of cores used in Agora to achieve real-time performance (shown in gray color) as well as Median processing time (with 99.9th percentile as errorbar) in Agora and its pipeline-parallel variant over different frame lengths. All plots are based on 64×16 MIMO.

(a) RENEW hardware in an anechoic chamber used for experiments requiring an isolated RF environment.

(b) RENEW hardware deployed at a new rooftop location.

FIGURE 6. POWDER Testbed Deployment of RENEW mMIMO hardware. The testbed is open to the research community [25].

Data Collection with RENEWLab

The ability to characterize the wireless channel is key in developing many innovative ideas in wireless communications. Conversely, channel traces are sufficient to validate the feasibility of many novel ideas. For instance, to validate the performance of a new precoding technique in mobile environments without having to develop a fully functional system, researchers can collect channel traces from various mobility scenarios and evaluate the performance by post-processing the channel data. Examples of past novel research contributions using real channel traces are discussed later in the paper.

The RENEWLab *Channel Sounder* supports real-time mMIMO time-domain sample recording. It can capture and record sample traces from the communication between the RENEW base station antennas and users. The Channel Sounder software adopts a similar threading model as Agora to enable real-time recording of data from RENEW base stations. The traces are recorded with HDF5 format [24] as a multi-dimensional dataset, and metadata specifying the experiment scenario and operational parameters.

RENEWLab also provides a data analytics software as a baseline tool for post-processing the datasets and plotting various metrics, such as channel quality and achievable data rates for the recorded samples [18]. The datasets can be used for a variety of other research, such as wireless localization and imaging. They can also be used to train AI models for various applications of machine learning in wireless systems.

RENEW PUBLIC DEPLOYMENT

The overarching goal of our effort in RENEW is to create a platform to enable reproducible research [10]. Reproducibility requires a testbed that is shared among all researchers. The POWDER testbed is a public access software-defined *radio network*, deployed on the campus of the University of Utah, in Salt Lake City, UT. Through the POWDER portal, users can access bare-metal computing resources interfaced with radio equipment to perform software-defined experiments. POWDER is designed to enable the developing and sharing of repeatable wireless experiments for remote users. Therefore, research results from experiments performed on POWDER can be fully replicated by other users.

Among many unique elements in POWDER, the RENEW part of the testbed relates to mMIMO technology, which deploys the RENEW Hardware. The testbed enables the use of the RENEW software and hardware in an isolated network. Users can run both Agora and RENEWLab software on many-core servers connected to RENEW base stations and user terminals.

The POWDER testbed has planned and deployed three 64-antenna mMIMO RENEW base stations, along with many fixed and mobile user nodes across the University of Utah campus. Fig. 6 shows mMIMO base stations deployed on the POWDER testbed, including in an anechoic chamber (used for isolated and interference-free experiments) and on a rooftop site.

USE CASES

Channel measurements performed using the Argos platform, the predecessor of RENEW, have led to significant research results in the past few years in various domains. Here, we point out two important research directions. These research results show the research potential enabled by RENEW.

FDD mMIMO A key challenge for frequency-division duplexing (FDD) mMIMO is the large overhead in acquiring CSI for transmit beamforming. As a result, the FDD operation of mMIMO was dubbed the critical open question [5].

Using real-world measurements, it was discovered that only four downlink Angle-of-departures (AoDs) are sufficient to closely approximate the actual downlink channel, with an average correlation as high as 0.85. That is, the channel between one mobile antenna and the base station array can be characterized with much fewer parameters in the angular domain (4 complex channel coefficients) than antenna space (64 complex channel coefficients), thereby reducing the overall measurement dimension. Additionally, and more importantly, it is shown that at the base station, the uplink Angle-of-arrival (AoA) set has a strong correlation with the downlink AoD set, in that uplink AoAs are very close in number and magnitude to the downlink AoDs. Therefore, the estimated uplink AoA set can be directly applied as an estimated downlink AoD set [30].

mMIMO Full-duplex Single-antenna full-duplex was demonstrated in two simultaneous works [8, 11] back in 2010. However, it quickly became evident that scaling this concept to large MIMO systems was much more challenging. Through large-scale channel measurements using a 72-element Argos platform in different environments, a new technique for mMIMO in-band full-duplex was presented in [12]. This new technique, called SoftNull, enables a large reduction in self-interference, while sacrificing relatively few effective antennas. However, the amount of reduction depends on the environment: more scattering results in less suppression. In an outdoor low-scattering environment, SoftNull provides sufficient self-interference reduction while sacrificing only a few effective antennas. This fine understanding, based on the channel environment, can also be explained using analysis. This enabled a subsequent work [13], named JointNull, which considers joint beamforming and self-interference suppression and outperforms SoftNull significantly.

OPPORTUNITIES

There are still many big challenges in the area of mMIMO communications, which can be investigated using a deployed platform. User mobility in real-world cellular networks causes significant overhead in CSI measurement and results in deterioration of the beamforming gains. RENEW software and the POWDER platform, which is set to provide mobile users deployed on shuttle buses, provide an excellent research opportunity for this problem. With ongoing mMIMO deployment in 5G networks, evaluation and improvement of mMIMO performance in multi-cell deployments is also a timely topic. More specifically, characterizing inter-cell interference in mMIMO and its effect on beamforming performance is possible using this platform. Additionally, exploring more radical ideas, such as the design of cell-free mMIMO systems, becomes feasible using RENEW. On the computing side, RAN virtualization, by going beyond baseband processing in mMIMO systems, is an excellent direction for future research. For e.g., optimal multi-user scheduling in the MAC layer, which is an active research area, could bring about the real potential of mMIMO in terms of spectral efficiency. Upcoming releases of Agora will open up a great tool for innovation by the user community in this domain as well. ■

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REFERENCES

[1] C-RAN: the road towards green RAN. 2011. Tech. rep., China Mobile Research Institute.

[2] Improving wireless connectivity through small cell deployment. 2016. Tech. rep., GSMA.

[3] Making 5G-NR a reality: Leading the technology inventions for a unified, more capable 5G air interface. Tech. rep., December 2016. Qualcomm Inc.

[4] M. Bansal, A. Schulman, and S. Katti. 2015. Atomix: A framework for deploying signal processing applications on wireless infrastructure. *NSDI.*

[5] E. Björnson, E.G. Larsson, and T.L. Marzetta. February 2016. Massive MIMO: Ten myths and one critical question. *IEEE Communications Magazine*, vol. 54, 114-123.

[6] E. Björnson, L. Sanguinetti, H. Wymeersch, J. Hoydis, and T. Marzetta. 2019. Massive mimo is a reality—what is next?: Five promising research directions for antenna arrays. *Digital Signal Processing 94*, 3–20.

[7] E. Blossom. Gnu radio: Tools for exploring the radio frequency spectrum. June 2004. *Linux Journal*, 122.

[8] J.I. Choi, M. Jain, K. Srinivasan, P.A. Levis, and S. Katti. 2010. Achieving single channel, full duplex wireless communication. *Proceedings of the Sixteenth Annual International Conference on Mobile Computing and Networking*.

[9] J. Ding, R. Doost-Mohammady, A. Kalia, and L. Zhong. 2020. Agora: Real-time massive mimo baseband processing in software. *CoNEXT.*

[10] R. Doost-Mohammady, O. Bejarano, and A. Sabharwal. 2021. Good times for wireless research. *Computer Networks,188.*

[11] M. Duarte, and A. Sabharwal. November 2010. Full-duplex wireless communications using off-the-shelf radios: Feasibility and first results. *Proceedings of the Forty Fourth Asilomar Conference on Signals, Systems and Computers*.

[12] E. Everett, C. Shepard, L. Zhong, and A. Sabharwal. September 2016. Softnull: Many-antenna full-duplex wireless via digital beamforming. *IEEE Transactions on Wireless Communications*, vol. 15, 8077-8092.

[13] N.M. Gowda, and A. Sabharwal. January 2018. Jointnull: Combining partial analog cancellation with transmit beamforming for large-antenna full-duplex wireless systems. *IEEE Transactions on Wireless Communications*, vol. 17, 2094–2108.

[14] F. Khan, *LTE for 4G mobile broadband: Air interface technologies and performance*. Cambridge University Press, 2009.

[15] T.L. Marzetta. Noncooperative cellular wireless with unlimited numbers of base station antennas, 3590–3600.

[16] P. Murphy, C. Shepard, L. Zhong, C. Dick, and A. Sabharwal. August 2014. FPGAs help characterize massive-MIMO channels. *Xcell Journal.*

[17] O-RAN Alliance. 2019. Operator Defined Open and Intelligent Radio Access Networks. https://www.o-ran.org/.

[18] Rice University. 2022. Renew software git repository. https://github.com/renew-wireless.

[19] Rice University Wireless Open Access Research Platform. warp.rice.edu.

[20] C. Shepard, H. Yu, N. Anand, E. Li, T. Marzetta, R. Yang, and L. Zhong. 2012. Argos: Practical many-antenna base stations. *MOBICOM*.

[21] C. Shepard, H. Yu, and L. Zhong. 2013. Argosv2: A flexible many-antenna research platform. *Demonstration Abstract: Proceedings of the ACM Annual International Conference on Mobile Computing and Networking*, 163-166.

[22] A. Sriraman, and T.F. Wenisch. 2018. µTune: Auto-tuned threading for OLDI microservices. *OSDI*.

[23] K. Tan, J. Zhang, J. Fang, H. Liu, Y. Ye, S. Wang, Y. Zhang, H. Wu, W. Wang, and G.M. Voelker. 2009. Sora: High performance software radio using general purpose multi-core processors. *Proceedings of USENIX Symposium on NSDI*.

[24] The HDF5 Group. 2006. Hdf5 library and file format. https://www.hdfgroup.org/solutions/hdf5.

[25] University of Utah. 2022. Platform for open wireless data-driven experimental research. https://powderwireless.net.

[26] M. Welsh, D. Culler, E. Brewer. 2001. SEDA: An architecture for well-conditioned, scalable internet services. *SOSP.*

[27] M. Wolfe. 2016. CommScope definitions: What is C-RAN? https://www.commscope.com/Blog/ CommScope-Definitions-What-is-C-RAN.

[28] Xilinx Inc. 2017. Zynq-7000 all programmable soc data sheet: Overview. https://www.xilinx.com/support/documentation/data_sheets/ds190-Zynq-7000-Overview.pdf.

[29] Q. Yang, X. Li, H. Yao, J. Fang, K. Tan, W. Hu, J. Zhang, and Y. Zhang. 2013. BigStation: Enabling scalable real-time signal processing in large MU-MIMO systems. *Proceedings of the ACM SIGCOMM.*

[30] X. Zhang, L. Zhong, and A. Sabharwal. 2018. Directional training for FDD massive MIMO. *IEEE Transactions on Wireless Communications,* vol. 17, 5183–5197.