ArgosNet: A Multi-Cell Many-Antenna MU-MIMO Platform

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***Abstract*—We built and deployed a multi-cell network testbed of massive-MIMO base stations across Rice University campus, called ArgosNet. While ArgosNet is highly configurable, its default configuration employs four 100-antenna base stations to serve 40 battery-powered mobile clients at 3.7 GHz. In ArgosNet, the base stations are time-frequency synchronized and have direct fiber connections to a server cluster, enabling advanced wireless techniques such as Coordinated Multipoint (CoMP). We extended the Argos channel measurement system to support multi-cell topologies, then conducted initial measurements showing the performance of CoMP in many-antenna MU-MIMO networks.**

I. Introduction

Many-antenna Multi-User MIMO (MU-MIMO), or massive-MIMO at large scale, is a key technology for next-generation wireless systems. Researchers have repeatedly demonstrated enormous gains from massive-MIMO in controlled environments [1]–[3], but it has yet to be characterized in realistic at-scale deployments or multi-cell topologies. One of the most promising features of massive-MIMO is its ability to reduce inter-cell network interference [4], however this aspect has been left relatively unexplored experimentally due to the lack of a *multi-cell* massive-MIMO testbeds.

This paper describes *ArgosNet*, the first at-scale multi-cell many-antenna MU-MIMO research platform. ArgosNet features an entirely new many-antenna MIMO base-station design called *ArgosV3* [5]. Based on our experience in prototyping two previous generations of Argos many-antenna base stations, [1], [6], we designed and built ArgosV3 to be extremely scalable and real-world deployable. ArgosV3 fully implements the distributed Argos architecture reported in [1], enabling MU-MIMO arrays with hundreds or even thousands of antennas. Leveraging frequency-agile transceivers, ArgosV3 supports carrier frequencies from 50 MHz to 3.8 GHz with up to 56 MHz of channel bandwidth. ArgosV3 is designed to be highly power, space, and cost-efficient, enabling weatherproof many-antenna MIMO base stations with 160 antennas in less than 2 ft^3.

Leveraging extensive site surveys, we chose 5 locations on Rice University campus to provide not only complete coverage of the campus, but also diverse propagation environments and coverage overlap to facilitate next-generation research. We deployed fiber, power, and mounting to these sites, each with support for multiple sectors. In its default configuration ArgosNet employs four 100-antenna base stations serving 40 mobile clients, however these radios can be flexibly reallocated to more sites or sectors, or consolidated in to a single 400-antenna base station.

These sites are directly connected to the *ArgosCloud*, a 208-core server cluster with FPGA and GPU acceleration. The direct fiber connection allows these base stations to be synchronized by either Next-Generation Fronthaul Interface (NGFI) (SyncE and PTP) or Common Public Radio Interface (CPRI). The outdoor base stations also contain integrated GPS with support for time-frequency synchronization. This high-precision time-frequency synchronization enables advanced wireless techniques such as massive-MIMO CoMP or proposed theoretical techniques such as Pilot Contamination Precoding [7]. Additional small-cells can be deployed anywhere on campus with Ethernet connectivity for heterogenous experiments.

ArgosV3 supports multiple software frameworks, including SoapySDR, GNU Radio, and OpenAirInterface [8]. Because none of these frameworks currently provide multi-cell integration, we updated the Argos realtime framework, [9], to support ArgosV3 as well as multi-cell measurements. Using this framework we collected initial multi-cell measurements to demonstrate massive-MIMO's ability to reduce network interference, as well as the potential gains from massive-MIMO CoMP.

II. Background and Related Work

Over the past five years, multiple massive MIMO testbeds have been reported [1]–[3], [5], [6], [10]–[13]. To the best of our knowledge, ArgosNet is the first at-scale multi-cell massive-MIMO platform.

Network interference is well known to be the key limiting performance factor in cellular networks [14]. By nature, beamforming techniques reduce both intra and inter-cell interference by focusing their radiated power on the intended user(s), as described in [4]. The more focused the beams, e.g., by using more antennas in a massive-MIMO system, the less resulting network interference there is. While this feature is well-known, and can even be inferred from previous measurements, e.g., this the underlying principle behind multi-user conjugate beamforming, it has been left relatively uncharacterized experimentally due to the lack of multi-cell massive-MIMO testbeds.

Coordinated Multipoint (CoMP) provides multiple techniques to reduce inter-cell interference and improve cell-edge performance, and has already been adopted in 3GPP

Fig. 1. Single 160-radio CBRS weatherproof ArgosV3 base station mounted outdoors. Four single-mode fiber pairs provide up to 40 Gbps connectivity.

standards. These techniques range significantly in complexity and performance, and have varying levels of synchronization requirements [15]. The simplest form of CoMP is coordinated scheduling, where base stations will only schedule transmission from one of the adjacent cells to or from a user on the cell edge to avoid interference. More advanced techniques include null steering towards users in adjacent cells as well as both coherent and non-coherent joint transmission or reception. These techniques can be directly applied to massive-MIMO, however their performance has yet to characterized experimentally. Given the inherent beamforming capabilities of massive-MIMO, the joint coherent transmission and reception (beamforming) methods are particularly attractive, though they require strict time-frequency synchronization. ArgosNet supports all of these CoMP techniques, and we provide some initial measurements in Section V-C.

III. ArgosNet

A. ArgosV3

The basis of ArgosNet is ArgosV3, a scalable Massive-MIMO hardware platform designed from scratch to be power, cost, and space efficient in order to enable outdoor multi-cell deployments. We defer to [5] to provide details on ArgosV3 hardware and only summarize its features important to ArgosNet.

While ArgosV3 flexibly supports frequencies ranging from 50 MHz to 3.8 GHz with 56 MHz bandwidth, ArgosNet leverages a configuration optimized for the 3.55 to 3.7 GHz CBRS band. Shown in Figure 1, this CBRS configuration enables 160 radios and antennas in a compact weatherproof enclosure that is less than 2 ft^3 and consumes less than 1.5 kW of power. Each radio provides up to 28 dBm of transmit power, and is connected to a custom dual-polarized antenna element that provides 6 dBi of gain. Internally ArgosV3 consists of 8 chains of 10 radio modules connected in series to a hub; this hub is based on a Xilinx ZCU102 development kit with a custom daughtercard to provide clocking, power, and data to each chain of radio modules. Leveraging the ZCU102's internal four SFP+ ports, ArgosV3 base stations can support up to 40 Gbps Ethernet or CPRI backhaul.

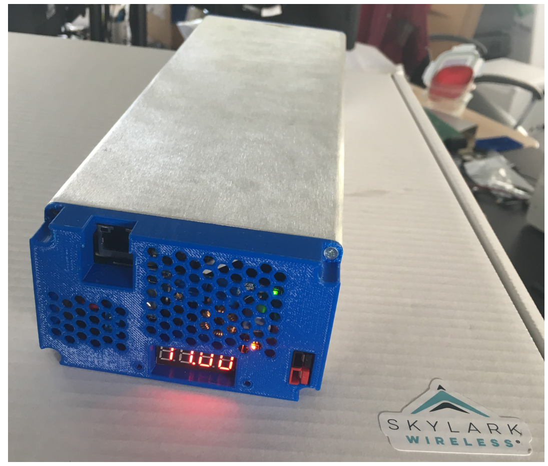

Fig. 2. ArgosMobile with integrated WiFi, GPS, and a 12-hour battery life.

Additionally, ArgosV3 provides an updated autonomous battery-powered mobile user shown in Figure 2. This ArgosMobile provides two radios, integrated GPS and WiFi, and over 12 hours of battery life. Since the performance of MU-MIMO is fundamentally limited by mobility, these truly mobile users are critical for realistically characterizing MU-MIMO performance.

ArgosV3 flexibly provides both CPU and FPGA resources at almost every layer of its architecture, and fully enables the original Argos architecture [1]. It currently supports multiple frameworks, including GNU Radio, SoapySDR, OpenAirInterface, and our custom Argos realtime flow.

B. ArgosNet Architecture

The logical ArgosNet architecture, shown in Figure 4, is relatively straightforward: each ArgosV3 base station is connected directly to a cluster, the ArgosCloud, via four single-mode fiber pairs. These fibers can support CPRI, however in our default configuration we use Ethernet with SyncE and PTP support.

The ArgosCloud consists of commodity servers with Nvidia GTX 1080 Ti GPUs and a combined 208 CPU cores. Additionally, ArgosCloud has a 52-port 10 GbE Arista 7150S switch for flexible networking, and a ZCU102 with an SFP+ daughtercard to provide 12 SFP+ ports, expandable up to 20, with CPRI or 10 GbE SyncE/PTP support. In the default configuration, ArgosNet currently contains four 100-radio base stations. Each base station has one 10 GbE SyncE/PTP connection the central ZCU102, one 10 GbE ethernet connection to a dedicated server, and two 10 GbE connections to the switch. Notably, this network topology is quite flexible and can be reconfigured for any desired connectivity, e.g., to replicate an LTE network with an Evolved Packet Core (EPC).

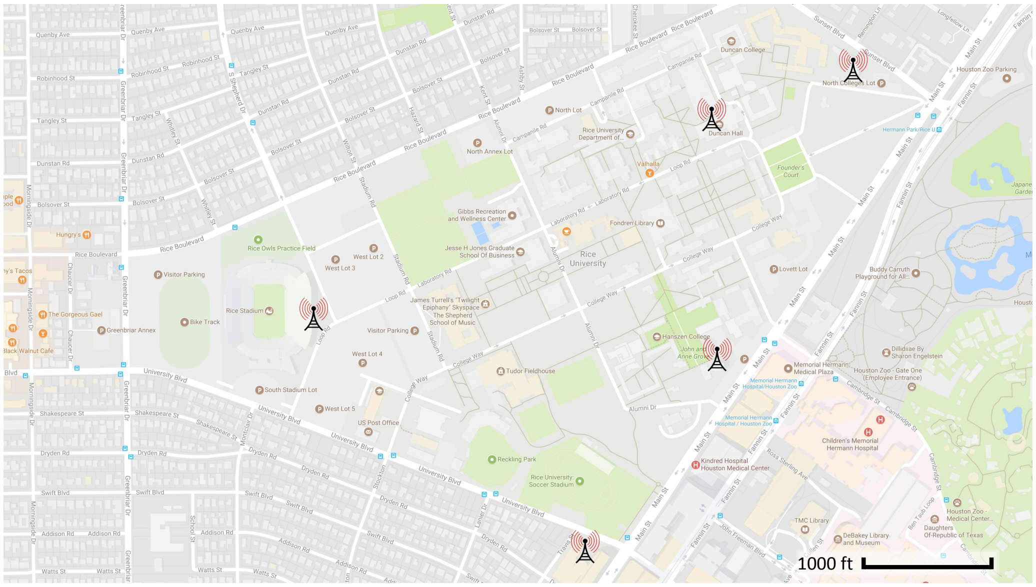

Fig. 3. ArgosNet base station locations. Each location has mounting, power, and direct fiber to ArgosCloud. All locations are outdoor sites except for Duncan Hall *top middle*, which is our indoor lab environment.

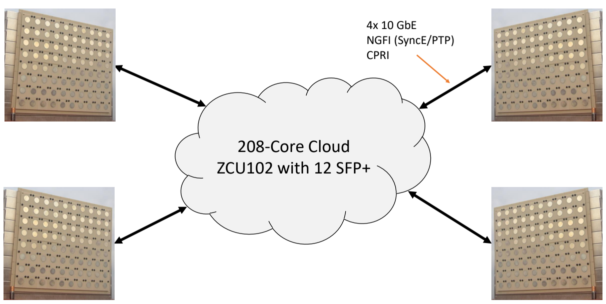

Fig. 4. ArgosNet logical architecture. Each base station has four single-mode 10 GbE fiber pairs connected to the 208-core ArgosCloud. In addition to commodity servers, the cloud has a 52-port 10 GbE switch and a Xilinx ZCU102 development kit for distributing NGFI (SyncE/PTP) or CPRI. The ZCU102 has four built-in SFP+ ports, and can be expanded to up to 20 SFP+ ports using FMC expansion cards.

Conveniently the individual radio modules in the ArgosV3 base station can be used standalone with 2 antennas and powered by PoE. This allows them to be connected anywhere there is Ethernet on campus to act as either a stationary client or a small cell to enable heterogeneous topologies in the future. Moreover, multiple radio modules can be connected together to provide more antennas at these stationary nodes.

C. *ArgosNet Deployment*

To provide flexible experimentation topologies, we deployed power, fiber, and mounting to 5 locations across Rice University campus, 4 outdoor and 1 indoor, shown in Figure 3. Each location can support multiple base stations to test multi-sector topologies, as well as provide different coverage areas. All of the outdoor base stations are mounted on the top of buildings to provide complete coverage of the campus, and three of the locations are adjacent to existing cell sites. In our default configuration three base stations are located outdoors on Brown College, Sid Richardson College, and the Stadium, and one base station is indoors, in our lab in Duncan Hall.

Conveniently all 4 outdoor locations have unobstructed line-of-sight (LOS) connectivity to each other, which enables direct multi-cell implicit calibration techniques. We obtained an FCC license, call sign WI2XLO, that provides experimental coverage of the UHF, ISM, and CBRS bands.

D. *Cell Synchronization*

Multi-cell time and frequency synchronization are critical components of next-generation wireless systems, and systems that implement CoMP have even tighter requirements [16]. In general, timing synchronization is used to ensure that protocol frame counters and transmitted symbols across distributed radios are aligned in time, while clock frequency and phase synchronization is used to ensure that transmissions are coherent and beamforming remains accurate [16]. In ArgosNet base stations can be synchronized at long-range using either their direct fiber connection to ArgosCloud or by using GPS. Each approach has its drawbacks and implications for system design.

The direct fiber connection can provide both timing and clock synchronization using CPRI or NGFI, which enables synchronization using the standards-compliant SyncE and PTP protocols. Our ArgosV3 base stations also leverage a u-blox UBX-M8030-KT-FT GNSS module to provide GPS time-frequency synchronization.

All reference clocks go through a clock jitter cleaner in the ArgosV3 base station, ensuring that transmission losses and introduced noise do not diminish radio performance while still allowing clock frequency and phase synchronization across large distributed cellular deployments. We compared three different schemes for clock synchronization: 1) two base

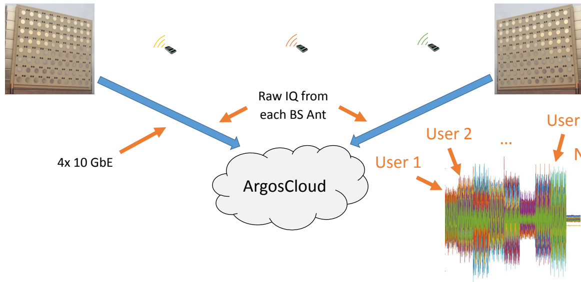

Fig. 5. Overview of the multi-cell channel measurement system design. At the beginning of each frame all base stations send a beacon to synchronize the users. Each user then sends orthogonal pilots, which every base station radio module records. At the end of the pilot phase, base-station radio modules report the raw pilot IQ samples to the ArgosCloud, which records them to an HDF5 file.

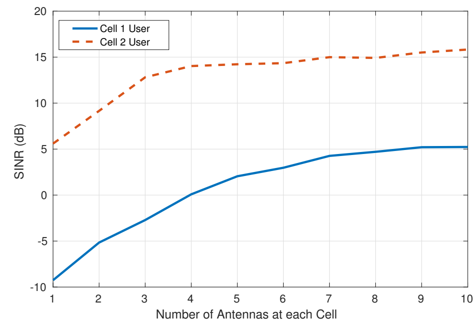

Fig. 6. SINR of users vs. number of base station antennas in two cells, each with one user. Increasing the number of base station antennas naturally reduces network interference through beamforming.

stations synchronized to their respective GNSS modules; 2) two base stations synchronized via SyncE over 10 GbE fiber; 3) two base stations in a master/slave configuration with direct clock sharing. Using a Tektronix MSO5054 with DPOJET jitter analysis package, the difference in jitter performance between clocking configurations was undetectable given the noise floor of the measurement equipment.

IV. Measurement System

The Argos realtime framework enables reliably collecting high time-frequency resolution many-antenna MU-MIMO channel traces [9]. Based on the *Faros* many-antenna control channel, [17], this measurement framework is incredibly flexible and can collect longitudinal traces with billions of measurements without missing a single channel estimation. We ported this realtime flow to ArgosV3, as well as extended it to support multi-cell topologies.

The Faros control channel has four phases: 1) a beacon to synchronize the users, 2) uplink pilots which can be used to implicitly estimate the downlink channel, 3) downlink data, 4) uplink data, though not necessarily in that order. For the measurement system, shown in Figure 5, during the pilot phase, and optionally the uplink data phase, each base station antenna transmits raw IQ samples to the ArgosCloud to be recorded or processed.

Synchronizing users in the multi-cell environment is relatively straightforward, we simply treat all the base stations as one large base station. Since the base stations are time-frequency synchronized, we can ensure that their beacons are aligned. While Faros would typically assign different beacons to different base stations, to simplify the measurement system, all of the base stations send the same beacon. Thus the beacons from different base stations simply look like multiple paths to the users, and the first strong path the user receives will be detected and enable it to synchronize. To avoid inter-symbol interference during the pilot phase given the discrepant path lengths, we use extra-long cyclic prefixes to ensure there is no symbol overlap in time.

The most significant challenge to multi-cell channel traces is Automatic Gain Control (AGC). In single base station measurements feedback can be used to adjust user gains, however in the multi-base station flow it is difficult to set gains for all of the base stations simultaneously due to their potentially highly discrepant paths. Thus to ensure pilots that are received within the dynamic range of all of the base stations, users step through preset transmit gains every frame. This sacrifices some time-resolution, but enables reliable multi-cell measurements. Of course gains can still be set manually, or set using AGC to a specific base station (either once or at each frame), depending on the experimental requirements.

V. Results

We analyze initial multi-cell traces and demonstrate the ability for many-antenna beamforming to reduce network interference, as well as the ability for many-antenna CoMP to drastically increase performance, particularly at the cell edge. These preliminary results are not intended to be comprehensive, but simply demonstrate the capabilities of the ArgosNet platform and measurement system. We are currently performing an at-scale measurement campaign leveraging the full ArgosNet installation. When it is complete, the measurement tools, channel traces, and analysis toolbox will be made freely available on the Argos Channel Measurement Repository [18].

A. *Experimental Setup*

We setup indoor lab experiments with two 10-antennna base stations placed 3 m apart, operating at 2.484 GHz with two users. Both base stations are locked to a common clock source and they receive a GPIO trigger pulse for initial time synchronization.

Leveraging the Argos channel measurement system described in Section IV, we collect full CSI traces at a time resolution of 10 ms and a frequency resolution of 20 MHz. We place a stationary user near the first base station and a mobile user on a 2.5 m Cinetics track to enable constant linear motion at approximately 2.2 cm/s. At the start of the measurement, this mobile user is in close proximity to the second base station then moves away from it toward the fist base station at a constant speed. Both users have LOS to both base stations.

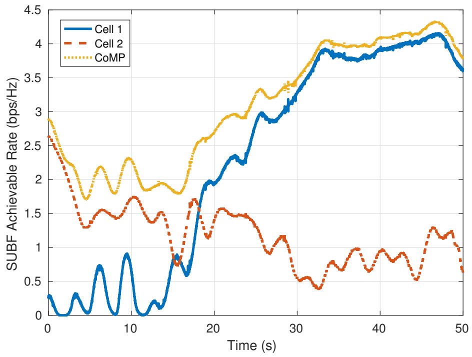

Fig. 7. Achievable rate of a user moving from one 10-antenna cell to another over time when be served by each cell individually as well as CoMP with coherent joint transmission, i.e., beamforming.

B. Network Interference

To demonstrate the ability for beamforming to naturally suppress network interference, as discussed in [4], we emulate two cells each with one user, where users experience strong inter-cell interference. In Figure 6 we see that adding additional antennas drastically improves SINR by reducing inter-cell interference. By increasing the number of antennas on a base station, beamforming maintains the same signal strength to the intended user, while reducing the total emitted power, thus also reducing network interference.

C. Coordinated Multipoint

We implement the most advanced form of CoMP, coherent joint transmission, i.e., beamforming, and show its ability to drastically improve performance on the cell edge. Figure 7 compares the achievable rate of a single user moving from one cell to the other while served by each cell individually, as well as with CoMP coherent joint transmission. In this scenario we see that CoMP almost doubles capacity at the cell edge, at approximately 15 s, the hardest locations to serve in cellular networks. Notably, Figure 6 also demonstrates the negligible benefit of complex CoMP schemes when users are not on the cell edge.

VI. Conclusion

We present ArgosNet, an incredibly flexible at-scale multi-cell massive-MIMO platform. ArgosNet not only provides a platform to test and verify multi-cell massive-MIMO performance, but also provides high-resolution time-frequency synchronization to enable advanced techniques, such as CoMP, and proposed techniques, such as Pilot Contamination Precoding [7]. Battery-powered ArgosMobiles as well as compatibility with open-source LTE stacks, e.g., OpenAirInterface [8], enable experiments with realistic mobility.

Furthermore, we extend the Argos realtime flow to support ArgosV3 and multi-cell measurements, then take initial measurements. Our measurements show not only the ability for massive-MIMO to reduce inter-cell interference, but also demonstrate the potential for massive-MIMO CoMP. We are currently performing a multi-cell measurement campaign, when complete the measurement tools, channel traces, and analysis toolbox will be posted on the Argos Channel Measurement Repository [18]. We intend these traces and tools to help guide the design of next-generation MU-MIMO systems.

Acknowledgments

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