MEGAMIMO 2.0

Distributed Multiple Output Multiple Input

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Real-time DMIMO Systems specified the networking technology MEGAMIMO 2.0 and was composed by researchers at the Computer Science and Artificial Intelligence Laboratory (CSAIL) at the Massachusetts Institute of Technology. The researchers Ezzeldin Hammed, Hariharan Rahul, Mohammed A. Abdelghany, and Dina Katabi aimed to develop a technology that combatted Spectrum Crunch and network congestion. MEGAMIMO 2.0 is a real-time distributed system that coordinates (and calibrates) Access Points (APs) on a network to scale throughput and improve range via the use of Distributed Multiple Input Multiple Output (DMIMO). MEGAMIMO 2.0 implements Joint Multi-user Beamforming (JMB), specified in *JMB: Scaling Wireless Capacity with User Demands* by the same set of researchers. JMB enables the coordination of multiple APs and simulates a singular, large, MIMO node. Coordination is not a simple to address across a distributed, asynchronous, system without a shared clock. Because of this, the challenges that MEGAMIMO 2.0 faces is split threefold: real time channel updates, power control, and architecture. Real-time channel updates and addresses the issue of channel reciprocity (or calibration factor). When expanding and applying channel reciprocity from point-to-point MIMO systems to DMIMO systems, the approach incurs a lot of overhead. Luckily, the calibration factor can be achieved without additional overhead. Power control addresses the dynamic adjustment of Automatic Gain Control (AGC) across a DMIMO system. AGC must be calibrated across time and space to enable the use of JMB in MEGAMIMO 2.0. Since MEGAMIMO 2.0 must react to all interactions that take place across the network, this implies that the architecture of the baseband and firmware must be reconfigured. This section will discuss the extension of the Physical layer (PHY) – Medium Access Control (MAC) interface and the enhancement of the real-time components of the MAC. MEGAMIMO 2.0 is the first real-time distributed 802.11 MIMO system that delivers a full-fledged 802.11 PHY. Additionally, this technology has the ability to scale throughput in accordance with the number of APs clustered on the network. Hence, throughput is scaled by a linear factor.

Joint Multi-User Beamforming

In traditional wireless networks, when two or more APs transmit data simultaneously on the same frequency band, this introduces collision. [1] This distorts the transmitted data and makes it unreadable. MEGAMIMO 2.0 APs mitigate signal collision via the modification of transmitted frequencies. This modification still produces collision. However, it results in the production of the desired signal. This enables the transmission and delivery of multiple signals to multiple clients. [2] Joint Multi-User Beamforming is the foundational technology that enables the coordination of multiple APs in MEGAMIMO 2.0, all while manipulating signal collision to achieve the desired signals. [1] JMB was initially developed for use in MEGAMIMO (1.0). JMB allows the coordination of multiple, independent APs and this technology allows them to coordinate and beamform their signals. [2] This functionality allows distributed APs to function as if they were a single MIMO transmitter. Additionally, this enables distributed APs to communicate with clients on the same channel. [2] Developed to combat Spectrum Crunch, MEGAMIMO 2.0 addresses and mitigates network congestion. Spectrum Crunch dictates the discrete expanse of the wireless spectrum. [3] Given this finite and the unlimited demand for connectivity in wireless technologies, JMB aims to address and alleviate Spectrum Crunch and network congestion.

Recent ventures into distributed beamforming have posited the improvements of increase communication range, increased throughput, and energy efficiency. Additionally, distributed beamforming provides for PHY layer security, the reduction of interference, and base station anonymity. [4] JMB evolved from multi-user beamforming which allows a singular MIMO transmitter to stream to clients with fewer antennas. In a network that implements multiuser beamforming, with two antennas on the MIMO transmitter, said transmitter can deliver one packet to two antennas on the receiver device(s). [2] Multiuser beamforming does not address network congestion. The key attribute of JMB is the distributed transmission of packets and concurrent delivery at the client side. JMB was designed with the wireless downlink channel in mind. On the client side, this technology can be implemented with off-the-shelf components which improves the probability of rapid deployment. Additionally, the techniques used to coordinate JMB and MEGAMIMO 2.0 are scalable and can be applied to cellular networks, however this may not function in a plug-n-play manner with off-the-shelf components. [2] The coordination inherent to JMB aims to cluster the distributed APs which emulates a singular large MIMO AP.

Real Time Channel Updates and Tracking

An important prerequisite of MIMO is concerned with knowledge of the channels across the topology. Before a DMIMO AP can perform distributed beamforming, it must be aware of the downlink channels established to the clients. [5] MEGAMIMO 2.0 features a channel update subsystem that measures the channels from the APs to the clients. This introduces challenges for DMIMO systems as learning and tracking channels can result in extreme overhead. As the size of clients and APs grows in DMIMO systems, overhead for discovery and tracking grows quadratically. [5] This technique is an extension of P2P MIMO concept for extracting channel reciprocity. The PHY layer must be modified to support efficient, real-time channel estimation. Luckily, the adaptation in MEGAMIMO 2.0 features a passive, real-time, solution for uncovering and tracking the downlink channels.

Reciprocity, in traditional MIMO, refers to the discovery of the uplink and downlink channels – from AP to client. [2] The AP can utilize reciprocity to combat feedback overhead. The AP can uncover the uplink channel and convert that measurement to the downlink channel by scaling the value by a calibration factor. This factor is only computed once and remains constant throughout operation. Reciprocity, in a DMIMO system, is a difficult issue to address. In a traditional P2P MIMO system, antennas on the AP are controlled by the same oscillator. In DMIMO systems, antennas on different APs are controlled by different oscillators. Due to the distributed nature of the system, this implies that the calibration factor is not constant across time. [5] Across distributed APs, the difference between oscillators would be considered the calibration factor, however this too does not remain constant. When reciprocity is omitted and the channel downlink estimates are obtained without calibration, this introduces error. When error is present without calibration (regardless of size), this drift accumulates over time and this leads to unacceptable errors in the estimate of the downlink channel. [5] Flawed estimations of channel reciprocity can destroy joint transmission capacity of JMB.

Distributed reciprocity aims to extract time-dependent calibration parameters. All slave APs calibrate in accordance with the master AP. Without correction, the master AP's uplink channel estimates are assigned as the downlink channels estimates. Similarly, all slave APs assume the uplink channel estimates as their downlink channel estimates. [5] However, each slave AP performs a corrective measure and alter their downlink channel estimates by a factor relative to the master AP. When the channel is measured, the calibration factor is extracted. MEGAMIMO 2.0's calibration takes place in two steps: update and initialization. Initialization occurs when and AP joins a DMIMO network, or immediately upon reboot of the network. In turn, initialization estimates magnitude and phase and the AP computes the refence channel from master to slave. The update occurs when clients receive information. At this point the AP updates the estimation of the calibration factor which accounts for alterations to phase relative to the master AP. The synchronization trailer aids in the in the synchronization of the reception function at each slave. The master AP follows the client transmission via the use of the synchronization trailer. [5] MEGAMIMO 2.0 utilizes the MAC layer acknowledgment transmission for the master AP. This acknowledges the client's transmission and serves as a synchronization trailer at all slaves. Due to oscillator rotation during channel estimation, each slave AP applies an additional phase rotation to determine the initial downlink channel. [5] These channel estimates allow for the implementation of JMB.

Power Control

Power control is a vital component of a DMIMO systems. For specificity, power control regards the ability to perform Automatic Gain Control. To maximally utilize the range of the application delivery controller, AGC amplifies the received signal to fill the desired range. [5] In traditional MIMO implementations, power control is performed locally. [2] Due to MEGAMIMO 2.0's distributed topology, each AP must cooperate to jointly transmit data. In turn, this indicates that power control must be performed in a distributed and coordinated fashion. AGC must be coordinated across time and space. Additionally, the transmit power at each AP must be coordinated. The PHY layer must be modified to coordinate distributed power control and enable accurate calibration factors.

For each transmission across the DMIMO system, AGC generates new gain values on a per-packet basis and does not have a memory to store these values as time drives forward. [5] When the slave APs adapt their channel phase, in reference to the master AP, this can manipulate the AGC negatively. The AGC makes a new scaling decision for every transmission it encounters from the Master AP. In account for noise on the medium, a lot of uncertainty is present in this scaling decision made by the AGC. Varying decisions can produce synchronization errors as each slave can falsely translate these changes as oscillator drifts. [5] To combat this false-positive actions, MEGAMIMO 2.0 corrects phase on a per-packet basis. Calibration occurs in the following way. Each antenna across the MEGAMIMO 2.0 network calculates the loopback channel. [5] The APs then measure the received channels for each gain setting. Upon these computations, MEGAMIMO 2.0 deciphers the scaling factor of the measure channel with respect to the reference gain setting. [5] If phase was not calibrated across a DMIMO system, phase change would prevent the ability of APs to beamform their signals.

As previously mentioned, AGC must be coordinated across time and space. Since, geographic distance from client to each distributed AP on the network varies, the channel from AP to client must be scaled differently. Slave APs, in MEGAMIMO 2.0, must account for phase and magnitude alterations introduced by AGC. This must be done before the slave APs transmit their channel measurements to the master AP. To coordinate AGC across space, MEGAMIMO 2.0 must conduct coordination across time and must compute the following ratio: channel magnitude in each subcarrier / refence channel to Master AP. This ratio scales and corrects the magnitude in each subcarrier. [5] Of course, this all happens before using the channels are used for beamforming coordination. Calibrating the AGC across space is a vital operation as it corrects the functionality of DMIMO.

In order to coordinate transmission power across a DMIMO system, the precoding matrix plays an important role. The matrix ensures that the desired signal cancelation occurs to perform the desired beamforming signals. Essentially, the client's data must be encoded by the precoding matrix to perform JMB. [2] To optimize this multiplication, the signal must be divided into digital and analog domains which takes place in in two steps. The digital section ensures that the signal can span the range of the digital-to-analog converter. The analog section controls the attenuation which safeguards the resolution of the analog signal. [5] This improves the signal-to-noise ratio (SNR) across the DMIMO system.

Architecture

To meet the real-time component of MEGAMIMO 2.0, the firmware and hardware interface must be redesigned. In conventional wireless networks, event timing occurs locally, on individual devices. This functionality is embedded at a hardware level. [2] Due to the distributed nature of MEGAMIMO 2.0, the hardware of each AP must react to inter-device events and must perform coordinated actions accords the distributed APs. [5] To account for distributed coordination, MEGAMIMO 2.0 extends the PHY-MAC interface and MAC to enhance the real-time component via the local actions. MAC, when applied to a DMIMO system, has multiple functions which include deciding which APs will jointly transmit, updating channels, and more. [5] The PHY-MAC interface is comprised of two features: controlling and reporting various subsystems.

In accordance with protocol 802.11, TXVECTOR provides the ability to specify (via MAC) payload, length, precoding matrix, modulation, and coding scheme in the PHY-MAC interface. [5] In a DMIMO system, this interface must be expanded at the transmitter to account for: time synchronization, initial phase correction, and frequency offset correction. [5] In this context, time synchronization refers to PHY layer ability to transmit packets at specific times. This feature aids in the functionality of a triggered transmission. A triggered transmission is composed of two parts, condition and elapsed time. The triggered condition refers to a signal encoded with the MAC address of the master AP. Of course, elapse time refers to the timestamp of said trigger. The initial phase must be corrected in order to successful broadcast a join transmission in MEGAMIMO 2.0. [5] Essentially, this means that all slave APs must correct phase offset in reference to the master AP at the moment of transmission. To guarantee accuracy in this calibration, the MAC parameters, slope and intercept, are applied to the OFDM subcarriers. [5] This correction allows MEGAMIMO 2.0 to calibrate slave APs upon the initiation of a joint transmission.

At the receiver side, the PHY-MAC interface is adjusted to account for frequency offset estimation and channel reporting. To acquire the frequency offset estimation the receiver must estimate the offset of the transmitter for each packet received. This information is forwarded to the MAC, where it is saved. The MAC retains attributes associated with the master AP which will be used as calibration for joint transmissions. The receiver must also, report the attributes of each channel to the designated sub carriers. [5] The channel is handled according to whether it is a reference channel, or a channel used for joint transmission.

Finally, the MAC to PHY interface must utilize a timing synchronization subsystem and a subsystem for synchronizing phase and frequency. These subsystems must be implemented at a hardware level to ensure the synchronization of the distributed system. [5] The subsystem in change of synchronizing time features the use of the aforementioned triggered transmissions. To commence a joint transmission, the MAC layer must generate two packets destined for the PHY layer. These packets are the synchronization header and the joint transmission. The latter transmission occurs upon the triggered transmission of the former. The MAC at each slave AP in the topology inspects each packet that arrive. When the local MACs are triggered and they join in cooperative transmission. The synchronization subsystem which coordinates both frequency and phase operates as an extension of the timing subsystem. [5] Similarly, this subsystem deconstructs each packet and checks to see if there is a synchronization header present. If the synchronization header is present, then the MAC evaluates calibration factors unique to frequency and phase offsets. Further, this subsystem analyzes the channel which carried the synchronization header. [5] This channel is then compared with the reference channel to master and this determines the phase offset of initial joint transmission.

Evaluation and Results

MEGAMIMO 2.0 was evaluated indoors and each AP in the network was constructed from off the shelf components: Zedboard and Analog FMCOMMS2 transceiver. The Zedboard features an ARM Cortex A9 dual core processor connected to and an Artix field programable gate array (FPGA) via high-speed bus. The baseband system was implemented via Verilog on the FPGA. The core of the baseband functions from full-fledged, real time, 802.11 a/g/n PHY layer. [5] As previously mentioned, the PHY layer was enhanced to support DMIMO. As a restriction of the system lies with the equipped FPGA, only four distributed APs served four roaming clients. The control system that measures channels, updates channels, and computes precoding matrices was also used. The FMCOMS2 board that interfaces with the Zed board functioned on the 2.4GHz range on channel 10 for all tests. All Zedboards come equipped with gigabit ethernet ports. [5]

MEGAMIMO 2.0 was evaluated via the use of microbenchmarks (applied to individual components). Additionally, the system was assessed as a whole. First, the testbed environment simulated a congested conference other high congestion area. The APs were placed up high on the walls, near the ceiling, and the clients were placed low to the ground. The environment was furnished, had pillars, and had protruding walls. The system was evaluated with mobile and non-mobile clients. Laptops equipped with off-the-shelf 802.11n wireless cards on top of Roomba robots emulated mobile clients. [1] All hardware adhered to protocol 802.11n. The performance of MEGAMIMO 2.0 was compared to both traditional wireless networks and DMIMO systems. The metrics extracted for qualitative evaluation consist of SNR after beamforming, total network throughput, and client throughput. The researchers benchmark the accuracy of reciprocity, AGC calibration, Real-time Performance, and the performance in a static environment. [5]

The accuracy of reciprocity was accessed via a two transmitter, two receiver system with non-mobile clients. 90 percent of the traffic of the network was concentrated on the downlink. Two methodologies for testing were implemented. First, the APs transmitted packets to clients and they received channel feedback measurements from the clients. Second, The APs utilized MEGAMIMO 2.0's reciprocity protocol to infer downlink channels without explicit feedback. This was tested across multiple locations and the results were examined for SNR. When signal reciprocity is mapped as a function of SNR, the plot indicates that the MEGAMIMO 2.0's reciprocity estimates perform similarly to explicit channel feedback across the range of 802.11. Therefore, MEGAMIMO 2.0 can safely utilize the inference of channel downlinks to avoid the overhead incurred from explicit channel feedback. [5]

The calibration of AGC was evaluated on a four transmitter, four receiver system with nonmobile clients. The APs on the network perform DMIMO beamforming based on channel estimation. Both the uplink and downlink have 10% load. This test was performed across multiple environments. This resulted in MEGAMIMO2.0, with AGC and (phase and magnitude) calibration, achieving the highest throughput. When MEGAMIMO function with magnitude calibration and no phase calibration, the system resulted in inconsistencies with beamforming (beamforming became very sensitive to minor changes). This also resulted in gain errors. This modification resulted in the loss of performance when compared to full-fledge MEGAMIMO 2.0. The system that was calibrated with manual gain control performed the lowest in this test. [5]

The tests for real-time performance evaluated whether MEGAMIMO 2.0 can operate as a DMIMO system given the real-time constraint. Dynamic environments, meaning typical indoor features, were considered for extracting results. Dynamic movement was used in two cases: non-mobile clients with moving humans and mobile clients with moving humans. The clients travelled either by Roomba robot, or they were carried by a human. This environment featured four APs and four clients. Two configurations were tested for. First, the DMIMO system was tested with explicit channel feedback. Then, it was tested with distributed reciprocity in mind. The results indicated that MEGMIMO 2.0 real-time PHY has the ability to adapt dynamic environments and mobile clients. Additionally, DMIMO with reciprocity obtained the highest throughput in all tests. Finally, the results of this test indicate that reciprocity is essential as the size of the network grows. [5]

Finally, performance in a static environment is evaluated similarly to the last test. However, there are no roaming clients and there are no human obstacles. The experiment was conducted 15 times. At each round, the client's locations were changed. The results indicated that MEGAMIMO 2.0 with reciprocity improves throughput by a factor of 3.6 when four distributed APs populate the network. [5]

Future Work

The foundations of MEGAMIMO 2.0 rooted in the theoretical fabric of DMIMO and the researchers of the CSAIL at MIT will continue to improve the technology. MEGAMIMO 2.0 will serve as the bedrock for understanding theoretical DMIMO. [6] The issues and obstacles encountered during development only contribute to the further development of the technology. The researchers propose the addition on a higher, non-real-time MAC layer. [5] To optimize fairness and throughput across the network, the additional MAC layer will establish communication between APs and clients in accordance with network traffic. Additionally, this MAC layer will select the channels established from APs to clients. Finally, the largest improvement involves the addition of dynamism when electing the Master AP for individual transmissions. [5] To improve communication and limit delays, the Master AP elected would need to be, geographically, centered relative to the client. The team of researchers plan to adapt and expand this technology to include additional networking components. They are actively working on scaling MEGAMIMO 2.0 in order to adapt to multiple routers simultaneously. [7] Theoretically, this would scale throughput by a linear factor.

Conclusion

In conclusion, MEGAMIMO 2.0 was developed by the research team, led by Dr. Katabi, at the CSAIL Laboratory at MIT, to establish a tool which combats Spectrum Crunch and network congestion. MEGAMIMO 2.0 scales throughput and range via the coordination of independent APs on a network. JMB is used as a tool to simulate the action of a singular MIMO transmitter across a DMIMO system. Due to the inherent nature of asynchronous distributed systems, MEGAMIMO 2.0 addresses real time channel updates, power control, and rearchitecting the baseband and firmware. Without the introduction of additional overhead and to meet the constraint of real-time functionality, channel updates are calculated via inference parameters obtained from the reference channel from slave to master AP. This fosters the emulation of synchronization across a distributed system with no common clock. To enable the use of JMB, power control is dynamically employed to calibrate AGC across time and space. To coordinate distributed power control and enable accurate calibration factors, the PHY layer was modified to obtain the desired precoding matrix to achieve the desire beamforming signal cancellation. Additionally, the AGC scaling factor is extracted from the comparison of the measured channel with respect to the reference gain setting. This, too, allows JMB to properly function across the distributed APs. Rearchitecting the baseband and firm ware refers to the extension and enhancement of the PHY-MAC and MAC to PHY interfaces. This is a necessary adaptation in MEGAMIMO 2.0 as each AP on the network must react to interactions across the network. MEGAMIMO 2.0 can linearly scale throughput in accordance with the number of APs clustered on the network.

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