Massive MIMO Full-duplex: Platform, Experiments & Theory

Ashu Sabharwal

Joint work with Evan Everett, Clay Shepard and Lin Zhong
Department of Electrical and Computer Engineering
Rice University
Outline for Today’s Talk

- Wireless open-Access Research Platform (WARP) [12 min]
  - History, components and impact
- Massive MIMO Full-duplex
  - Argos: Massive MIMO Platform [8 min]
  - Theory results [10 min]
  - Experimental results [20 min]
Early 2000

- Mesh networks
- MAC, routing
- Scheduling

Edward Knightly
Ashu Sabharwal

Behnaam Aazhang
Ashu Sabharwal

- MIMO
- Feedback
- Cooperative

Low-power high throughput architectures

Joe Cavallaro
Early 2000

- Mesh networks
- MAC, routing
- Scheduling

Edward Knightly
Ashu Sabharwal

Low-power high throughput architectures

Joe Cavallaro

Will Our S**t Ever Work Together?
How do we Evaluate Systems?

Vastly different metrics and tools

Network (overhead, delay, Goodput) ns-2

PHY (transmit power, BW, bits/s/Hz) MATLAB

Architectures (device power, area, throughput) Verilog
Failed Attempts

Started with off-the-shelf hardware, e.g. from Sundance

- DSP and FPGA on same board
- No radios
- Painful, painful, painful – programming two processors and making them play nice took all our time.
- We got nothing useful done.
Failed Attempts

Needed radios – custom built by a small design firm
- Very expensive (development $ + $12K/radio)
- Built out of discrete parts
- Never worked as promised, not much digital control
- Programming interface were a !@!@#
Failed Attempts

Mental Error
- MY research is the more challenging part
- Treated research platform as second grade citizen

2003 was our breakout year – NSF ITR to study data-driven theory
WARP: Wireless Open-Access Research Platform

- Laid out clear specs
  - Single processor – FPGA was only choice
  - No discrete-component radios – digitally controllable
- 4-antenna MIMO, extensible hardware
- Virtex-II pro based board, using Maxim 2829 (802.11n) radios
3 Design Flows: One Platform for Multiple Communities

**PHYsical Layer**

WARPLab = WARP + MATLAB
Control of multiple boards from one computer
*True channels in Matlab*

**Network Layer**

Real-time WARP
Based of 802.11g
*Complete network stack*

WARPnet
Control & measure a network of nodes
*Real-time network scale experiments*
Personal Use to Community Use

- Our friends wanted WARP
- We shipped first 80 kits from Rice!
- Project open-sourced using a NSF CRI Grant in 2006
- Spun off as Mango Communications (2008), by Rice student inventor Patrick Murphy & I stayed out of it
Three Generations of Hardware

- V2 used Virtex-4, also designed by a student at Rice
- All open-source frameworks, all designed at Rice
- V3 uses Virtex-6, fully designed at Mango
- Project has been self-sustaining since 2008
Impact at Rice

**Education**
Real “wireless” in wireless curricula

**Research**
- System-level thinking
- “what if” questions

**Collaboration**
80+ papers with > 2 faculty co-authors
Impact Beyond Rice

- All code-base is open-source at http://warp.rice.edu
- In-use at 125+ research groups worldwide
- Has facilitated 250+ publications (by end of 2014)
- 11 two-day intl. workshops in 5 years – 400+ participants
- WARP support forums, managed by inventors, have been crucial
My Personal Evolution

- Hardware was a dirty word in theory community
- Doing experiment-driven work meant poor reputation
- Most people did not know that I am “Mr. WARP”
Outline for Today’s Talk

• Wireless open-Access Research Platform (WARP) [12 min]
  • History, components and impact

• Massive MIMO Full-duplex
  • Argos: Massive MIMO Platform [8 min]
  • Theory results [10 min]
  • Experimental results [20 min]
Data Rate Through Generations

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<tbody>
<tr>
<td>Peak Rate</td>
<td>172 kbps</td>
<td>7 Mbps</td>
<td>42 Mbps</td>
<td>~150 Mbps</td>
<td>~1 Gbps</td>
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Gains from Spectrum & Spectral Efficiency
Spectral Efficiency Increase

![Graph showing spectral efficiency increase for various technologies: GPRS, EDGE, WCDMA, HSPDA, Rel 5, HSPA, Rel 6, HSPA, Rel 7, LTE.]
MIMO @ Infrastructure

Each generation has more infrastructure antennas

3GPP is considering 64-element 2-D arrays
With Single Antenna
With Many Antennas

Power gain via beamforming

\[ R \sim \log M \]
With Many More Antennas

Power gain via beamforming

\[ R \sim \log M \]
With Single Antenna

Time/frequency division
With Many Antennas

Multiplexing gain via multi-user beamforming

\[ R \sim K \log M, \quad M \geq K \]
 Massive MIMO Regime: When $M \gg K$

Noncooperative Cellular Wireless with Unlimited Numbers of Base Station Antennas

Thomas L. Marzetta

- Simple processing (conjugate beamforming) is optimal
- Inter-cell interference no longer an issue
Rice Argos V1: 64 Antennas
Project Lead: Prof. Lin Zhong, Clay Shepard
Argos Architecture
Argos Implementation

Central Controller (PC with MATLAB)

Argos Hub
- Ethernet
- Sync Pulse
- Clock Distribution

WARP Module

FPGA
- Power PC

FPGA Fabric
- Peripherals and Other I/O
- Hardware Model

Clock Board

WARP Module Daughter Cards
- Radio 1
- Radio 2
- Radio 3
- Radio 4
Rice Argos V2: 96 Antennas (November 2013)
ArgosNet: Total of 400 Radios

Today, Another Use Many Antennas

All-digital Architecture for Massive MIMO Full-duplex

- All full-duplex proposals require additional analog
- Build full-duplex using no additional analog?
Full-duplex Wireless
Full-duplex Wireless

Base Station

Uplink

Downlink

Half duplex
Full-duplex Wireless

Base Station

Uplink

Downlink

Full duplex
Full-duplex Wireless

Base Station

2x Efficiency

Uplink

Downlink

Full duplex
Full-duplex Wireless: Two Main Interferences

- Self-interference
- Inter-node interference

Base Station

Uplink

Downlink

Full duplex
Full-duplex Wireless: Focus on Self-Interference

Self-interference

10^6 to 10^9 x stronger

Full duplex
**Full-duplex State-of-the-art**

- Near perfect full-duplex using a combination of analog and digital cancellation

- Full-duplex feasible at small cell range (~120 m)

Self-interference suppression
Self-interference suppression
Self-interference Suppression With Many Antennas

Complex analog circuity
- Scales with square of array size
- Ill-suited for large arrays
Goal: All-digital Full-duplex Architecture

Must prevent RF saturation
Goal: All-digital Full-duplex Architecture via Beamforming
Questions to Answer

1. In what conditions is all-digital FD feasible?

2. What are practical algorithms for all-digital FD?
Questions to Answer

1. In what conditions is all-digital FD feasible?
2. What are practical algorithms for all-digital FD?

Answer with info-theoretic analysis
Answer with design and experiment
Components of Self-Interference

Experimental Evidence for Backscattering

\[ |h(t)|^2 \text{ (dB)} \]

\[ 0 \quad 20 \quad 40 \quad 60 \quad 80 \quad 100 \]

\[ t \text{ (ns)} \]

Room

Anechoic

The Challenge of Backscattering

Backscattering becomes bottleneck

Direct-path can be passively suppressed

Can we do a better job of spatial isolation in a backscattering environment?

Yes, but there is a catch!
Spatial Multiplexing

Base station

Rx  Tx

Stream 1
Stream 2

Uplink

Downlink

Degrees-of-freedom (DoF) = \frac{\text{# of data streams}}{\text{# of time slots}}
Half-duplex Spatial Multiplexing

Time slot 1

Base station

Rx
Tx

Stream 1
Stream 2

Uplink

Downlink
Half-duplex Spatial Multiplexing

Time slot 2

Uplink DoF = \( \frac{2 \text{ data streams}}{2 \text{ time slots}} \) = 1

Downlink DoF = \( \frac{2 \text{ data streams}}{2 \text{ time slots}} \) = 1
Full-duplex Spatial Multiplexing

The catch: beamformed suppression can “cost” spatial multiplexing
Full-duplex Spatial Multiplexing

How do we balance beamformed suppression and spatial multiplexing?

Information Theory Analysis
(Gain Understanding)
Modeling Scattering

Base station

Rx
Tx

Uplink
Downlink

Modeling Scattering

Base station

Rx

Tx

Uplink

Downlink

Forward-scattering intervals

Backscattering intervals

Solving the Degrees-of-freedom Tradeoff

Everett and Sabharwal, “Spatial Self-interference Isolation for In-band Full-duplex Wireless…,”
When, and By How Much, Is Full-duplex Better?
If scattering overlapped, and base station arrays no larger than mobile arrays, **no gain**
Gain proportional to non-overlap between backscattering and forward scattering.
Gain proportional to non-overlap between backscattering and forward scattering.
Further improve full-duplex with larger arrays at base station

Leverage extra DoFs for nulling
Further improve full-duplex with larger arrays at base station

Leverage extra DoFs for nulling
Further improve full-duplex with larger arrays at base station (Massive MIMO Regime)
Suppression via Transmit Beamforming

- For 2D arrays, no single direct self-interference path
- Transmit beamforming must suppress both direct and reflected paths
Nulling Interference is Not Possible

- $(\# \text{ of Tx antennas}) - (\# \text{ of Nulls}) = \# \text{ of Effective antennas}$

- More nulls means fewer users served
Suppression & Transmit Dimension Tradeoff

• $(\text{# of Tx antennas}) - (\text{# of Nulls}) = \text{# of Effective antennas}$

• More nulls means less power to each user
Do we really need to null self-interference?

Must prevent overwhelming dynamic range

Self-interference

Desired Signal
Do we really need to *null* self-interference?
Do we really need to null self-interference?
**SoftNull**

- Given a required # of effective Tx antennas, $D_{TX}$

- Select beam-weight matrix, $P_{self}$, which maximally suppresses self-interference

- Effective self-interference channel: $H_{self} P_{self}$

\[ P_{self} = \arg \min \| H_{self} P_{self} \|_F, \]
\[ \text{s.t. } P_{self}^H P_{self} = I_{D_{TX} \times D_{TX}} \]

Close form solution!
Softnull example:
Self-interference power vs. # of effective Tx antennas, $D_{TX}$
**Softnull example:**
Self-interference power vs. # of effective Tx antennas, $D_{TX}$

- **SoftNull tradeoff**
  - As # of effective antennas decreases:
    - Uplink benefits from better self-interference suppression
    - Downlink suffers due to lower SNR
Softnull Feasibility Study

- Is a “good” SoftNull tradeoff feasible for real channels?
  - Impact of array partitioning
  - Impact of backscattering
- Is benefit to uplink SoftNull worth the cost to the downlink?
Argos-based Measurement Platform

- NASA Array+Argos Base Station
  - 72 patch antennas, 8x9 grid
  - 18 WARP nodes
- 4 Users via WARP Measure 72 X 72 self-coupling channel
- OFDM pilots from each antenna while all others listen
  - Enables comparison of arbitrary Tx/Rx partitions
  - Measure 72x4 uplink and 4x72 downlink channel
Measurement Campaign: 3 Environments

Anechoic Chamber  

Outdoor  

Indoor
Softnull Feasibility Study

• Is a “good” SoftNull tradeoff feasible for real channels?
  • Impact of array partitioning
  • Impact of backscattering
• Is benefit to uplink worth the cost to the downlink?
Tx/Rx Partitioning

- East-West
- North-South
- Northwest-Southeast (NW-SE)
- Interleaved
Tx/Rx Partitioning Results (Anechoic Chamber)

- East-West
- North-South
- Northwest-Southeast (NW-SE)
- Interleaved

![Graph showing SI Reduction (dB) vs effective antennas, $D_{Tx}$]

- **Random**
- **North-South**
- **East-West**
- **NW-SE**
- **Interleaved**
Tx/Rx Partitioning Results (Anechoic Chamber)

- Contiguous splits are best
- Minimizes angular spread of the self-interference
Softnull Feasibility Study

• Is a “good” tradeoff feasible for real channels?
  • Impact of array partitioning
  • Impact of backscattering
• Is benefit to uplink worth the cost to the downlink?
Impact of Back-scattering

- Backscattering leads to less suppression (as theory predicts)
- Reason: backscatter breaks antenna correlation
Softnull Feasibility Study

• Is a “good” tradeoff feasible for real channels?
  • Impact of array partitioning
  • Impact of backscattering

• Is benefit to uplink worth the cost to the downlink?
Is Benefit to Uplink Worth the Cost to the Downlink?

- Scenario: East-West split, indoor and outdoor
- Methodology: simulation using real measured channels
- Compare uplink and downlink rates of softNull versus half duplex and ideal full-duplex

Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Base station power</td>
<td>0 dBm</td>
</tr>
<tr>
<td>Mobile user power</td>
<td>-10 dBm</td>
</tr>
<tr>
<td>Noise power</td>
<td>-95 dBm</td>
</tr>
<tr>
<td>Dynamic range limit</td>
<td>25 dB</td>
</tr>
<tr>
<td>Number of users</td>
<td>4</td>
</tr>
<tr>
<td>Path Loss</td>
<td>85 dB (300m)</td>
</tr>
</tbody>
</table>
Is benefit worth the loss in downlink SNR?

East-West

Uplink:

<table>
<thead>
<tr>
<th>Outdoor</th>
<th>Indoor</th>
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- Half duplex
- Ideal full duplex
- SoftNull

Effective antennas, $D_{Tx}$
Is benefit worth the loss in downlink SNR?

East-West

Outdoor

Indoor

Uplink:

Downlink:

Outdoor

Indoor

Effective antennas, $D_{Tx}$
Is benefit worth the loss in downlink SNR?

East-West

Uplink:

Downlink:

Outdoor

Indoor
Is benefit worth the loss in downlink SNR?

East-West

Uplink:

Downlink:

Uplink+Downlink:
Is benefit worth the loss in downlink SNR?

Uplink:

Downlink:

Uplink+Downlink:
Impact of distance (i.e. path loss)

- East-West

70 dB path loss (50m LoS)
Impact of distance (i.e. path loss)

70 dB path loss (50m LoS)

85 dB path loss (300m LoS)
Impact of distance (i.e. path loss)

70 dB path loss (50m LoS)

85 dB path loss (300m LoS)

100 dB path loss (1km LoS)
Impact of number of users

East-West

Outdoor

Indoor

Achievable Rate (bps/Hz)

Number of users, K
Impact of number of users

East-West

Outdoor

Indoor

Achievable Rate (bps/Hz)

Number of users, K

- Half Dplx $L_p = 70$ dB
- SoftNull $L_p = 70$ dB
- Half Dplx $L_p = 85$ dB
- SoftNull $L_p = 85$ dB
- Half Dplx $L_p = 100$ dB
- SoftNull $L_p = 100$ dB
Impact of number of users

East-West

Outdoor

Indoor

- Half Dplx $L_p = 70$ dB
- SoftNull $L_p = 70$ dB
- Half Dplx $L_p = 85$ dB
- SoftNull $L_p = 85$ dB
- Half Dplx $L_p = 100$ dB
- SoftNull $L_p = 100$ dB

Achievable Rate (bps/Hz) vs Number of users, $K$
Softnull Feasibility Study

• Is a “good” tradeoff feasible for real channels?
  • Yes, when array partitioned contiguously
  • Especially in low-backscattering deployments

• Is benefit to uplink worth the cost to the downlink?
  • Yes, when path loss is not too large
  • Especially when # of antennas >> # number of users
Conclusions

• Massive MIMO means many more transmit dimensions

• New design space!

• SoftNull uses it for all-digital full-duplex

• Good in Massive MIMO regime, where # of users $<<$ # of antennas

• Platform crucial

• Currently working on a real-time evaluation
Questions or Comments?

WARP: http://warp.rice.edu

Argos: http://argos.rice.edu