Massive MIMO: It Really Works!

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The future: augmented reality everywhere

- Throughputs: 100 – 1000x
- Latency: 1/10 – 1/100x
Timeless truths about wireless

- Demand for wireless throughput, both mobile and fixed, will always increase: 10x, 100x, 1000x

- The quantity of available electromagnetic spectrum will never increase
  - The best spectrum is below 5 GHz
  - you can’t lay down more of this!
Spectrum below 5 Ghz: the most valuable resource in the world!

- FCC AWS-3 spectrum auction, January 2015
  - 65 MHz: 1695-1710 MHz, 1755-1780 MHz, 2155-2180 MHz
  - $41.3 billion
  - $630/Hz
Outline

- Taxonomy of MIMO
- How to distinguish Massive MIMO from impostors
- Numerical case studies
- New research directions
Taxonomy of MIMO
Point-to-Point MIMO

Roy & Ottersten (1991); Paulraj & Kailath (1993); Foschini (1995); Raleigh & Cioffi (1998); Telatar (1999)

- Brilliant invention
- But not scalable
  - unfavorable propagation
  - time required for training grows with system size
  - disappointing multiplexing gains at cell edges

8x4 link, -3.0 dB SNR

<table>
<thead>
<tr>
<th># base station antennas</th>
<th>1</th>
<th>2</th>
<th>4</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>bits/second/Hz</td>
<td>1.51</td>
<td>1.83</td>
<td>2.06</td>
<td>2.19</td>
</tr>
</tbody>
</table>

In every wireless standard, but no further practical development possible.
Multi-User MIMO

Caire & Shamai (2003); Viswanath & Tse (2003); Vishwanath, Jindal, & Goldsmith (2003)

- Splitting the multi-antenna user into autonomous single-antenna users doesn’t decrease the sum-throughput!
- Only single-antenna terminals required
- Propagation is almost always favorable
- But not scalable in its original form
  - dirty-paper coding/decoding needed
  - both ends of link have to know channel state information (CSI)

Dual CSI requirement \(\rightarrow\) fundamentally unscalable
Massive MIMO
Marzetta (2006); Marzetta (2010)

- Add many more base station antennas
- CSI isn’t everything: it’s the only thing!
  - channel state information (CSI) only available to the base station
  - use linear pre-coding/de-coding instead of dirty-paper
  - users don’t do any signal processing

A practical Massive MIMO system can be much bigger than an orthodox-Shannon system
Benefits of Massive MIMO

- Area spectral efficiency (bits/sec/Hz/square-kilometer)
- Scalability
- Great service to *all* users via power control
- Energy efficiency (bits/Joule)
- Simplicity

* A game-changer
How to Distinguish Massive MIMO From Impostors
More than just many antennas

- Many physically small, low power, individually controlled antennas
  - channel orthogonality
  - channel hardening
- Create parallel flat virtual connections between base station and terminals
  - every terminal uses *all* time/frequency resources
- Utilize *measured* channels rather than *assumed* channels
Downlink data transmission: Maximum-Ratio

antennas transmit the weighted message-bearing symbols to arrive in-phase at the intended user & out-of-phase elsewhere

The simplest possible pre-coding, but often very effective
Uplink data transmission: Maximum-Ratio

*base station weights and adds received signals for constructive reinforcement of the transmission from each user*
TDD slot structure ensures timely CSI: $M$ service-antennas, $K$ users, unlimited $M$

- **TDD slot: training** $\propto K$
  
  | Up Data | $K$ Up Pilots | Down Data |

- **FDD slot: training** $\propto 2M + K$
  
  | Down Link | $M$ Pilots | Down Data |
  | Up Link   | $M$ CSI    | $K$ Pilots | Up Data |

Mobility limits the number of active users; FDD is a disaster!
Why so important to utilize measured propagation?

- **Measured** channels
  - scalable
  - gain grows linearly with number of antennas
    - irrespective of noisiness of CSI
    - no tightening of array tolerance required
- **Assumed** channels
  - not scalable
  - gain eventually grows only logarithmically

If channels are assumed, then not Massive MIMO!
Scientific foundations of Massive MIMO

- Using *measured* channels: Beamforming gain grows linearly with number of antennas, irrespective of the noisiness of the measurements.
- Frequency-independent power control: Based solely on long-scale (slow) fading; exceedingly effective.
- Pilot contamination: Ultimate limitation in non-cooperative multi-cell systems.

No new mathematics, but a new philosophy!
Experimental validation of Massive MIMO

<table>
<thead>
<tr>
<th></th>
<th>Service antennas</th>
<th>Terminals</th>
<th>System spectral efficiency (b/s/Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bristol University / Lund University</td>
<td>128</td>
<td>12</td>
<td>80 → 140</td>
</tr>
<tr>
<td>Bell Labs “FutureCell”</td>
<td>64</td>
<td>2 → 10</td>
<td>20 → 100</td>
</tr>
<tr>
<td>Facebook “Project ARIES”</td>
<td>96</td>
<td>24</td>
<td>71 → 100</td>
</tr>
<tr>
<td>Google</td>
<td>32</td>
<td>32</td>
<td>20</td>
</tr>
</tbody>
</table>
Numerical Case Studies
Mitigation of pilot contamination: Pilot re-use Factor 3, 4, 7
re-use of pilot sequences causes coherent inter-cell interference

The cost: extra training overhead
## Dense-urban/suburban cellular access

**optimum pilot re-use factor?**

<table>
<thead>
<tr>
<th></th>
<th>Dense Urban</th>
<th>Suburban</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Carrier frequency(GHz)</strong></td>
<td>1.9</td>
<td>1.9</td>
</tr>
<tr>
<td><strong>TDD spectral bandwidth (MHz)</strong></td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td><strong>Slot duration (ms)</strong></td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td><strong>User allowed mobility (km/h)</strong></td>
<td>71</td>
<td>142</td>
</tr>
<tr>
<td><strong>Uplink radiated power/user (mW)</strong></td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td><strong>Number of service antennas</strong></td>
<td>64</td>
<td>256</td>
</tr>
<tr>
<td><strong>Total downlink radiated power (W)</strong></td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td><strong>Active users/cell</strong></td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td><strong>Cell radius (km)</strong></td>
<td>.50</td>
<td>2.0</td>
</tr>
<tr>
<td><strong>Power control</strong></td>
<td>Max/min</td>
<td>Max/min</td>
</tr>
<tr>
<td><strong>Pilot re-use factor</strong></td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td><strong>Pre-coding/de-coding</strong></td>
<td>Maximum-ratio</td>
<td>Maximum-ratio</td>
</tr>
<tr>
<td><strong>95% likely throughput/terminal Mb/s</strong></td>
<td>4.5 down, 3.1 up</td>
<td>3.2 down, 1.1 up</td>
</tr>
</tbody>
</table>

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**Max-min power control: uniformly good service *everywhere!*
Fixed wireless access: 3000 rural homes, each 20 Mbps down, 10 Mbps up

- 3000 homes randomly distributed over 11.3 km radius
- Target down-link throughput: 20 Mbps for every home simultaneously
- Target up-link throughput: 10 Mbps for every home simultaneously
- 10 W total downlink radiated power
- 1 W uplink radiated power per terminal
- 50 ms coherence time
- 800 MHz carrier frequency
- 20 MHz spectral bandwidth

How many antennas are needed?
How many antennas are needed?

- Zero-forcing: 3200 antennas (11m x 11m)
- Maximum ratio: 8200 antennas (17m x 17m)

Total system throughput: 90 Gbs; 4500 b/s/Hz !!!
New Research Directions
Massive MIMO extensions

- Unlicensed spectrum operation
  - mitigation of non-cooperative interference

- Massive MIMO of Things: MMOT
  - huge numbers of things
  - sporadic service
  - short-duration messages

- Limit behavior of Cell-Free Massive MIMO
  - continuum of access points (holographic MIMO)
“a mathematical theory of communication” → “a physical theory of communication” is 10x beyond Massive MIMO possible?

- Rigorously combine electromagnetic theory with communication theory
- Re-examine old concepts
  - Super-directivity
  - Resonant evanescent wave coupling
- Meta-materials (negative dielectric constant) for antenna arrays
- What is the minimum power that we have to draw from an antenna? $E_b/N_0 > \ln 2$: a purely *mathematical* construct
- Concepts from near-field optical sub-wavelength imaging?

*Multidisciplinary effort: wave propagation, electronics, mathematics, ...
Resonant evanescent wave coupling

WITRICITY (MIT, 2007): 60 Watts, 2 meters, @ 10 MHz, 40% efficient

- Wavelength 30 meters
- Near-field dominated by evanescent waves
  - Exponential decay
  - Reactive power only
- Tuned receiver coil alters boundary conditions, and pulls in power
Wireless neurosensing: implantable intercranial transmitter


- 100 7.8 kHz neural channels: 3.2 – 3.8 GHz
- Could MIMO handle 1000, 10000, … channels?
- What are the ultimate limitations of near-field wireless communication?
Massive sensor telemetry

*Continuous recording of signals from vast numbers of sensors*

- “Sensor networks” paradigm
  - Impossible to collect all data wirelessly at one access point
  - We couldn’t process so much data, even if we could collect it
  - We have to pre-process and prune data

- Massive MIMO changes the game!
  - We can collect *all* of the data, intact
  - Data governed by mathematical physics should be sampled at the Nyquist rate
    - Big Data easier to process than Small Data (computer tomography, SAR, seismic exploration)

- Potential applications of Massive Sensor Telemetry
  - 3D exploration seismic surveys
  - Monitoring of volcanoes
  - Structural health monitoring
MIMO in nonstandard media

Electromagnetic propagation isn’t the only way

- Still more hyperbolic MIMO
  - Acoustic waves
  - Elastic waves

- Parabolic MIMO: heat equation
  - Time scales as the square of distance
  - Nanocommunications?

- Elliptic MIMO: electrical conduction
  - Updated version of Ground Telegraphy
    - Lee Deforest, Arnold Sommerfeld, Richard Courant
Conclusions

- Future apps, such as Augmented Reality will require revolutionary developments at the physical layer.
- Massive MIMO is the only technology that can fully utilize the sub-5 GHz bands.
- Wireless communications will continue to be a vital research area, but future breakthroughs will result from multi-disciplinary collaborations.