MIMO and Beamforming in the 5G Context
SBrT 2017

Created by Will Stitch
Presented by Bruno Duarte
A Brief History of Keysight

1939–1998: Hewlett-Packard years
A company founded on electronic measurement innovation

1999–2013: Agilent Technologies years
Spun off from HP, Agilent became the World’s Premier Measurement Company
In September 2013, it announced the spinoff of its electronic measurement business

2014+: Keysight years
On November 1, Keysight became an independent company focused on the electronic measurement industry
In April 2017, Keysight acquired Ixia to strengthen its end-to-end software-driven testing and deliver insights into network operations

HARDWARE + SOFTWARE + PEOPLE = INSIGHTS
5G Drivers and Expectations

- Massive Growth in Mobile Data Demand
- Massive Growth in No. of Connected Devices
- Exploding Diversity of Wireless Applications
- Dramatic Change in User Expectations of Network

For the User*

- Amazingly fast
- Great service in a crowd
- Best experience follows you
- Super real-time and reliable communications
- Ubiquitous things communicating

*Courtesy of METIS

All founded on a solid business model.

100x Data Rates
1000x Capacity
100x Densification
1ms Latency
Reliability 99.999%
100x Energy Efficiency
The importance of MIMO to deliver the 5G
It brings us more data

Shannon-Hartley Theorem:

**Capacity = # Channels* BW * log2 (1 + S/N)**

Increase data capacity by:

- Increasing #channels → MIMO
  - Exploiting spatial multiplexing to deliver multiple streams of data within the same resource block (time and frequency)
  - Channel state information
- Increasing BW → mmWave frequencies require Beamforming
- Increasing S/N
Types of Multiple Antenna Systems

**SISO**
- No diversity
- Protection against fading

**SIMO**
- Rx diversity
- Rx smart antenna (beamforming)
- Improved SINR

**MISO**
- Tx diversity
- Tx smart antenna (beamforming)
- Improved SINR

**MIMO**
- Tx/Rx diversity
- Tx/Rx smart antenna (beamforming)
- Spatial multiplexing
- Improved SINR
  - Or
- Improved spectral efficiency/data rates
Single User MIMO

Multiple Spatial Channels for Higher Data Rates to 1 User

In this simple example, the receiver is responsible for demultiplexing the two data streams. The receiver does this with knowledge of the channel \( [H] \).

\[
\begin{bmatrix}
  r_0 \\
  r_1
\end{bmatrix} = \begin{bmatrix}
  h_{00} & h_{01} \\
  h_{10} & h_{11}
\end{bmatrix} \begin{bmatrix}
  s_0 \\
  s_1
\end{bmatrix}
\]

\[ R = HS \]

or

\[ \hat{S} = H^{-1}R \]

Note: This is a conceptual implementation only. It doesn’t take noise or non-square matrices into account.
Multi User MIMO

Pre-coding Data for Multiple Users at the Same Time

Note: This is a conceptual implementation only. It doesn't take noise or non-square matrices into account.

In this simple example, the transmitter is responsible for pre-coding (W) the data using knowledge of the channel [H].

\[ \hat{S} = HX = HWS = (HW)S \]

So it seems we want \( HW = I \) (identity matrix) to allow for non-square matrices, and for inversion reasons use pseudo inverse.

\[ W = H^T(HH^T)^{-1} \]
MIMO improves reliability and capacity

Sounds awesome! I want MIMO!

Spatial Diversity
- Same signal sent over different paths
- Improves reliability; addresses low-SNR cell edge problem

Spatial Multiplexing
- Different signals sent over different paths
- Improves communication capacity (and spectral efficiency)

Closed loop feedback
- UEs send codes that instruct base station about channel
- Improves type/quality of base station encoding
MIMO Adoption and Evolution

- LTE MIMO has been in 3GPP standards since Release 8 (early 2009)
- LTE-Advanced (3GPP Rel. 10, 2011) supports 8 streams of DL MIMO
- LTE-A Pro (Release 13; early 2016) has Full Dimension MIMO (FD-MIMO)
- Massive MIMO is a key component of 5G, currently being developed
MIMO visualized

Spatial Multiplexing:
Different data, different paths
Understanding Massive MIMO

**Description:** MU MIMO with Number of BS antennas >> number of UE’s

**Motivation:** Higher reliability, higher throughput, lower TX power, simple single antenna UE design

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**The Graphics**
Overly simplified!

**The Math**
Not completely intuitive!

\[
\tilde{y}_j = \tilde{G}_{jj}^* \tilde{x}_j \\
= \left( \sqrt{\frac{\rho}{\mu}} \sum_{\ell=1}^{L} G_{j\ell}^* \tilde{x}_j + V_j \right)^* \left( \sqrt{\frac{\rho}{\mu}} \sum_{\ell=1}^{L} G_{j\ell} \tilde{a}_\ell + \tilde{w}_j \right), \\
\frac{1}{M} \sqrt{\frac{\rho}{\mu}} y_{kj} \rightarrow \beta_{kj} a_k + \sum_{\ell \neq j} \beta_{j\ell} a_\ell.
\]

\[
\tilde{x}_\ell = \sqrt{\frac{\rho}{\mu}} \sum_{j=1}^{L} G_{j\ell}^* \tilde{G}_{jj} \tilde{a}_j + \tilde{w}_\ell, \\
= \sqrt{\frac{\rho}{\mu}} \sum_{j=1}^{L} G_{j\ell}^* \left[ \sqrt{\frac{\rho}{\mu}} \sum_{\ell=1}^{L} G_{j\ell} + V_j \right]^* \tilde{a}_j + \tilde{w}_\ell
\]

Equations from “Noncooperative Cellular Wireless with Unlimited Numbers of Base Station Antennas”, by Thomas L. Marzetta

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Massive MIMO is different from other MIMO

Base stations transmit to all UEs in each resource block

Massive MIMO has a digital architecture:

- One TRX per antenna array element
- Many more antenna elements than UEs
- Supports many streams (# elements)
- Supports many users (# UEs)
- Flexible transmission modes
- TDD networks only
- Requires UEs to send pilot tones and the base station to calculate real-time Channel State Information for each UE
2D Massive MIMO, Free-space Path Loss Only

Reference Configuration with 4 Users: Total TX Power 0 dB Relative

Target UE (solid)
Victim UEs (hollow)

50 omni elements
Linear Array
½ λ Spacing

UE2

UE3

UE4
Massive MIMO Free Space

200 Ant, $\frac{1}{2} \lambda$, Total Power Relative to Reference: -9.5 dB
Observations of Massive MIMO
Number of Base Station Antennas

- Initial Analysis of 1, 2, 4, 8 and 16 base station antennas showed that more antennas always improved performance.

- In the limit of an infinite number of base stations, more antennas continue to improve performance.

- Studies trying to quantify the optimal number of base station antennas suggest a range of a “several hundred” antennas may be the optimal number.

Source:
- HOW MUCH TRAINING IS REQUIRED FOR MULTIUSER MIMO? Thomas L. Marzetta
- Noncooperative Cellular Wireless with Unlimited Numbers of Base Station Antennas Thomas L. Marzetta
- Massive MIMO in the UL/DL of Cellular Networks: How Many Antennas Do We Need? Jakob Hoydis, Stephan ten Brink, Mounaue Debbah
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“Beamforming”
What Does This Mean?

Beamforming uses multiple antennas to control the direction of a wave-front by appropriately weighting the magnitude and phase of individual antenna signals in an array of multiple antennas.

FD-MIMO Has 10 Tx Modes
Only 2 of these perform beamforming and these reduce the number of streams to less than 2.
# MIMO and Beamforming Summarized

<table>
<thead>
<tr>
<th></th>
<th>4G LTE and LTE-A MIMO</th>
<th>4.5G LTE-A Pro FD-MIMO</th>
<th>5G &lt;6GHz Massive MIMO</th>
<th>Verizon Pre-5G Specification</th>
<th>Analog mmWave Beamforming</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frequencies</strong></td>
<td>~2.5GHz</td>
<td>~2.5GHz</td>
<td>&lt;6GHz</td>
<td>28GHz</td>
<td>20+GHz</td>
</tr>
<tr>
<td><strong>Aggregated BW</strong></td>
<td>100MHz</td>
<td>100MHz</td>
<td>100MHz</td>
<td>800MHz</td>
<td>1-3+GHz</td>
</tr>
<tr>
<td><strong>Is it MIMO?</strong></td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td><strong>Uses Beamforming</strong></td>
<td>Yes, one or two streams</td>
<td>Yes</td>
<td>Not really</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Is it Standardized?</strong></td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td><strong>Is it Deployed</strong></td>
<td>Yes</td>
<td>Yes (just starting)</td>
<td>No (trials underway)</td>
<td>No (trials underway)</td>
<td>Yes (but not for cellular)</td>
</tr>
<tr>
<td><strong>How Many Antennas?</strong></td>
<td>Up to 4 or 8</td>
<td>64</td>
<td>Probably 128 (&gt; &gt; # of UEs/cell)</td>
<td>256 or more</td>
<td></td>
</tr>
<tr>
<td><strong>How Many Streams?</strong></td>
<td>Up to 2, 4, or 8</td>
<td>10</td>
<td># antennas</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td><strong>Channel State Information Process</strong></td>
<td>DL Estimated (Calculated by the UE)</td>
<td>DL Estimated (Calculated by the UE)</td>
<td>UL Measured (Calculated by the base station)</td>
<td>TBD</td>
<td></td>
</tr>
<tr>
<td><strong>Compatible With LTE/LTE-A</strong></td>
<td>Yes</td>
<td>Yes</td>
<td>Not yet</td>
<td>TBD</td>
<td></td>
</tr>
</tbody>
</table>
Keysight MIMO and Beamforming Solutions
For Components, Circuits, Devices, Systems

- Simulate & Visualize: Electronic Design Automation Software
- Calibrate & Capture: World’s Fastest and Most Accurate Measurement Science
- Emulate in Real Time: Emulation, Visualization, Performance Metrics
- Scale & Adapt: Software-Enabled Reference Solutions and Services

Communications modelling
Dig.IQ generation & analysis
RF signal generation & analysis
Test case manager
Test automation and analysis
MIMO Explorer Reference Solution

Accelerate MIMO designs and gain deeper insight
FD-MIMO Measurement
8 LTE carriers; simultaneous demod and measurement
Beamforming Test System
Thank You !!!
Questions and Answers

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Observations of Massive MIMO

TDD vs. FDD

- In TDD, the training time is proportional to the number of user terminals.

- In FDD, the training time is proportional to the number of users plus the number of base station antennas.
  - Both downlink and uplink channels need to be trained.
  - Training on the downlink channel scales with the number of base station antennas.

- The use of massive MIMO in FDD systems remains as one of the key research areas currently under investigation.