Ten Things You Should Know About MIMO

4G World 2009

presented by:

David L. Barner
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The Full Agenda

Intro

System Operation

1: Cellular MIMO uses downlink and uplink differently
2: MIMO needs at least 2 transmitters and 2 receivers

MIMO signal transmission and recovery

3: MIMO signal recovery is a 2 step process
4: Transmit & receive phase differences don’t affect open loop MIMO
5: BS and MS antenna configuration has a big impact on path correlation
6: MIMO needs a better SNR than SISO
7: Precoding and eigenbeamforming couple the signals to suit the channel

Single and Multiple input measurements

8: Cross channel measurements can be made with a single input analyzer
9: Condition number measures the short term channel performance
10: Distortion in one component can degrade all the data streams
Intro

MIMO – the art of getting from THIS to THIS

The "channel"

Increased capacity from a given spectrum occupancy
Intro

Multiple Antennas can be used in a variety of ways:

• Diversity Techniques
  – Transmit Diversity
  – Receive Diversity

• MIMO Techniques
  – DL (SU-MIMO)
  – UL (MU-MIMO)

• Beamforming Techniques
Intro

Multiple Antennas can be used in a variety of ways:

**Diversity** techniques protect against fading, and improve coverage

- Same data on antennas
- Picks the best (strongest) multipath signals
- Combines multipath for best overall result
- Improves S/N
Intro

Multiple Antennas can be used in a variety of ways:

**MIMO** techniques increases the spectral efficiency of the transmission, increasing capacity by using Spatial Multiplexing and Precoding

- MIMO Spatial Multiplexing is the simultaneous use of the same frequencies to transmit independent data streams
- Precoding (mixing) of the two streams is used to optimize the transmission into the channel so that the receiver has the best chance of recovering the original data streams.

Adding diversity to MIMO will improve performance
Intro

Multiple Antennas can be used in a variety of ways:

**Beamforming** techniques reduces interference when there are many users, and may improve the S/N in some cases

- Beamforming is the opposite of Spatial Multiplexing / MIMO
  - It relies on the channel being correlated rather than uncorrelated
- The goal is to combine the energy from each transmitter and direct it towards the receiver to improve the received SNR but not the data rate.
- Beamforming becomes most useful with larger numbers of transmit antennas
## Terminology I

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial Multiplexing</td>
<td>The mechanism used to distribute user data for simultaneous, same frequency transmission</td>
</tr>
<tr>
<td>Channel</td>
<td>The entire route, from transmission to reception, including the antennas</td>
</tr>
<tr>
<td>(Channel) Rank</td>
<td>The number of independent signal routes usable in a multi-antenna radio system. An LTE UE sends a Rank Index value to the eNB to indicate what it thinks should be used</td>
</tr>
<tr>
<td>Correlation</td>
<td>A (statistical) measure of the relationship between different signals transmitted or received</td>
</tr>
<tr>
<td>Condition Number</td>
<td>A short term measure of the increase in SNR needed to recover a MIMO signal</td>
</tr>
</tbody>
</table>
## Terminology II

<table>
<thead>
<tr>
<th>Layer</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream</td>
<td>WLAN / WiMAX term to describe items of spatially multiplexed data</td>
</tr>
<tr>
<td>Closed Loop MIMO</td>
<td>A mechanism used to continuously adapt the transmitted signal to suit the channel characteristics</td>
</tr>
<tr>
<td>Precoding</td>
<td>The process of cross coupling the signals before transmission (used in closed loop operation) to equalise the performance of the recovered data</td>
</tr>
<tr>
<td>Codeword</td>
<td>The LTE equivalent of a (user) data stream</td>
</tr>
<tr>
<td>Codebook</td>
<td>The look-up table of cross coupling factors used for precoding, and shared by the mobile and base-station</td>
</tr>
</tbody>
</table>
10 Things about MIMO: The Simplified Agenda

System Operation

MIMO signal transmission and recovery

Single and Multiple input measurements
1: MIMO is Used Differently in the Downlink and Uplink of a Cellular System

- In the Downlink, it’s like WLAN, the whole MIMO transmission is given to a Single User (SU)
- The scheduler in the LTE Base Station multiplexes user data traffic into codewords
- If there are more transmitters available than codewords, layer mapping is used (layer in LTE = stream in WiMAX)
MIMO in the Downlink – Coupling in the Channel

- The channel starts after precoding
- Unwanted coupling in the radio will introduce errors in precoding
- The antennas are a critical part of the channel
MIMO in the Downlink - Reception

A single mobile recovers the MIMO transmission via 2 receivers

1 Base Station (eNB)

User Data
Multiplex into Codewords
Map into Layers (Streams)
Precoding

The "Channel"

1 Mobile Station (UE)

User Data
Cross channel De-Mapping
Received Codeword (Stream)
Demultiplex
MIMO in the Downlink – Closed Loop

1 Base Station (eNB)

User Data

Precoding

Scheduler

The "Channel"

• “Precoding” is applied for closed loop operation

• The mobile measures the channel to send reports back to the BS

• The BS decides how to modify the transmission

CQI, RI, PMI reports
2: MIMO Operation Requires at Least Two Transmitters & Two Receivers

- In cellular MIMO, two mobiles are used together in the Uplink to create the MIMO signal
- Known as “Collaborative” MIMO in WiMAX. “Multi-User MIMO” in LTE
- Increased capacity benefit achieved w/ lower cost and less battery drain per phone (i.e., 1 TX/phone vs. 2 TX/phone)

The receivers (in a live system) have to be in the same device - because both signals are needed to calculate the amount of cross coupling. Transmitters don’t! Hence MU-MIMO possible.
….at Least Two Transmitters & Two Receivers (e.g., How we measure and verify MIMO precoding)

Infinium Scope

- x4 BB or RF inputs
- Time, Freq and Phase Coherent

Dual MXAs

- x2 RF inputs
- Time and Freq Coherent

Freq Ref.

Trig.
10 Things about MIMO The Agenda

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3: MIMO Signal Recovery is a Two Step Process

Step 1: Recover the channel coefficients

Need a robust signal format that uniquely identify each transmitter

Step 2: Separate and demodulate the signals

(Real only) examples values are for a single OFDM subcarrier at one instant in time

Use High school simultaneous equations to express $T_0$, $T_1$ in terms of $R_0$, $R_1$
MIMO Signal Recovery

Recovering the channel coefficients via Reference Signals (RS) or Pilots!

In WiMAX and LTE, specific subcarriers are allocated as pilots.

Their location is changed from symbol to symbol.

Their power is boosted to ensure errors from recovering the training signal do not dominate the demodulator performance.
MIMO Signal Recovery – Spectrum View

The traces in this LTE signal show how the Reference Signals (pilots) are on different frequencies at any instant in time.

Unlike 802.16 OFDMA, the LTE RS is not present on all symbols.
# Channel Training Signals Vary with Technology

## Summary Table

<table>
<thead>
<tr>
<th>Technology</th>
<th>LTE</th>
<th>WiMAX</th>
<th>Wireless LAN</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reference signals</strong>&lt;br&gt;(pilots) use different subcarriers for each transmitter</td>
<td>BPSK Pilot subcarriers use different frequencies. Their positions vary symbol by symbol within a subframe, but are constant from frame to frame.&lt;br&gt;Subcarrier coverage builds over several symbols, allowing interpolation&lt;br&gt;Details depend on the zone type (e.g. PUSC, AMC)</td>
<td>A preamble is used for training. The same subcarriers are used for all transmitters. Signals are separated by a CDMA code&lt;br&gt;4 orthogonal QPSK pilots are used (6 for 40MHz), sharing the same subcarriers. They are never transmitted without data</td>
<td></td>
</tr>
<tr>
<td>The QPSK Reference signals are transmitted every 3rd or 4th symbol, mixed with data</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>HSPA+</strong> uses code channels on the Common Pilot Channel, CPICH, with unique symbol bit patterns having different locations in the OVSF code domain</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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10 Things About MIMO
8th October 2008
Open Loop MIMO is a direct mapping technique

- In Open Loop MIMO, the communications channel does not utilize explicit information regarding the propagation channel.
- Common Open Loop MIMO techniques include Space Time Block Coding (STBC), Spatial Multiplexing (SM-MIMO) and Collaborative Uplink MIMO.
- In WiMAX systems MIMO Matrix A refers to the STBC technique and MIMO Matrix B refers to the SM-MIMO technique.
- Beamforming is an example of Closed Loop MIMO via Channel feedback to the TX.
Phase Differences

*Phase only matters if you couple the same signals*
Consider the case of an individual OFDM subcarrier (pilot)

\[ \begin{align*}
\text{Phase Differences} \\
\text{Phase only matters if you couple the same signals} \\
\text{Consider the case of an individual OFDM subcarrier (pilot)}
\end{align*} \]

Summing different (e.g., pilots) signals the first time does not affect the individual components
Phase Differences

but summing common signals

leads to vector addition

As may the case in Closed Loop MIMO (i.e., Beamforming)
Application to Test Limits of Receiver Performance

Combine the coded signal with controlled impairments using the signal generators

- Differences in amplitude
- Timing Offset
- Frequency offsets
- Phase Noise

Remember: Phase and Small Frequency Differences and Time Offsets are removed by the Tracking Processes in the Demodulator
This configuration has the flexibility to expand to 3 or 4 generators.

Using separate generators, there is no constraint on RF frequency range.

Timing synchronization is dealt with by instrument firmware.
5: BS and MS Antenna Configuration Has a Big Impact on the Channel Path Correlation

Path correlation defines the coupling relationship between signals received at the antennas.

It is important because it affects how easy or difficult it is to recover the individual codewords (data streams).

Each multipath item can have its own correlation factors.
Example: The angle of departure from the BS antennas is typically narrower than the angle of arrival at the MS.

This gives the MS receivers the possibility of recovering different signals even if the antennas are closely spaced.
BS and MS Antenna Configuration and Correlation

The antenna configuration and correlation “type” determine the correlation matrices.

In this example, there are 6 paths, each with complex cross coupling coefficients.
Impact of Antenna Configuration on Correlation

High Correlation

Low Correlation
N5106A PXB MIMO Receiver Tester

The flexibility of the PXB is used to verify receiver performance throughout the design cycle, at baseband or RF.

Signal Inputs

RF

Signal Creation Tools

PXB

Signal Outputs

Analog I/Q
- Direct from PXB
- Connect to any DUT or RF vector signal generator with analog I/Q inputs

Digital I/Q

N5102A

RF

ESG or MXG

MXA
Channel Matrix Condition Number

Why it is important:

a) A way to check your MIMO system is functioning correctly

b) A short term indication of the CNR you need to recover a MIMO signal

c) If the condition number is larger than the CNR of the signal, it is likely that MIMO separation of the multiple data streams will not work correctly.

How you calculate it: Find the *singular values* of the channel matrix, and take the ratio of the highest / lowest

Simple examples:

A good channel

A poor channel
6: MIMO Needs Better Carrier/Noise (CNR) than SISO

This graph compares the difference of additional CNR needed for MIMO vs. SISO as a function of Condition Number for equivalent EVM performance.
MIMO Needs Better CNR than SISO

Example: MIMO Signal w/Condition Number = 10 requires ~7dB more (better) CNR than SISO for same EVM.

<table>
<thead>
<tr>
<th>Good</th>
<th>Condition Number (dB)</th>
<th>Poor</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>5</td>
<td>25</td>
</tr>
<tr>
<td>10</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>20</td>
<td>25</td>
<td></td>
</tr>
</tbody>
</table>

Example:
- MIMO Signal w/Condition Number = 10 requires ~7dB more (better) CNR than SISO for same EVM

CNR for 32% EVM:
- MIMO SM: ~7dB
- SISO: 10 dB
Example of MIMO versus SISO performance

Introduce a delay in a static channel to make the channel condition number vary with frequency

With a constant CNR, EVM gets worse as condition number increases

Better not to use these subcarriers for MIMO
7: Precoding and Eigenbeamforming Couple the Transmit Signals to Suit the Channel

Precoding can be very simple (LTE **Codebook 0** is **Direct Mapped**)

Some WLAN devices always apply Spatial Expansion

(Eigen) beamforming is the general case, where the channel coefficients are mapped with higher resolution
The Reality of Precoding in 3GPP LTE

6.3.4.2.3 Codebook for precoding

For transmission on two antenna ports, \( p \in \{0,1\} \), the precoding matrix \( W(p) \) for zero, small, and large-delay CDD shall be selected from Table 6.3.4.2.3-1 or a subset thereof.

Table 6.3.4.2.3-1: Codebook for transmission on antenna ports \( \{0,1\} \).

<table>
<thead>
<tr>
<th>Codebook index</th>
<th>Number of layers 1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>[1]</td>
<td>[1 0]</td>
</tr>
<tr>
<td>1</td>
<td>[0]</td>
<td>[1 1]</td>
</tr>
<tr>
<td>2</td>
<td>[1]</td>
<td>[1 -1]</td>
</tr>
<tr>
<td>3</td>
<td>[1]</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>[1]</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>[1]</td>
<td>-</td>
</tr>
</tbody>
</table>

Ripped from 3GPP TS 36.211 V8.1.0 (2007-11)
10 Things The Agenda

System Operation

MIMO signal transmission and recovery

Single and Multiple input measurements
8: Cross Channel Measurements Can Be Made With a Single Input Analyzer

The Reference signals (pilots) uniquely identify each transmitter.

We use this to allow measurements on each separately.

In LTE, the RS are not precoded. These measurements continue to work even when the signal is not direct mapped.
Cross Channel Timing & Phase Measurement using a Power Combiner & Single Input

Using a power combiner removes ANY uncertainty due to timing jitter or calibration.

The demodulation process recovers the time and phase relationship between the transmitters at the power combiner input.

Cable calibration may still be required.
## How Many Inputs Do I Need?

<table>
<thead>
<tr>
<th>Measurement objective</th>
<th>Number of measurement inputs required</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>SISO &amp; MISO errors due to phase noise, timing errors and amplitude clipping</td>
<td>•</td>
</tr>
<tr>
<td>Spectrum Mask, Harmonics and Spurious</td>
<td>•</td>
</tr>
<tr>
<td>RF Phase and Baseband Timing Alignment, using RS-based measurements</td>
<td>Using a power combiner.</td>
</tr>
<tr>
<td>Cross Channel Isolation. Using RS-based measurement</td>
<td>•</td>
</tr>
<tr>
<td>Interference, Grounding, Transient settling</td>
<td>•</td>
</tr>
<tr>
<td>Transmit Diversity Space Time Coding (Control channel and PDSCH)</td>
<td>•</td>
</tr>
<tr>
<td>MIMO Spatial Multiplexing (with unwanted coupling) and coding verification</td>
<td>Individual (Direct Mapped) layers</td>
</tr>
</tbody>
</table>
9: Condition Number Measures the Short Term MIMO Channel Performance

\[ C = \sum_{i=1}^{N} B_i \cdot \log_2 \left( 1 + \frac{\rho_i}{N} \sigma_i^2 (H) \right) \]

where

- \( N \) = the number of independent transmitter-receiver pairs
- \( \sigma_i^2 (H) \) = the singular values of the radio channel matrix, \( H \)

**Condition Number = Ratio of Singular Values**

How you calculate it:

Channel, \( H \):

\[
\begin{bmatrix}
1.15 & 0.39 \\
0.26 & -1.03
\end{bmatrix}
\]

Transpose Matrix \( H^T \):

\[
\begin{bmatrix}
1.15 & 0.26 \\
0.39 & -1.03
\end{bmatrix}
\]

Singular Values:

\[
\begin{bmatrix}
0.957 \\
0.815
\end{bmatrix}
\]

Condition Number:

\[ \frac{0.957}{0.815} = 1.17 \]
Ped. B Channel Condition number measurements

Three channel samples at different times during the fading profile
Lower overall condition number results in a tighter constellation
10: Distortion in One Component Can Degrade all the Data Streams

If the data streams are precoded, each signal passes through both transmitters (receiver) chains.

- One channel distorted
- Both streams affected
- A diversity signal hides the error
One Component can Degrade all the Streams

We can use *Ref Input Channel* selection to separate these problems
Summary

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Single and Multiple input measurements

8: Cross channel measurements can be made with a single input analyzer
9: Condition number measures the short term channel performance
10: Distortion in one component can degrade all the data streams
The Poster – Summarizes today’s presentation
Additional Resources

www.agilent.com/find/mimo

MIMO WLAN PHY layer Operation and Measurement AN1509

Video: “Single-channel measurements for WiMAX matrix A and B”

“WiMAX Wave 2 Testing - MIMO & STC” Agilent webcast 17 Jan 2008
http://www.techonline.com/learning/livewebinar/204203534

Thank You
“Excuse me, is this the Society for Asking Stupid Questions?”

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