Antenna Technology for MIMO Capable Wireless Systems

a different design paradigm

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Acknowledgements (incomplete): Mark Schamberger, Umesh Navsariwala, prof. Jin-Fa Lee, Tim Thomas, Bill Turney, …
PURPOSE & OUTLINE

PURPOSE

- To increase awareness of the need for Cross-Layer and Multidisciplinary design
- To outline a framework for Cross-Layer Design

OUTLINE

INFORMATION & CAPACITY
SMART ANTENNA SYSTEMS
CROSS-LAYER DESIGN (Capacity as “the” Antenna Design Performance Metric)
  MIMO Antenna Design Problem, Solution and Examples
CHALLENGES AND CONCLUSIONS
Outgoing clusters of rays with their Angles of Departure

Incoming clusters of rays with their Angles of Arrival

MIMO offers additional degrees of freedom → better opportunities to take advantage of multipath

WE HAVE TOOLS AND EXPERTISE TO ADDRESS THE PROBLEM FROM BASEBAND TO BASEBAND OFFERING UNPARALLELED CAPABILITY TO DESIGN OPTIMUM PERFORMANCE PRODUCTS IN SMALLER SIZE AND AT A LOWER COST.
Shannon (paraphrased & certainly not doing justice to the master):

How many different numbers can you reliably send across? Ans. = M

How many bits are needed to represent M? Ans. = m

\[ M = 2^m = \frac{(N+S)}{N} \Rightarrow m = \log_2[1+\text{SNR}] \]

This determines the number of bits you can reliably transmit.

Capacity = m x Bandwidth = BW x \( \log_2[1+\text{SNR}] \)

So, the Maximum Achievable Capacity, per Hz, is:

\[ C = \log_2[1+\text{SNR}] \]

\[ P_{Rx} = \frac{|E_o|^2}{2Z_o} \frac{4Z_L R_{in}}{Z_L + Z_{in}} \frac{\lambda^2}{4\pi} G_R(\pi - \theta, \pi + \phi) \]

**LOS special case**

\[ C = B \log_2\left(1 + \frac{P_r}{KTB}\right) \]

At high SNR’s, doubling the power increases the link efficiency by 1 bps/Hz

\[
C_b = \log_2 \left( 1 + \frac{P_b}{N} \right) = \log_2 \left( 1 + \frac{P_b}{P_a} \frac{P_a}{N} \right) \approx \log_2 \left( \frac{P_b}{P_a} \right) + \log_2 \left( \frac{P_a}{N} \right) \approx \log_2 \left( \frac{P_b}{P_a} \right) + \log_2 \left( 1 + \frac{P_a}{N} \right)
\]

\[
\Rightarrow C_b = C_a + \log_2 \left( \frac{P_b}{P_a} \right)
\]
Keep all constant except DUT, calibrate with standard gain antennas, determine G.

\[ P_R = P_T \cdot G_T(\theta, \phi) \cdot G_R(\pi - \theta, \pi + \phi) \left( \frac{\lambda}{4\pi r} \right)^2 \left| \frac{\alpha_T^\dagger \cdot \alpha_R}{Z_g + Z_{T_{in}}} \right|^2 \frac{4Z_g R_{T_{in}}}{Z_L + Z_{R_{in}}} \frac{4Z_L R_{R_{in}}}{Z_L + Z_{R_{in}}} \]
ELECTRICALLY LARGE PROBLEMS (DOMAIN DECOMPOSITION with OSU)
Run Time: **100 Sec** on P4 2.8GHz CPU, Rx Sensitivity: -100dBm, Angular Resolution: 1deg., No of Rx: 6100
Ray Tracing vs. Measurements

- Two strongest paths are from ceiling reflections
- Simulation agrees well with measured data

Elevation = 12 degrees (max power)

Delay and azimuth range predicted by ray tracing
Predicted elevation range: 2-13 degs
Angular spread and delay profile of dominant cluster is relatively insensitive to elevation.

Data shown is for the receiver and transmitter both vertically polarized.

Cross polarized data and data with receiver and transmitter horizontally polarized are very similar.

5GHz Data is very similar.
MIMO: PUTTING IT ALL TOGETHER

- Antenna-port to antenna-port EM analysis
  - Full Wave EM for the antennas, user, etc.
  - Plane wave decomposition for the environment (Ray Tracing, 3D-TGn, etc.)

- Directional coupler system used in the calibration scheme
- Over-the-air calibration schemes exist (no couplers required)

- M+N+2 “reciprocal” microwave network whose UL transfer function is used to “estimate” the DL one.

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Baseband to baseband calibration measurements

The rf "channel" representing the environment from calibration transceiver baseband to antenna transceiver baseband is NON-reciprocal!
UL channel sounding measurements (orange)
DL regular transmissions (green)

The rf channel representing the environment from ant reference plane to antenna reference plane is reciprocal. i.e. rays travel back and forth on the same paths.

M+N+2 “reciprocal” microwave network whose UL transfer function is used to “estimate” the DL one.
  • directional coupler system used in the calibration scheme
  • Over-the-air calibration schemes exist (no couplers required)
SMART ANTENNA SYSTEMS: PUTTING IT ALL TOGETHER

INPUTS

- BS Array Geometry and design parameters
- Environment description
- SS Array Geometry and design parameters

measurements

Ray Tracing
3D extension to TGn-like prop models
3D EM solvers

OUTPUTS

- Z_kj
- \sum \overrightarrow{g_i} \cdot RT(\theta_R, \phi_R; \theta_T, \phi_T) \cdot \overrightarrow{g_j}
- Composite channel and eigenspectrum
- Max achievable capacity
- SNR required for certain capacity

MIMO INTERFACE

\begin{align*}
H_{ij} &= \frac{Z_{Li}}{\sum \overrightarrow{g_i} \cdot RT(\theta_R, \phi_R; \theta_T, \phi_T) \cdot \overrightarrow{g_j}}
\end{align*}
MIMOv vs MoM (D=60 cm Offset=0cm)

H derivation: MIMOv
3x2 MIMO; LOS prop model

H derivation: S-parameters (MoM)
5-port MEA system

Channel mag relative error

Channel phase error

H_{22} = H_{11}
H_{21} = H_{12}
H_{31} = H_{32}
MIMObit vs MoM (D=90 cm Offset=0cm)

H derivation: MIMObit
3x2 MIMO; LOS prop model

H derivation: S-parameters (MoM)
5-port MEA system

Channel mag relative error

\( H_{22} = H_{11} \)
\( H_{21} = H_{12} \)
\( H_{31} = H_{32} \)

Channel phase error

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MIMO vs MoM (D=120 cm Offset=0cm)

H derivation: MIMO
3x2 MIMO; LOS prop model

H derivation: S-parameters (MoM)
5-port MEA system

Channel mag relative error

\[
\begin{align*}
H_{22} &= H_{11} \\
H_{21} &= H_{12} \\
H_{31} &= H_{32}
\end{align*}
\]
THE PROMISE OF SMART ANTENNA SYSTEMS
CAPACITY

Shannon (paraphrased & certainly not doing justice to the master):
How many different numbers can you reliably send across? Ans. = M
How many bits are needed to represent M? Ans. = m

\[ M = 2^m = \frac{(N+S)}{N} \Rightarrow m = \log_2 \left[ 1 + SNR \right] \]

This determines the number of bits you can reliably transmit.

Capacity = \( m \times \) Bandwidth = \( BW \times \log_2 \left[ 1 + SNR \right] \)

So, the Maximum Achievable Capacity, per Hz, is:

\[ C = \log_2 \left[ 1 + SNR \right] \]

Channel power transfer function

LOS special case

\[ C = B \log_2 \left( 1 + \frac{P_R}{KTB} \right) \quad ; \quad P_{Rx} = P_{Tx,avail} \quad G_T(\theta, \phi) \quad G_R(\pi - \theta, \pi + \phi) \left( \frac{\lambda}{4\pi r} \right)^2 |\overline{a}_T^\dagger \cdot \overline{a}_R|^2 \frac{4Z_s R_T^m}{\left[ Z_g + Z_{T_{in}} \right]^2} \frac{4Z_L R_{R_{in}}}{\left[ Z_L + Z_{R_{in}} \right]^2} \]

A Multi Element Antenna (MEA) extension (Open Loop) is:

\[ C = \log_2 \left\{ \det \left( \overline{I} + \left( \frac{P_{Tx}/n_{Tx}}{N_{o,Rx}} \right) \overline{H} \cdot \overline{H}^\dagger \right) \right\} \]

\[ ; \text{ where } \overline{H} = \text{Channel Matrix} \]

Power at the Rx:

\[ \frac{1}{2} \text{Re} \left\{ \overline{V}^* \cdot \overline{I}^* \right\} = \frac{1}{2} \text{Re} \left\{ \overline{V}^H \cdot \overline{Y}_L \cdot \overline{V} \right\} \]

This simplifies iff all the impedances are the same!
WHY MIMO?

SISO

Open Loop MIMO

Identical antennas, Uniform Linear Array, just Array Factor (no coupling) ==> 

\[ G_{Tx} = n_{Tx} G_o \quad ; \quad G_{Rx} = n_{Rx} G_o = n_{Tx} G_o \]

\[ SNR_{Rx} = \frac{P_{Rx}}{KTB} = \frac{P_{Tx} n_{Tx} G_o n_{Tx} G_o PL}{KTB} \]

\[ = n_{Tx}^2 SNR_o \quad ; \quad SNR_o = \frac{P_{Tx} G_o^2 PL}{KTB} \]

\[ C_{SISO} = \log_2 \left( 1 + n_{Tx}^2 SNR_o \right) \]

\[ H = G_o \sqrt{PL} \tilde{I} \]

\[ P_{Tx} = \frac{P_{Tx}}{n_{Tx}} ; \forall i = 1, 2, \ldots n_{Tx} \]

\[ \left\{ SNR_{Tx} \right\}_{perport} = \frac{P_{Tx}/n_{Tx}}{KTB} \]

\[ C_{MIMO} = \log_2 \left\{ \det \left( \tilde{I} + \left\{ SNR_{Tx} \right\} H \cdot H^\dagger \right) \right\} \]

\[ = \log_2 \left\{ \det \left( \tilde{I} + \frac{P_{Tx} G_o^2 PL}{n_{Tx} KTB} \tilde{I} \right) \right\} \]

\[ = \log_2 \left\{ \prod_{i=1}^{n_{Tx}} \left( 1 + \frac{1}{n_{Tx} SNR_o} \right) \right\} \]

\[ C_{MIMO} = n_{Tx} \log_2 \left( 1 + \frac{1}{n_{Tx} SNR_o} \right) \]
Different views of the $C_{SISO}$ and $C_{MIMO}$ for 0 to 36 antennas and -10 to 20 dB $SNR_o$.

**NOTE:** This plot assumes Open Loop MIMO. When the SNR is low, other MIMO algorithms are used to increase Capacity. E.g. MIMO can inherently duplicate the “corporate feed” of our example. All it needs is to know the “channel” via the “channel estimation” process (i.e. just a bit of overhead and you can “emulate” the corporate feed.
CTIA 2x2 MIMO TEST PLAN (DL LTE)

Outdoor Ranges: ground reflection, interference

Anechoic Chambers: difficult to kill reflections for all scenarios/frequencies, etc
CAPACITY per Hz (ISOTROPIC VS. DIPOLE example)

WORSE

Isotropic & Dipole Antennas on IID Channel (ray directions uniform over the sphere)

Elevation angles have 90º mean and different AS’s

BETTER

Dipole Antennas on a biased IID Channel (ray directions uniform in azimuth, Laplacian in elevation)
MIMO ANTENNA SYSTEMS USED
IEEE 802.11n TGn B PROPAGATION MODEL

Incoming clusters of rays with their AoA's

Channel Specific Fixed Angle Between Clusters

SCM multipath environment

Outgoing clusters of rays with their AoD's

\( \Phi_{\text{cluster}} \): Uniform, Fixed, or Laplacian Distribution

Isotropic Transmitter

Antennas Under Test

<table>
<thead>
<tr>
<th>( \alpha )</th>
<th>Tap-index</th>
<th>1( \alpha )</th>
<th>2( \alpha )</th>
<th>3( \alpha )</th>
<th>4( \alpha )</th>
<th>5( \alpha )</th>
<th>6( \alpha )</th>
<th>7( \alpha )</th>
<th>8( \alpha )</th>
<th>9( \alpha )</th>
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<tbody>
<tr>
<td>Cluster 1( \alpha )</td>
<td>Power( [\text{dB}] )</td>
<td>( 0 \alpha )</td>
<td>-5.4( \alpha )</td>
<td>-10.8( \alpha )</td>
<td>-16.2( \alpha )</td>
<td>-21.7( \alpha )</td>
<td>( \square )</td>
<td>( \square )</td>
<td>( \square )</td>
<td>( \square )</td>
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<tr>
<td>AoA( \alpha )</td>
<td>AoA( [\degree] )</td>
<td>4.3( \alpha )</td>
<td>4.3( \alpha )</td>
<td>4.3( \alpha )</td>
<td>4.3( \alpha )</td>
<td>4.3( \alpha )</td>
<td>( \square )</td>
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</tr>
<tr>
<td>AS( \phi ) (receiver) ( \alpha )</td>
<td>AS( \phi ) [\degree]</td>
<td>14.4( \alpha )</td>
<td>14.4( \alpha )</td>
<td>14.4( \alpha )</td>
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<td>14.4( \alpha )</td>
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</tr>
<tr>
<td>AoD( \alpha )</td>
<td>AoD( [\degree] )</td>
<td>225.1( \alpha )</td>
<td>225.1( \alpha )</td>
<td>225.1( \alpha )</td>
<td>225.1( \alpha )</td>
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</tr>
<tr>
<td>AS( \phi ) (transmitter) ( \alpha )</td>
<td>AS( \phi ) [\degree]</td>
<td>14.4( \alpha )</td>
<td>14.4( \alpha )</td>
<td>14.4( \alpha )</td>
<td>14.4( \alpha )</td>
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</tr>
<tr>
<td>Cluster 2( \alpha )</td>
<td>Power( [\text{dB}] )</td>
<td>( \square )</td>
<td>( \square )</td>
<td>-3.2( \alpha )</td>
<td>-6.3( \alpha )</td>
<td>-9.4( \alpha )</td>
<td>-12.5( \alpha )</td>
<td>-15.6( \alpha )</td>
<td>-18.7( \alpha )</td>
<td>-21.8( \alpha )</td>
</tr>
<tr>
<td>AoA( \alpha )</td>
<td>AoA( [\degree] )</td>
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<td>( \square )</td>
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3V DIPOLES ANALYSIS (traditional)
CDF vs. Tx ANTENNA SYSTEM (current analysis)

Analyses and plots obtained via the use of MIMObit 1.0
MIMO ANTENNA SYSTEMS: Mesh Networks Access Point

FROM THIS

TO THIS

Traditional Design

Integrated Design

~1400 mm

250 mm

500 mm

125 mm

Nick Buris
Measurements consistently show ≈2x improvement in system throughput compared to external dipole antennas.
MIMO ANTENNA SYSTEMS: Mesh Networks Access Point

Throughput results

<table>
<thead>
<tr>
<th>Antenna Type</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipoles (2V,1H)</td>
<td>$448</td>
</tr>
<tr>
<td>Dipoles (3V)</td>
<td>$378</td>
</tr>
<tr>
<td>Patch Arrays (2V,1H)</td>
<td>$222</td>
</tr>
</tbody>
</table>

Test conditions:
- AP: Symbol 7131 with AUT
- SU: Netgear WN511B PC Card

Indoor to Outdoor Environment

Test conditions:
- AP: Linksys WRT300N with AUT
- SU: Linksys WMP300N with AUT

Outdoor to Outdoor Environment

Throughput (Mbps)

1. Field tests by Pertti Alapuranen of the Mesh Networks Engineering Team
Different antenna and channel configurations were investigated

Antenna configurations

- Straight Slot Antennas $0.00$
- Slanted Slot Antennas $0.00$
- Two Back-to-Back Patch Antennas $5.00$
- Two Back-to-Back 14dBi Gain Patch Arrays $15.00$
Q1: What is the effect of the elevation angular spread on the 1x2 MIMO system?

Mean elevation angle has a Laplacian distribution with a mean of 90° (horizon) and spread as specified and mean azimuthal angle has a uniform distribution

Q2: What is the effect of antenna orientation in a directional channel?

Mean azimuthal angle is stepped through 360°

Mean Capacity - TGN-b model, Uniform Azimuthal Angle

Slot antennas show an increase in mean capacity as the elevation angular spread is increased

Slanted slot antennas and Back-to-back patch antennas do not vary much in capacity with the elevation angular spread

For a moderate elevation angular spread of 90°, the patch and slot antennas show very low failure rates with only a little variation

High-gain Back-to-back Patch Arrays show a large drop in mean capacity as the elevation angular spread is increased

The high gain patch arrays show a lot of variation and the mean capacity is higher or lower than the other antennas depending on the orientation

For a moderate elevation angular spread of 90°, the patch antennas show more variation compared to the slot antennas in the mean capacity

The high gain patch arrays show high probability of link failure depending on the orientation
SMART PHONE EXAMPLE

BS antennas
Dual-polarized
0° separation
45° slanted [3]

Analyses and plots
obtained via the use of
MIMObit 1.0

Flat Oriented DUT Capacities

Flat Oriented DUT C vs. angle
SMART PHONE EXAMPLE (Cont.)

BS antennas
Dual-polarized
0° separation
45° slanted [3]

#3MIMO
ILA antenna

#4MIMO
IFA antenna

#2 MIMO
Loop antenna

#1 Main
Loop antenna

Analyses and plots
obtained via the use of
MIMObit 1.0

Vertical Oriented DUT Capacities

Vertically Oriented DUT C vs. angle
5G

- 28, 38, 60 and 72–73 GHz ; 5G below 6GHz (?)
  - What does the prop env look like at 60GHz?

- Massive MIMO
  - Many antennas => SDMA => many users on the same Freq-Time resources
  - MIMO algorithms will tend to render the antennas ‘phased arrays’

Elevation = 12 degrees (max power)
Summary & Conclusions

- Simple Introduction to Information and Capacity
- Outlined key characteristics of MIMO systems
- Capacity and Throughput are the Ultimate Performance Criteria
- Multi Element Antennas for MIMO Capable Wireless Systems can and should be designed with a Cross-Layer Approach
  - Allows for cost/size/performance optimization of product
  - A Tool, MIMObit, exists to perform such Cross-Layer analyses
  - Antenna Design challenges in 5G