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

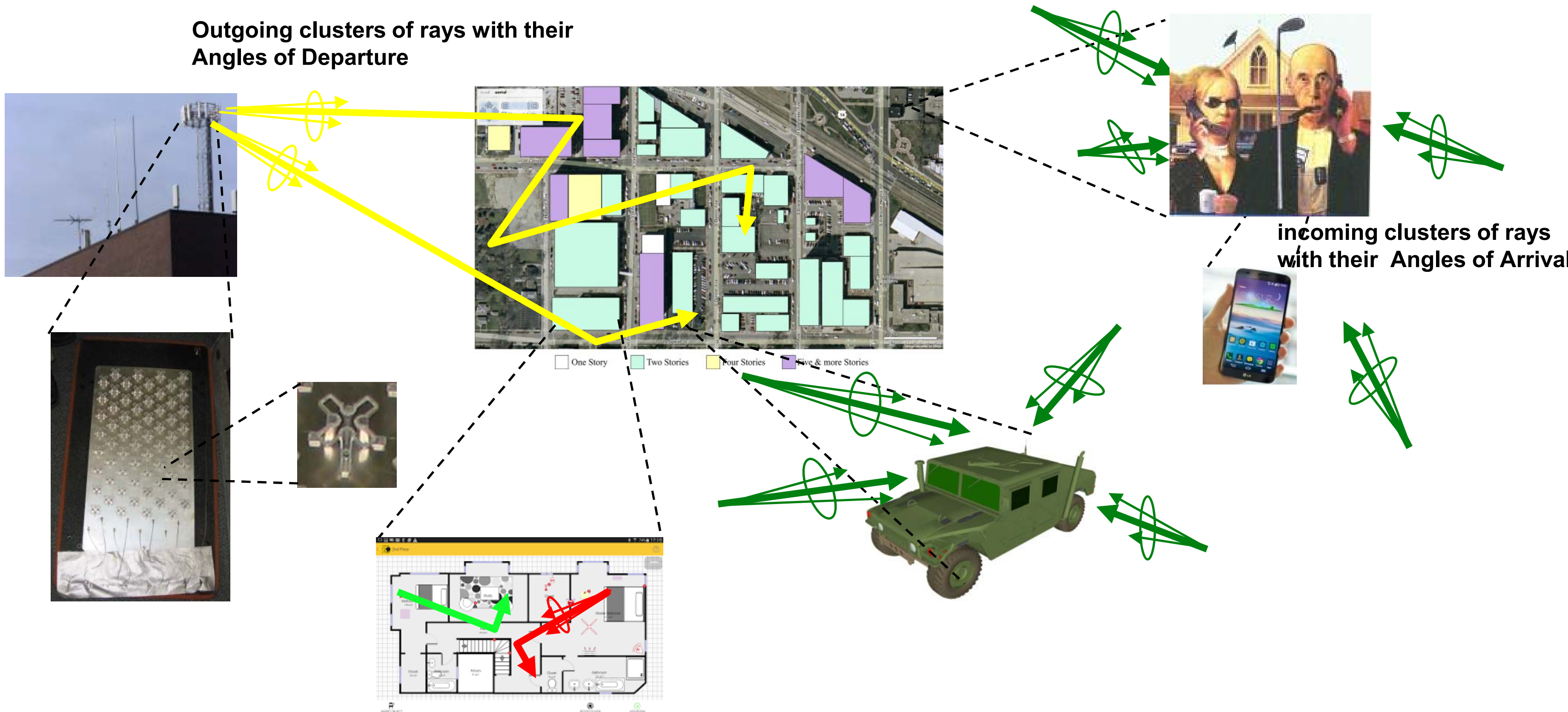
SMART ANTENNA SYSTEMS

CROSS-LAYER DESIGN (Capacity as "the" Antenna Design Performance Metric)

MIMO Antenna Design Problem, Solution and Examples

CHALLENGES AND CONCLUSIONS

THE PROPAGATION ENVIRON & MIMO SMART ANTENNA SYSTEMS

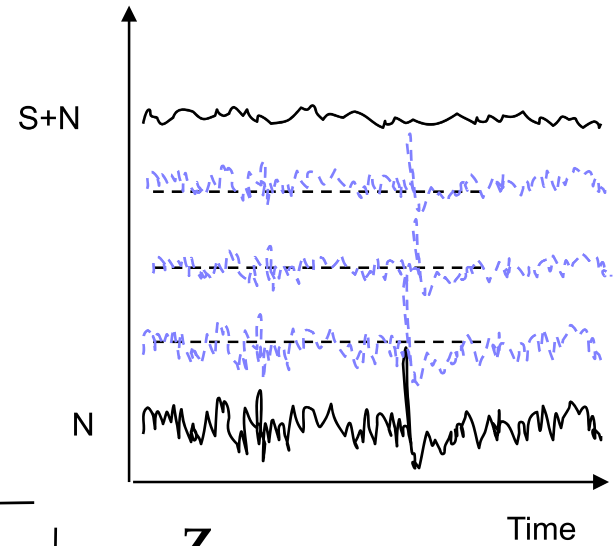


MIMO offers additional degrees of freedom ➡ better opportunities to take advantage of multipath

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 AND INFORMATION THEORY

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

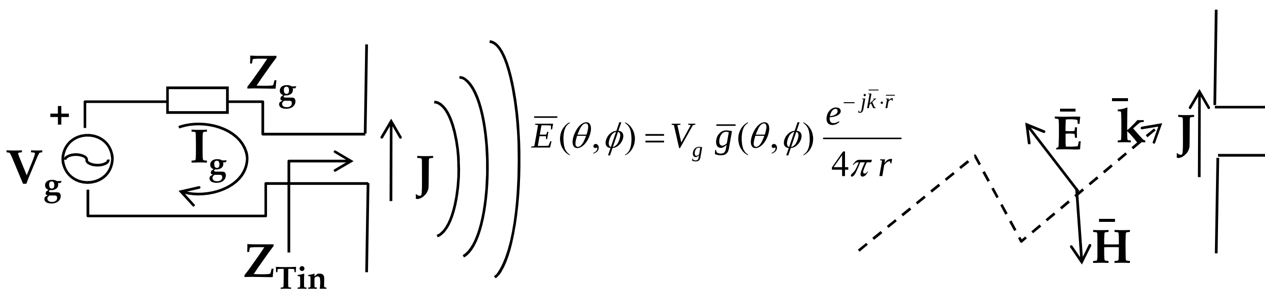


$\boxed{M = 2^m = (N+S)/N \Rightarrow m = \log_2[\,1+SNR\,]}$

This determines the number of bits you can reliably transmit.

$\boxed{\text{Capacity} = m \times \text{Bandwidth} = BW \times \log_2[\,1+SNR\,]}$

So, the Maximum Achievable Capacity, per Hz, is: $\boxed{C=\log_2[\,1+SNR\,]}$ **@ Rx!**



$$\bar{E}(\theta,\phi) = V_g\,\bar{g}(\theta,\phi)\,\frac{e^{-j\bar{k}\cdot\bar{r}}}{4\pi r}$$

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

<u>LOS special case</u>

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

NOTE: The well known KTB expressions for the Noise power from resistors come from Max Plank’s Black Body Radiation theory and the treatment of Noise in two-ports is well documented in Hermann A. Haus, et al., “Representation of Noise in Linear Twoports”, Proceedings of the IRE, Jan. 1960.

ANTENNA RELATED DISCIPLINES

PA output impedance

PL measurements, prop. models

LNA input impedance

Tx power mask

Space comms

F=Rx Noise Factor

$$P_R = P_T\ G_T(\theta,\phi)\, G_R(\pi-\theta,\ \pi+\phi)\left(\frac{\lambda}{4\pi r}\right)^2 \left|\bar{a}_T^{\dagger}\cdot\bar{a}_R\right|^2 \frac{4Z_g R_{T_{in}}}{\left|Z_g+Z_{T_{in}}\right|^2}\frac{4Z_L R_{R_{in}}}{\left|Z_L+Z_{R_{in}}\right|^2}$$

$$C = B\log_2\left(1+\frac{P_R}{F\,KTB+I}\right)$$

Pattern design/synthesis
parabolic reflectors, phased arrays, etc.

Broadband (Low Q) matching
adaptive front ends, etc.

cryogenic receivers
(radioastronomy)

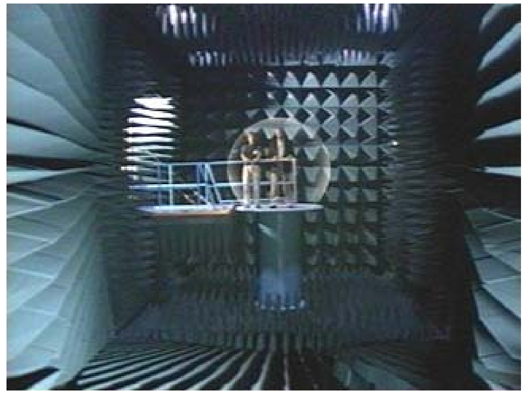
EMI/EMC

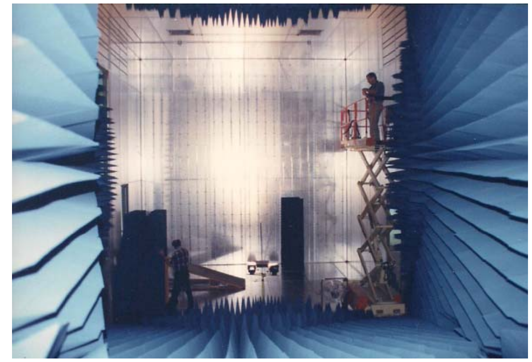
At high SNR's, doubling the power increases the link efficiency by 1 bps/Hz

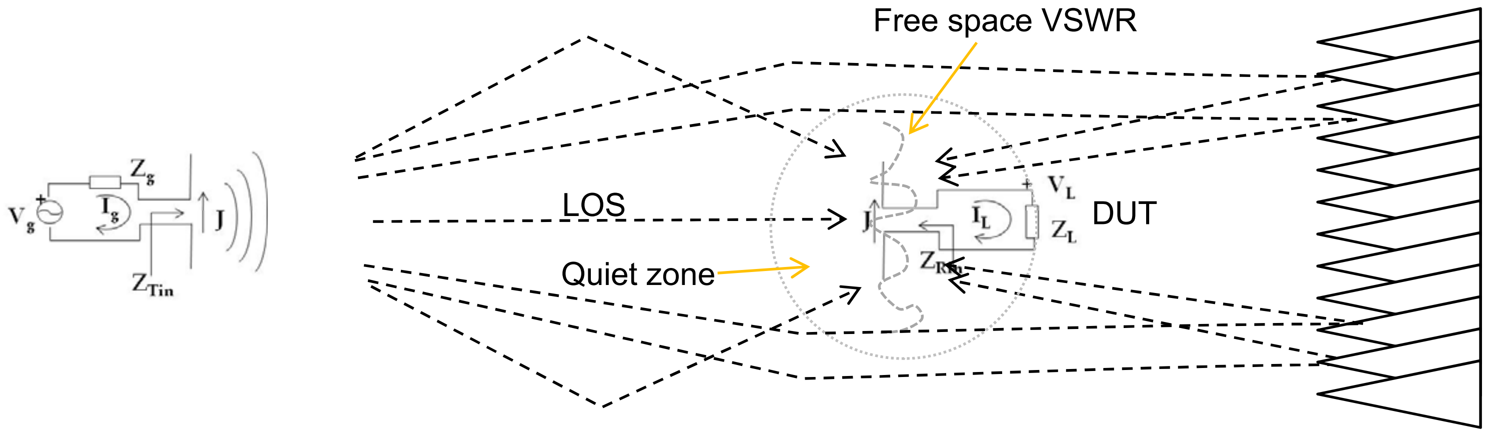
$$C_b = \log_2\left(1+\frac{P_b}{N}\right) = \log_2\left(1+\frac{P_b}{P_a}\frac{P_a}{N}\right) \approx \log_2\left(\frac{P_b}{P_a}\frac{P_a}{N}\right) = \log_2\left(\frac{P_b}{P_a}\right)+\log_2\left(\frac{P_a}{N}\right) \approx \log_2\left(\frac{P_b}{P_a}\right)+\log_2\left(1+\frac{P_a}{N}\right)$$

$$\Longrightarrow C_b = C_a + \log_2\left(\frac{P_b}{P_a}\right)$$

ANECHOIC CHAMBER ANTENNA MEASUREMENTS



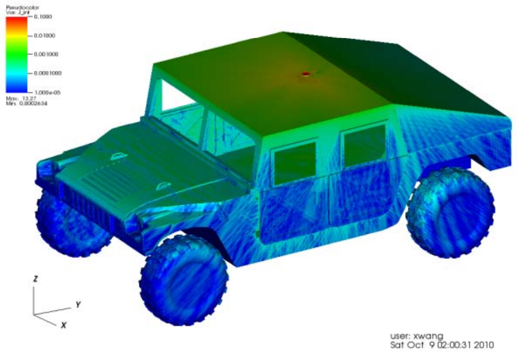


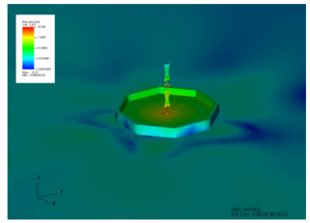


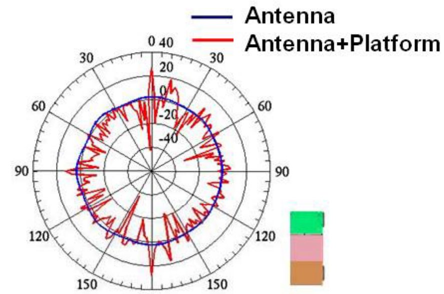
$$P_R = P_T \; G_T(\theta,\phi)\, G_R(\pi-\theta,\, \pi+\phi) \left(\frac{\lambda}{4\pi r}\right)^2 \left|\bar{a}_T^{\dagger}\cdot \bar{a}_R\right|^2 \frac{4Z_g R_{T_{in}}}{\left|Z_g + Z_{T_{in}}\right|^2} \frac{4Z_L R_{R_{in}}}{\left|Z_L + Z_{R_{in}}\right|^2}$$

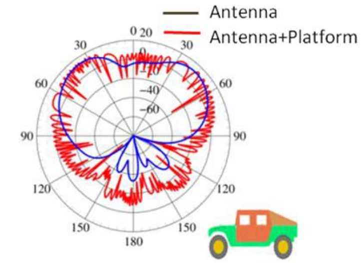
Keep all constant exept DUT, calibrate with standard gain antennas, determine G.

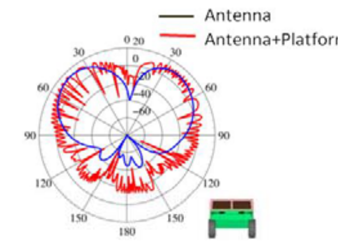
ELECTRICALLY LARGE PROBLEMS (DOMAIN DECOMPOSITION with OSU)

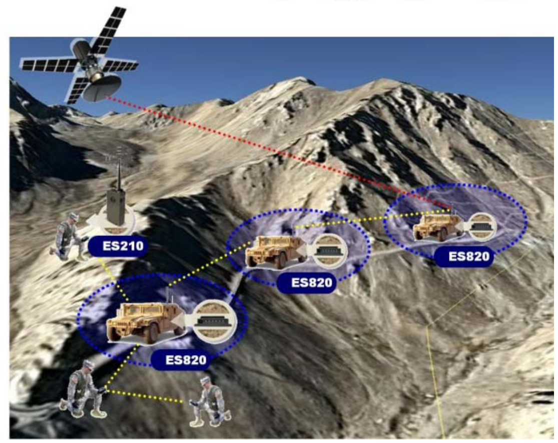


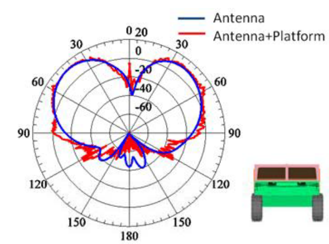


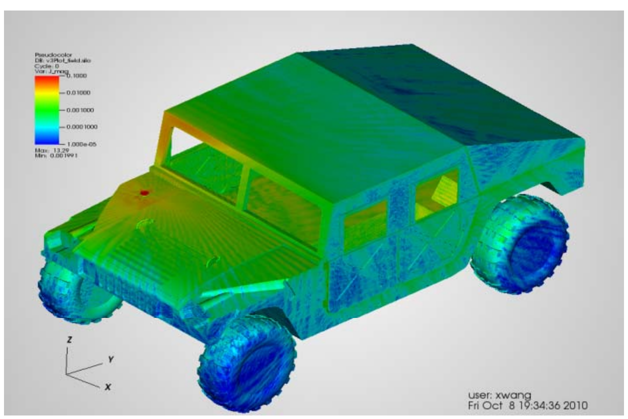


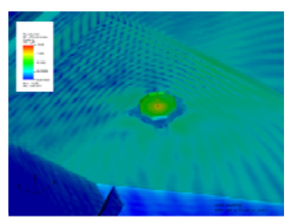


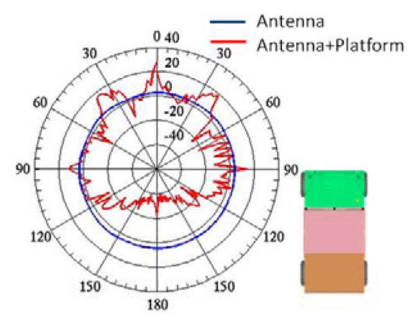


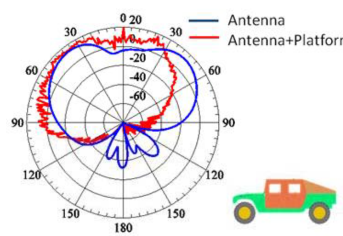




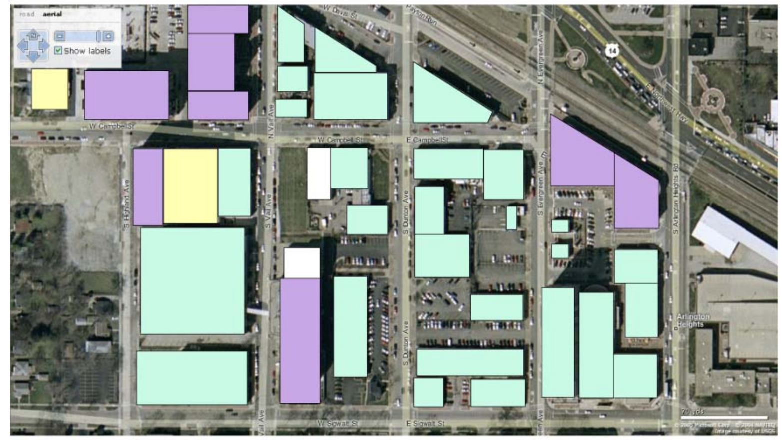


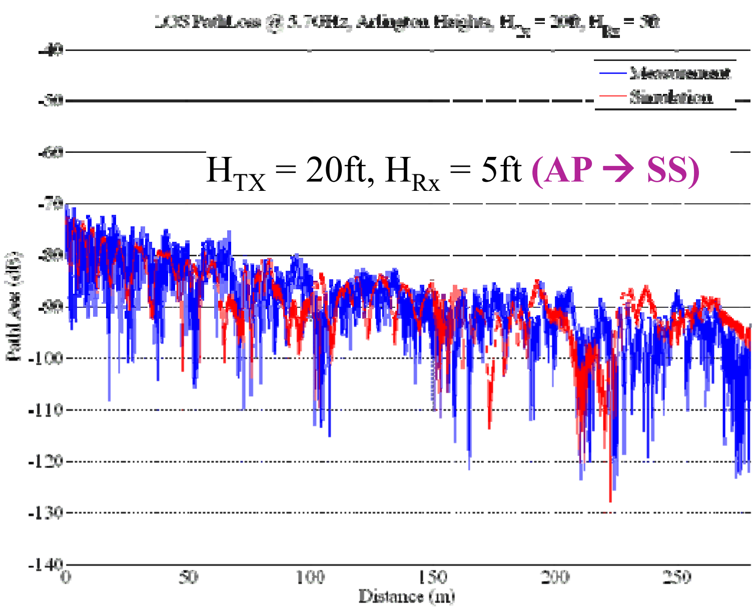






PROPAGATION ENVIRON & PROGRESS IN RAY TRACING



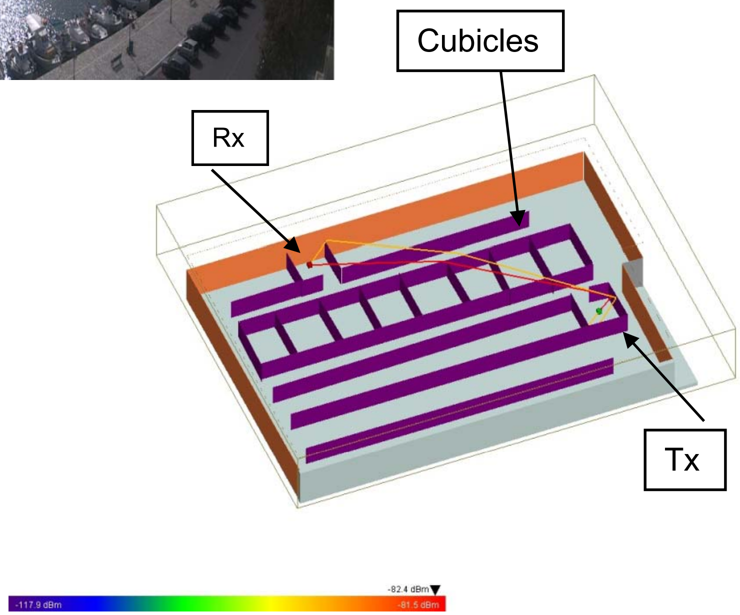


Run Time: **100 Sec** on P4 2.8GHz CPU, Rx Sensitivity: -100dBm, Angular Resolution: 1deg., No of Rx: 6100

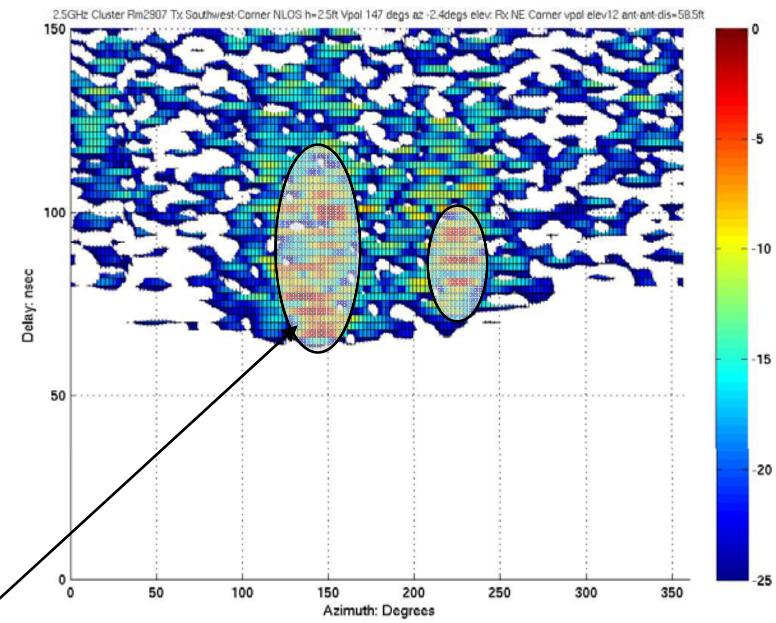
North-East side

South-West side

RAY TRACING vs. MEASUREMENTS



Elevation = 12 degrees (max power)

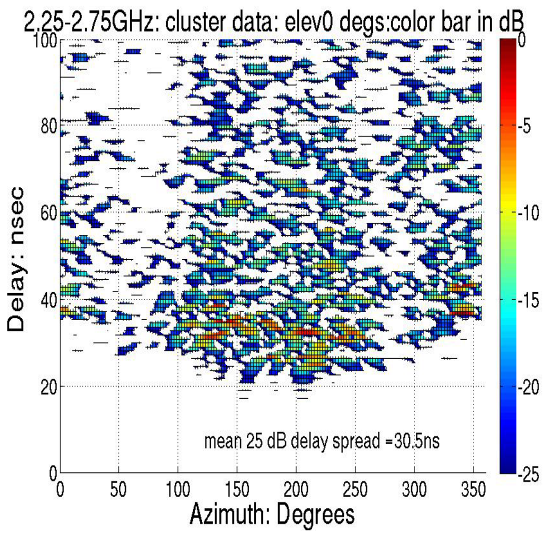


- Two strongest paths are from ceiling reflections
- Simulation agrees well with measured data

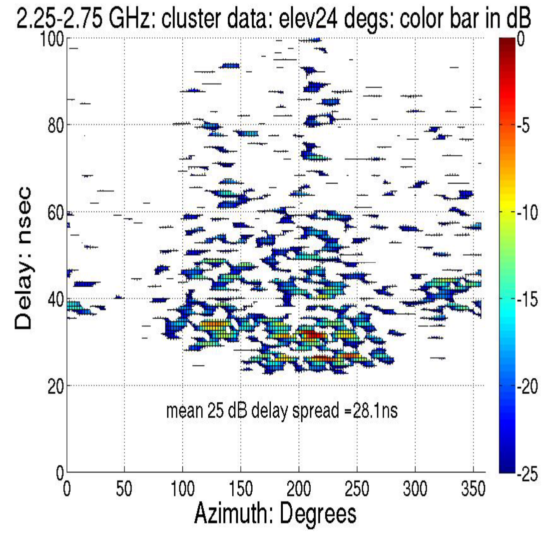
Delay and azimuth range predicted by ray tracing

Predicted elevation range: 2-13 degs

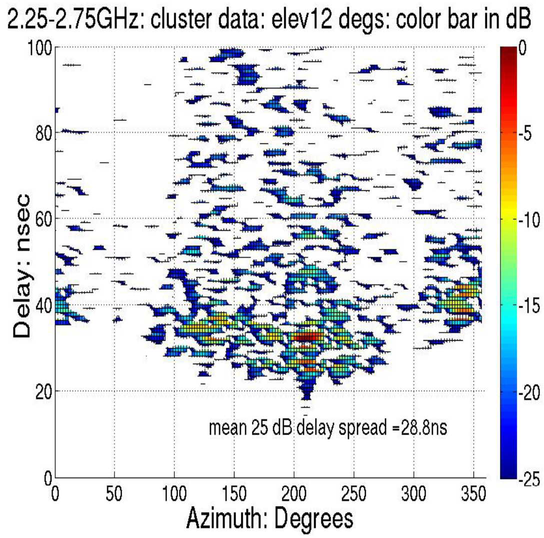
MEASURED DATA: TIME-SPACE PARAMETERS vs. ELEVATION



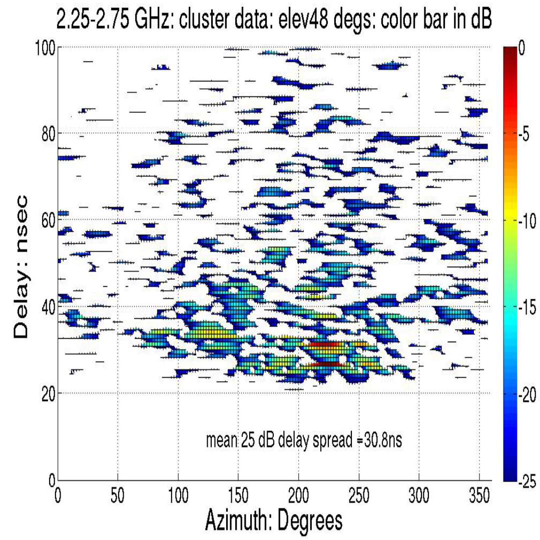
Elevation = 0 degrees



Elevation = 24 degrees



Elevation =12 degrees



Elevation = 48 degrees

Angular spread and delay profile of dominant cluster is relatively insensitive to elevation

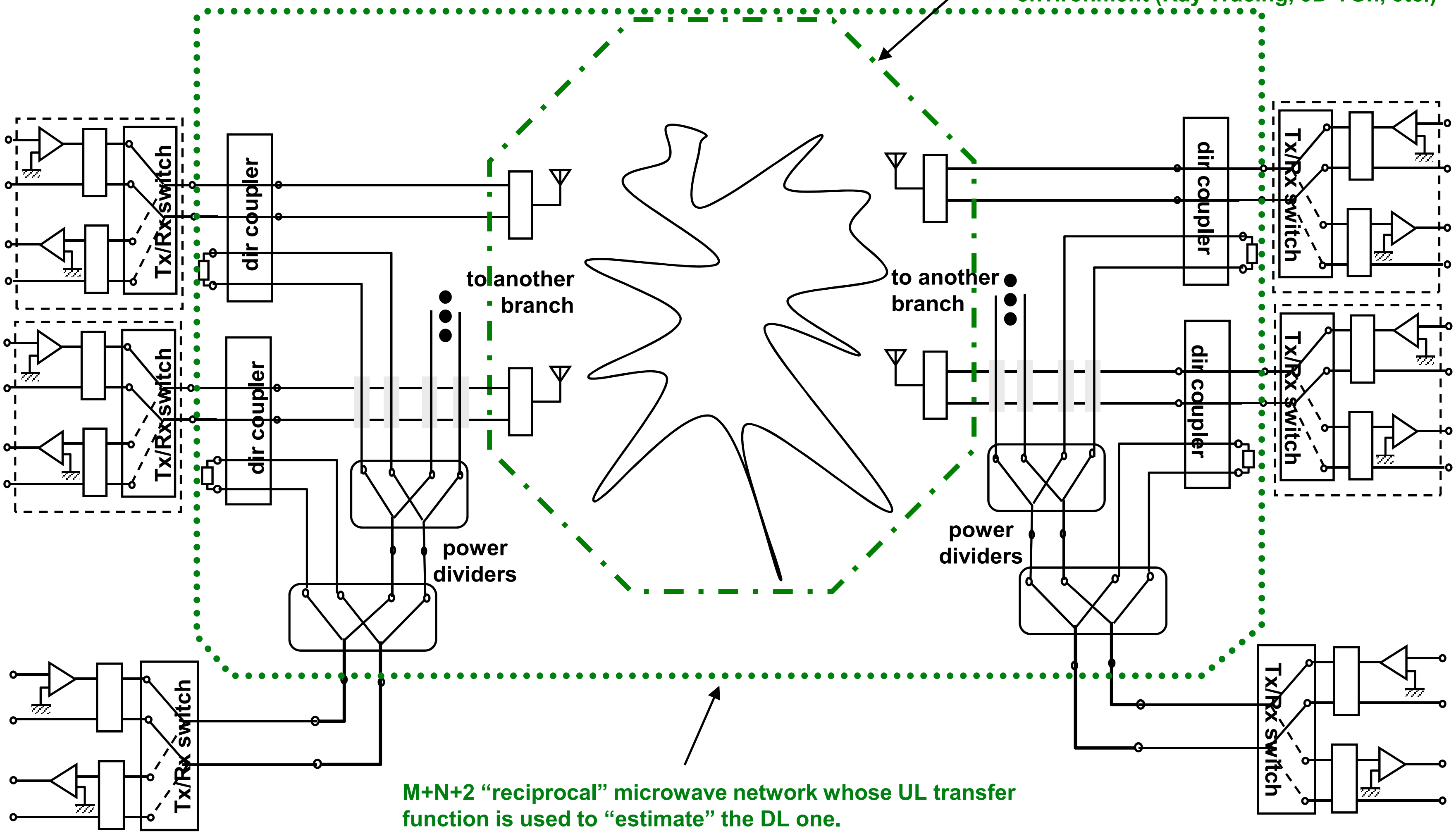
Data shown is for the receiver and transmitter both vertically polarized.

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.)



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)

CALIBRATION & CHANNEL ESTIMATION (TDD system e.g. WiMAX, LTE)

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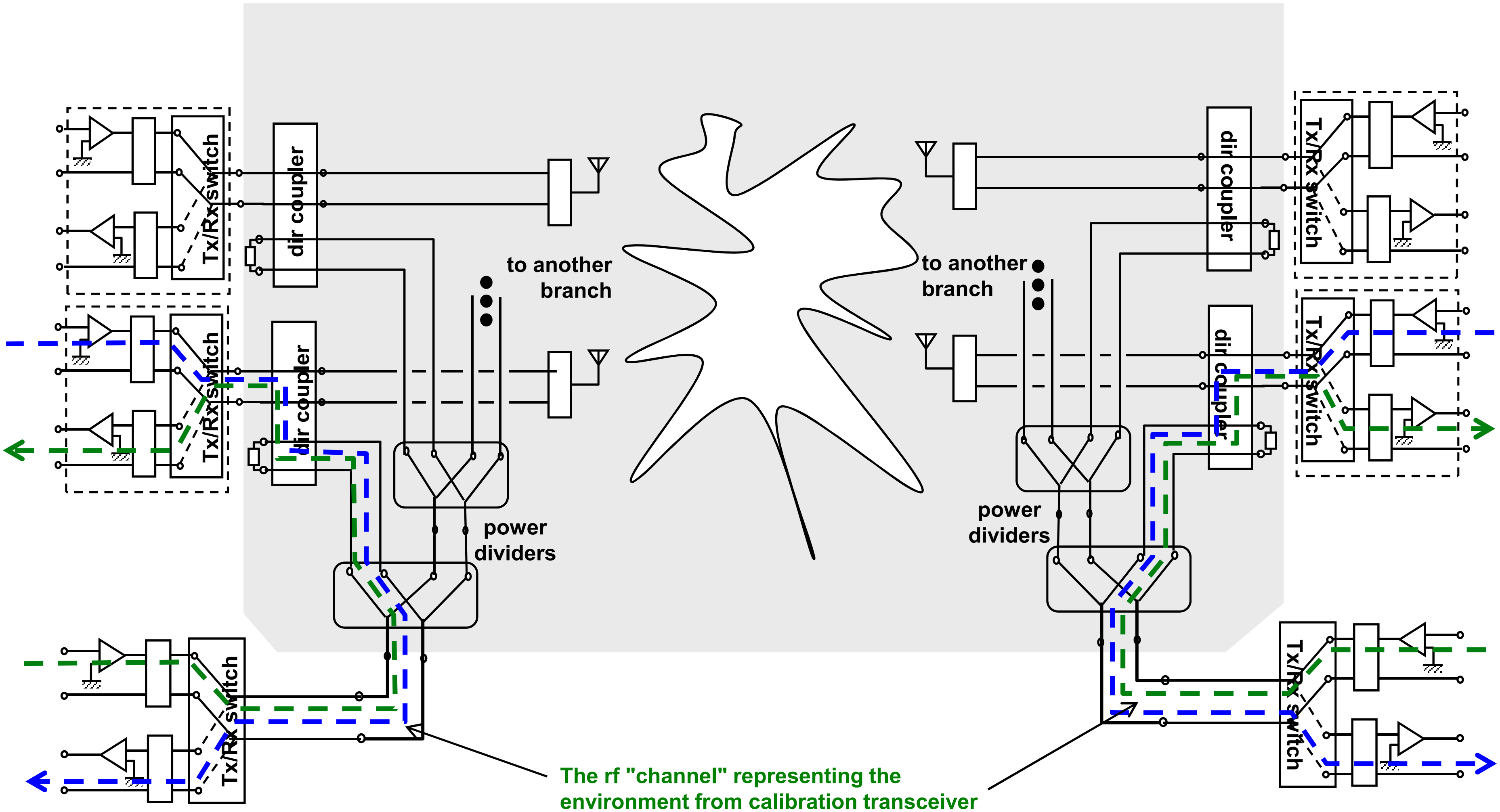
Baseband to baseband calibration measurements

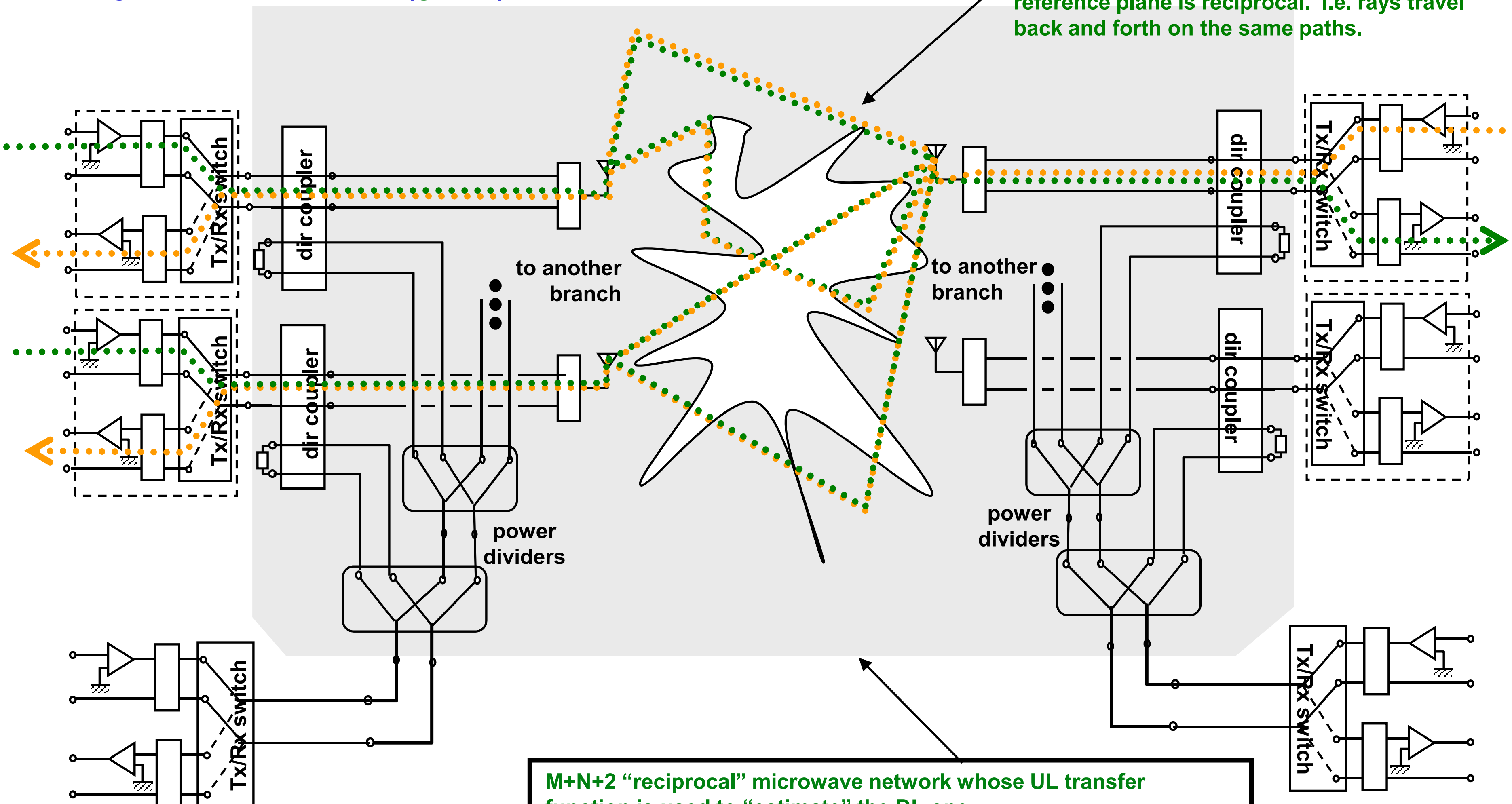


The rf "channel" representing the environment from calibration transceiver baseband to antenna transceiver baseband is NON-reciprocal!

CALIBRATION & CHANNEL ESTIMATION (TDD system e.g. WiMAX, LTE)

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.



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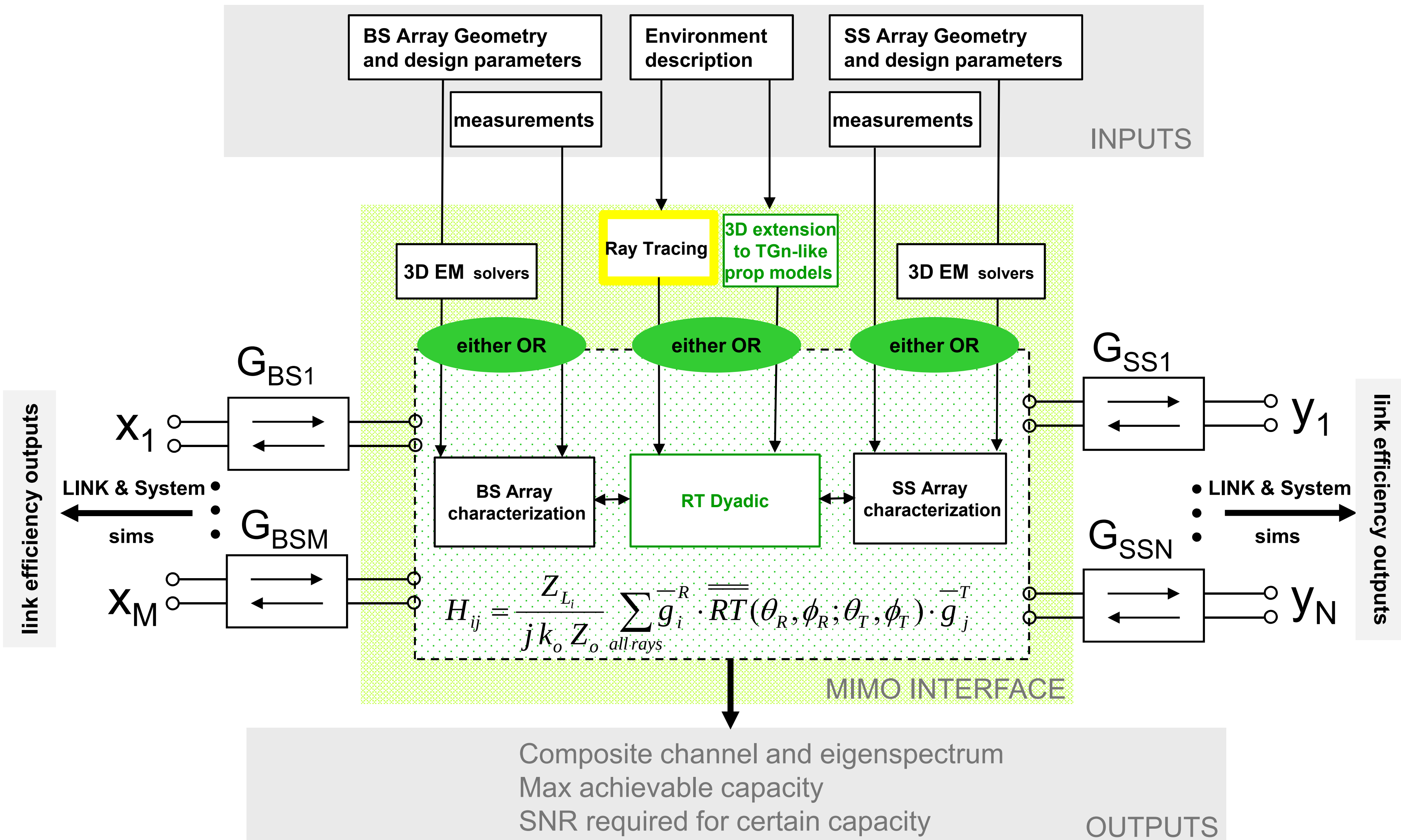
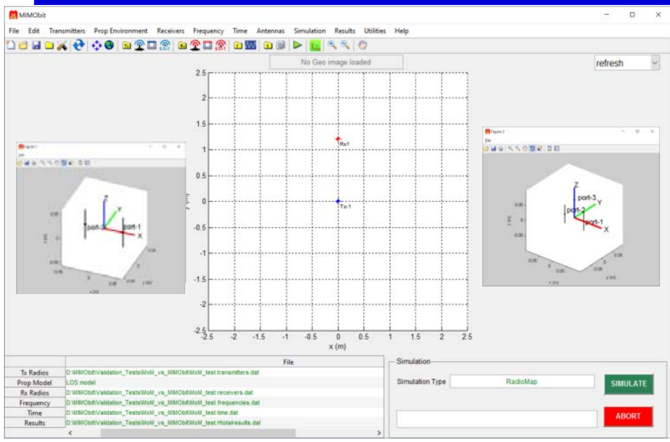
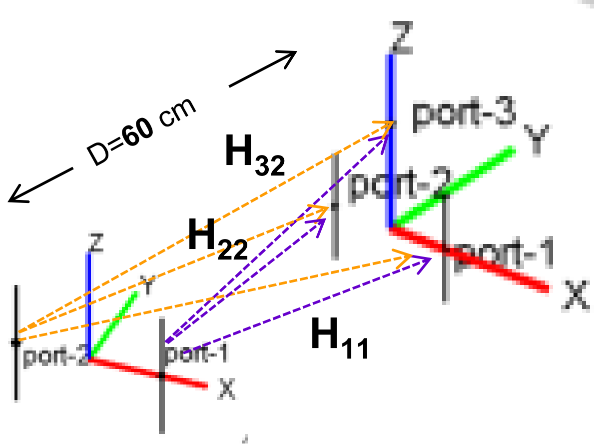
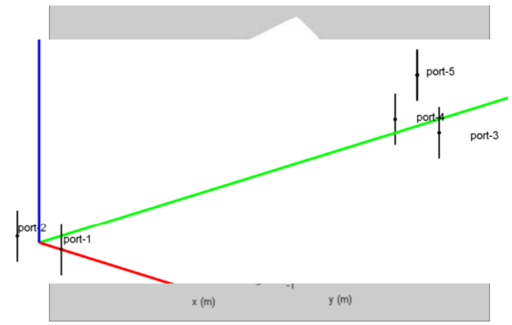
SMART ANTENNA SYSTEMS: PUTTING IT ALL TOGETHER



MIMObit vs MoM (D=60 cm Offset=0cm)



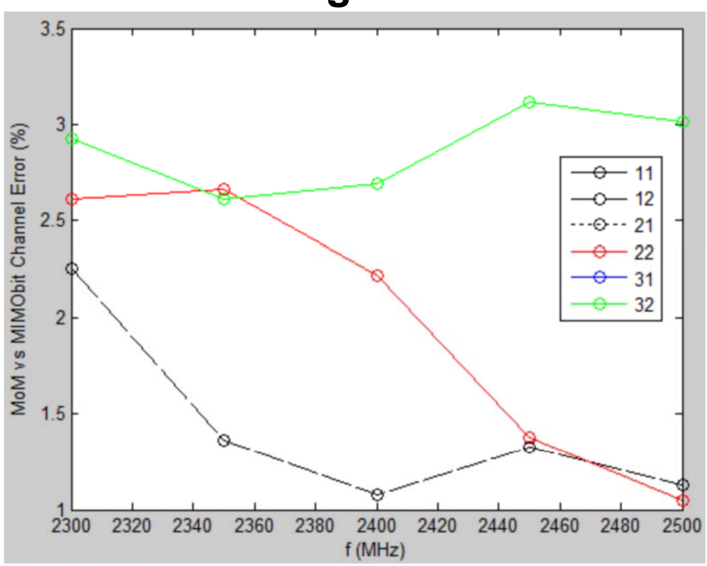




H derivation: MIMObit
3x2 MIMO; LOS prop model

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

Channel mag relative error

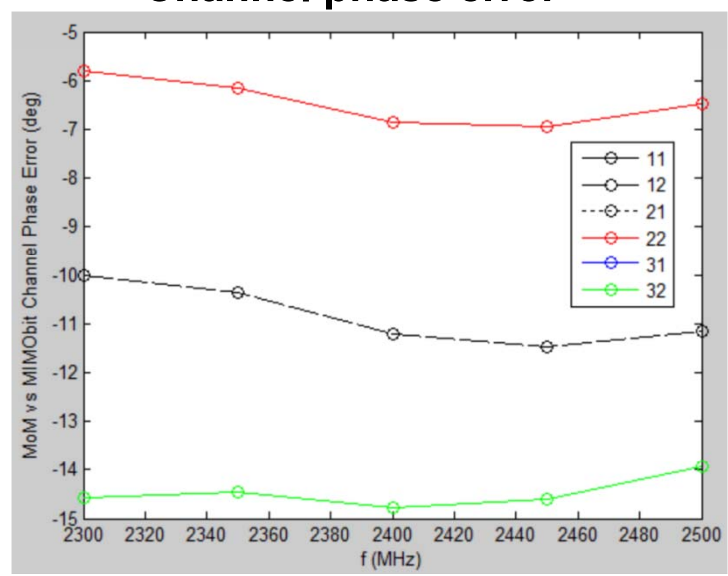


$H_{22} = H_{11}$

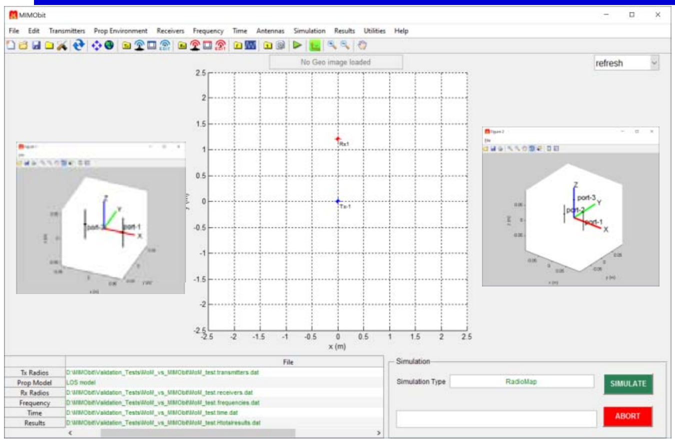
$H_{21} = H_{12}$

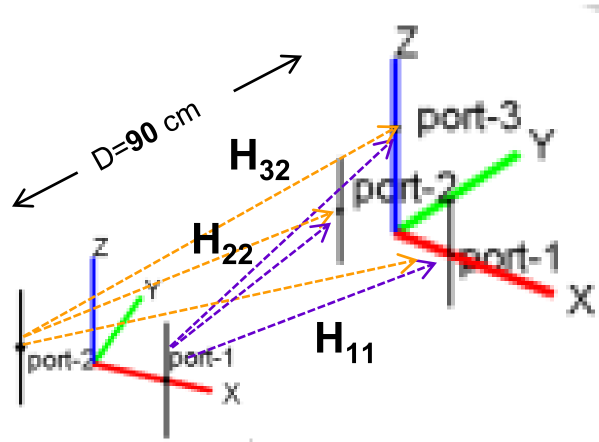
$H_{31} = H_{32}$

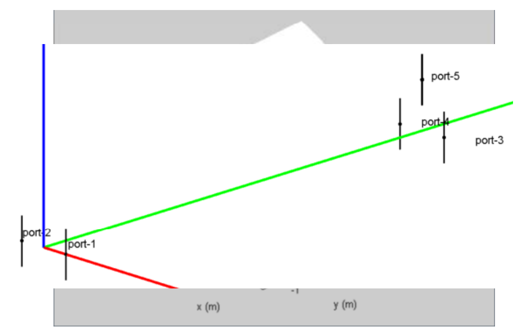
Channel phase error



MIMObit vs MoM (D=90 cm Offset=0cm)







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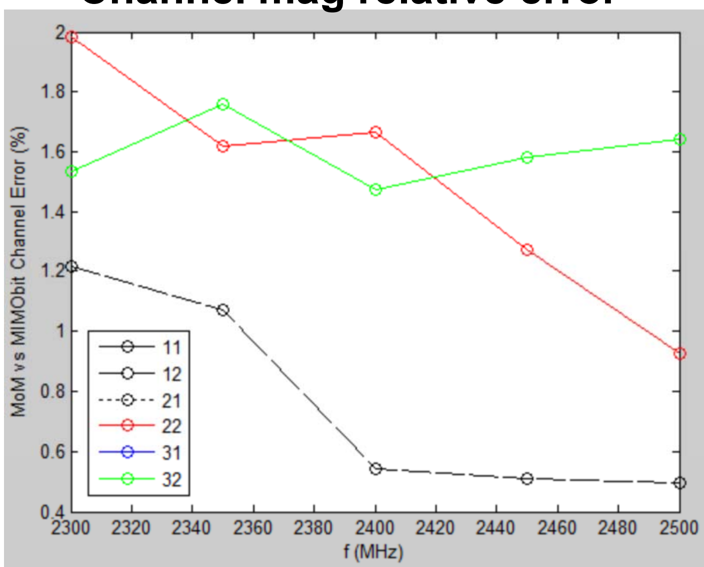

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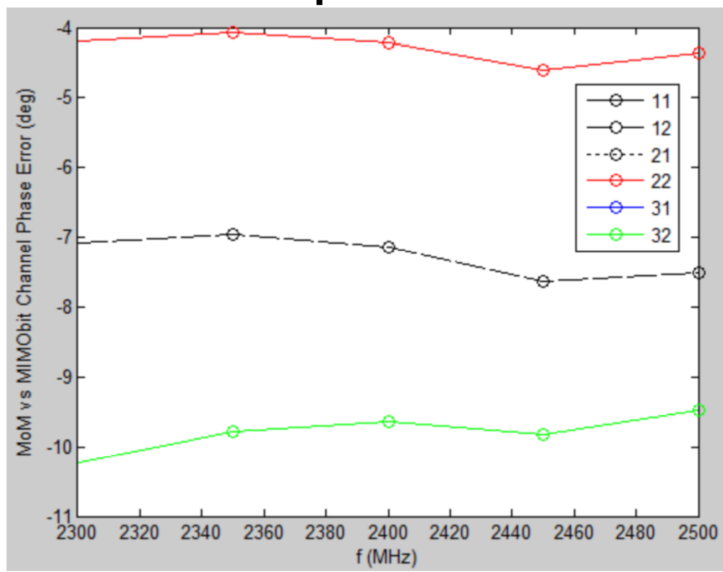
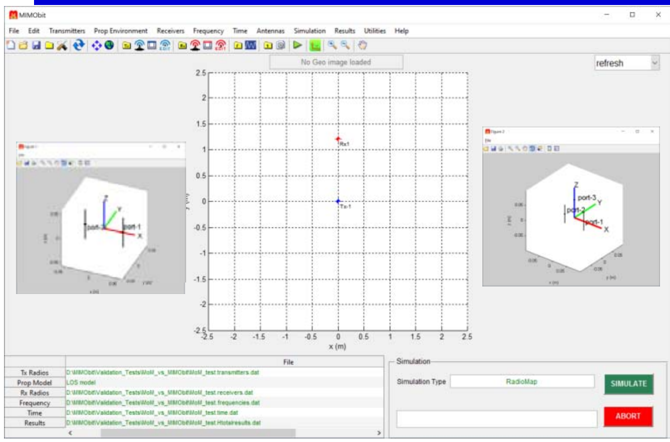
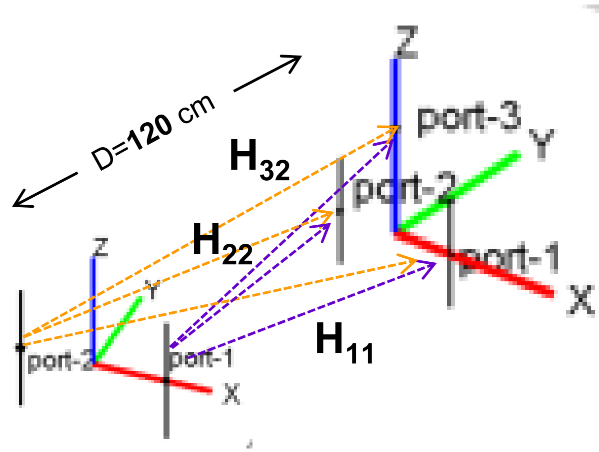
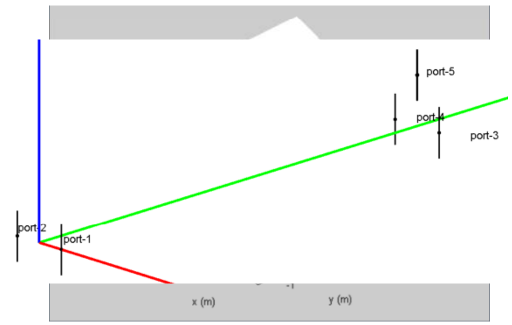


MIMObit vs MoM (D=120 cm Offset=0cm)







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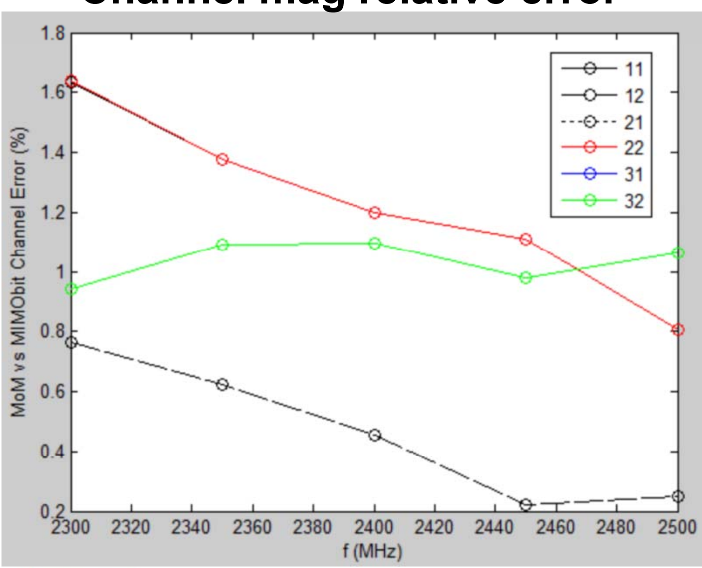

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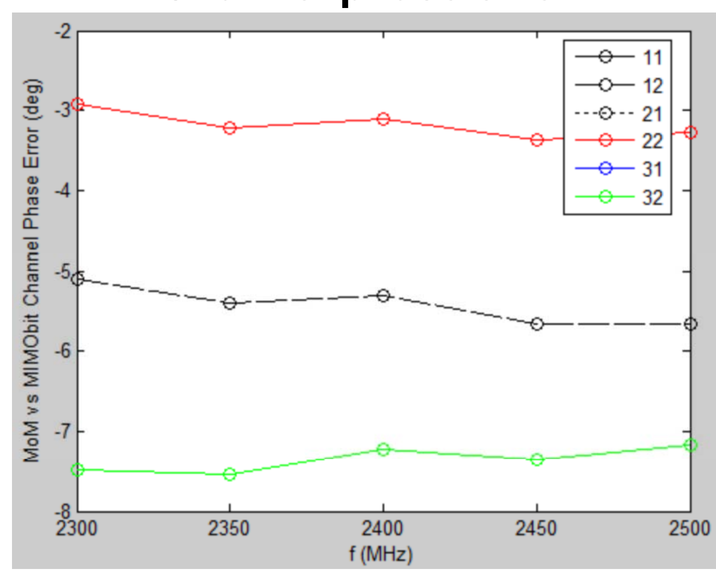
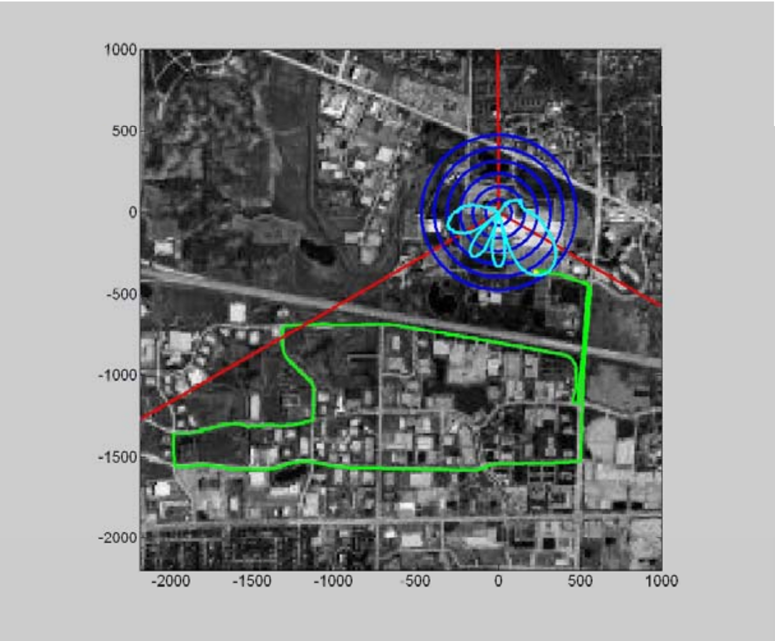
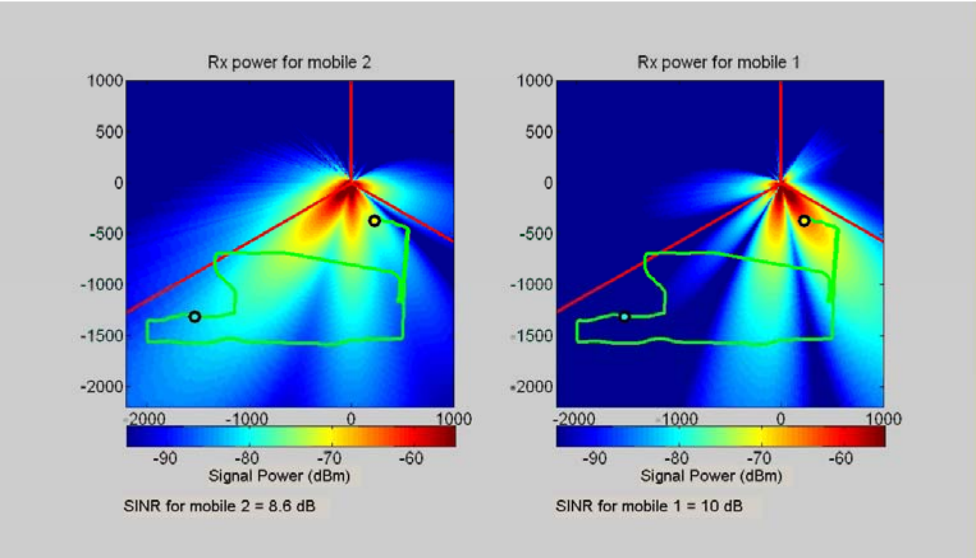


THE PROMISE OF SMART ANTENNA SYSTEMS





CAPACITY

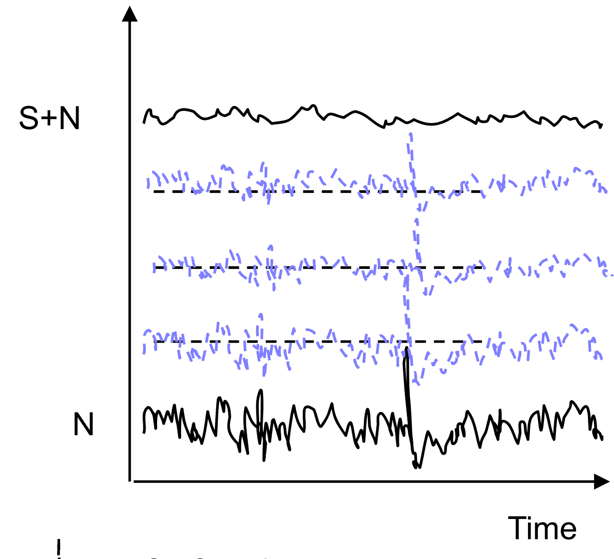
Shannon (paraphrased & certainly not doing justice to the master):
How many different numbers can you reliably send across? Ans. = M
How many bits are needed to represent M? Ans.= m

$M = 2^m = (N+S)/N \Rightarrow m = \log_2[\,1+SNR\,]$

This determines the number of bits you can reliably transmit.

Capacity = m x Bandwidth = BW x $\log_2[\,1+SNR\,]$

So, the Maximum Achievable Capacity, per Hz, is: $C=\log_2[\,1+SNR\,]$ — **@ Rx!**



Channel power transfer function

LOS special case

$$C = B\log_2\left(1+\frac{P_R}{KTB}\right) \quad ; \quad P_{Rx} = P_{Tx_{avail}}\, \underbrace{G_T(\theta,\phi)\, G_R(\pi-\theta,\, \pi+\phi)\left(\frac{\lambda}{4\pi r}\right)^2 \left|\bar{a}_T^{\dagger}\cdot\bar{a}_R\right|^2 \frac{4Z_g R_{T_{in}}}{\left|Z_g+Z_{T_{in}}\right|^2}\frac{4Z_L R_{R_{in}}}{\left|Z_L+Z_{R_{in}}\right|^2}}_{\text{Channel power transfer function}}$$

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

$$C=\log_2\left\{\det\left(\bar{\bar{I}}+\left\langle\frac{P_{Tx}/n_{Tx}}{N_o|_{Rx}}\right\rangle \bar{\bar{H}}\cdot\bar{\bar{H}}^{\dagger}\right)\right\}$$

; where $\bar{\bar{H}}$ = Channel Matrix

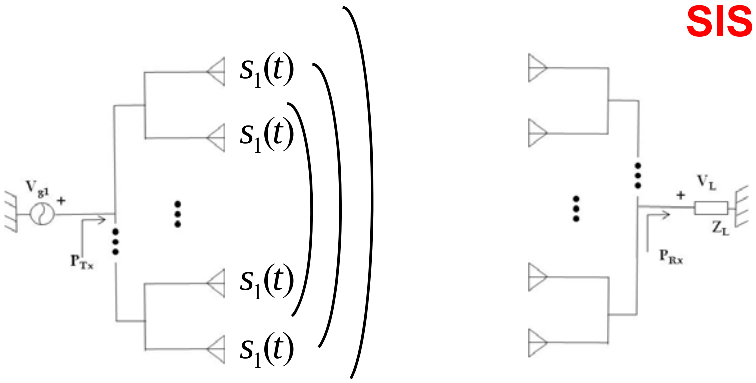
ATTENTION: P @ Tx & Noise @ Rx

Power at the Rx: $\frac{1}{2}\mathrm{Re}\left\{\overline{V}_S^{\,t}\cdot\overline{I}_S^{\,*}\right\}=\frac{1}{2}\mathrm{Re}\left\{\overline{V}_S^{\,H}\cdot\hat{Y}_L\cdot\overline{V}_S\right\}$

This simplifies iff all the impedances are the same!

WHY MIMO ?

SISO



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

$$G_{Tx} = n_{Tx} G_o \quad ; \quad G_{Rx} = n_{Rx} G_o = n_{Tx} G_o$$

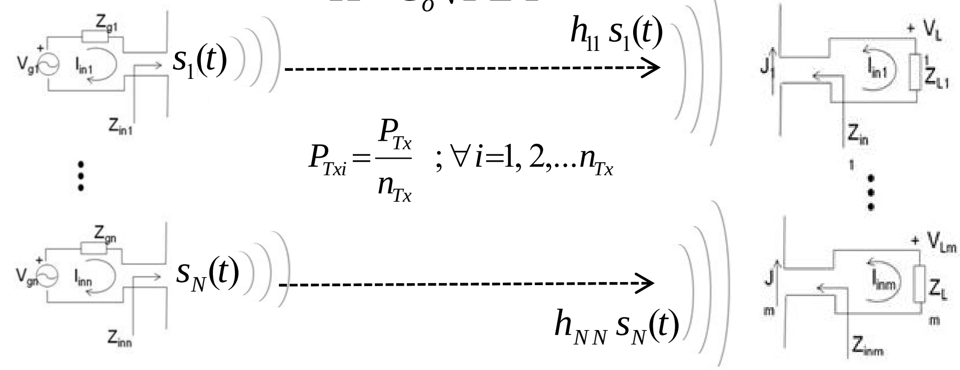
$$SNR_{Rx} = \frac{P_{Rx}}{KTB} \overset{Friis}{==} \frac{P_{Tx}\, n_{Tx} G_o\, n_{Tx} G_o\, PL}{KTB}$$

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

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

Open Loop MIMO

$$\overline{\overline{H}} = G_o \sqrt{PL}\, \overline{\overline{I}}$$



$$P_{Txi} = \frac{P_{Tx}}{n_{Tx}} \quad ; \forall i = 1, 2, \ldots n_{Tx}$$

$$\left\langle SNR_{Tx} \right\rangle_{per\ port} = \frac{P_{Tx}/n_{Tx}}{KTB}$$

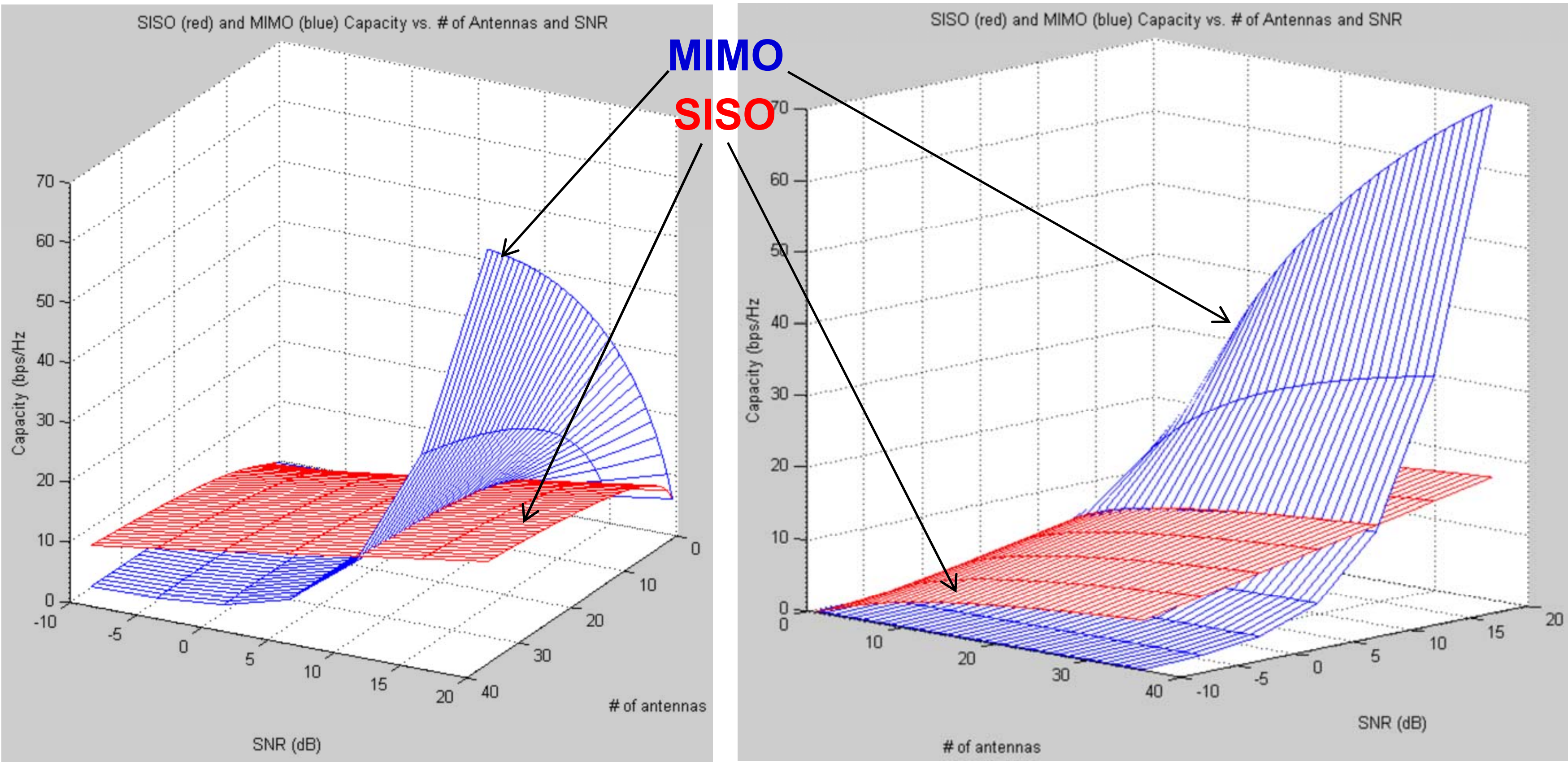
$$C_{MIMO} = \log_2 \left\{ \det \left(\overline{\overline{I}} + \left\langle SNR_{Tx} \right\rangle \overline{\overline{H}} \cdot \overline{\overline{H}}^{\dagger} \right) \right\}$$

$$= \log_2 \left\{ \det \left(\overline{\overline{I}} + \frac{P_{Tx}}{n_{Tx}} \frac{G_o^2\, PL}{KTB} \overline{\overline{I}} \right) \right\}$$

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

$$C_{MIMO} = n_{Tx} \log_2 \left(1 + \frac{1}{n_{Tx}} SNR_o \right)$$

THIS WHY MIMO !



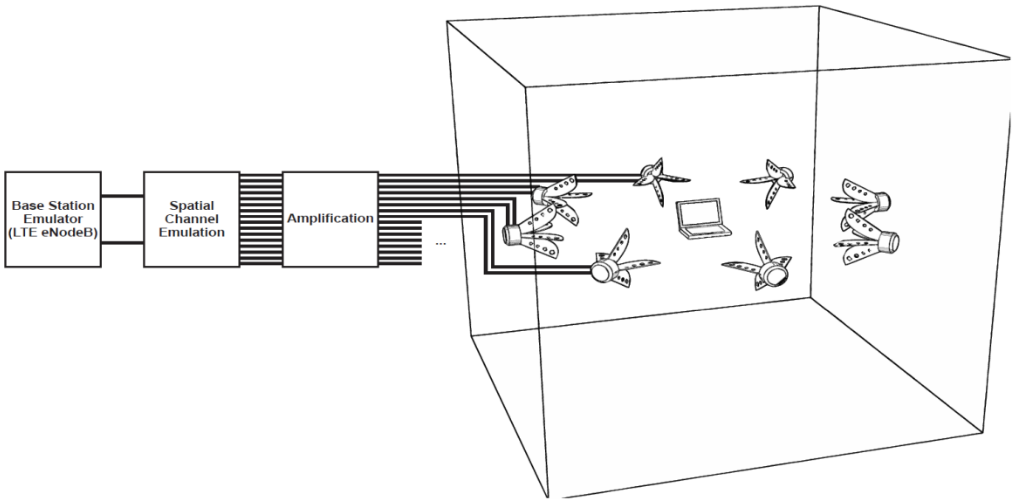
Different views of the C_{SISO} and C_{MIMO} for 0 to 36 antennas and -10 to 20 dB SNR_o .

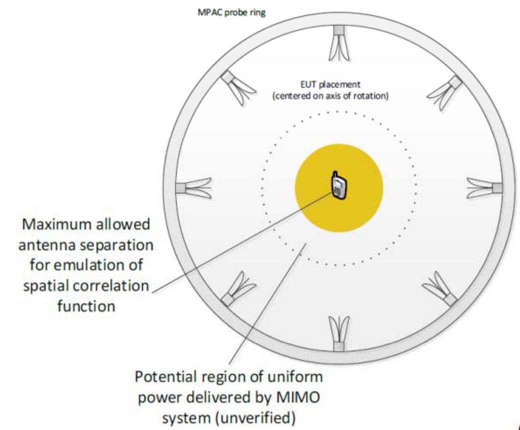
NOTE: This plot assumes Open Loop MIMO. When the SNR is low, other MIMO algorithms are used to increase Capacity. E.g. MIMO can inherently duplicate the “corporate feed” of our example. All it needs is to know the “channel” via the “channel estimation” process (i.e. just a bit of overhead and you can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

CTIA 2x2 MIMO TEST PLAN (DL LTE)

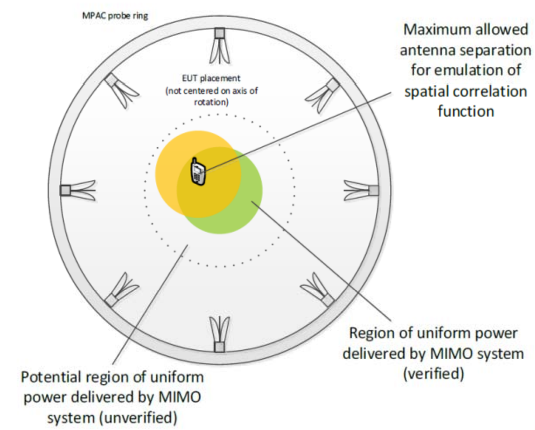
Outdoor Ranges: ground reflection, interference

Anechoic Chambers: difficult to kill reflections for all scenarios/frequencies, etc

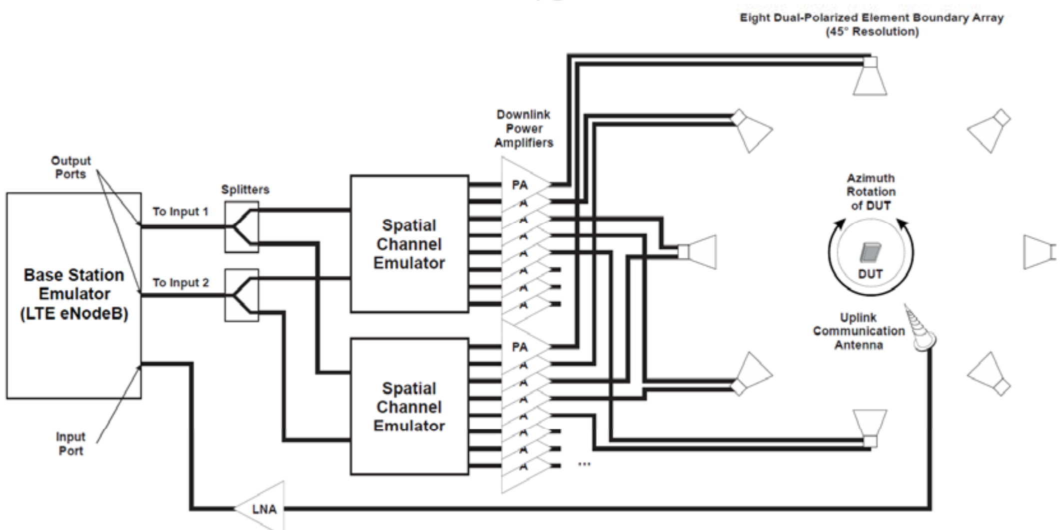




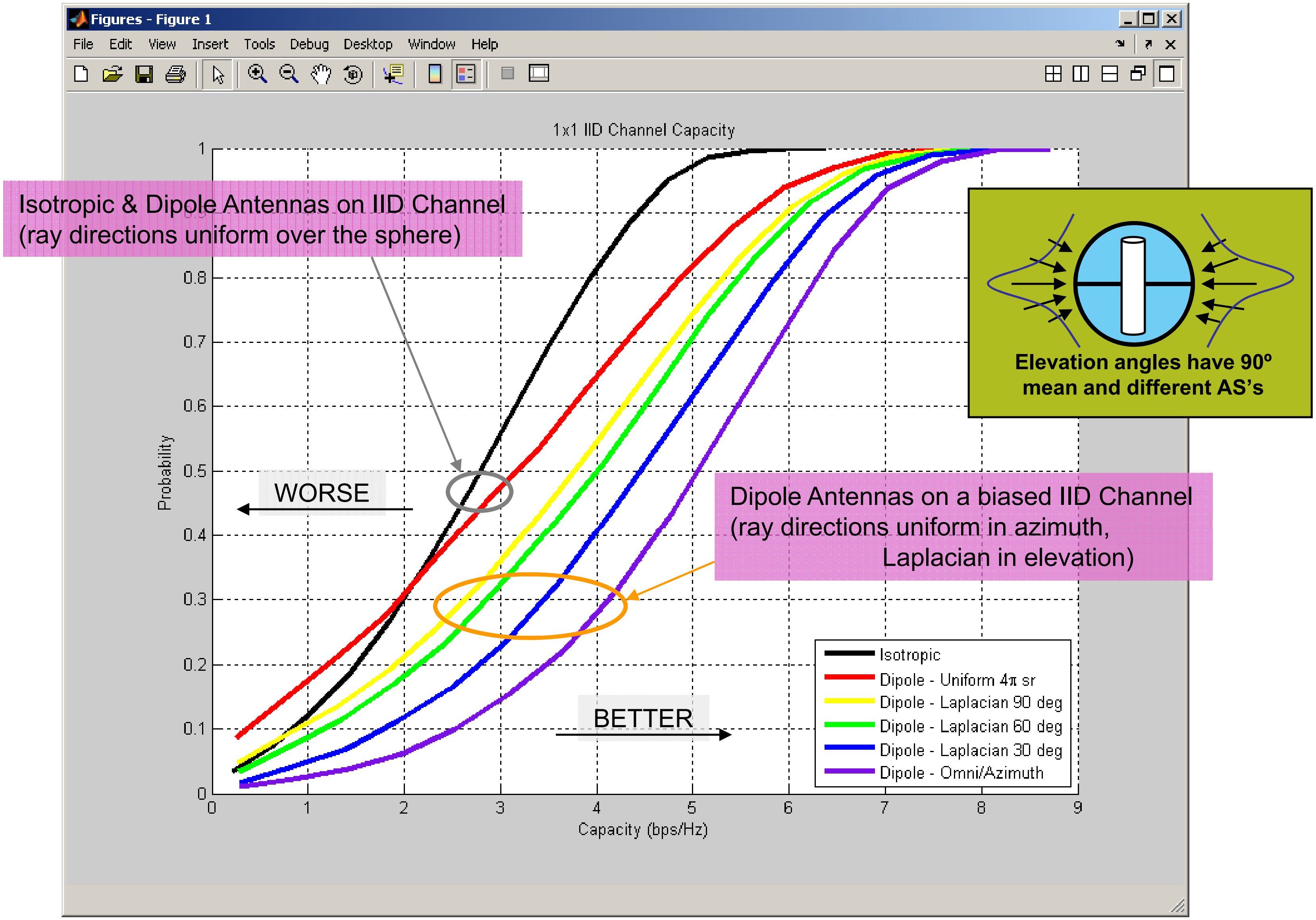
(A)



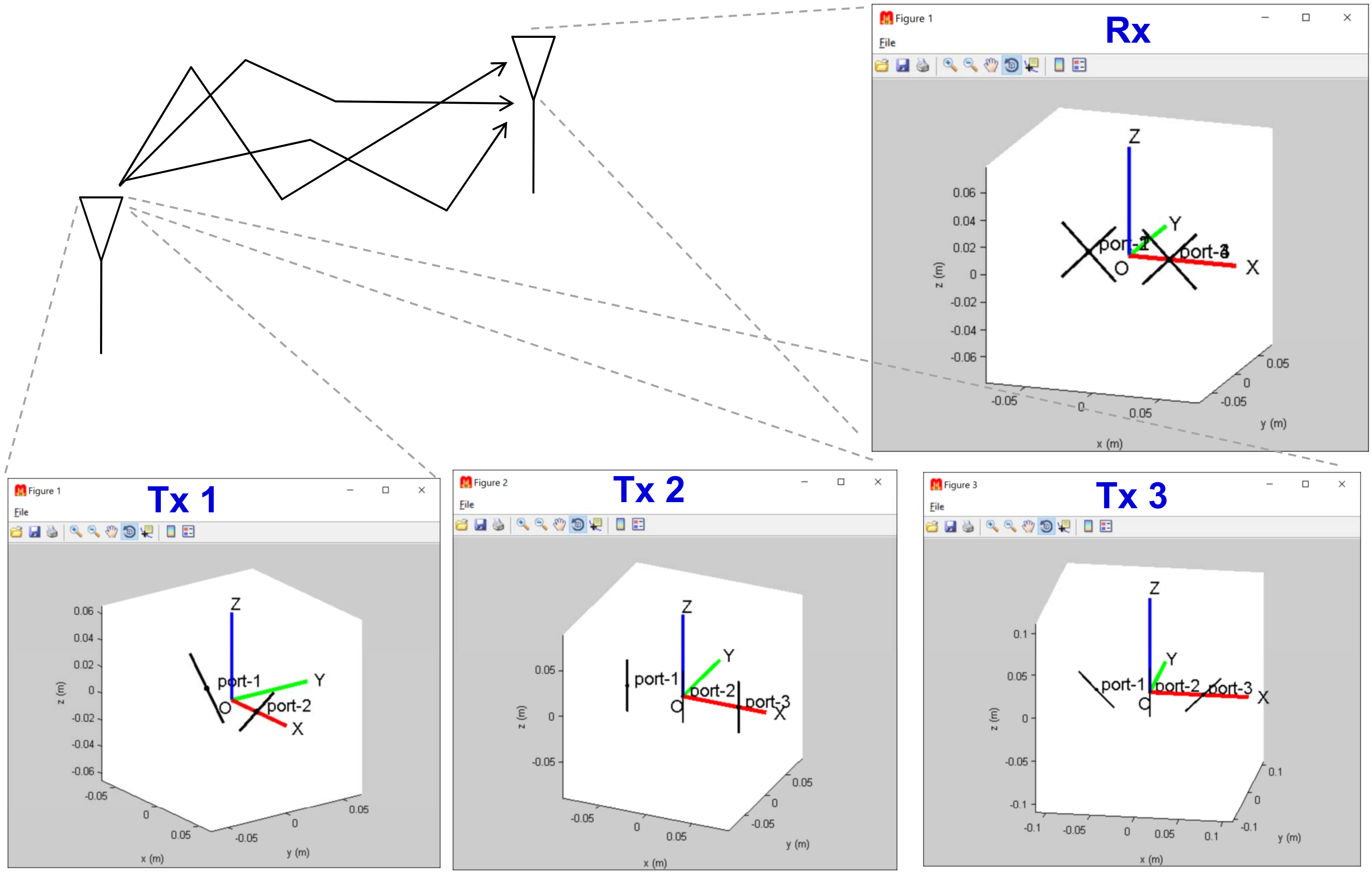
(B)



CAPACITY per Hz (ISOTROPIC VS. DIPOLE example)



MIMO ANTENNA SYSTEMS USED



IEEE 802.11n TGn B   PROPAGATION MODEL

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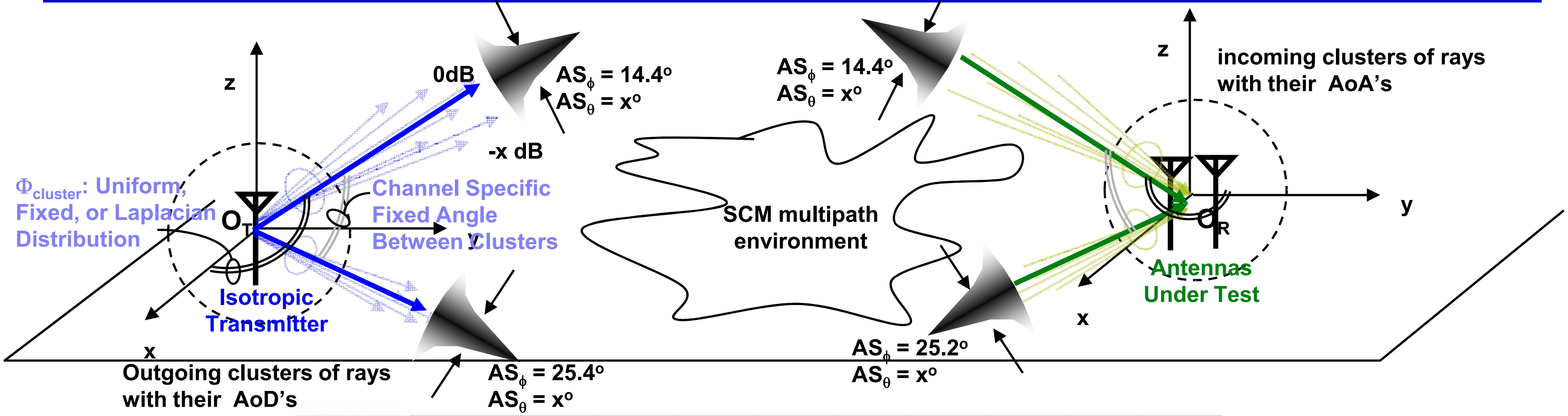
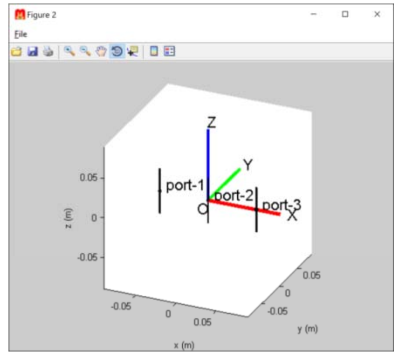
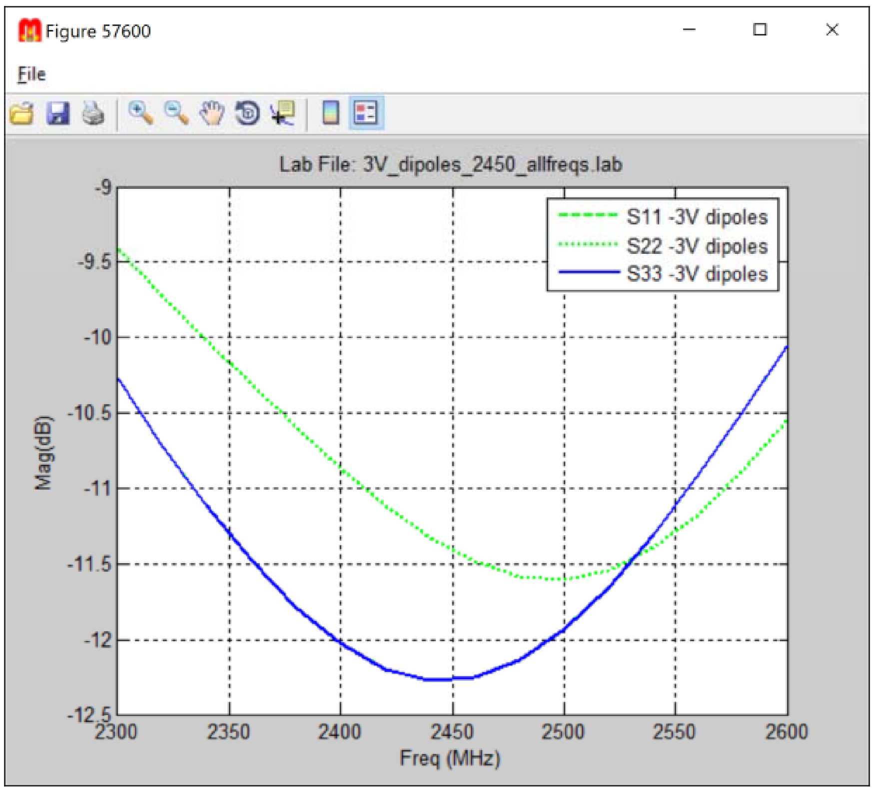
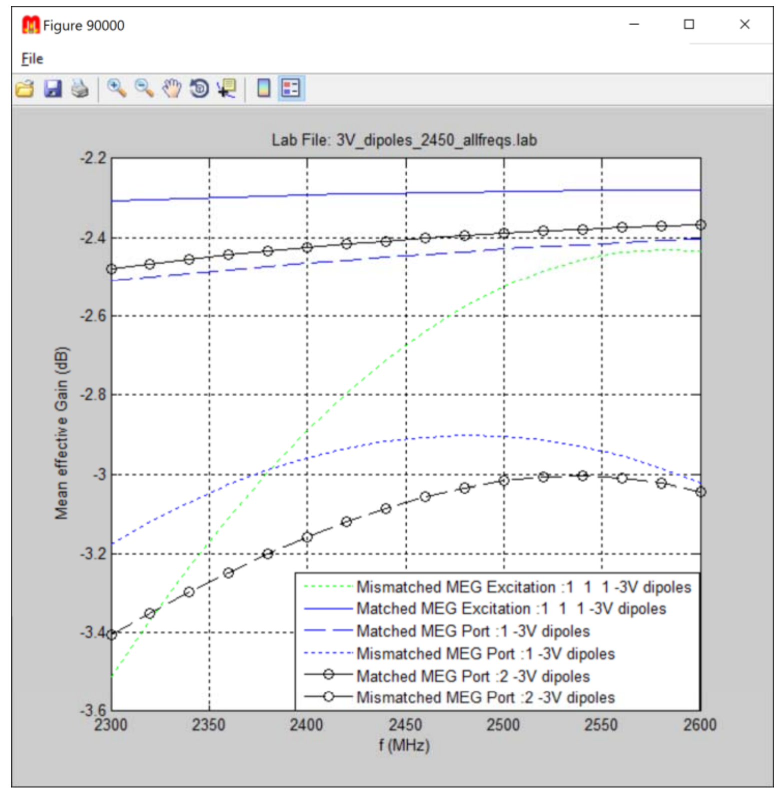


	Tap index	1	2	3	4	5	6	7	8	9
	Excess delay [ns]	0	10	20	30	40	50	60	70	80
Cluster 1	Power [dB]	0	-5.4	-10.8	-16.2	-21.7				
AoA	AoA [°]	4.3	4.3	4.3	4.3	4.3				
AS (receiver)	AS [°]	14.4	14.4	14.4	14.4	14.4				
AoD	AoD [°]	225.1	225.1	225.1	225.1	225.1				
AS (transmitter)	AS [°]	14.4	14.4	14.4	14.4	14.4				
Cluster 2	Power [dB]			-3.2	-6.3	-9.4	-12.5	-15.6	-18.7	-21.8
AoA	AoA [°]			118.4	118.4	118.4	118.4	118.4	118.4	118.4
AS	AS [°]			25.2	25.2	25.2	25.2	25.2	25.2	25.2
AoD	AoD [°]			106.5	106.5	106.5	106.5	106.5	106.5	106.5
AS	AS [°]			25.4	25.4	25.4	25.4	25.4	25.4	25.4

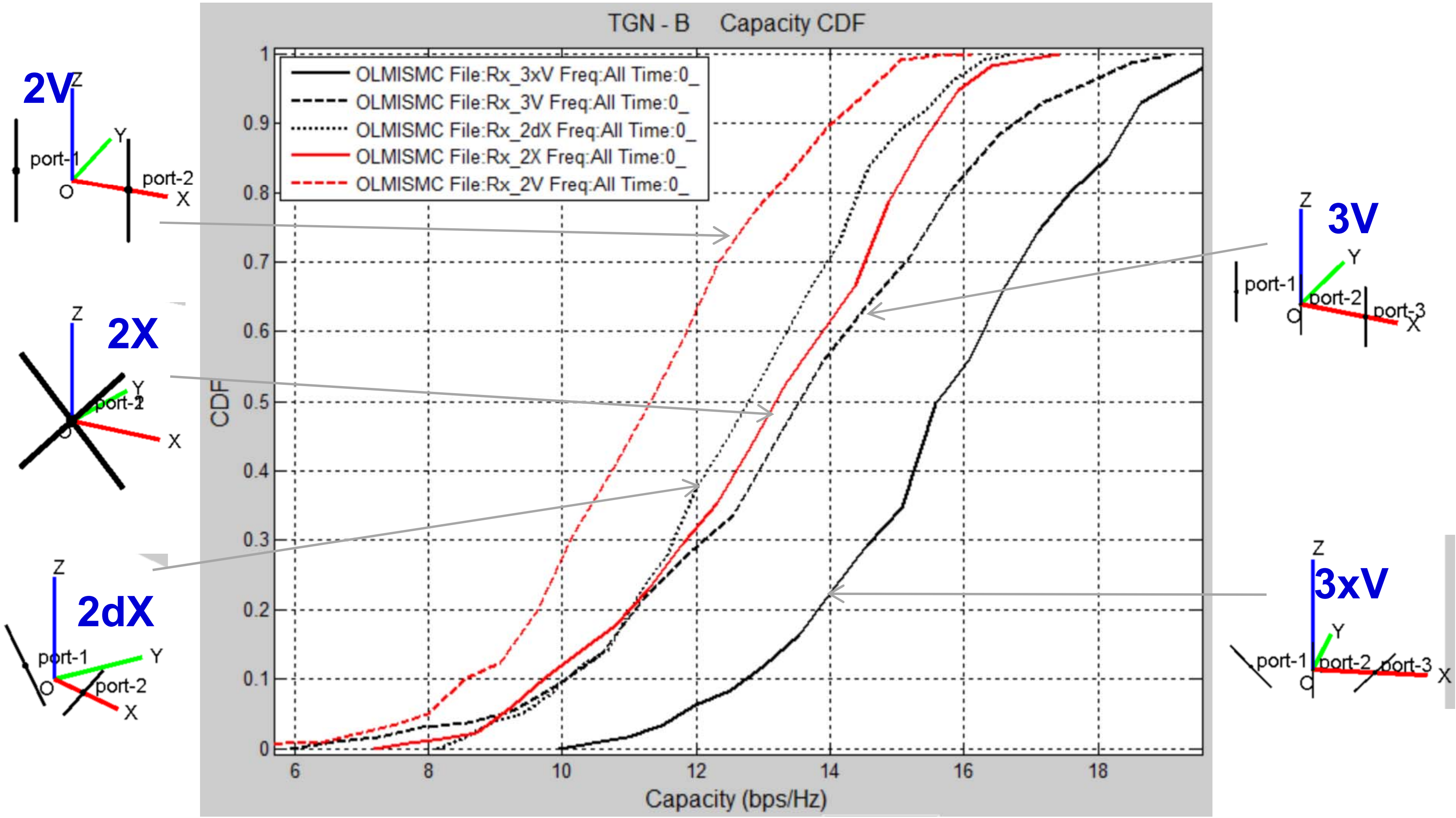
3V DIPOLES ANALYSIS (traditional)







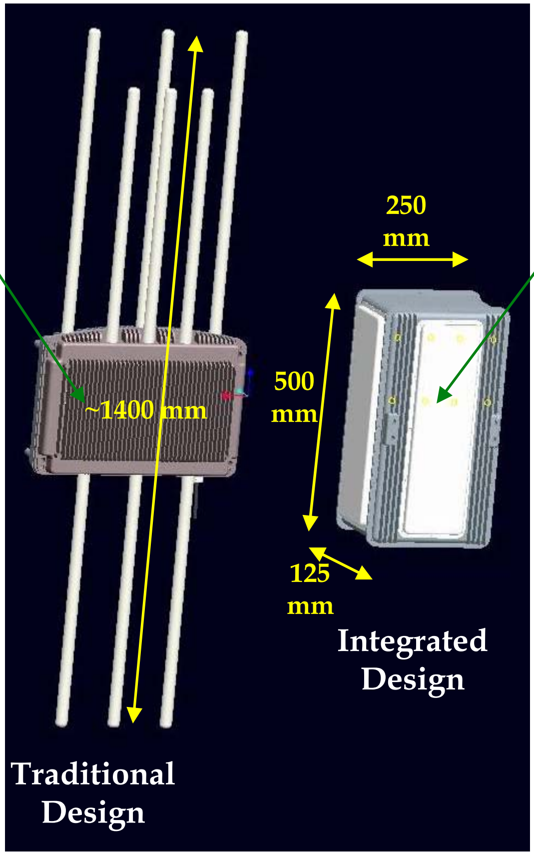
CDF vs. Tx ANTENNA SYSTEM (current analysis)



Analyses and plots obtained via the use of MIMObit 1.0

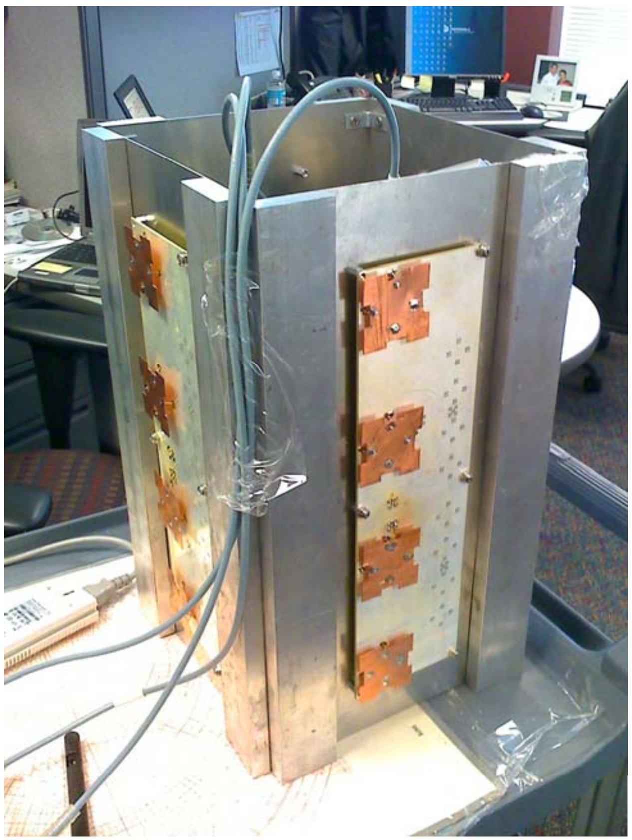
FROM THIS

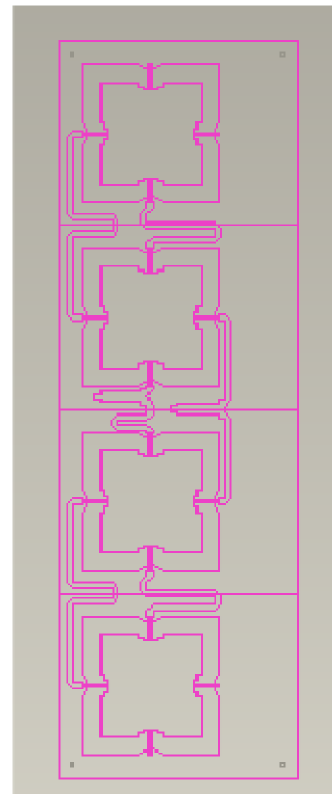
TO THIS



MIMO ANTENNA SYSTEMS: Mesh Networks Access Point

Measurements consistently show ≈2x improvement in system throughput compared to external dipole antennas





MIMO ANTENNA SYSTEMS: Mesh Networks Access Point

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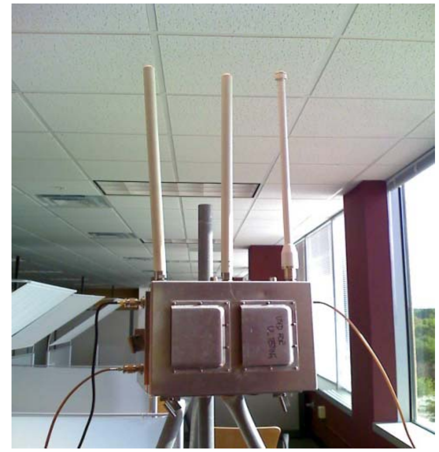
Throughput results

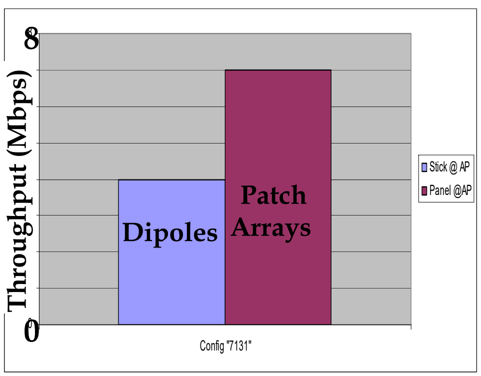
Patch Arrays (2V,1H)
Cost: $222

Dipoles (2V,1H)
Cost: $448

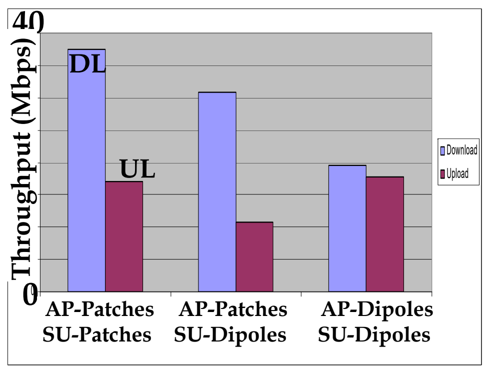


Dipoles (3V)
Cost: $378

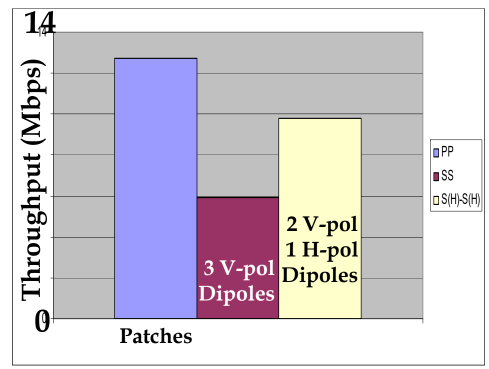
Test conditions:
AP: Symbol 7131 with AUT
SU: Netgear WN511B PC Card
Indoor to Outdoor Environment



Test conditions:
AP: Linksys WRT300N with AUT
SU: Linksys WMP300N with AUT
Outdoor to Outdoor Environment

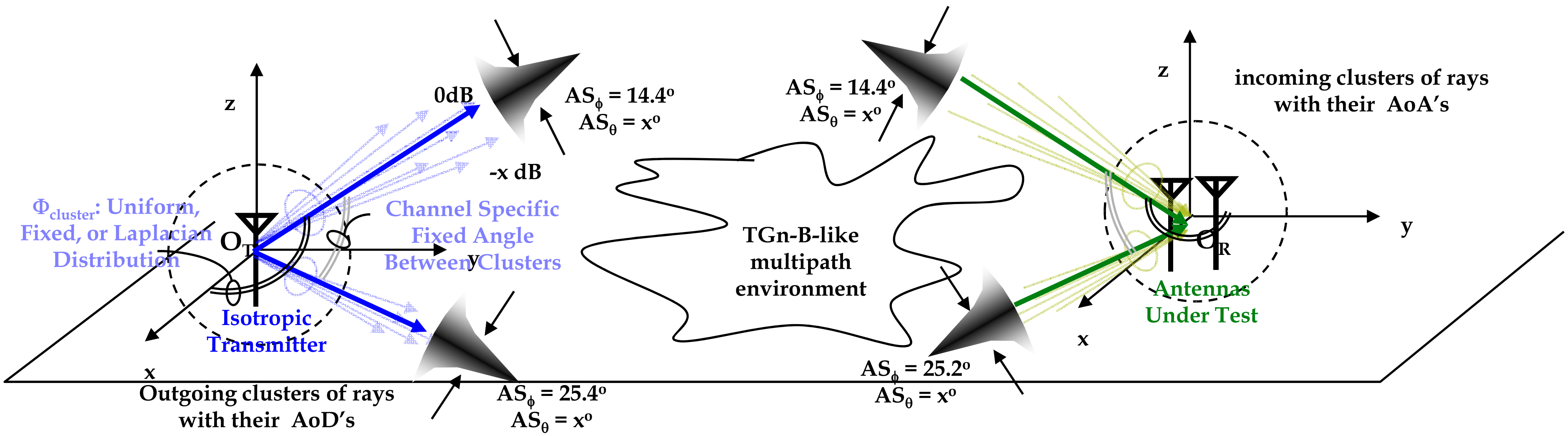


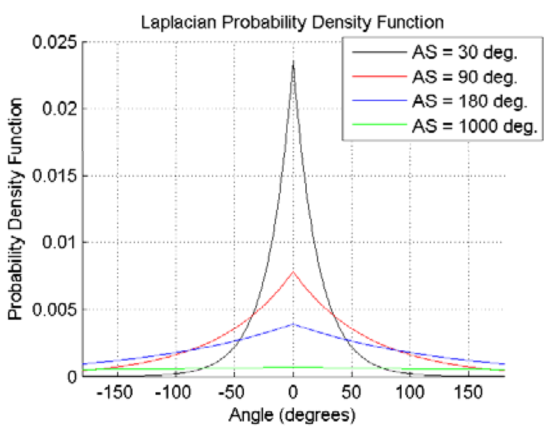
Test conditions:
AP: Linksys WRT300N with AUT
SU: Linksys WMP300N with AUT
Outdoor to Outdoor Environment



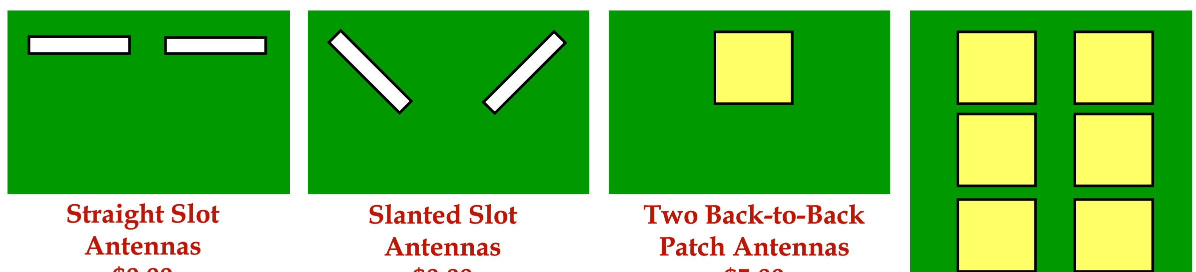
1. Field tests by Pertti Alapuranen of the Mesh Networks Engineering Team

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

MIMO ANTENNA SYSTEMS: AP CPEs

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

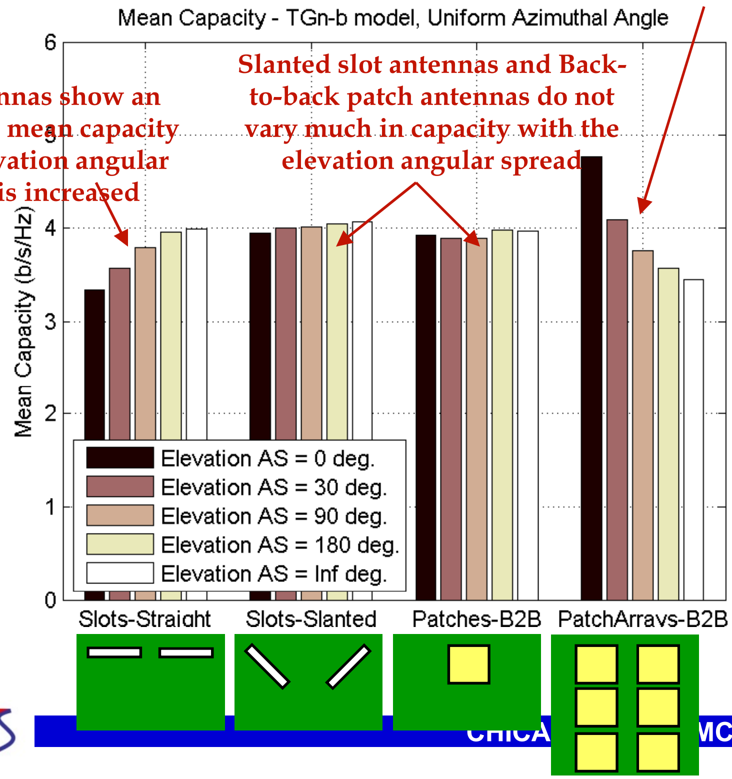
Q2: What is the effect of antenna orientation in a directional channel?

Mean azimuthal angle is stepped through 360°

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

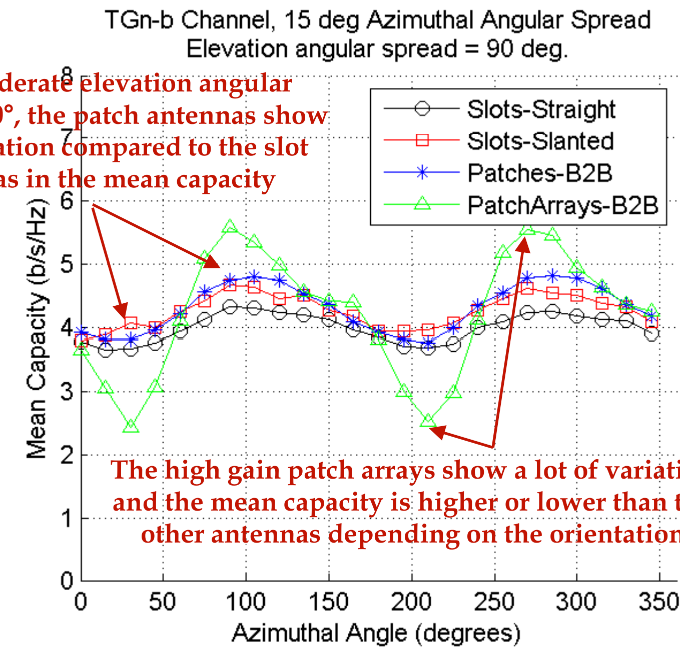
Slot antennas show an increase in mean capacity as the elevation angular spread is increased

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



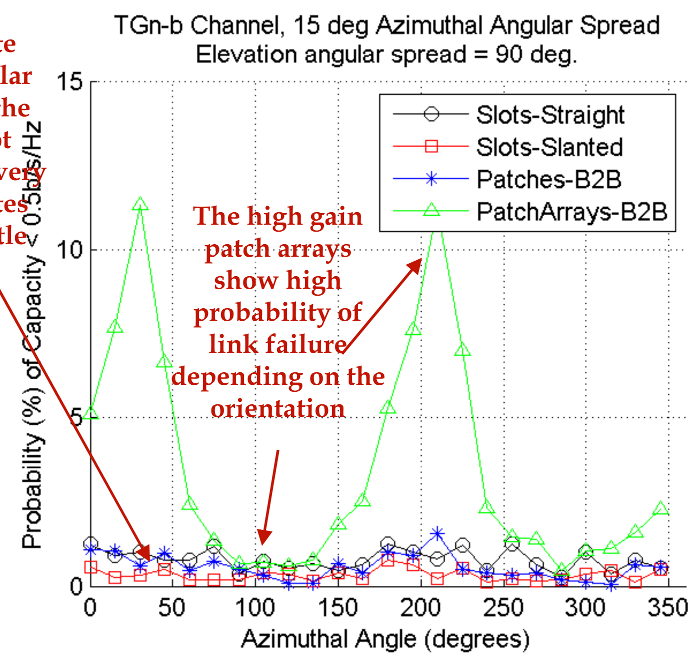
For a moderate elevation angular spread of 90°, the patch antennas show more variation compared to the slot antennas in the mean capacity

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



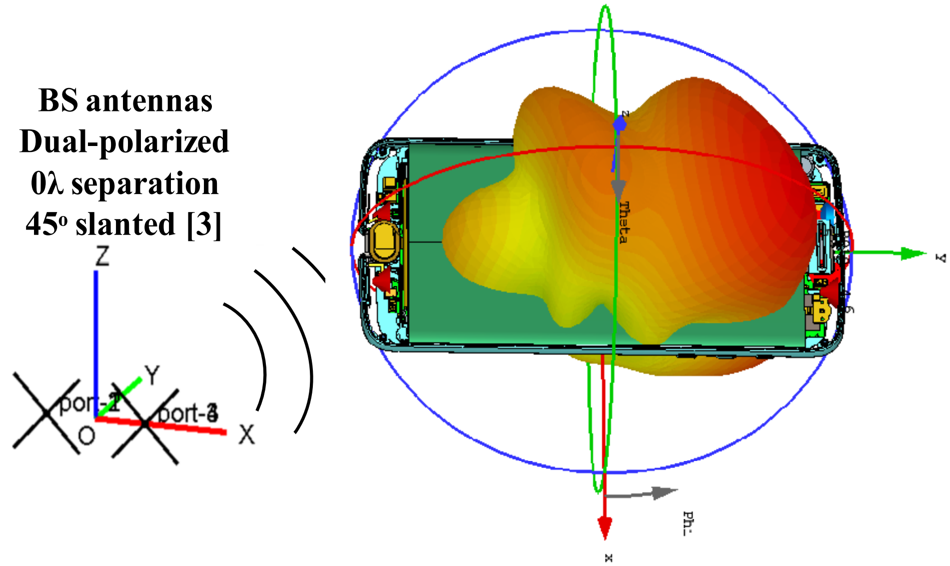
For a moderate elevation angular spread of 90°, the patch and slot antennas show very low failure rates with only a little variation

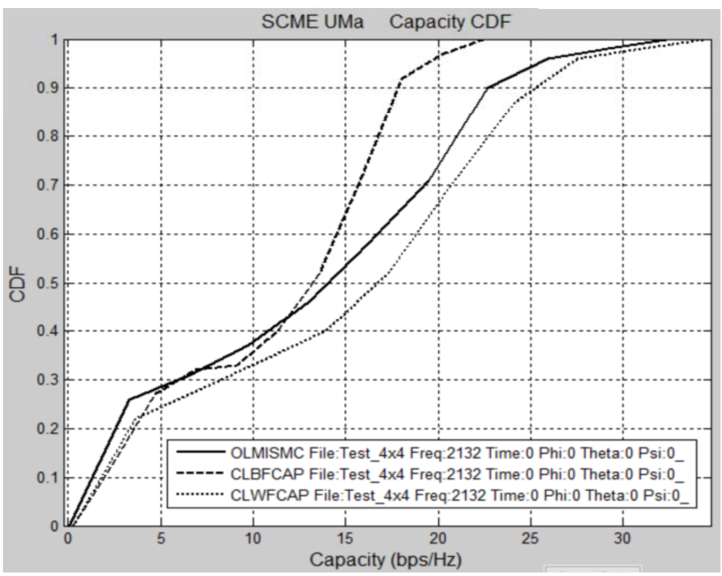
The high gain patch arrays show high probability of link failure depending on the orientation



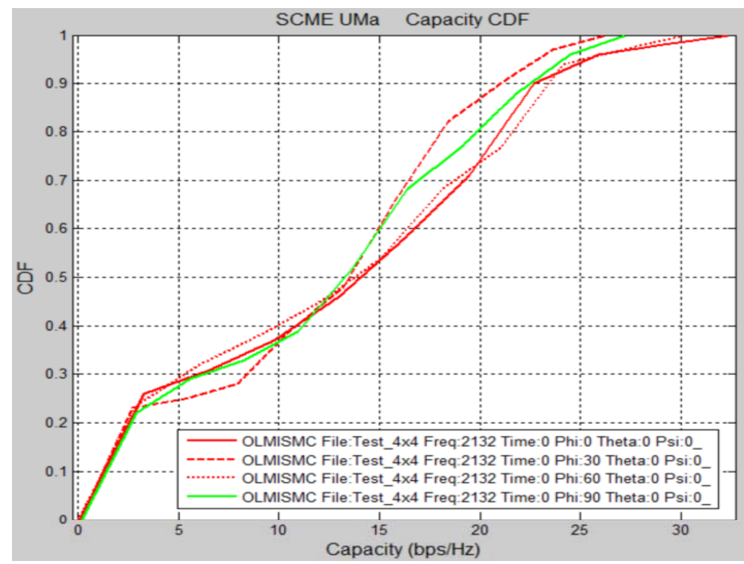
SMART PHONE EXAMPLE

Analyses and plots obtained via the use of MIMObit 1.0



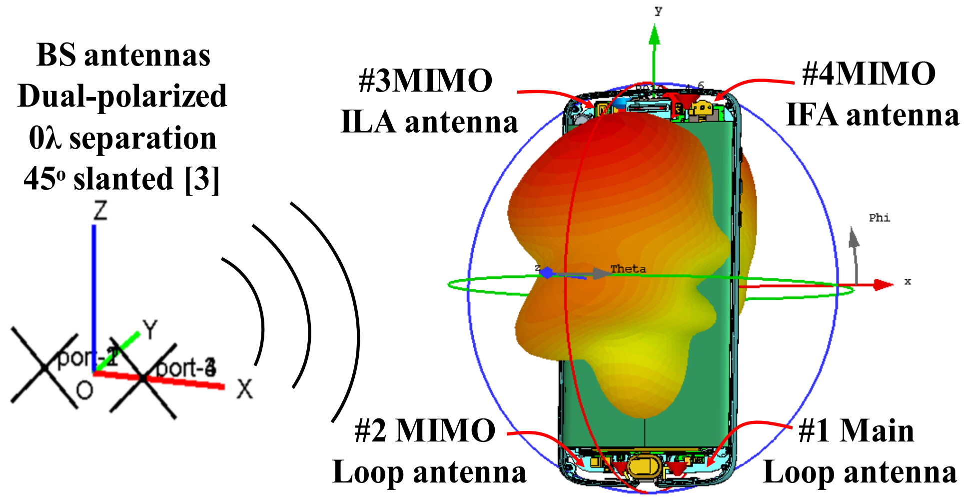


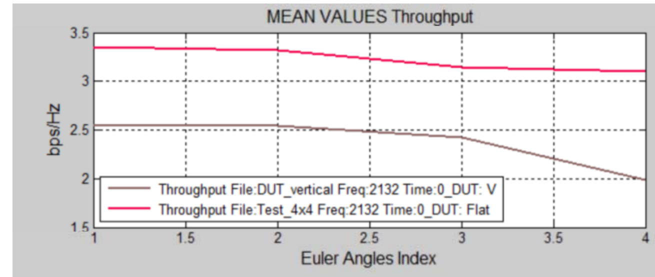
Flat Oriented DUT Capacities



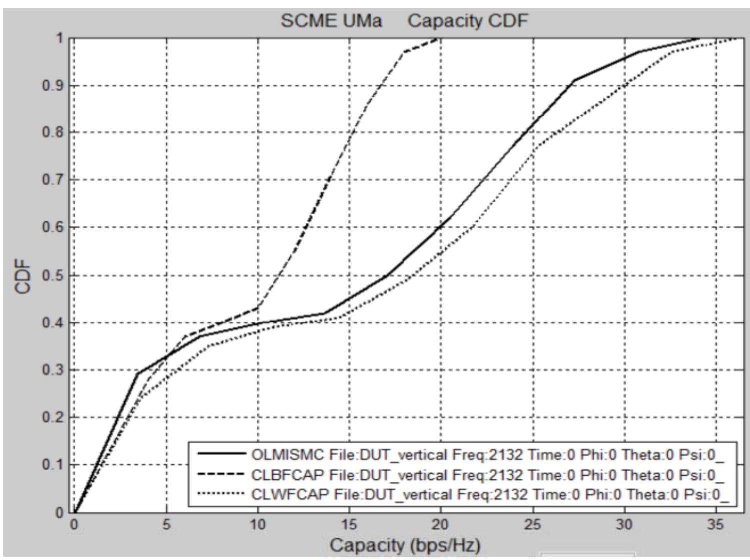
Flat Oriented DUT C vs. angle

SMART PHONE EXAMPLE (Cont.)

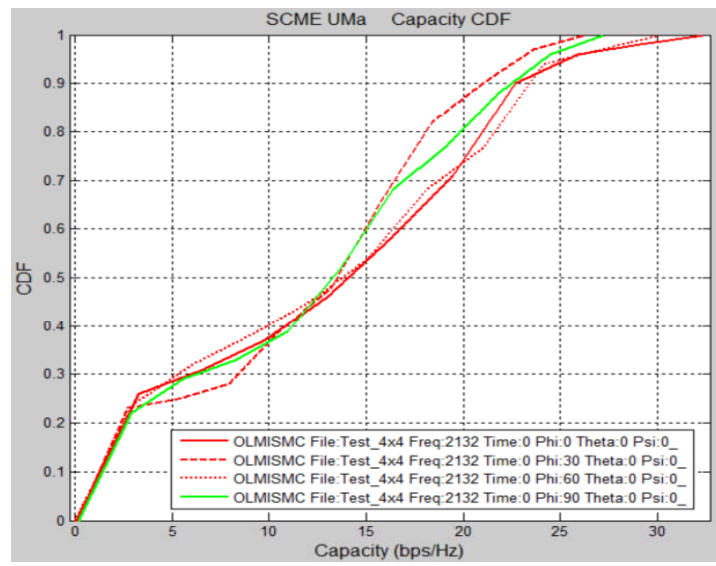




Analyses and plots obtained via the use of MIMObit 1.0



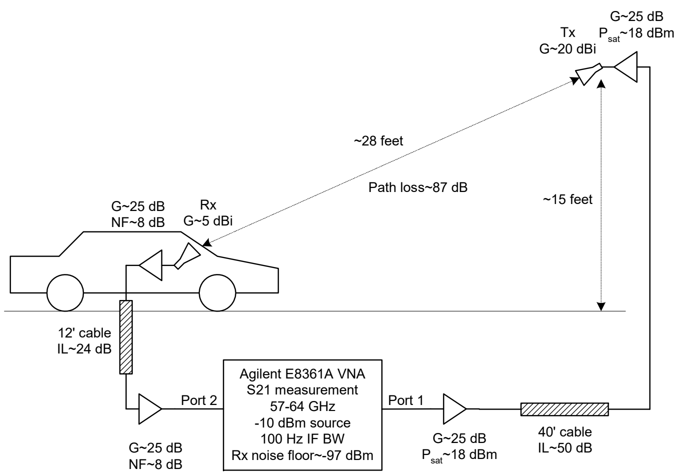
Vertical Oriented DUT Capacities

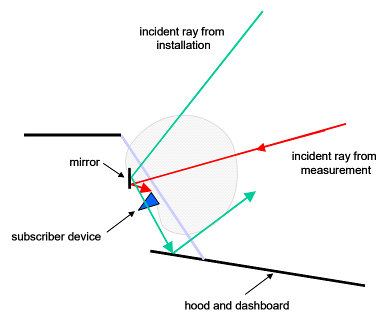


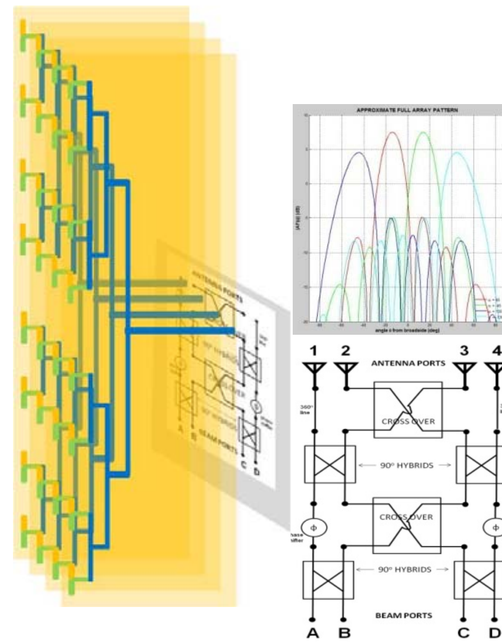
Vertically Oriented DUT C vs. angle

- **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'**







the 'old' way

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