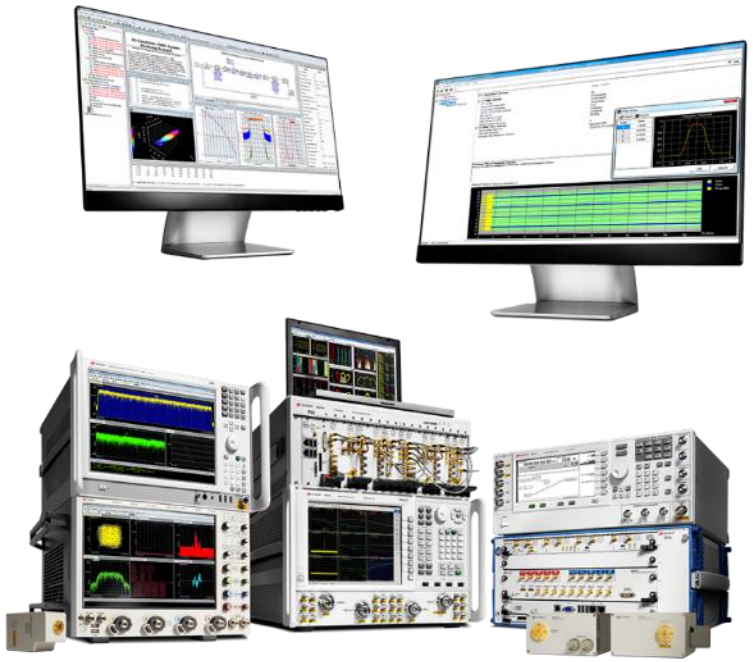
MIMO and Beamforming in the 5G Context

SBrT 2017

05/09/2017



Created by Will Sitch
Presented by Bruno Duarte

KEYSIGHT TECHNOLOGIES

A Brief History of Keysight

HARDWARE + SOFTWARE + PEOPLE = INSIGHTS

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

KEYSIGHT TECHNOLOGIES

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

100x Data Rates

1000x Capacity

100x Densification

1ms Latency

Reliability 99.999%

100x Energy Efficiency

All founded on a solid business model.

KEYSIGHT TECHNOLOGIES

The importance of MIMO to deliver the 5G

It brings us more data

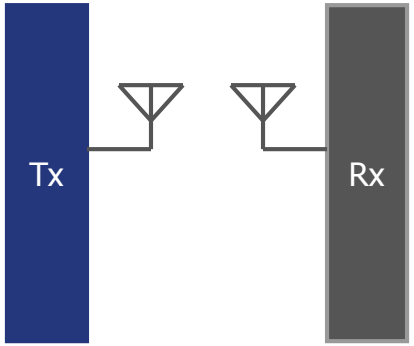
Shannon-Hartley Theorem:

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

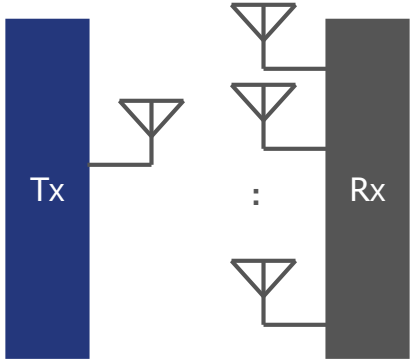
Increase data capacity by:

- 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

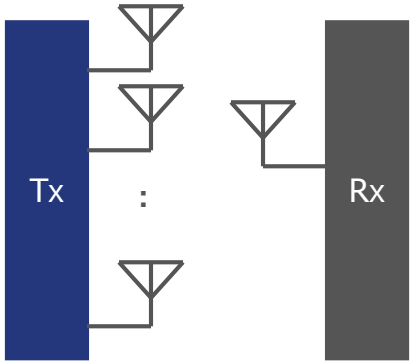
Types of Multiple Antenna Systems



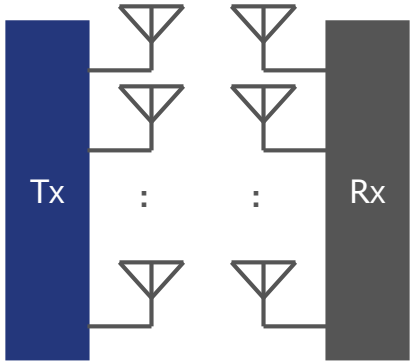
SISO
- No diversity protection against fading



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



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



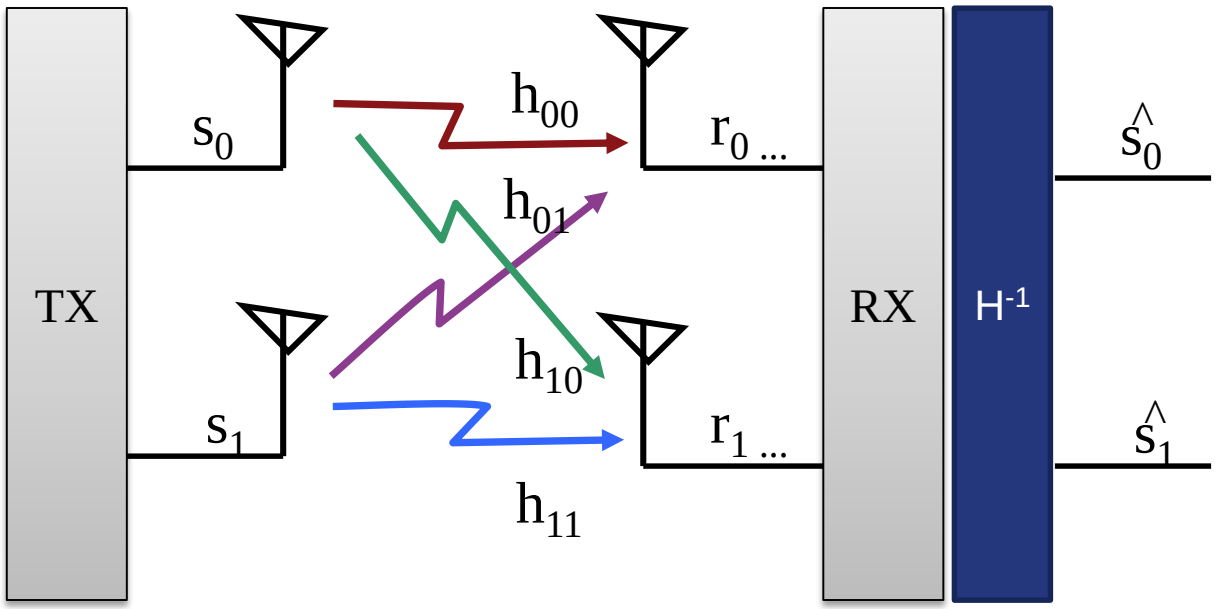
MIMO
- Tx/Rx diversity
- Tx/Rx smart antenna (beamforming)
- Spatial multiplexing
- Improved SINR

Or

Improved spectral efficiency/data rates

Single User MIMO

Multiple Spatial Channels for Higher Data Rates to 1 User



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

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

$$R = HS$$

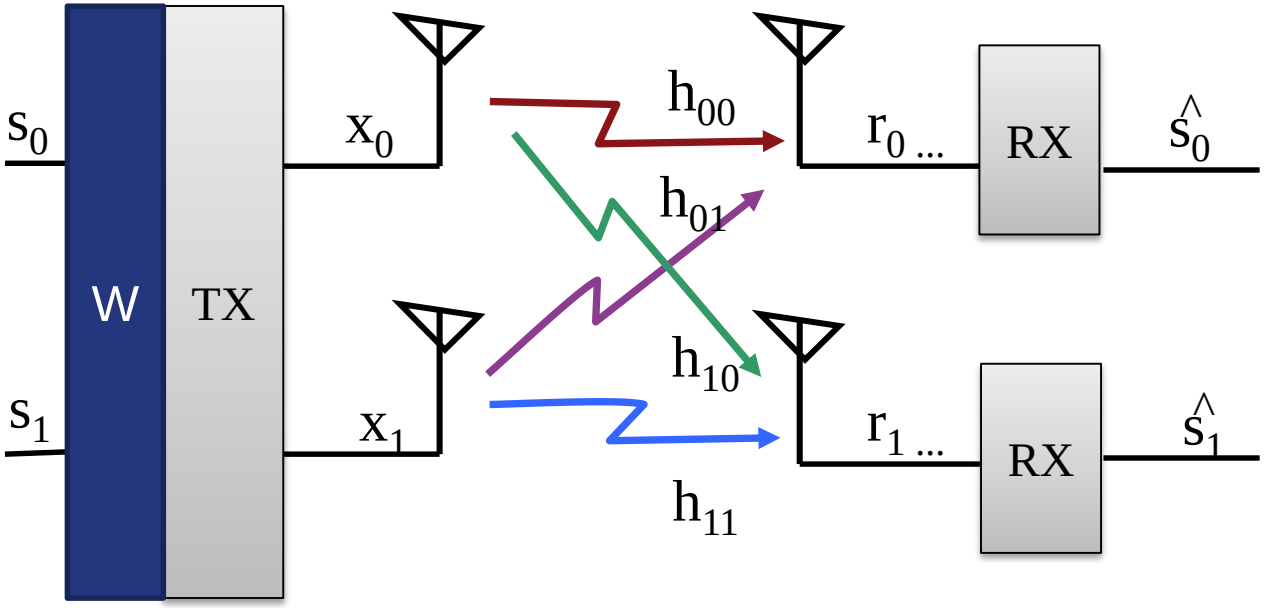
or

$$\hat{S} = H^{-1}R$$

In this simple example, the receiver is responsible for de-multiplexing the two data streams. The receiver does this with knowledge of the channel [H]

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]

$$\begin{bmatrix} x_0 \\ x_1 \end{bmatrix} = \begin{bmatrix} w_{00} & w_{01} \\ w_{10} & w_{11} \end{bmatrix} \begin{bmatrix} s_0 \\ s_1 \end{bmatrix} \qquad \begin{bmatrix} \hat{s}_0 \\ \hat{s}_1 \end{bmatrix} = \begin{bmatrix} h_{00} & h_{01} \\ h_{10} & h_{11} \end{bmatrix} \begin{bmatrix} x_0 \\ x_1 \end{bmatrix}$$

$$\hat{S} = HX = HWS = (HW)S$$

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

$$\cancel{W = H^{-1}} \qquad \boxed{W = H^T(HH^T)^{-1}}$$

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

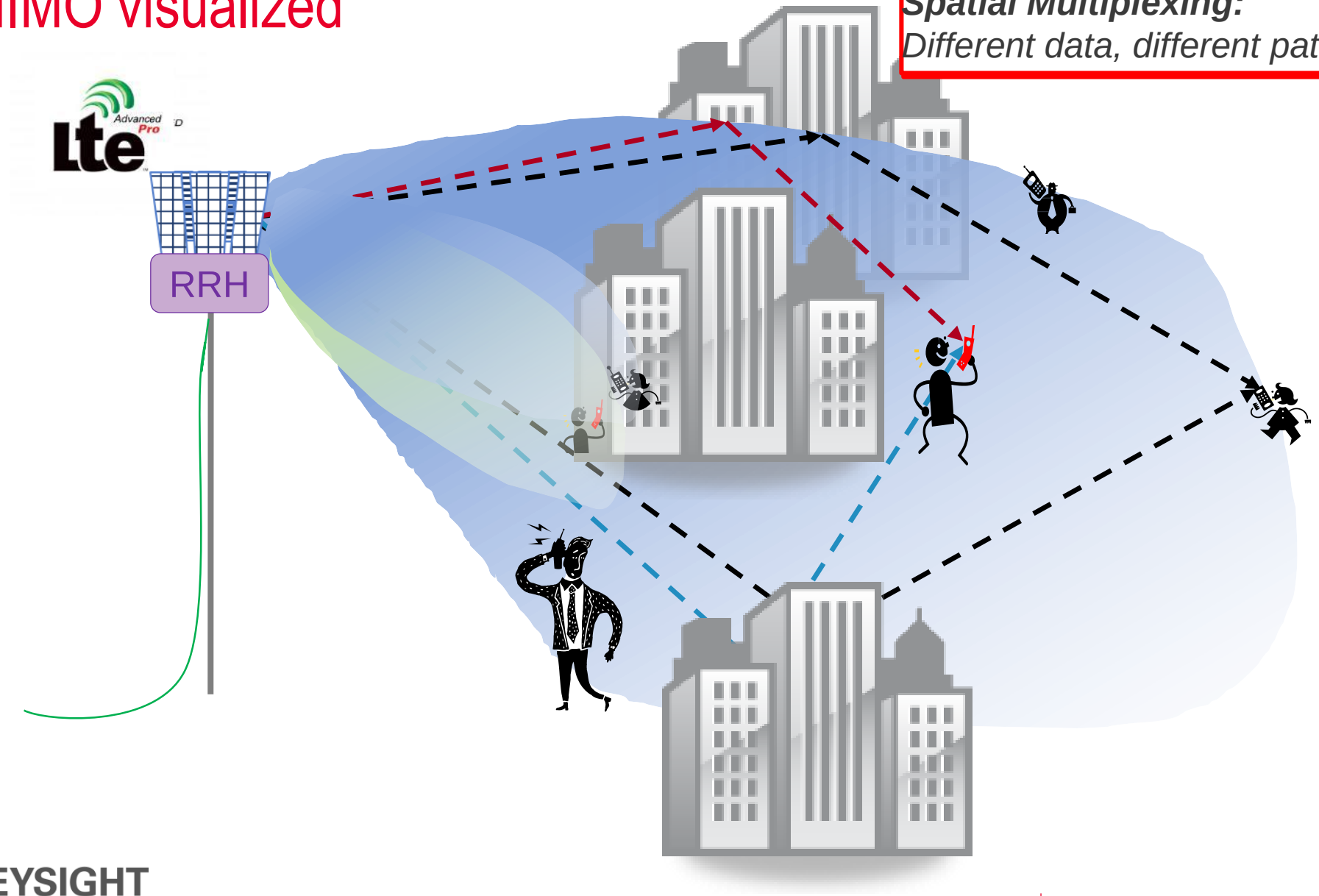
- UEs send codes that instruct base station about channel
- Improves type/quality of base station encoding

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



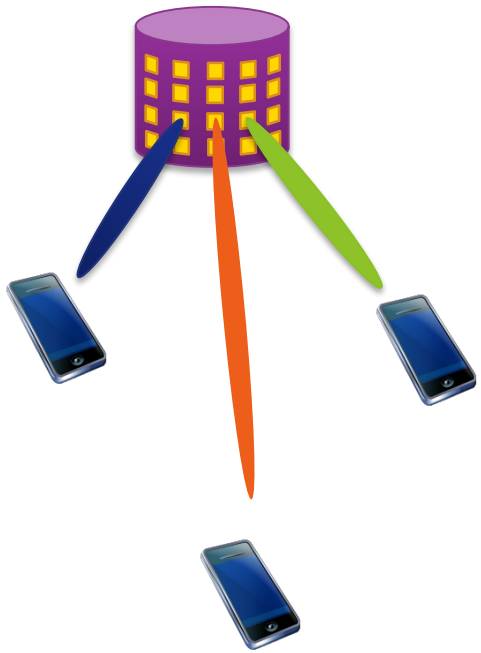
Understanding Massive MIMO

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*

The Graphics

Overly simplified!



The Math

Not completely intuitive!

$$\bar{y}_j \equiv \hat{G}_{jj}^{\dagger}\bar{x}_j$$
$$= \left[\sqrt{\rho_{\mathrm{p}}}\sum_{\ell_1=1}^{L} G_{j\ell_1} + V_j\right]^{\dagger}\left[\sqrt{\rho_{\mathrm{r}}}\sum_{\ell_2=1}^{L} G_{j\ell_2}\bar{a}_{\ell_2} + \bar{w}_j\right],$$

$$\frac{1}{M\sqrt{\rho_{\mathrm{p}}\rho_{\mathrm{r}}}}y_{kj} \to \beta_{jkj}a_{kj} + \sum_{\ell\neq j}\beta_{jk\ell}a_{k\ell}.$$

$$\bar{x}_\ell = \sqrt{\rho_{\mathrm{f}}}\sum_{j=1}^{L} G_{j\ell}^{T}\hat{G}_{jj}^{*}\bar{a}_j + \bar{w}_\ell,$$
$$= \sqrt{\rho_{\mathrm{f}}}\sum_{j=1}^{L} G_{j\ell}^{T}\left[\sqrt{\rho_{\mathrm{p}}}\sum_{\ell=1}^{L} G_{j\ell} + V_j\right]^{*}\bar{a}_j + \bar{w}_\ell$$

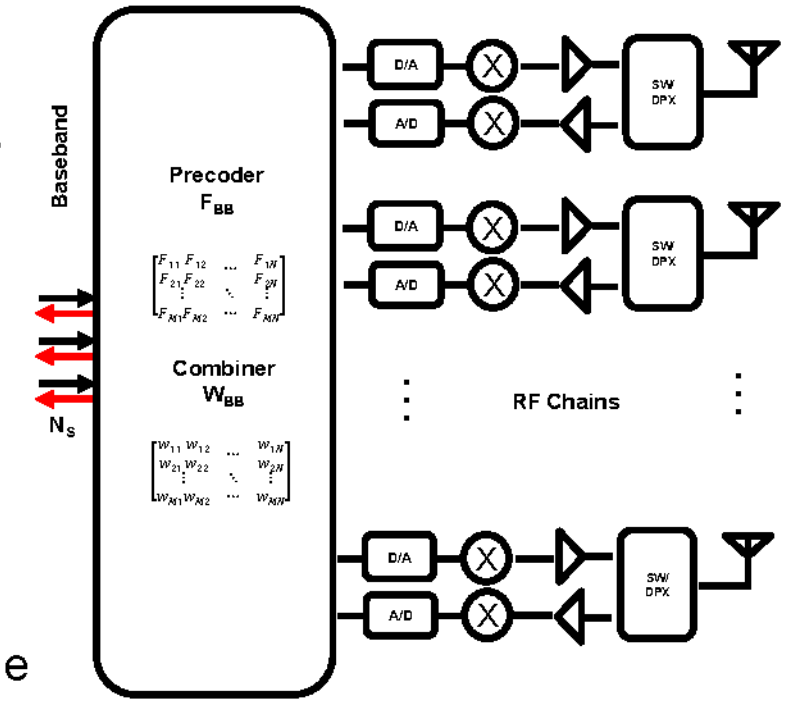
Equations from "Noncooperative Cellular Wireless with Unlimited Numbers of Base Station Antennas", by Thomas L. Marzetta

Massive MIMO is different from other MIMO

Base stations transmit to all UEs in each resource block

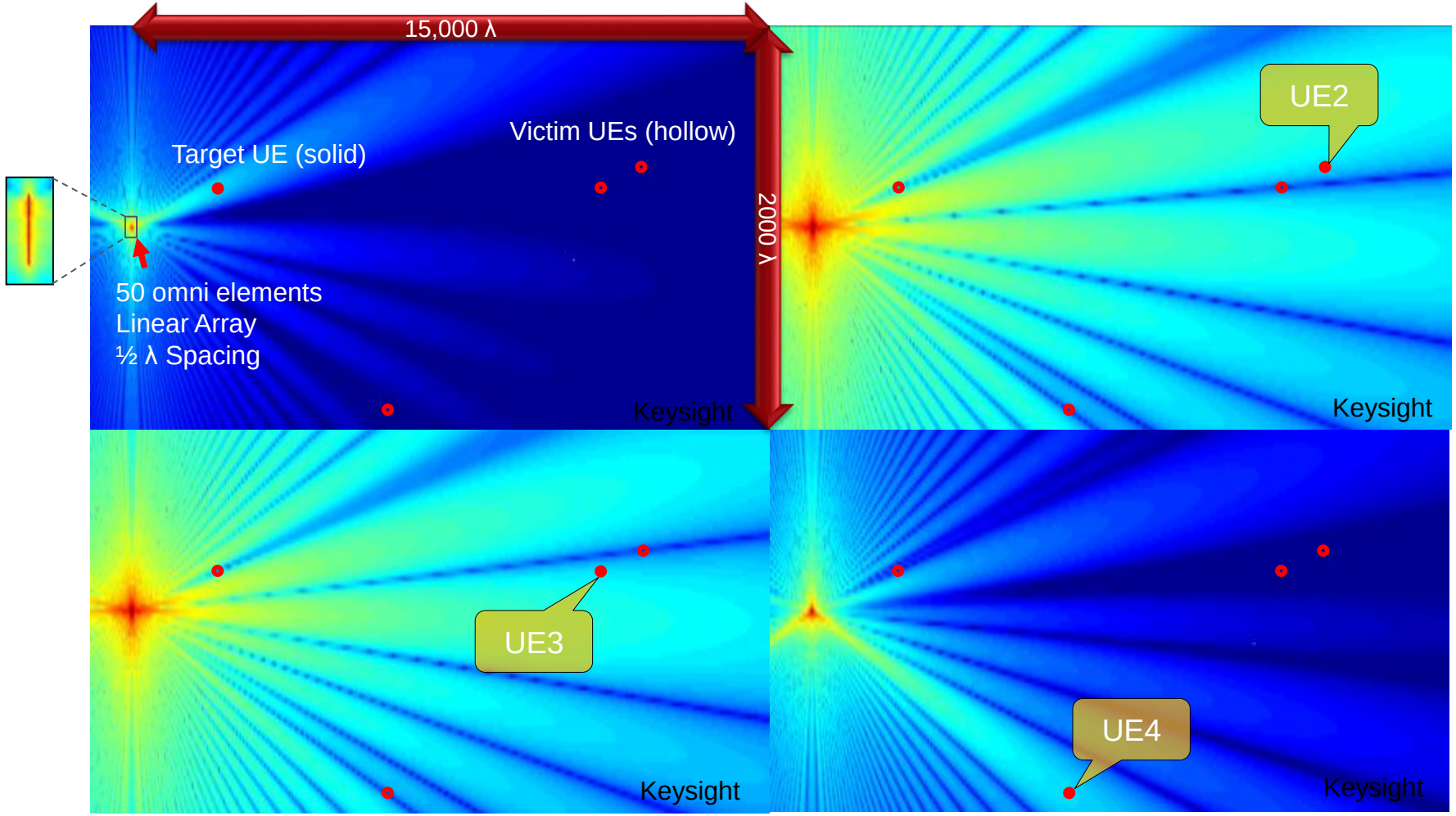
Massive MIMO has a digital architecture:

- 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



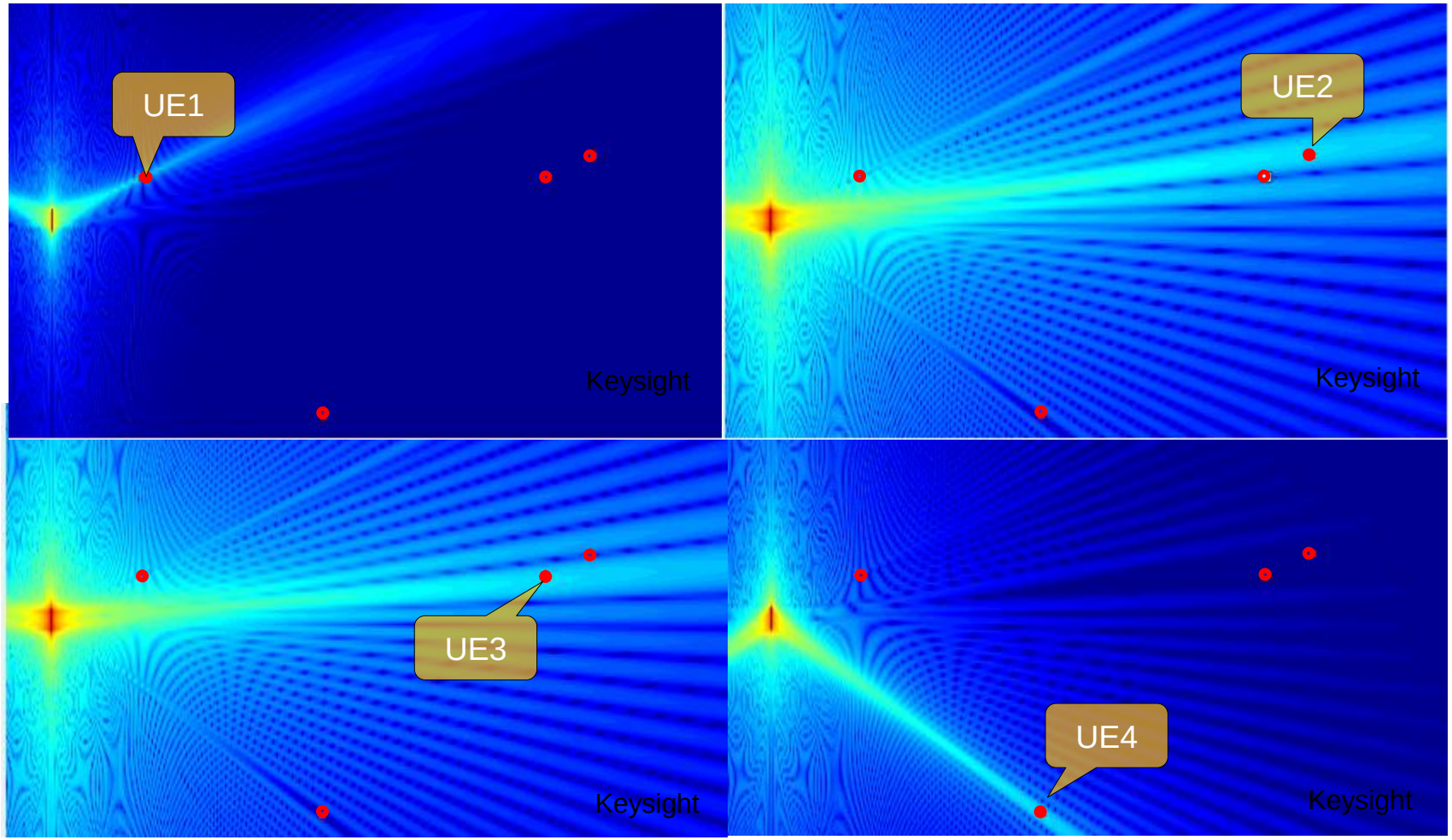
2D Massive MIMO, Free-space Path Loss Only

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



Massive MIMO Free Space

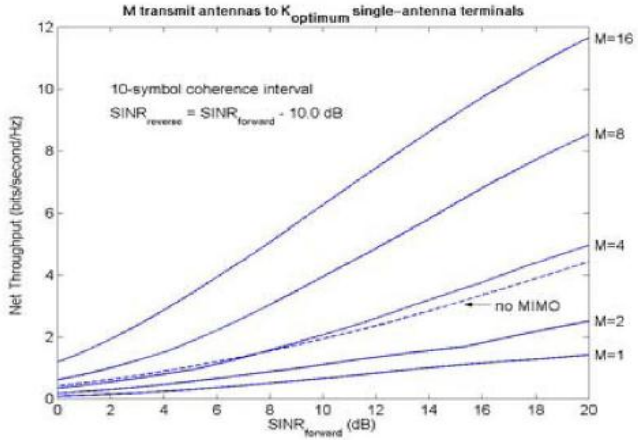
200 Ant,1/2 λ, Total Power Relative to Reference: -9.5 dB

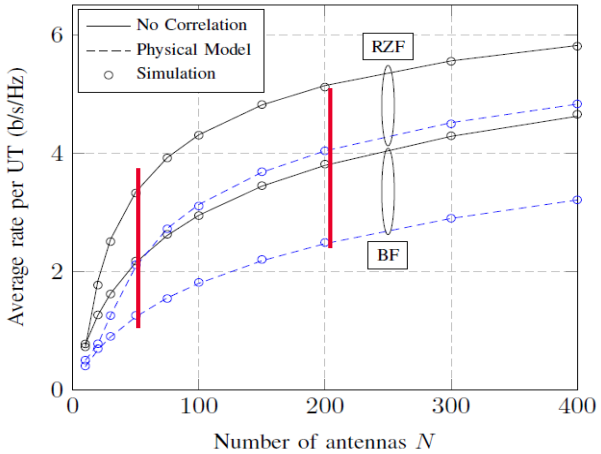


Observations of Massive MIMO

Number of Base Station Antennas

- Initial Analysis of 1, 2, 4, 8 an 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, M´erouane Debbah*

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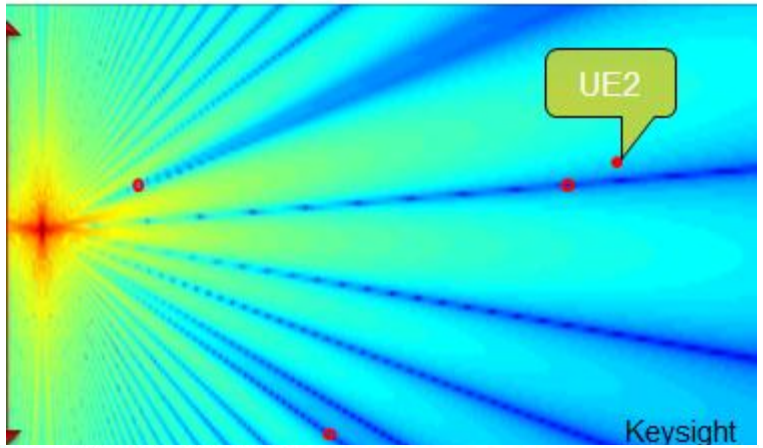

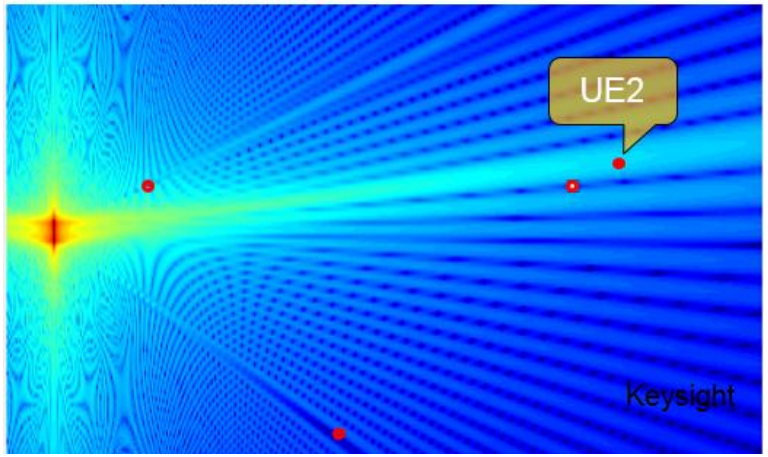

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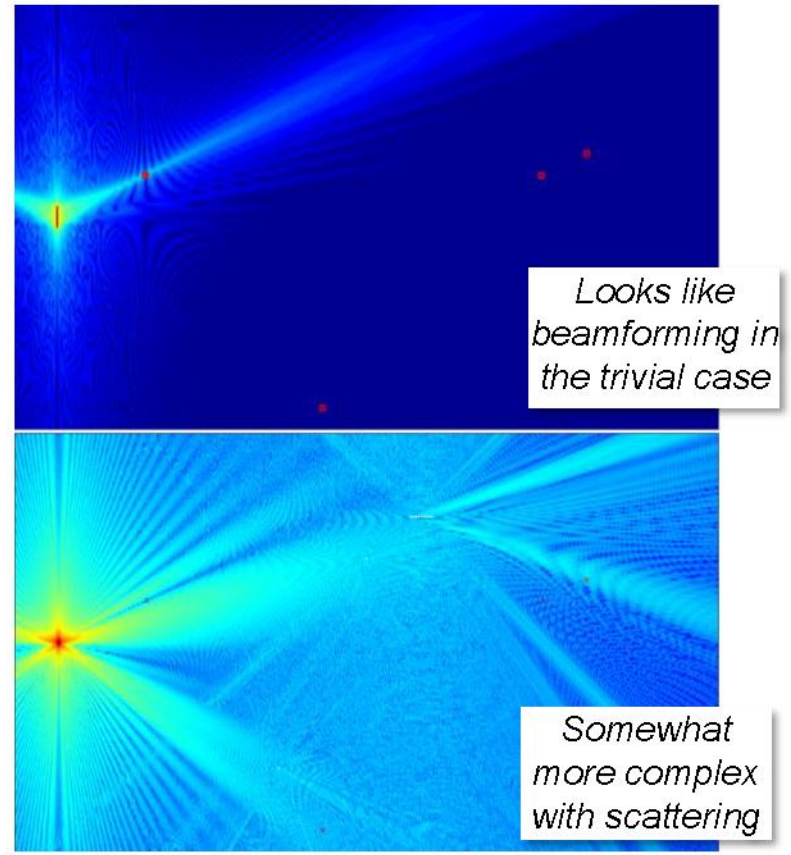
"Beamforming"

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.

Massive MIMO



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

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

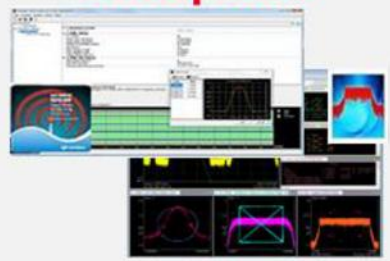
Keysight MIMO and Beamforming Solutions

For Components, Circuits, Devices, Systems

Simulate & Visualize

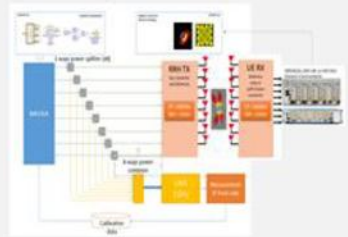
Electronic Design Automation Software

Calibrate & Capture



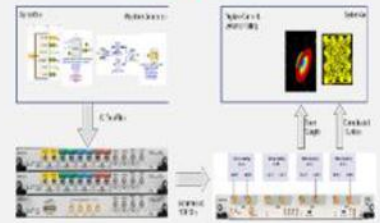
World's Fastest and Most Accurate Measurement Science

Emulate in Real Time

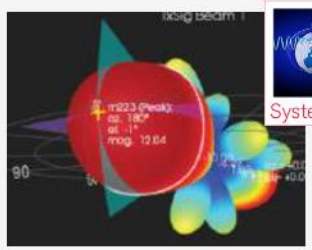


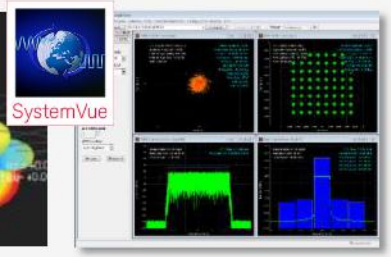
Emulation, Visualization, Performance Metrics

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

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MIMO Explorer Reference Solution

Accelerate MIMO designs and gain deeper insight

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FD-MIMO Measurement

8 LTE carriers; simultaneous demod and measurement

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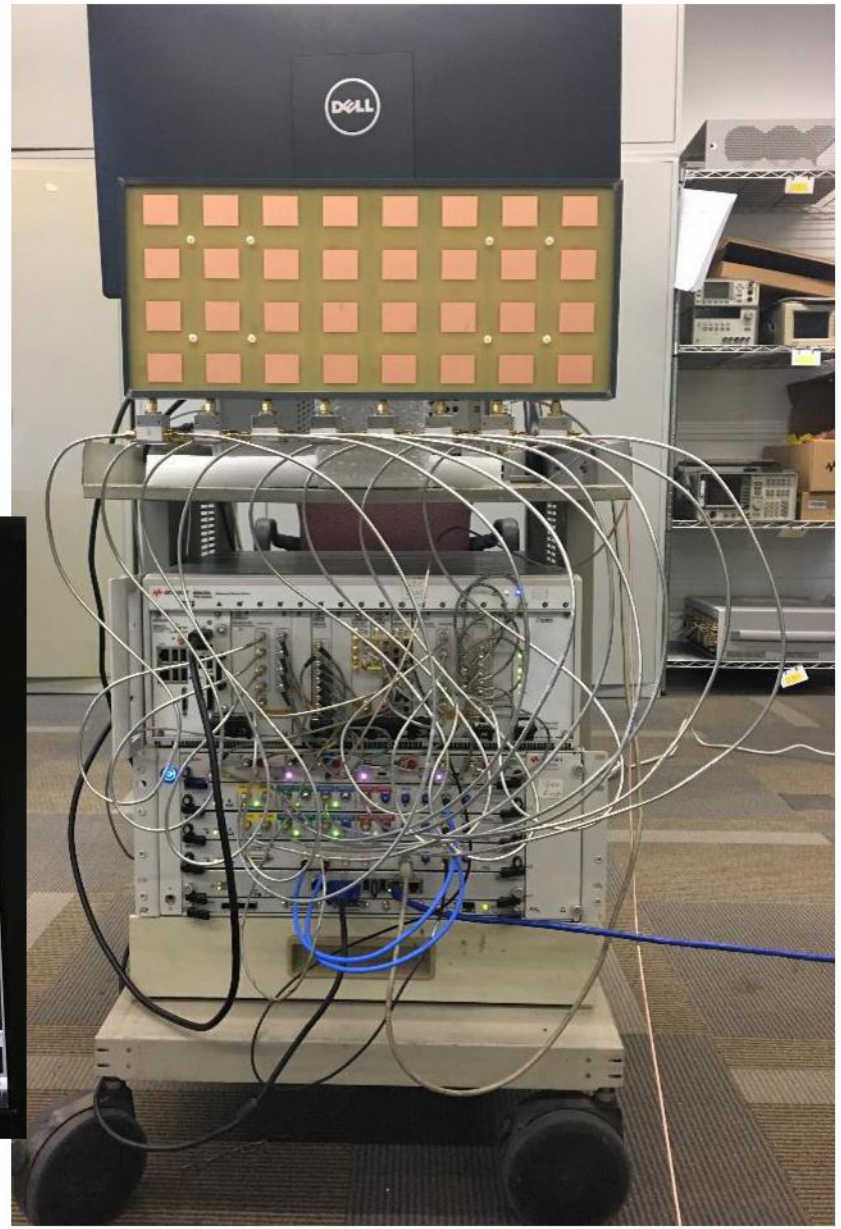
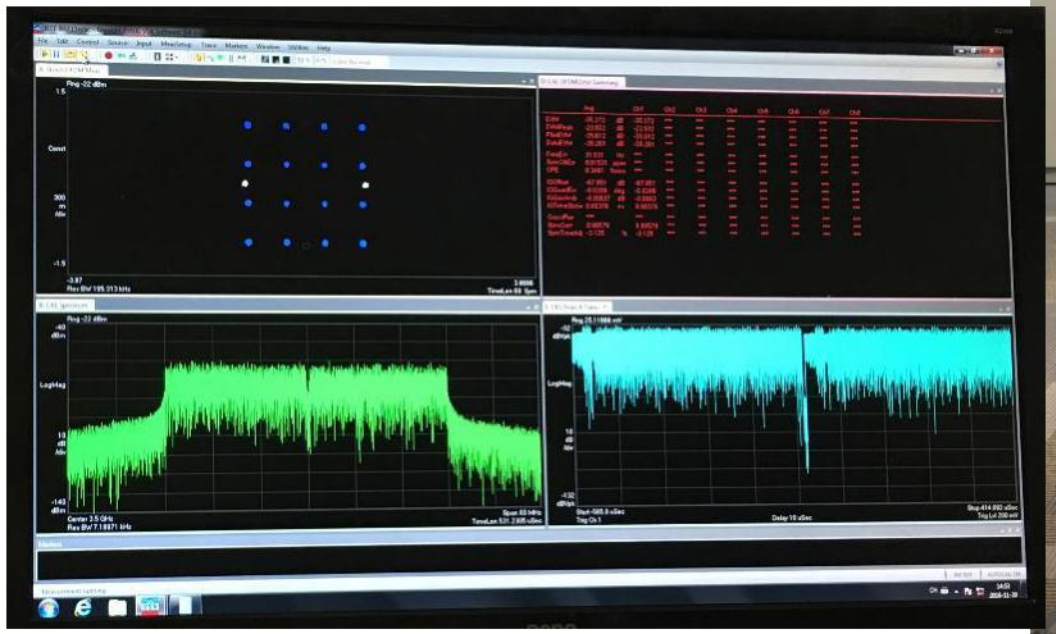
Beamforming Test System





KEYSIGHT TECHNOLOGIES

Thank You !!!

Questions and Answers

Bruno Duarte

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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