IEEE COMMUNICATIONS SOCIETY Boston Chapter

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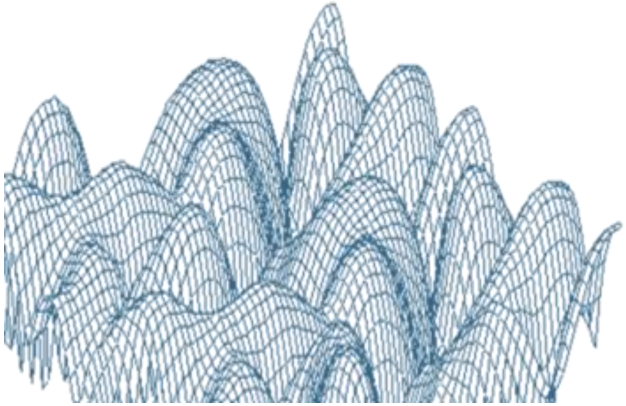
THROUGHPUT TEST METHODS FOR MIMO RADIOS



9-Jan-2014

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IEEE Women in Engineering

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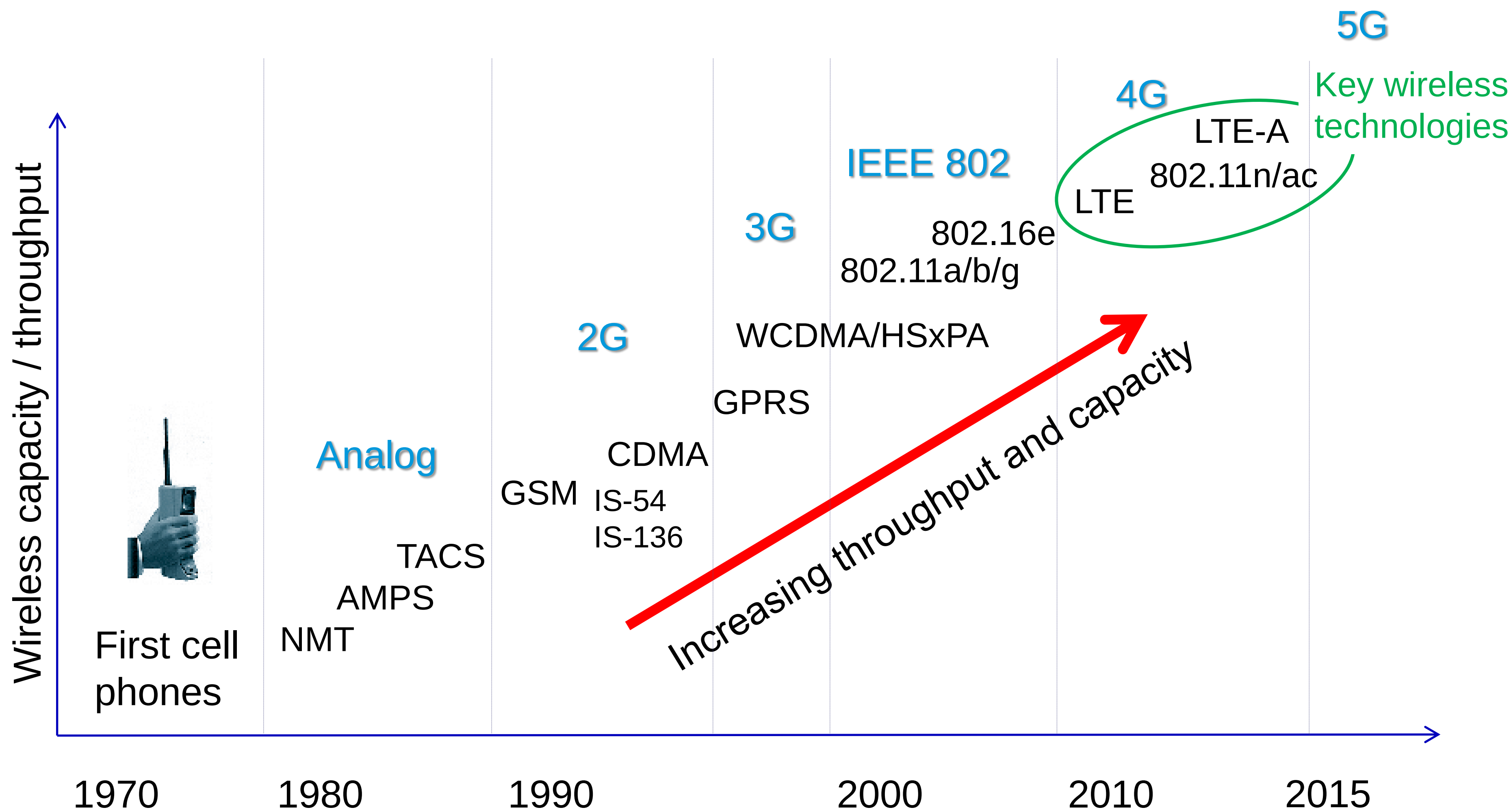
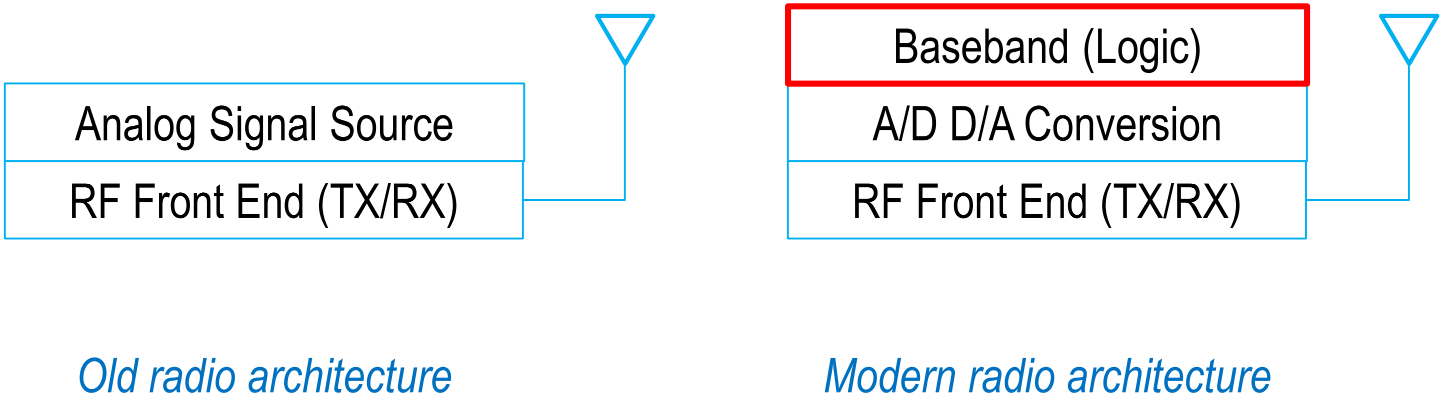
Brief History of Wireless



G = generation

Analog to Logic Transition in Radio Architecture



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The Gs

G		Peak Data Rate (Mbps)	
		Downlink	Uplink
1	Analog	19.2 kbps	
2	Digital – TDMA, CDMA	14.4 kbps	
3	Improved CDMA variants (WCDMA, CDMA2000)	144 kbps (1xRTT); 384 kbps (UMTS); 2.4 Mbps (EVDO)	
3.5	HSPA (today)	14 Mbps	2 Mbps
3.75	HSPA (Release 7) DL 64QAM or 2x2 MIMO; UL 16QAM	28 Mbps	11.5 Mbps
	HSPA (Release 8) DL 64QAM and 2x2 MIMO	42 Mbps	11.5 Mbps
3.9	WiMAX Release 1.0 TDD (2:1 UL/DL ratio), 10 MHz channel	40 Mbps	10 Mbps
	LTE, FDD 5 MHz UL/DL, 2 Layers DL	43.2 Mbps	21.6 Mbps
	LTE CAT-3	100 Mbps	50 Mbps
4	LTE-Advanced	1000 Mbps	500 Mbps

History of IEEE 802.11

- **1989**: FCC authorizes ISM bands
  - 900 MHz, 2.4 GHz, 5 GHz
- **1990**: IEEE begins work on 802.11
- **1994**: 2.4 GHz products begin shipping
- **1997**: 802.11 standard approved
- **1998**: FCC authorizes UNII Band, 5 GHz
- **1999**: 802.11a, b ratified
- **2003:** 802.11g ratified
- **2006:** 802.11n draft 2 certification by the Wi-Fi Alliance begins
- **2009:** 802.11n certification
- **2013:** 802.11ad (up to 6.8 Gbps)

→ **2014:** 802.11ac (up to 6.9 Gbps)

802.11 has pioneered commercial deployment of OFDM and MIMO – key wireless signaling technologies

ISM = industrial, scientific and medical
UNII = Unlicensed National Information Infrastructure

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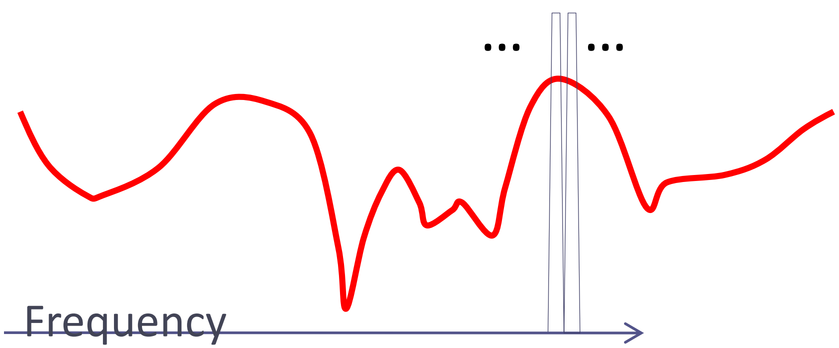
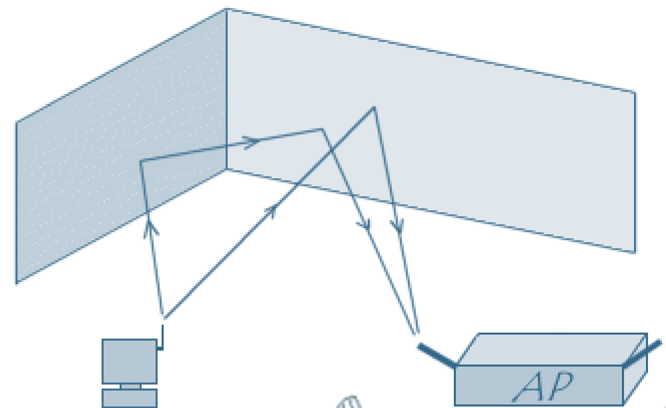
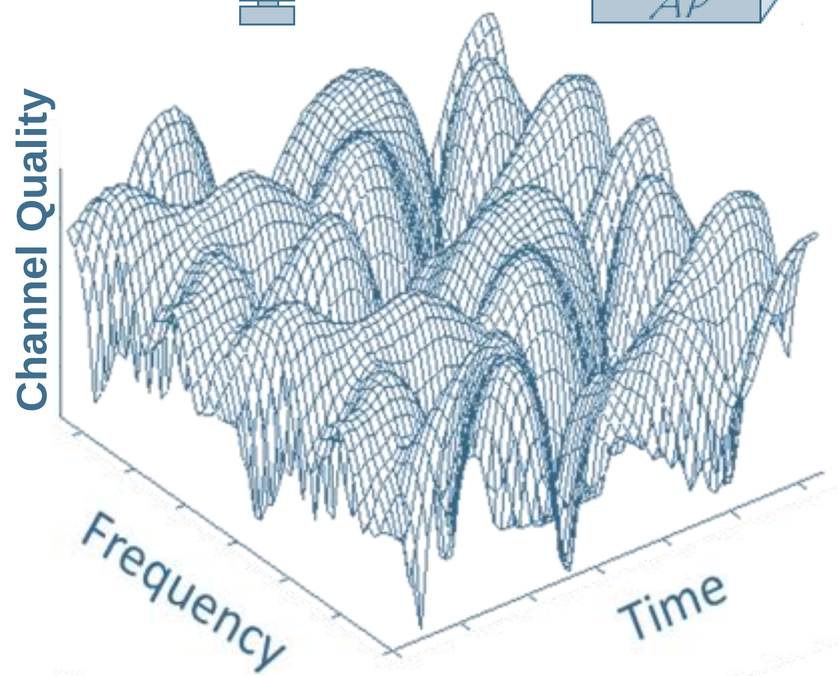
Wireless Channel

- Time and frequency variable
- OFDM transforms a frequency- and time-variable fading channel into parallel correlated flat-fading channels, enabling wide bandwidth operation



Frequency-variable channel appears flat over the narrow band of an OFDM subcarrier.

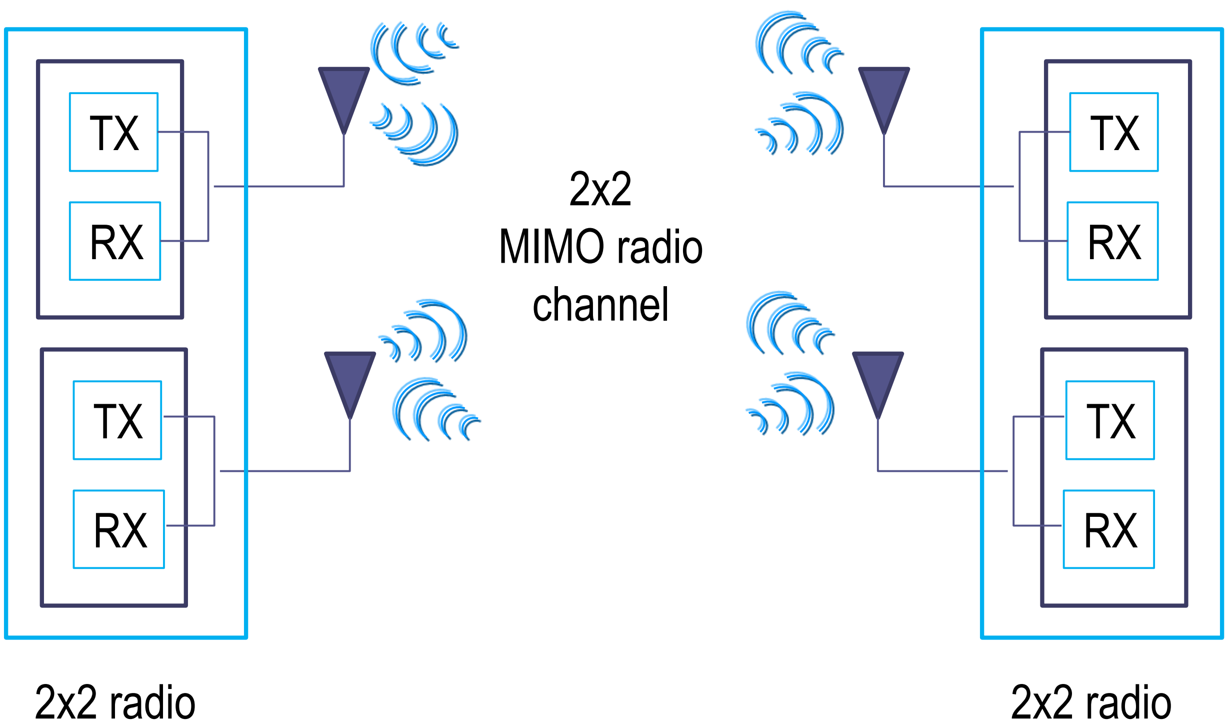




OFDM = orthogonal frequency division multiplexing

MIMO Systems

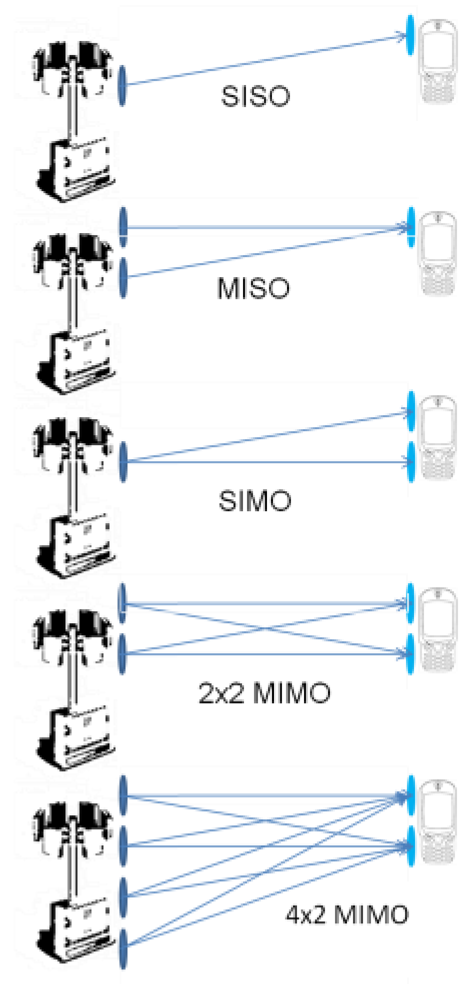
MIMO systems are typically described as NxM, where N is the number of transmitters and M is the number of receivers.



MIMO = multiple input multiple output

MIMO Configurations

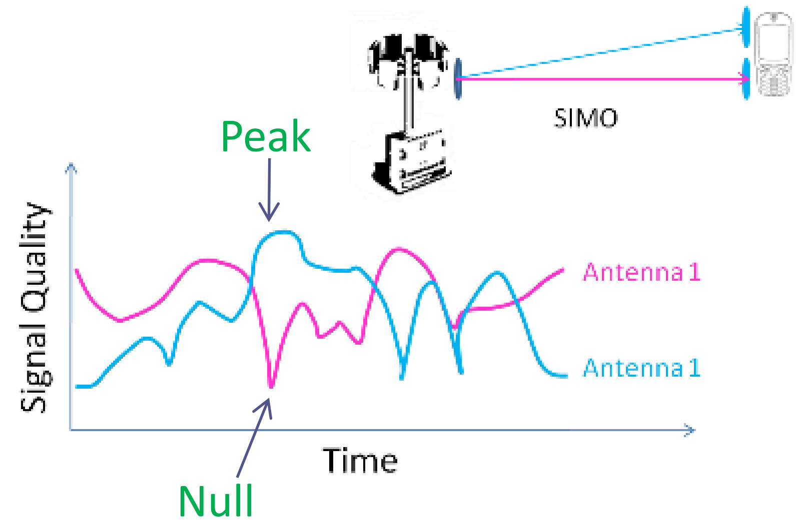
- SISO (Single Input Single Output)
  - Traditional radio
- MISO (Multiple Input Single Output)
  - Transmit diversity (STBC, SFBC, CDD)
- SIMO (Single Input Multiple Output)
  - Receive diversity, MRC
- MIMO (Multiple Input Multiple Output)
  - SM to transmit multiple streams simultaneously; can be used in conjunction with CDD; works best in high SNR environments and channels de-correlated by multipath
  - TX and RX diversity, used independently or together; used to enhance throughput in the presence of adverse channel conditions
- Beamforming

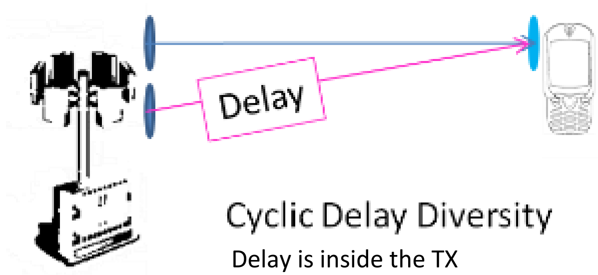


MIMO = multiple input multiple output
SM = spatial multiplexing
SFBC = space frequency block coding
STBC = space time block coding
CDD = cyclic delay diversity
MRC = maximal ratio combining
SM = Spatial Multiplexing
SNR = signal to noise ratio

MIMO Based RX and TX Diversity

- When 2 receivers are available in a MIMO radio MRC can be used instead of simple diversity to combine signals from two or more antennas, improving SNR
- MIMO also enables transmit diversity techniques, including CDD, STBC, SFBC
- TX diversity is used to spread the signal so as to create artificial multipath to decorrelate signals from different transmitters so as to optimize signal reception





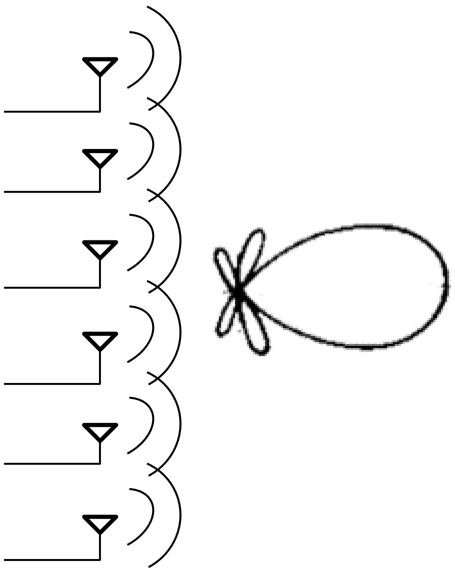
MIMO = multiple input multiple output
SIMO = single input multiple outputs
SM = spatial multiplexing
SFBC = space frequency block coding
STBC = space time block coding
CDD = cyclic delay diversity
MRC = maximal ratio combining
SNR = signal to noise ratio

MIMO Channel Correlation

- Correlation represents an ability to send multiple spatial streams in the same channel and in the same cell
- According to Shannon law *the lower the MIMO channel correlation the higher the MIMO channel capacity*
- Correlation is a function of
  - TX and RX antenna correlation (function of antenna spacing and polarization)
  - Angular spread of reflections (multipath widens AS and thus lowers correlation)
  - TX diversity techniques (e.g. time offsetting of two TX transmissions to emulate multipath, reduce correlation)
  - Beamforming

MIMO = multiple input multiple output
MU-MIMO multi-user MIMO
SM = spatial multiplexing

Beamforming example



Focused RF beam forms by combining radiation from multiple phase-locked antenna elements.

Helps enable SM and MU-MIMO

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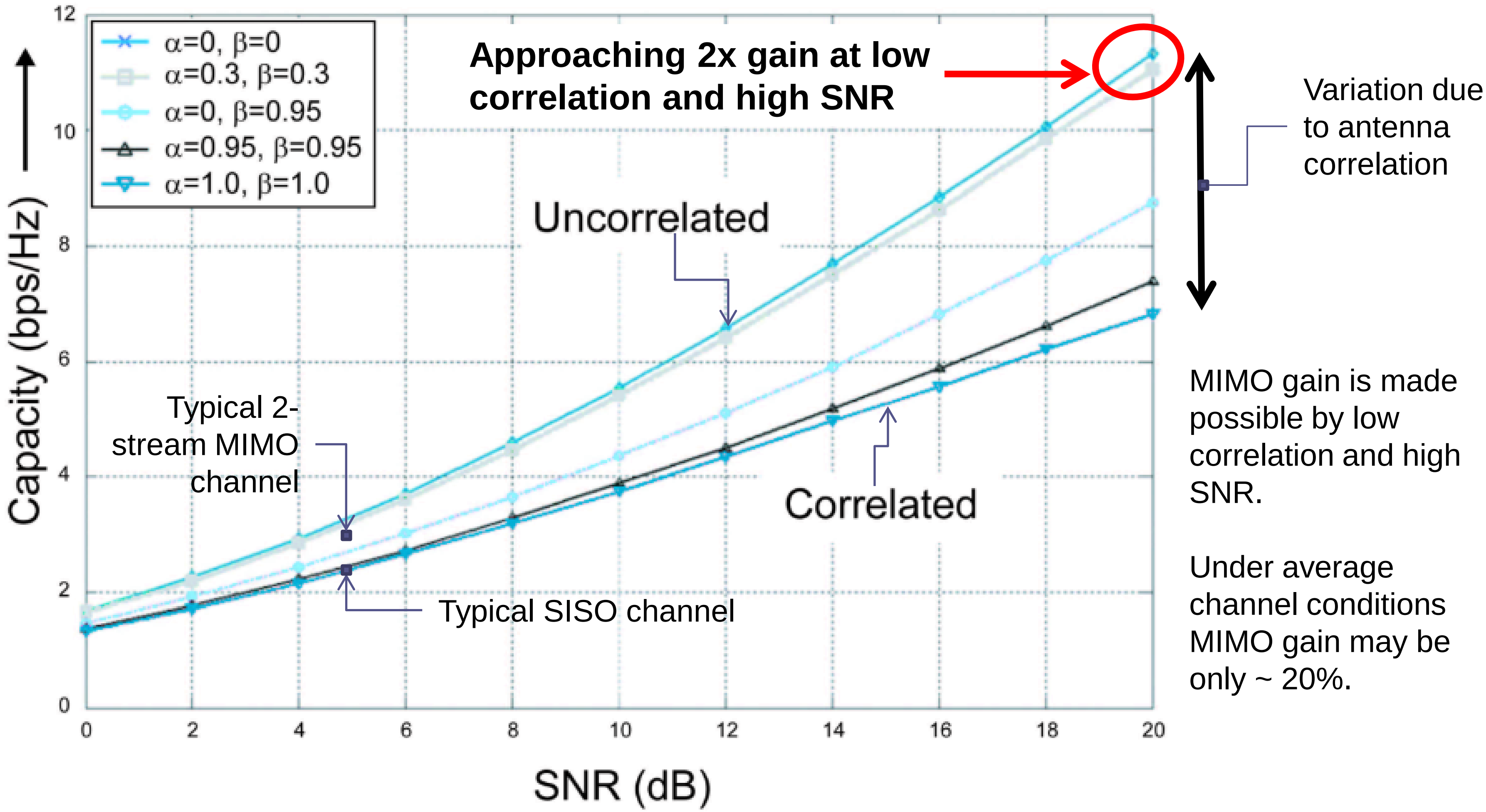
MIMO Channel Capacity



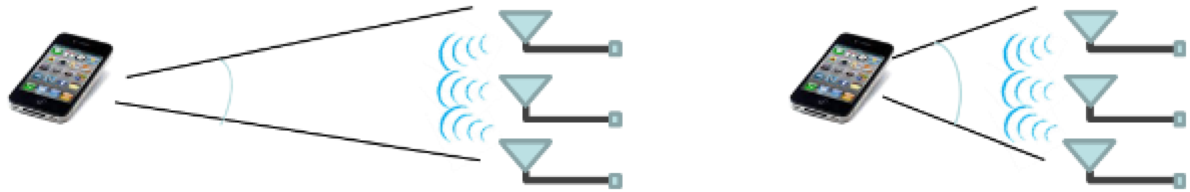
MIMO gain is made possible by low correlation and high SNR.

Under average channel conditions MIMO gain may be only ~ 20%.

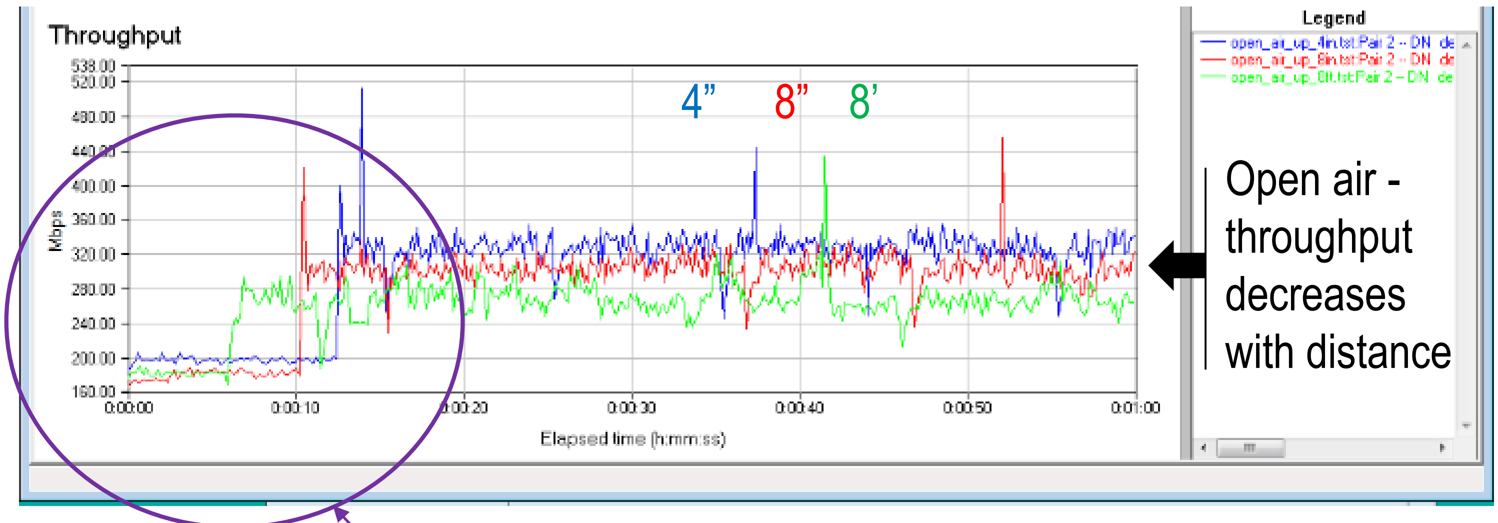
SNR = signal to noise ratio
α = TX antenna correlation
β = RX antenna correlation

Credit: Moray Rumney
Agilent Technologies Inc.

Throughput vs. Angular Spread



Shorter distance = wider angular spread = higher throughput



Initiation algorithm ?exploring the airlink for a few seconds?

Source: SmallNetBuilder.com measurement (linksys_ea6500_5ghz_80mhz_up_mpe_vs_openair.png)

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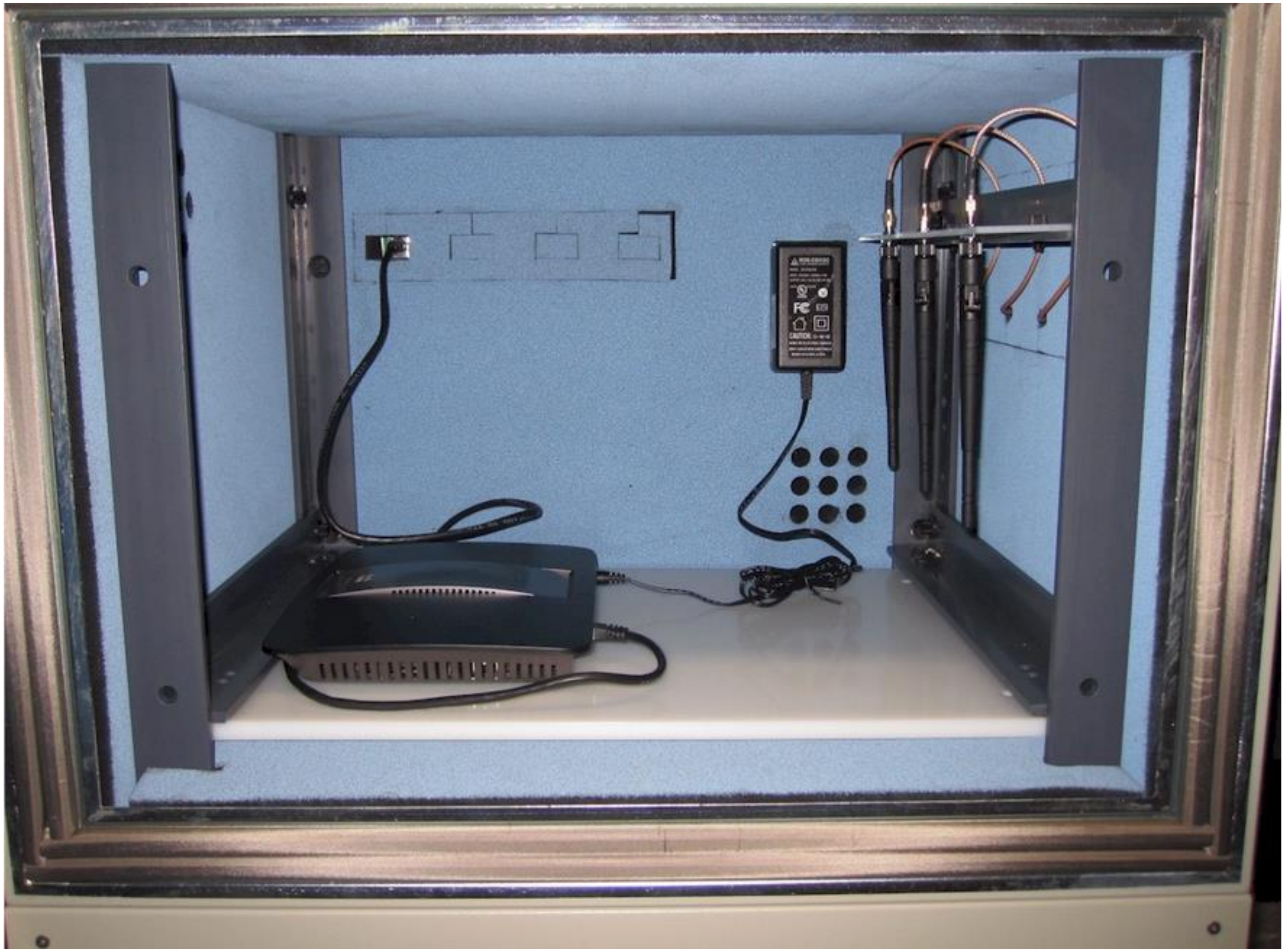
Linksys EA6500 3x3 11a/b/g/n/ac AP/router

Wide angular spread in a small anechoic chamber



http://www.smallnetbuilder.com/wireless/wireless-howto/32082-how-we-test-wireless-products-revison-7

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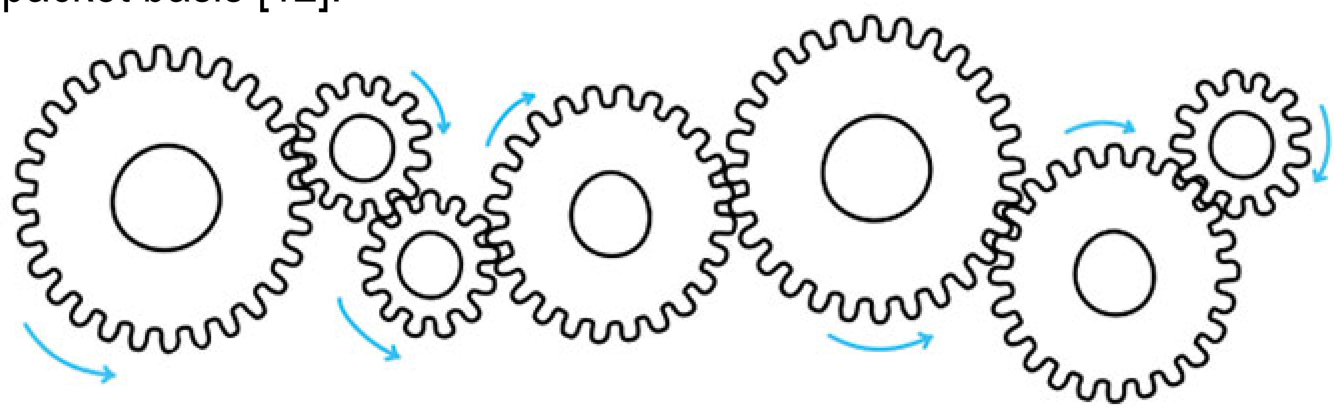
MIMO Test Challenges

- Getting repeatable and consistent measurements is next to impossible in open air conditions. The reasons?
  1. Modern wireless devices are designed to automatically adapt to the changing channel conditions.
  2. Adaptation algorithms programmed into the baseband layer of these radios are complex and sometimes get into unintended states.
  3. Wireless environment is time-, frequency- and position- variable in terms of path loss, multipath, Doppler effects and interference, often stumping the decision logic of the adaptation algorithms.
- MIMO radios can change their data rate from 1 Mbps to over 1 Gbps on a packet-by-packet basis [12].



Adaptation Parameters – 802.11a/b/g/n/ac

Adaptation	Variables
Modulation	BPSK, QPSK, 16-QAM, 65-QAM, 256-QAM
Signaling	CCK, DSSS, OFDM
Coding rate	1/2, 3/4, 5/6
# spatial streams	1 to 8
Channel width	Wi-Fi: 20/40/80/160 MHz LTE: up to 20 MHz
Guard Interval (GI)	Wi-Fi: 400/800 ns; LTE: 5.2 usec
MIMO mode	Spatial Multiplexing (SM) TX diversity RX diversity Beamforming

Refer to 802.11ac document [2] for details of the latest 802.11 technology

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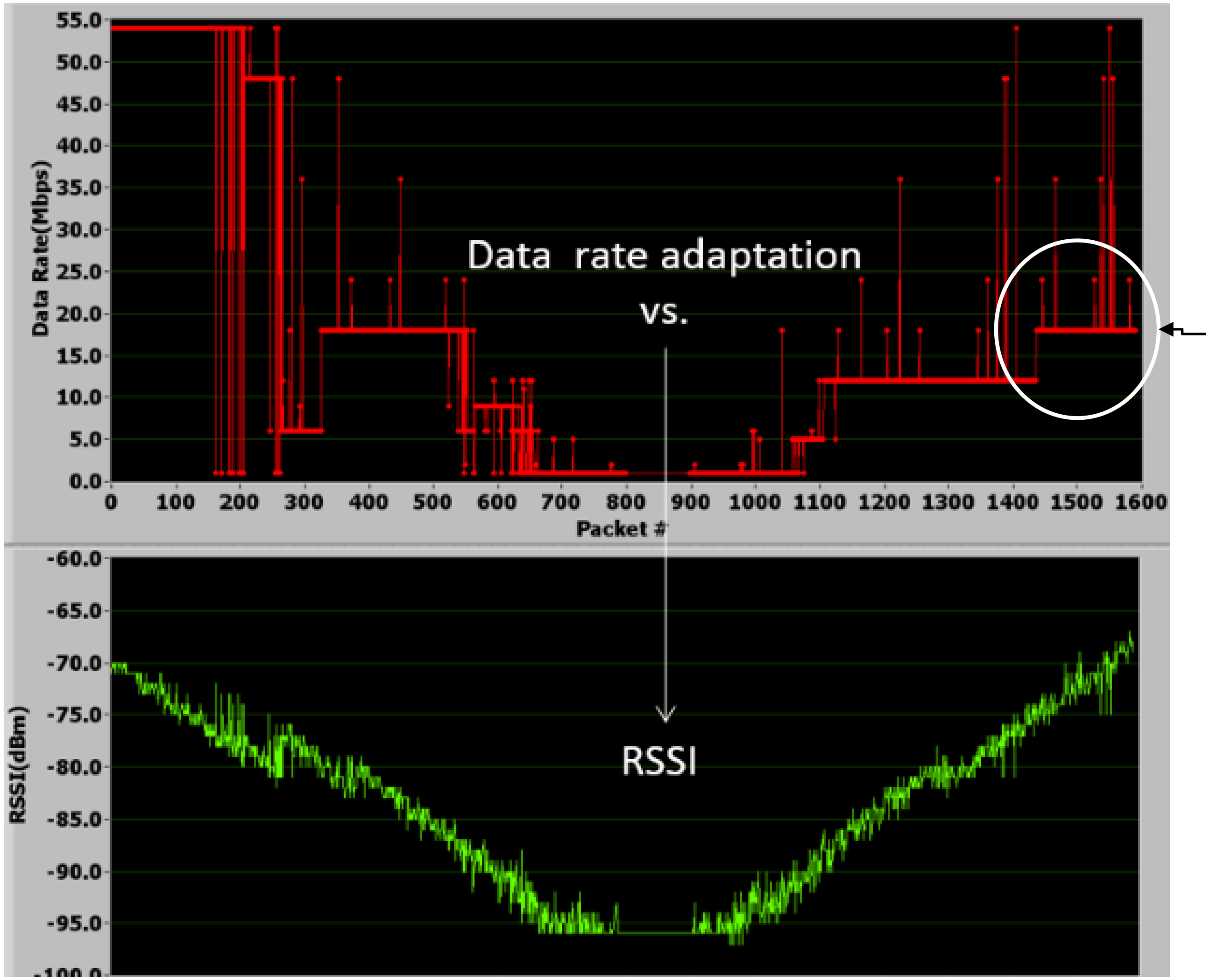
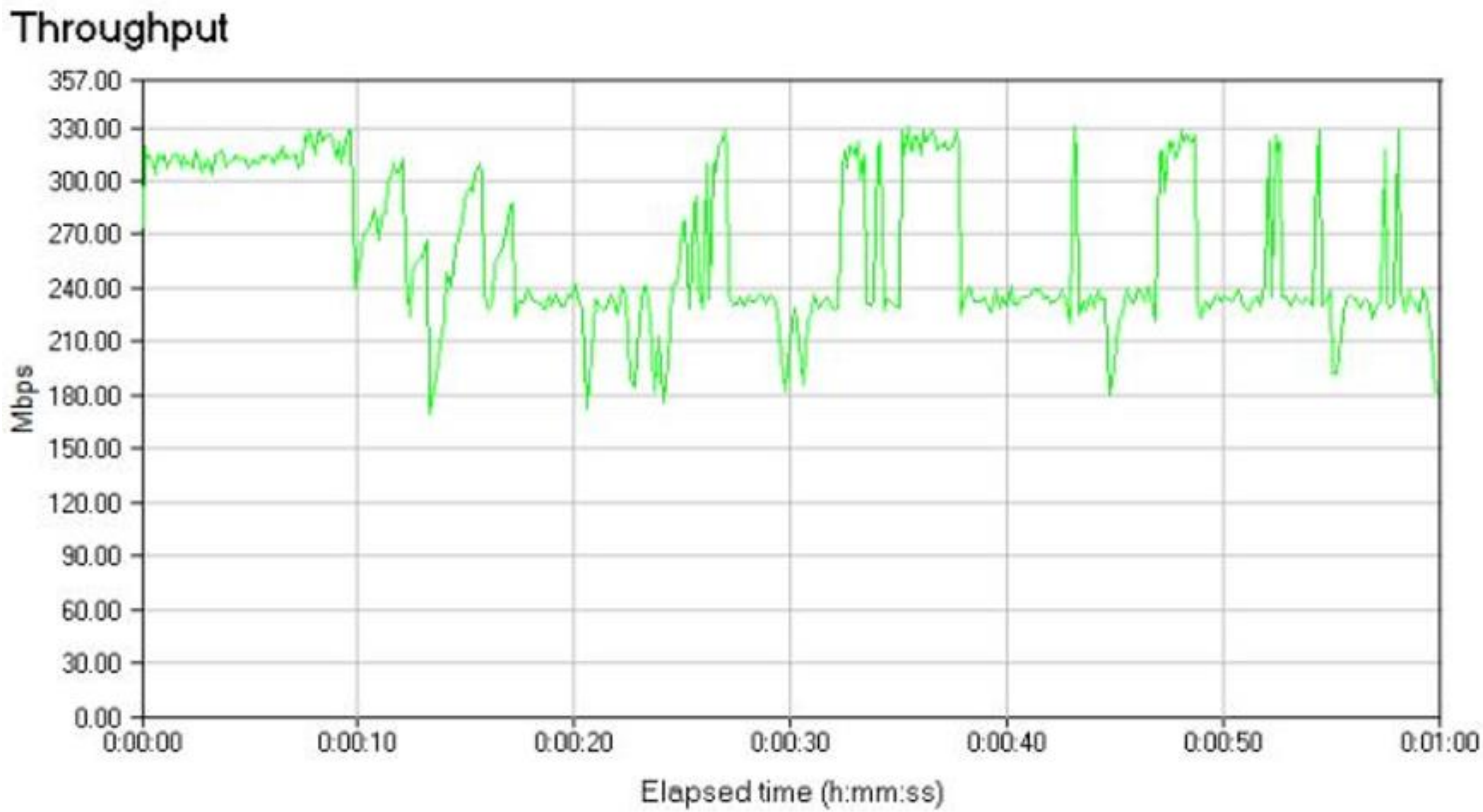
Data Rate Adaptation Example - 802.11g



Adaptation algorithms are stateful.

In this example data rate never recovers to its peak value of 54 Mbps even though favorable channel conditions are restored.

Example of 802.11ac Device Throughput



Example of throughput measurement of an 802.11ac link using IxChariot™. In this example the test conditions are static, but it appears that the adaptation algorithm of the TX DUT keeps making adjustments resulting in throughput fluctuations vs. time.

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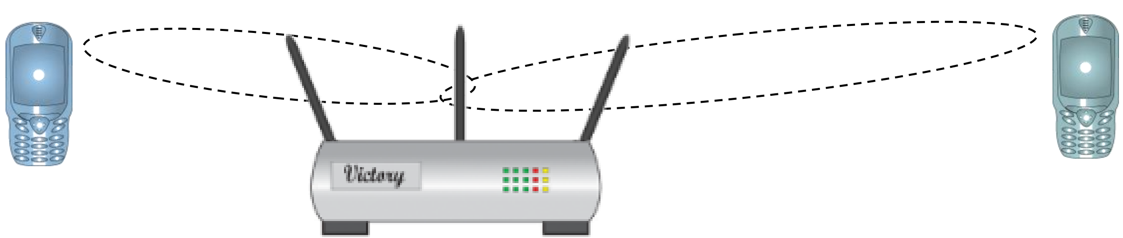
MIMO Modes of Transmission

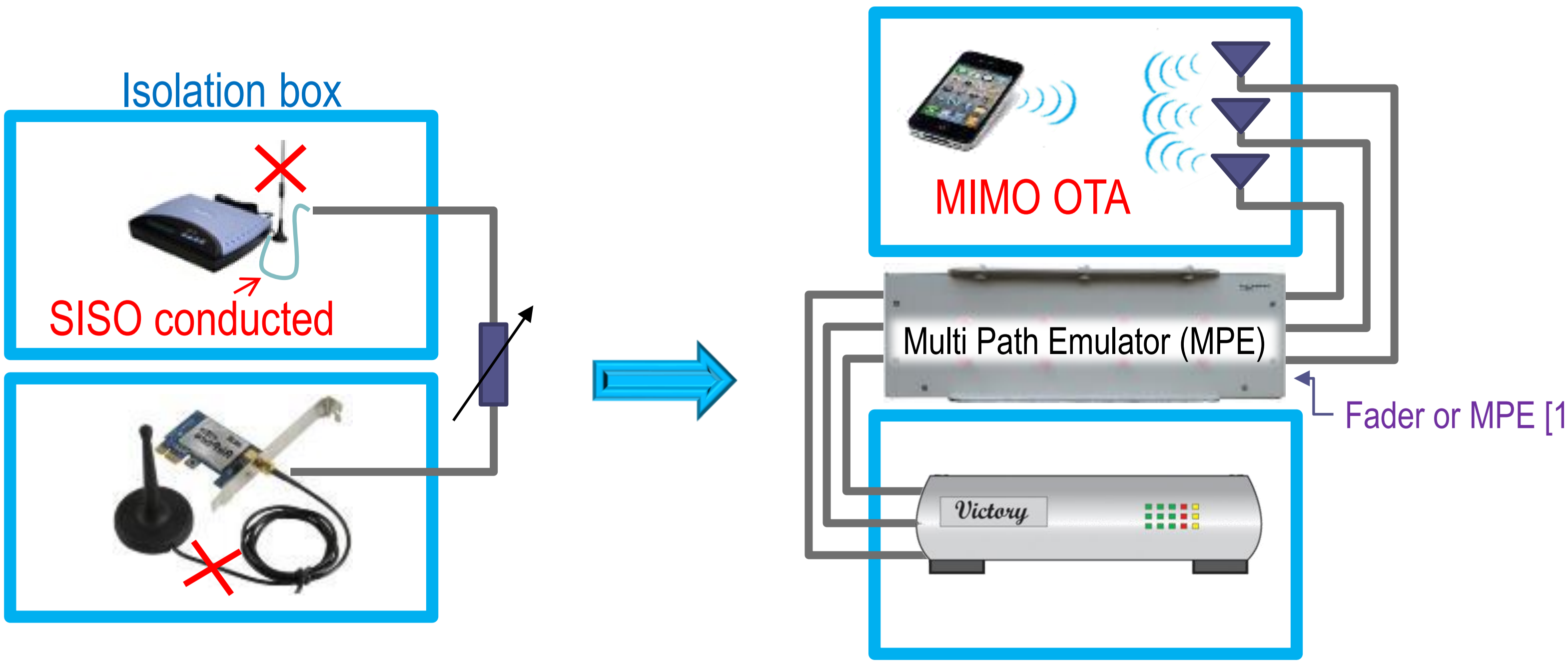
MIMO Mode	Explanation
Spatial Multiplexing	Use of multiple MIMO radios to transmit two or more data streams in the same channel.
TX diversity	Use of multiple MIMO radios to transmit slightly different versions of the same signal in order to optimize reception of at least one of these versions. TX diversity schemes include space time block coding (STBC), space frequency block coding (SFBC) and cyclic delay diversity (CDD).
RX diversity	Use of multiple MIMO radios to combine multiple received versions of the same signal in order to minimize PER. A common RX diversity technique is maximal ratio combining (MRC).
Combination of TX and RX diversity	Use of TX diversity at the transmitting device in combination with RX diversity at the receiving device.
Beamforming	Use of multiple MIMO transmitters to create a focused beam, thereby extending the range of the link or enabling SM.
Multi-user MIMO (MU-MIMO)	Forming multiple focused beams or using TX diversity techniques to enable simultaneous communications with multiple device. Typically beamforming is done by a base station or an access point (AP) to communicate simultaneously with multiple client devices.



Factors Impacting MIMO Throughput

Factors	Explanation/Impact	Notes
MIMO channel correlation	Function of several variables including device antenna spacing, antenna polarization and multipath	The lower the correlation the higher the throughput
Angular spread of the received signal	Related to correlation and strongly influenced by multipath in the channel	Multipath causes signal to bounce around and arrive at different angles, thereby widening the angular spread at a receiver. Typically, the wider the angular spread the higher the MIMO throughput.
Device antenna spacing and device orientation	Related to angular spread and correlation	MIMO throughput will vary vs. device orientation and antenna spacing. Typically, the wider the antenna spacing the lower the correlation and the higher the throughput.
Antenna polarization	Vertical, horizontal or circular	Cross-polarization (vertical and horizontal) is sometimes used to lower MIMO correlation, thus enabling spatial multiplexing. Multipath reflections can alter polarization.
Noise and interference	High noise power with respect to signal power results in low SNR (signal to noise ratio)	MIMO devices can adapt to the environment by selecting the most suitable mode of operation (e.g. TX diversity in low SNR conditions; spatial multiplexing in high SNR, low correlation conditions).
Motion of devices or multipath reflectors	Causes Doppler spread of the signal	OFDM signaling is sensitive to Doppler spread. Throughput should be measured in a variety of Doppler environments.
Delay spread of reflections	Causes clusters of reflections to arrive at the receiver at different times	Delay spread is higher for larger spaces (e.g. outdoors) than for smaller spaces (e.g. home environment)

Evolution of Wireless Testbed Architecture

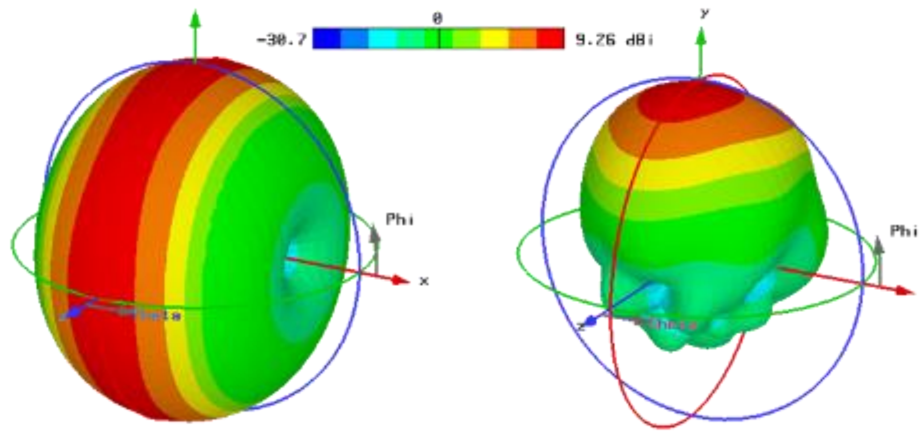


New generation wireless testbeds must support MIMO OTA testing to accommodate MIMO and multi-radio devices with internal antennas.

Shape of Antenna Field

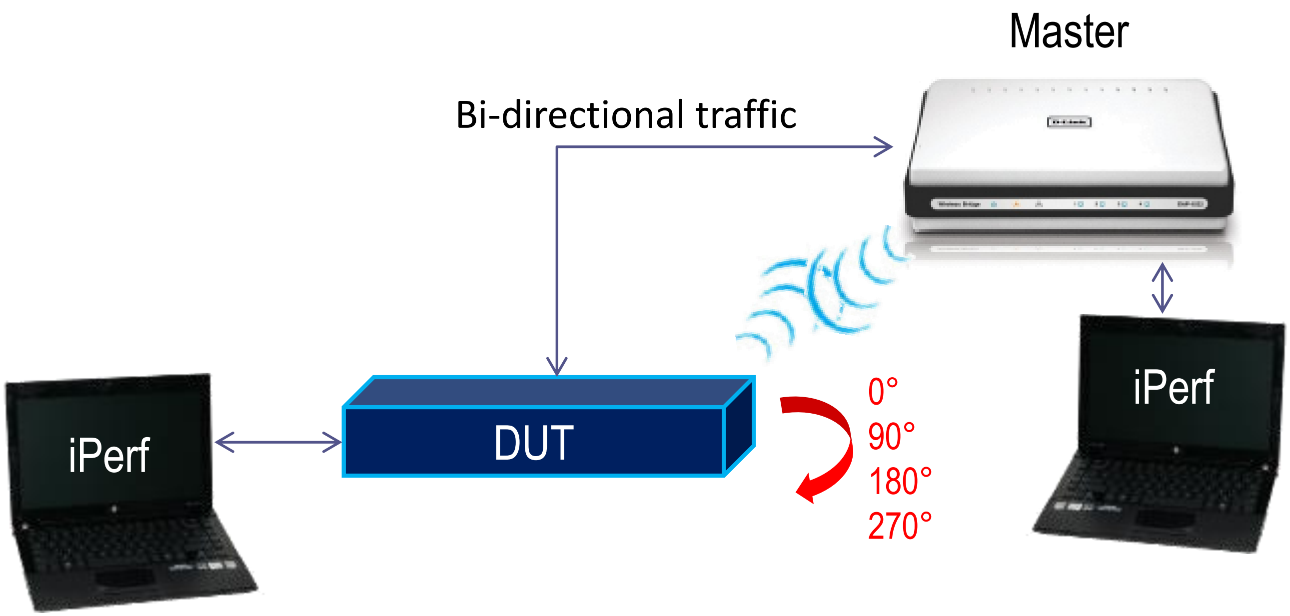
- Shape of the antenna field varies from product to product
- Field can be blocked by metal surfaces such as batteries, ground planes, etc.

simulation of a dipole antenna field



open air *inside a Wi-Fi device*

DUT Rotation for Throughput Testing



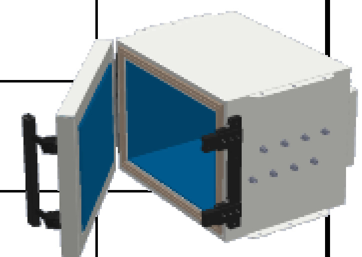
Rotate the DUT and average results for at least 4 orientations. Alternatively, place DUT on a turntable.

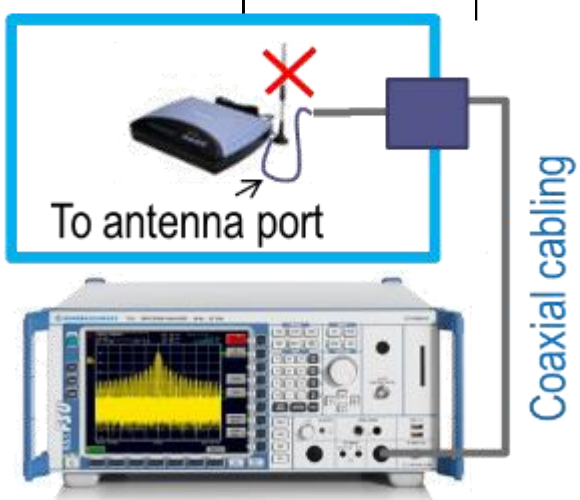
Test Environments per 802.11.2

Table 1—Cross-reference of metrics and environments *(continued)*

Source: 802.11.2 [14]

	√	√				√
Metric	**Conducted test environment**	**Calibrated over the air test (COAT)**	**Over the air outdoor LOS**	**Over the air indoor NLOS**	**Over the air indoor LOS**	**Over the air shielded enclosure**
Transmit rate adaptation	Y					
Antenna diversity	Y					
Adjacent channel interference	Y					





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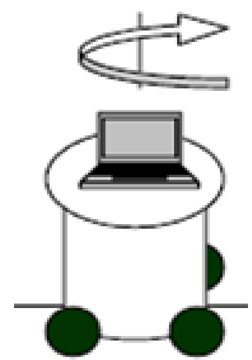
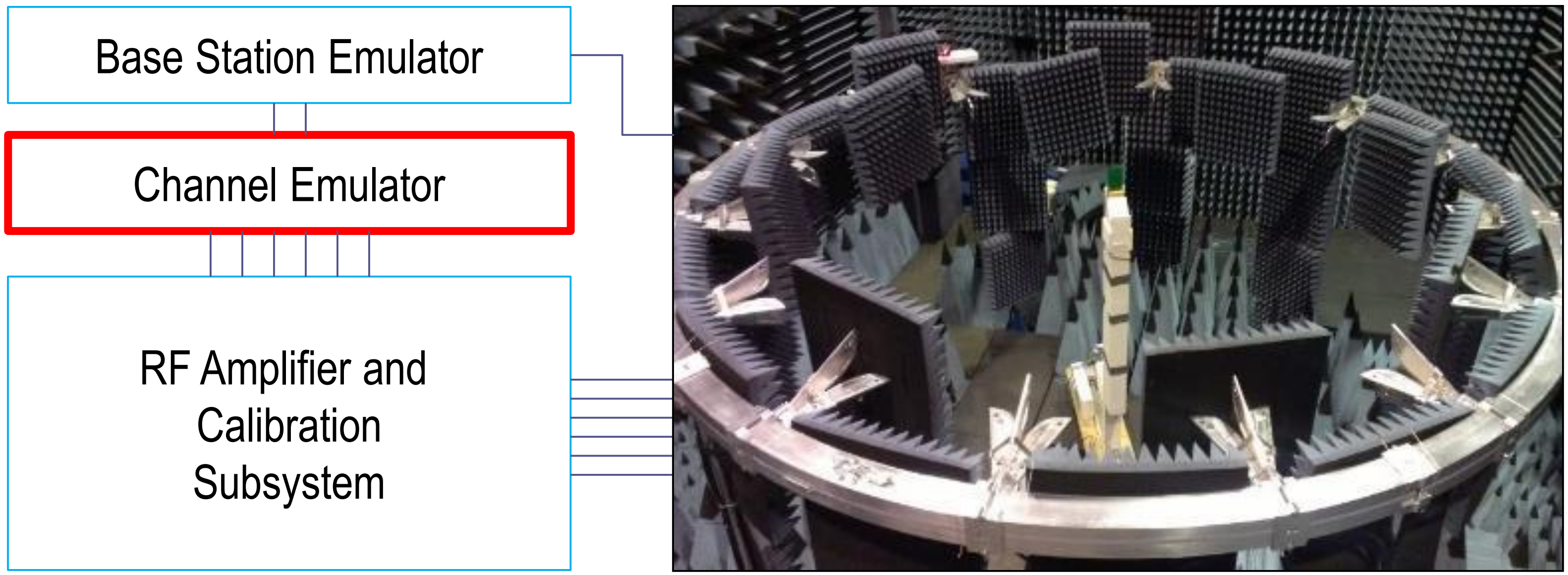


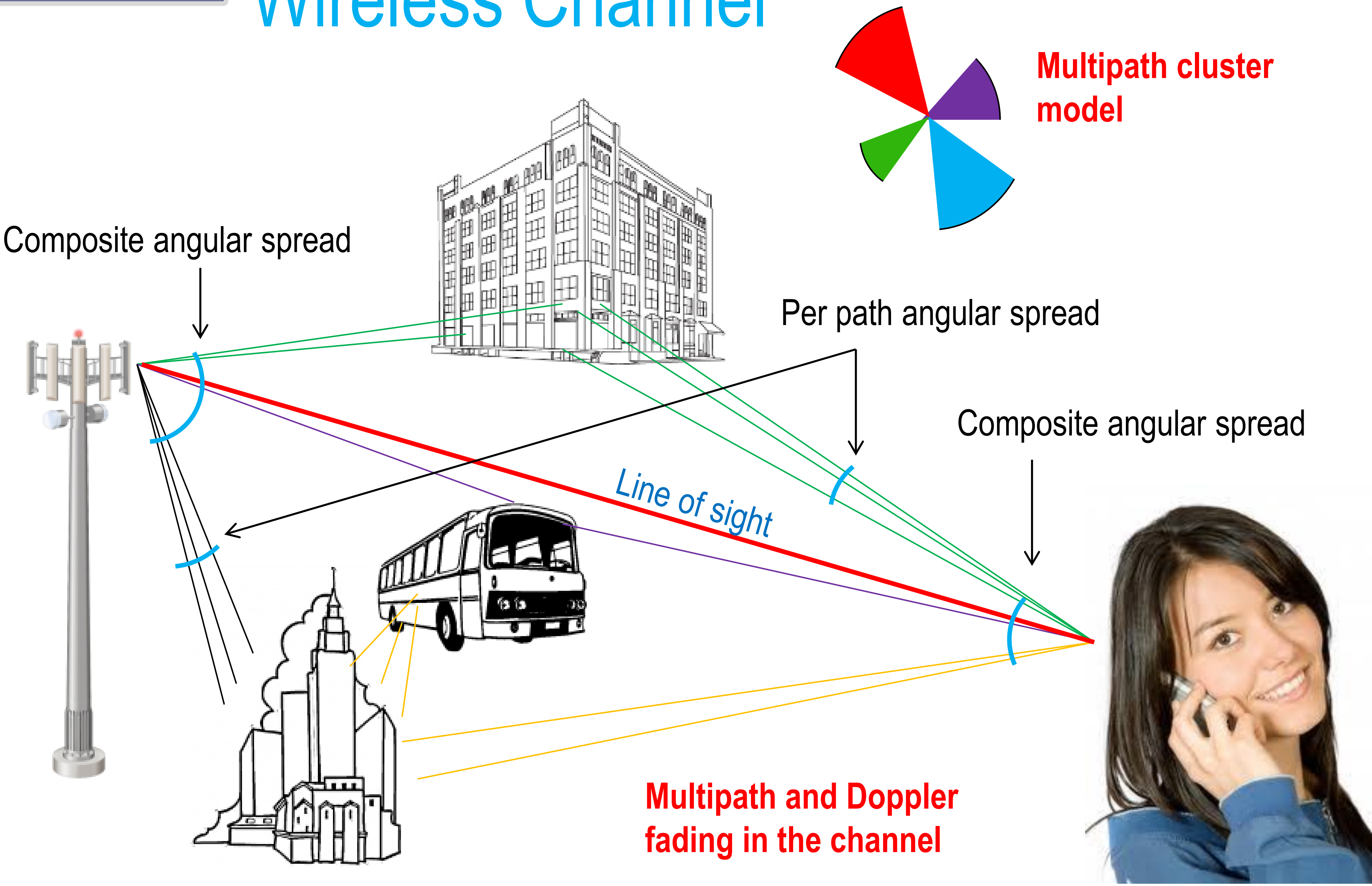
√ = controlled environment

MIMO OTA Test Methods

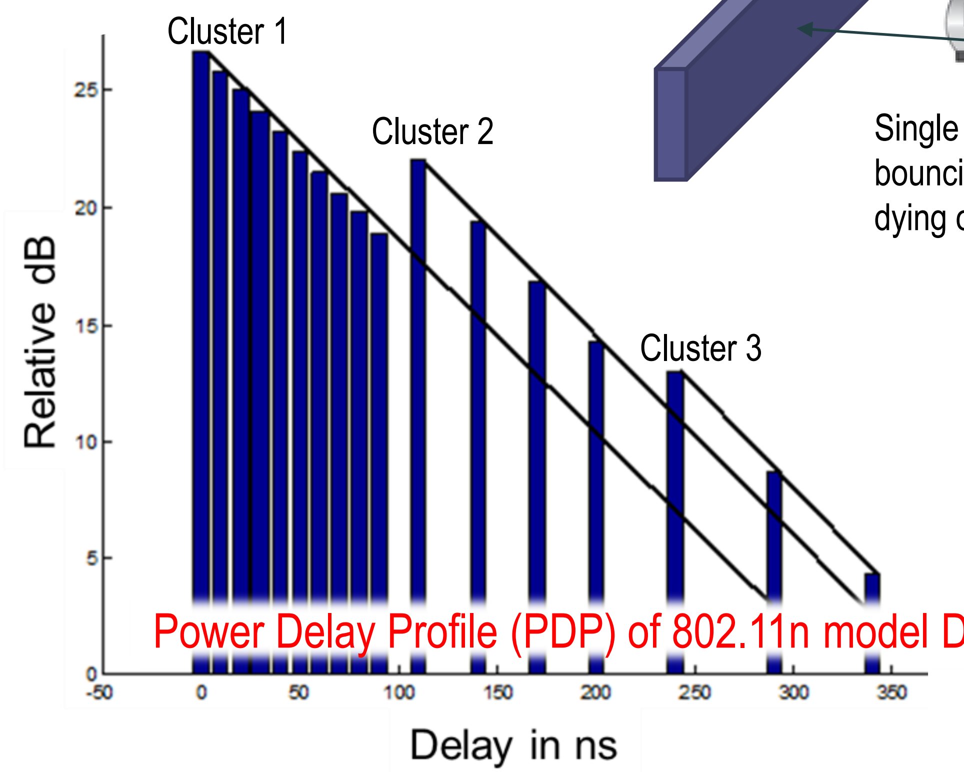


- Being standardized by 3GPP [10] and CTIA [11]
  - Anechoic chamber
  - Reverberation chamber

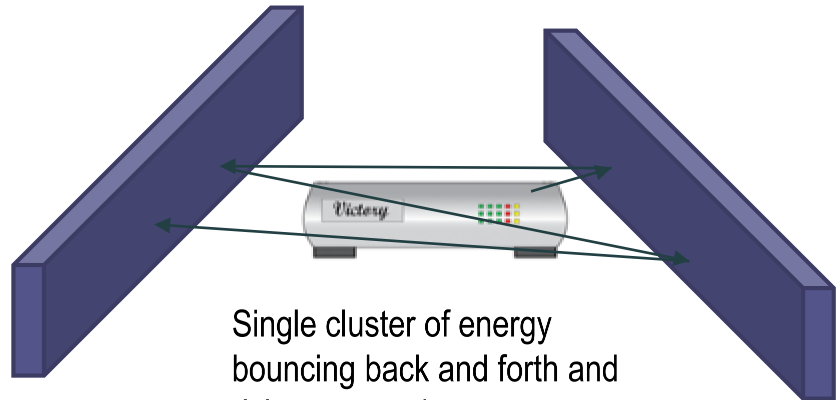
Wireless Channel



Concept of Clusters and Power Delay Profile



Power Delay Profile (PDP) of 802.11n model D



Single cluster of energy bouncing back and forth and dying out vs. time.

802.11n Channel Models - Summary

Model [3]		Distance to 1st wall (avg)	# taps	Delay spread (rms)	Max delay	# clusters
A*	test model		1	0 ns	0 ns	
B	Residential	5 m	9	15 ns	80 ns	2
C	small office	5 m	14	30 ns	200 ns	2
D	typical office	10 m	18	50 ns	390 ns	3
E	large office	20 m	18	100 ns	730 ns	4
F	large space (indoor or outdoor)	30 m	18	150 ns	1050 ns	6

* Model A is a flat fading model; no delay spread and no multipath

The LOS component is not present if the distance between the transmitter and the receiver is greater than the distance to 1st wall.

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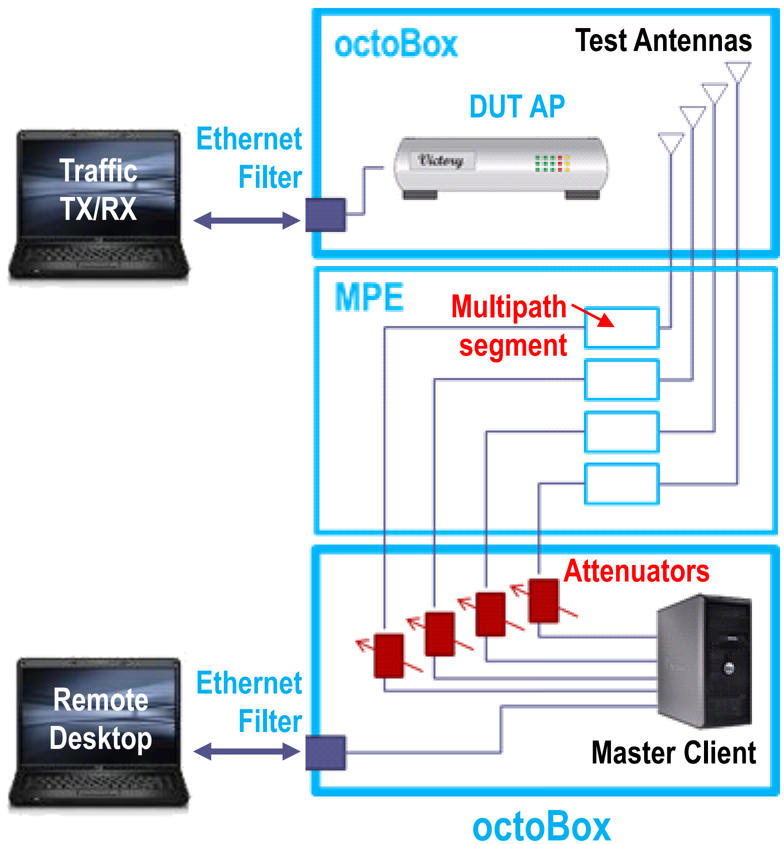
Channel Emulation – Requirements Summary

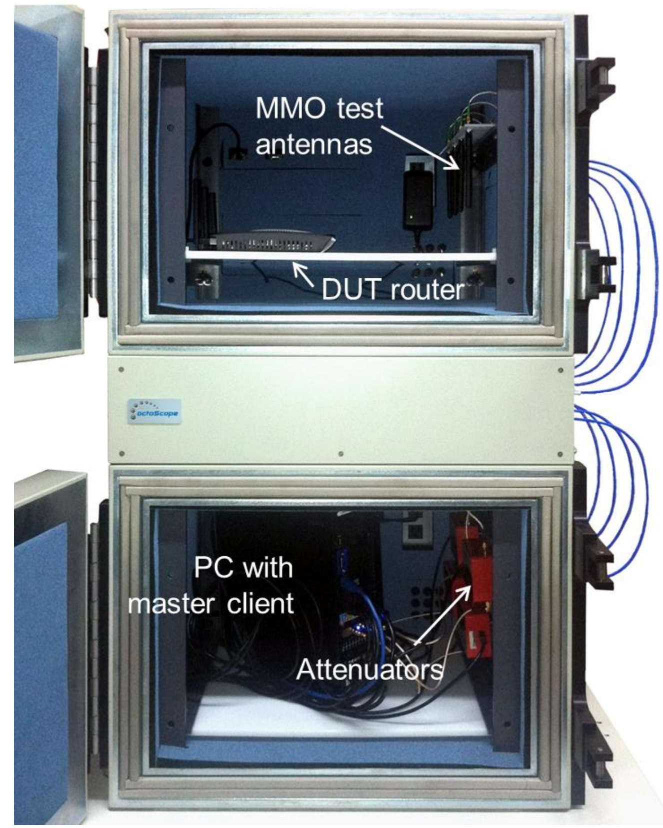
	802.11n	802.11ac		LTE (36-521 Annex B)
		80 MHz	160 MHz	
RF bandwidth (no channel aggregation)	40 MHz	80 MHz	160 MHz	20 MHz
EVM (avg down-fading is -40 dB)	-28 dBm (64QAM)	-32 dBm (256QAM)	-32 dBm (256QAM)	-22 dBm (8% 64QAM)
TDL Taps	18	35	69	9
Delay resolution	10 ns	5 ns	2.5 ns	10 ns

3GPP and 802.11 Channel Models

Parameter	Model Name	References and Notes
3GPP Models (RTL)	**LTE:** EPA 5Hz; EVA 5Hz; EVA 70Hz; ETU 70Hz; ETU 300Hz; High speed train; MBSFN	3GPP TS 36.521-1 V10.0.0 (2011-12) 3GPP TS 36.101 V10.5.0 (2011-12)
	GSM: RAx; HTx; TUx; EQx; TIx	3GPP TS 45.005 V10.3.0 (2011-11) Annex C
	3G: PA3; PB3; VA30; VA120; High speed train; Birth-Death propagation; Moving propagation; MBSFN	3GPP TS 25.101 V11.0.0 (2011-12) 3GPP TS 25.104 V11.0.0 (2011-12) 3GPP TS 36.521-1 V10.0.0 (2011-12)
IEEE 802.11n/ac Models (software)	A, B, C, D, E, F	IEEE 802.11-03/940r4 IEEE 11-09-0569
Channel modelling building blocks (RTL)	Tap: delay, Doppler, PDP weight Path: list of taps System: NxM, correlation matrix	

octoBox MPE MIMO OTA Testbed





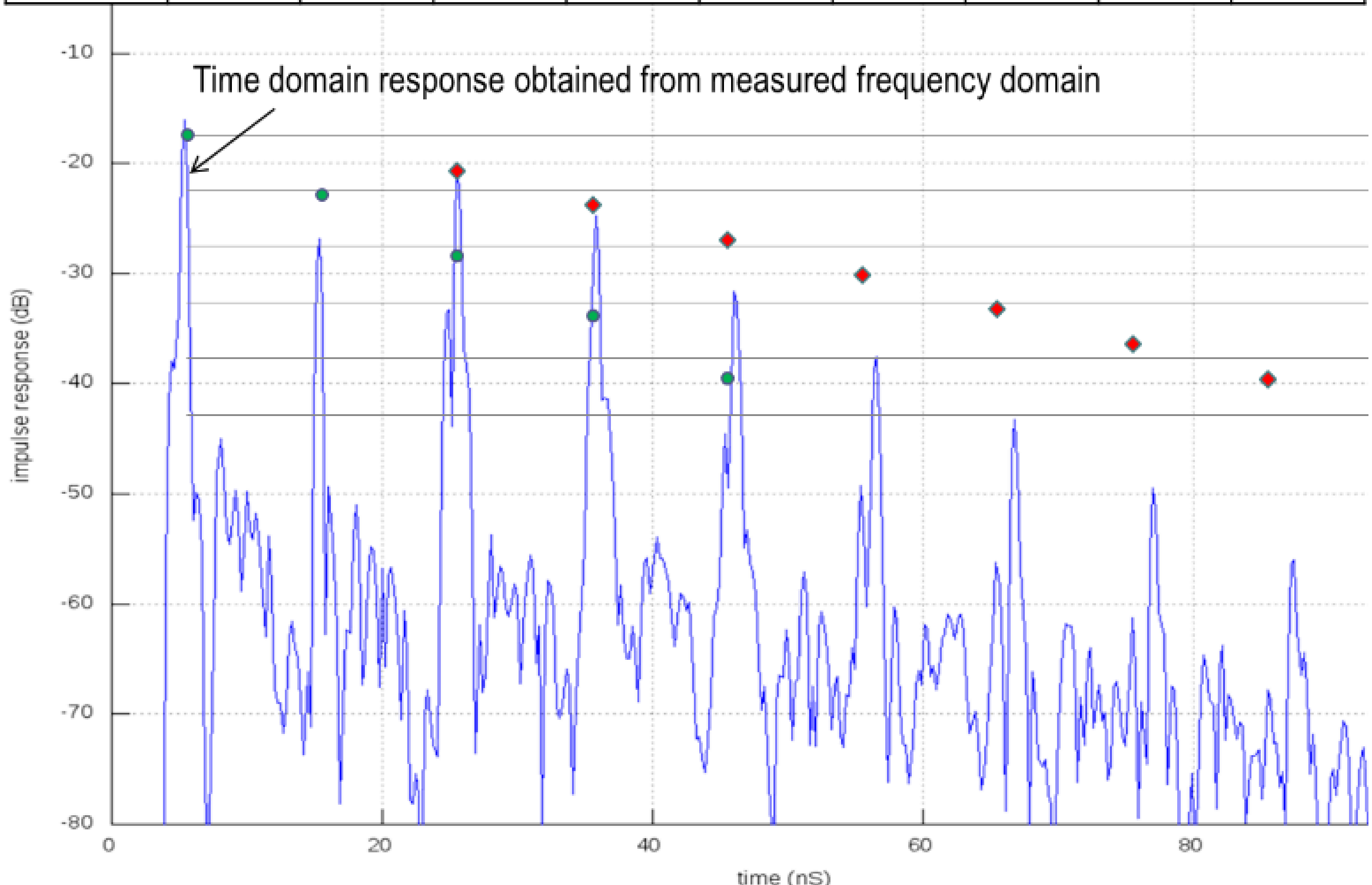
Testbed being used for benchmarking

http://www.smallnetbuilder.com/wireless/wireless-howto/32082-how-we-test-wireless-products-revison-7

MPE = multi path emulator

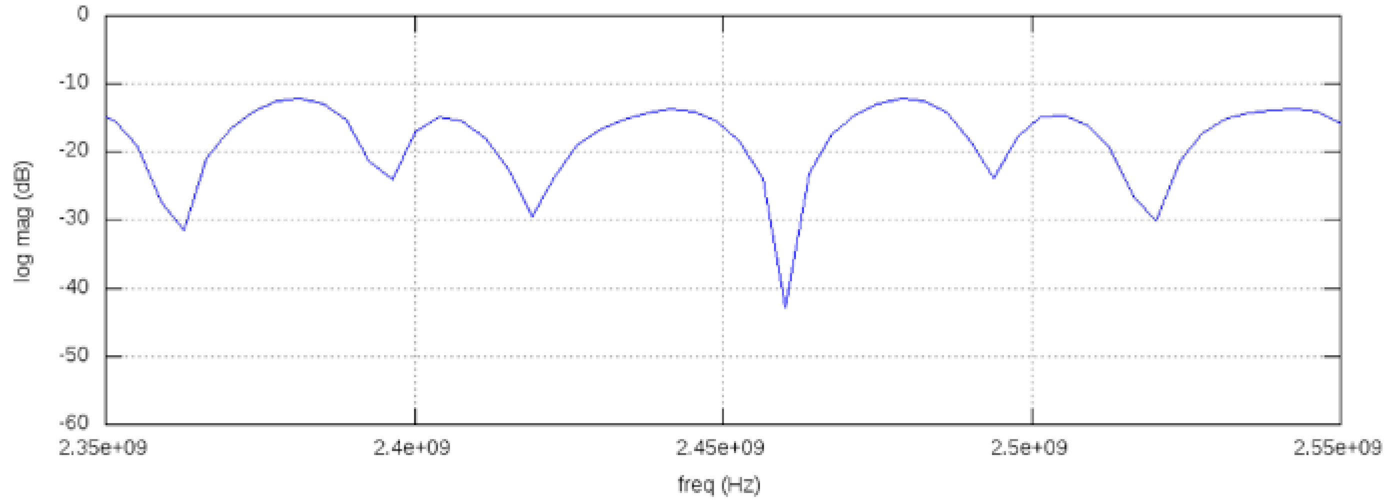
octoBox MPE Response vs. IEEE Model B

Model B	0ns	10 ns	20ns	30ns	40ns	50ns	60ns	70ns	80ns
Cluster 1	0	-5.4	-10.8	-16.2	-21.7				
Cluster 2			-3.2	-6.3	-9.4	-12.5	-15.6	-18.7	-21.8

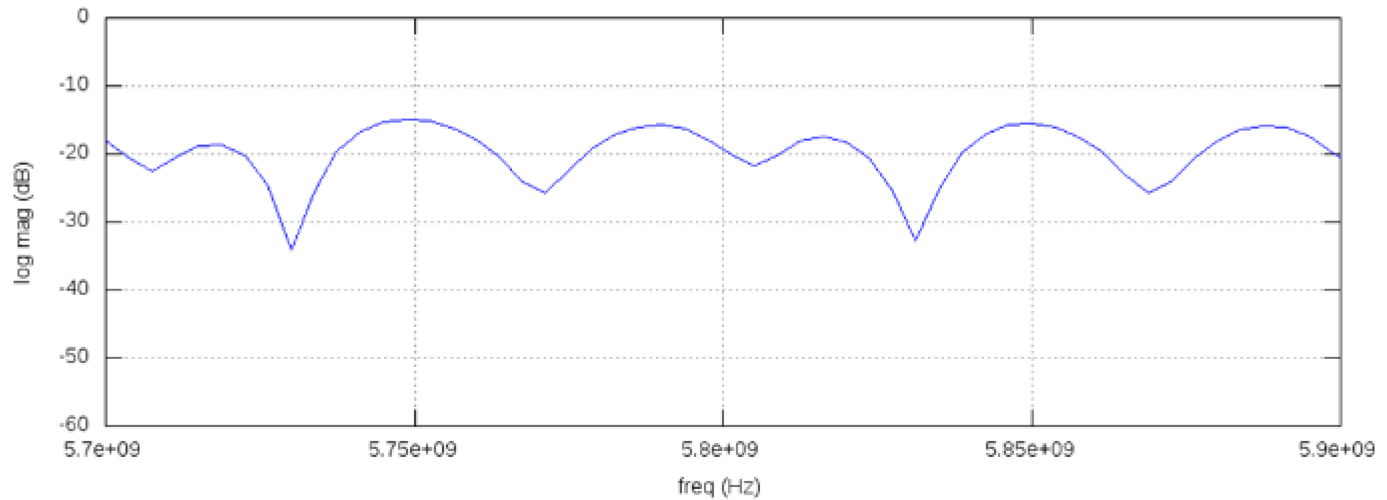


octoBox MPE Frequency Response

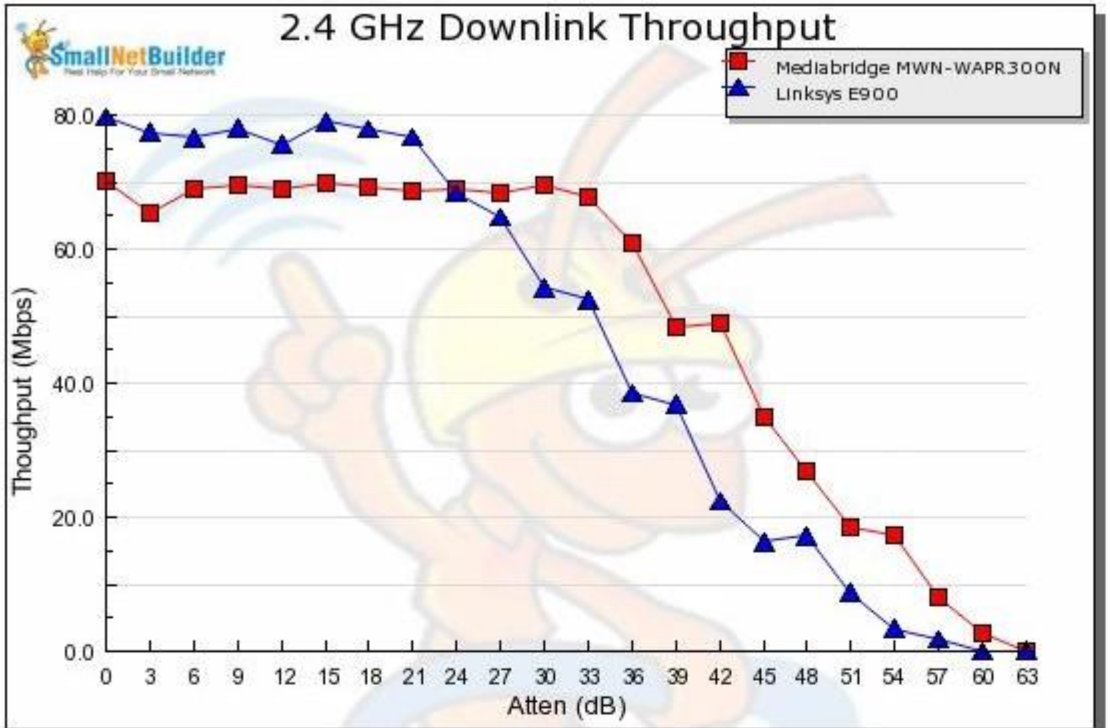
2.4 GHz band



5 GHz band



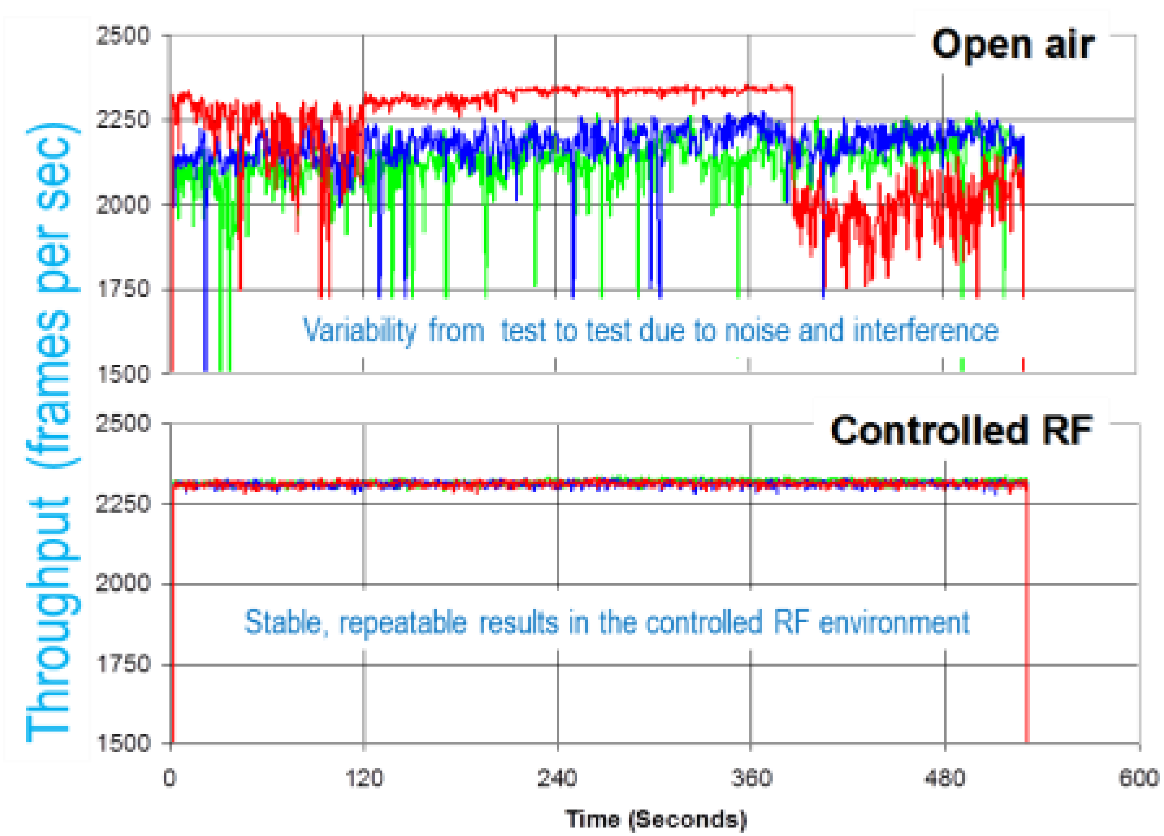
Example Throughput vs. Atten Measurements

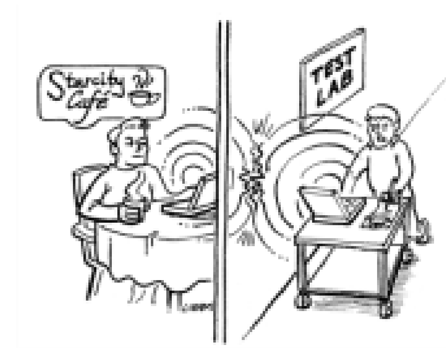


Product	Atten (dB)																					
	0	3	6	9	12	15	18	21	24	27	30	33	36	39	42	45	48	51	54	57	60	63
Mediabridge Medialink Wireless N Broadband Router (MWN-WAPR300N)	70	65	69	70	69	70	69	69	69	69	70	68	61	49	49	35	27	18	17	8	3	0
Test Notes for Mediabridge Medialink Wireless N Broadband Router (MWN-WAPR300N): Test client: ASUS PCE-AC66U (Win 7 6.30.95.26 driver) for 2.4 & 5 GHz tests																						
Linksys Wireless-N300 Router (E900)	80	77	77	78	76	79	78	77	68	65	54	52	39	37	22	16	17	9	3	2	0	0
Test Notes for Linksys Wireless-N300 Router (E900): Test client: ASUS PCE-AC66U (Win 7 6.30.95.26 driver) for 2.4 & 5 GHz tests																						

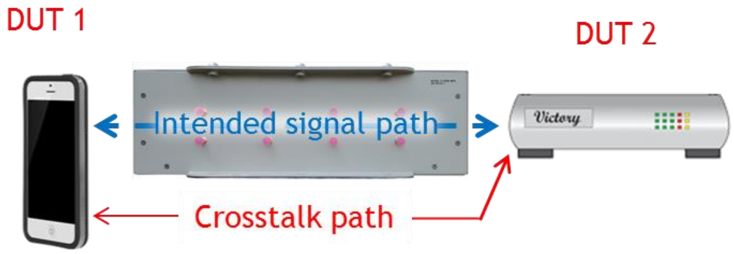
Source: www.smallnetbuilder.com

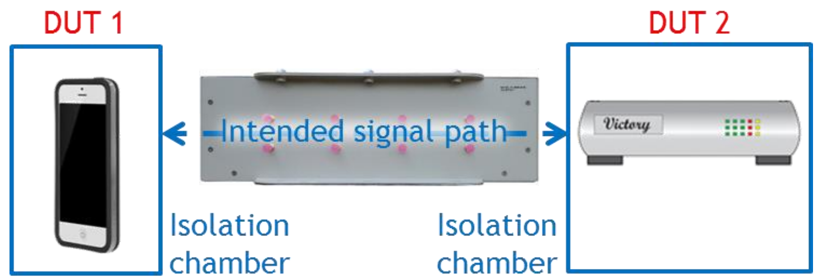
Controlled RF Environment Testing

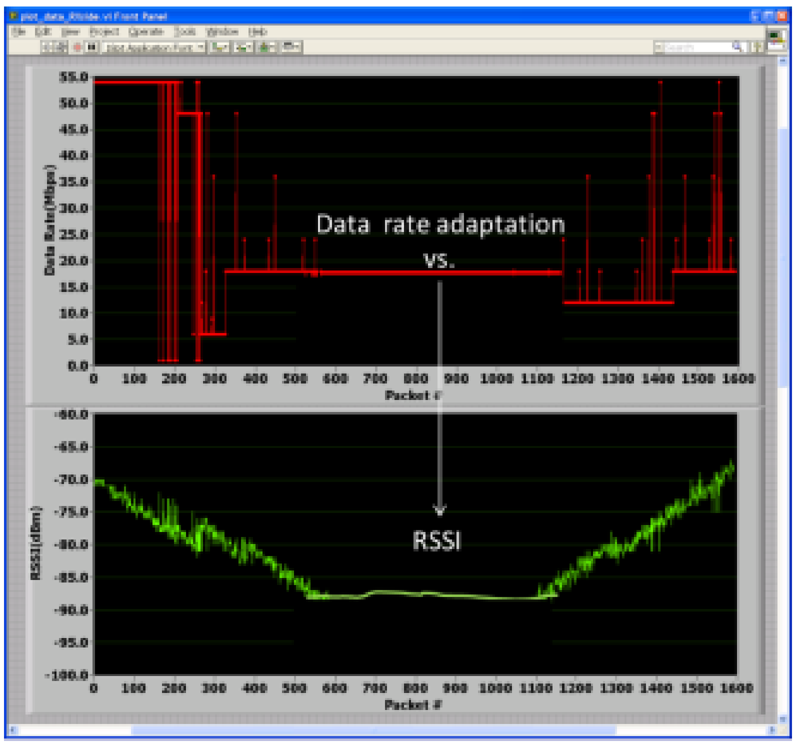


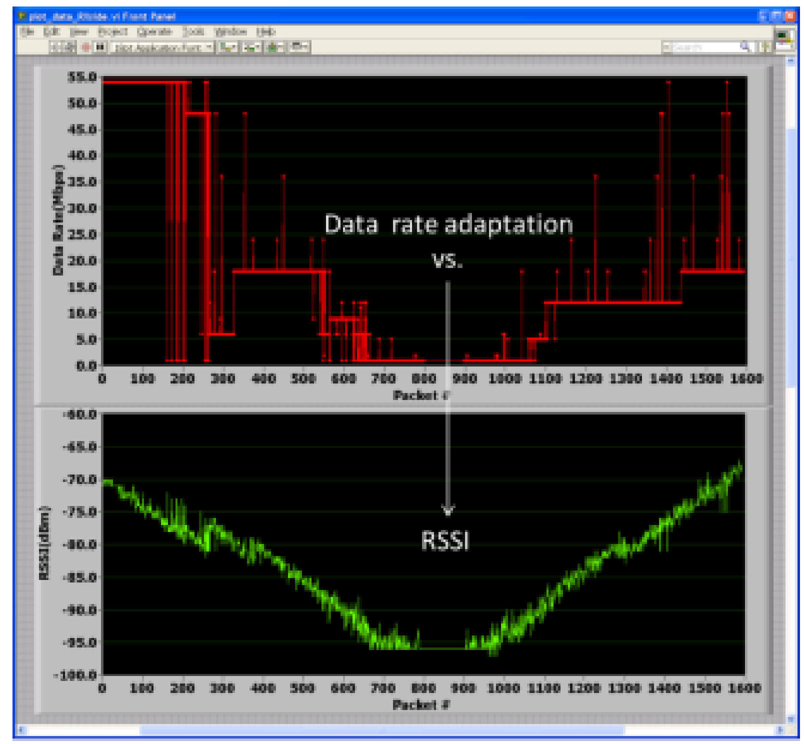


Isolating DUTs in a Wireless Testbed









How to Select RF Isolation Chamber

- There are two issues to be aware of when selecting an isolation chamber:
  - Isolation specifications often don't include the impact of data and power cables that must penetrate the walls of the chamber to power and control the DUT inside during the test.
  - Most isolation boxes on the market are not designed for OTA coupling. OTA support requires high isolation, absorption and special conditions to enable high MIMO throughput.

OTA = over the air

Concluding Thoughts

- Test engineers face difficult challenges when measuring MIMO throughput because
  - Wireless channel environment is constantly changing
  - Radio operating mode changes to adapt to the changing environment
  - Makes it difficult to obtain repeatable test results
- To guarantee repeatable and meaningful results the testbed must be
  - Capable of creating a range of realistic wireless channel conditions in a consistent manner
  - Well isolated to keep interference from impacting the performance of highly sensitive radios
  - Easy to maintain isolation vs. use
- A testbed used for benchmarking must be able to support multiple spatial streams showing maximum throughput of the DUT

References

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4. IEEE, 11-09-0569 , "TGac Channel Model Addendum Supporting Material", May 2009
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7. TS 36.521-1, Annex B, "Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) conformance specification Radio transmission and reception Part 1: Conformance Testing"
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9. TS 51.010-1, "Mobile Station (MS) conformance specification; Part 1: Conformance specification"
10. 3GPP TR 37.977 V1.2.0 (2013-11), "Verification of radiated multi-antenna reception performance of User Equipment (UE)", Release 12, November 2013
11. CTIA, "Test Plan for Mobile Station Over the Air Performance - Method of Measurement for Radiated RF Power and Receiver Performance", Revision 3.1, January 2011
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13. "octoBox Isolation Test Report", 12/2013, http://www.octoscope.com/English/Collaterals/Documents/octoBox_Isolation_Measurements.pdf
14. IEEE P802.11.2/D1.0, "Draft Recommended Practice for the Evaluation of 802.11 Wireless Performance", April 2007

For More Information

- To download white papers, presentations, test reports and articles on wireless topics, please visit http://www.octoscope.com/English/Resources/Articles.html

Thank you

www.octoscope.com

octoScope

LTE Throughput Test

- Informal drive-through testing of initial Verizon LTE deployments in the Boston area
- Measure throughput using www.speedtest.net
- Based on our sniffer measurements of the speedtest.net running on the desktop and iPhone:
  - The program uses HTTP protocol to download and upload large images multiple times
- The test runs for about 10 sec in each direction
- Ookla operates speedtest.net using many servers around the world and routing the test traffic to the nearest server
  - http://www.ookla.com/speedtest.php

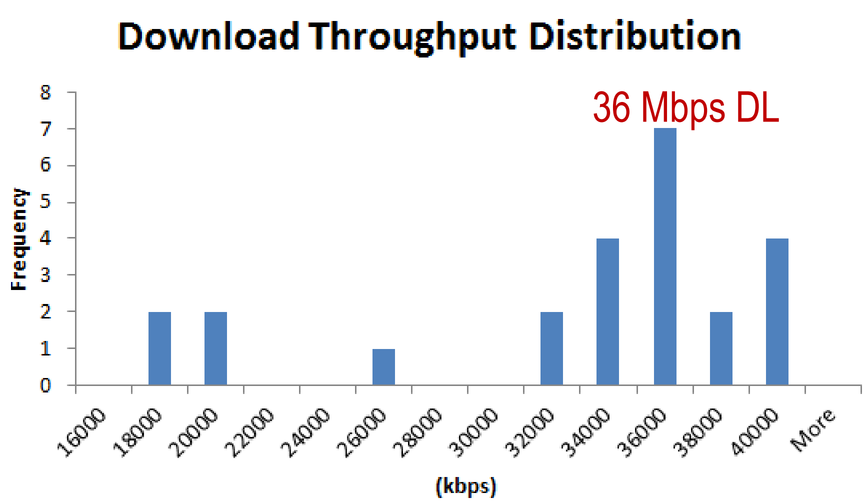
octoScope's LTE Throughput Measurements

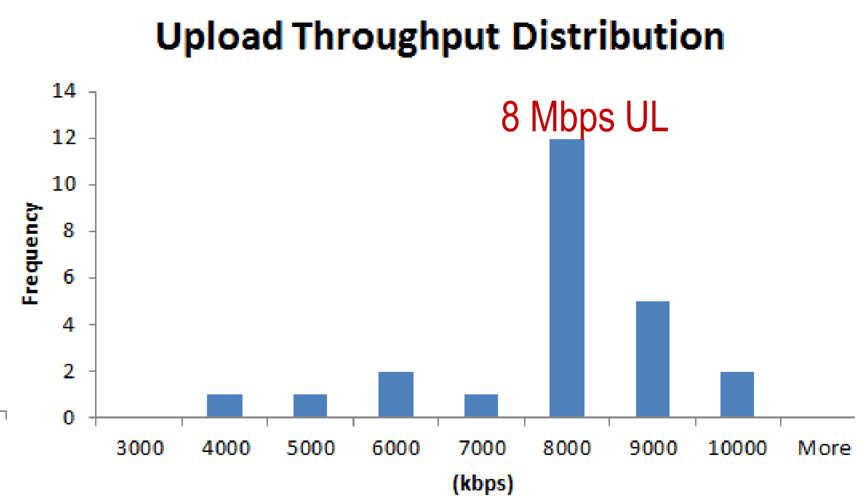
DL/UL, Mbps

LTE Measurements

Location in the car	DL (kbps)	UL (kbps)	Latency (ms)
Inside center of the car	14800	5499	112
Inside driver front window	14527	8824	107
Inside passenger front window	13687	8001	111
Outside the car	19703	8587	112

LTE Measurements: Impact of Speed (60 mph in open space)





Measurements performed by octoScope in October 2011

DL = downlink
UL = uplink
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