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Wireless test solutions and services

THROUGHPUT TEST METHODS FOR MIMO RADIOS

Achieving high throughput and repeatable results

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1/14/2014

ABSTRACT: This paper discusses the challenges and methods of achieving maximum MIMO throughput and repeatable measurements over a wide dynamic range and under a variety of wireless channel conditions. It focuses on MIMO over the air (OTA) test methods.

Rev. B 1/2014

As many engineers know, getting repeatable and consistent measurements, particularly when testing MIMO devices, is next to impossible. The reasons?

1. Modern wireless devices are designed to automatically adapt to the changing channel conditions.
2. Wireless environment constantly changes vs. time, frequency and radio motion. The time-variability of path loss, multipath, Doppler effects and interference often baffles the decision-making logic of the adaptation algorithms.
3. Adaptation algorithms are complex and sometimes get into unintended states.

Modern radios can change their data rate from 1 Mbps to over 1 Gbps on a packet-by-packet basis in response to impairments, such as signal fades or interference [13].

In addition to data rate adaptation, MIMO radios are adaptable in terms of their MIMO mode of operation. A few representative MIMO modes are explained in Table 1.

Table 1: *MIMO modes of transmission*

MIMO Mode	Explanation
Spatial Multiplexing (SM)	Use of MIMO radios to transmit two or more spatial streams in the same frequency channel.
TX diversity	Use of 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 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 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.

Commercial wireless chipsets typically support a subset of the MIMO modes outlined in Table 1 and some implement other proprietary modes. In the fast-changing wireless environment and with real-time decision making process, wireless devices sometimes exhibit flaws in their adaptation algorithms. Adaptation issues can severely impact throughput, but can be difficult to identify and track in the changing real-life environment.

Later in this paper we will discuss the benefits of controlled environment testbeds. But first, let's examine how MIMO radios work.

What factors impact MIMO throughput?

Many factors associated with the wireless channel and DUT antennas impact MIMO throughput. These include MIMO channel correlation, DUT antenna spacing, motion of the DUTs and reflectors, multipath reflections, interference and other factors. Table 2 summarizes and explains these factors.

Table 2: *Factors that impact 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 (e.g. both 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) conditions. The term SINR (signal to interference + noise ratio) is also sometimes used.	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)

When considering a controlled environment wireless testbed, Table 2 should serve as a guide. The testbed should be able to configure in a reproducible manner the conditions listed in Table 2. Furthermore, the testbed should be able to create an optimum environment that brings about maximum throughput and range of any device under test (DUT). The latter is important for benchmarking.

What are the requirements for a laboratory based wireless testbed?

A laboratory based wireless testbed has to offer an environment that:

1. Creates conditions under which throughput of the DUT is maximized
2. Emulates a range of realistic conditions, including path loss, multipath, noise and interference
3. Guarantees repeatable measurements reproducible at labs around the world; metrics to include throughput, packet error rate (PER) and range of the DUT - with and without channel impairments

The present day challenge for the industry is to create a wireless testbed that accommodates all 3 of the above criteria while supporting multiple input multiple output (MIMO) transmission over the air (OTA) to test the latest LTE-Advanced and IEEE 802.11n/ac devices.

Legacy single input single output (SISO) devices typically contain a single radio and often have external antennas. Historically, legacy radios have been tested via a conducted connection to their antenna ports (Figure 1, left).

New generation smartphones, access points (APs), base stations, pads and sensors have multiple radios (e.g. cellular, Wi-Fi, Bluetooth, GPS) and often have only internal antennas, making conducted connections difficult. Thus, new generation wireless testbeds must support both conducted and OTA coupling and be able to test MIMO capable devices over the air.

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

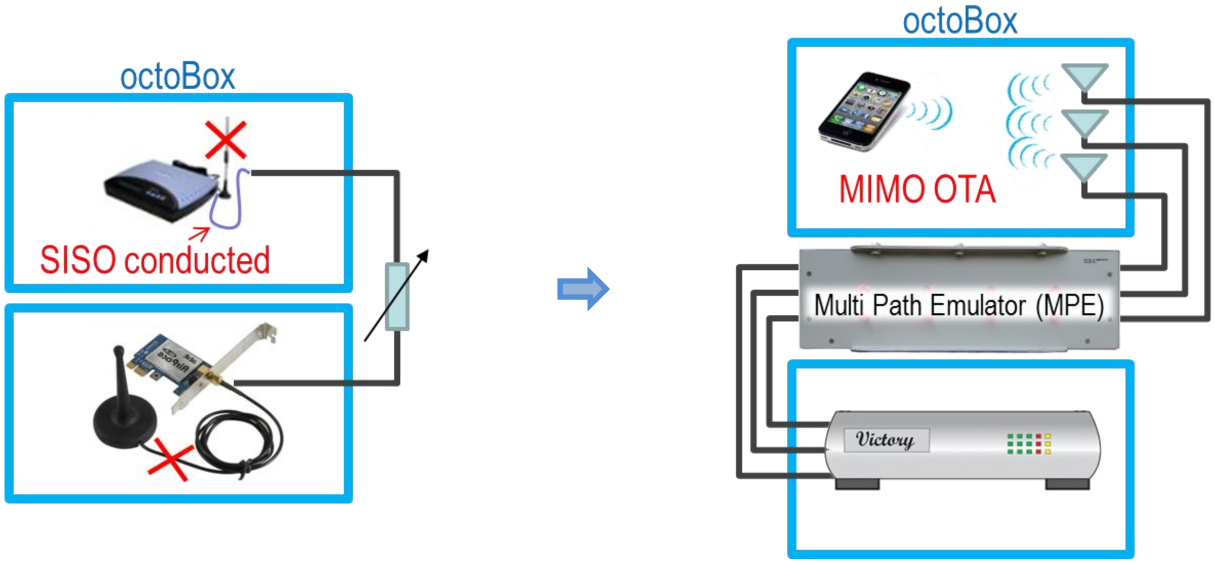

Figure 1: *SISO conducted (left) vs. MIMO OTA (right) test configurations. DUT and partner (master) devices are is placed into isolation chambers and coupled to one another to create a test link.*

What's the best way to set up realistic MIMO channel environment for repeatable radio testing?

Engineers testing MIMO radios need to create a range of channel conditions in order to validate the radios' adaptability and throughput performance. This can be accomplished using a MIMO channel emulator (fader) or an octoScope multipath emulator, MPE [1]. A fader or an MPE can interconnect two or more devices via cabling to the device antenna ports or over the air. For devices such as smartphones, pads or sensors with difficult-to-reach internal antennas OTA coupling is highly desirable.

When testing devices with internal antennas, device orientation with respect to the test antennas can have a significant impact on the measured throughput. The reason is that the radiated field of internal antennas can be non-uniform, as shown in Figure 3 on the right. The field of an internal antenna may have nulls and peaks because the antennas are sometimes blocked by batteries, PC board ground planes and other metal surfaces of the device.

The shape of the antenna field varies from product to product and test results vary vs. DUT orientation with respect to the test antennas.

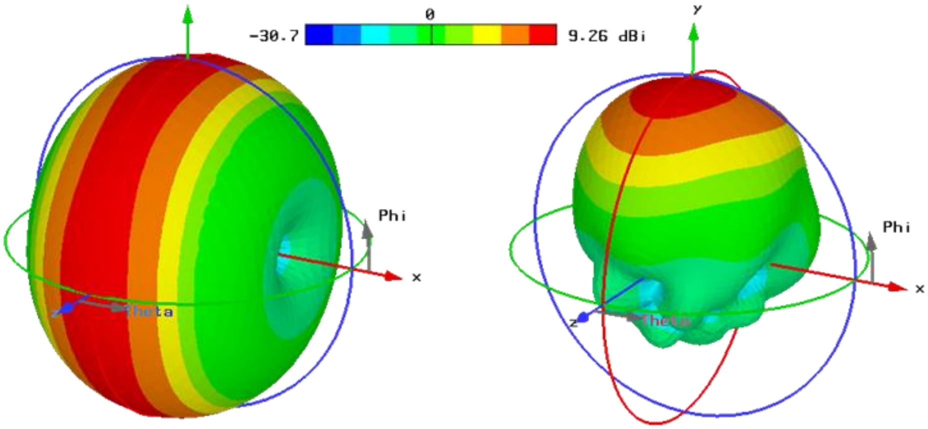

Figure 3: *Antenna field example. CST Microwave Studio simulation of a dipole antenna field (left) and the same antenna simulated inside a Wi-Fi device (right). The red areas represent high antenna gain (see scale on top). DUT orientation with respect to test antennas impacts the signal power coupled OTA.*

When testing over the air, engineers sometimes rotate the device and measure performance in 4 orientations: 0, 90, 180 and 270 degrees with respect to the test antennas. The 0 degree orientation is arbitrary and simply represents the starting orientation.

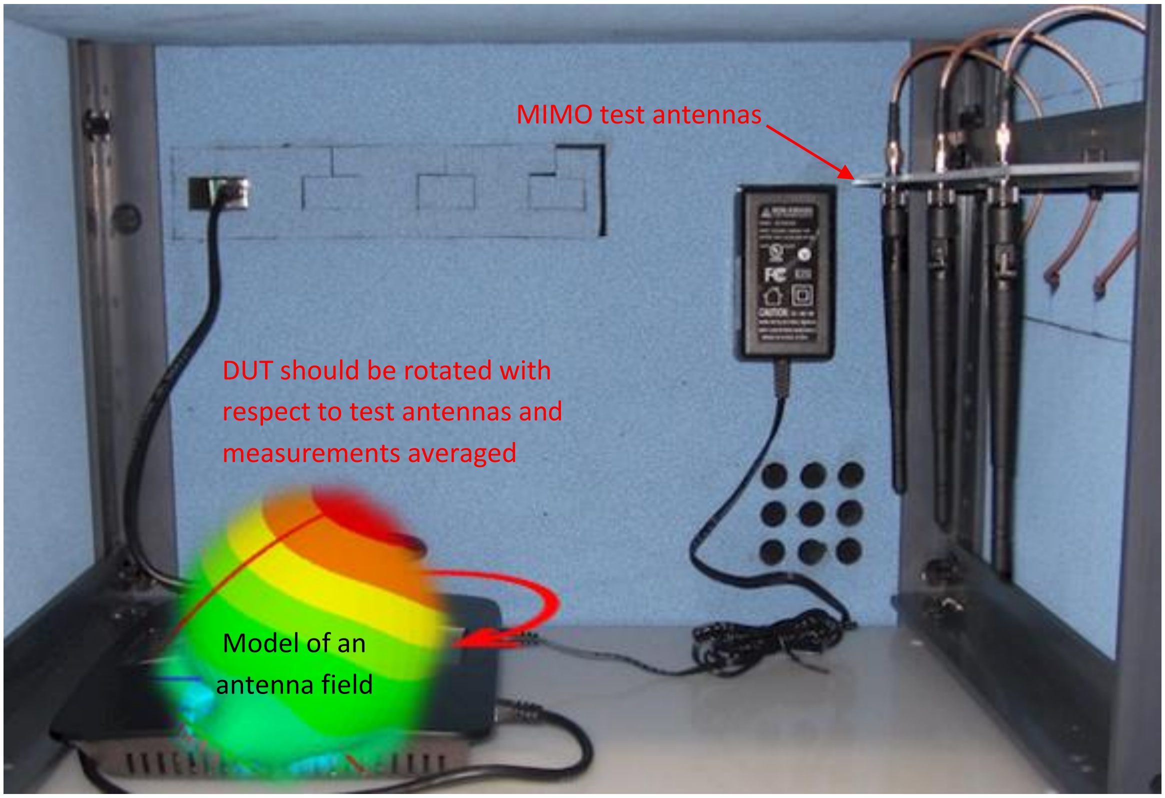

Figure 4: *Because antenna field of the DUT is typically characterized by peaks and nulls, engineers sometimes measure throughput at different orientations of the DUT with respect to test antennas.*

With MIMO devices, multiple antennas operate simultaneously, forming a multi-beam field. For devices such as APs, manufacturers typically try to have the MIMO antenna field be uniform around the azimuthal (horizontal) plane. For devices such as phones, the field may be specifically designed to point in one direction, for example upwards towards a base station.

How do device antennas impact MIMO throughput?

One aspect of MIMO radio technology is the use multiple antennas to minimize nulls in the combined multi-antenna field. This is done by spacing the MIMO antennas far enough away from one another and at a distance equal to a multiple of the signal ¼ wavelength. In a multipath environment, some reflections of the radiated signal can arrive vertically polarized and some horizontally polarizes. For this reason, sometimes device manufacturers cross-polarize the antennas (e.g. 2 antennas vertically polarized and 2 antennas horizontally polarized). Cross-polarization of device antennas also helps reduce MIMO correlation and thus increase the theoretical capacity of a MIMO channel.

To maximize MIMO throughput of omnidirectional devices, such as Wi-Fi APs, manufacturers ‘point’ the MIMO antennas in all directions in order to couple the signal that’s reflected from all directions. And when the antennas are pointed in all directions, the maximum MIMO throughput is achieved when the signal arrives from all directions, typically due to multipath. Hence multipath helps increase throughput in typical Wi-Fi networks.

Multipath typically widens the angular spread of the signal at the receiving device by virtue of reflections from opposing surfaces, thus reducing MIMO correlation of the channel and increasing MIMO throughput.

The wider the MIMO antenna spacing, the wider the angular spread of the signal, the lower the MIMO correlation and the higher the throughput. In a small handset where there is no room to space apart the antennas, correlation may be high, causing MIMO gains in throughput to be so low as to offer little benefit over the conventional SISO technology.

Multipath typically widens the angular spread of the signal at the receiving device by virtue of reflections from opposing surfaces, thus reducing MIMO correlation of the channel and increasing MIMO throughput.

Delay spread of multipath reflections

In addition to *angular* spread of the signal, in the real-world environment we also have *delay* spread. Delay spread is the difference between the longest and shortest delays of the reflections and is statistical in nature. Radios are designed to operate with a certain range of multipath delay spread, which can be longer outdoors and shorter indoors. Cyclic prefix (CP) or guard interval (GI) in the OFDM symbol must be of sufficient duration to allow multipath reflections to settle prior to decoding the symbol.

To help engineers optimize radio design for specific environments (e.g. phones for outdoors, APs for indoors), the wireless industry has developed a few standard channel models for indoor and outdoor spaces. Commercial faders implement IEEE and 3GPP models [4-12] to enable radio testing in a range of standards-based emulated environments.

A summary of IEEE 802.11n indoor channel models [4] is shown in Table 3.

Table 3: *IEEE 802.11n standard channel models*

Model		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	30 m	18	150 ns	1050 ns	6

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

Notice how delay and delay spread in Table 3 increase as larger spaces are being modeled by the IEEE models A through F. IEEE 802.11n/ac channel models [4-5] are defined in terms of 'clusters' of multipath reflections. A cluster is a group of rays reflecting together from, for example, a corner of a room or a wall and propagating as a group. The IEEE Model B, modeling a house, has 2 clusters. Model D, modeling a larger space, has 3 clusters. Figure 5 demonstrates the concept of clusters.

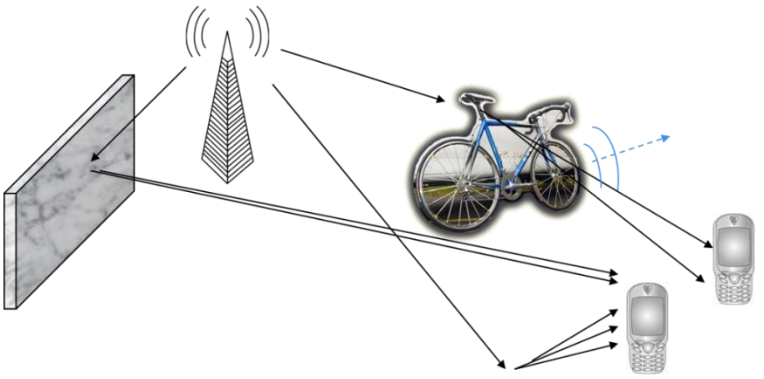

Figure 5: *Multipath reflections travel in clusters and arrive at the receiving device as multiple clusters of energy spaced in time.*

Reflectors can be mobile (e.g. a vehicle). Moving reflectors or moving radios introduce a Doppler shift to the signal.

A cluster typically arrives at the receiver multiple times as it bounces back and forth between opposite surfaces, as shown in Figure 6. Each time the cluster arrives at the receiver its power is lower. Multiple clusters can overlap in time, creating what's called a Power Delay Profile (PDP) of the signal at the receiver. Figure 6 shows the 3-cluster PDP of Model D.

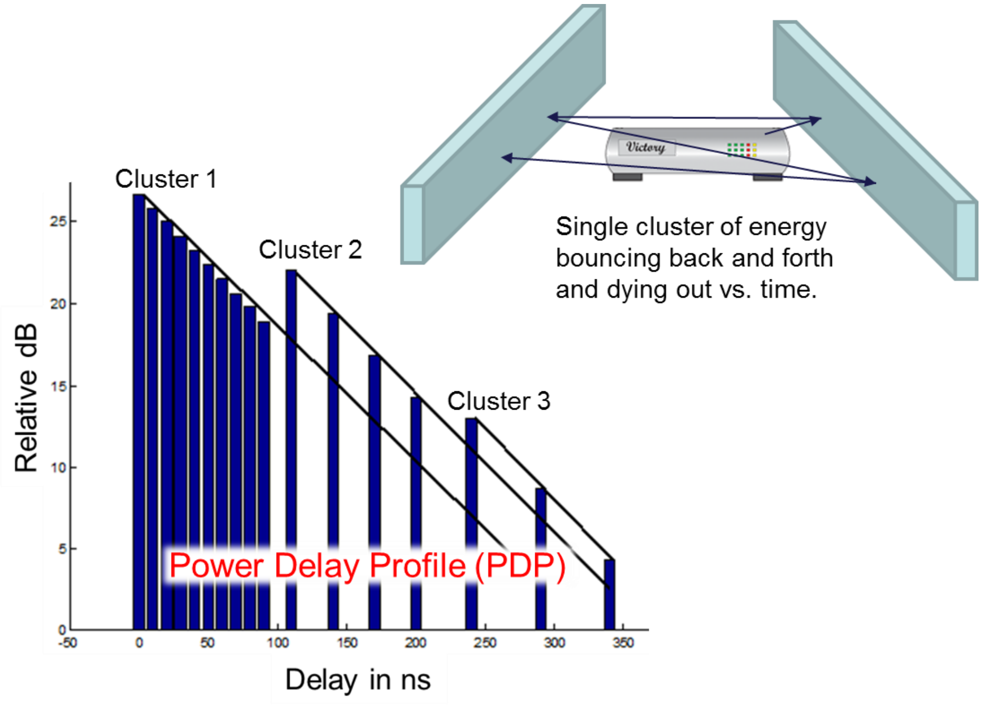

Figure 6: *IEEE Model D 3-cluster PDP. Each cluster bounces back and forth, monotonically diminishing in power with each bounce. Multiple clusters overlap in time and add together to form PDP.*

Source of PDP plot: [4].

Faders typically model angular spread, PDP, Doppler shift, SNR and other channel impairments. Because conventional faders are designed to connect to the DUT via conducted connections, they also model MIMO antenna arrays and correlation in the wireless channel. New OTA models are becoming available for MIMO faders for use in the emerging MIMO OTA testbeds [11-12].

When selecting a fader, make sure that it offers OTA support. Traditional channel models incorporate the modeling of MIMO antenna arrays, which makes them unsuitable for use with real test antennas.

Is it possible to maximize MIMO OTA throughput in a small anechoic chamber?

Device manufacturers want MIMO OTA testbeds that can demonstrate the upper limit of their product's performance consistently, repeatably and at multiple locations around the world.

To maximize MIMO OTA throughput we need to create a multipath environment, making sure that:

1. The signal arrives at the MIMO DUT with a wide angular spread (i.e. from all directions)
2. Multipath reflections conform to industry standard PDPs in terms of delay spread
3. The testbed guarantees repeatable results

As an example, let's take a look at the octoBox^{TM} wireless testbed. octoBox is a small anechoic chamber lined with gradient absorber.

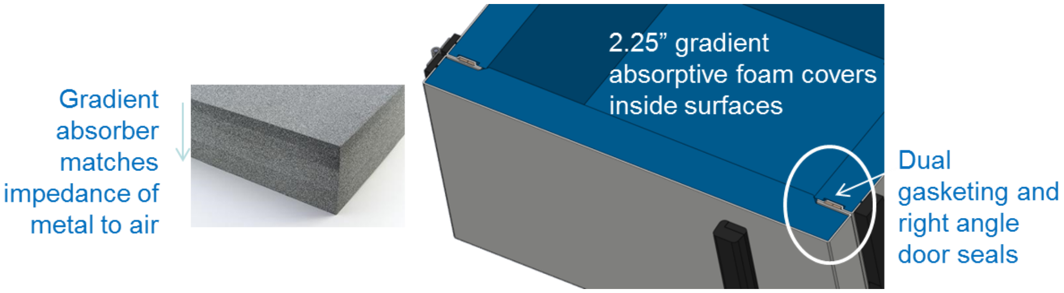

Figure 7: *Gradient absorber is composed of layers of monotonically increasing impedance, matching the low impedance of the metal surfaces of octoBox to the high impedance of air.*

The absorber guarantees 20 dB of damping on any reflections from the walls, floor and ceiling of the chamber in the frequency range of 1 to 6 GHz and 15 dB damping down to 700 MHz, which is a realistic magnitude of reflections in a typical house. With reflections surrounding the DUT from walls, ceiling and floor of octoBox, we create a wide-angular-spread environment modeling non-line-of-sight (NLOS) multipath reflections to help achieve maximum throughput.

The direct line of sight (LOS) transmission between the test antennas and the DUT is also set up to have a wide angular spread, which is a function of the proximity of test antennas to the DUT, as demonstrated in Figure 8.

Figure 8: *Narrower angular spread due to longer distance to the test antenna array (left); wider angular spread resulting from proximity to the test antenna array (right).*

Antenna spacing inside octoBox is adjustable and set at the factory to resemble an antenna array of a real MIMO device (e.g. a MIMO AP), as shown in Figure 9.

Figure 9: *Example of MIMO test antenna arrangement inside octoBox small anechoic chamber. The MIMO antennas are spaced approximately the same way as they would be on an access point. All corner brackets and antenna rails are made of non-reflective plastic.*

But how do we achieve a long enough multipath delay spread in a small box to render multipath realistic?

In real life delay spread depends on the physical space. It is shorter for small rooms and longer for larger rooms or outdoor spaces. Conventional faders emulate both delay spread and angular spread of a wireless channel. These instruments perform emulation computationally on a digitized signal, which results in complex and expensive solutions [15]. Taking a simpler and closer-to-reality approach, octoBox MPE (multi path emulator) emulates realistic delay spread of multipath reflections by bouncing the signal off the ends of precisely tuned RF cables.

What is octoBox MPE testbed?

octoBox MPE testbed, shown in Figure 10, consists of 2 octoBox chambers and an MPE module stacked between the chambers. MPE creates multipath that conforms to the IEEE standard PDP on multiple MIMO paths. The MIMO paths couple to the MIMO antenna array located in the top chamber together with the DUT.

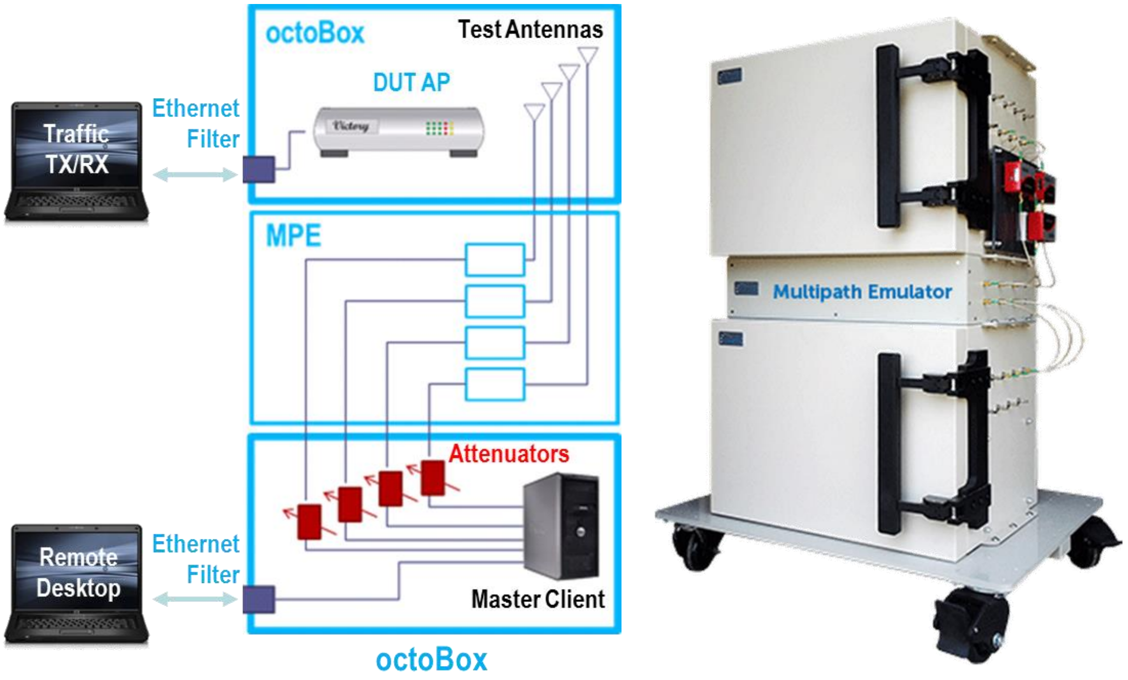

Figure 10: *octoBox MPE testbed for MIMO OTA measurements. Left: block diagram; right: photo*

Programmable RF attenuators in-line with each MIMO path introduce flat path loss, modeling losses through walls or air. The MPE module models multipath on each of the 4 MIMO paths.

To measure throughput or PER, we can use external PCs to transfer traffic. External PCs communicate with the equipment inside octoBoxes and can be cabled via feed-through Ethernet or USB filters built into octoBox (more on filters below). The bottom external PC in Figure 10 serves as a remote desktop controlling the PC inside the bottom chamber that houses the client adapter. This client is the 'master' for testing an AP DUT. When testing a client DUT, such as a smartphone, the 'master' device would typically be an AP or a base station. A photo of the testbed and a close-up of the bottom box are shown in Figures 11 and 12.

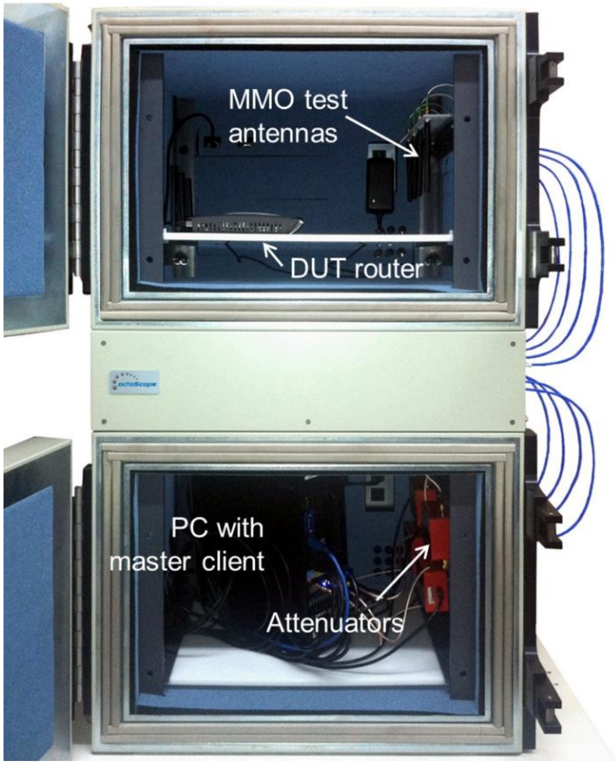

Figure 11: *MPE testbed photo. The bottom chamber houses a 'master' device and attenuators. Since the DUT here is an AP, the master is a client device. If the DUT were a client (e.g. phone or pad), the master would be an AP or a base station.*

The top chamber houses the DUT and the test antennas. The bottom chamber houses the master and programmable attenuators. The master device is conductively coupled.

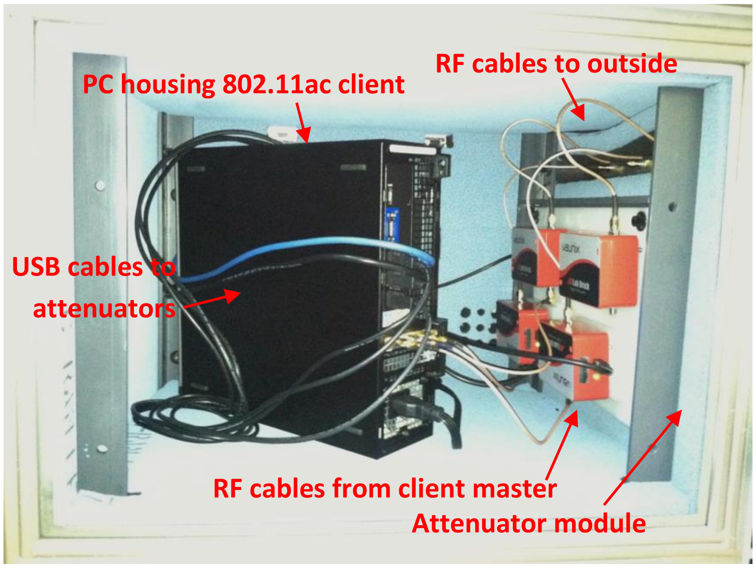

Figure 12: *Close-up view of the bottom octoBox chamber. In this example, a PCIe Wi-Fi client device is plugged into a mini-tower PC. The client's antenna ports are connected via coaxial cables to the attenuators. The opposite ports of the attenuators are connected via coaxial cables to the RF connectors on the side of the octoBox, which couple the RF signals outside for conection to the MPE and the top chamber (see block diagram in Figure 10).*

Why is the master device coupled via conducted connections while the DUT is coupled OTA?

In a real life test configuration there is a single OTA link: between the master antennas and the DUT antennas. In the octoBox MPE testbed this OTA link is in the top chamber. If we were to also couple the master device OTA in the bottom chamber, we would have two points of OTA coupling, which would be inconsistent with real life.

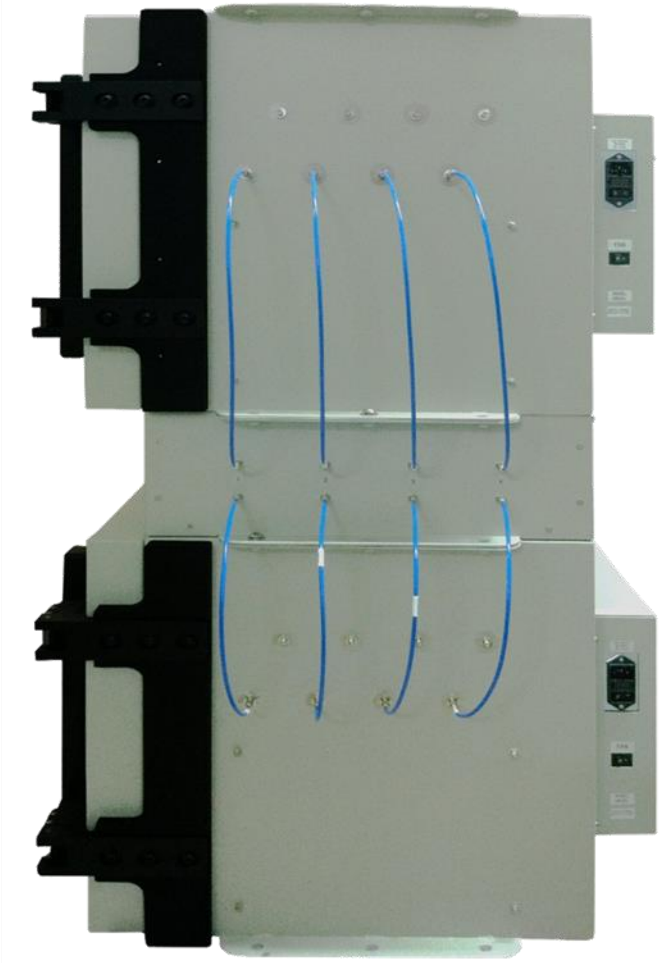

Figure 13: *External interconnections of the octoBox MPE stack.*

Double-shielded RF cables are used to interconnect the programmable attenuators in the bottom chamber to the MPE module and the MPE module to the test antennas in the upper chamber (see block diagram in Figure 10).

Extra RF ports can be used to connect monitor probes, interference sources or other devices into the testbed.

SmallNetBuilder (www.smallnetbuilder.com) uses octoBox MPE testbed to evaluate and benchmark the performance of 802.11 devices.[1] SmallNetBuilder has been able to measure inside octoBox top data rates achievable today by the 802.11ac devices. Using programmable attenuators, SmallNetBuilder is able to create plots of throughput vs. path loss, as shown in Figure 14.

SmallNetBuilder measures throughput using IxChariot™ software from Ixia. IxChariot support measurements on the TCP/IP or UDP/IP layer. The IP layer throughput is strongly influenced by the IxChariot test file size. SmallNetBuilder uses 2,000,000 to 5,000,000 Byte file size. Higher throughput may be achievable using IxChariot high performance throughput script, which transmits 10,000,000 Byte files.

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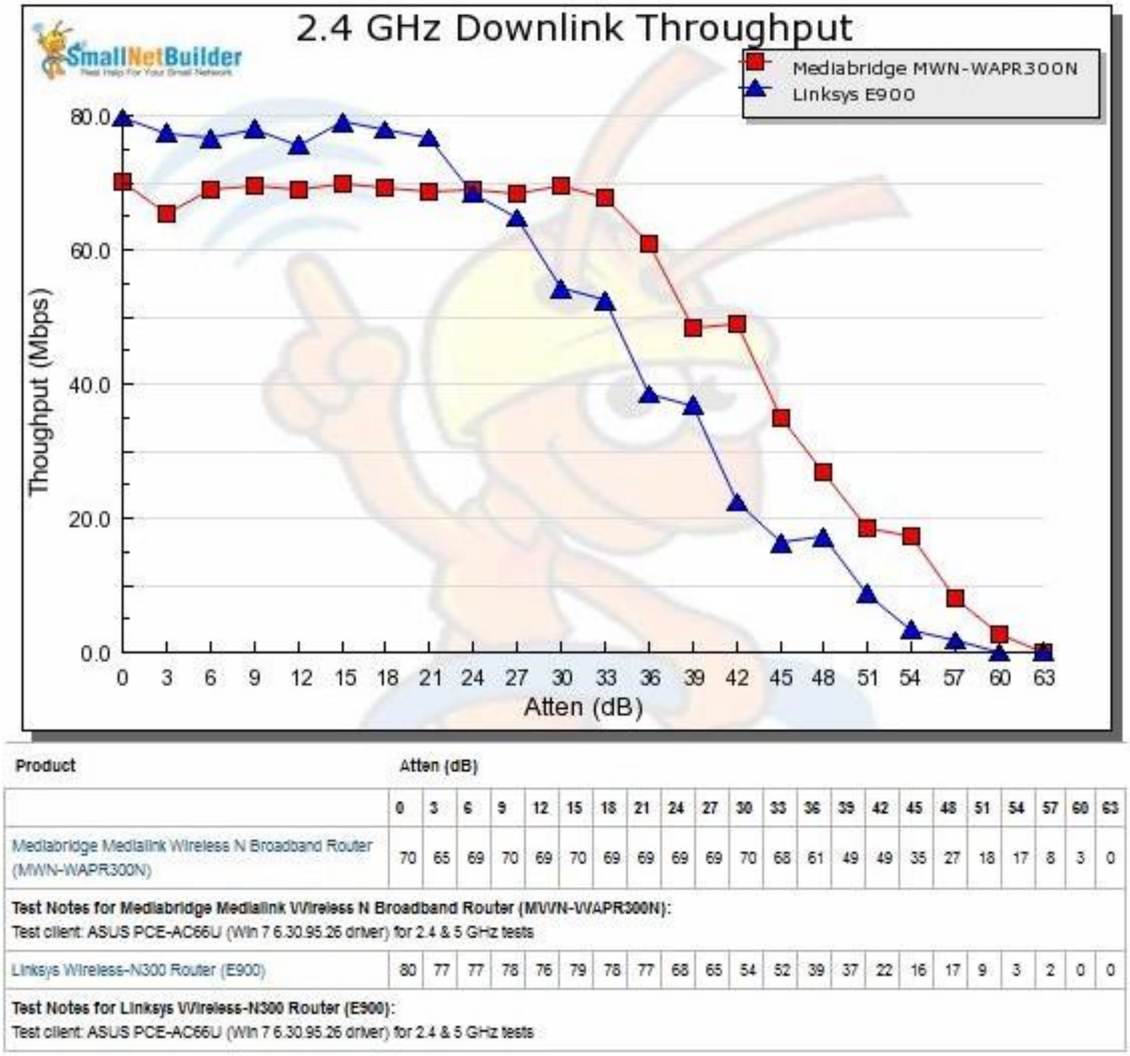
[1] http://www.smallnetbuilder.com/wireless/wireless-howto/32082-how-we-test-wireless-products-revison-7



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																						

Figure 14: *Example of a throughput vs. attenuation plots produced by* *www.smallnetbuilder.com*

How does MPE implement industry-standard channel models?

octoBox MPE models PDP of each MIMO path per the IEEE 802.11n/ac channel modeling specifications [4-5]. The block diagram of the MPE testbed is essentially the same as that of a conventional fader, but internal circuitry of the MPE is simpler and closer to real life.

Figure 15 shows how well the MPE module matches the PDP of the IEEE Model B. The standard [4] defines PDP for model B in terms of 2 clusters with each cluster being modeled by multiple back-and-forth reflections with each reflection monotonically decreasing in power (see Figure 6 above).

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

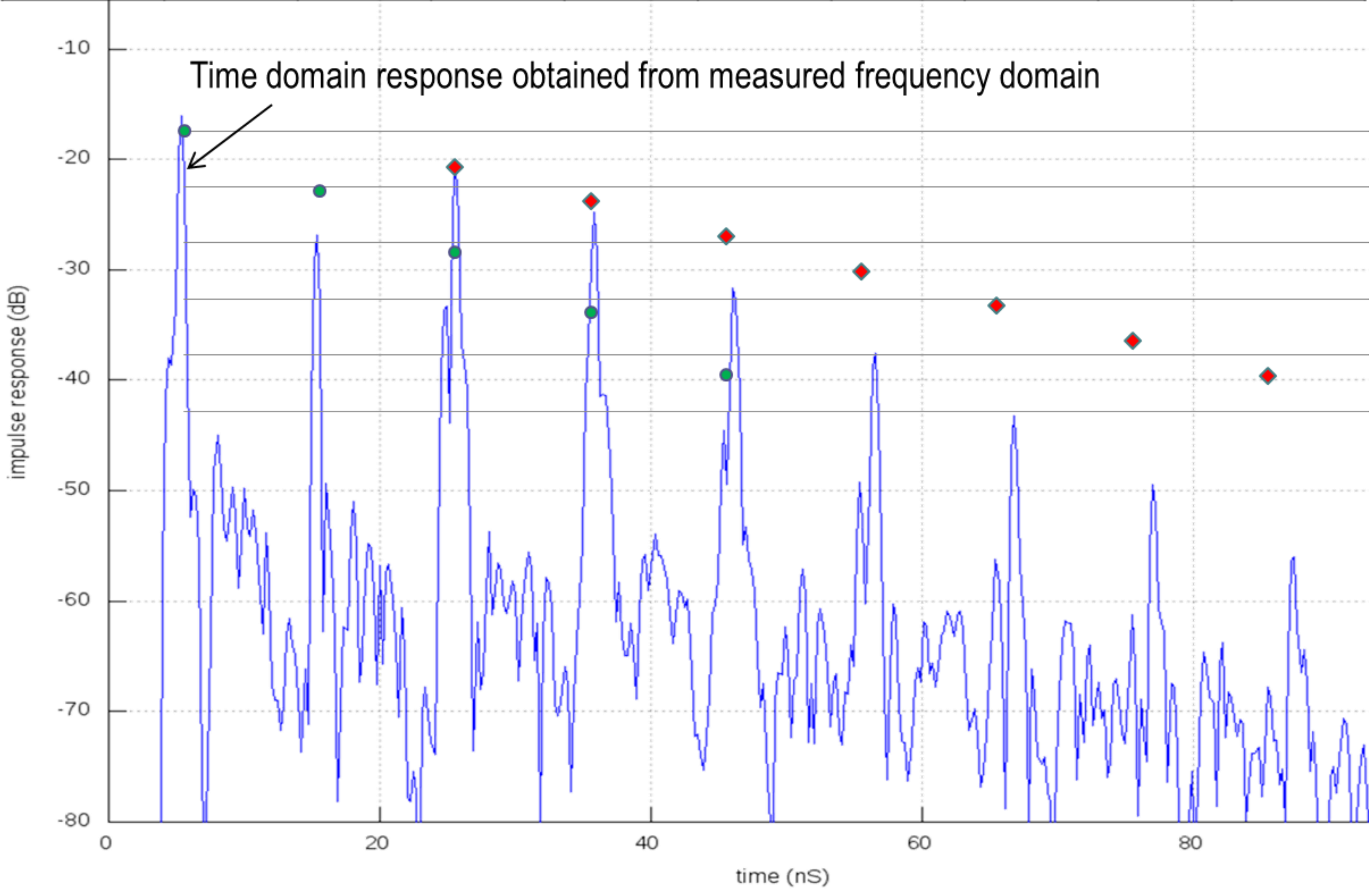
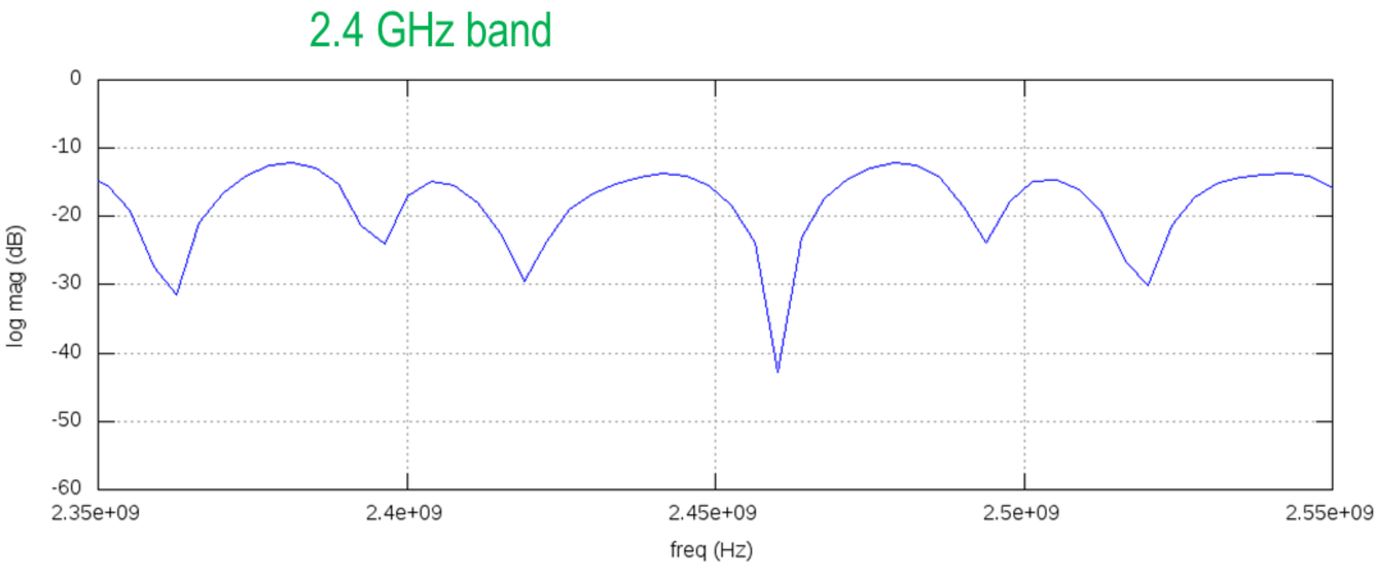


Figure 15: *The measured response of octoBox MPE (shown in blue) closely approximates the IEEE model (shown as green dots for cluster 1 and red dots for cluster 2).*

The frequency response of the multipath generated by the MPE is shown in Figure 16 and is representative of typical multipath in the home environment.



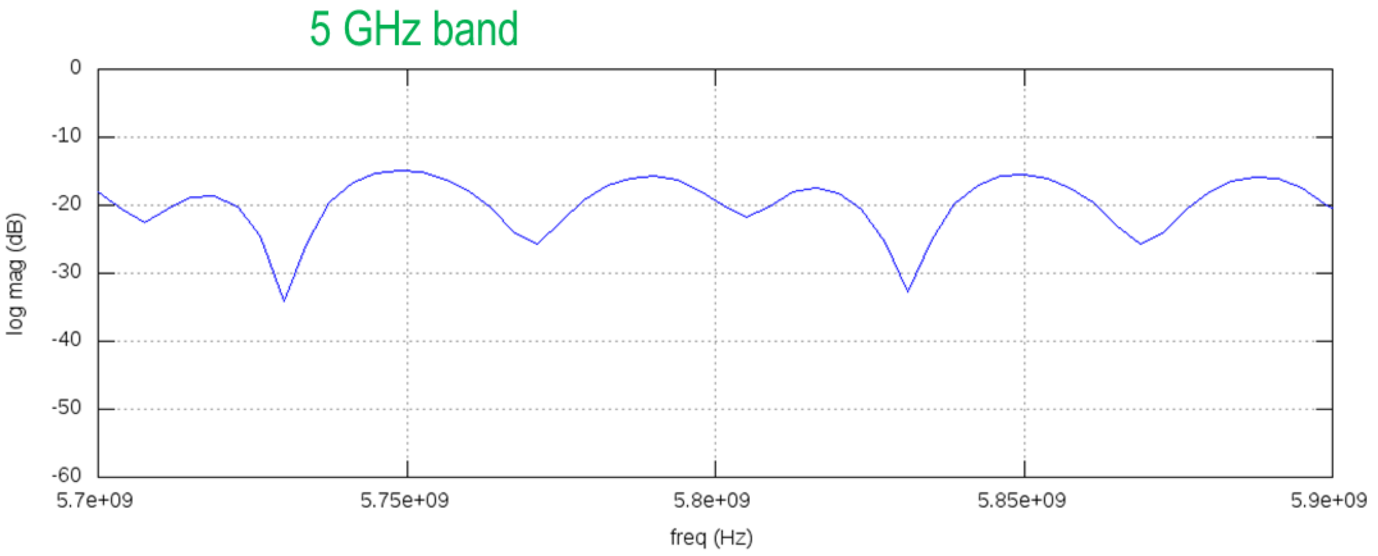


Figure 16: *octoBox MPE frequency response in the 2.4 GHz (top) and 5 GHz (bottom) Wi-Fi bands*

octoBox MPE is a broadband device, supporting any channel width, including the widest 802.11ac channel of 160 MHz. Its broadband frequency response is shown in Figure 17.

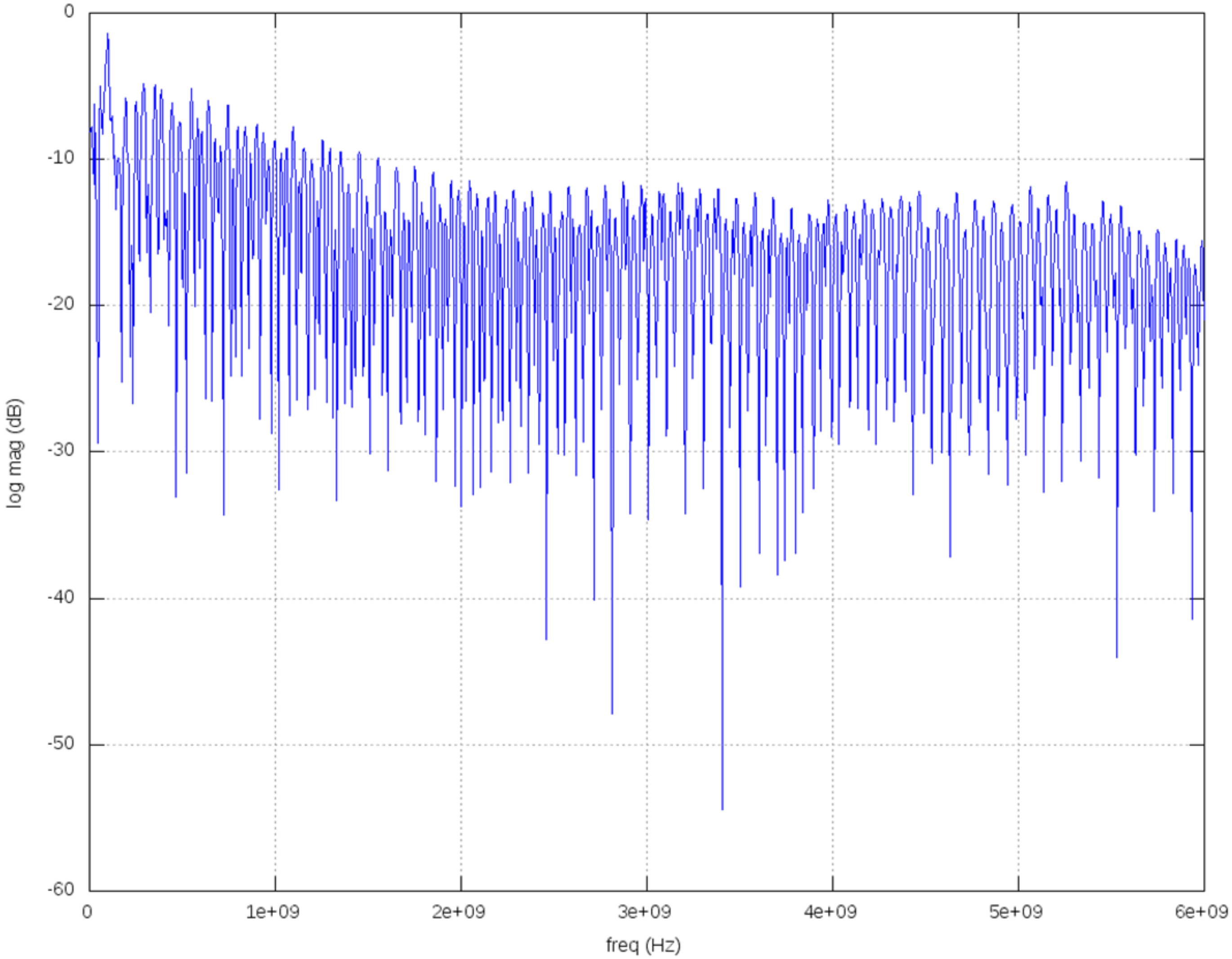


Figure 17: *octoBox MPE wideband frequency response from near DC to 6 GHz*

octoBox MPE testbed provides realistic RF environment achieved by the carefully arranged anechoic conditions, by the MPE module emulating multipath with a realistic delay spread and by programmable attenuators emulating path loss.

The next questions is: How does octoBox MPE testbed guarantee repeatable measurements?

How to achieve repeatable measurements

In today's connected world, most laboratories and test sites are saturated with interfering wireless traffic. Wireless signals from nearby cellular or Wi-Fi networks can impact the measured throughput at random, making measurements non-repeatable, as shown in Figure 18.

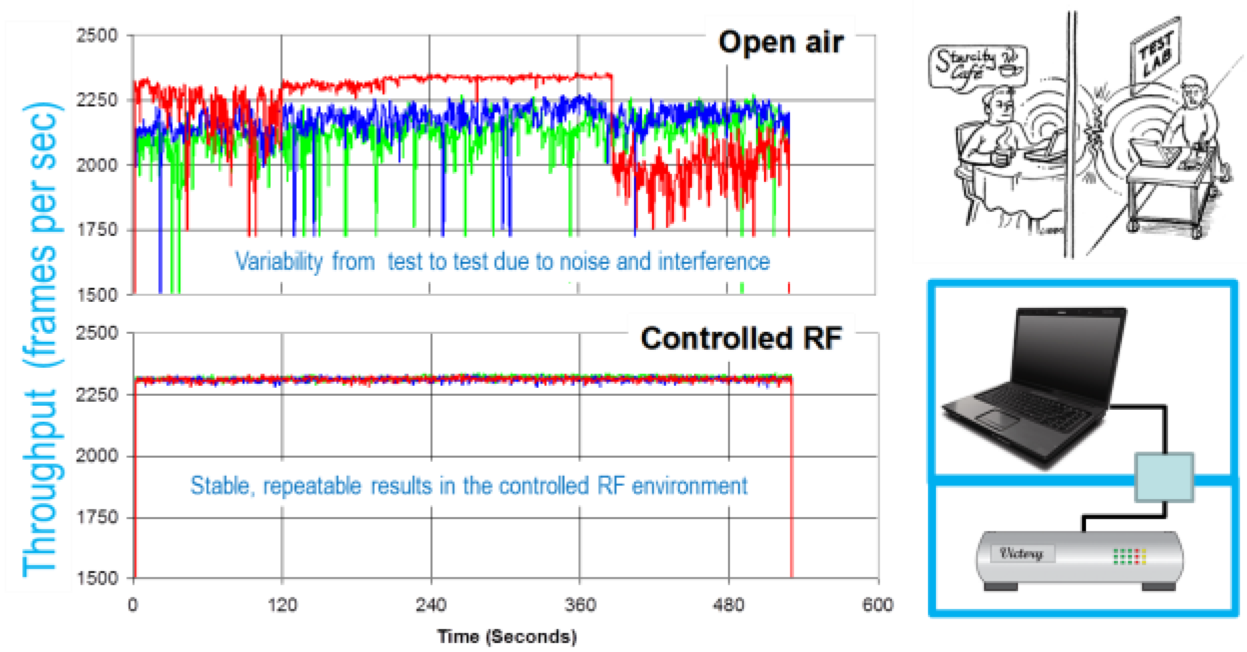


Figure 18: *Open air throughput measurement varies vs. time due to interference from neighboring wireless networks and devices (top). To make measurements stable and repeatable DUTs are placed into isolated environment (bottom).*

Today's wireless receivers are sensitive down to below -90 dBm and detect even the weakest interfering signals, which can disturb the test.

Screen rooms are often used to protect from external interference, but inside a screen room the DUTs and devices in the testbed still need to be isolated from one another, as shown in Figure 19.

Screen rooms are often used to protect from external interference, but inside a screen room the DUTs and devices in the testbed still need to be isolated from one another.

A DUT placed in the vicinity of a master can often establish a link and communicate even if its antennas are removed. Under such crosstalk conditions, signal level cannot be attenuated below the level of crosstalk (Figure 19 bottom left), which can cut the dynamic range by 40-50 dB. This puts a limitation on testing of the adaptation algorithms since the testbed cannot emulate the high path loss conditions (preferably down to -100 dBm) when the link is barely active or broken. To test over the entire dynamic range, devices in the link under test should be isolated from one another by being placed into individual isolation chambers, even when they are conductively coupled.

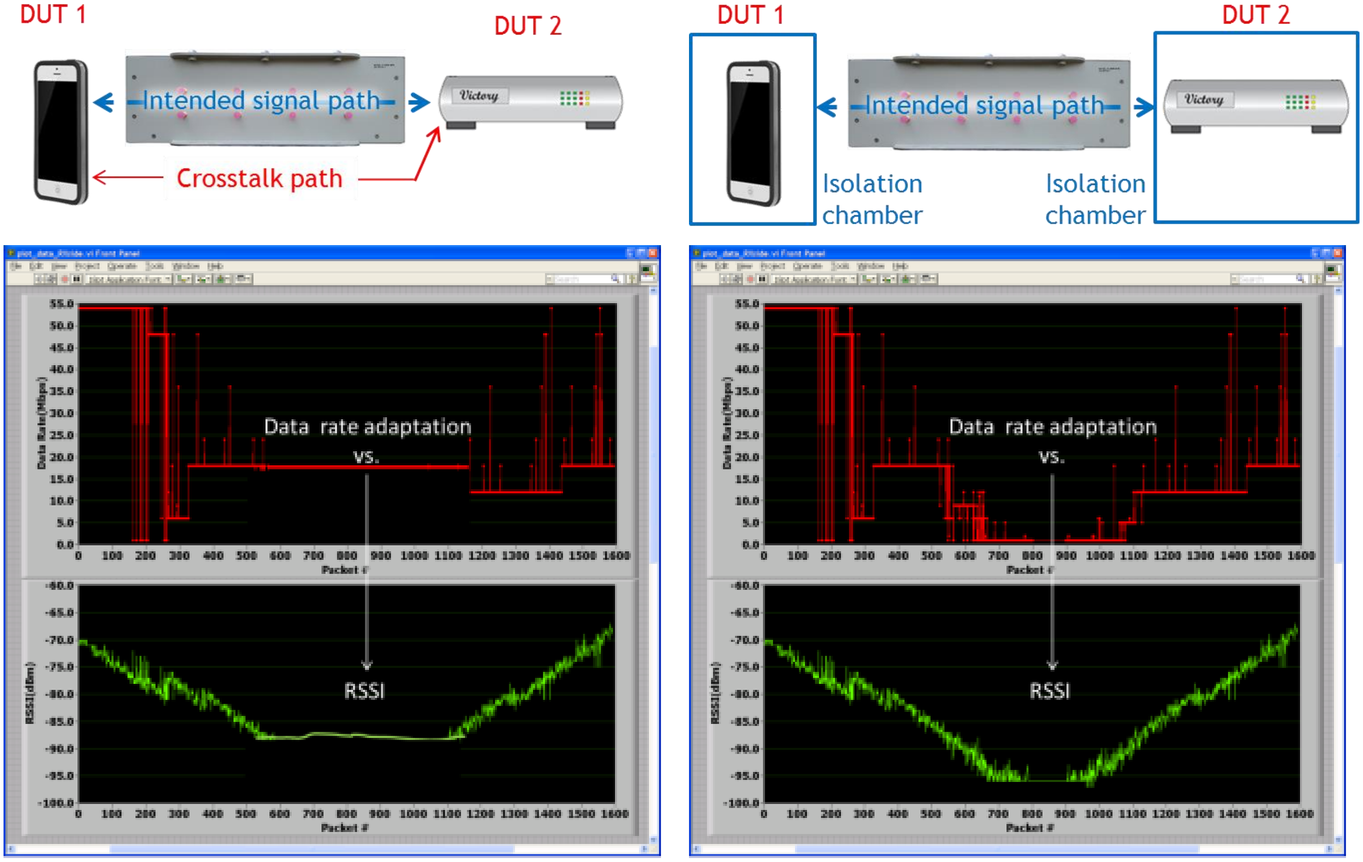


Figure 19: *Example of a conducted test configuration with the DUTs sharing the airlink (left) vs. with isolation between the DUTs provided by isolation chambers (right).*

Chambers used for OTA testing must have higher isolation than chambers used for conducted testing because signal power at the antennas is much stronger than when antennas are replaced with cabled connections. Most small isolation boxes on the market today are unsuitable for OTA coupling due to inadequate isolation and poor internal absorption.

How to select an RF isolation chamber

There are two issues to be aware of when selecting an isolation chamber:

1. Isolation specifications can be misleading because they 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.
2. Most shielded boxes on the market are not designed for OTA coupling. OTA support requires high isolation, absorption and special conditions to enable high MIMO throughput.

Another important consideration is maintenance. RF gasketing can wear out after a year of normal use, severely compromising chamber isolation. Gasketing should be easy to replace. Figure 20 shows octoBox gasketing, which is peel-and-stick and available off the shelf, enabling easy maintenance.

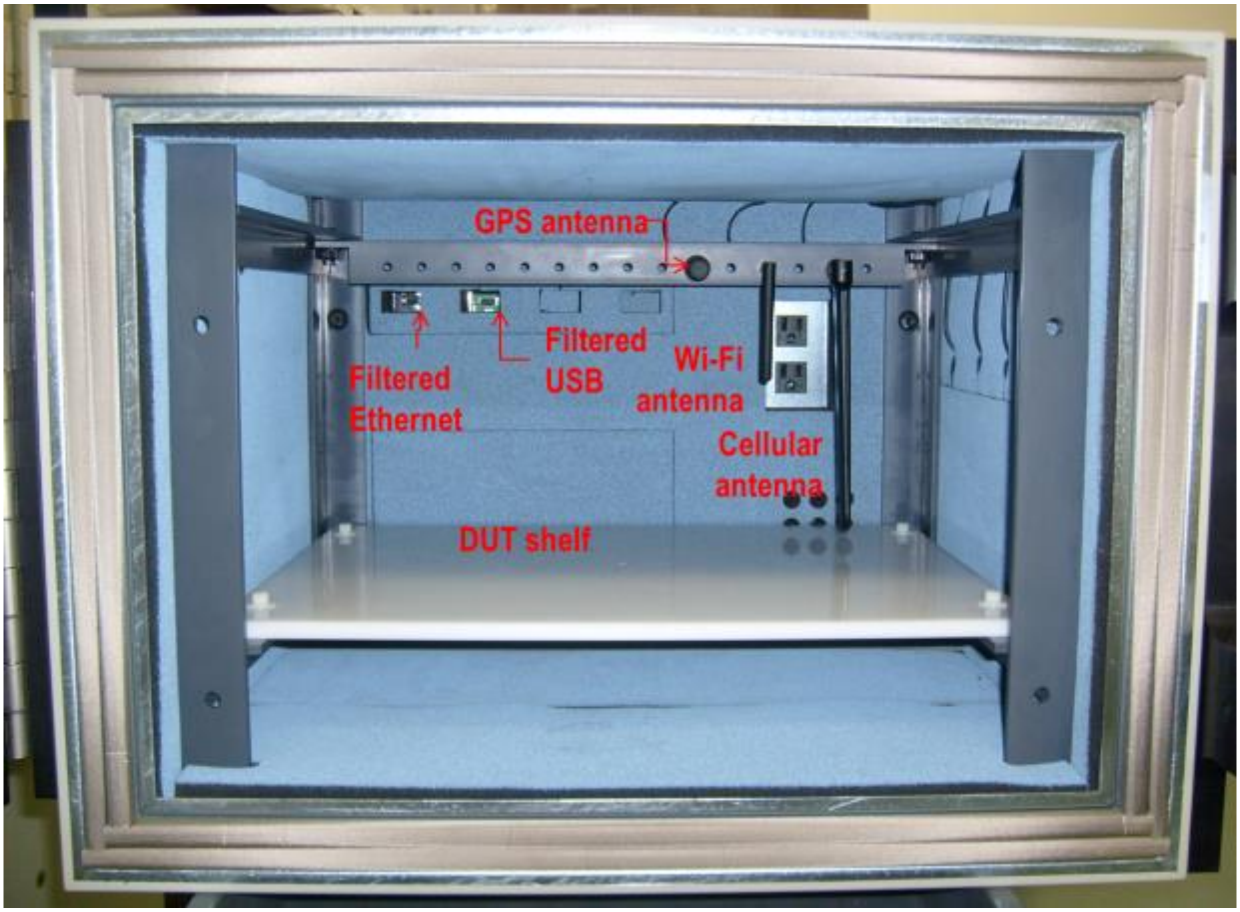


Figure 20: *octoBox uses peel-and-stick gasketing for easy maintenance. Double gasketing in combination with dual door latching mechanism (not shown), creates a perfect seal. Rails and shelf are made of RF-transparent plastic to avoid reflections.*

Most surfaces inside an anechoic chamber should be either covered with absorber or be made of RF-transparent material, such as plastic or wood to dampen reflections. Reflections cause standing waves that result in signal strength fluctuation vs. position of the DUT. For OTA coupling, look for a chamber with good positional stability. One or two small metal surfaces with no opposing reflectors are OK.

Look for a chamber that:

- Provides feed-through filters for connecting power, Ethernet, USB, HDMI and other interfaces to the DUT inside the chamber
- Has sufficient isolation such that the DUT with all data and power cables connected to it through the walls of the chamber cannot detect external interference
- Supports the highest required MIMO data rate over the air

Most cellular, LTE and Wi-Fi services operate within the 700 MHz to 6 GHz band and this is the band where data and power filters must ensure good isolation.

Provided the enclosure is well constructed and sealed, data and power filters are typically 'the weakest link' when it comes to isolation. Copper cables can act as antennas picking up signals in the air and carrying them into and out of the chamber.

Data filters must suppress any signals in the operating band of 700 MHz to 6 GHz, so that interfering signals cannot disturb the test. Filtering is most challenging for data cabling carrying high frequency signals, such as Ethernet, USB and HDMI. The reason is that the passband of the filter is wide (e.g. 400 MHz for USB 2.0) and rejection has to start at the low end of the frequency range (700 MHz), requiring a filter with a steep roll off. Data and power filters must provide at least 60 dB of suppression in the entire rejection band of 700 MHz to 6 GHz, something that ordinary LC filters may not adequately provide. There is typically an additional 20-30 dB of rejection due to coupling losses from the air onto the cables, resulting in total rejection of more than 80 dB. Isolation should be measured with data cables attached through the filters.

When the interfering source is within a close proximity, octoBox isolation is better than 80 dB across the operating band[2]. With the interfering source a few feet away, interference is not detectable inside octoBox, providing very stable test conditions. Figure 21 shows the octoBox isolation measurements.

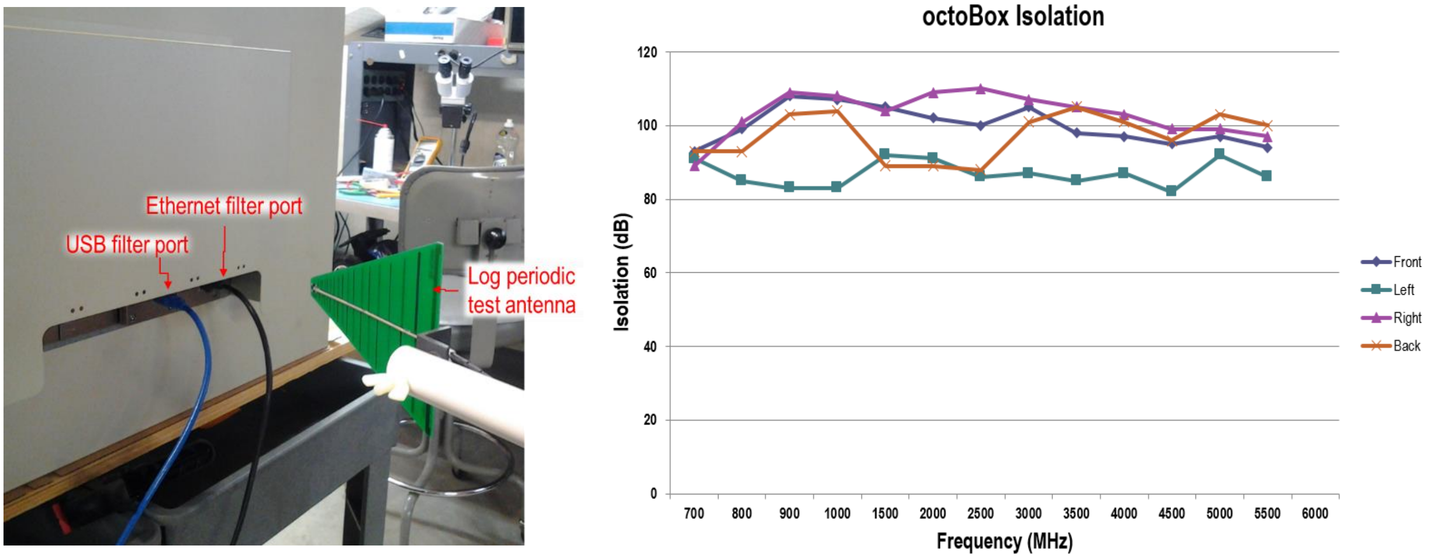


Figure 21: *octoBox isolation is measured with cables connected through the data filters on the inside and outside of the box. Isolation is measured from all sides of the box [15]. Back of the box is shown.*

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[2] Some interfaces, such as USB 3.0 and HDMI, have passband overlapping with the 2.4 GHz Wi-Fi band. When cabling is connected through these filters, isolation in the passband of the filter, including in the 2.4 GHz Wi-Fi band, may be compromised. The 5 GHz Wi-Fi band is still well isolated when using octoBox filters.

octoBox can be configured with up to 4 data filters, including Ethernet, USB and HDMI filters. Power connections are also filtered and cooling vents are constructed as waveguides to prevent interfering signals from entering the chamber.

Summary

Test engineers face difficult challenges when measuring MIMO throughput because wireless channel environment is constantly changing and radio operating mode changes to adapt to the changing environment. In other words, we have 'too many moving parts', making it difficult to obtain repeatable measurements. To guarantee repeatable and meaningful results the testbed must be capable of creating a variety of wireless channel conditions in a consistent manner. It must also be well enough isolated to keep interference from impacting the performance of highly sensitive radios. Table 2 above explains the factors that impact MIMO throughput. Table 4 summarizes how octoBox MPE testbed controls these factors to provide an environment where device behavior and performance can be reliably characterized.

Table 4: *How octoBox MPE testbed controls factors that impact MIMO throughput*

Factors	Corresponding octoBox MPE testbed capabilities
MIMO channel correlation	Low correlation can be achieved via wide spacing of test antennas. The lower the correlation the higher the theoretical MIMO throughput
Angular spread of the received signal	(1) Test antenna array is close to the DUT antennas, widening the angular spread of the LOS signal; (2) chamber geometry creates -20 dB reflections surrounding the DUT. Both of these factors maximize angular spread of the test channel thereby maximizing MIMO throughput.
Device antenna spacing and device orientation	Test antenna spacing can be adjusted. DUT can be rotated with respect to test antennas.
Antenna polarization	Test antennas can be cross-polarized. However, reflections inside the chamber and metal surfaces in the DUT (ground planes, batteries, etc.) will also alter polarization of the signal that reaches the DUT antennas.
Noise and interference	Can be injected in a controlled manner via extra RF ports.
Motion of devices or multipath reflectors	Can be implemented via phase dithering of the signal or by using a fader.
Delay spread of reflections	octoBox MPE module models IEEE standard delay spread.

A wireless testbed should emulate a variety of channel conditions, including multipath, path loss and noise. At the same time, the testbed should be capable of emulating a MIMO channel that supports maximum throughput of devices being tested. The testbed should also guarantee repeatable and consistent test results in labs around the world.

References

[1] Azimuth ACE, Spirent VR5, Anite Propsim faders are the most popular faders on the market today. octoScope's multipath emulator, MPE, is a simpler non-programmable fader that comes built into a controlled environment test bed with 2 octoBox anechoic chambers.

[2] IEEE P802.11-REVmc/D2.3, "Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications", December 2013

[3] IEEE P802.11ac/D6.0, "Draft STANDARD for Information Technology — Telecommunications and information exchange between systems — Local and metropolitan area networks — Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications Amendment 4: Enhancements for Very High Throughput for Operation in Bands below 6 GHz", July 2013

[4] IEEE, 802.11-03/940r4: TGn Channel Models; May 10, 2004

[5] IEEE, 11-09-0569 , "TGac Channel Model Addendum Supporting Material", May 2009

[6] TS 25.101, Annex B, "User Equipment (UE) radio transmission and reception (FDD)",

[7] TS 36.101, Annex B, "Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio transmission and reception"

[8] 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"

[9] TS 45.005, Annex C, "GSM/EDGE Radio Access Network; Radio transmission and reception"

[10] TS 51.010-1, "Mobile Station (MS) conformance specification; Part 1: Conformance specification"

[11] 3GPP TR 37.977 V1.2.0 (2013-11), "Verification of radiated multi-antenna reception performance of User Equipment (UE)", Release 12, November 2013

[12] 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

[13] "How MIMO Radios Work", by Fanny Mlinarsky, January 2013

[14] "octoBox Isolation Test Report", 12/2013, http://www.octoscope.com/English/Collaterals/Documents/octoBox_Isolation_Measurements.pdf

[15] octoFade^{TM} product presentation incudes material on channel emulators: http://www.octoscope.com/English/Collaterals/Presentations/octoScope_octoFade_Product_Presentation.pdf

Glossary

3GPP	3rd Generation Partnership Project
ACK	Acknowledgement
AP	Access Point
CDD	Cyclic Delay Diversity
CP	Cyclic Prefix (aka GI)
Gbps	Gigabits per second
GI	Guard Interval (aka CP)
IEEE	Institute of Electronics and Electrical Engineers
LOS	Line Of Sight
LTE	Long Term Evolution
Mbps	Megabits per second
MIMO	Multiple Input Multiple Output
MPE	Multi Path Emulator
MRC	Maximal Ratio Combining
NLOS	Non Line Of Sight
OTA	Over The Air
PDP	Power Delay Profile
PER	Packet Error Rate
SFBC	Space Frequency Block Coding
SINR	Signal to Interference and Noise Ratio
SISO	Single Input Single Output
SM	Spatial Multiplexing
SNR	Signal to Noise Ratio
STBC	Space Time Frequency Coding