Fanny Mlinarsky - May 06, 2014

As cellular and Wifi systems move from single to multiple wireless signals, handsets and the chipsets that go inside them need testing. Because of the multiple signals in a MIMO (multiple input, multiple output) system, testing handsets using a wired connection doesn't emulate the needed test conditions.

This 3-part series will take a deep dive into the modern radio architecture and MIMO signaling. It will examine sophisticated new baseband algorithms designed to optimize throughput of 802.11n/ac and 4G systems. We will study the nature of a MIMO airlink channel and RF propagation and outline the factors that impact MIMO throughput. Finally, we will look at methods of measuring throughput and characterizing the behavior of baseband algorithms.

### How MIMO radios work

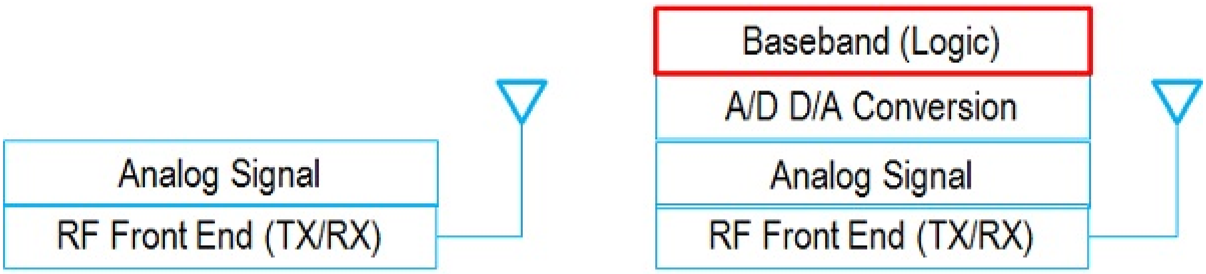
Getting repeatable and consistent performance measurements of 802.11n/ac and LTE MIMO devices is, for several reasons, a monumental challenge. For example:

- Modern wireless devices are designed to adapt automatically to the changing channel conditions.
- Wireless environment constantly changes vs. time, frequency and motion of radios and reflectors.
- The time-variability of path loss, multipath, Doppler and interference often baffles the decision-making logic of the adaptation algorithms and sometimes puts radios into unintended states.

IEEE 802.11ac radios can change their data rate over three orders of magnitude, ranging from 1 Mbit/s to over 1 Gbit/s for products sold today, with a theoretical maximum rate of 6.9 Gbits/s. Data rate adaptation happens on a packet-by-packet basis in response to time-variable airlink impairments, such as signal fades or interference.

The sophisticated adaptation capability resides in the Baseband layer of the radio—the intelligent logic layer. Radios have evolved since mobile phones first emerged in the 1970s from purely analog to very sophisticated logic and this logic we will examine here.

Early radios directed the voice signal out of the microphone to modulate the RF carrier (**Figure 1** left). Modern radios include a baseband layer that houses the (DSP)—a technology that changes everything about radios and enables dynamic adaptation to the time-variable channel conditions, resulting in vast improvements in throughput and range.



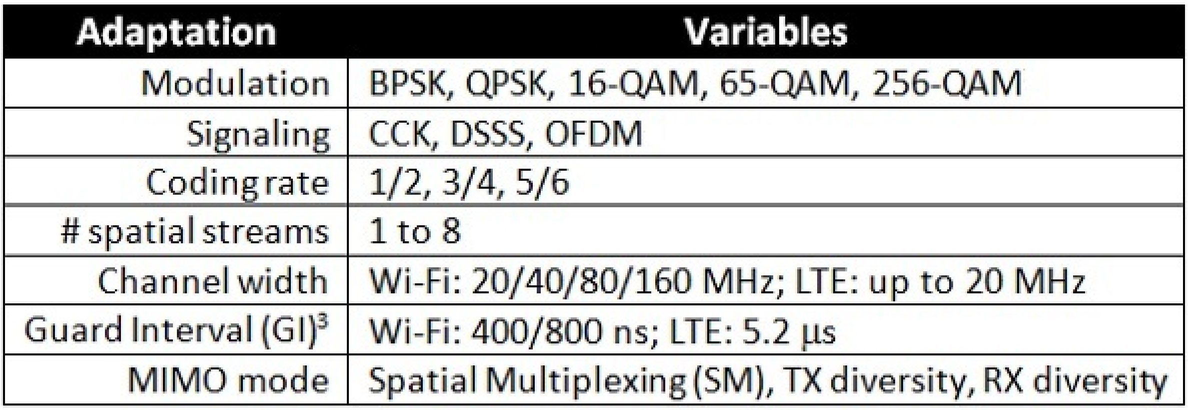
Old radio architecture

Modern radio architecture

**Figure 1. A traditional analog radio (left) would modulate a signal onto an RF carrier. In a baseband radio (right), baseband logic can make the radio adaptable to time-variable wireless channel conditions.**

Today's MIMO 802.11n/ac and LTE radios have more complex adaptation algorithms than legacy SISO (Single Input Single Output) 2G/3G and 802.11a/b/g devices. While SISO devices only vary modulation, MIMO radios work with a more complex MCS (Modulation Coding Scheme).

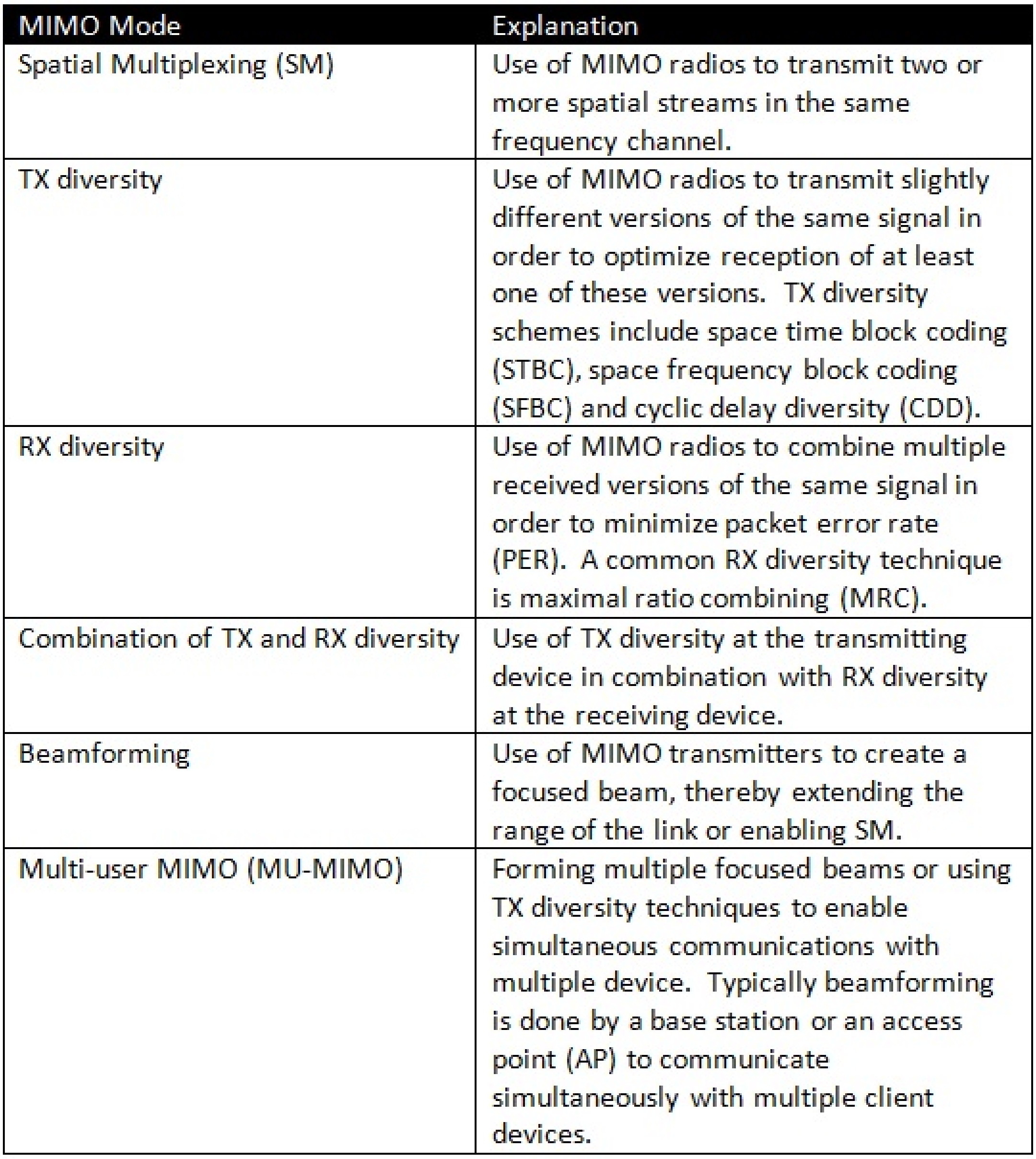
An MCS includes the following variables: modulation, coding rate, GI (guard interval), channel width, and the number of spatial streams. Thus, MIMO adaptation algorithms have several degrees of freedom, as summarized in **Table 1**. A spreadsheet found here provides the formulas and computes data rates for all 802.11n and 802.11ac MCSs as they are defined in the IEEE 802.11 standard. By studying the spreadsheet, you will understand how the variables listed in Table 1 combine to set the data rate on the airlink.



| 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)[3] | Wi-Fi: 400/800 ns; LTE: 5.2 µs |
| MIMO mode | Spatial Multiplexing (SM), TX diversity, RX diversity |

**Table 1. Wireless adaptation techniques typically supported by baseband logic.**

The technique of transmitting multiple spatial streams in the same frequency channel is called SM (Spatial Multiplexing). SM only works under favorable channel conditions, that is, in wireless channels with low signal to noise ratio (SNR) and low MIMO correlation. MIMO modes of transmission are explained in **Table 2**.

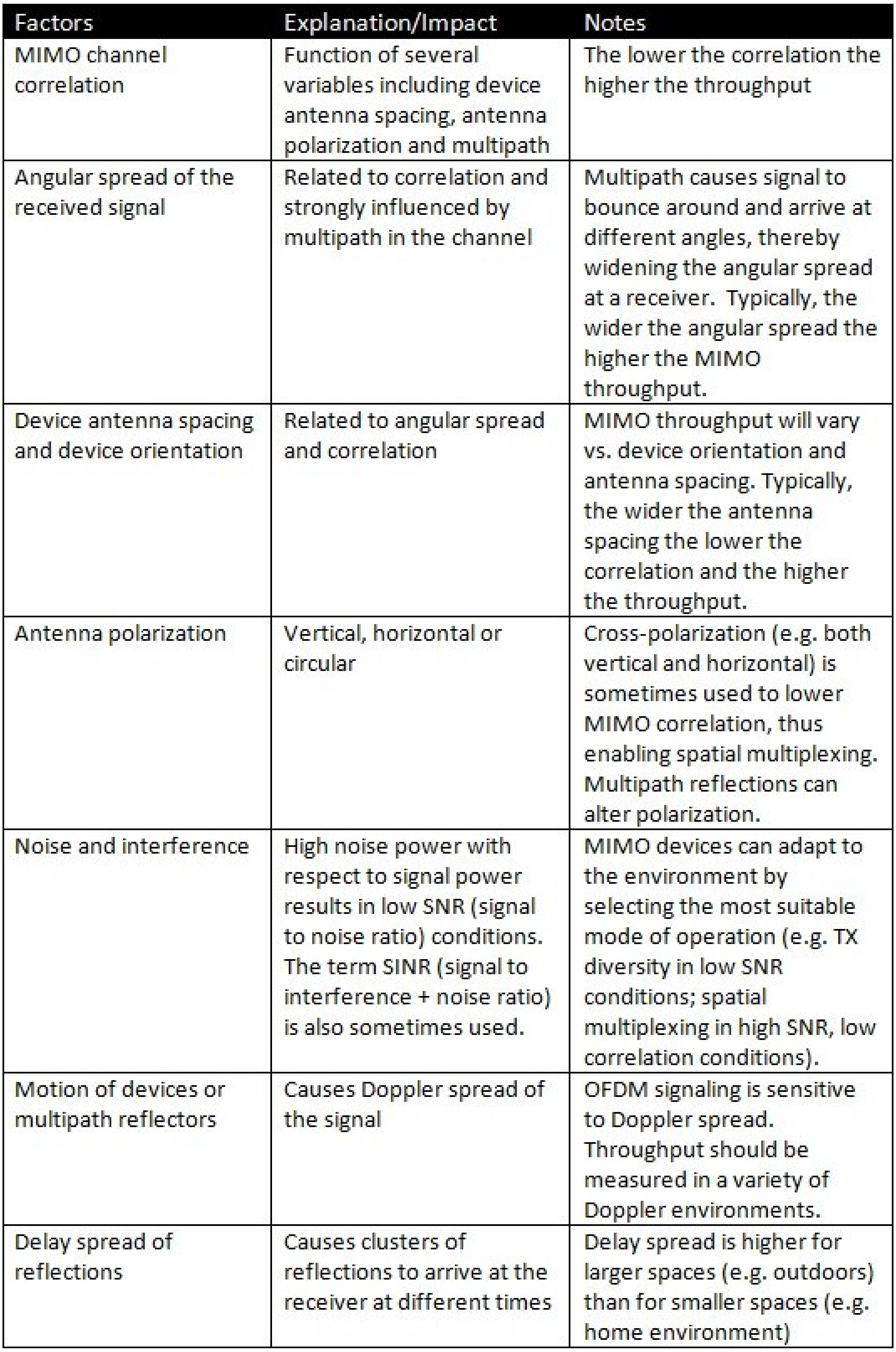


| MIMO Mode | Explanation |
|---|---|
| Spatial Multiplexing (SM) | Use of MIMO radios to transmit two or more spatial streams in the same frequency channel. |
| TX diversity | Use of MIMO radios to transmit slightly different versions of the same signal in order to optimize reception of at least one 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 packet error rate (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. |

**Table 2: MIMO modes of transmission.**

Commercial wireless chipsets typically support a subset of the MIMO modes outlined in Table 2 and some implement other proprietary modes. In the fast-changing wireless environment and with real-time decision making process, adaptation algorithms are still evolving and engineers are struggling to optimize throughput under all conditions. Any odd behavior or faults with adaptation algorithms can be difficult to catch in the field amidst constantly changing uncontrolled interference and motion of devices and reflectors.

Let’s look at the time-variable factors that impact MIMO throughput, outlined in **Table 3**. These are explained in detail in the octoScope white paper, Throughput Test Methods for MIMO Radios.



| 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) |

**Table 3. Factors that impact MIMO throughput.**

When considering a controlled environment wireless testbed, you can use Table 3 as a guide. In part 2, we will focus on controlled environment MIMO test beds.

EDN NETWORK

# Measure throughput of cellular and WiFi MIMO radios, part 2

**Fanny Mlinarsky** - May 20, 2014

In Part 1 of this series, we presented the background of how MIMO radios work. We examined wireless adaptation techniques and MIMO modes of transmission. We also outlined the factors that impact MIMO throughput. Now in Part 2, we compare the conducted measurement techniques to new over the air (OTA) techniques. We'll explore the challenges of MIMO OTA test methods and factors that can make measurements non-repeatable.

### Controlled channel, repeatable tests

As outlined in Part 1, engineers testing MIMO radios need to create a range of channel conditions from which to validate a radio's adaptability and throughput performance. This can be accomplished using a MIMO fader such as Azimuth ACE, Spirent VR5, or Anite Propsim), or a multipath emulator, such as the octoScope MPE. A fader or a multipath emulator can connect two or more devices through cables to the device antenna ports or over the air. For devices such as smartphones, tablets, or sensors with difficult-to-reach internal antennas, OTA coupling is highly desirable.

When most wireless communication radios were SISO (single input single output) and antennas were external, you could test a handset or other device by disconnecting it's antenna and connecting a programmable attenuator or a fader between a Master (reference) device and a DUT (**Figure 1**) left). Testing of MIMO radios with internal antennas requires a MIMO OTA testbed (Figure 1 right) that support stable and repeatable MIMO measurements. Of course, challenges arise when we couple signals over-the-air in a shielded box.

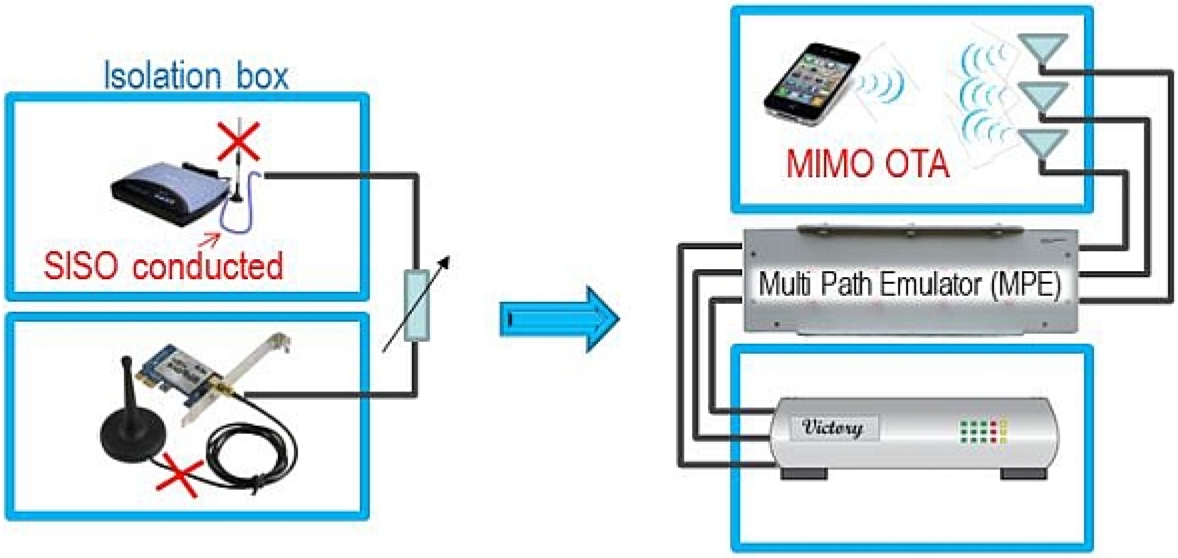


**Figure 1. Radio test-bed architecture is evolving from conducted SISO to MIMO OTA.**

### OTA signal coupling

There are two issues with OTA measurements inside a metal enclosure. First, the signal can reflect from the metal walls and form nulls completely altering the shape of the field and introducing positional variation of signal power. Anechoic chambers must be used to avoid this variation. Refer to octoScope white paper, Throughput Test Methods for MIMO Radios, for more details.

Second, 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 is often non-uniform with strong lobes and nulls, as shown in **Figure 2** on the right. The field of an internal antenna typically has nulls and peaks because the signal can be blocked by batteries, PCB ground planes, and other metal surfaces.

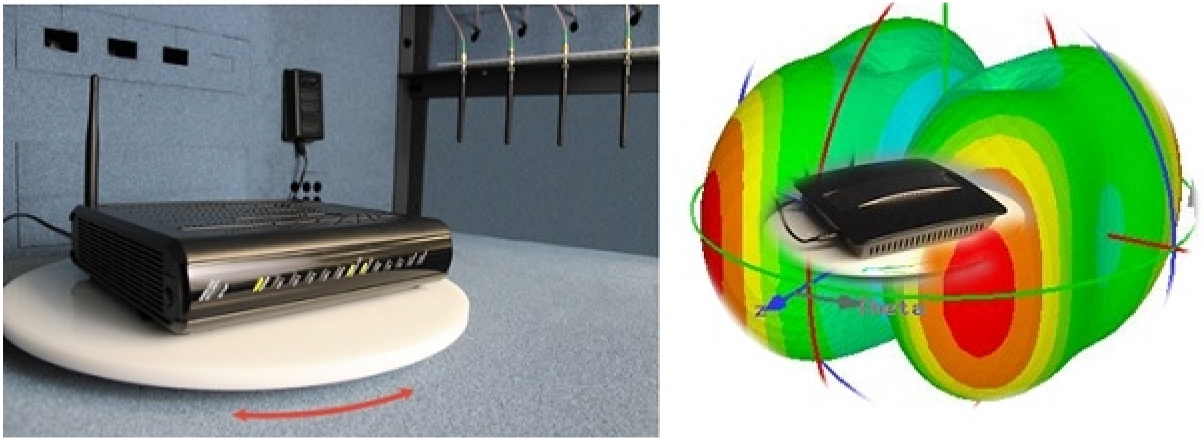


**Figure 2: Left: An octoBox small anechoic chamber with a built-in turntable can rotate the DUT while measuring MIMO throughput performance. Right: An example MIMO antenna field pattern shows red areas indicating high antenna gain and blue areas indicating nulls in the antenna field.**

When performing OTA tests, you should rotate the device with respect to the test antennas. That lets you average the performance versus orientation or you can find the optimum and worst-case DUT orientation.

### Beamforming test using a turntable

The latest 802.11ac APs (access points) feature beamforming capabilities – the ability of the AP to adapt the power and phase on each of its MIMO antennas to direct signal energy so as to optimize the range of the link. Beamforming typically requires that a channel sounding be performed between the AP and the target client.

One possible way to test beamforming capability of the new 802.11ac devices is to use a turntable to rotate the DUT with respect to test antennas, first with beamforming on and then with beamforming off. The difference in performance versus DUT orientation, signal power, and multipath conditions will indicate how much impact beamforming has on throughput.

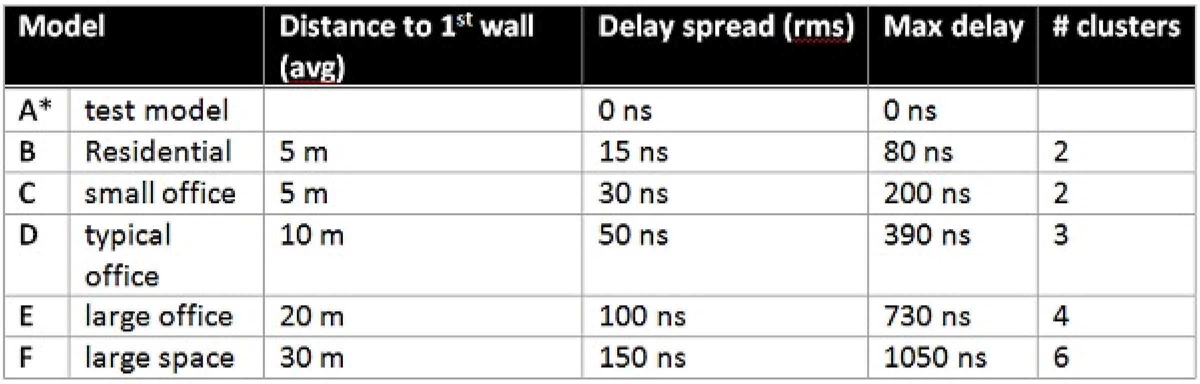
It's important to perform this test in the presence of multipath and path loss because the impact of beamforming may not be apparent in ideal conditions. Emulation of multipath and path loss in the testbed will be discussed in Part 3.

### Multipath

**Multipath**

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 these channel models to enable radio testing in a range of standards-based emulated environments.

IEEE 802.11n/ac channel models characterize indoor environment. A summary of IEEE 802.11n/ac channel models is shown in **Table 1**. Notice how delay and delay spread in Table 1 increases as larger spaces are being modeled by the IEEE models A through F.



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

**Table 1. IEEE 802.11n/ac standard channel models. *Model A is a flat fading model; no delay spread and no multipath.**

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. IEEE 802.11n/ac channel models 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 two clusters. Model D, modeling a larger space, has three clusters.

A cluster typically arrives at the receiver multiple times as it bounces back and forth between opposite surfaces. Each time the cluster arrives at the receiver, its power is lower. For indoor models, such as the IEEE models, multiple clusters can overlap in time, forming a particular PDP (Power Delay Profile) of the signal at the receiver. **Figure 3** shows the 3-cluster PDP of Model D.

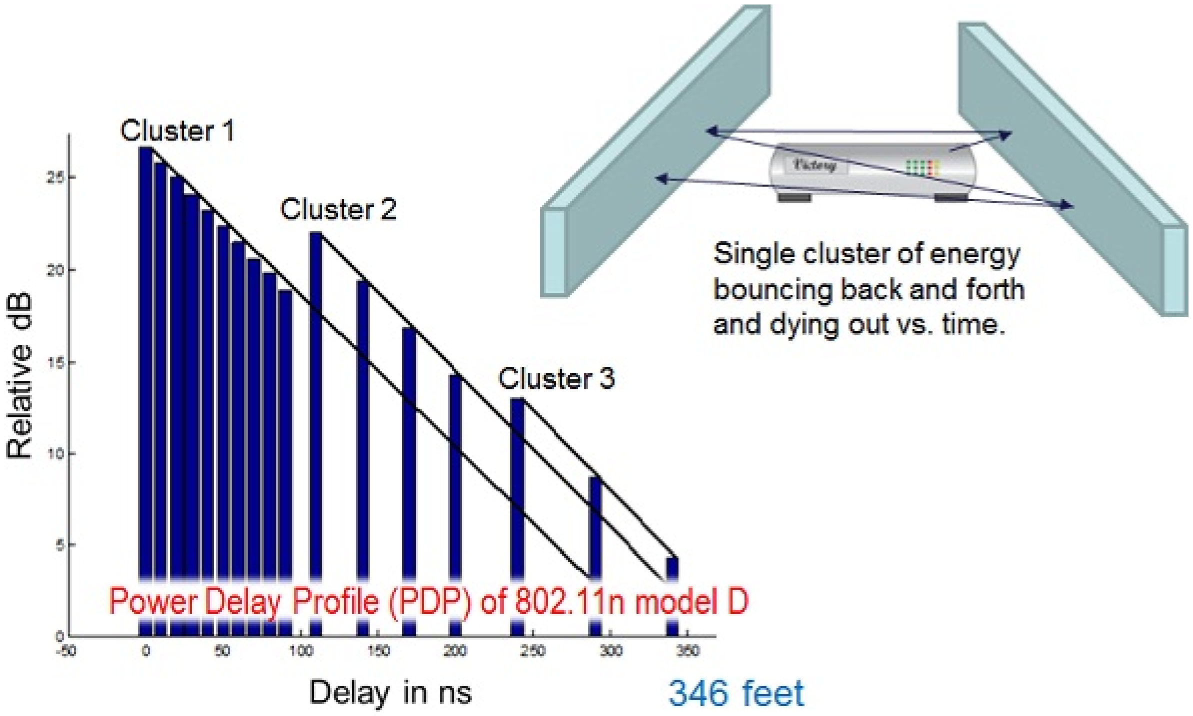


**Figure 3. In an IEEE Model D 3-cluster PDP, each cluster bounces back and forth, monotonically diminishing in power with each bounce. Multiple clusters overlap in time and add together to form PDP.**

PDP is a plot of clustered energy reflections vs. time (Figure 3) and is a function of delay spread in the channel. PDP for standards-based channel models is defined by standards bodies, such as IEEE and 3GPP.

PDP is akin to a signature of a wireless channel and is unique for each environment. Because every environment is unique, we use the representative industry standard models in Table 1 for testing radios. Standards-based channel models specify statistically typical PDPs for a few representative environments. A wireless testbed should be able to accurately model industry standard channel conditions, including multipath and interference.

Part 3 focuses on emulating real-life channel conditions and on MIMO OTA testing in a small anechoic chamber.

# Measuring throughput of cellular and WiFi MIMO radios, Part 3

Fanny Mlinarsky - June 03, 2014

In Part 2 of this series, we compared conducted throughput measurement techniques to new OTA (over the air) techniques. We examined the challenges of MIMO OTA test methods, including time-variable wireless environments and antenna field non-uniformity. In this final installment, we discuss the requirements and challenges of constructing a MIMO OTA test bed.

**Maximizing MIMO OTA throughput**

A MIMO OTA test bed has to demonstrate the upper limit of the DUT performance consistently, repeatedly, and at multiple locations around the world. Referring back to Part 1 Table 3, to maximize MIMO OTA throughput, we need to create a multipath environment, making sure that:

- The signal arrives at the MIMO DUT with a wide angular spread (i.e. from all directions)
- Multipath reflections conform to industry standard PDPs (power delay profiles)
- The test bed guarantees repeatable results

For LOS (line of sight) transmission, angular spread is a function of geometry. The closer the test antenna array, the wider the angular spread, as demonstrated in **Figure 1**.

**Figure 1. Narrower angular spread due to longer distance to the test antenna array (top left); wider angular spread resulting from proximity to the test antenna array (top right).**

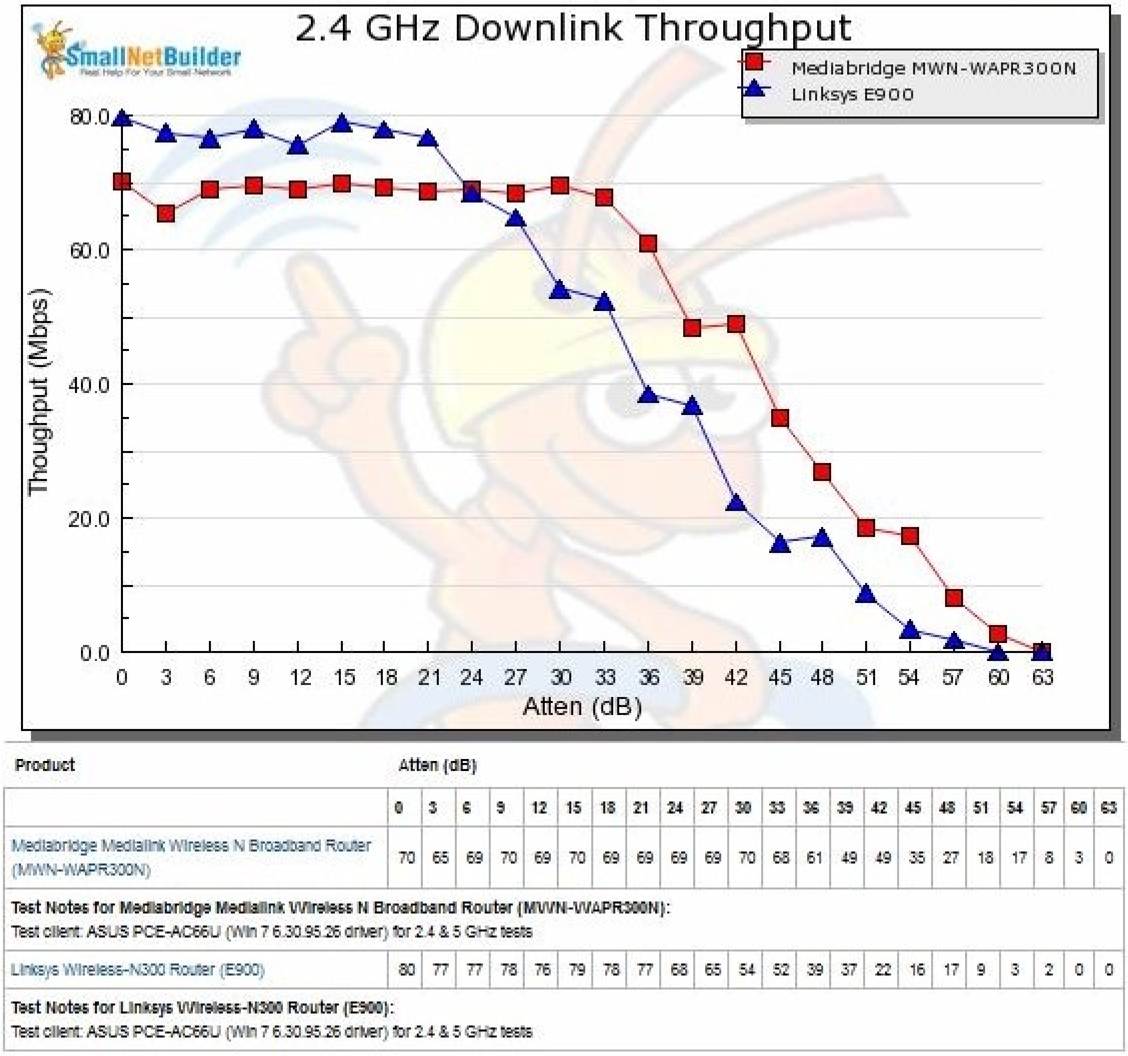
The next question is, how to emulate realistic multipath characterized by a standards-based PDP in a small anechoic chamber? Part 2 explained how the delay spread of a given wireless channel is a function of the size of the physical space. Delay spread is shorter for small rooms and longer for larger rooms or outdoor spaces. Channel emulators such as Azimuth ACE, Anite Propsim and Spirent VR5 emulate delay spread, noise, and motion in a wireless channel.

SmallNetBuilder.com uses an octoBox MPE testbed to evaluate and benchmark the performance of 802.11 devices (**Figure 2**).

**Figure 2. A handset (left) under test in a chamber that uses multiple MIMO test antennas (right).**

SmallNetBuilder measures throughput using IxChariot software from Ixia, which supports measurements on the TCP/IP or UDP/IP layer. Measurements can also be reported in terms of PER (packet error rate) or BER (bit error rate), but collecting PER or BER statistics requires specialized test software that may not always be available when testing off-the-shelf devices. Thus, reviewers and quality assurance (QA) engineers often use layer 3 traffic for measuring throughput.

Using programmable attenuators, SmallNetBuilder creates plots of throughput versus path loss, as shown in **Figure 3**.



| 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):**<br>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):**<br>Test client: ASUS PCE-AC66U (Win 7 6.30.95.26 driver) for 2.4 & 5 GHz tests | | | | | | | | | | | | | | | | | | | | | | |

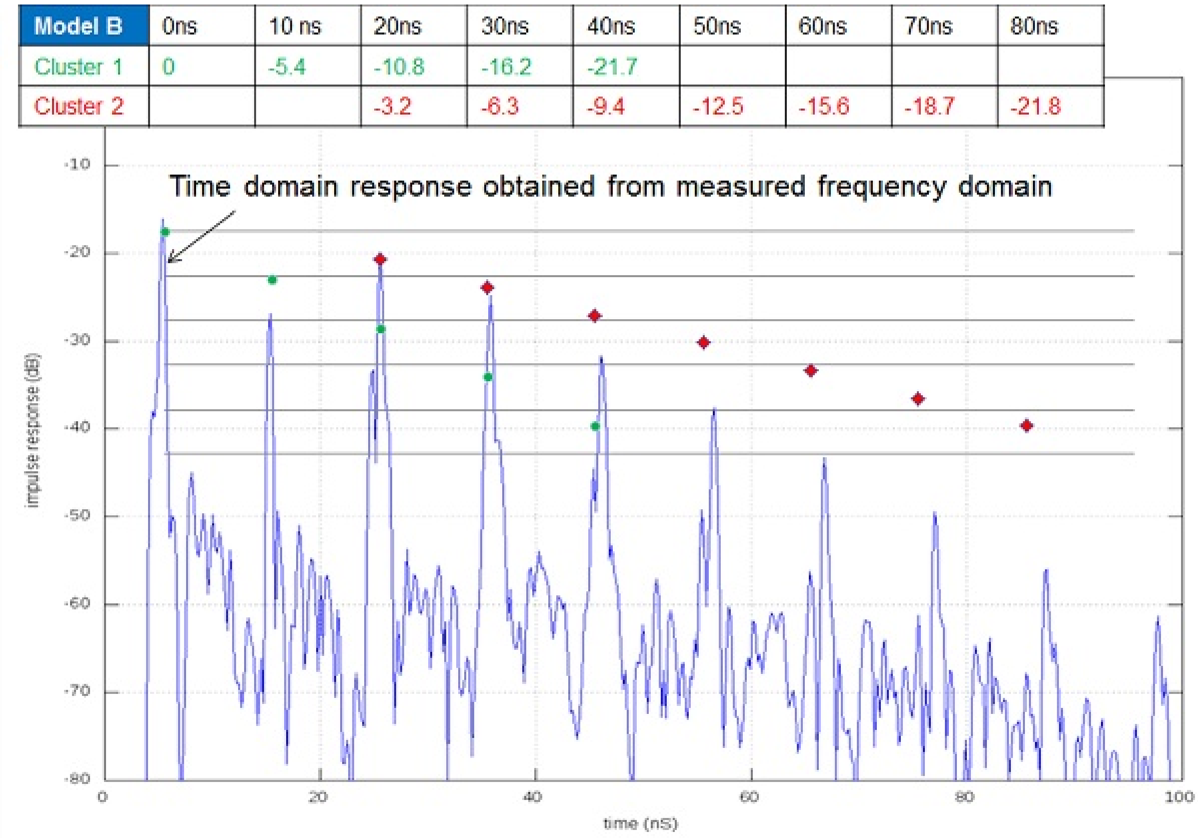
**Figure 3. Example of a throughput vs. attenuation plots produced by [www.smallnetbuilder.com](www.smallnetbuilder.com).**

The IP layer throughput is strongly influenced by the IxChariot test file size. That's because the network stack implementation and the way TCP or UDP frames get queued into buffers and then converted by the 802.11 MAC layer into 802.11 packets on the wireless network. Assuming back-t--back packet transmission with a minimum inter-packet gap, the longer the 802.11 packets, the higher the throughput. Each 802.11 packet contains 802.11 MAC layer and TCP or UDP/IP layer headers, which are overhead. Longer the packets result in a lower portion of a packet being the overhead traffic. Thus, larger test files result in longer packets on the 802.11 airlink medium. SmallNetBuilder uses 2,000,000 to 5,000,000 Byte file size. Higher throughput, as much as double the data rate in some cases, may be achievable using IxChariot high performance throughput script, which transmits 10,000,000 Byte files.

### Industry-standard channel models

**Industry-standard channel models**

octoBox MPE models PDP of each MIMO path per the IEEE 802.11n/ac channel modeling specifications, as shown in **Figure 4**. PDP of the IEEE Model B is defined as being composed of two clusters. A cluster is a model of multiple back-and-forth reflections with each reflection monotonically decreasing in power, as described in Part 2 of this article series.



| 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 4. The measured response of octoBox MPE, shown in blue, closely approximates the IEEE model B PDP, shown as green circles for cluster 1 and red diamonds for cluster 2.**

The frequency response of the MPE is shown in Figures 5 and 6 and is representative of typical multipath in the home environment.

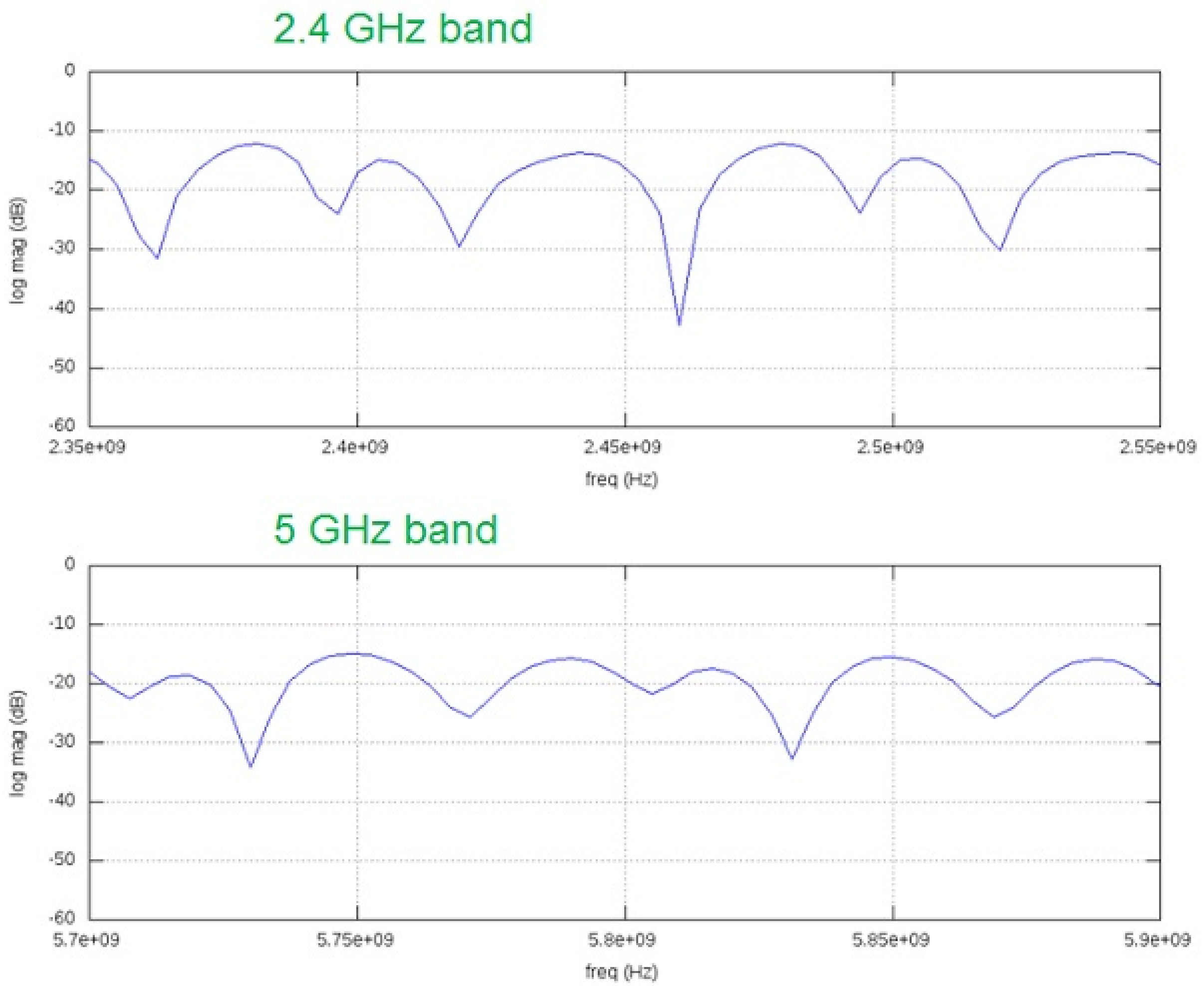


**Figure 5. octoBox MPE frequency response in the 2.4 GHz (top) and 5 GHz (bottom) Wi-Fi bands.**

The broadband frequency response of the MPE is shown in **Figure 6**.

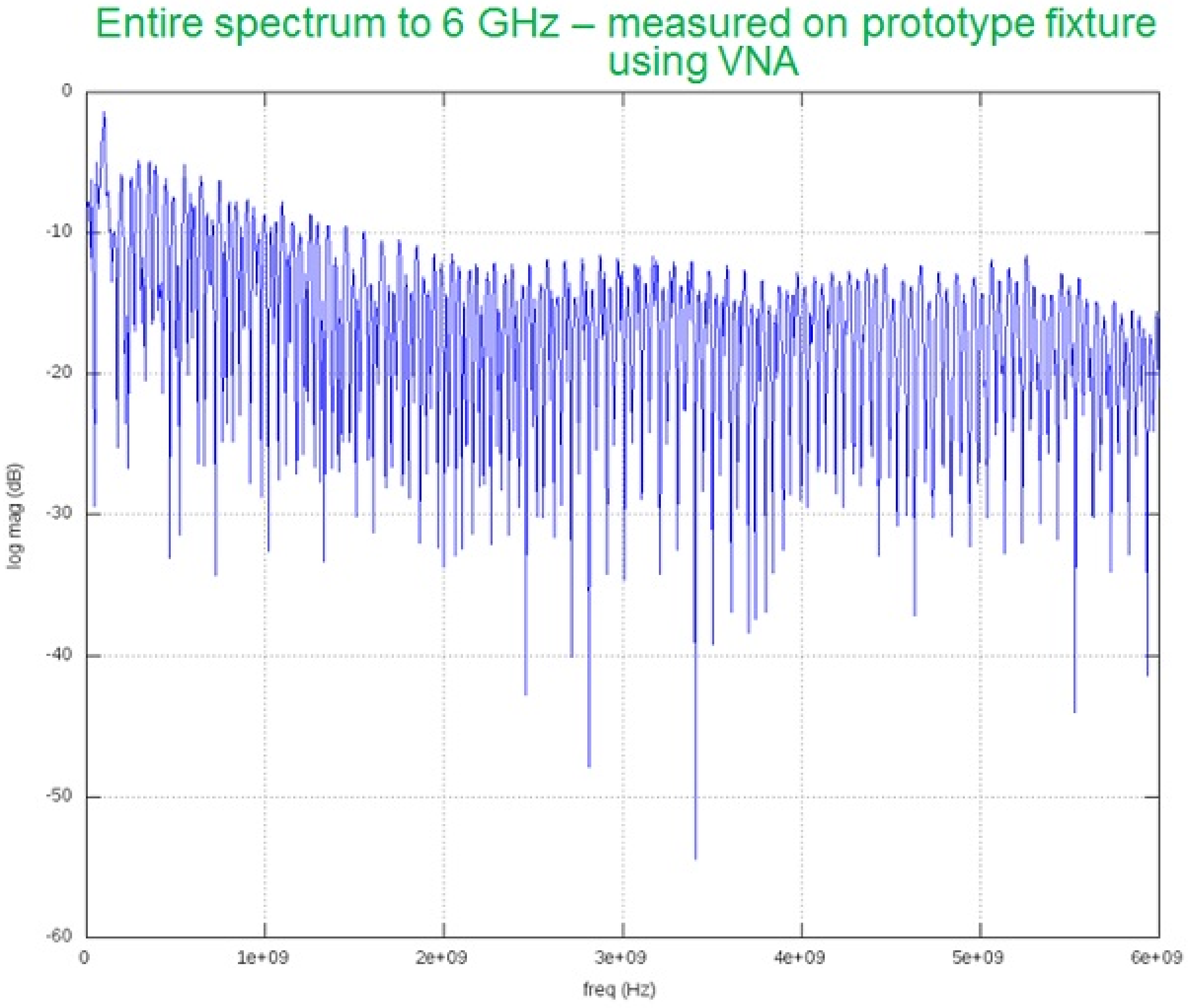


**Figure 6. octoBox MPE wideband frequency response from near DC to 6 GHz.**

Now that we can set up a multipath environment in a small anechoic chamber, we must guarantee that the test results are repeatable from lab to lab around the world.

### How to select an RF isolation chamber

There are three 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. In addition to high isolation, OTA support requires absorption and special conditions to enable multi-stream MIMO throughput.
3. RF gasketing can wear out after a year of normal use, severely compromising chamber isolation. Gasketing should be peel and stick and easy to replace, as shown in **Figure 7**. When gaskets wear out, interference can penetrate the box through imperfect RF seal in the door and impact test results.

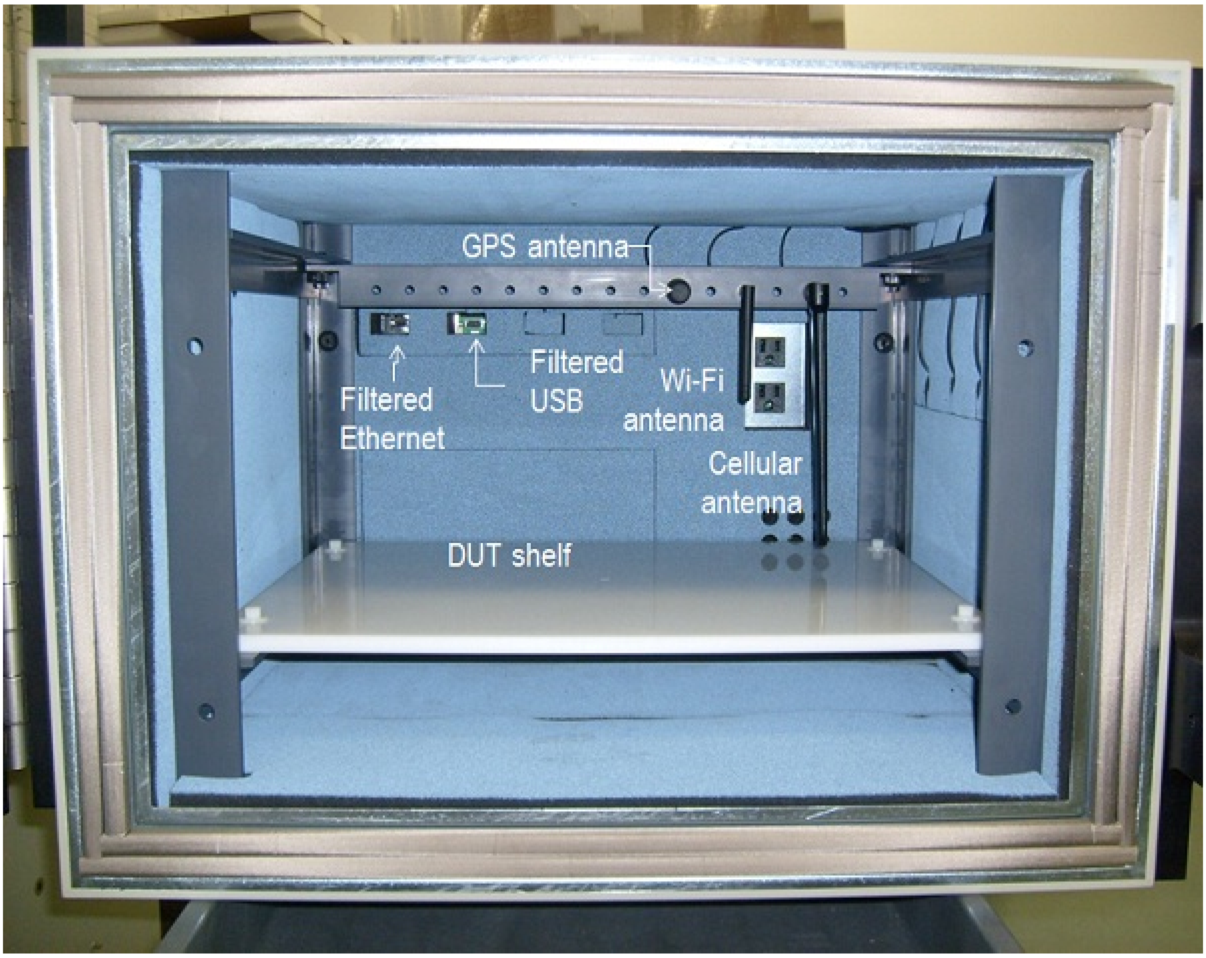


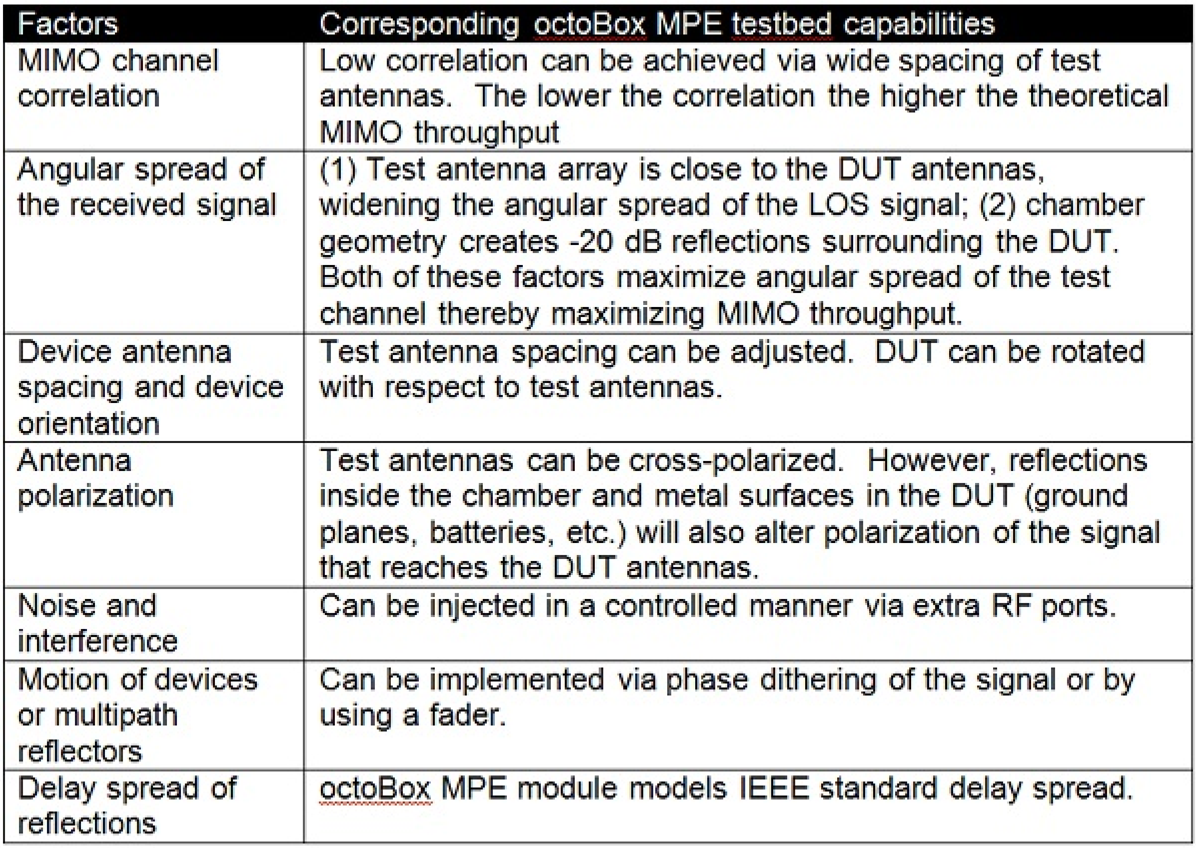
**Figure 7. octoBox peel-and-stick dual row of gaskets in a grove for easy maintenance.**

## Summary

Test engineers face difficult challenges when measuring MIMO throughput because wireless channel environment is constantly changing and radio operating mode is constantly adapting 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. Part 1 of this article series explains the factors that impact MIMO throughput. **Table 3** summarizes how octoBox MPE testbed controls these factors to provide an environment where device behavior and performance can be reliably characterized.

**Table 1. 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 test bed should emulate a variety of channel conditions, including multipath, path loss and noise. At the same time, the test bed should be capable of emulating a MIMO channel that supports maximum throughput of devices being tested. The test bed should also guarantee repeatable and consistent test results in labs around the world.