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Embracing Complexity: MIMO Over-the-Air Testing with the Reverberation Chamber

Explanation as to why the reverberation chamber is uniquely suited to provide insight into MIMO device performance

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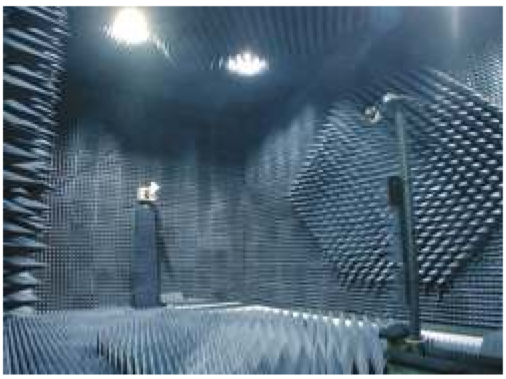
This article describes a repeatable reference environment for over-the-air (OTA) testing of multiple input multiple output (MIMO) devices and why the reverberation chamber is uniquely suited to provide insight into MIMO device performance. The importance of reference environments and the characteristics of the reverberation chamber in the context of 4G wireless systems are reviewed. Statistically based measurements are described and compared with the line-of-sight solutions implemented in an anechoic chamber environment.

MIMO systems are specifically designed to create efficiency gains in the spatial domain. Diversity gain is fundamentally affected by the configuration and design of the multiple antennas inside these devices. Ideally, the antennas should be maximally efficient and fully independent of each other, but today's wireless trends of reduced size and higher complexity make this increasingly difficult. In short, the entire physical structure of the final phone design, combined with the hands and body of the user, will strongly affect MIMO performance. For this reason, MIMO makes testing the entire device including antennas and chassis, etc., more important than ever. Unlike breakthroughs in wireless modulation and system design, which could largely be diagnosed with conductive tests, spatial diversity gain is more difficult to predict without physically measuring the OTA performance of the complete device.



Importance of Wireless Reference Environments

One of the greatest challenges of OTA testing is getting repeatable measurements independent of location. Antenna test engineers have traditionally used large outdoor ranges where distance alone reduces the power of potential interfering signals or spurious reflections. The anechoic chamber (see **Figure 1**) does the same

Figure 1 Typical anechoic chamber.

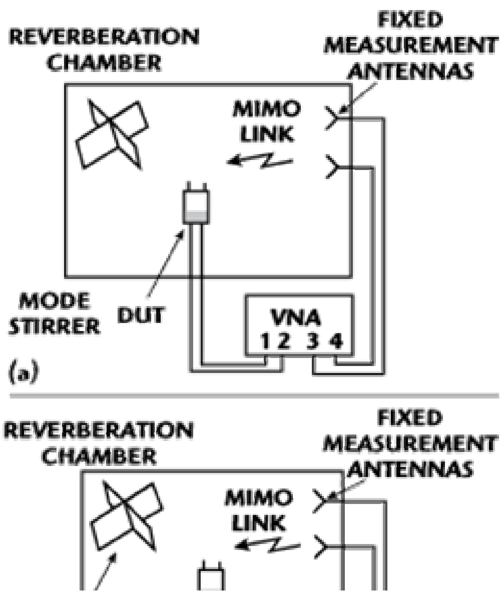
thing in an even more controllable way. By eliminating extraneous signals and absorbing transmitted signals, the anechoic chamber creates a reference environment with a controlled "quiet zone" that zeros out all the signal channel variables. This is an excellent solution to the repeatability problem for direct transmit-receive systems. This quiet, unreflecting, line-of-sight measurement system is naturally associated with the spatial pattern data that is the traditional base for spatial antenna information.

By definition, the anechoic chamber carefully eliminates multipath reflections, but in order to test for MIMO, the effects of multipath must somehow be added back to the measurement system. A new kind of reference environment must be implemented to test these new devices. There are various ways to do this with and without anechoic chambers.

Figure 2 Typical reverberation chamber.

The reverberation chamber, shown in **Figure 2**, takes the opposite approach to an anechoic chamber in creating an OTA test environment.[1] While both can provide high isolation from outside signals, the reverberation chamber is a highly reflective cavity. These reflections fill the chamber with standing waves, which are mechanically stirred to expose the device under test (DUT) to a full distribution of this highly variable propagation environment. At any given moment, the DUT could see a large variation in signal, but across many samples, the statistical response of the DUT to this controlled reflective environment can be accurately characterized.

Instead of trying to avoid the noisy complexity of multipath reflections, the reverberation chamber takes the opposite approach and embraces multipath completely. This highly reflective chamber, combined with a thorough mode stirring and sampling process, essentially creates a general multipath environment. With proper calibration of the chamber, a highly repeatable reference environment can be created that encompasses exactly the kinds of conditions that are challenging wireless devices today.



MIMO OTA Measurements

The complexity of testing in a rapidly changing channel is absorbed into the statistics of the measurement process, allowing designers to focus on the performance of the device and its network. **Figure 3** shows the basic measurement setup for both passive and active MIMO tests in the reverberation chamber. The OTA MIMO link is established with the DUT via two or more fixed antennas in the reverberation chamber. The fixed antennas are connected to either a vector network analyzer (VNA) or a base station simulator, depending upon whether the DUT is a passive multi-element antenna or an active MIMO handset. The system software

Figure 3 Set up for measurement of passive multi-element antennas (a) and of multi-antenna user terminal (b) in reverberation chamber.

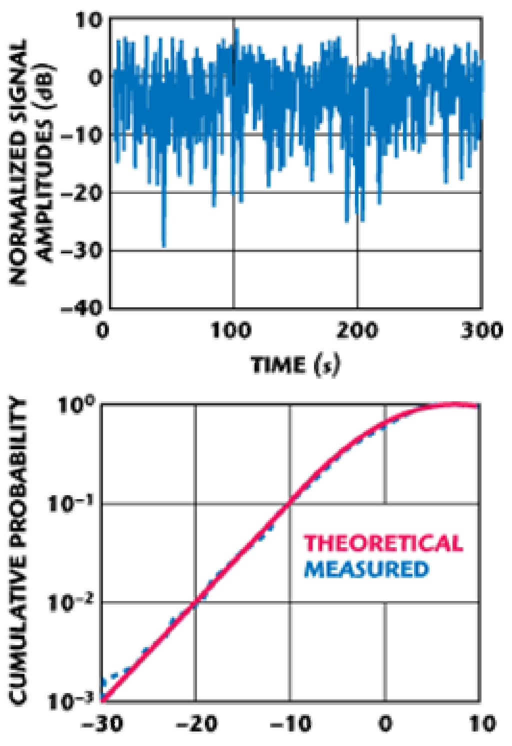
coordinates the data collection with the integrated mode stirring to provide a rich multipath dataset.[2]

This reverberation chamber setup is not used for MIMO measurements alone. The basic multipath reference environment is also ideal for rapidly characterizing single antennas and SISO systems in both active and passive tests. These tests are also important for diagnosing and optimizing complex MIMO network interactions, including measurements such as antenna efficiency and correlation, impedance mismatch, element isolation, diversity gain, throughput/capacity, total isotropic sensitivity (TIS), total radiated power (TRP) and average fading sensitivity (AFS).

Many of these are the same measurements that have traditionally been made in an anechoic chamber. Despite the process difference in acquiring this data, the results are repeatable across both chamber methods as confirmed in multiple laboratories.[3-5] The basic reverberation chamber principle is that once the complete device or single antenna is measured against the rich modal multipath, the resulting power transmission parameters can be summarized in a variety of traditional ways. In fact, the only common wireless antenna measurement that is missing from this list is the gain pattern. This lack of pattern information makes the reverberation test method less suited for point-to-point antennas, where directionality is a functional requirement, but entirely relevant to today's small wireless devices. For these devices, there is no inherent directional orientation and the constantly varying uses of the device make the measurement of patterns irrelevant compared to overall transmission efficiency in a challenging channel environment.

Characteristics of the Reverberation Chamber Environment

How realistic is this multipath reference environment? Obviously channel models of the real world are infinitely unique and variable and the industry has gone to great lengths to enumerate channel variables and build descriptive models. The opportunities for channel modeling are endless; from a static point-to-point unimpeded channel to a highly reflecting, rapidly changing, multi-source source environment. What does the reverberation chamber emulate and how much can it be varied and controlled?



The reflective cavity of the reverberation chamber, with its multiple stirred modes, creates a near-ideal isotropic Rayleigh fading distribution. It maximizes the multipath and measures the signal fades throughout the mode stirring. As seen in **Figure 4**, the chamber replicates a statistical sampling of as many fades and modes as possible. The Rayleigh distribution is the generalized distribution of a complex random variable, so it reflects the central limit theorem of combined random variations in phase and amplitude. In other words, if all channel models of the world were to be combined, the statistical result would be this isotropic Rayleigh distribution. The reverberation chamber then, tends toward creating the general case channel model.[6]

The isotropic nature emphasizes that the

Figure 4 Theoretical Rayleigh fading response (red) and measured in reverberation chamber (blue).

environment in the reverberation chamber is a full 3D multipath environment. Unlike anechoic systems, there are no discrete measurement planes or angles that segment the physical reference environment. There has been some research into selectively modifying the reflectivity of reverberation chambers to change the isotropic profile into a more directional one. This would shift the fading statistics from a general Rayleigh environment to a Ricean fading distribution with stronger line-of-sight components. However, this increases uncertainty for some tests and also narrows the range of environment scenarios covered by the test.[6] Ultimately, the full 3D environment is a critical requirement in the world of portable devices that are expected to operate with unknown orientation.

Defining a Calibrated Reference Environment

Calibration of the chamber is performed by measuring all S-parameters through the chamber during a complete stirring sequence, thereby deriving the transfer function of the chamber. Then connector and cable insertion losses to the chamber are added to the calibration for a full characterization.

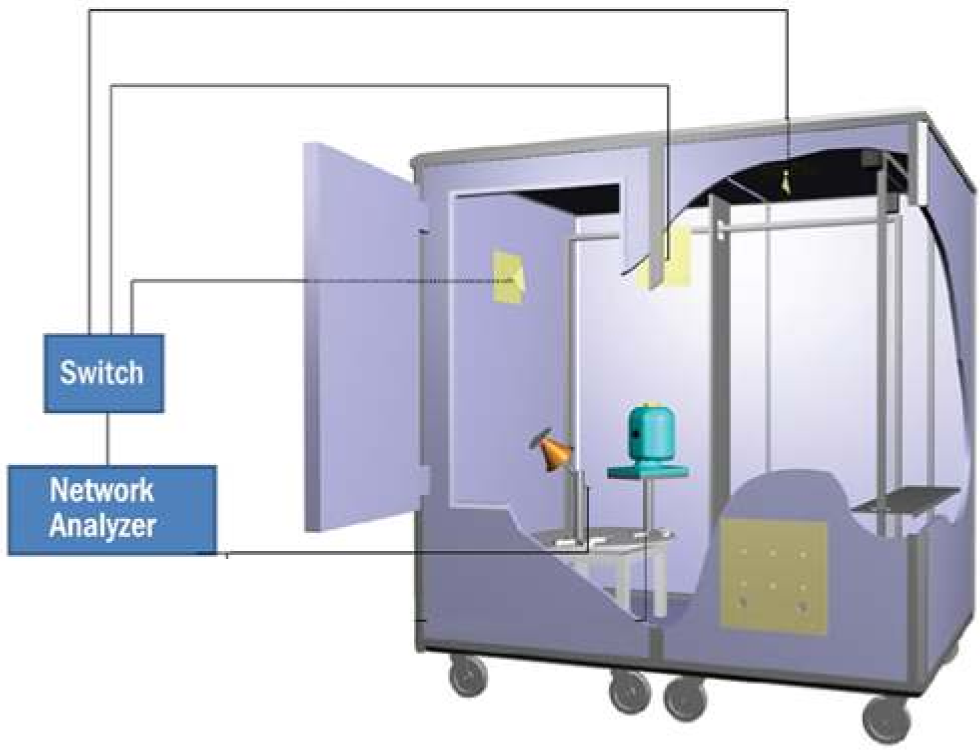


Figure 5 Calibration setup block diagram.

Since the transfer function in this resonant cavity will be sensitive to frequency, to make the calibration straightforward in practice, a broadband measurement antenna and swept VNA is used. With optimized system software, this setup makes chamber calibration almost as fast as a simple conducted fixture calibration. **Figure 5** shows the calibration setup block diagram.

Due to the large sample sets over the spatial signal diversity in the chamber, a calibrated chamber can obtain highly repeatable measurements for an OTA system. Due to the large number of variables and uncertainties in traditional OTA testing, it is much more difficult to obtain the same kinds of measurement uncertainties without significant post-processing of large quantities of acquired scanner data. In contrast, the reverberation chamber test system can quickly gather the significant data sets needed for repeatable measurements.

Although the ideal reverberation chamber only generates the theoretical isotropic Rayleigh fading environment, in practice, these chambers can exhibit non-idealities such as leakage, loading, insufficient modality and under-stirring. The effects of these non-idealities can be either calibrated out of the desired measurement or, to a limited extent, manipulated to create a desired modification to the reference environment:

Leakage: Adds to the measurement uncertainty by limiting the potential dynamic range of the mode peaks and nulls. It can also allow signals into the chamber that may interfere with the measurement.

Loading: Absorbs energy that would normally resonate within the chamber. Loading, as recent research is uncovering, also influences the power delay profiles within the chamber.[10] Loading effects are an important consideration in the chamber calibration process.

Size: The number of modes in the chamber is a function of the chamber size and test frequencies. Lower test frequencies require a larger chamber to generate a sufficient number of standing waves to provide a repeatable measurement distribution. A typical measurement chamber for most wireless frequencies is less than 2 m in height and length and 1.5 m wide.

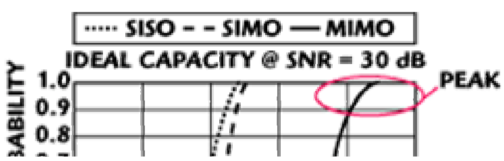
By adding a channel emulator to the input signal path, even more variables to the channel environment in a reverberation chamber can be added, simulating different distributions of spatial multipath for testing the robustness of diversity hardware and algorithms.[8,9] New research involving linked reverberation chambers also shows some interesting testing opportunities.[10] The amount of flexibility is still limited by the hard realities of the reflective cavity walls and the statistical, not deterministic, measurement process. In the end, the chamber will primarily emulate the isotropic Rayleigh fading environment.

It should be emphasized how this isotropic Rayleigh fading environment is considered increasingly useful for testing today's wireless devices. Measurements of digital wireless signal profiles in urban environments show that channel multipath characteristics are very similar to the Rayleigh fading environment and the exponential power delay profile seen in the reverberation chamber.[11,12] This is different from the Ricean distributions that have been traditionally considered in wireless systems with strong line-of-sight components. For highly portable devices, used in any orientation and where direct line-of-sight paths to a base station is the exception (rather than the rule), the typical environment of the reverberation chamber becomes an increasingly realistic reference environment.

Statistically Based Measurements

The primary conceptual shift in measuring in a reverberation chamber versus traditional anechoic methods is in the statistical extraction of measurement results, instead of the deterministic extraction of results based on angle-of-arrival (AoA). The reason this statistical method is being used so much more today is due to the complex and varied use models of today's wireless devices.

The statistical method builds in a wide distribution of link conditions into common MIMO metrics such as throughput—and does so very rapidly. Since a distribution of multipath conditions in a 3D environment can be characterized in less than a minute,[4] large sets of information about device response can be quickly obtained under varying signal types, configurations and power levels.



MIMO devices, in particular, can leverage the distribution of signal modes to quickly measure and plot the throughput capacity of the device link. Naturally, this throughput capacity will

Figure 6 Distribution of throughput capacity for ideal SISO, SIMO and MIMO systems.

vary, often dramatically, with the changing channel conditions.[13] A common way to visualize this is by plotting the cumulative probability of throughput capacity. **Figure 6** clearly shows the potential of a MIMO system that strongly shifts the capacity to higher throughput rates for the same uncertainty levels compared to SISO and SIMO. Testing in a reverberation chamber quickly generates such a capacity plot showing device performance over a range of peak, average and outage capacity channel conditions. This kind of statistical description of a throughput measurement provides wide insight into device performance over the range of conditions today's devices will regularly experience.[14]

Conclusion

Despite the usefulness of these reference environments, both the anechoic and the reverberation chamber fail to be sufficiently "realistic" for complete and detailed recreation of specific wireless channels. With the success of test equipment that can generate accurate channel simulations in a conducted test environment (even replaying drive test data), there is an expectation for an over-the-air test chamber that can accurately and dynamically replicate a full 3D RF signal channel. Currently, such a test system would be prohibitively complex and costly. Even if this was not the case, the question would remain: Which of all real-world environment simulations should be used across labs to compare test results? This reemphasizes the need for simplified reference environments. Engineers can reference both extremes of signal environments: A rich multipath reference in the reverberation chamber and a directional quiet-zone reference in the anechoic chamber.

The reverberation chamber creates a fixed multipath reference environment that is analogous, but complimentary, to the anechoic chamber's fixed line-of-sight reference environment. By making multipath an inherent physical property of the test chamber and providing a calibrated response to that property, a new approach to testing wireless devices can be developed. This approach offers particular insight into the challenges of MIMO and small, complex, radiating systems.

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