The Future of MIMO Over-the-Air Testing

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ABSTRACT

Wireless radios implementing multiple-antenna or adaptive antenna technologies are pervading LTE and Wi-Fi. These technologies involve some level of interaction with the RF environment, and their dynamic nature means that traditional performance tests that do not adequately reflect the real-world environment will not provide the desired device performance information. In fact, the benefits of some of these approaches can only be tested in an over-the-air environment that reflects an expected use case. This article describes some of the challenges and issues with RF performance tests in a multiple-input multiple-output over-the-air environment, surveys recent approaches used to address these topics, and covers some open areas of current work.

INTRODUCTION

The use of multiple-input multiple-output (MIMO) in wireless is set to explode. More specifically, wireless radios that implement various multiple-antenna and/or adaptive antenna technologies are pervading modern Long Term Evolution (LTE) and IEEE 802.11 (Wi-Fi) technologies. These multiple-antenna technologies include what we refer to as MIMO, that is, multiple-input multiple-output spatial multiplexing through time/space coding; as well as concepts such as transmit or receive diversity of various types, and transmit or receive beamforming. In addition, there are other adaptive antenna techniques that do not necessarily rely on multiple antennas, but instead alter the impedance and/or radiation pattern of one (or more) antenna(s) in a device in order to enhance performance under certain conditions. All of these technologies imply some level of interaction with the RF environment in which they are used and sometimes even the physical orientation within that environment. The dynamic nature of these adaptive technologies means performance tests that do not adequately reflect the real world environment to which the device is designed to adapt, such as the traditional total radiated power (TRP) and total isotropic sensitivity (TIS) test methods [1], will not provide the desired device performance information. More important, the benefits of some of these approaches and their implementations cannot even be tested in anything other than an over-the-air (OTA) test environment that reflects an expected usage case.

In addition to the physical antenna challenges, we are seeing the emergence of broadband bandwidth enhancement techniques such as carrier aggregation in LTE-Advanced, which will eventually aggregate up to 100 MHz of spectrum, and the 160 MHz channels supported by IEEE 802.11ac. These enhancements further stretch the limits of the capabilities of today's test and measurement equipment.

WHY OTA?

Previous publications [2, 3] have stressed the traditional reasons for OTA testing of metrics like TRP and TIS. These primarily center around the so-called *interaction factors* such as cellular desensitization, which cause the combined performance of a radio and antenna system to differ from the result predicted by combining conducted radio tests with passive antenna pattern information. These traditional single-input single-output (SISO) OTA tests are based on common antenna pattern measurement techniques [4], and thus operate under the fundamental assumption that the measured radiation pattern is a static behavior of the device under test. As we look at more advanced radios that include MIMO and other adaptive techniques, this is no longer the case, and it becomes more difficult to separate the radio performance from the antenna. How does one separate the impedance and pattern changes of an adaptive antenna from the radio's reaction to those changes, or the software algorithm that controls those changes from the impact of the environment that is causing it to alter the antenna behavior? We are now dealing with a complex antenna system, the resultant performance of which is more (or less) than the sum of its individual parts. There are certain performance metrics that can only be evaluated properly by testing the antenna system, and even the entire network system, including both ends of the radio link and intervening environmental effects, as a whole.

On the other hand, while we may eventually reach a point where the only testing that can be done is OTA (60 GHz antenna systems on a chip come to mind), we are not there yet. It is critical that the industry look closely at the tests being considered for OTA testing to ensure that the metrics extracted provide unique information that can only be obtained from an OTA test. For most RF conformance tests performed on a radio (error vector magnitude or EVM,

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spectrum emission mask, etc.), it is probably redundant to attempt to perform those tests in an OTA environment. On the other hand, there may be some tests, such as spectrum flatness, that would see the impact of the antenna frequency response if tested over the air. However, the same information could be determined reliably enough with a passive test of the antenna to determine its frequency response. Thus, given the added complexity of creating a simulated environment and then testing various device usage cases within that environment, we must choose carefully when determining which tests need to be performed over the air. It should also be noted that while wireless device certification programs like that of the CTIA-The Wireless Association may only look at a specific subset of the possible test cases, manufacturers developing these new devices often wish to perform more extensive testing to better understand how their device performs.

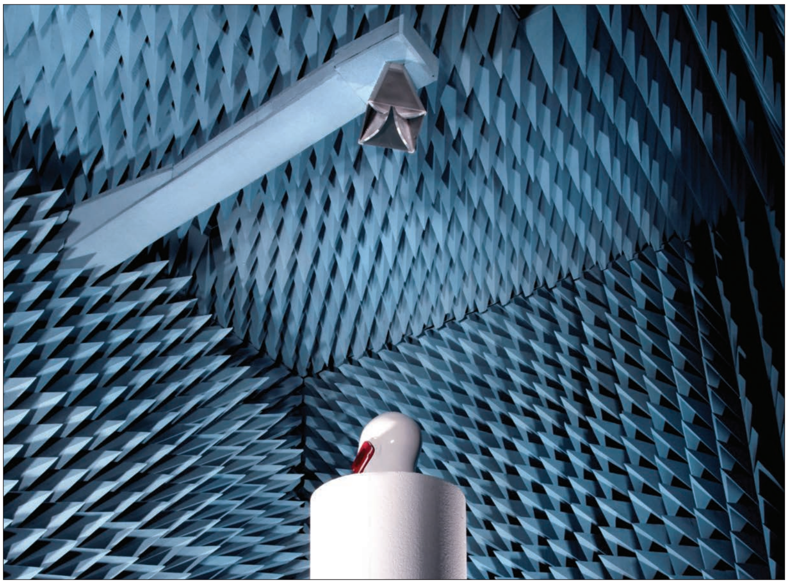

Figure 1. SISO TRP and TIS tests use common antenna pattern measurement techniques to probe the performance of an active wireless device from each direction around the device. No multi-path communication is involved, and one fundamental assumption is that the device behavior is static during the test.

LTE Carrier Aggregation

With the move toward LTE-Advanced, Third Generation Partnership Project (3GPP) Release 10 [5], many manufacturers are developing their first LTE-A handsets and expecting that they will need to perform some sort of OTA testing for carrier aggregation (CA). Carrier aggregation involves combining one or more separate RF channels to be shared by a single user in order to increase overall available bandwidth and resulting throughput [6]. Since most cellular network operators are likely to have small unconnected bits of spectrum in a given market, CA provides a mechanism for them to allow individual users to have access to the entire bandwidth they have available. Carrier aggregation supports both intra-band and inter-band aggregation, with up to five 20 MHz channels (100 MHz total bandwidth) in the short-term plan. These could be adjacent channels (intra-band contiguous, which is similar to IEEE 802.11n 40 MHz channels, but with a few critical differences) or different channels within the same band (intra-band non-contiguous), or they could be channels in entirely different bands (inter-band). Envisioned network implementations include the use of a macrocell as the primary cell (the one providing all the control signals and maintaining the call) and then aggregating carriers from the same cell, other macrocell(s), or smaller micro- or picocell arrangements that give more bandwidth in a localized region.

These various scenarios provide a lot of possible ground for testing different combinations, but one must still ask the question of what needs to be tested OTA in order to get the right answer. At the time of this writing, the CTIA's Certification Program Working Group OTA Performance subgroup has just started a CA Task Force to determine what sort of OTA testing the organization will likely require in the future. So far, the only known case where CA is necessary would be to perform TIS testing for Band 29, which is the downlink-only band that was repurposed from a defunct forward link only digital video streaming channel. Since this band does not have an associated uplink channel, it can only possibly be used in the current LTE architecture by aggregating the band with another primary channel. Likewise, since TIS testing uses the normal bidirectional communication link of a cellular call to obtain the digital block error rate from the mobile device, there must be an uplink channel available in order to measure the sensitivity of the receiver on the downlink channel. By using Band 29 as the secondary cell in an aggregate channel, the error rate information may be obtained on the primary cell uplink.

This test, like all OTA testing, requires signaling communication in the communication test equipment. That is, the test requires establishing a normal bidirectional communication link (e.g., a phone call) and performing tests using the data packets transferred back and forth between the communication tester and the device under test (DUT). While LTE-A emulation options are now available for most signaling communication testers used for LTE OTA testing, currently published white papers on performing RF tests of CA implementations only describe non-signaling applications using a vector signal generator and vector signal analyzer setup. Thus, it is unclear what performance-related test cases might look like. Certainly, from a basic standpoint, there is no reason to expect that the TRP for a single uplink channel in an aggregate would be different from that measured when the channel is used alone. Other than the possibility of allowed or required (e.g., regulatory) pull-back on the maximum output power when multiple transmit channels are present (similar to what is done for a MIMO channel), there are only a few possible unexpected behaviors that come to mind. The first is simply that the components (amplifiers, power supply, etc.) cannot handle the increased load, and thus the output power is reduced. One would expect that such behavior

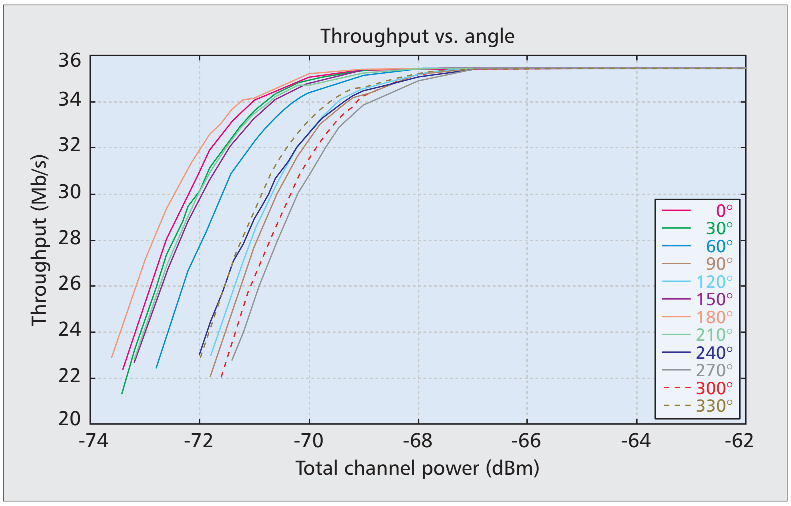

Figure 2. Example of throughput vs. received power as a function of device orientation within a simulated multi-path environment.

would be seen in a conducted test as well as an OTA test. The other possibility, which may require an OTA test in order to manifest, would be mutual coupling between the two transmitters such that the PA(s) see a larger return power level. That, in turn, could cause heating or other nonlinear effects that change the output power more than the single-channel case.

For TIS testing, it is necessary to again question whether or not the aggregate sensitivity of a given receiver will be any different than its single-channel performance, and if it is, whether any of that is due to the antenna/radiating properties of the device. Given the aforementioned differences in propagation channels for the inter-band case, it does not seem to make sense to evaluate the sensitivity of both channels at the same power level simultaneously, since it is highly unlikely that would ever be the case in real life. Each aggregate channel will operate with its own modulation and coding scheme (MCS) based on a given power level, each with potentially different resource block allocations (RF bandwidth and time slot assignments) within the channel, and the secondary connection will be set up or torn down as network conditions require. Thus, a dual channel sensitivity would appear to have little meaning. Similarly, other than the one special case of Band 29 mentioned above, it is not clear that testing the sensitivity of a single aggregate channel (while leaving the other(s) fixed) adds any information over the individual channel TIS tests. One possibility to investigate is that of self-desensitization, where the uplink of one aggregate carrier causes interference to the downlink of the other. Since this condition does not normally exist in the single-channel test, this does appear to be a likely candidate for an OTA test. However, in most current radio designs, it would seem unlikely that the addition of the mobile antenna would significantly increase the possible coupling between the transmitter and receiver, as opposed to possible conducted coupling paths. Nonetheless, secondary receivers, and designs with completely separate antennas for the two CA radios, would probably require OTA testing to fully investigate the potential for self-interference. It is important to note, however, that the selection of suitable bands for generating inter-band CA is being driven by this potential for self-interference, and thus this potential may be mitigated somewhat by the choice of supported CA combinations. Any standardized test for CA TIS would be likely to resemble the cellular desensitization test in the CTIA/Wi-Fi Alliance "Test Plan for RF Performance Evaluation of Wi-Fi Mobile Converged Devices," where specific channel combinations are evaluated for possible degradation in performance, rather than performing complete TIS tests. After all, the radiation patterns of the individual channels have no reason to change unless intentionally designed to do so when in CA mode. The same is true, of course, for the TRP behaviors mentioned above as well.

It is worthwhile to note here one significant difference between LTE CA and the wider channel bandwidths supported by IEEE 802.11n and 802.11ac. In the latter case, the aggregation of channels is done in such a way as to create a single wider channel, generally with the removal of intervening guard intervals and so on. The increase in bandwidth generally means that the channel is more susceptible to interference, so testing sensitivity on a 40 MHz 802.11n channel can be expected to give a different result than the sensitivity of two 20 MHz channels replaced by the wider channel. Likewise, the meaning of TRP could also be affected, although again, the radiation pattern effects can be expected to remain the same. While there has been some consideration given in 3GPP to allowing adjacent channel aggregation to make adjustments that would let a single receiver decode a wider net channel, the basic assumption of LTE-A CA is that separate transmitters/receivers operating at independent MCSs are used to handle each aggregated carrier.

MIMO

There are a number of proposed approaches to MIMO OTA testing, each with their own pros and cons. These have been discussed in detail elsewhere [7–10], so except for certain test cases that might require specific capabilities, those differences will not be reviewed here. As mentioned briefly in the introductory sections, MIMO OTA testing is really about RF environmental simulation. Any radio technology that uses features of the environment or otherwise adapts to the environment cannot be evaluated reliably without providing a realistic test condition for the device to operate normally.

In general, MIMO testing is all about measuring data throughput. The whole point of spatial multiplexing is to obtain more information bandwidth in the same amount of RF bandwidth. While TRP and TIS are considered "edge of link" metrics, indicating when a mobile is likely to lose a connection, MIMO metrics are more about the "edge of bandwidth," where a user might, for example, see substantial degradation in a streaming video or other high-bandwidth application. Thus, these tests are typically performed at higher data rates than traditional TRP/TIS tests. Throughput is typically moni-

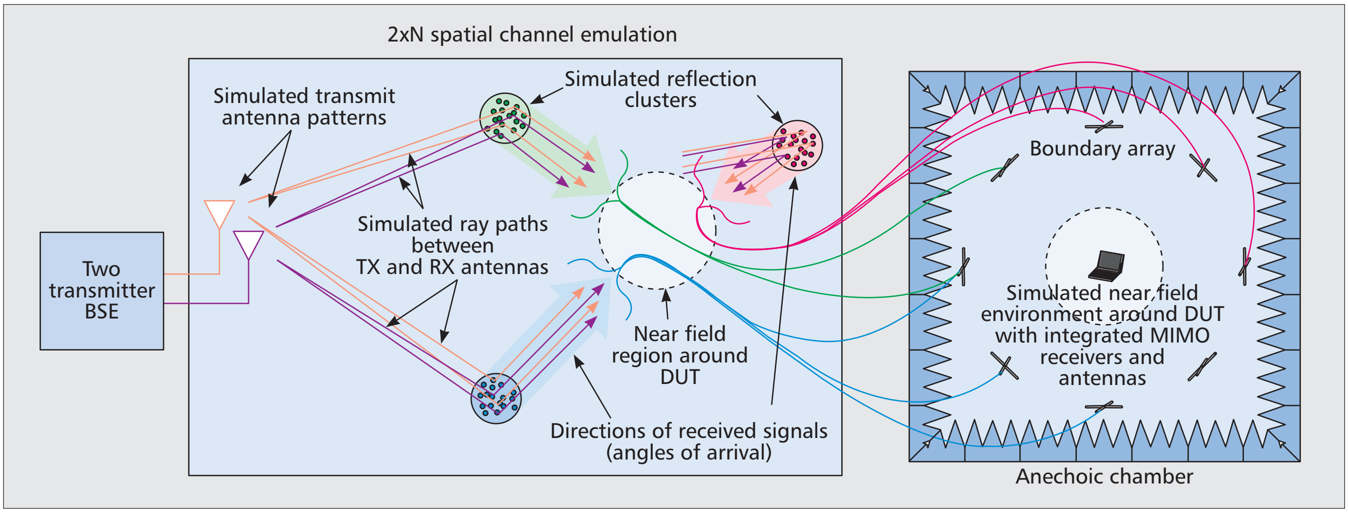

Figure 3. Illustration of the Boundary Array concept for creating a simulated RF environment using a spatial channel model. The spatial information in the model is used to simultaneously drive an array of antennas around a DUT to recreate a target field structure in the near field environment.

tored as a function of downlink power level, which corresponds to the increased path loss seen as a mobile station moves further from the base station, while maintaining the same spatial relationship and fading behavior of the simulated environment around the DUT. In order to represent the average user experience, the various methods will typically evaluate the DUT in different orientations within the simulated environment, reflecting the expected usage cases that might be seen in the real world, and then producing either an average throughput for a given power level or an average power level that produces a given throughput.

Most of the efforts for MIMO OTA testing have been directed toward downlink MIMO. In the case of LTE, this is obviously related to the fact that LTE is only using MIMO in the downlink direction, with mobiles typically having only one uplink antenna. However, this also has to do with the fact that the throughput test is essentially a digital error rate test; hence, the measurement of physical layer throughput vs. power is really just a MIMO sensitivity test of the DUT receiver. An equivalent uplink test would test the sensitivity of the test equipment receiver and thus have little meaning in terms of the performance of the DUT.

The CTIA and 3GPP have run several interlaboratory test campaigns for evaluating multipath environment simulation and MIMO testing. Those methods have concentrated on measuring throughput vs. power using a fixed reference channel (FRC) operating at a single MCS data rate. Thus, they are not really testing the range control adaptation which would normally happen on a real network, since that behavior is dependent on the base station, and there is a concern that a so-called *variable reference channel* (VRC) could not be guaranteed to behave the same for different test equipment vendors. Since the data rate setting of an FRC does not change as the throughput drops, the only point of interest is really where the next data rate curve would intersect the throughput curve of the data rate being tested. At that point, one would expect the network to adapt to a lower data rate to extend the range for that lower throughput level, allowing the radio to more closely approach the theoretical bandwidth limit (Shannon capacity) for a given signal-to-noise ratio (SNR). Thus, other than occasionally showing unexpected behavior from a DUT, the throughput vs. power curve spends an inordinate amount of the test time measuring data (100 percent throughput), which is of very little use in evaluating the DUT performance. For any sort of standardized test, the more practical approach would be to perform a sensitivity search for a target throughput level, allowing for an optimized test process that minimizes the amount of time spent looking at power levels that produce uninteresting results. The only thing left to do then is to decide which throughput level is of interest. At the moment, the members of the various working groups have expressed interest in both the 95 percent throughput point, which is likely to be the point where a switch to a lower data rate setting would occur, and the 70 percent point, which is typically on a more linear portion of the throughput roll-off curve.

Figure 2 shows a typical set of throughput vs. power curves for an FRC measured in an anechoic boundary array (Fig. 3). The boundary array method simulates a chosen RF environment using a spatial channel model to simulate the environment outside the test volume. An array of antennas simultaneously transmit signals representing the various distributions of reflections and fading conditions so that they arrive at the DUT from different directions as though they were scattered about the real world, re-creating the desired near field environment around the DUT. In the same way the computer and display screens in a flight simulator project simulated images of flight conditions, a boundary array and spatial channel emulator project a simulation of the desired RF environment into the test volume. The DUT is then rotated through different positions and orientations representing typical usage cases to determine its average performance.

While Fig. 2 illustrates the dependence of the device performance on its orientation within the test environment, it is desirable to use a single figure of merit to reflect the average performance of the device. Figure 4 illustrates two such average performance metrics that are typically determined from the angular dependent data. The first is the average throughput vs. power, which would essentially be equivalent to measuring throughput continuously while the device rotates slowly through all orientations and then reporting the resulting average throughput. The alternate approach is to determine what downlink power level produces a given throughput level at each position and then report throughput as a function of the average power level. Note, however, that this is typically treated as a sensitivity test, so the average is performed over the inverse of the linear power (e.g., the average attenuation between transmitter and receiver) to determine the average performance. It should also be noted that unlike TIS testing, where the average is performed over a receive antenna pattern which is inverted when measured using a sensitivity search, the choice to use the average of the inverse power is somewhat arbitrary in this case. Unlike TIS testing, which evaluates an inherent property of the device's radiation pattern and thus gives more weight to stronger signals than weaker ones, the MIMO test in the boundary array evaluates device performance in a variety of orientations in the simulated environment to judge the expected user experience. Thus, if one particular orientation were to give exceptional performance, while most other orientations produced performance many dB below the best performance, it does not make sense to give the better performance condition more weight on a linear power scale, since the average user experience would be well below that level of performance. Thus, it may make more sense to average performance over the power scale in dB rather than in linear units to eliminate this bias.

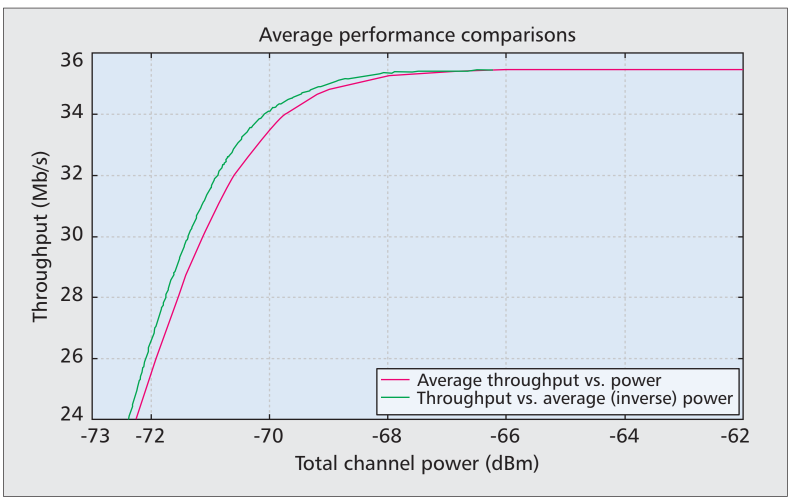

Figure 4. Comparison of different potential metrics for overall device performance.

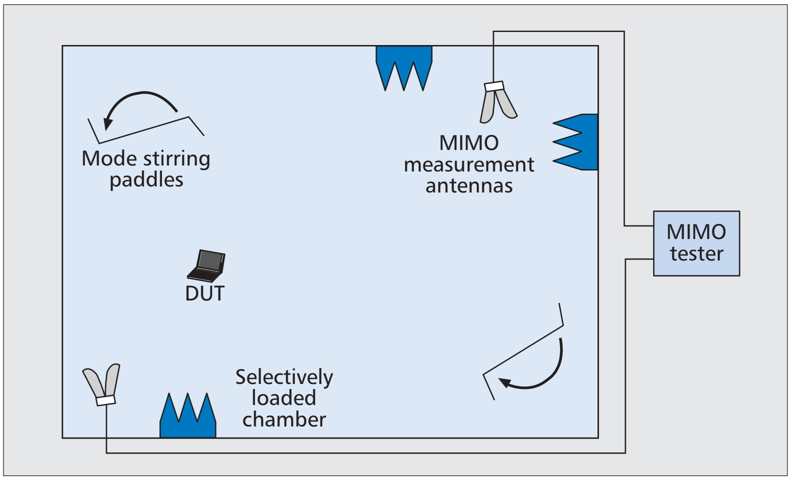

Figure 5. Diagram of a typical reverberation chamber configured for MIMO testing. Small amounts of RF absorber are used to load the cell and reduce the RMS delay spread sufficiently to support wireless communication.

While the two metrics in Fig. 4 provide almost identical results in this instance, that is not always the case. Another proposed methodology for MIMO OTA testing is the reverberation chamber (Fig. 5), which can be theoretically represented as a collection of states with a uniform spherical probability distribution of plane waves with random phases and magnitudes, and with a very high degree of multi-path propagation. What this means is that in any given state, the incident fields as seen from a given point within the chamber will appear as a nearly random collection of "hot" and "cold" spots (imagine static on a TV screen), but on averaging across all states will appear as a (nearly) statistically uniform (e.g., grey) or isotropic environment, to within some overall uncertainty. Given this uniform probability distribution, the chamber does not represent any particular or even realistic environment, but can be considered to be an ensemble of possible three-dimensional environments with no net preference as to the angle of arrival(s) of the MIMO signals. As such, it is not possible to consider DUT performance in a particular usage case, since there is no net orientation information on the ensemble average, but instead the result must be viewed as an average indication of how a device might perform in any orientation; even upside down!

Figure 6 shows throughput vs. power curves measured for various states within a reverberation chamber, determined by stepping the mode stirring paddles and DUT turntable to each successive position in a stirring sequence and measuring throughput vs. power. Figure 7 again compares the metrics of average throughput vs. power and average power vs. throughput, again weighting the average power by the linear inverse. This time, since each individual state has a very rapid cutoff in throughput, the average power case retains that sharp slope, while the average throughput case produces a much more gradual drop in performance. If one were to choose a number like 32 Mb/s as the desired throughput target, these two metrics would produce considerably different answers, with approximately 3 dB difference in performance. On the other hand, if one looks at the distribution of the performance of each step state at 32 Mb/s, the result clearly peaks with almost a Laplacian distribution at about 1 dB above the average power case and 2 dB below the average throughput case. So which metric better represents the average user experience?

MIMO AND INTERFERENCE

Measuring throughput vs. power, or switching to a throughput sensitivity search, is analogous to the SISO TIS test, where the limiting factors are the thermal noise of the receiver and the platform interference sources that leak into the receiver through the antenna or conducted paths. This is certainly the case for the edge-of-link conditions evaluated with TIS testing, and thus have interest for evaluating the MIMO fallback conditions such as transmit and receive diversity, which serve to increase the range of a radio link in a faded channel. However, the argument can be made that since MIMO only operates at a high SNR and thus must be relatively near the base station in order to perform, the most likely limiting factor is going to be interference caused by a neighboring radio from another user or another cell, rather than due to platform noise. Thus, an alternate throughput test can be defined where, rather than varying the downlink power level, the power is fixed at a level well above the platform noise, and then an intentional interferer is injected with the signal in order to determine throughput vs. SIR. (The astute observer may note that this is actually signal-to-interference-plus-noise ratio, SINR, but with the assumption that the interference and signal are both well above the platform noise, this essentially reduces to SIR.)

There are a number of complexities with performing an SIR measurement, the first of which is selecting the interferer. Given the likely scenario described above, the logical choice would be to create an interferer simulating another mobile device in operation in the vicinity of the DUT. While simple in concept, this adds several additional degrees of freedom to the test, since the orientation of the interferer relative to the DUT could be anywhere in the local environment. Thus, not only does the DUT need to rotate against the simulated environment relative to the base station, but the interferer, which could be both a mobile device and its associated base station, would have to have its own environmental model that could vary relative to both the DUT and the base station model. On top of that, the potential list of interfering frequencies approaches a factorial complexity. The simplest solution to both of these problems is to assume a temporally and spatially uncorrelated and spatially uniform additive white Gaussian noise (AWGN) signal covering the bandwidth of the receiver as the interferer. While being generally easier to implement and immediately eliminating several degrees of freedom from the testing, this approach still retains the advantage of allowing the gain patterns of the receive antennas to benefit from the spatial variations of the channel model, while the effect of the interference is averaged uniformly across the receive patterns. On the other hand, there are still some complexities in providing both temporal and spatial decorrelation that are challenging for different

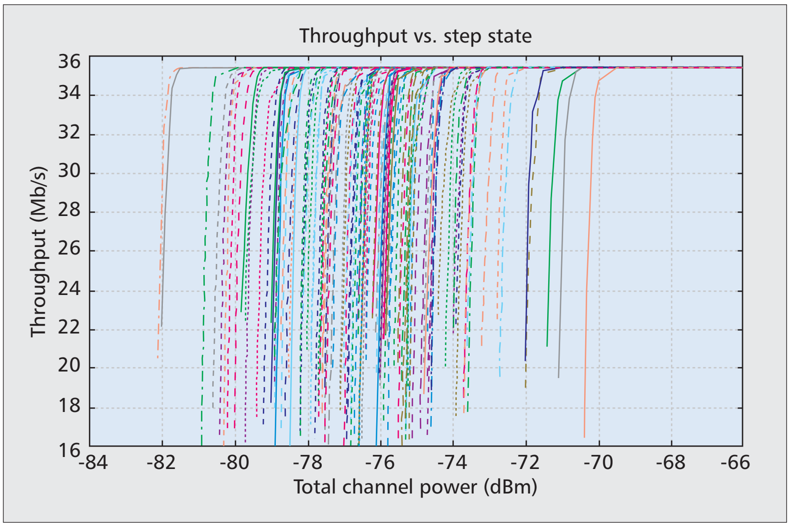

Figure 6. Throughput vs. power curves for a collection of step-stirred states within a reverberation chamber.

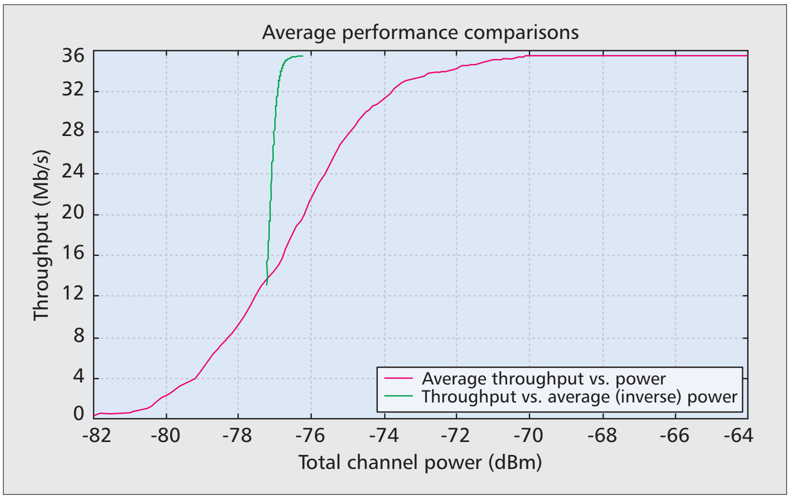

Figure 7. Comparison of different potential metrics for overall device performance based on step-stirred reverberation chamber results.

MIMO test systems. It is obvious that the noise should not be spatially correlated to the base station. If a base station is the source of an interferer (other than possibly due to an adjacent connection), it is defective and should be repaired. The mobile performance is not of interest in that case. Thus, the uniform noise should be injected after all fading and other environmental simulations have been applied. In some cases, this is physically impossible for the test method, and cost considerations may lead to the desire to use the readily available AWGN generator on the communications test equipment, despite the fact that it may not reflect reality.

APPLICATION LAYER MIMO THROUGHPUT

In addition to the fixed reference channel approach commonly seen with communication test equipment, manufacturers are often inter-

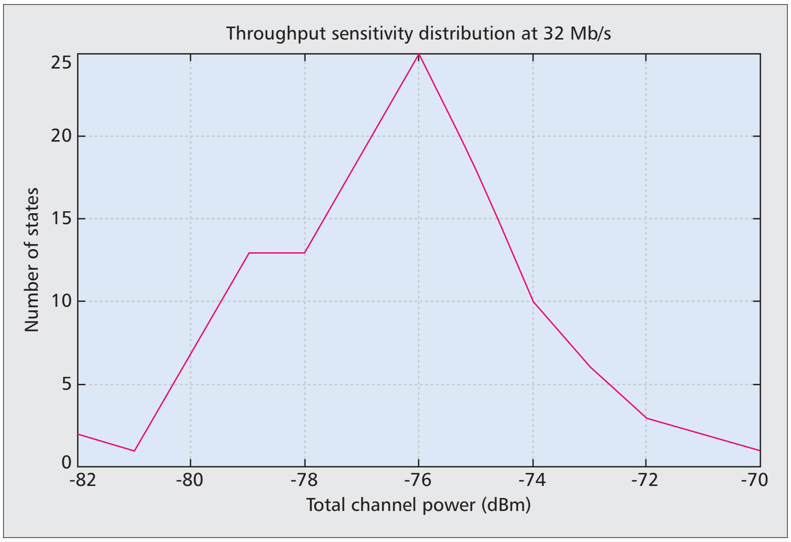

Figure 8. Power distribution of the various reverberation chamber step states at 32 Mb/s throughput.

ested in how their device interacts with its expected counterpart in the real world. This is quite common in Wi-Fi testing, where most of the test cases center around interoperability, and even for OTA performance testing, it is often easier to obtain an off-the-shelf access point (AP) or client and use the "golden radio" approach to testing device performance. This approach is also used by cellular network operators and even some device manufacturers who use representative base station radios as their golden radio at the other end of the link. For data applications, then, the usual throughput test is an application layer metric that uses TCP or UDP data transfer rates to evaluate network throughput over the wireless link. By using variable attenuators or the gain control of channel emulators in a MIMO system, it is possible to measure application layer throughput vs. power. Likewise, with the addition of an interference source, throughput vs. SIR type sensitivity measurements are also possible. Another potential benefit of using real-world golden radios is that now throughput tests are performed over a real variable reference channel using whatever data rate is negotiated for the link at each power level. The result is a true "rate vs. range" representation of the DUT performance, producing the "waterfall" curves representative of wireless link adaptation and the device's corresponding performance at each data rate.

MIMO plus Carrier Aggregation

While MIMO is one of the major bandwidth enhancing techniques in LTE, LTE-Advanced adds aggregation of multiple RF channels to the MIMO OTA testing equation. The combination of both different frequency bands and different cell sizes implies that multiple channel models would be required to adequately simulate the spatial environment conditions these radios will be expected to handle. In addition, the frequency span required to simulate these channels in different bands exceeds the single-band bandwidth capabilities of available channel emulators, necessitating the use of two or more separate bands of channel emulation to create the aggregate channel.

Uplink Testing

Although uplink MIMO has not yet been deployed for LTE, there is still a desire in the industry to perform some sort of uplink MIMO testing. There are several pertinent drivers here. First off, IEEE 802.11n and 802.11ac support bidirectional MIMO. At the physical layer, there is no conceptual difference in a wireless station (STA) regardless of whether it is an AP or a client. In addition, TDD technologies like Wi-Fi and time-division LTE (TD-LTE) can use channel sounding on the uplink to pre-code the MIMO transmission on the downlink. Thus, while TD-LTE devices are not actually transmitting MIMO on the uplink (at present), there is still a potential benefit to having a symmetrical bidirectional channel for testing the downlink performance. Finally, there is often a general desire to measure throughput on the uplink side in addition to the downlink, including all pertinent channel impairments.

From an RF performance link budget perspective, the only metric that matters is the maximum amount of power that the mobile can deliver to the network (TRP). That power should remain the same, regardless of the channel between the mobile and the base station. The ability of the base station to receive and decode this signal is a property of the base station receiver's sensitivity, not that of the mobile. Granted, there are other radio properties of the mobile that might impact uplink performance, but most of those are independent of the antenna performance of the device. The notable exceptions to that are the concepts of beam forming arrays and adaptive antennas (see the next section).

Another problem with evaluating uplink performance on a faded channel is that the radio communication tester (i.e., base station emulator) which would typically form the other end of that radio link is really not designed for OTA communication. Thus, the instrumentation receiver designs are typically not implemented with a rake receiver or the MIMO channel equalization that would be necessary to handle a faded uplink signal for SISO or MIMO testing. Hence, not only would an uplink throughput vs. power (really a throughput vs. uplink path loss) test be evaluating the sensitivity of the test equipment, but it would be attempting to test a receiver that is not designed to work at all under those conditions!

All of the above leads to the conclusion that the only place where uplink MIMO throughput testing might make sense is for the golden radio approach, where a real counterpart radio is used at the other end of the link. In that case, there is still the question of what is being tested on the uplink. Certainly testing the downlink with full adaptation based on uplink channel sounding is possible, but measuring throughput vs. power or throughput vs. SIR on the uplink would again only be testing the reference radio, not the DUT. There is the potential of testing uplink performance as a function of downlink power or interference, but since that would generally result in the loss of ACKs or other control signals usually more robust than the targeted communication data rate, it is not clear what benefit it might offer. On the other hand, for LTE devices, where closed loop power control is available from the base station, it then becomes possible to measure throughput vs. transmit power, testing for any performance degradation due to distortions in the output power amplifier or other components. Again, it is not totally clear that such a test would be antenna related, so a conducted test might gain the same information. However, when evaluating MIMO performance, where the antenna correlation and environmental effects are critical, some problems may only be detected through OTA testing.

Beyond that, the potential of some MIMO OTA measurement techniques to isolate the device orientation behavior from the environment geometry does give users the option to evaluate the directional performance of their device, even though the metric may be based on the receiver sensitivity of the reference radio. If we assume that the receiver is stable, the intermediate data (e.g., throughput vs. angle) available from the boundary array approach provides useful information about the relative performance of the device as a function of orientation or usage case within the environment, even if the absolute value of the sensitivity result has no real meaning.

Adaptive Antenna Systems

While multi-antenna beamforming has been a commonly considered range enhancement fallback technique lumped under the general category of MIMO, a new class of related techniques has begun to emerge in wireless devices. These techniques, generally referred to as adaptive antenna systems (AASs), allow a device to alter its radiation pattern or other antenna performance parameters (e.g., impedance) in response to its environment. While the concept of the AAS is certainly nothing new [11], the technology required to implement such systems in a small mobile platform has only become practical in recent years with the sensing and computing power available in today's smart phones. The algorithms controlling these alterations can vary between the use of RF parametrics or even gravity or light sensors, allowing the device to change its radiation pattern based on orientation or usage case (e.g. against the head vs. hand only). These techniques add a new level of complexity to OTA testing, especially when the adaptation algorithms respond to something other than just the RF parameters of the test. The CTIA has already acted to add a requirement that such features be locked or disabled during TRP/TIS testing in order to ensure that the tests evaluate only one possible state of the DUT at a time. However, the whole point of testing in a simulated RF environment as described above is to allow the device to adapt as it would in the real world. This will restrict such testing to only use those techniques that can produce both the desired spatial RF environment and the corresponding physical geometries that reflect the real-world usage case of the DUT. Certainly AAS will be problematic for any of the indirect measurement techniques that would attempt to embed a fixed radiation pattern of the DUT into a conducted channel model. Since the DUT cannot freely adapt the radiation pattern embedded in the model, the desired behaviors cannot be tested.

Touching on the uplink/downlink testing scenarios discussed previously, AASs offer a new degree of freedom to the problem and open up new test case possibilities. Certainly, an uplink test which reflects the impact of the device adapting its radiation pattern to its environment will bring additional information that may only be available from an OTA test. The possible variants of the additional testing degrees of freedom are as wide as the number of different techniques the adaptation algorithm designers can think of for the device to respond to. The culmination of such testing will likely result in advanced "virtual drive testing," where both the RF and near-field environments and orientation of the DUT will progress over the duration of the test. However, further discussion of this topic is beyond the scope of this article.

Conclusions

While MIMO OTA test methodologies continue to advance, the industry is still left with many questions on determining the MIMO performance of their devices. Device complexity is growing faster than the ability of the industry to standardize on test methods, possibly making some methods obsolete before they can be implemented. LTE testing has been the main driver for downlink MIMO testing, but uplink test requirements are not far behind. Carrier aggregation adds another level of complexity, if indeed there is a need for OTA testing of aggregated channels. It is important that the wireless industry consider what makes up an OTA test, especially when considering uplink testing, in order to guide the test and measurement technique development toward a solution they can use. Emerging adaptive antenna systems will require environment simulation techniques that can stimulate the various sensors used by the device to adapt in order to adequately evaluate the performance gains offered by these techniques.

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