Testing 5G: Time to Throw Away the Cables

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Back in August 2010, Microwave Journal published a series of articles called, “Masters of MIMO,” opening with an overview article from me called, “The MIMO Antenna: Unseen, Unloved, Untested!” I predicted then that MIMO over the air (OTA) testing was the biggest challenge I had seen in 20 years of standards development. Looking back over the intervening six years, I can now see that I underestimated that challenge as the work within CTIA and 3GPP to develop MIMO OTA test methods are still in the final stages of validation. In the meantime, the sophistication of MIMO standards has grown considerably from the original LTE Release 8 through LTE-Advanced Pro in Release 14. Yet, as I write, antenna designers still don’t have basic 2×2 MIMO performance requirements for the receivers of their Release 8 capable devices.

Looking ahead, the focus of this article is describing the test challenges of the next generation, the fifth generation. Having underestimated the difficulty in standardizing basic MIMO OTA testing for 4G (LTE), it is humbling to be making predictions this early for the next generation. But here is my best shot: The emergence of the fifth generation of mobile communications is set to revolutionize everything we know about the design, testing and operation of cellular systems. The primary reason for this is the assumption that to deliver on many key 5G objectives, a new air interface is required, one that will operate in the millimeter wave (mmWave) frequency bands (i.e., 28 GHz and above), with channel bandwidths around 1 GHz and higher. To overcome the radio propagation path losses at these operating frequencies, it is assumed that both the base station and mobile devices will need to incorporate medium or large-scale antenna arrays (sometimes referred to as massive MIMO on the base station side) to maintain a usable link budget. The result will be a 5G air interface that relies on beam-steered antennas at both ends of the link, in what will be a sparse and highly dynamic 3D narrow beam propagation environment.

For 4G, MIMO OTA testing was an obvious and useful evolution from traditional cabled testing, but MIMO OTA was never essential for 4G, since MIMO-enabled devices have been shipping for years. The untested static antennas have at least functioned, even if we don’t know how well. However, mmWave devices with massive antenna arrays cannot be tested using cables, because there will be no possibility to add connectors for every antenna element. In addition, the dynamic (active) nature of antenna arrays means it is not possible to extrapolate end-to-end performance from measurements of individual antenna elements. So yes, for testing 5G, it really is time to throw away the cables — whether we want to or not!

Compared to the 4G MIMO OTA test challenge, with its basic 2×2 transmission mode and static 2D geometry, it seems safe to predict that what lies ahead for testing 5G will be a revolution compared to the mere evolution that we saw in the transition from 3G to 4G. To add one final opening point, there is so little time! The industry goal to deploy 5G in the 2020 timeframe demands mmWave OTA test solutions and requirements in little more than half the time taken to develop the basic 4G MIMO OTA test methods we have today — even without performance requirements.
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### TABLE 1

<table>
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<th>Future mmWave</th>
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### MOVE TO RADIATED TESTING

Table 1 summarizes the different types of device testing across the product lifecycle that the industry needs to address. Each area has its own specific needs, in terms of cost and sophistication. Design verification and production testing will be handled outside of standards bodies, while RF/baseband conformance and radiated performance test methods and requirements will be specified by 3GPP.

In addition to the UE MIMO OTA work that started in 2009, 3GPP also commenced radiated test standards in 2011 for base station active antenna array systems (AAS). Traditionally, as with mobile devices, all base station RF requirements such as output power, sensitivity, blocking/spurious and error vector magnitude (EVM) have been measured at the temporary antenna connectors; the actual base station antenna impact is not considered. However, with the introduction in Release 13 of full dimension MIMO (FD-MIMO), also known as elevation beam forming, it is now accepted that the active nature of base station antennas means cabled testing without the antennas is no longer sufficient. This led 3GPP to develop the first radiated test methods for base stations.

Currently, only total radiated power (TRP) and total radiated sensitivity (TRS) tests at boresight are defined, but more will be developed in the Release 14 evolved AAS (eAAS) work item. Today’s AAS scope characterizes the antenna in a static line-of-sight channel using one of four defined test methods, all simpler than UE MIMO OTA test methods using spatial fields. However, the AAS work does point to what will happen with basic 5G device testing when operating frequencies approach mmWave, when there will be multiple antenna elements and no temporary antenna connectors.

Tests which were straightforward using cables become much more involved when carried out OTA. Take blocking, for instance: The requirements for blocking were derived from 2D spatial system simulations, and the base station blocking levels were statistically derived from summing the power from three spatially separate mobiles. In the conducted domain, this just looks like an omnidirectional power to be added to the wanted signal. However, if we move back to the radiated domain, how should the blocking signal be constructed? Recreating the system level parameters implies spatially separate blocking signals interacting with the directional base station antenna, so an exhaustive test of all spatial combinations and frequencies would extend today’s already long tests beyond the pale. So there are difficult choices yet to be made about how AAS and ultimately mmWave OTA tests are to be developed.

### mmWAVE CHANNEL MODELS

Despite the challenges in AAS and eAAS to replace current RF and demodulation tests with line-of-sight radiated equivalents, the area of performance testing in realistic radio environments presents the greatest test challenge. This is the test area UE MIMO OTA has been occupying since 2009 and is the focus for the rest of this article. Central to useful performance testing is a correct understanding of the radio propagation environment. Traditional cabled performance tests look like omnidirectional faded signals to the receiver, and there are aspects of this type of test that may be retained for mmWave receivers. More important is radiated performance testing which has to take into account the antenna patterns at both ends of the link, as well as the propagation environment, all of which are highly dynamic. By comparison, UE MIMO OTA is not even a walk in the park, it’s like sitting on the park bench.

For 4G systems below 6 GHz, the 2D spatial channel extended models (referred to as SCME) were chosen as sufficient, and test methods implementing those have been developed. At mmWave frequencies, new channel models need to be developed, and this was one of the first tasks within 3GPP for the development of the 5G new radio (aka NR, for the time being). The first publication of these models for the 6 to 100 GHz range is based on extending the existing stochastic models developed for under 6 GHz up in frequency. This was a pragmatic response by 3GPP to the tight timescales of the ITU’s IMT-2020 (5G) project, so that the next stage of NR development can start. In addition to the stochastic models, the initial set of channel models includes an alternate hybrid model. It is based on using deterministic map-based modeling of the static large-scale parameters in the environment, coupled with a stochastic approach for small scale parameters like people or vehicles that are...
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Bristol. Venturers’ Building, University of Bristol. The system, using antennas with a 3 dB beam width of 12 to 15 degrees, has been used to study corner diffraction, diffuse surface scattering and beam pointing algorithms.

Corner Diffraction Study

Figure 2 shows the experimental layout to study corner diffraction. A receiver on a cart was moved past an internal wall in an atrium, at varying distances from the wall, to study the transition from non-line-of-sight to line-of-sight. The results (see Figure 3) indicate that the behavior of the signal is quasi-optical at 60 GHz, with the signal dropping 30 dB over very short distances, around 20 cm. Simulations showed that at a 2 m distance from the wall, 40 cm of travel causes a 25 dB drop at 60 GHz, compared to only 8 dB at 3.5 GHz. This indicates that the speed of signal acquisition and tracking at mmWave frequencies will have to be much faster than at low frequencies.

Mixed Wall Surface Scattering Study

The channel sounding system was mounted on a single trolley to investigate the scattering properties of different surface materials in the local environment (see Figure 4). Figure 5 shows the results for a mixed surface wall containing a window. The received power shows a huge variation that depends on the surface. This is equivalent to a user walking past the window and experiencing only a reflected signal from a transmitter across the street, due to body shadowing. Figure 6 shows the in-channel analysis for the signal reflected from the glass. The power vs. channel bandwidth (2 GHz) of the vertically polarized transmitted signal is shown in yellow in the top left trace. The blue trace (below) shows the residual horizontal power, indicating well-behaved specular reflection with a nearly flat frequency response. This contrasts sharply with the signal reflected from the rough wall, shown in Figure 7. Apart from the significant 25 dB power loss seen for the rough stone, the in-channel analysis in the top left trace shows a complete loss of polarization diversity in the lower 1 GHz of the channel bandwidth, followed by a dominance of the transmitted vertical component in the upper 1 GHz. Figure 8 shows the in-channel analysis at one of the glass-to-wood transitions. The channel flatness in the top left trace shows a 20 dB dropout at mid channel, the result of a strong 1 ns reflection that can be seen in the time domain plot in the lower right. Figure 9 shows the results of this same measurement at a position 8 mm further along the track. Despite the short distance, the frequency response of the channel has completely changed, due to the phase cancellation caused by the 5 mm wavelength at 60 GHz. This is an example of the “ground bound” effect, when two strong signals can reach the receiver with very short (30 cm) difference.
ences in path length. Such differences cause large variations in the 2 GHz channel bandwidth, meaning this is a very difficult signal to demodulate when the user is moving at any speed.

**Beam Steering Simulation Study**

In this simulation, a user moves 2 m down a corridor, and the specular and diffuse reflections are computed to investigate the benefit of beam steering (see Figure 10). The transmitter (on the left) is blocked by a barrier from line-of-sight to the user (on the right). The upper wall is made of rough concrete, the lower wall smooth sheetrock (plasterboard). The permittivity and K-factor of the wall surfaces used in the simulation were based on measurements of the actual materials. The transmitter has 32 antennas, the receiver 8, giving a potential beam forming gain of 24 dB. Due to its permittivity, the specular reflection from the rough concrete was 6 dB higher than the sheetrock and constant over the 2 m of user movement. However, Figure 11 shows large differences in the diffuse power from each surface as a function of user movement.

**Figure 12** illustrates the effect of beam forming. The lower two traces show the available power from the specular and diffuse components (both surfaces combined) using an isotropic antenna (i.e., no beam forming) at both ends of the link. The upper two traces reflect both ends of the link making “ideal” beam forming choices, yielding around 20 dB more power. The simulation shows six beam pointing angles available (see Figure 13). To capture the maximum power as the user moves down the corridor, the transmitter...
and receiver need to rapidly alter which surface and angle each points to. By performing a cumulative distribution function (CDF) analysis of the power distribution using the optimal beam selection as 100 percent, pointing only at the best single concrete wall reflection (beam 2) has a 5 dB loss at 95 percent confidence, while the best single shatterproof reflection (beam 2) has a 17 dB loss.

This simple simulation shows just how dynamic mmWave channels can be, motivating the need for sophisticated beam steering algorithms at both ends of the link to optimize performance. By comparison, recent 3GPP measurements of commercial devices at 2.6 GHz showed that even for the directional SCME urban micro channel model used for MIMO OTA testing, the variation in performance was typically less than 3 dB over a 360 degree rotation. A mmWave device with fixed antennas would only operate for a fraction of the available angles, when the source and receiver signal directions happen to coincide.

**PERFORMANCE TESTING AT mmWAVE**

The limited examples of mmWave propagation discussed here illustrate the challenge that faces 5G OTA performance testing. Such variability is not yet predicted by the preliminary stochastic channel models, but may be predicted using more advanced hybrid channel models. At RF, the challenge was “how good is my signal”, at mmWave the new question is “where is my signal?” Steerable antennas can only go so far, and it is likely that to provide sufficient quality of service, mmWave networks will have to rely on multi-site connections. This will ensure the UE can simultaneously monitor, acquire and track the available line-of-sight base stations and strong reflections in the environment, with the goal of performing a handover at the subframe level to maintain connectivity and latency. This redundancy is not so different than the soft handover concept built into CDMA systems to handle cell edge signal problems. Falling back to 4G at RF is always possible, but it won’t provide 5G performance.

To properly test 5G systems, it will be necessary to first pick appropriate channel conditions that adequately reflect the environment of choice. This must take into account fast-changing in-channel impairments, as well as numerous sources of blocking caused by the physical environment and dynamic factors such as vehicle and device movement and body/hand blocking. Any realistic test system will have to emulate similar conditions, but do the existing test methods specified by 3GPP scale up to mmWave?

The radiated two stage (RTS) method relies on measuring the antenna pattern before convolving this with the channel model to create the signal to be used for device testing in the receiver after the antennas. Since mmWave systems will rely heavily on steerable antennas, the RTS method does not have an obvious role in black box conformance testing of devices; however, it may prove to be useful during device development. The reverberation chamber plus channel emulator (RC + CE) method is capable of creating stochastic reflections, although not with any specific control on direction and limited control of reflection.
count, controlled by attenuation in the chamber. It is not clear what role reverberation chambers will play at mmWave, although they may have the potential for some aspects of cable replacement testing where spatial control is not required. The multi-probe anechoic (MPAC) test method has potential for extension to mmWave frequencies. Figure 14 shows a plan view of a typical 8×2 chamber. The usable area within an MPAC system is determined by two properties: the quiet zone and the smaller test zone. The quiet zone is the area within which the power is controlled and is largely determined by the chamber size relative to the signal wavelength. At mmWave frequencies, the quiet zone is not an issue. The smaller test zone is the area within which the power is controlled and is determined by the angular separation of the probes; 8×2 probes provide an ideal test zone of 0.7λ before starting to degrade, rising to 1.6λ with 16×2 probes. Unfortunately, at 60 GHz the wavelength is only 5 mm, which equates to a test zone of just 12.5 mm. Extending this with more probes is possible, but cost becomes a significant factor.

It is likely that an alternative test concept will be needed for mmWave OTA. One possibility comprises an anechoic chamber with a small number of mmWave remote radio heads (RRH) coupled to an L1/MAC baseband transceiver with channel emulation capability (see Figure 15). Such a system would not be able to arbitrarily generate any spatial channel, although it could create a diversity of potential use cases: shadow fading and in-channel impairments like frequency-selective ground bound and Doppler shift. This would test the capability of the device to both acquire and track multiple signals during a test sequence. The downside of not being able to generate spatial signals with arbitrary angles of arrival — needed for SCME at RF — is less significant. At mmWave frequencies, most signals will already have narrow beamwidths of 10 to 15 degrees, which can be generated by a single antenna.

CONCLUSION

The author hopes this article has set the scene for what lies ahead to test 5G at mmWave frequencies, almost all OTA without cables. The challenges compared to today’s RF OTA testing are formidable, since existing test methods have limited scalability and timescales are extremely short. This should motivate the industry to focus and, indeed, 5G testability is already getting attention in the early NR discussions at 3GPP.

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