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Introduction: Millimeter Waves in 5G

To meet the needs of a networked society, next-generation 5G cellular networks promise revolutionary improvements in network capacity, data rates and latency, with greatly increased network flexibility and efficiency. At the same time, network operators will expect lower operational and infrastructure costs than today [1], [2]. Achieving these challenging goals will require extensive and multi-faceted changes in all aspects of the cellular eco-system, from chipsets and devices to base stations and small cells, from front haul and back haul to network management and data center performance. Many new technologies such as network function virtualization (NFV), adaptive beamforming and beamtracking techniques, tight integration with 4G LTE and new designs for mobile devices will be developed to enhance network performance, but by themselves, they will not be sufficient.

Fully realizing the 5G vision will require much additional spectrum. Although additional spectrum below 6 GHz has been identified and, in some countries, already allocated for cellular communications, much larger contiguous spectrum is available in the centimeter and millimeter-wave (mmWave) bands above 24 GHz. Figure 1 [3] shows some of the candidate mmWave bands in various regions of the world for 5G NR (New Radio). For convenience, this document will refer to frequency bands above 6 GHz as mmWave.

Frequencies above 40 GHz are also under consideration for applications such as broadband distribution and backhaul. While arguably not strictly ‘5G’, work in these areas is under way and presents many similar challenges to those of the frequency bands around 28 GHz and 39 GHz, which are driving much of today’s 5G NR development.

The amount of new spectrum that policy-makers are allocating offers a seemingly straightforward path toward higher capacity, higher data-rates, and lower latency. However, any additional mmWave spectrum comes with consequences and trade-offs. Incorporating mmWave devices into the network will introduce new complexity and require new technology development—and will drive new radiated, or over the air (OTA) test requirements. This document will focus on these OTA challenges and the associated test methods.
Technology Challenges for a mmWave 5G Network

Channel sounding and modeling at mmWave

Understanding the transmission properties of mmWaves in real-world environments is fundamental to the core design of the 5G NR UEs and base stations (gNB). As the wavelengths get smaller, physical processes such as diffraction, scattering, material penetration loss, and free space path loss, all make the channel properties of mmWave bands significantly different from today’s sub 6 GHz bands. Channel models have been developed over many years from 2G to 4G based primarily on channel measurements (sounding), originally presenting non-spatial models but evolving over time to 3-D spatial models [4].

The 3GPP study on 5G channel model for frequencies from 0.5 to 100 GHz [5] considers several scenarios including Urban Micro, Urban Macro, Indoor, Backhaul, Device to Device (D2D), Vehicle to Vehicle (V2V), and Stadium. The number of spatial clusters and multipath components per cluster in the mmWave channel, and the spatial dynamics, has far-reaching implications on the design of the network components. For example, if the channel model defines a spatially rich channel, the antenna beamsteering requirements are not so important, and many Eigenmodes will be available for Single-User MIMO (SU-MIMO) but the resulting fast fading caused by the addition of so many multi-path signals will be complex. On the other hand, a more sparse channel will contain few Eigenmodes, less fading but require much better beamsteering. This is why realistic channel modeling is important for both device design and defining realistic and useful test cases.

Since the publication of [5] mmWave channel modeling activities have been continuing at companies, universities, and at government institutions in an effort to develop a greater understanding of the mmWave channel and its behavior.

Path loss modeling

Ignoring atmospheric effects, the received power for a transmitter and a receiver communicating via free space is easily calculated using the Friis transmission equation [6] given as Equation 1.

\[ \frac{P_r}{P_t} = \left( \frac{c}{4\pi R f} \right)^2 G_t G_r \]

Equation 1

where \( P_r \) is the received power, \( P_t \) is the transmitted power, \( R \) is the distance between the transmitter and receiver, \( f \) is the frequency, \( c \) is the speed of light, \( G_t \) is the gain of the transmitter antenna, and \( G_r \) is the gain of the receiver antenna.

\( P_t \) is thus inversely proportional to the square of the frequency, \( f \). For example, moving from 3 to 30 GHz using the same antenna gain adds 20 dB of path loss that, without mitigation, would severely impact network performance. In addition to the free space path loss, OTA communications at mmWave also need to take into account the effects of atmospheric absorption, humidity, blocking, precipitation and other factors which can increase the effective path loss between transmitter and receiver. For indoor channels, path loss is less of a concern but other effects like blocking need to be mitigated.

The mechanism typically employed to overcome additional path loss at mmWave frequencies is to increase the gain and therefore the directivity of the antennas. Base stations in a 5G network are likely to have antennas with > 20 dBi directivity, and user devices (UEs) for 5G are also expected to incorporate directional antennas, though with more moderate directivity. The 3GPP co-existence studies in [7] assume gNB directivity for 30 dBi and UE of 25 dBi although practical UE directivity may be a lot lower unless for
fixed wireless access applications. In addition to countering the path loss of the mmWave channel, directivity also supports spatial reuse of the channel allowing the gNB to support multiple users in one cell with spatially separate beams. A further advantage of directivity is reduced interference to neighbor cells in the network which generally improves spectral efficiency. Consequently, 5G networks utilizing mmWave frequencies will require both base stations and UEs to steer relatively narrow beams toward each other (and via reflective surfaces) to optimize the link budget and provide effective communication. Developing protocols for enabling base stations and UEs to find and track each other and perform inter-cell handovers represents a key technical challenge of mmWave communications for 5G.

**Phased Array Technology, Beamforming and Beamsteering**

Phased array antennas [8] are a practical and low-cost means of creating narrow beams (beamforming) and dynamically pointing them in the desired direction (beamsteering). They enable beam steering without mechanical motion and are expected to be the principle mmWave antennas used for both base stations and UEs. A phased array antenna is formed by an array of smaller antenna elements, such as individual patches or dipoles. By varying the relative phases and amplitudes of the signals applied to the individual elements, the antenna array can shape and steer a beam in a chosen direction. Figure 2 [9] illustrates the basic operation of a phased array. A signal from a transmitter (Tx) is distributed to several antenna elements. Phase shifters are controlled to adjust the individual phase of the signal transmitted from each element, thereby enabling beamforming at a variable angle theta ($\theta$).

![Figure 2: Basic operation of a phased array](image-url)
Three types of beamforming architectures are being considered for 5G networks: digital (implemented in baseband), analog (implemented at IF or RF), and hybrid [10]. Each has its relative merits. For cost and power reasons, beamforming in UEs is expected to be analog, whereas the beamforming of base stations may be either analog, digital, or hybrid.

Figure 3 shows a Time Domain Duplex (TDD) simulation of propagation from a 50-element linear array with zero-forcing pre-coding. Individual beams are steered to target UEs, while a null is steered towards other UEs and interference sources.

**Figure 3. Simulation of a 2-D phased array steering beams to target UEs while steering a null to interfering sources**

**Radio and Antenna Integration, and the Elimination of RF Connectors**

A number of factors contribute to the increasing levels of integration in 5G mmWave devices. These factors are interrelated and are driven by the combination of high frequencies, large numbers of antenna elements, the need to minimize signal path attenuation, and the need to reduce cost. A significant consequence of the resulting integration is that traditional RF connectors at the boundary between the radio distribution network circuit and the antenna system are no longer possible to implement. The distribution network employed to connect mmWave signals from the radio to the antenna must be extremely compact, especially in handheld devices and other user equipment. As a result, transceiver systems for 5G mmWave devices will be directly integrated with the antenna arrays as shown in Figure 4. In these types of devices, there are no longer connectors or probe points that might enable conducted tests; instead, the great majority of testing must now be accomplished OTA.
Device Calibration

Establishing a methodology for OTA calibration of the phase and gain states of phased array devices (Tx and Rx paths) is a key R&D activity that necessarily will be performed OTA. Calibration is required to ensure that beams transmitted from UEs and base stations produce the correct beam width or gain over the required range of pointing angles, that power output limits are met, and that beamforming characteristics are operating as intended. These characteristics include coarse/fine resolution scan operation, accuracy of scan angle, and gain flatness compensation.

Which methodology to choose for OTA calibration will depend on the device architecture and the control interface of the device. For example, if each individual antenna element can be controlled independently, then the relative phase between antenna elements can be measured and corrected. If antenna elements can only be controlled in blocks or rows, then more sophisticated calibration routines are required.

New OTA Test Implications of mmWave 5G

The previous sections make it clear that the use of mmWave frequencies for 5G NR systems adds complexity to the devices used in the network and to the operation of the radio access network itself. Test systems will play a critical role in the development and validation of 5G NR, from R&D through conformance test, manufacturing and installation and maintenance. The high level of radio and antenna integration means that much of this testing will be OTA, while the wide variety of test needs (capability, accuracy, size, and cost) requires a correspondingly flexible range of test solutions. The next sections describe OTA test methods for 5G mmWave systems.
Measurement of Radiated Fields

OTA measurements are typically made in either the radiated near-field or radiated far-field regions of the antenna system under test, as shown in Figure 5.

Very near the antenna itself, typically on the order of a few wavelengths or less, is the reactive near-field. In this region, absorption or coupling to objects (e.g., a probe antenna) has an impact on the E and H field components radiated from the antenna. As shown in Figure 5, this region extends to a distance approximately defined as:

$$ R \geq 0.62 \sqrt{\frac{D^3}{\lambda}} $$

where $D$ is the diameter of the smallest sphere encapsulating all the radiating elements of the antenna, which may include passive elements.

Beyond this distance, a probe antenna will not affect the signal radiated by the antenna. In the radiated near-field, known as the Fresnel region, the radiated angular field distribution evolves with distance from the antenna, though the evolution slows as the distance grows. The radial components of E and H fields may be appreciable in this region, reducing in strength rapidly with distance $R$. For antennas where $D >> \lambda$, the far-field or Fraunhofer distance begins at $2D^2/\lambda$ from the antenna. Beyond the Fraunhofer distance, the E and H field components are transverse and orthogonal, and the radial field components are negligible.

The boundary to the Fraunhofer region is not a sudden transition in the evolution of the radiated patterns. The distribution of radiated power does continue to evolve beyond this distance, so an antenna pattern measured at $2D^2/\lambda$ will differ slightly from the pattern measured much further away, but it is close enough for many OTA test purposes. As the distance increases from the antenna, the amplitude of the peaks, sidelobes, and nulls in its radiation pattern stabilize.
**Direct Far-Field Test Method**

Measurement in the far-field is conceptually the simplest type of OTA measurement system, and is an approved method identified by 3GPP for base station RF measurements and is the baseline UE RF test method. A typical far-field anechoic chamber is shown in Figure 6.

![Diagram of a far-field anechoic chamber](image)

**Figure 6.** Far-field anechoic chamber

The device-under-test (DUT) is mounted on a positioner that rotates in two planes; azimuth and elevation, or azimuth and roll, to allow any 3D angle to be probed. Some chamber systems deploy an array of probe antennas instead of a single antenna, which can simplify the standard positioner movement at the expense of increased switching and calibration complexity.

From the far-field Fraunhofer distance equation, it can be seen that the far-field distance and therefore the size of the required chamber can vary significantly with antenna size and frequency. Table 1 gives some representative far-field distances at frequencies of interest for 5G. Since the direct far-field chamber must itself be larger than this minimum distance, size and cost of such systems can quickly escalate.

<table>
<thead>
<tr>
<th>Far-Field Distance (m)</th>
<th>28 GHz</th>
<th>39 GHz</th>
<th>60 GHz</th>
</tr>
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<tbody>
<tr>
<td>50</td>
<td>0.47</td>
<td>0.65</td>
<td>1</td>
</tr>
<tr>
<td>100</td>
<td>1.9</td>
<td>2.6</td>
<td>4</td>
</tr>
<tr>
<td>150</td>
<td>4.2</td>
<td>5.9</td>
<td>9</td>
</tr>
<tr>
<td>200</td>
<td>7.5</td>
<td>10.4</td>
<td>16</td>
</tr>
<tr>
<td>300</td>
<td>16.8</td>
<td>23.4</td>
<td>36.0</td>
</tr>
</tbody>
</table>

**Table 1.** Far-field distances for antennas of various sizes

Typical active antenna array systems (AAS) for base stations operating at mmWave frequencies can be in the range of 100 mm to 300 mm (depending on whether a sub-array or the entire array is active), requiring direct far-field anechoic chambers to be large room-sized installations. Millimeter-wave 5G UEs will have antenna arrays significantly smaller than 100 mm, making use of direct far-field anechoic chambers more feasible.
However, it is not always straightforward to define the $D$ to be used in the far-field equation. For a typical antenna array, $D$ is the diagonal extent of the array. When that array is incorporated into an UE or a base station, the array may couple to the ground plane behind it and to nearby conducting materials causing the effective radiating area to increase. For mmWave 5G UEs, another complicating factor in determining the value of $D$ is that these devices are anticipated to have multiple antenna arrays to enable full spherical coverage. Multiple arrays also overcome situations where the signal is blocked by a human hand or head [12]. Figure 7 shows examples of possible array placements.

![Figure 7: Potential antenna array configurations for a mmWave 5G UE](image)

There are two approaches that can be taken for measuring devices with one or more antenna arrays. The first “white box” approach is based on prior knowledge of the antenna array position on the DUT. This position could be determined either by design, declaration, or near-field scanning. The DUT is then positioned such that the center of radiation is placed at the center of the test zone. The far-field distance can then be calculated with $D$ being set to the largest dimension of the array (assuming no significant ground plane effects). Typical array dimensions would then lead to a far-field distance of much less than 1 m for an UE. To test the entire device requires repositioning the DUT for each array.

The alternative approach does not require knowledge of any antenna array position(s) and is known as the “black box” approach. In this instance, the geometric center of the DUT is placed at the center of the test zone and the D used for calculating the far-field is the maximum dimension of the DUT. The far field for this approach is much larger than for the white box approach (e.g., 4.2 m for a 150 mm DUT at 28 GHz), but the device does not need to be repositioned regardless of which antenna arrays are active.

The use of the white box approach is attractive in a development environment since the far-field distance is much shorter and knowledge of the antenna structure more likely. However, for conformance testing, 3GPP has decided that only the black box approach can be used. This is due to the requirements for white box testing outlined in [13] not being accepted by UE vendors who preferred not to declare the antenna structure. In addition, no mechanism exists for the UE to signal when it changes its array, and the white box approach also rules out use of more than one array at a time.
Alternative Far-Field Test Method – Compact Antenna Test Range (CATR)

The Compact Antenna Test Range (CATR) method is recognized as a standard means for far-field characterization [14]. At least one quasi-optical element, such as a parabolic reflector, is used to collimate radiation from a test probe [15]. The basic configuration and operation are illustrated in Figure 8.

Figure 8 shows the main elements of the CATR method: a feed or probe antenna, a parabolic reflector system, and a rotating positioner to accommodate the DUT.

A diverging beam from the probe antenna situated at the focus of the mirror illuminates the parabolic reflector, which then collimates the original beam and directs it to the DUT. The collimated beam has a nearly uniform amplitude and phase across its extent; it provides a nominally ideal plane-wave illumination to the DUT. The reflector allows the DUT to be tested under far-field plane wave conditions at a shorter distance than $\frac{2D^2}{\lambda}$, resulting in a system with potentially a much smaller footprint and lower path loss than the equivalent direct far-field method.

The volume in any chamber in which a DUT is illuminated with nearly uniform amplitude and phase is called the quiet zone. In a CATR, the quiet zone is typically cylindrical or elliptical in shape with the diameter or axis set by the extent of the collimated beam within which the phase and amplitude are within particular limits. The zone begins a short distance behind the probe antenna [16]. Typical quiet zone specifications are 10 degrees of phase variation, ± 0.5 dB of amplitude ripple, and 1 dB of amplitude taper, which is the roll-off toward the edges of the quiet zone.

Accurate device characterization requires that the entire radiating volume of the device be within the quiet zone. The rotating positioner then allows characterization of the device or antenna as a function of angle (azimuth and elevation). This configuration is reciprocal so that the device can be measured either in transmit or receive mode without repositioning [17].
Direct Far-Field vs. CATR: Compare and Contrast

Both far-field and CATR methods can provide comparable far-field measurements. Figure 9 shows 28 GHz antenna pattern measurements of a standard gain horn performed in two different chambers. The blue far-field measurements in Figure 9 were performed in a large (> 3 m) direct far-field chamber. The red CATR measurements were obtained using a CATR chamber at Keysight Laboratories. The results are in excellent agreement, where the direct far-field results have sufficient dynamic range for comparison.

While both the CATR method and the direct far-field method provide far-field device characterization, each has certain performance tradeoffs. The most obvious difference is that CATR measurements can be accomplished in a much smaller footprint when the DUT is electrically large (e.g., for a gNB antenna array operating at mmWave frequencies). Taking the example of a DUT of $D = 300$ mm at 28 GHz with a far-field of nearly 17 m from Table 1, a CATR chamber whose quiet zone encloses the DUT with some margin would be approximately 3 m long.

With a collimated beam, the CATR provides characterization in the far-field (well beyond $2D^2/\lambda$), which allows for accurate measurements of side-lobes and nulls. However, the parabolic element that enables this compactness also introduces a degree of cross-polarization into the CATR. With proper design, a typical CATR quiet zone can be specified with better than 30 dB of cross-polarization isolation. At that level, the impact on measurements is negligible for many applications.

In the direct far-field method, it is critical that the DUT antenna be placed at the center of the probe antenna’s beam. Characterizing a device with multiple antennas at a far-field distance based on the array size would involve repositioning the device so that each array can be characterized. To avoid repositioning, the far-field distance has to be based on the maximum device dimension, resulting in a much larger far-field chamber. With the CATR method, however, all the antennas inside the quiet zone can be characterized simultaneously.

The value of the distance $R$ in equation 1 for path loss (the Friis equation) is different for the two systems. For the direct far-field method, the distance is the separation between the probe and DUT antennas. In the CATR system, however, the relevant distance in calculating path loss is the separation between the probe antenna and the reflector (approximately the focal length). The same path loss, determined by the probe feed to mirror distance, applies whether in transmit or receive mode [17].
In cases where the CATR focal length is shorter than the far-field distance of the DUT, the CATR system will have a lower path loss than the direct far-field method. The total propagation loss of the test system must also include the gains of the probe and DUT antennas. Depending on the antenna gains used in specific setups, a CATR system with lower path loss than a direct far-field system may not always have a lower total propagation loss.

Table 2 summarizes some performance trade-offs between the direct far-field method and the CATR method.

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Direct far-field</th>
<th>Compact antenna test range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chamber size</td>
<td>Determined by required far-field distance; Example: 150 mm diameter array at 28 GHz has far-field distance 4.2 m, and chamber length of at least 5.5 m</td>
<td>Determined by required quiet zone diameter; Example: 150 mm diameter array at 28 GHz. Chamber length approximately 2 m</td>
</tr>
<tr>
<td>Path loss</td>
<td>Determined by distance between DUT and probe antenna; Example: for a far-field distance of 4.2 m at 28 GHz, free-space path loss 74 dB</td>
<td>Determined by focal length of reflector; Example: 150 mm diameter QZ, free-space path loss 58 dB</td>
</tr>
<tr>
<td>Cross-polarization isolation</td>
<td>High</td>
<td>~30 dB (curved reflector generates cross-polar component)</td>
</tr>
<tr>
<td>Antenna Pattern Measurements</td>
<td>Measurement accuracy of side lobes and nulls is better at larger distances between DUT and probe antenna</td>
<td>Antenna pattern measurements are equivalent to those measured in direct far-field (Figure 9), measurement accuracy of nulls and side lobes depends on QZ flatness</td>
</tr>
<tr>
<td>Position of DUT relative to probe antenna beam</td>
<td>White box: Center of radiation of DUT antenna array must be at center of quiet zone. Black box: Geometric center of DUT must be at center of quiet zone</td>
<td>All DUT antenna arrays must be contained within the quiet zone [18]</td>
</tr>
<tr>
<td>Cost</td>
<td>Scales with chamber size</td>
<td>Cost of precision reflector offset by smaller chamber</td>
</tr>
</tbody>
</table>

Table 2. Direct far-field vs. CATR
Near-Field Measurement Systems

Near-field measurement systems sample the phase and amplitude of the electrical field in the radiated near-field region (Figure 5), also known as the Fresnel region, over a two-dimensional surface using high-precision positioners. This surface is either planar, cylindrical, or spherical (Figure 10). The far-field antenna pattern is then calculated using Fourier transform algorithms.

This approach for antenna pattern measurements can be achieved with relatively small test chambers which are considerably less expensive than indoor far-field ranges. Measurement accuracy and the calculated far-field antenna patterns can compare very well with far-field methods. [19]

Which type of near-field system is best for a particular application will depend on the antenna characteristics of the device to be tested. Mathematically, the planar surface method is the most straightforward; it is well-suited to measurements of directional antennas with minimal backward lobe typical of many mmWave 5G gNB antenna arrays. Planar systems also allow the use of mechanical surface alignment to ensure accurate parallel movement of the scan probe with respect to the DUT array surface. For some 5G DUTs, spherical or spherical-spiral (“sphiral”) scan systems perform measurement of the DUT in a nearly-complete sphere around the DUT, allowing measurement of radiation from the edge or back of the array under test as well as in the main lobe. Cylindrical scan systems can be well-suited to antennas arranged in a linear fashion or a sectorized layout.

Once the electric field is measured at each point in the grid, the data undergoes a Fourier transform to obtain a linear combination of plane waves at various angles. These plane waves, represented in a spherical coordinate system, provide the far-field antenna patterns [15]. This is a transform from near-field measurements at multiple positions to far-field angular patterns [20]. In the case of the planar scan system, the extent of the scan is typically significantly larger than the DUT itself, and this extent used to set the angular resolution in the far-field. Accurate far-field results require compensation for the directive properties of the probe antenna.

Near-field scanning is useful as a diagnostic tool in R&D since transforms can also be applied that reveal the distribution of surface currents on an antenna array, and identify faulty elements or other conditions. Near-field scanning can also be a relatively fast measurement method – several techniques to reduce the required sample set have been developed [21], including the sphiral scan with data interpolation (Figure 12).
While the near-field to far-field approach offers the most compact means for antenna characterization, it does pose challenges for mmWave device characterization. For example, a fast vector network analyzer (VNA) is typically used in near-field measurements because both phase and amplitude information are required for the mathematical transformations. However, unlike antennas, mmWave 5G devices are single-ended so will not support the use of a VNA. The high level of integration between the radio and the antenna array mean characterization of only the device antenna may not be possible due to lack of connectors.

Several techniques are available for recovering phase in single-ended devices. One technique requires the measurement of the electric-field amplitude on two different near-field surfaces. This information is applied iteratively with an initial estimate of the phase on a surface to retrieve the unknown phase. With the measured amplitude and derived phase on a surface, the far-field antenna pattern can then be derived [23]. Another technique uses several probe antennas where one or more antennas remain fixed to provide a reference for phase recovery while the other(s) perform a near-field scan. The relative phases measured by the two sets of antennas are then used in the far-field transformation [24].

When measuring mmWave NR devices in the near-field, the far-field transformation for antenna pattern measurements becomes problematic when a wideband modulated signal is transmitted, since the phase can vary across the signal. Traditionally, near-field antenna pattern measurements are performed using CW signals. However, simulated and real data show that the antenna patterns of wideband modulated signals measured in the far-field can show some differences compared with CW patterns, particularly in side lobe level (higher than CW for modulated) and null depth (less deep than CW for modulated). To measure these antenna patterns accurately may require either a far-field or CATR chamber, or measuring the phase of each subcarrier and combining the resulting data.

The applicability of near-field scanning to calculate far-field Tx patterns is clear and involves sequential measurement of the near field followed by post-processing of the Fourier transform. The applicability of near-field for receiver testing is less obvious. For receiver testing that involves real time measurement of throughput, the inverse of the transmitter measurement procedure would require real time generation of a spatial near field signal. This is not practical as the near-field system can probably generate only one point in space. One solution to this problem is to take a two-stage approach by first measuring the receiver near field antenna pattern with the assistance of amplitude and phase measurements in the DUT followed by a second stage where the transformed far-field Rx antenna pattern is applied to the test signal [25]. This approach also extends to applying a spatial channel model to the test signal.

**Measurement Requirements through the 5G NR Development Lifecycle**

The types of measurements required for 5G NR devices varies throughout the development lifecycle. For example, during the design and development phase, R&D teams aim to measure as many RF characteristics of their devices as possible. Those measurements which can be performed will depend on the particular device and the stage of development of its features and functions, and will also depend on the level of integration of the device under test.
In any communications system, transmitted and received signals are never ideal. A mmWave transmitter chain adds nonlinearities, noise and other impairments to the desired baseband signal to be transmitted. Likewise, the receiver adds distortions and impairments that degrade the received signal. To understand the behavior of mmWave transmitter and receivers it is necessary to characterize their performance over the air using test equipment that can generate and analyze wideband 5G waveforms. It is known that achievable OTA accuracy is not as good as conducted accuracy, so this is an important discussion at 3GPP.

Not all R&D measurements will apply equally to base stations and UEs, and test procedures and performance requirements will be different depending on the device being measured. Table 3 lists the draft 3GPP Technical Specifications for radio transmission and reception of NR UE's and base stations. The documents listed are currently skeleton documents containing headings but limited detail.

<table>
<thead>
<tr>
<th>UE</th>
<th>Base Station</th>
</tr>
</thead>
<tbody>
<tr>
<td>Documents</td>
<td>TS 38.101 User Equipment (UE) radio transmission and reception</td>
</tr>
<tr>
<td>TS 38.141 Base Station (BS) conformance testing</td>
<td></td>
</tr>
<tr>
<td>Radiated transmitter tests</td>
<td>Transmitter power</td>
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<tr>
<td>Output power dynamics</td>
<td>Base station output power</td>
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<tr>
<td>Transmit signal quality</td>
<td>Output power dynamics</td>
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<tr>
<td>Output RF spectrum emissions</td>
<td>Transmit ON/OFF power</td>
</tr>
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<td>Minimum output power</td>
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<td>Spurious emissions</td>
<td>Transmitted signal quality</td>
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<td>Occupied bandwidth</td>
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<td>Adjacent channel leakage ratio (ACLR)</td>
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<td>Transmitter spurious emissions</td>
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<td>Transmitter intermodulation</td>
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<td>Maximum input level</td>
<td>Dynamic range</td>
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<td>Receiver spurious emissions</td>
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<td>Receiver intermodulation</td>
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<td>In-channel selectivity</td>
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Table 3. 5G NR radio transmission and reception test requirements
In general, OTA measurements in R&D will also include the following:
- Beam pattern measurements in both 2D and 3D, to measure beam width, side lobe levels, null depths, and symmetry.
- Cross-polar measurements, to understand the level of cross-polar isolation of the antenna system
- Beamsteering or null steering performance, to confirm that the beam (or beams for base stations) can point in the correct direction while maintaining the correct gain pattern over the desired steering range.

**Testing Over Extreme Conditions**

UEs and base stations must be tested over extreme conditions including temperature. The operating temperature range for a base station situated outdoors can extend from -60°C to +45°C, so OTA measurement techniques need to be developed to enable this type of characterization. The challenge for this type of testing is to accurately control the temperature and humidity for the device’s immediate environment, while ensuring the OTA measurement system is kept within its much narrower specified operating range.

**Measuring Adaptive Behavior**

Far more challenging than static RF measurements are tests of a dynamic nature in which the adaptive functionality of the device is measured, and these require a signaling link to be established between devices. An example of this would be measuring the ability of a base station to acquire and spatially track an UE or several UEs, all of which are transmitting and receiving using narrow mmWave beams.

The integration of steerable antennas is fundamental to the function of 5G NR systems, but presents a number of formidable test challenges. The requirements and test methods for measuring adaptive behavior are under discussion at 3GPP.

**NR Conformance Testing**

Conformance testing happens relatively late in a product’s lifecycle and refers specifically to ensuring the device meets 3GPP minimum requirements. 3GPP conformance tests can be grouped into RF, Radio Resource Management (RRM), demodulation, and signaling. The first priority in 3GPP is developing the UE and gNB core requirements by December 2017. The performance requirements (demodulation and RRM test cases) will follow by December 2018.

At the time of writing, discussions on core requirements and specification structure for Release 15 are not yet finalized, so a summary of requirements and test methods is out of scope for this document. Once these requirements are specified, future publications will describe them in detail.

**Manufacturing Test**

Requirements for manufacturing test are driven by the need to establish confidence that the manufacturing process and supply-chain ensure devices meet conformance and other non-standardized requirements. For that reason, manufacturing test processes are limited to those parameters that are expected to vary. They are limited in scope principally by cost of test and test speed. Key device specifications must be verified while keeping the overall test time and complexity to acceptable levels.
Factors to consider in developing a manufacturing test strategy will include the following:

- Minimizing the time spent on measurements over multiple spatial dimensions (compared with cabled test with no spatial dimension).
- Reduced or eliminated angular-dependent measurements.
- Fast OTA antenna and transmitter/receiver calibration and verification.
- Minimized or no mechanical positioning movement.
- Deployment of small and inexpensive chambers or enclosures.
- A means to cope with the increased measurement uncertainty of OTA measurements compared with cabled measurements.

Like most manufacturing systems, test coverage and test time will be expected to reduce over time. Aggressive goals are already being set to achieve cost of test and throughput targets that will serve to mitigate inherent test time increases associated with the move from cabled to OTA test.

Conclusion

The push into mmWave frequency bands to access new spectrum for 5G NR is creating an abrupt and significant shift in the way commercial communications devices and systems will be designed and verified. Measurements that were previously implemented using cabled connections are moving to the radiated spatial domain; active beamforming systems, steerable arrays and highly integrated designs will require that virtually all testing at mmWave must be done using radiated OTA methods.

In this document, the key challenges in making mmWave OTA measurements have been highlighted, and an overview of the main RF OTA test methods described. Due to the range of test requirements across the design and validation lifecycle, no single test method can fully cover all possible tests.

5G NR is evolving rapidly, and OTA measurements are an integral part of the success of the next generation of cellular systems.
References


[5] 3GPP, “TR 38.901 v14.1.1 TSG RAN “Study on channel model for frequencies from 0.5 to 100GHz,” 2017.


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