White Paper

Advancing beyond

OTA Testing in 5G NR: Challenges, Solutions & Best Practices

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Synopsis

Radio testing of base stations or User Equipment (UE) was established with the early 2G systems based primarily on conducted connections. Even on a component level usually an RF connector was available, allowing connection of a test instrument to measure the metrics of interest. Why do 5G devices and base stations need to be tested Over-The-Air (OTA)? What does a typical OTA test environment consist of? What is the Quiet Zone (QZ)? Which test metrics does 3GPP specify for 5G OTA testing? How can we measure them? This white paper addresses all these questions. It describes the available OTA test methods and provides guidance on choosing the right solution in different scenarios. Introducing OTA measurements in the validation and conformance process introduces numerous challenges in achieving a desired measurement accuracy. This white paper includes an overview of the main challenges, solutions and best practices of an OTA testing environment. Choosing the best test solution helps to speed time to market, lower cost-of-test and give companies a competitive advantage in the new frontier of wireless.

Contents

The Need to Test 5G Devices and Base Stations Over-The-Air (OTA)

Radio testing of Base Stations (BS) or User Equipment (UE) was established with the early 2G systems based primarily on conducted connections. Even on a component level usually an RF connector was available, allowing connection of a test instrument to measure the metrics of interest. The reason is that most implementations, even up to operation of 4G networks, include passive antennas. The first Over-The-Air (OTA) test methods were discussed in conjunction with the commercial adoption of Multiple-Input-Multiple-Output (MIMO) schemes in UEs. This resulted in OTA test cases for UEs, including radiated output power and radiated sensitivity tests, as specified in 3GPP TS 37.544. With the adoption of active antennas in BS, radiated output power and sensitivity tests were adopted, as defined in 3GPP TS 36.104. Despite these initial steps towards OTA testing, the vast majority of 2G through 4G testing was and is still executed in a conducted manner.

5G new radio (NR) aims at offering enhanced mobile broadband (eMBB), with data rates as high as 20 Gbps. Shannon theorem imposes wider and ideally contiguous channel bandwidths to achieve higher data throughputs. Below 6 GHz the spectrum is very crowded, therefore the focus has shifted to higher frequency bands, namely millimetre waves (mm-waves). 3GPP has designated frequencies between 24.25 GHz – 52.6 GHz as 5G NR frequency range 2 (FR2). Designing a standardized mobile infrastructure network at higher frequencies brings new challenges, among which surely a significant increase in pathloss. In FR2, mm-wave signals suffer from more than 60 dB path loss per meter. They are also highly vulnerable to human/vehicular blocking, which could further increase signal attenuation. To mitigate the impact of losses, beamforming techniques have been designed and developed by means of active antenna arrays (AAS), with multiple phase steered antennas. In AAS, the transceiver frontends are integrated together with the antenna array to reduce signal losses. In other words, no traditional RF output ports are available, and no cable connection is possible. Although a UE may require a lower number of applied antenna elements, similar challenges apply when developing UE transceivers. Completely integrated solutions, with RF front-end and phased array antennas in the form of Antenna on Chip (AoC) and Antenna in Package (AiP) modules, are the cornerstones of 5G deployment. OTA testing is therefore no longer an add-on topic consisting of a limited number of test cases, but has become the default 5G test case, at least for FR2. This significantly affects the overall test procedures and requires achievement of the measurement uncertainty in OTA scenarios. In addition, shielding is typically required, not only to prevent external leakage of the radiating in the test environment including r the Device Under Test (DUT), but also to create a test environment that eliminates the effects of the radiation outside the chamber. OTA - or Radiated - tests are performed either in an anechoic chamber or in a reverberation chamber. The first uses absorbers to eliminate reflections of electromagnetic waves (an-echoic meaning "non-reflective, non-echoing, echo-free"). The second is essentially a cavity resonator with a high Q factor and with strongly inhomogeneous field spatial distribution (standing waves). To reduce this inhomogeneity, one or more tuners (stirrers) are used. A tuner is a construction with large metallic reflectors that can be moved to different orientations to achieve different boundary conditions.

UEs and gNB OTA Testing

The approach to OTA testing is different for BS and UEs. Table 1 illustrates the 5G NR conformance test for user equipment (UE) and base stations (gNB).

Base station manufacturers need to declare the type of BS they are implementing. 3GPP identifies:

- BS type 1-C: NR base station operating at FR1 only with conducted requirements defined at individual antenna connectors.
- BS type 1-H: NR base station operating at FR1 with conducted requirements defined at individual TAB connectors and OTA requirements defined at Radiated Interface Boundary (RIB).
- BS type 1-O: NR base station operating at FR1 with OTA requirements defined at the RIB.
- BS type 2-O: NR base station operating at FR2 with OTA requirements defined at the RIB.

Table 1. 3GPP Technical Specification for 5G NR UE and BS testing.

Device	Minimum requirements	Conformance Tests		Notes
UE	TS 38.101	Conducted tests	TS 38.521-1	FR1
		Radiated tests	TS 38.521-2	FR2
		Conducted/radiated	TS 38.521-3	Interworking Operation
gNB	TS 38.104	Conducted tests	TS 38.141-1	FR1
		Radiated tests	TS 38.141-2	FR1 and FR2

3GPP TS 38.141-2 specifies the radiated RF test methods and conformance requirements for NR BS type 1-H, BS type 1-O and BS type 2-O. Key test metrics include Effective Isotropic Radiated Power (EIRP), Total Radiated Power (TRP) and Effective Isotropic Sensitivity (EIS), Error Vector Magnitude (EVM) and blocking.

UE OTA testing requirements depend on the frequency bands in which they operate. In FR1 the availability of RF connectors is assumed and most testing is still conducted. UEs supporting FR2 must be tested OTA, as per 3GPP TS 38.101-2. 3GPP TR 38.810 defines OTA testing methodologies for UE RF, UE Radio Resource Management (RRM), and UE demodulation requirements for 5G NR, along with the associated measurement uncertainty budgets, and the related test tolerances. RF testing comprises transmitter and receiver requirements, such as maximum output power, modulation performance like Error Vector Magnitude (EVM), sensitivity or the ability to maintain a certain throughput performance in the presence of a blocking signal. RRM testing ensures the efficient use of the available radio resources. The requirements that are tested include, among others, cell reselection in idle mode and support for mobility (handover) in connected mode. Finally, UE demodulation and Channel State Information (CSI) testing cover the baseband performance of the receiver under various fading conditions and the UE ability to correctly measure and report CSI to the network.

For a better understanding, the let’s describe the key OTA Tx/Rx test metrics.

a. Equivalent Isotropic Radiated Power (EIRP)

EIRP (see Figure 1) is direction dependent and represents the gain of a transmitting antenna, in a specific direction, multiplied by the power delivered to the antenna from the transmitter. In other words, if an antenna has a 5 dB gain in a given direction and the transmitter delivers to it 2 mW (3 dBm), the EIRP in that direction is 8 dBm. The signal in that direction would be the same as if the antenna were isotropic and driven with 8 dBm signal level. Radiated transmit power is defined as the EIRP level for a declared beam at a specific beam peak direction. Using EIRP to specify maximum output levels means that power measurements are no longer just a single scalar value, as they are with conducted measurements. They are now a spherical field, reflecting the antenna gains and beamforming across the full range of angles. Because of this, the maximum power specifications are not given as a single value with a tolerance, but in terms of peak EIRP and a given %-ile value.

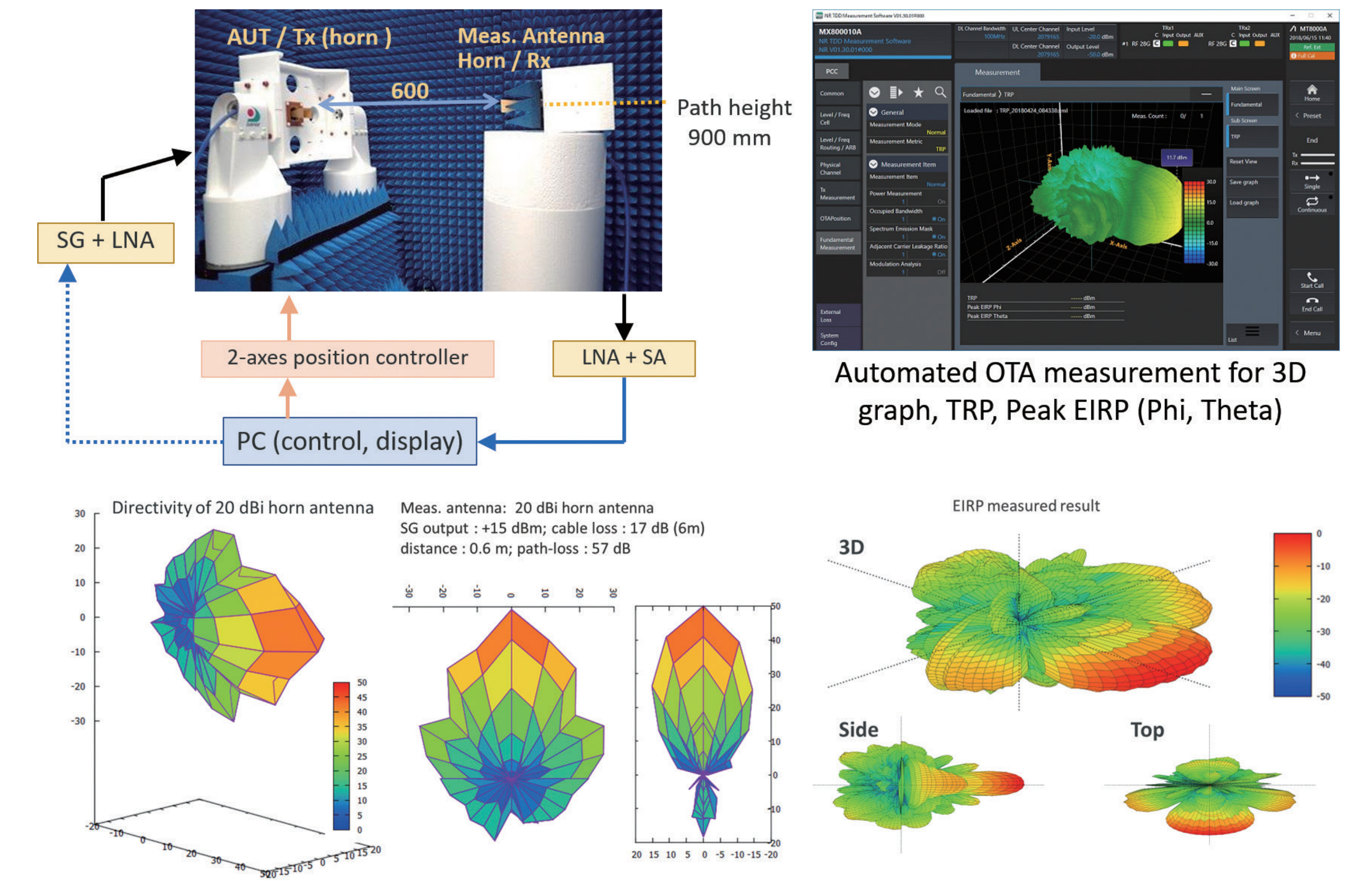


Figure 1. EIRP Measurement setup (top-left); automated SW (top-right); measured horn antenna directivity at 28 GHz (bottom-left); measured EIRP (bottom-right).

b. Total Radiated Power (TRP)

TRP measures the total level of power which is radiated by an antenna when this is connected to an actual radio (or transmitter). TRP is an active measurement, in that a powered transmitter is used to transmit through the antenna. TRP is calculated and summed up over all possible angles; hence, it is a spherical or 3D measurement. For a transmitter with an output power of 20 dBm (i.e. 100 mW), if the total received power measured in the far-field is 17.0 dBm, the resultant TRP is 17.0 dBm (hence 3dB of losses incurred from the transmitter output to the antenna output). TRP is strongly dependent upon both antenna and radio. As such, it is a key parameter that mobile operators need to specify when certifying a UE.

c. Equivalent Isotropic Sensitivity (EIS)

The sensitivity is the lowest power level that can be injected into a receiver while still allowing a reliable communication. EIS is the sensitivity for an isotropic device equivalent to the sensitivity of the device when exposed to an incoming wave from a defined Angle of Arrival (AoA). It is usually expressed in dBm. It reflects the effective usable sensitivity offered at the air interface and therefore includes all gains and losses in the RF and digital path of the receiving system.

d. Total Isotropic Sensitivity (TIS)

TIS is a measure of the average sensitivity of a receiver-antenna system averaged over a full 3D sphere. It is strongly related to the antenna's radiation pattern. The TIS of a system (i.e. receiver/antenna package) is determined using a dedicated Feed antenna within an anechoic chamber. The power is lowered until the Bit-Error-Rate (BER) reaches the threshold. TIS depends on two parameters: receiver sensitivity without the antenna (i.e. conducted receiver sensitivity) and antenna efficiency. In real devices, however, another factor can affect TIS: self-interference, also known as self-jamming or self-quieting. These are emissions from the device itself—not necessarily related to the receiver or radio—that are emitted at the same frequency as the signals the receiver is trying to receive.

e. Error Vector Magnitude (EVM)

EVM measures how accurately a system transmits symbols within its constellation. As such, it is an expression of the modulation accuracy. It quantifies the quality of the signal as a function of noise, interfering signals, nonlinear distortion, and load. The difference between the ideal signal vector and the actual signal vector is called error vector. EVM is the magnitude of the error vector. It is typically measured in dB, sometimes in percent. An EVM of -20 dB means that the error vector has a magnitude that is 20 dB less than the average signal vector (or the average energy transmitted per symbol). The range of directions where the EVM requirement must be met is declared by the manufacturer as OTA coverage range, while the requirement itself is considered directional.

f. Blocking characteristics

The OTA in-band blocking characteristics measure the receiver's ability to detect a wanted signal at its assigned channel in the presence of an unwanted interferer. This effect should be measured at the RIB of a unit specified by the 3GPP. Both wanted and interferer signals are specified by the 3GPP in OTA environment. The interferer is either a general blocking NR signal or an NR signal with one RB (Resource Block) for narrowband blocking. In 3GPP TS 38.141-2, receiver blocking test is described as a test that stresses the receiver's ability to withstand interference coming from unwanted signals at specified bands, which can be within the operating band (IB) or outside of it (OOB). If the unit can withstand the interfering signals without degrading its sensitivity, it means that the unit is operating like it should. These measurements are associated with the RIB of the unit, as it is stated in 3GPP. The same requirement applies for the general OTA out-of-band blocking to the wanted signal for each supported polarization, where it is assumed that polarizations match correctly. This requirement is assumed to be the same for both in-band and out-of-band.

g. Frequency Error

OTA frequency error measures the difference between the actual transmit frequency and the assigned frequency. The same source shall be used for RF frequency and data clock generation. The OTA frequency error is coherent and has a flat response in the spatial domain, therefore it does not depend on the measurement point within the beam's compliance directions set.

h. Time Alignment Error (TAE)

This requirement applies to frame timing in MIMO transmission, carrier aggregation and their combinations. It is defined as the largest timing difference between any two different NR signals. The OTA TAE requirement is defined as a directional requirement at the RIB and shall be met within the OTA coverage range. It is beneficial to coordinate testing of OTA TAE with testing of other transmitter parameters such as OTA frequency error and radiated transmit power.

i. Occupied Bandwidth

The OTA occupied bandwidth is the width of a frequency band such that, below the lower and above the

upper frequency limits, the mean powers emitted are each equal to a specified percentage of the total mean transmitted power. It allows verifying that the emission at the RIB does not occupy an excessive bandwidth for the service to be provided and is, therefore, not likely to create interference to other users of the spectrum beyond undue limits. For occupied bandwidth, the beam characteristics are not important. The requirement should however cover the fact that all transmitter is active and the system is operating at the maximum declared rated total radiated power. Occupied bandwidth is specified as a directional requirement valid over the OTA coverage range.

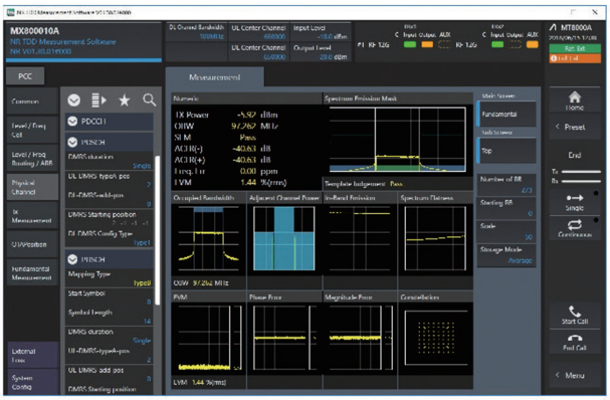
j. Adjacent Channel Leakage Power Ratio (ACLR)

OTA ACLR is the ratio of two EIRP measures: the filtered mean power centred on the assigned channel frequency to the filtered mean power centred on an adjacent channel frequency.

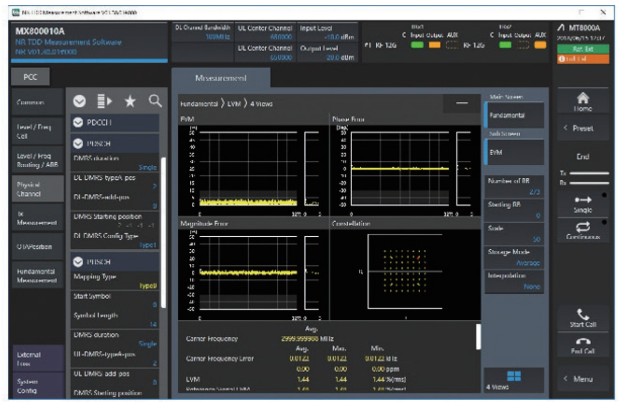
k. Operating Band Unwanted Emissions

This test measures the emissions of an operating RF system close to the assigned channel bandwidth of the wanted signal. The OTA limits for operating band unwanted emissions are specified as TRP per RIB, unless otherwise stated. The requirement in the OTA domain must capture all emissions around the DUT by application of the TRP metric.

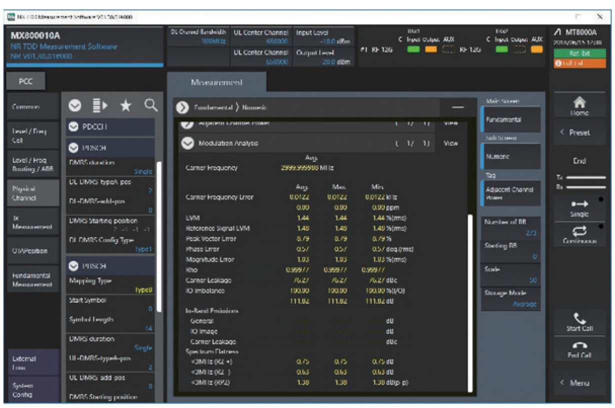
Figure 2 shows how the 5G NR TRx OTA RF metrics can be displayed in an intuitive Graphical User Interface (GUI) using a commercially available SW (NR TDD OTA Measurement Software MX800010A-002).



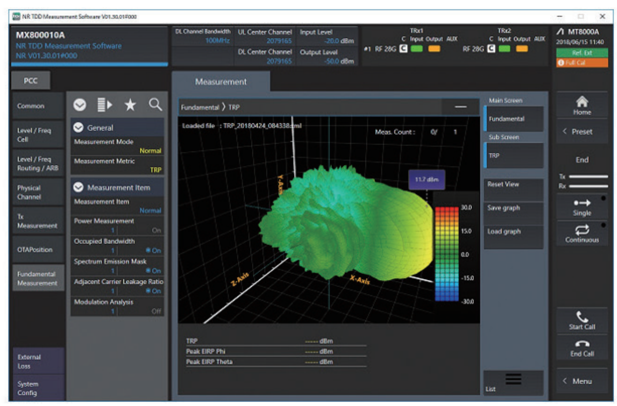
Tx Power, OBW, SEM, ACLR, Frequency Error



EVM, Phase Error, Magnitude Error, Constellation



Various PHY parameters configuration
Reference sensitivity, max. input level



Automated OTA measurement for 3D graph,
TRP, Peak EIRP (Phi, Theta)

Figure 2. SW (NR TDD OTA Measurement Software MX800010A-002) with GUI to display and report OTA RF TRx test items, (Tx Power, OBW, SEM, ACLR, Frequency Error, EVM, Phase Error, Constellation), and FR2 measurement metrics.

OTA testing is performed using anechoic or reverberation test chambers. The DUT may be placed on a positioner; this allows measuring the DUT from multiple angles as well as multiple polarizations. When designing an anechoic chamber, the goal is to obtain a volume within which any reflected energy from the walls of the range (ceiling and floor) is much lower than any of the features of interest on the radiation pattern. To fully understand the existing OTA test methods, three key parameters need to be defined first: far-field distance, Quiet Zone (QZ), and DUT size.

Far-Field Distance

The field behavior and characteristics vary with the distance from a transmitting antenna. A simplified model defines three regions: reactive Near-Field (reactive NF), radiated Near-Field (radiated NF), and radiated Far-Field (radiated FF). The transitions between these regions are not distinct and changes between them are gradual.

Reactive Near-Field: is the closest region to the DUT, where non-propagating evanescent fields are predominant. If a probe antenna sits in this region, it will also react with the DUT, effectively becoming part of the DUT radiating apparatus. This significantly limits the measurements permitted in this region (no RF parametric measurements like EVM, ACLR etc.). Specific Absorption Rate (SAR) measurements are performed in reactive NF, because the interest is to mimic and measure how much energy is absorbed by the human body when e.g. holding the mobile phone close to the ear.

Radiated Near-Field: is a region in which the probe antenna no longer reacts with the DUT and radiated fields predominate. The angular distribution is still evolving, and radial field components exist. The field behavior and phase front are thus not easily predictable and well-behaved. Measurements in this region require access to phase recovery in both the transmit and receive paths for a compensation algorithm. No RF parametric measurements like EVM, ACLR etc. can be performed in this region. The entire sphere must be measured in the radiated NF to understand the field distribution and transform this to far-field. To achieve this, typically a positioner is used. Measurements in the radiated NF can be complex and time consuming. No receiver measurements are possible in the radiated NF. Only some parameters (e.g. TRP, Peak EIRP) can be measured directly in radiated NF (i.e. without far-field transformation), but the measurement uncertainties are higher than in far-field.

Radiated Far-Field: is an area in which the angular field distribution stops evolving, only transverse fields are present. The phase front, with a variation lower than 22.5°, can be estimated as approximating a flat plane. It follows the formula $R > 2D^2/\lambda$, where R is the minimum far-field distance, λ is the wavelength and D is the diameter of the smallest sphere that encloses the radiating parts of DUT. This area is ideal for the measurement of both phase and amplitude but has the drawback of greater path-loss and larger (especially for larger DUT sizes and higher frequency) distances between the DUT and the probe antenna. Measurements in the far-field are comparably easy. Here all RF measurements can be performed (EIRP/EIS, beam measurements for R&D and production, EVM, ACLR, SEM, OBW, BLER etc.).

Definition of DUT Size

The DUT can range from being a radiating element to an entire device. In handsets the DUT size includes the mechanical size of the antenna plus the coupling to the radiating elements. 3GPP has identified three approaches for OTA measurement: "White Box", "Gray Box", and "Black Box" (see Figure 3).

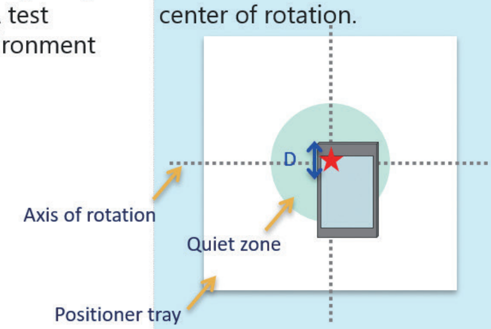
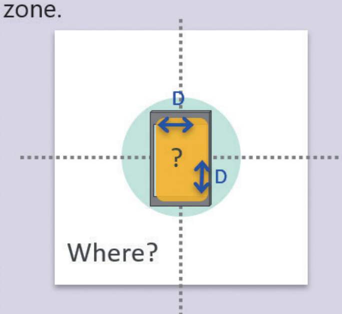
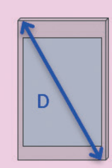
	White Box	Grey Box	Black Box
Antenna size	Known	Known	Unknown
Antenna position	Known	Unknown	Unknown
Setting image for OTA test environment	Put active antenna on the center of rotation.  ★ : activate antenna D : antenna size (= Actual antenna length)	Put active antenna in the Quiet zone.  : antenna allocated area D : antenna size (= Actual antenna length)	 D : antenna size (= UE diagonal length)

Figure 3. OTA Test Approaches specified by 3GPP: White Box, Black Box and Gray Box.

The white box approach is referred to when the exact location of the antenna under test is known. Chipset makers and OEM fit into this category. In this case, the antenna can be located exactly onto the centre of axis of rotation of the positioning system, and this ensures that the rotation is made exactly around this point. This is required to ensure that the distance to the antenna is maintained and measurement uncertainty from variations in this coupling distance are prevented. If a known fixed offset from the centre location is present, to ensure accurate measurements this can be mathematically compensated for during post-processing.

The black box approach assumes that the antenna location is unknown, and that measurement uncertainty must be maintained for any layout of antennas within the UE. For this to be valid the UE must be sufficiently far from the reference antenna, leading to a flat phase and amplitude patterns at the UE. This ensures that no phase or amplitude change occurs when the location of antenna is changed.

The grey box approach is a compromise between black and white. The antenna location is restricted within a certain zone. The exact antenna location is not known. A test house would fit into this category. For R&D testing, either white box or grey box approaches may be used, as the designer will know the locations of antennas for the device being tested. For certification test, which is often done in a third-party location, the black box approach is required as the device vendor may not wish to disclose publicly the exact location and operation of the antennas. For white box and grey box approaches the Tx beam phase and amplitude are not altered, therefore the angle of arrival characteristics are maintained. These approaches may be used for beam management tests.

Quiet Zone (QZ)

Each antenna, or antenna element, emits a multitude of spherical waves. As the waves are travelling away from the antenna, their energy locally decreases with the distance as it distributes over an increasing sphere. At a given point far enough away from the antenna, the emitted wave looks like a plane wave (within certain limits of flatness). This region is called Quiet Zone (QZ), a volume within the anechoic chamber with low electric-field fluctuation and where electromagnetic waves reflected and scattered from the walls are stated to below a certain specified minimum. QZ size is a function of chamber design. To increase the size of the quiet zone there are several options: moving further away from the antenna, manipulating the field distribution, using overlapping fields from multiple antennas. This is important for accuracy and repeatability, especially for the testing of RF parameters or when low amplitude and phase variations are needed. The wording "Quiet zone size" generally refers to a diameter. The quiet zone needs to be large enough to contain the key item being tested—whether that is an entire device, or just the antenna. The size of the device or antenna being tested determines the requirements for the size of the quiet zone. The larger the required quiet zone, the larger the chamber needs to be.

Let's consider the test of a 5G smartphone at 28 GHz (i.e. wavelength of ~1 cm), with an antenna aperture size of 3 cm and a diagonal size of 12 cm. If the location of the antenna within the mobile phone is known the White Box testing approach can be used. The diameter D of the smallest sphere that encloses the radiating parts of DUT coincides with the aperture size (i.e. 3 cm). The FF distance is 17 cm. At the same frequency, if the location of the antenna within the UE is unknown, the Black Box testing approach needs to be used. This means considering the mobile phone diagonal size of 12 cm as D, leading to a FF of 2.7 m. In other words, depending on the test frequency and the DUT size, the FF distance and therefore the chamber size can be anywhere from 20 cm to 3 m. The chamber size needed to test using direct far-field a DUT in FR2 (i.e. from 24 to 53 GHz), depends on the approach. If the White Box testing approach can be adopted, the chamber size can be <0.5 m. On the other hand, when a Black Box approach is needed, the chamber size to use the DFF method ranges from 3 m to 6 m, depending on the frequency.

Which OTA Test Methods Exist?

3GPP in TS 38.810 defines three permitted OTA UE test methods: Direct Far-Field (DFF), Indirect Far-Field (IFF) and Near-Field to Far-Field Transform (NFTF). Determining the best one for a particular application is determined by several factors, including the radiating DUT antenna size and configuration. 5G NR BS conformance OTA test methods are described and specified in 3GPP TS 37.941. Along with the three above mentioned methods specified also for UEs, BS can be tested also using a 1-dimensional compact range, a Plane Wave Synthesizer (PWS), any other suitable OTA chamber which shields the BS and test antenna from external interference and prevents reflections within the chamber from altering the coupling between the BS and the test antenna, or a Reverberation Chamber. The following paragraphs describe the existing 5G NR OTA test methods specified by 3GPP.

Direct Far-Field (DFF)

DFF consists in dimensioning the chamber so that the test antenna and the DUT are at a distance greater than $2D^2/\lambda$. This distance increases with the antenna size D and with frequency. Therefore, when D is large and/or the frequency is high, the DFF approach leads to unpractical and prohibitively expensive large chambers. Figure 4 shows the relationship between far-field distance and QZ size for DFF, at different frequencies. Very often the device is in its own casing during the test, therefore the exact DUT antenna size and/or location are unknown. The largest device size (i.e. diagonal = D) should be used in these cases, leading to very large chambers even for relatively small devices. In such cases, more practical ways to create far-field distance testing conditions exist. DFF undoubtably has some advantages: it allows creating a “real-world” DUT environment; it supports antenna beam pattern characterization, EIRP/TRP, EIS measurements, beamforming, and beam-steering validation (see Figure 5), RF parametric tests (if S/N is high enough); and can fit blocking sources. On the other hand, it can be very large and expensive (construction/installation) and suffer from high to very high path-loss.

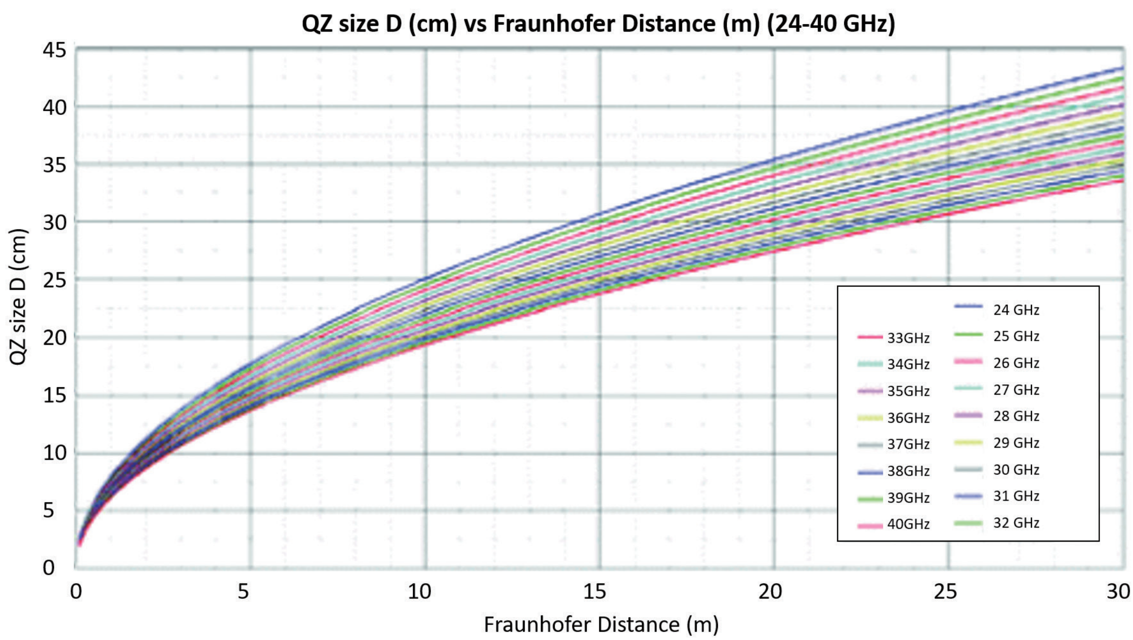


Figure 4. Relationship between far-field distance and QZ size for DFF method, at different frequencies.

DEF BEAM Management AoA

RF Chamber MA8171A

Test Use Case

- Handover
- AoA test
- Beam Switch

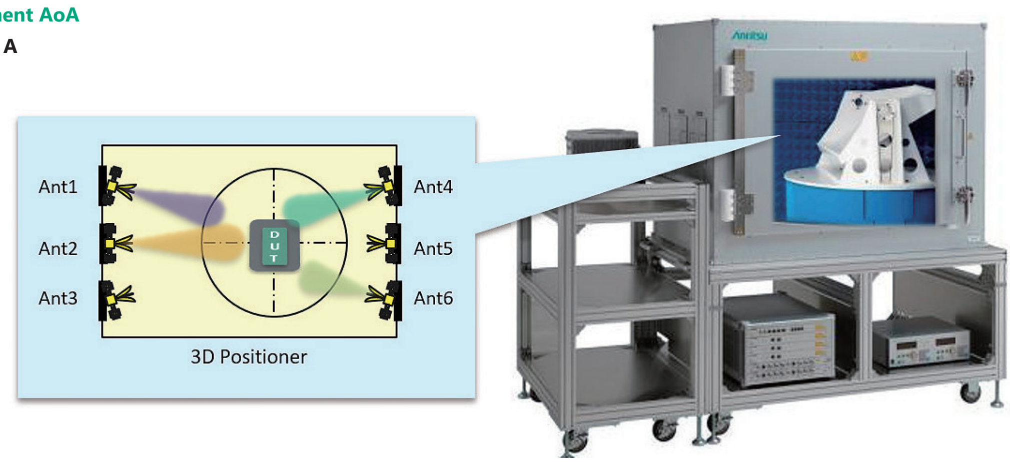


Figure 5. DFF RF Chamber for integrated RF/protocol tests, such as 5G NR mmWave beamforming management tests, etc.
For both 5G NR Standalone (SA) and Non-standalone (NSA) modes.
Ideal for development of 5G NR chipsets and devices as well as UE mmWave development.
It supports 5G NR mmWave RF ERP/TIRP measurements, etc.

Which OTA Test Methods Exist?

Indirect Far-Field (IFF)

IFF methods allow overcoming the big challenge of high path-loss present in DFF. They create far-field conditions within reduced chamber sizes and typically bigger QZ than in DFF. There are two methods for HW transformation: Compact Antenna Test Range (CATR) and Plane Wave Synthesizer (PWS). While offering a smaller footprint and lower path-losses than DFF, IFF methods still support at a reasonable speed of test RF parametric measurements to characterize beam-patterns and validate beam-steering, EIRP/TRP and EIS testing, and beamforming validation. The main drawback of IFF methods is that they are limited to measuring a single Angle of Arrival, AoA, so they can't support some RRM test cases, nor the beam management tests.

Compact Antenna Test Range (CATR)

CATR uses a parabolic reflector to transform a spherical wave into a planar wave distribution. To mitigate edge diffractions, which would contaminate the QZ by producing ripples and cross-polarization, the reflector is manufactured with serrations or rolled edges that scatter the energy away from the QZ. The size and shape of the serrated/rolled edges determines the lowest operating frequency limit (the serrations are ~ 5λ), whereas the surface roughness determines the upper frequency limit. The rolled edge design slightly bends the edges of the reflector backwards, which decreases the possible reflected energy at its edges. Reflectors with rolled edges are generally twice the QZ size, whereas a serrated reflector is 3-4 times the QZ size. CATR dimensions can be reduced to 10% of that of DFF chambers. The size of the QZ that can be created in a CATR system depends on the reflector size, on the focal length (i.e. distance between feed antenna and reflector), and on the Half Power Beam Width (HPBW) of feed antenna (i.e. how well the reflector is illuminated). The less the variation of the HPBW with frequency, the less will the QZ change at different frequencies. CATR systems typically use feedhorns specifically designed to work with the given design, to ensure that the QZ specifications are achieved. They can be dual-polarized or linear (single polarized), with a gain of ~10 dB and a wide beamwidth (45-60 deg) to ensure correct illumination of the CATR reflector.

A typical CATR setup is shown in Figure 6. It is a reciprocal system where a beam transmitted from the DUT in the QZ is focused back to the probe feed. In Tx measurements the DUT radiates a spherical wavefront to the range collimator, which focuses into the feed antenna only the propagation vector matching with the boresight direction of the reflector. In Rx measurements the feed antenna radiates a spherical wavefront to the range reflector, which is collimated towards the DUT. This transforms the spherical wavefront into a plane wavefront at the DUT. CATR has the same capabilities as a DFF system in terms of instantaneity and direct measurements of RF transceiver metrics in both Tx and Rx.

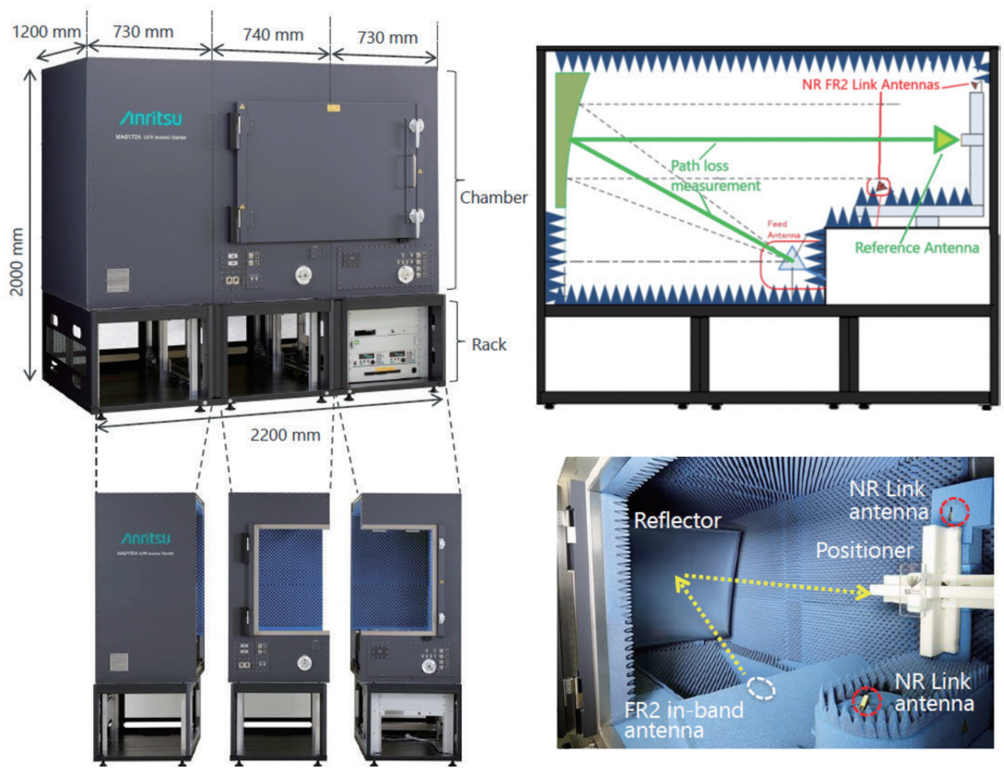


Figure 6. MA8172A CATR for FR2 5G NR OTA Testing of UEs.
The system is designed to minimize losses, improve SNR, reduce measurement uncertainty and increase test accuracy. It includes a spurious unit positioned next to the antennas (inside the CATR), RF converters for in-band measurements positioned next to the feed antenna, and LNAs for each band to minimize noise floor and maximize sensitivity.

CATR systems can be calibrated using a reference antenna with known gain values placed at the center of the QZ (top-right in Figure 6). If an antenna with moving phase center is used, a multi-segmented approach could be chosen for multiple frequency segments. The calibration process determines the composite loss (path-loss and polarization-loss) of the entire transmission and receiver chain path gains (measurement antenna, amplification) and losses (switches, combiners, cables, path loss, etc.). The calibration measurement is repeated for each measurement path (two orthogonal polarizations and each signal path).

By reducing path-losses, CATR offers an improved dynamic range compared to DFF. In CATR path-losses for both Tx and Rx measurements at a particular frequency are fixed and determined by the focal length (i.e. distance from parabolic reflector to probe feed). When transmitting from the QZ (Tx case – DUT transmitting) the spherical wavefront is imaged into the focal point by the lens/reflector. When transmitting from the focal point (Rx case – DUT receiving) the spherical wavefront from the feed becomes a "perfect" plane wave after the lens/reflector. In both cases the attenuation in the system is proportional to the free-space path-loss provided by the distance between the feed and lens/reflector. The attenuation is independent from the distance to the QZ.

PWS (Plane Wave Synthesizer)

This method is a natural extension of CATR. The reflector is replaced by an antenna array, or PWS, capable of approximating a plane wave within a specified quiet zone. It typically consists of two main components: an array of radiating elements and the feeding system. The architecture of the latter depends on the adopted technology; it could be fed by a standard Beam Forming Network (BFN) or by an active system. By tuning the phase and amplitude of the signals from the array, a QZ containing planar waves as a linear superposition of spherical radiation waves can be created within the near-field of the array. As in the case of CATRs, the PWS allows creating far-field testing conditions in a shorts distance than with DFF methods.

Near-Field to Far-Field Transform (NFTF)

The Near-Field to Far-Field Transform (NFTF) method samples the phase and amplitude of the electrical field in the near region and uses Fourier transform math to predict the far-field pattern. While being a compact, low-cost method, it is subject to transmitter interference that impacts measurement accuracy. It is also limited to single line-of-sight measurements. NFTF is a 3GPP permitted test method for EIRP, TRP, and spurious emissions metrics of 5G FR2 UEs. Most of the OTA parameters of interest depend on quality of the signal in the main beam of the array, rather than over the entire pattern. To predict the pattern in the main beam, NFTF must measure a large portion of it at a very high resolution to meet the Nyquist requirements based on maximum radial extent (MRE). Therefore, the larger the device the more data must be measured to predict the peak EIRP value needed for the center of the main lobe of the pattern. The required test time, considering the different tests needed and the sheer volume of wireless devices to be evaluated, may easily be longer than a typical product design cycle. Even when the test time could be accepted, e.g. in device qualification testing, it would still be not viable for applications such as production line testing that need to evaluate these metrics quickly. Another obstacle to the adoption of NFTF is finding a way to characterize active modulated performance metrics. To date, no successful active NFTF tests on an unmodified wireless receiver (requiring access to phase information only available inside the radio) have been reported. A big question mark is how modulation error quantities like EVM propagate through the NFTF equations. Considering 1 GHz of channel bandwidth subdivided into subcarriers every 15 kHz, the frequency resolution to be acquired and transformed becomes prohibitively demanding. Symbol data and error contributions are instantaneous and pseudo-random; therefore, a swept angular measurement of the near-field data would not give the correct result. For Tx mode tests, techniques performing phase-retrieval have been introduced, addressing the case of a DUT transmitting a modulated signal with no access to the antenna feed port. These include interferometric techniques, multi-port phase coherent receivers and time-domain scanning. TRP and Peak EIRP can be directly measured in radiated near-field (without far-field transformation), but the measurement uncertainties are higher than in far-field. The reciprocity assumption does not apply to highly integrated 5G mm-Wave UEs, in which the Rx RF chain is typically different from the Tx RF chain. Therefore, no NFTF solution for Rx mode allowing fast and reliable EIS-type evaluation exists to date. In FR2, the number of required sampling grid points is large, making the Fourier transform in NFTF time-consuming and complex. In summary, NFTF is suitable for standard 3D antenna pattern measurement, antenna and transceiver calibrations and antenna diagnostics based on equivalent current technique in R&D and mass production phases. Per TR 38.810, the NFTF test method is only applicable for DUTs with radiating apertures of D ≤ 5 cm. Requires high accuracy positioners for mmW.

DFF vs. IFF

Depending on DUT size and weight, positioner requirements, QZ size and shielding, different measurement solutions should be adopted. The main benefits of IFF versus DFF are the shorter test distance as well as lower path-losses. The large free-space path-loss in OTA measurements is a key challenge, especially when transitioning to mm-wave tests. In DFF the chamber size is simply determined by the far-field distance achievable with the given antenna. A 150 mm diameter array at 28 GHz has far-field distance of 4.2 m and chamber length of at least 5.5 m. With a far-field distance of 4.2 m at 28 GHz the free-pace path-loss is 74 dB. In IFF the size is determined by the required QZ. A 150 mm diameter array at 28 GHz leads to a chamber length of approximately 2 m. For both Tx and Rx measurements, at a particular frequency CATR path-losses are fixed and determined by the focal length. A CATR designed with a 30 cm QZ (i.e. twice as large as needed for this DUT). The reflector for this CATR is 50 cm × 50 cm. The focal length is 76 cm, determining a free-space path-loss of 59 dB. In other words, DUTs whose dimensions dictate different far-field distances can be measured in a CATR with fixed dimensions and fixed path loss.

The cross-polarization isolation is typically higher in DFF systems; for IFF systems is ~30 dB (curved reflector generates cross-polar component). For antenna pattern measurements, DFF provide an accuracy of side lobes and nulls that is better at larger DUT/probe antenna distances. IFF-based antenna pattern measurements are equivalent to those measured in direct far-field and the measurement accuracy of nulls and side lobes depends on QZ flatness. The requirements on the DUT position relative to probe antenna beam are also a bit different. In DFF the center of radiation and/or geometric center of DUT antenna array must be at center of QZ. In IFF all DUT antenna arrays must be contained within the QZ. Finally, the cost scales with chamber size for DFF chambers, whereas in IFF the cost of precision reflector easily is offset by a smaller chamber.

Choosing the Right OTA Method

A typical 5G mm-wave UE development process includes several stages: research & development (R&D), integration & verification, mass production and certification. Evaluation and qualification are required through the whole process and test requirements vary across different stages. Therefore, no single OTA test method can be ascertained as the final solution towards comprehensively characterizing 5G FR2 devices. Engineers could choose the optimal OTA method based on various factors, including test interface, metrics and test requirements of different phases, cost of the test setup involved and trade-off between measurement uncertainties and test time. Figure 7 shows an overview of OTA chamber solutions to satisfy the variety of test needs for different DUT size and weight, QZ dimension requirements, and need for spherical or non-spherical testing. Table 2 shows a high-level summary (some RRM testing requires 2 AoA, so DFF is required, or multi-IFF probes) of fidelity and applicability of 5G OTA test environments.

Model	MA8161A	MA8171A	MA8172A
Type	Shield Box	Anechoic Chamber	CATR Anechoic Chamber
Figure	 		
Solution	Protocol Test - IP/PHY Throughput - Functional test	RF Test · Protocol Test - R&D (White box) Protocol Test - PCT · CAT Beam management - R&D & PCT/CAT	RF Test - R&D (Black box) - RF CT - TRX/Performance
Support Product	MT8000A (RTD/SmartStudio)/ME7834NR	MT8000A/ME7834NR	MT8000A/ME7834NR
Antenna Type	Spiral Antenna (Max. 2×2 × 4 antennas)	Multi Antenna (Max. 4 antennas)	Reflector Antenna (CATR)
Meas. Condition	White Box (Gray Box)	White Box (Gray Box)	Black Box
	Radiative NFM	Direct FFM for Protocl & RF Test	Indirect FFM
Measurable DUT Size	300 (W) × 15 (H) × 200 (D) mm or less	(Diagonal) 300 mm or less	(Diagonal) 330 mm or less
Outer Size	0.44 (W) × 0.27 (H) × 0.33 (D) m	2.08 (W) × 1.79 (H) × 1.00 (D) m (with rack)	2.20 (W) × 2.00 (H) × 1.20 (D) m (with rack)

Figure 7. Overview of OTA chamber solutions to satisfy the variety of test needs for different DUT size and weight, QZ dimension requirements, and need for spherical or non-spherical testing.

Table 2. High-level summary (some RRM testing requires 2 AoA, so DFF is required, or multi-IFF probes) of fidelity and applicability of 5G OTA test environments.

	AUT Size	DFF	IFF	NFTF
RF Testing	Small UEs			**Tx only**
	Large UEs			**Tx only**
	gNBs			**Tx only**
Demod Testing	Small UEs			
	Large UEs			
	gNBs			
RRM Testing	Small UEs			
	Large UEs			
	gNBs			

Conclusion

OTA measurement is mandatory to evaluate the performance of for 5G mm-Wave devices. It poses numerous challenges in achieving the desired measurement accuracy for the validation and conformance processes. This white paper presented an overview of the main challenges, solutions, and best practices in OTA testing. Applicability and critical aspects of different OTA methods have been outlined and discussed. No single OTA method can be ascertained as the unique solution towards characterizing 5G mm-Wave devices comprehensively. The optimal choice is based on trade-offs between different performance metrics to be evaluated, measurement accuracy, cost-effectiveness, complexity of different test environments, repeatability in a controlled environment, etc. Choosing the best test solution helps to speed time to market, lower cost-of-test and gives a competitive advantage in the new frontier of wireless. Partnering with a test manufacturer with experience in each element of the OTA environment will help meet RF, demodulation, and functional test requirements. Unnecessary rework, which can lead to delayed time-to-market and additional design costs, will be avoided as a result.

Advancing beyond

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