Waveguide Antenna Considerations When Testing 5G New Radio User Equipment

White Paper

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The realization of 5G involves the integration of new radio access technologies (RATs) in a singular radio network architecture for seamless connectivity regardless of the location, traffic load, and mobility of the user. In order to accomplish this, higher frequency and millimeter-wave blocks spectrum have been incorporated into the 5G infrastructure for a greater amount of harmonized spectrum. At the World Radiocommunication Conference (WRC) meet in 2019 (WRC-19), the 26 GHz, 28 GHz, 40 GHz, 50 GHz, and 66 GHz spectrum bands were approved officially including millimeter-wave bands primarily for ultra-high speed and ultra-low latency communications.

Waveguide antennas have been a cornerstone component for compliance and reliability testing of 5G devices and components at frequencies beyond 1 GHz. This is particularly true for standardized EMC testing with over-the-air (OTA) testing techniques where the types of test antennas are very well defined. Next generation 5G wireless networks can be divided into low-band (sub-GHz), mid-band (1 GHz to 6 GHz or sub-6 Ghz), and high-band (24 GHz and up) networks. This whitepaper is intended to grant the reader insight into critical conformance and compliance testing for 5G devices and how waveguide antennas are leveraged to test mid-band and high-band 5G systems.

Why Waveguides?

For the vast majority of RF applications, coaxial and planar transmission lines such as microstrips and coplanar waveguides (CPWs) are primarily used. Waveguides, however, are typically employed for highly specific use cases that require high power and/or millimeter-wave signal propagation. And, when compared to other media for high frequency signal propagation, waveguides have much more legacy with roots back in the early 1930s. While waveguide technology is not considered the “cutting-edge” of the RF and microwave field, historically it proved itself irreplaceable in high-power radar for electronic warfare (EW) systems, high throughput point-to-point links, satellite communications (SATCOM), and various test/prototyping systems. As of recently, 5G has grown as a new contender occupying the millimeter-wave spectrum. A spectrum that was previously sparse with tiny bits occupied by highly specific test/measurement and radar applications.

This relatively new use case has provided a surge of growth for the waveguide market. According to Markets and Markets, the global millimeter-wave technology market is expected to more than triple in a five year time span from 2020 to 2025[1]. This massive increase in market share is due to the new infusion of mobile and telecom that is forecasted to take up the bulk of the millimeter-wave market that was previously dominated by radar and satellite communications. This has caused a natural increase in demand in waveguide -- components that were previously overlooked for their high cost to manufacture and structural bulkiness when compared to other transmission lines.

Waveguides Benefits

The waveguide’s salient features are as follows:

- Its ability to withstand high powers with pulse powers on the order of kilowatts and hundreds of watts continuous wave (CW)
- Very low loss within its specified bandwidth

From a strict thermal management perspective, the large surface area of the thick metallic walls allow for rapid heat dissipation. This is due to the combination of the high thermal conductivity of the metallic material and the thickness of the waveguide walls -- thicker metallic structures can hold more heat energy. This way, the waveguide can rapidly dissipate excess heat generated from high power signals through thermal radiation and in some cases, convective forced-air or liquid cooling.

Outside of this distinct advantage, waveguides have dominated applications at the Ka-band well into the sub-millimeter-wave spectrum, up to 325 GHz due its inherently low loss. Losses fall well below 2 dB/m up to the V-band and an excellent VSWR can be achieved within its bandwidth when compared to its frequently employed broadband coaxial cable counterpart. Intrinsic losses for a waveguide are mainly from the drop in conductivity of the plating materials at RF and millimeter-wave frequencies and the materials magnetic permeability. More often than not, there is an air-dielectric within the waveguide which leads to a loss tangent that is nearly zero and is therefore negligible. This loss in conductivity, however, can be found in any transmission line where at high frequencies the skin effect dominates losses. The skin effect is the tendency for the electrons flowing within a metallic material to group near the surface with the signal occupying less and less of the bulk material. It is a major consideration for waveguides and is often dealt with by plating the inner surface with a conformal coat of gold -- a material with a high skin depth relative to other metallic materials (e.g., copper and ferromagnetic conductors) for less loss at high frequencies. Coaxial cables, however, must consider losses due to the metallic inner and outer conductors as well as the dielectric materials. Because of this, losses are orders of magnitude larger than waveguide components at high frequencies. Moreover, phase changes will occur due to changes in the electrical length of the coax under flexure causing additional considerations for flexible millimeter-wave coaxial assemblies.

Understanding Some of the Major 5G Test Parameters

Testing within anechoic and reverberation chambers is cornerstone to assessing the various aspects of 5G systems. These systems can vary between handsets, tablets, wearables, fixed wireless access (FWA) terminals, all the way to full vehicles. Measurements of these 5G systems and devices can include antenna characterization, RFI/EMI testing for radiated and conducted emissions, effective isotropic radiated power (EIRP), total radiated power (TRP), effective isotropic sensitivity (EIS), error vector magnitude (EVM), blocking and high intensity radiated field (HIRF) testing. ***Table 1*** lists out some of the basic critical parameters that are required for the testing of 5G systems.

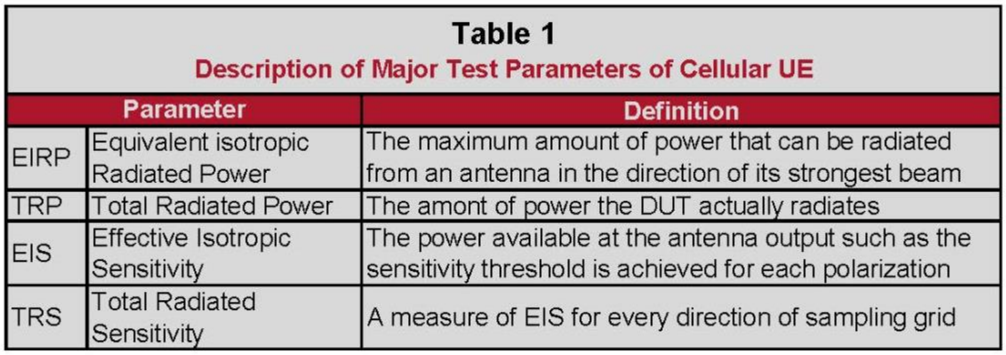


Table 1

Description of Major Test Parameters of Cellular UE

Parameter		Definition
EIRP	Equivalent isotropic Radiated Power	The maximum amount of power that can be radiated from an antenna in the direction of its strongest beam
TRP	Total Radiated Power	The amont of power the DUT actually radiates
EIS	Effective Isotropic Sensitivity	The power available at the antenna output such as the sensitivity threshold is achieved for each polarization
TRS	Total Radiated Sensitivity	A measure of EIS for every direction of sampling grid

Why are waveguide antennas used for testing 5G systems?

It's critical to note that standard gain horns (SGH) antennas are often the go-to aperture test antenna for measuring many of these parameters. Aperture antennas can vary in structure between pyramidal, conical, horn, and probe. Diverging from common “reflector” antennas such as the parabolic dish or corner antennas that merely reflect EM energy in a desired direction, aperture antennas provide gradual transitions from a radio and transmission line to free space by impedance matching between the waveguide portion and the aperture. For instance, a pyramidal horn antenna (or SGH) acts as a guiding system from waveguide mode, to free space. These highly directional antennas offer an excellent balance between directionality, gain, beamwidth, and bandwidth for OTA testing. This is especially relevant in millimeter-wave testing where the choices of directional, linearly polarized antennas grow slim. Most importantly, the fact that the electromagnetic energy in the far-field shifts from spherical wavefront to a planar. This offers a level of predictability when testing -- it ensures that the waves arriving at the device under test (DUT) or test antenna (e.g., SGH) are planar and the resulting beam patterns are correct. This is readily seen in EMC testing where biconical and log-periodic antennas are really only sufficient up until 1 GHz. Beyond that a waveguide aperture antenna is employed.

It is possible that the largest downside of this type of test stems from that critical factor of testing in the far-field. Anechoic chambers are bulky and expensive items, testing in the far field at some mid-band frequencies can even make testing in large chambers unrealizable. In these cases the indirect far-field (IFF) or compact test range (CATR) approach becomes more feasible. Discussing in a later section in this article, this test method leverages both an SGH and a parabolic dish reflector to mimic a far-field environment. Whether or not conformance, characterization, and compliance testing is performed mid-band or high-band, a waveguide aperture antenna, most often an SGH, is required for testing.

Defining power and sensitivity measurements

Effective isotropic radiated power (EIRP), total radiated power (TRP), effective isotropic sensitivity (EIS) and total radiated sensitivity (TRS) are all critical parameters for understanding the actual transmit power and sensitivity threshold of a 5G device. The FCC places many power and emission limits on 5G transmitter systems in order to mitigate interference in. highly congested bands. Understanding these parameters can offer insight into the importance of testing them properly.

Equivalent radiated power (ERP) describes the maximum amount of power that can be radiated from an antenna in the direction of the antennas strongest beam, or main lobe, with gain, transmitter power, and cable losses considered. Effective isotropic radiated power (EIRP) takes this value and multiplies it by the gain of an isotropic antenna such as a half-wave dipole antenna. This in turn, shifts the definition of EIRP to the amount of power an ideal isotropic antenna would need to radiate in order to achieve this measured value.

The total radiated power (TRP) is a measurement of the amount of power the antenna actually radiates when non-idealities such as antenna mismatch and losses are taken into account. Mathematically, the TRP is defined as the integral of the power transmitted in different directions over the entire radiation sphere and can be gained mathematically from an EIRP measurement.

The effective isotropic sensitivity (EIS) is the power available at the antenna output or the measured sensitivity in a single direction. In a transmit diversity transmission mode, two orthogonal signals are simultaneously transmitted to the two polarizations of the dual-polarized test antenna. In this case, the EIS would be the sensitivity threshold that is achieved for each antenna polarization[2]. The total radiated sensitivity (TRS) is the measure of EIS for every direction of a sampling grid, which ultimately yields the spherical sensitivity pattern of the device under test (DUT).

Test Methods for EIRP, TRP, EIS, TRS

Practically speaking, EIRP, TRP, EIS, and TRS are spherical or 3D measurements. The nature of these measurements vary slightly depending on the 5G test measurement technique (OTA, DFF, or IFF), sampling grid (beam peak, spherical, or TRP grids) and environment (anechoic or reverberation chamber). For each sampling grid for instance, there are a minimum number of test/grid points and a corresponding angular step size in degrees in order to achieve a specific systematic error in decibels (for beam peak measurements) or mean error (for spherical coverage measurements). In all these test methods, a link antenna is used to provide the DUT with a stable cellular signal link without precise path loss or polarization control. This cellular signal can either be an LTE link or a NR carrier aggregation (CA) mode signal with an FR1 (frequency range 4.1 GHz to 7.125 GHz) or an inter-band NR CA mode signal with an FR2 (frequency range 24.25 GHz to 52.6 GHz).

In the peak EIRP measurement procedure, the measurement antenna is rotated around the DUT and the DUT itself is rotated as well to form a specific angle (Ω) between the measurement antennas and DUT. The mean power of the modulated signal arriving at the measurement equipment is ascertained at two orthogonal linear polarizations (θ- and φ-polarizations). The EIRP is extrapolated from this information by adding the composite losses of the entire transmission path. From the EIRP measurement, the total radiated power (TRP) can be gained by measuring EIRP for every direction of a selected sampling grid. The peak EIS measurement procedure follows a similar test process.

The total isotropic sensitivity (TIS) is the average sensitivity of a receiver-antenna system over a three dimensional sphere (***Figure 1***). To practically determine the TIS, the DUT is placed in an anechoic chamber and the horn antenna transmits at the DUT. The power is reduced until the block error rate (BLER) reaches a certain threshold and that provides effective isotropic sensitivity (EIS) at a single angle. The TRS can practically be gained by measuring EIS for every direction of a selected sampling grid using two orthogonal polarizations.

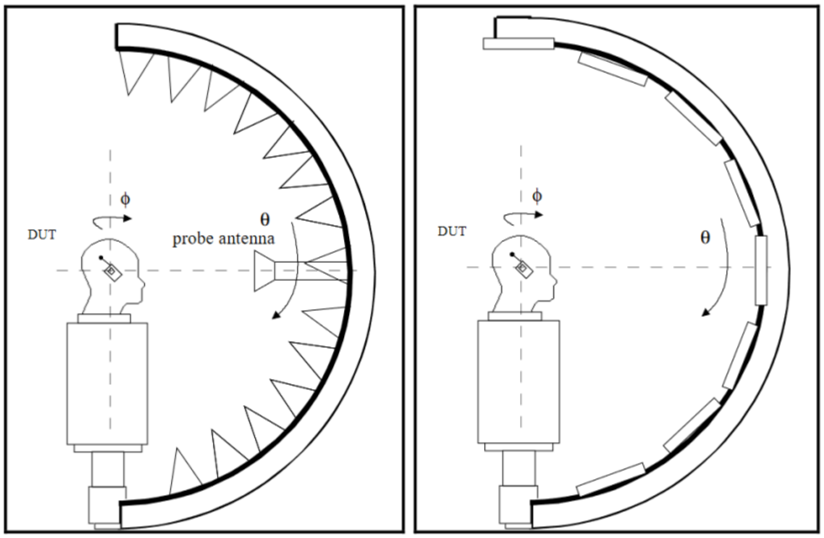


Figure 1: Sample set up with spherical position system and moving probe antenna14.
Source: ETSI]

Defining Conducted and Radiated Emissions

Spurious emissions are inherent to any switching device within a circuit however, minimizing the strength of these emissions is critical in ensuring electromagnetic compliance (EMC). Radiated emissions testing involves obtaining the electromagnetic field strength of the unintentionally generated emissions from a device. Conducted emissions is defined by the amount of emissions that can couple back onto the power supply. These tests are typically performed on devices that connect to an AC power supply.

Test Methods for EMC

The standard gain horn (SGH) and its variants are the standard for measurements beyond 1 GHz for the major EMC emissions testing standards including: ANSI C63.4, MIL-STD-461, EN 55022/55011 and CISPR 16. There are currently no 3GPP standards covering EMC test requirements for 5G UEs. As shown in ***Figure 2***, test arrangements for conducted and radiated emissions are set up with equipment on a nonconductive turntable/test bench set a prespecified height above the ground that is composed of a conducting ground plane. The equipment under test (EUT) placed on the turntable is set at a predetermined distance from the antenna. Both the antenna and EUT are rotated on a mechanical mast and turntable respectively while observing the emissions. For instance, in final radiated emissions measurements in ANSI 63.4-2014 for the 9 kHz to 1 GHz frequencies, the EUT is rotated 360o where the antenna height is scanned between 1 m and 4 m, and rotated by 90o relative to the ground plane to accomplish measurements for horizontal and vertical polarizations[3]. All of this occurs within an open-area test site (OATS), or a test cell/screened with an anechoic chamber or a reverberating chamber.

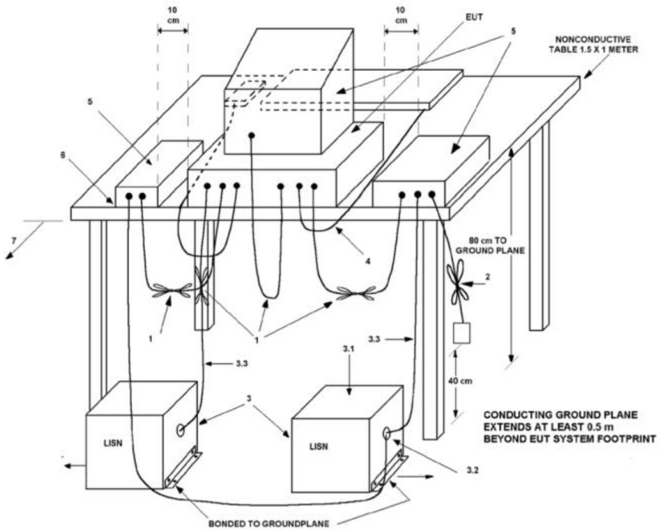


Figure 2: Sample conducted emissions test setup from ANSI C63.4-2014[3].
Source: ANSI

Defining SAR and Power Density

RF exposure parameters vary from low to high frequencies. At DC to low, sub-GHz frequencies, RF exposure is based upon contact current in order to avoid shock or burns. In the mid-band, this parameter shifts to specific absorption rate (SAR), or the rate of energy absorbed by the body due to exposure to an RF transmitting source. In FCC 2.1093, these limits for the general population are 0.08 W/kg averaged over the whole body, with a peak SAR below 1.6 W/kg over any 1 gram of tissue. However, in the bands above 10 GHz, power density is the parameter often leveraged to describe RF exposure from portable devices. Absorbed power becomes less of a concern at higher frequencies since the penetration depth decreases rapidly to the point where only localized surface exposure is a concern. For devices below 10 GHz, it was assumed that most equipment would operate at a frequency beyond 1.4 GHz, therefore having a penetration depth in body tissues below 30 mm. In this case, power density is the amount of localized power the body is exposed to and is measured in W/m2. The FCC has not yet defined the limits for this metric at higher frequencies, however a proposal is underway with the unapproved limit of 40 W/m2 averaged over 1 cm^2[4].

Test Methods for RF Exposure

SAR testing leverages standard models of the human head and body for testing. These specific anthropomorphic mannequins (SAMs) are made of low-loss material and are filled with a liquid that has the same permittivity as human tissue. The 5G portable device is then tested at its highest power level in all frequency bands in various positions on the dummy's head and body that mimic common ways cell phones are held. Similar to tests for radiated power and sensitivity, measurements are taken via a robotic probe antenna (standard gain horn) with pre-defined sampling grids in order to obtain the peak SAR or power density value.

Waveguides Antenna Considerations in 5G Testing

How 5G NR DFF, and IFF measurement techniques impact choice and arrangement of test antennas

Measurement methods diverge slightly from traditional OTA test methods with the direct far-field (DFF) and indirect far-field (IFF) measurement techniques (Figure 3). The DFF technique is similar to the OTA measurements in that they are all taken in the far-field. In other words, the range length in the DFF technique is beyond the far-field Rayleigh distance (Equation 1). The near-field phase front of the aperture antenna is assumed to be spherical and the far-field radiation pattern is planar. The far-field test is intended to place the test antenna at a far enough distance from the DUT so that the phase front across the electrical aperture of the test antenna is near-planar. This effectively moves the test antenna position further away from the DUT.

$$R = \frac{2D^2}{\lambda}$$

Tests are specified to be taken within an anechoic chamber. The angle between both the device under test (DUT) and the test horn measurement antenna as well as the angle between the DUT and link antenna have at least two axes of freedom. In other words, at least the link and measurement antennas must be able to move with respect to the DUT on positioning systems. Various commercial 5G measurement systems leverage multi-axis positioners (MAPS) that can not only adjust the angle between the DUT and the test horn antenna, but also customize the range length between them.

The IFF test method, also known as compact antenna test range (CATR), uses a parabolic reflector and feed horn to create a field-field environment. The parabolic reflector is intended to collimate the spherical near-field wavefront emanating from the DUT into the feed antenna/receiver as a near-planar phase front. This also occurs in the reverse scenario, where the desirable far-field radiation pattern is simulated by coupling a plane-wave into the aperture of an antenna under test (AUT) via a parabolic reflector and horn feed antenna.

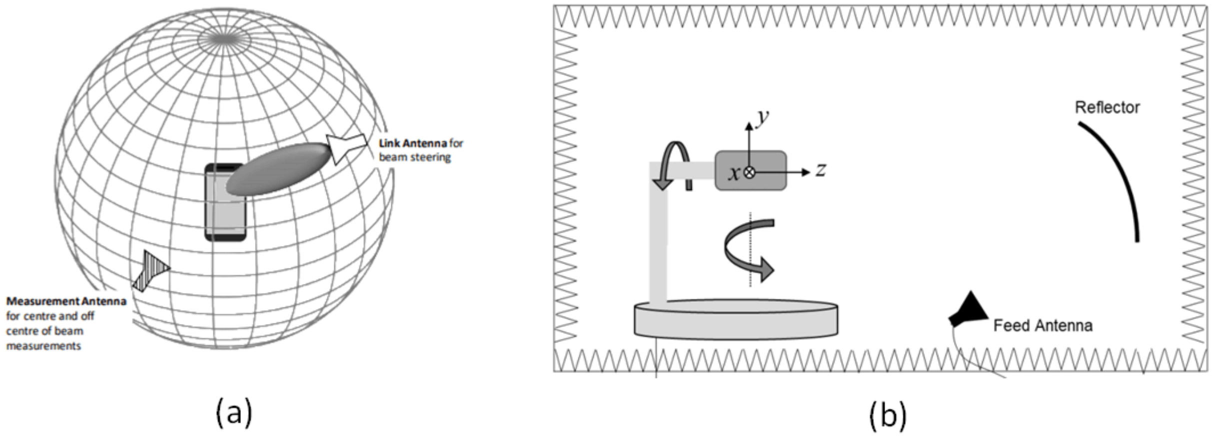


Figure 3: Measurement techniques for 5G NR involve either a (a)direct field-field (DFF) setup or, (b) the indirect far-field (IFF) method[2].

Source: 3GPP

Practical horn antenna considerations for power and sensitivity measurements

In all these tests, waveguide horn antennas remain a cornerstone component to the setup as they are often employed as the test antenna. For this reason, it is critical to accurately assess the near-field/far-field boundary in order to ensure the DFF test operates within the far field region. In the case of an IFF test, understanding the spherical wavefronts emanating from the aperture offer insights into the near-field radiation pattern.

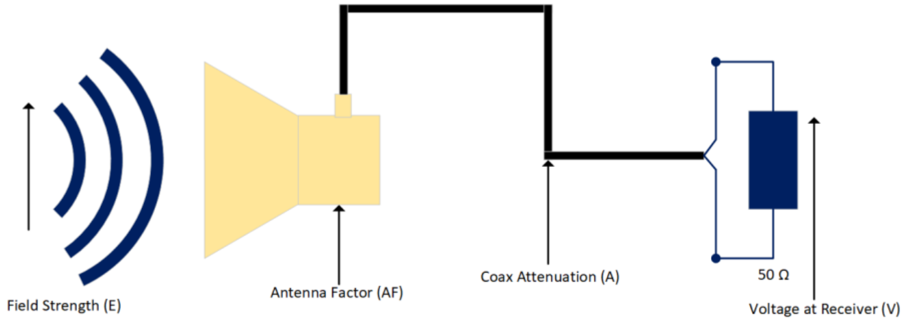
Leveraging the manufacturer's specifications on testing distance can add uncertainty to the measurements given that distance recommended is shorter than the actual far-field distance -- potentially leading to the passing of an underperforming UE. Another potential test inaccuracy related to measurement distance is caused by the changes in the phase center of the horn antenna with frequency. The calibration process determines the critical parameter of the composite loss (Lpath,pol) of the transmitter/receiver chains including the antenna, antenna feed, switches, combiners, amplifiers and so on. For this reason, there is an uncertainty term to estimate the testing inaccuracy caused by the misalignment of the phase center of the calibration (horn) antenna with the setup shown in Equation 2.

$$\pm 20log_{10}(\frac{d_m - d_p}{d_m})$$

Where dm is the measurement distance and dp is the maximum positional uncertainty. This goes into an uncertainty budget to assess test accuracy. In some studies, the actual near-field/far-field boundary of the horn antenna is obtained experimentally by measuring the antenna's path loss gradient -- path loss components are different in the near-field and far-field.

Practical antenna considerations for EMC measurements

From an EMI testing perspective there is a balance between the beamwidth of the main lobe and its gain. The more gain, the better the system noise performance. The broader the beamwidth, the more energy the antenna can collect over an area in one sweep. The most critical antenna parameter in EMC is the antenna factor (AF) which practically translates the effects the gain and beamwidth antenna specifications have on a test setup. The AF is a correction factor that is the ratio between the incident E-field at the antenna to the voltage received at its output (e.g., coaxial connector, waveguide interface, etc). This, in turn, gives the test engineer a more accurate assessment of the E-field levels emitted by the EUT based on the voltage readings seen at the receiver. The expression seen in ***Figure 4*** illuminates the basic relationship between the incident E-field strength emitted by an EUT and the voltage seen at the receiver with the influence of the test antenna as well as the antenna feed taken into the consideration.



$$E(dB\mu/m) = AF(dB/m) + A(dB) + V(dB\mu V)$$

Figure 4: Basic relationship between incident field strength and voltage seen at the receiver.

The power density decreases rapidly with distance where the power density patterns vary for both the near-field and far-field antenna radiation patterns. It is for this reason that horn antennas intended for EMC testing often have their gains and antenna factors defined at varying distances from the EUT specified in the datasheet (***Figure 5***).

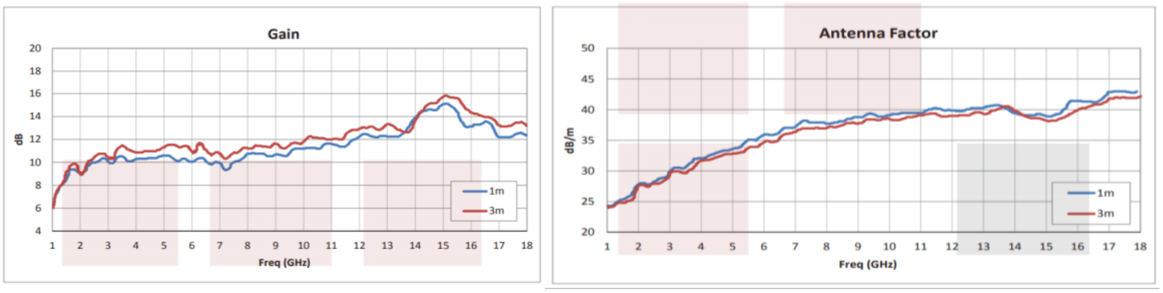


Figure 5: Sample datasheet gain and AF of DRGH antenna at varying** ranges**.

For an aperture antenna such as the double ridge guide horn (DRGH) or a horn antenna, the direct far-field technique (DFF) is used, the range length is specified to be small enough so that the measurement distance is greater than (or equal to) the Rayleigh distance (D2/2λ)[5]. This is due to the fact that under near-field conditions, measurement results may underestimate the actual emission levels by an unpredictable amount which presents an unacceptable risk of interference.

Considerations for RF exposure measurements

The same far-field equations can be applied to RF exposure measurements with SAR and power density. According to the FCC,” power density for instance is most appropriately used when the point of measurement is far enough away from an antenna to be located in the far-field zone of the antenna”.

However, this potentially leads to errors as the effective gain of the antenna is lower in the near-field than in the far-field. This means that calculations based upon this far-field gain value will also be larger than the actual SAR or power density. While this may be suitable for regulatory bodies, it potentially further constrains device manufacturers.

General waveguide antenna considerations for millimeter-wave tests

For 5G testing, aperture antennas such as horn antennas offer reliable performance and predictable directional radiation patterns causing them to be the go-to measurement antenna for many test setups. There are, however, serious considerations when selecting waveguides components. These issues only become more pronounced at higher, millimeter-wave frequencies.

Since the loss in conductivity due to skin effect becomes so pronounced at high frequencies, the quality of the coating on the internal wall of the waveguide structure becomes more critical. Moreover, waveguide tolerances become extremely small at millimeter-wave frequencies causing machining tolerances and soldering quality to be tight with strict quality control. Unlike the torsionally mated coaxial connectors, waveguide flanges are axially mated with bolts to secure an air-tight mate. Misalignment when connecting waveguide flanges is a real concern where xy and rotational displacement between the waveguide flange holes and the specified locations for the waveguide size/flange type leads to discernible losses[6]. For this reason, it is critical to leverage waveguides that undergo strict quality assurance (e.g., visual inspection, testing, etc) with the employment of the correct guide/dowel pins to ensure a precision alignment.

Conclusion

The analysis of 5G user equipment and systems requires the use of a high integrity test setup with a reliably noise-free environment, accurate calibration, and a precise measurement process to ensure accurate results. This fundamentally relies upon the test site, test equipment, connected cabling, and finally -- the location and quality of the measurement antenna. Standard gain horns are often a critical building block to 5G OTA testing, no matter what the test setup. This is especially true at millimeter-wave frequencies where most other antenna structures grow too small to provide enough gain. Waveguides have the inherent benefit of carrying higher powers and therefore carrying and transmitting more EM energy in a predictable, desirable method. This is critical for the increasingly tight testing and parameter tolerances for 5G devices. The increase in congestion in all relevant bands have created increasingly more stringent testing and acceptable error requirements around radiated power and emissions. The general concern around RF exposure, particularly at high frequencies, has caused tests around RF exposure to become more critical. With all of this, the reliance on quality passive antenna structures for testing is all the more important.

References

1. https://www.marketsandmarkets.com/Market-Reports/millimeter-wave-technology-market-981.html
2. 3GPP TR 38.810 V16.6.1 (2020-09)
3. "American National Standard for Methods of Measurement of Radio-Noise Emissions from Low-Voltage Electrical and Electronic Equipment in the Range of 9 kHz to 40 GHz," in ANSI C63.4-2014 (Revision of ANSI C63.4-2009) , vol., no., pp.1-170, 20 June 2014, doi: 10.1109/IEEESTD.2014.6840852.
4. https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=9019743
5. “American National Standard for Electromagnetic Compatibility–Radiated Emission Measurements in Electromagnetic Interference (EMI) Control–Calibration and Qualification of Antennas (9 kHz to 40 GHz),” ANSI C63.5-2017 (Revision of ANSI C63.5-2005), May 2017, pp.1–114.
6. https://www.microwavejournal.com/articles/print/26932-rf-waveguide-tips-and-facts-you-cant-learn-in-school