

# Demystifying over-the-air (OTA) testing

– important antenna  
parameters, test system  
setup and calibration

White paper

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# 1 Introduction to over-the-air measurements

Heinrich Hertz built the first antenna in 1887, and 10 years later, Marconi began experimenting with wireless communications. By the beginning of the 20th century, Marconi successfully transmitted the first transatlantic radio message. Finally, the first broadcast tower went live in the 1920s, nearly 100 years ago [1]. Huge developments followed in the field of wireless communications, antenna design and testing, and EMC testing. With such a long history behind wireless communications and antenna and EMC testing, why is over-the-air (OTA) testing the focus of this paper?

Today, given the increasing integration of chipsets and antennas as well as usage of higher frequencies, the lines between testing chipsets, RF testing and antenna characterization have become blurred. In upcoming mm-wave architectures (involving signals with wavelengths in the general millimeter region), there will be no connector between RF components like chipsets, a power amplifier (PA) and the attached antennas. Therefore, the chipset cannot be tested without the antenna and vice versa. Both analog and digital improvements are leading to the use of multiple radio frequency (RF) frontends, massive antenna arrays even in consumer grade hardware, and a combination of beamforming and multiple-input multiple-output (MIMO) technology known as massive MIMO, enhancing multi-user MIMO (MU-MIMO) and supporting high user capacities in the 5G New Radio (NR) standard.

Whether in low-cost devices targeting the IoT market, highly integrated radio frontends for satellite communications links, or mm-wave devices, integrated antennas are becoming more common with each development cycle. Therefore, OTA testing is becoming more important (or even mandatory) for a broader audience. The step from conducted measurements to OTA testing changes the measurement requirements to a certain degree. New user groups are thus required to have a basic understanding of antennas and antenna measurements.

This paper will provide an introduction to antennas in general, their parameters and different types, as well as antenna characterization and testing in Chapter 2. For more in-depth examination of antenna theory and design, suggested literature is referenced at the end of this paper.

Chapter 3 will focus on the importance and execution of OTA test setup calibration. The general concepts are valid for any OTA setup, e.g. in-chamber or lab-desk. Afterwards, calibration verification is discussed.

The last chapter will briefly discuss array antenna calibration methodologies.

## 2 Introduction to antenna characterization

Arguably, one of the most basic OTA measurements is antenna characterization. Even when not planning to perform antenna characterization, a basic knowledge of antenna parameters will help to grasp other OTA related topics. The following chapters aim to provide an introduction to antenna characterization and measurement.

If the basic antenna parameters are already known and active components are to be measured in combination with an antenna, be sure to read Chapter 2.4 on active and integrated antennas.

For further reading, IEEE publishes a standard with definitions of terms related to antennas [2]. Another white paper by Rohde&Schwarz describes the basic functionality of antennas and introduces different types of antennas [3]. "Antenna Theory and Design" [1] covers all important aspects of antenna theory, while a more compact guide to antenna basics can also be found on the web [4].

### 2.1 What is an antenna?

An antenna transmits and receives signals over the air. Therefore, antennas are used to transform guided electromagnetic waves or signals into electromagnetic waves that propagate in free space, and vice versa.

Generally, passive antennas can both transmit and receive energy, and are thus reciprocal. Therefore, all mentions of "radiation" and "transmission" are also valid for reception of radio waves. Chapter 2.4 discusses how active components may break the reciprocity.

### 2.2 Antenna parameters

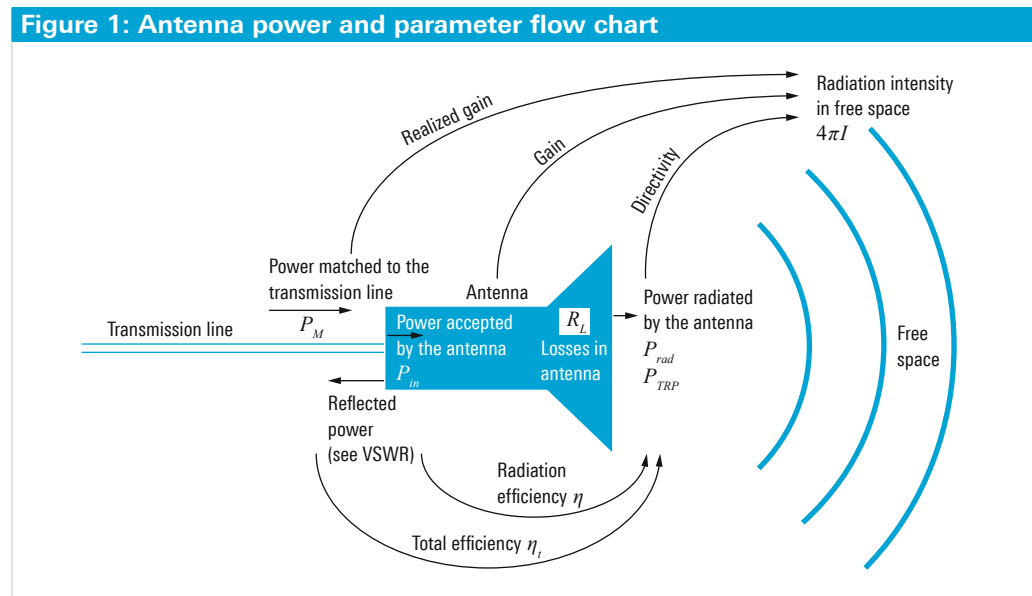


Figure 1 shows some antenna parameters as well as power values that occur in and around an antenna. The power  $P_M$  is matched to the transmission line by a generator and is available to the antenna. The antenna will accept some power ( $P_{in}$ ) and reflect some power depending on the matching (see VSWR in Chapter 2.2.1). Reduced by losses in the antenna caused by  $R_L$ , the remaining power is radiated from the antenna ( $P_{rad}$ ) to generate a certain radiant intensity ( $I$ ) in different directions from the antenna aperture.

$$P_{rad} \leq P_{in} \leq P_M$$

The following sections will discuss the antenna-specific parameters that define the power levels mentioned above and help to understand how antennas work and how they can be characterized.

### 2.2.1 Voltage standing wave ratio (VSWR)

The VSWR describes how much RF power is reflected by a load instead of being accepted. The VSWR is determined by measuring the reflection coefficient  $\Gamma$  ( $S_{11}$ ):

$$VSWR = \frac{|V_{\max}|}{|V_{\min}|} = \frac{1+|\Gamma|}{1-|\Gamma|} \geq 1, \quad |\Gamma| \leq 1$$

With exact impedance matching, 100% of the energy is delivered to the antenna. In reality, a small portion of the energy is reflected back into the transmission line (e.g. a coax cable) and causes interference in the line itself. The voltage variance caused by constructive and destructive interference is measured as the VSWR quantity. A VSWR of one (or 1:1) means no interference, i.e. perfect energy transmission.

The frequency spectrum for which an antenna has acceptable VSWR (above, but close to 1:1) is defined as the VSWR bandwidth of the antenna. Almost every open end of a coaxial cable, open wave guide or trace on a PCB can act as an antenna, either by design or by accident. However, effective transmission is expected only with antennas that are carefully matched for a certain frequency range.

### 2.2.2 Efficiency

The antenna radiation efficiency  $\eta$  describes the ratio of power radiated from the antenna  $P_{rad}$  to the power accepted by the antenna  $P_{in}$ . The radiation efficiency only accounts for losses in the antenna itself (e.g. conductive or dielectric losses), not taking the matching into consideration:

$$\eta = \frac{P_{rad}}{P_{in}} \leq 1$$

Therefore, even antennas with good matching can have bad radiation efficiency.

Unlike the radiation efficiency, the total efficiency  $\eta_t$  considers mismatch:

$$\eta_t = M \cdot \eta = \frac{P_{rad}}{P_{in}}, \quad M = 1 - |\Gamma|^2, \quad \eta_t \leq \eta$$

The total efficiency is thus dependent on the network the antenna is connected to. It characterizes all losses.

An ideal, lossless antenna is possible in theory, but in reality  $\eta_t < \eta < 1$  is assumed.

### 2.2.3 Total radiated power (TRP)

The power radiated by the antenna ( $P_{rad}$ ) is also called the total radiated power ( $P_{TRP}$ ). It is defined as the radiant intensity  $I(\theta, \phi)$  integrated over the whole sphere around the antenna:

$$P_{TRP} = \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi} I(\theta, \phi) \cdot \sin \theta \, d\theta d\phi$$

The radiant intensity  $I$  is expressed in Watt per steradian ( $W \cdot sr^{-1}$ ), thus the radiant flux transmitted per solid angle.

### 2.2.4 Directivity

Directivity describes how directed the power of an antenna is to a certain direction. It is the ratio of the radiation intensity for a given direction to the radiation intensity that would be produced if the **radiated power** ( $P_{TRP}$ ) were radiated isotropically:

$$D(\theta, \phi) = \frac{I(\theta, \phi)}{P_{TRP} / 4\pi}$$

When the direction  $(\theta, \phi)$  is not given, the direction of maximum radiation intensity is implied:

$$D = \max_{\theta, \phi} D(\theta, \phi)$$

The larger the peak directivity of an antenna, the more focused the energy. Highly directive antennas focus the energy to the desired angle while the radiation intensity in other directions is reduced.

Commonly, the directivity is expressed in decibels, relative to the directivity of an isotropic radiator, which has a directivity of 1:

$$D_{dBi} = 10 \cdot \log_{10}(D)$$

### 2.2.5 Gain

The antenna gain is the most common parameter used to describe an antenna. The gain is the ratio of the radiation intensity in a given direction to the radiation intensity that would be produced if the **accepted power** ( $P_{in}$ ) were radiated isotropically.

$$G(\theta, \phi) = \frac{I(\theta, \phi)}{P_{in} / 4\pi}$$

As can be seen, the difference between gain and directivity is only the reference power by which the radiation intensity is normalized. As the factor between radiated power and accepted power is the radiation efficiency, gain equals directivity and efficiency:

$$G = \eta \cdot D, \quad G(\theta, \phi) = \eta \cdot D(\theta, \phi)$$

As for directivity, the direction of maximum radiation intensity is implied if omitted. Also, gain is typically expressed in dB, relative to an ideal isotropic radiator with gain of 1:

$$G_{dBi} = 10 \cdot \log_{10}(G)$$

**Note:** As defined, the gain does not include losses from impedance mismatches.  $P_{in}$  is the power that is accepted by the antenna. The "realized gain" considers the impedance mismatch and is therefore relative to the power matched to the transmission line ( $P_M$ ):

$$G_R = \frac{I(\theta, \phi)}{P_M / 4\pi}, \quad G_R = \eta_t \cdot D$$

The realized gain depends on the matching of the network. Since mismatch will result in additional losses, realized gain is smaller than gain. The gain in return is smaller than the directivity due to the radiation efficiency. Only for an ideal lossless antenna and perfect matching can the three parameters be theoretically equal.

### 2.2.6 Effective isotropic radiated power (EIRP)

The EIRP denotes the absolute output power in a given direction. If no direction is defined, the direction of maximum radiation intensity is implied. The EIRP is the power an ideal isotropic radiator requires as input power to achieve the same power density in the given direction. EIRP is the power accepted by the antenna multiplied by the antenna gain, or radiated power multiplied by the directivity:

$$EIRP = P_{in} \cdot G, \quad EIRP_{dBm} = P_{in,dBm} + G_{dBi}$$

The closely related effective radiated power (ERP) is also often used and is defined as the power an ideal half-wavelength dipole requires as input power to achieve the same power density in the given direction:

$$EIRP = 1.64 \cdot ERP, \quad EIRP_{dB} = ERP_{dB} + 2.15$$

## 2.2.7 Radiation pattern

Figure 2: 3D radiation pattern

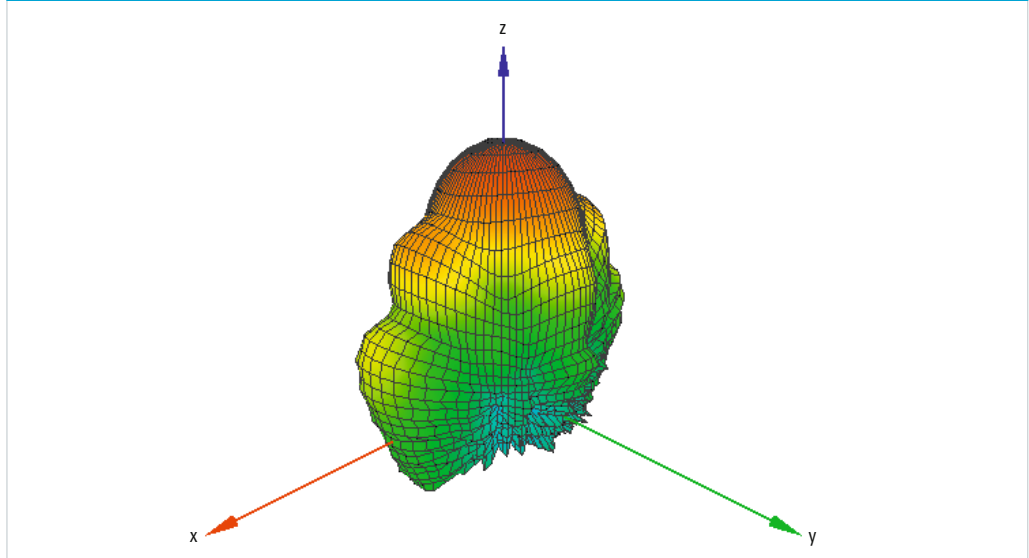
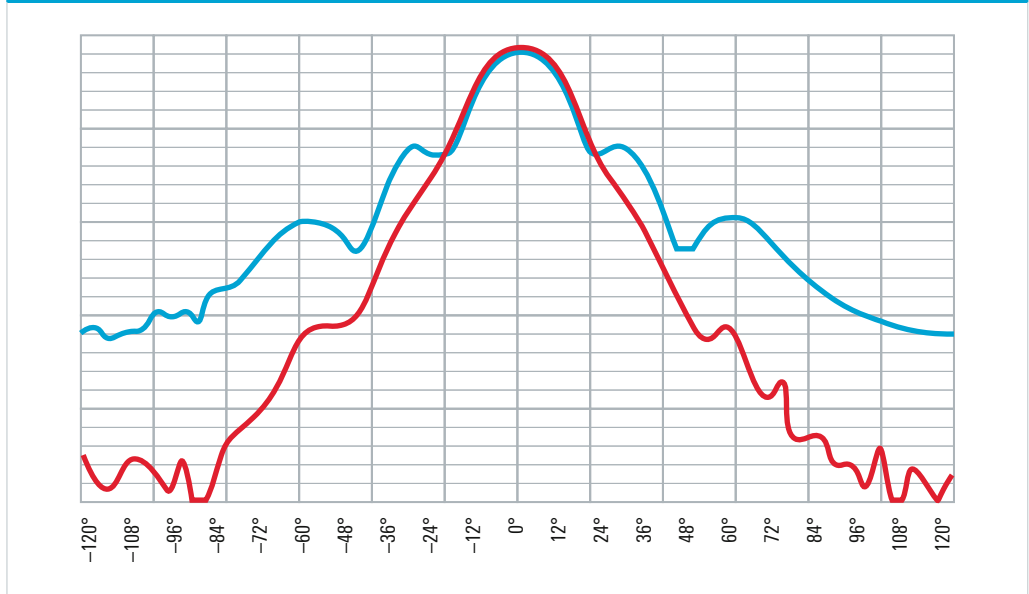


Figure 3: 2D cuts of radiation pattern in E- and H-plane



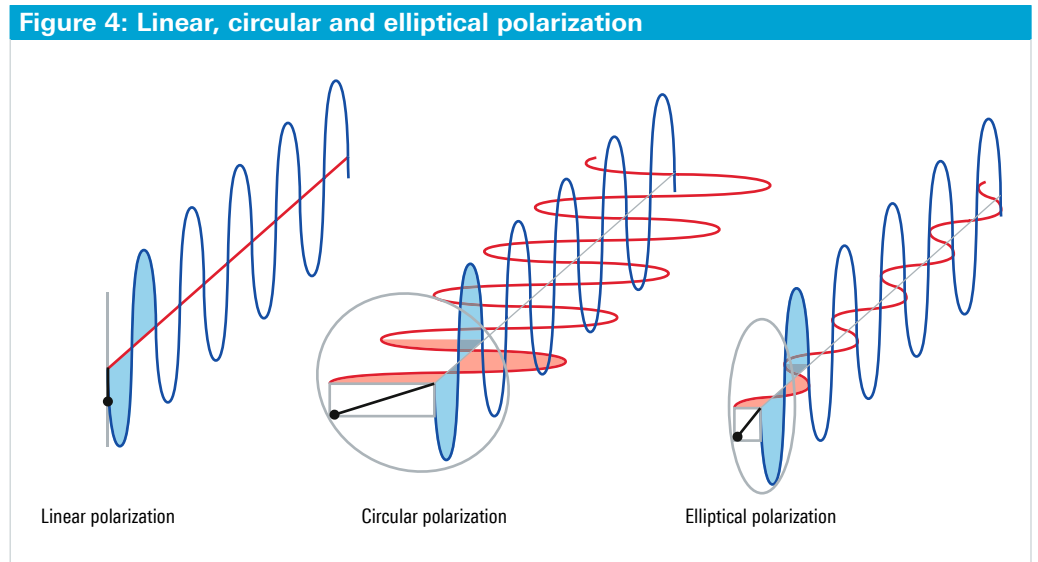
The radiation pattern represents the spatial distribution of a quantity that characterizes the electromagnetic field generated by an antenna. For reciprocal antennas, the transmit and receive patterns are identical. The antenna pattern can be expressed as a 3D plot, 2D pattern cuts or a mathematical function. The quantities used to characterize the pattern are proportional to the radiation intensity  $I(\theta, \phi)$  of the antenna. Often, directivity, gain or EIRP are used for radiation pattern representation.

Distinct value levels can be identified more easily with 2D cuts instead of 3D cuts. Therefore, the E-plane and H-plane cuts of the antenna pattern are typically found on antenna datasheets. They are the two orthogonal cuts through the 3D pattern corresponding to the direction of the E-field and H-field produced by the antenna (see Polarization).



### 2.2.8 Polarization

Every electromagnetic wave has a certain polarization, meaning the orientation of the E-field in space. The polarization of an antenna is determined by the polarization of the transmitted wave. One basic polarization type is linear polarization. The E- and H-fields of a linear polarized wave oscillate in a single direction. Two E-fields with the same amplitude oscillating  $90^\circ$  out of phase and orthogonal to one other create circular polarization (see Figure 4). The resulting field vector of the superimposed field rotates at constant rate. If the two fields oscillate with different amplitude or another phase, the result is elliptical polarization. Linear polarizations are defined as vertical, horizontal or slanted, while circular polarizations can rotate right or left (in the right hand sense or left hand sense, respectively). Elliptical polarizations are the generalization with linear and circular being the two extremes.



The polarization that is the intended polarization of an antenna is the "co-polarization" while the "cross-polarization" is orthogonal to it. The polarization efficiency describes how much of the energy is received for the incident wave of arbitrary polarization compared to the same wave in co-polarization. It is thus dependent on the antennas and incident wave orientation. The polarization efficiency is highest for co-polar waves. If the impinging wave's polarization is not aligned to the co-polarization of the antenna, less energy is transmitted. The cross-polar discrimination (XPD) of an antenna is the ratio of the co-polarized and cross-polarized power. Cross-polar isolation applies to dual polarized antennas and describes the ratio of the power coupled between two orthogonally polarized ports of the dual polarized antenna.

To measure an antenna under test (AUT) with arbitrary or unknown polarization, two orthogonal polarized probes are required to receive the full energy transmitted by the AUT. Alternatively, a single probe can be rotated to receive both polarization components if the impinging wave polarization can be assumed stationary for the duration of the two measurements.

### 2.2.9 Bandwidth

The bandwidth of an antenna is not an inherent antenna characteristic, but is defined as the range of useable frequencies in which the antenna performs as specified with respect to a freely defined set of parameters. Commonly, the frequencies for which matching is acceptable (e.g. VSWR of less than 1.5 or 1.4, as defined by the antenna manufacturer) define the antenna bandwidth. Depending on the use case, other parameters such as TRP, beam width, side lobe level or suppression can determine the bandwidth as well. Depending on the useable frequencies, the bandwidth is the factor between the lowest ( $f_L$ ) and highest frequency ( $f_H$ ):

$$BW = \frac{f_H}{f_L}$$

Antennas are defined as broadband when the factor is equal to or greater than 2.

### 2.2.10 Antenna beams, beam width and side lobes

For directed antennas, different beam widths may be defined. A beam is a global or local maximum in the antenna pattern pointing in a certain direction.

The half power beam width defines the angle between the first points for which the EIRP of an antenna pattern is 3 dB below peak value, with the peak EIRP direction typically being roughly in the center of the beam width. The beam width can also be defined to different power limits or up to the first null.

In addition to the desired beam direction, typically additional beams are formed by the antenna. These beams are called side lobes and are numbered by their order from the main beam. Figure 3 shows side lobes at around 35° and 60° for the blue curve.

The side lobe level is often given relative to the peak beam level and identifies how good the antenna manages side lobe suppression, which is especially important for beamforming using array antennas (see Array Antennas and Beamforming).

## 2.3 Different antenna types

There are many different types of antennas, each tailored to a specific use case. Designing an antenna is most often a compromise between optimizing for the different antenna parameters. Different antenna types include dipole, monopole, horn, vivaldi, yagi, patch, microstrip, paraboloid, log-periodic, wire, grid, loop, array and many more. Each of these antenna types is designed for a specific purpose. In addition, antennas of the same type can have very different characteristics. Antennas might have good matching for a wide bandwidth or only very defined, narrow bands, have high gain or an omnidirectional pattern, strong or weak polarization discrimination, are either large or small, and so on. Some antennas are also hybrids of other antenna types, always with the goal of maximizing the fit to the required/dependent antenna characteristics.

## 2.4 Active, integrated or on-chip antennas in a system

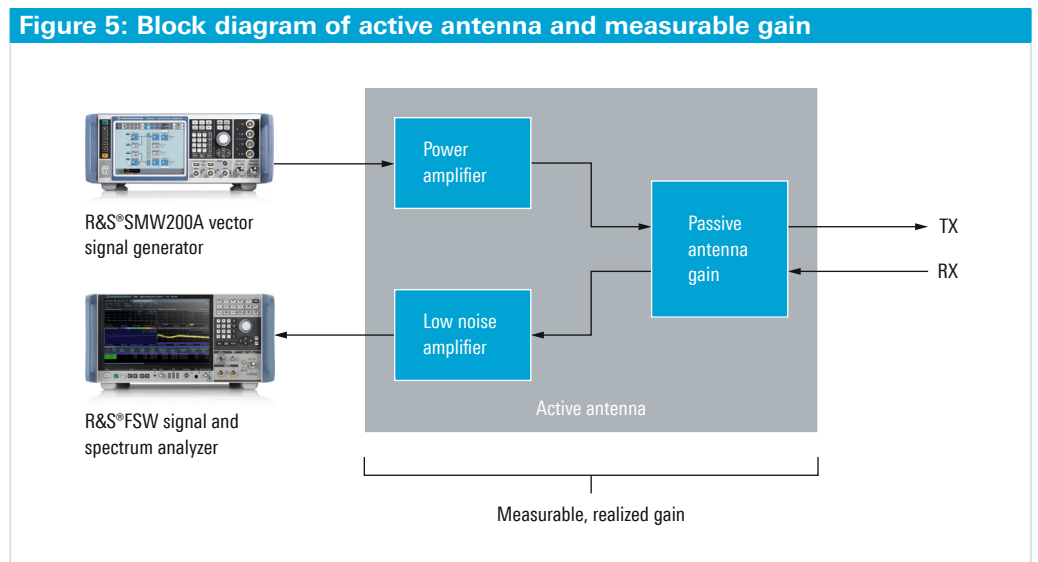
Antennas are passive components that typically can be considered separately. When considered from the system level perspective, antennas are combined with other components, for example transceivers and amplifiers. The possibility to separate the antenna from the rest of the system directly influences the ability to determine the antenna parameters.

The IEEE definition for active antennas simply states that any antenna packaged with an active device is an active antenna. Used in broadcast, active antennas may refer to antennas with integrated low noise amplifiers (LNA) to improve impedance matching of an antenna over a broader bandwidth or simply improve the SNR of the received signal. Also, used as wideband antennas with electrically small receptors, active antennas can feature improved performance. Active receivers are prominent, for example, in satellite TV dishes. Satellite receiver antennas combine a reflector dish, horn antenna and components like an LNA, frequency mixer, local oscillator and additional amplifier into a single device, the low-noise block (LNB) downconverter.

In the ecosystem of modern communications standards, active antennas refer to the generalized concept of having an antenna or even antenna array directly connected to the RF frontend that includes active components. In addition, the move to mm-wave technology amplifies the level of integration of active components and antennas. Many integrated circuits (IC) feature antennas directly on the printed circuit board (PCB) as a microstrip or patch antenna, and even on-chip antennas are used in mm-wave transceiver chips.

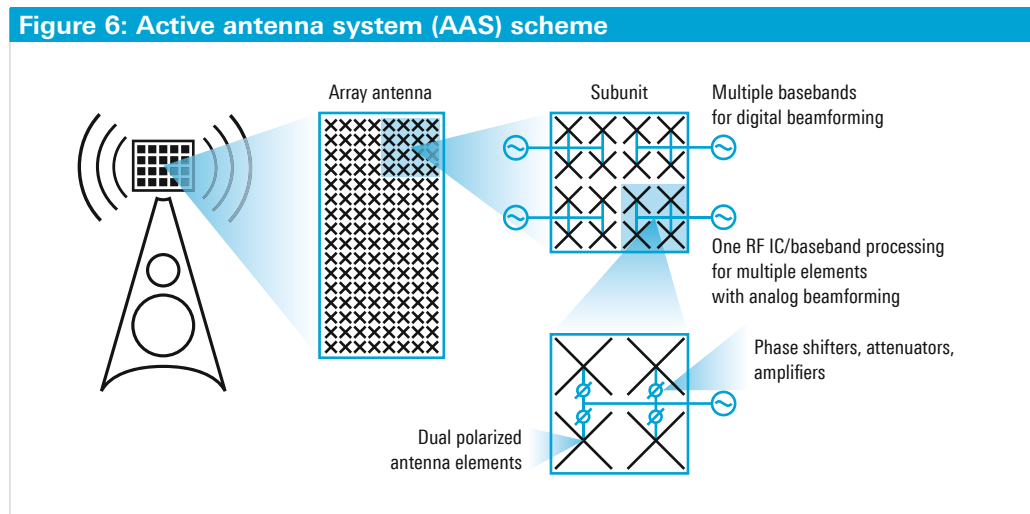
Regardless of the reason, when the (passive) antenna itself cannot be separated from the active components, determination of antenna-specific characteristics may be impractical or even impossible. If the active component (e.g. an LNA) and antenna both add a certain gain to a system, only the combined gain can be determined, without the ability to determine the antenna parameters individually (see Figure 5).

Total efficiency, for example, can be measured by comparing the input power of the RF signal and amplifier DC power with the total output power  $P_{TRP}$ , yielding the combined efficiency of the amplifier and the antenna's total efficiency.



Also, antenna-specific parameters like the beam width, side lobe level or null level may be of secondary interest when identifying the beamforming capabilities of an active antenna system base transmission station (AAS BTS) for massive multi-user multiple input multiple output (MU-MIMO). Due to active beam steering and fast switching of active

elements, angles and power levels, other performance indicators like the signal-to-noise-plus-interference-ratio (SINR) or higher layer parameters of individual users may play a more important role in system characterization.



As shown in Figure 6, AASs feature many different components in a highly integrated system with a very specialized task. They combine antennas, amplifiers, phase shifters and possibly even an RF IC to serve multiple users with a combination of digital and analog beamforming.

In the more and more complex systems emerging today, sensible prioritization of resources allocated to individual components and the determination of performance indicators for the components as well as the overall system require broad knowledge on the part of the responsible system engineer. In early stages of system development, the antenna may be characterized individually to get estimations for the combined implementation. Note, however, that the antenna is influenced by the components and materials in its direct vicinity. Therefore, it is important for the rest of the system to be present or simulated, e.g. by using a mock-up. The radiation pattern and frequency tuning can change significantly due to other objects in the near field (NF) of the antenna, especially for patch antennas as used in systems with a high level of integration on a small footprint. Also, the matching of the test equipment with the antenna might be different from the matching of the antenna to the integrated components in the system. As a consequence, the efficiency is changed in the integrated product.

In summary, the combination of antennas with other active components may render characterization of certain antenna parameters difficult or impossible. Here, a system level approach must be taken with proper definition of performance indicators. Individual testing at earlier stages is still valid and also important, but must already take into account the effects caused by integration.

## 2.5 Antenna measurements

During the design process, antenna development is largely based on simulations and software tools that can design antennas based on a defined parameter set. When it comes to final production or even integration, the real-world parameters can easily deviate from the simulation results. Especially in highly integrated systems where antennas are surrounded by other components, the antenna characteristics can change significantly and simulations have to take all other components of the system into account. Complex simulations can take a long time, while measurement times with modern test systems are down to a few minutes. Clearly, measurements are still the surest way to determine the real-life performance of the antenna or system. Therefore, verification measurements remain a vital part of antenna design.

As with the definition of antenna parameters, the defined "transmitter tests" in the different measurement chambers and methodology equally apply for "receiver tests".

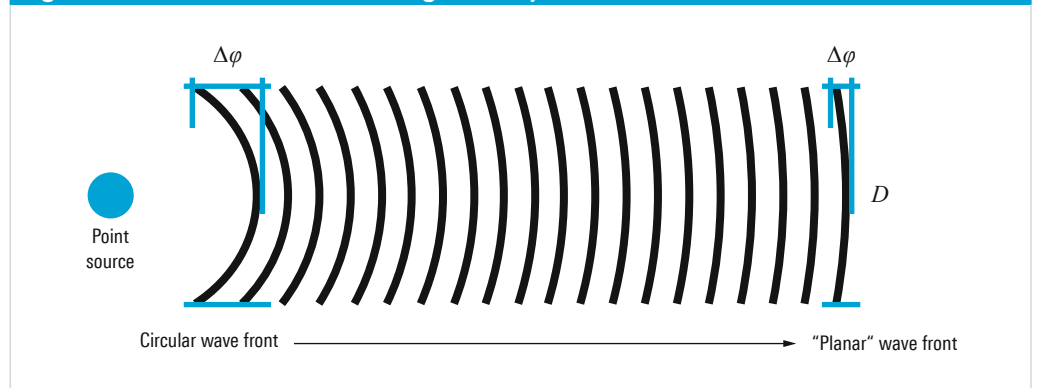
### 2.5.1 Near field and far field measurements

All common antenna properties are defined in the far field (FF) region. Per IEEE definition, the FF is the region where the field of the antenna is essentially independent of the distance from a point in the antenna region. In other words, in FF, free space and plane waves are assumed.

To achieve free space characteristics, the LOS including the first Fresnel ellipsoid between the AUT and probe antenna must be free of obstacles. Another important characteristic of free space is the absence of any reflections. Ideally, antenna measurements should be conducted in infinitely large rooms which can be approximated by minimizing reflections using RF absorbers (see Fully anechoic chamber) or ensuring enough free space around the test range.

An ideal plane wave consists of infinite parallel wave fronts, which are planes of constant phase. To achieve infinite parallel planes, infinite energy and space are required, rendering the mathematical constraint impractical. However, assuming a small portion of the wave front, the deviation from a plane wave will decrease with increasing distance from the source, as can be seen in Figure 7. The deviation from a plane wave will be noticeable in terms of the difference in amplitude and phase due to the different travel distances from the source. The probe antenna radiation pattern and imperfections like residual reflections can also cause a deviation from plane waves. To minimize the deviation, sufficient distance and free space around the direct line of sight (LOS) are required.

Figure 7: Scheme of wave front geometry



To determine the sufficient FF distance for electrically large antennas ( $D > \lambda$ ), the Fraunhofer distance  $r$  is used. This applies to almost all directed antennas:

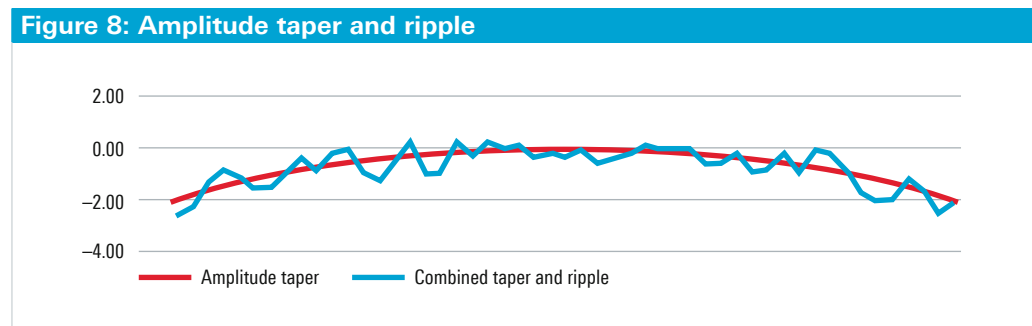
$$r \geq \frac{2D^2}{\lambda}, \text{ with } r \gg D, \quad r \gg \lambda$$

For electrically small antennas ( $D < \lambda$ ), this simplification applies:

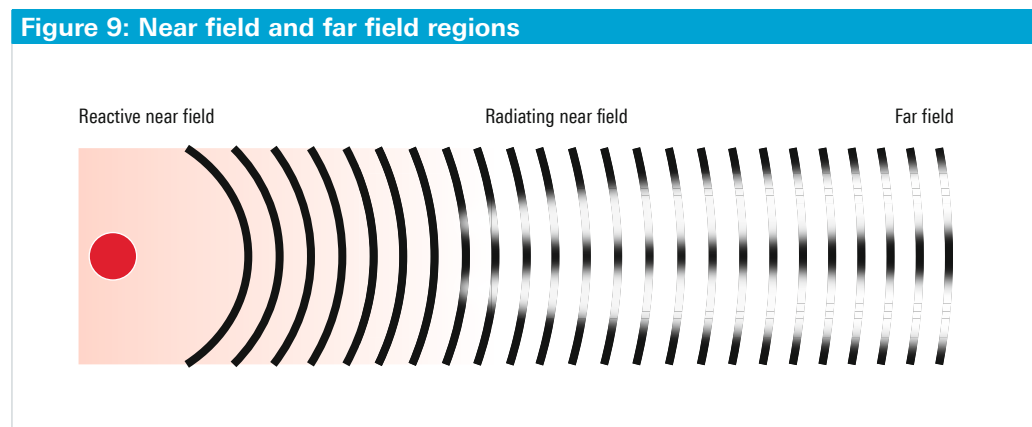
$$r \geq 2\lambda$$

According to the Fraunhofer distance, a maximum phase deviation of  $\Delta\phi = 22.5^\circ$  for a wave with wavelength  $\lambda$  over a region  $D$  is achieved at a minimum distance  $r$ . This means that for a given antenna of size  $D$ , the minimum distance at which FF can be assumed is  $r$ . Or, for a given distance  $r$ , there is a region of size  $D$  in which wave fronts can be assumed to be planar. This leads to the notion of a quiet zone (QZ): Inside the quiet zone for a given test range, plane waves are assumed.

Depending on the type of test range, the quiet zone may exhibit a taper and/or ripple in the amplitude and phase of the field generated by the probe antenna of the test range (see Quiet zone verification). Amplitude taper and ripple over one dimension in the quiet zone are shown in Figure 8. Similar graphs can be used to visualize phase deviation.



If the FF distance cannot be achieved, a plane wave as defined by FF conditions may also be created at a distance smaller than the Fraunhofer distance using additional hardware. To differentiate direct FF test ranges from smaller setups with FF conditions, the term indirect far field (IFF) is used. Some IFF test ranges are discussed starting in Chapter 2.5.5. If FF conditions cannot be achieved, near field (NF) measurements may also be used. The NF is assumed for distances smaller than the FF distance. The NF is divided into the reactive NF region very close to the antenna and the radiating NF (Fresnel) region between the reactive NF and FF as shown in Figure 9.



In the reactive NF, the electric and magnetic fields do not form a transversal electromagnetic (TEM) wave but are out of phase. The energy is not transmitted but stored (see red region in Figure 9). Other objects in the reactive NF change the antenna parameters. The field falls off predominantly with  $1/r^3$ . In the radiating near field, energy is transmitted but the wave fronts exhibit strong deviation from plane waves and the field falls off predominantly with  $1/r^2$ . In FF, TEM waves are assumed with approximately plane wave character. The field falls off predominantly with  $1/r$ . Nulls in the antenna pattern take shape with increasing distance in the far field region as the near field falls off.

If NF measurements are conducted, additional postprocessing steps are required to transform the recorded NF data into FF. NF measurement and transformation to FF are discussed further in Chapter 2.5.8.

### 2.5.2 Outdoor test ranges

Outdoor test ranges are large testing facilities in open space with either one or two towers for the probe antenna and AUT. Open area test sites (OATS) provide no shielding or only limited shielding against interference from other radiators in the environment. They are still used mainly for very large antennas or low frequencies due to the large required FF distance.

While the generic measurement setups are applicable to different types of test ranges, the specifics of outdoor test ranges will not be discussed in more detail in this paper.



Figure 10: Rohde&Schwarz OATS near Memmingen, Germany

### 2.5.3 EMC chambers

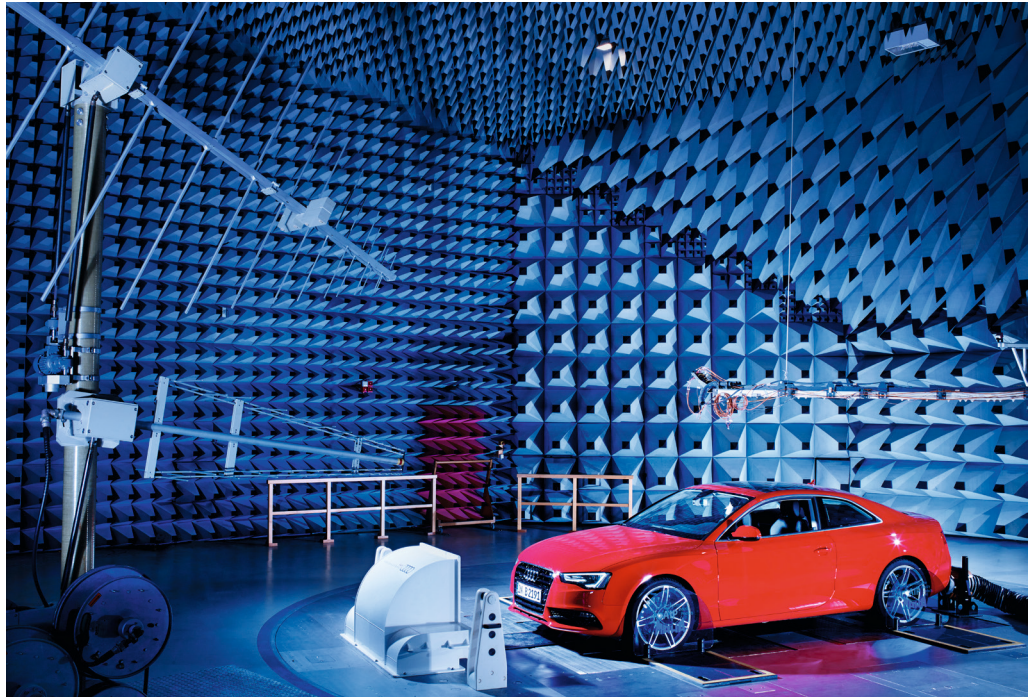


Figure 11: Car in EMC chamber at Rohde&Schwarz in Memmingen, Germany

Since EMC testing is mandatory even for products not using OTA transmission, the EMC community has a large user base with a long history of developments.

In close relation to real-world scenarios and outdoor test ranges, semi-anechoic chambers (SAC) feature a metal ground plane leading to a strong ground reflection influence during measurements. Most importantly, they feature no ambient RF interference and reduced size requirements compared to OATS.

When measuring DUTs in SACs, the measurement probe is moved at different positions in height to identify the maximum power level. The power level changes depending on the measurement position mainly due to the reflected field component and the directly received line-of-sight (LOS) component constructively and destructively interfering with one other.

To introduce even greater reflectivity, reverberation chambers (RVC) or mode-stirred chambers (MSC) feature a minimum number of absorbers leading to high field strength even with low power sources. Due to reverberation chambers being cavity resonators, standing waves in the chamber lead to highly inhomogeneous fields. Therefore, each reverberation chamber features a tuner in the form of large moveable reflectors to create different boundary conditions.

For all chambers that actively make use of reflections, power is received even in directions where no power is transmitted by the DUT. Obviously, this approach is ineffective for accurate determination of the radiation pattern and other antenna parameters. Therefore, other types of chambers are used for such tasks.



## 2.5.4 Fully anechoic chamber

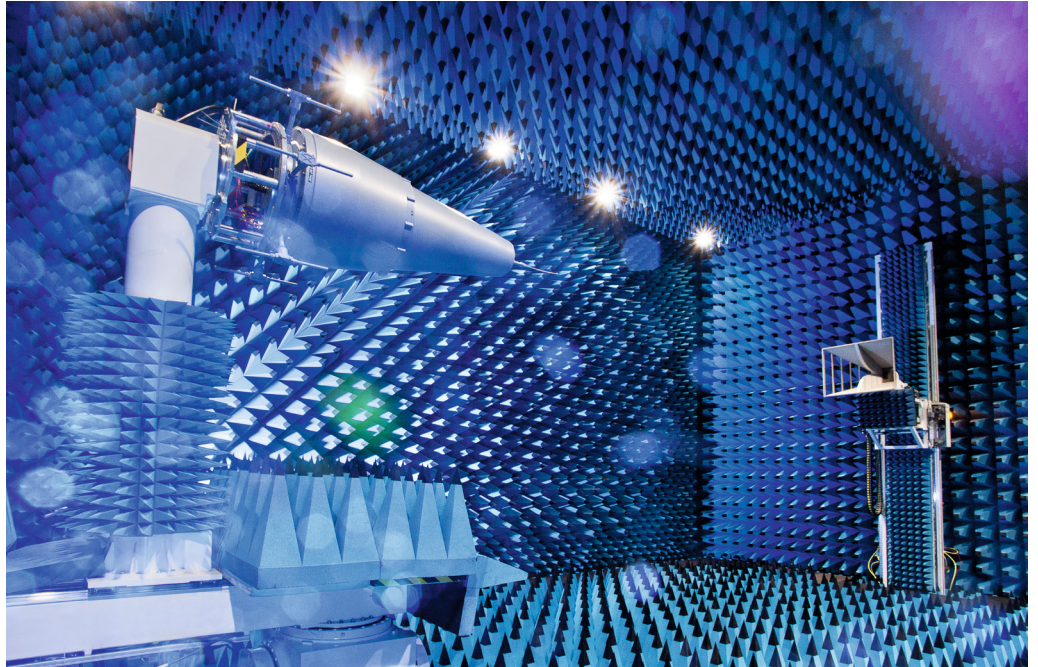


Figure 12: Antenna measurement chamber at Rohde & Schwarz in Memmingen, Germany

While SACs are commonly used for electromagnetic compatibility (EMC) testing, antenna characterization is normally done in fully anechoic chambers (FAC).

SACs better simulate real-world propagation due to the ground plane when compared to FACs. However, when interested in the radiation pattern of an antenna or transmitter/receiver testing without any interference caused by reflections, FACs are the better choice. They yield much more repeatable and accurate results as they mimic the free space characteristics of an infinitely large room. To achieve this, they are fitted with RF absorbing material (RAM) to limit reflections from the walls, ceiling and floor. In addition, the shielding prevents interference from the environment from entering the chamber and minimizes the signal power that leaks out of the chamber. This reduces interference to outside equipment and limits health risks for personnel in the area, especially for high-power antennas under test (AUT).

When sufficient space is available to achieve FF conditions, all measurements can be conducted in FF. Here, no special postprocessing steps are required to measure the antenna parameters. Compared to a direct far field (DFF) measurement, indirect far field (IFF) or near field (NF) measurements can be used to reduce the space requirement in exchange for a more expensive, complicated or bandwidth limited setup, or additional postprocessing steps (see Chapter 2.5.1).

## 2.5.5 Compact antenna test range

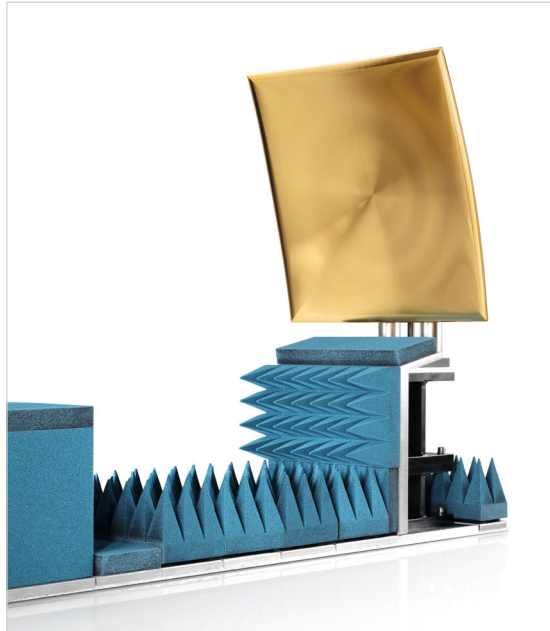


Figure 13: Benchtop mm-wave reflector

One solution for FF conditions in smaller test ranges is the use of a compact antenna test range (CATR) invented in the 1960s [5]. A parabolic RF reflector creates a plane wave at a short distance in front of the reflector. With the feed antenna located in the focus point of the paraboloid, there is only a very limited amount of energy outside of the intended QZ. The maximum size of AUT that can be measured is limited by the QZ size, which depends on the size of the reflector. Typically, the reflector must be twice as large as the intended quiet zone.

The surface roughness of the reflector has to be much smaller than the used wavelengths, as even the smallest bumps on the surface cause scattering and phase changes for the reflected RF waves. The surface roughness therefore determines the highest possible frequency. For example, reflectors useable for 50 GHz need a surface deviation of less than 60  $\mu\text{m}$ . The lower end of the useable frequency spectrum is determined by the edge treatment of the reflector. Scattering at the edges disturbs the QZ created by the reflector and can be minimized by using, for example, rolled or serrated edges.

All CATR systems exhibit amplitude taper and ripple in the QZ (see Figure 8). Amplitude ripple can arise due to the smallest deviations from a perfect paraboloid. Amplitude taper is caused mainly by the antenna pattern of the feed antenna. Peak gain is only achieved in the main beam direction, with the gain falling off in all directions. A broader half power beam width of the feed antenna helps in minimizing the amplitude taper in the QZ. Also, many antennas exhibit different radiation patterns in the E-field plane and H-field plane cuts (see Radiation pattern). Corrugated horns may be used instead of standard gain horns to obtain a wider bandwidth and minimize amplitude taper as well as E- and H-plane differences.

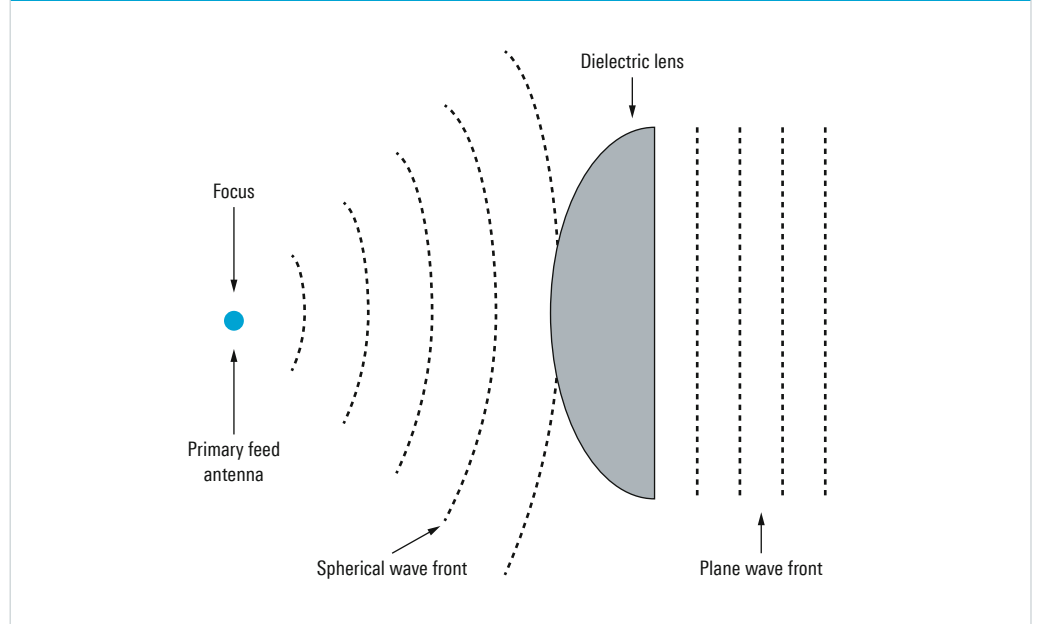
Additionally, the paraboloid shape will always cause diagonal cross-polarization effects for linear polarized waves. This reduces the XPD of the CATR.

The tradeoff between the different factors may lead to reduced performance of a CATR system compared to a well calibrated DFF chamber in certain cases. However, for many applications a CATR test range is the most economical option for accurate OTA

measurements in limited space. Additionally, CATR systems have much lower path loss compared to DFF chambers and offer more dynamic range to be used in the test instrument.

### 2.5.6 Lens-type compact antenna test range

**Figure 14: Scheme of lens antenna**



Just as the CATR reflector creates planar waves by reflection, lenses can be used to create planar waves by diffraction. Since the size and weight of the lens depend on the frequency range, investigations of lens systems mainly focus on usage for mm-waves [6] [7].

The two main types of lenses are the dielectric lens and the metal plate lens. The dielectric lens is also called a delay lens, as the dielectric material slows down the traveling waves. It therefore exhibits a convex shape towards the feed antenna (see Figure 14). Metal plate lenses on the other hand are concave towards the feed. This is due to the phase of the wave traveling faster in a metallic waveguide than in free space.

Generally, lenses are costlier compared to reflector systems, but they have the advantage that the feed antenna can be placed behind the lens to avoid obstructing the lens aperture.

## 2.5.7 Plane wave conversion

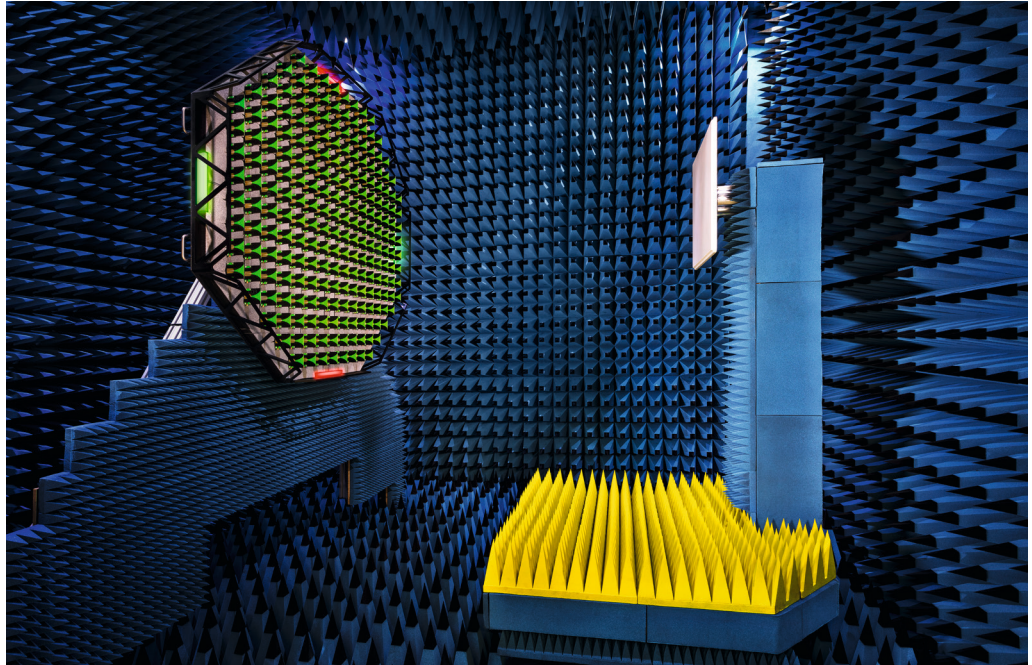


Figure 15: Plane wave converter (PWC) prototype at Rohde & Schwarz

Another approach for an IFF measurement involves plane wave conversion (PWC) with an antenna array as the measurement antenna. Each element emits a spherical wave and waves from multiple elements of one array antenna are superimposed in the air. By transmitting the same signal with dozens or hundreds of antenna elements in an antenna array and carefully adjusting the phase shift and amplitude of each antenna element, the resulting wave front can be designed to create a plane wave in a large QZ at a short distance to the antenna array. As with CATR, the plane wave characteristic of the FF region is achieved at a much smaller distance. The most limiting factor for this type of IFF test range is the restricted bandwidth due to the use of an antenna array.

## 2.5.8 Near field measurements

If the FF distance cannot be achieved and IFF measurement techniques are not applicable, NF measurements can also be conducted. Following Huygens's principle, the field values outside a closed volume  $V$  can be computed if the tangential fields on the surface  $A$  of this volume are known. Thus, it is possible to calculate the FF characteristics based on the measured tangential fields in NF. One approach is to measure the field surrounding the AUT with a spherical NF scan. Depending on the antenna type and directivity, cylindrical or planar scans might also be applicable. A Fourier transform is used to transform the NF measurements to their FF equivalent. For valid transformation, the horizontal and vertical polarization of the probe antenna must yield the exact same results in amplitude and phase for a given field strength. In addition, the probe antenna pattern will influence the measured near field values and therefore a probe correction must be applied as well. NF to FF transformation is further discussed in Chapter 3.3.1.

The downsides of NF measurements include non-real-time results and the need for small angular steps depending on the measurement frequency and AUT size. The smallest mechanical misalignments have a big impact on the measured phase and can lead to wrong transformation results. Therefore, the required mechanical precision of the test fixture and positioning device is high, especially for smaller wavelengths. The measurement points cannot be further than  $\lambda/2$  apart, requiring high position accuracy for mm-wave measurements along with many measurement points, which increases the required time.

In summary, NF to FF transformations require high accuracy in the test system (electrical and mechanical), knowledge about the probe antenna and additional postprocessing steps. Taking care of all prerequisites will, however, yield very accurate FF results in a much smaller measurement environment.

### 2.5.9 Extreme conditions

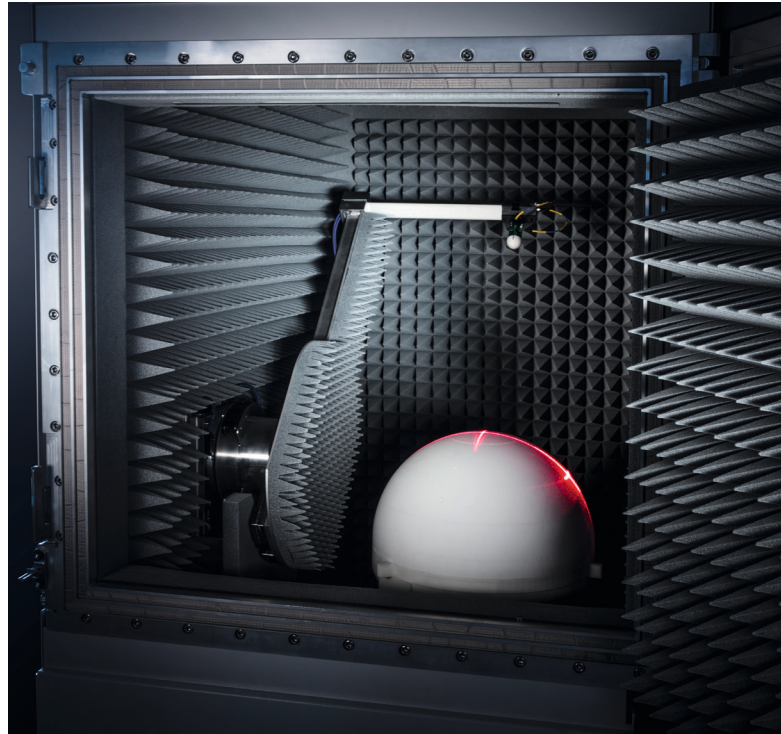
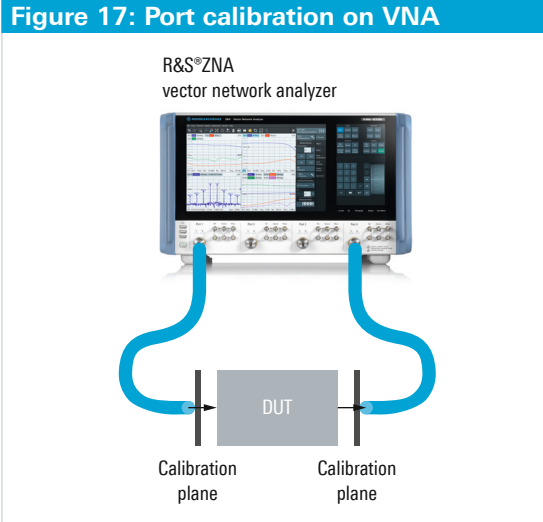


Figure 16: Rohde&Schwarz compact antenna test system with "temperature bubble"

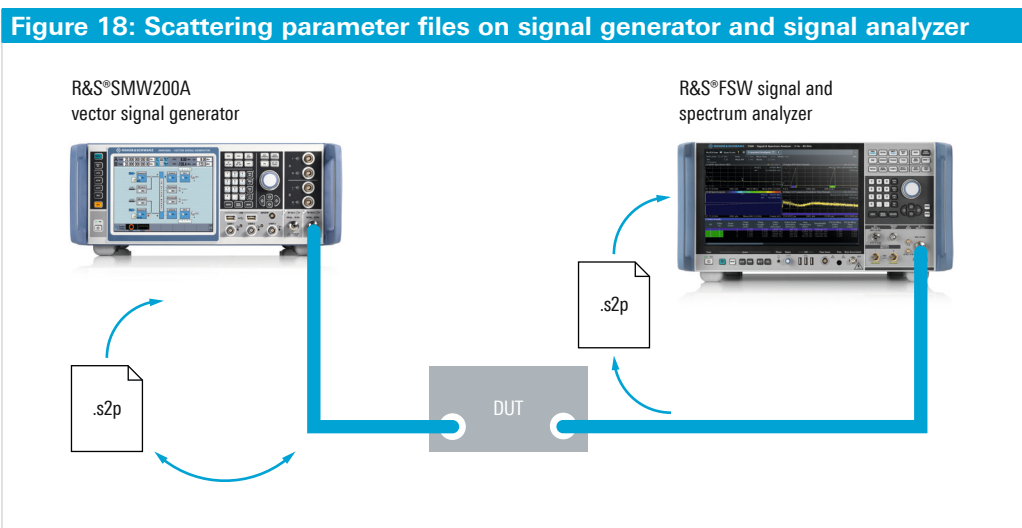
Sometimes OTA measurements have to be combined with extreme condition testing, e.g. high and low temperatures. The OTA link generally occupies a larger area, but it is not feasible to change the temperature in the whole OTA chamber or room. The wear on absorber materials, fixtures and the positioner system goes up unnecessarily, increasing maintenance and risking possible failure of the test range. In addition, it takes much more time and energy than necessary to apply temperature changes to the large volume contained in chambers. Instead, RF invisible material is used to contain the region of controlled temperature in a small space around the DUT. This keeps all other equipment in the chamber untouched by the extreme conditions and increases the efficiency for temperature changes. The challenge lies in accurate temperature and humidity control as well as using the right materials to contain the controlled region while not disturbing the traveling waves in a way that degrades the measurement data.

### 3 System calibration/correction



Whenever a DUT is measured, the measurement results should not be dependent on the test setup. Therefore, calibration is required for each measurement setup. For calibration of conducted setups, a network analyzer can straightforwardly measure the scattering parameters of the used cable. The frequency response information and reflection coefficient of the cables are used by the test instrument to compensate for these effects. Successive measurements of a DUT will feature a clean and well-defined signal at the DUT input and the received signal parameters will reflect the actual parameters at the DUT output. In other words, all measurements are relative to the newly defined "calibration planes" located at the DUT connectors (Figure 17).

Modern signal generators and signal or spectrum analyzers can use the scattering parameters of a test setup to move the calibration plane of their measurements, similar to the port calibration of a network analyzer. Depending on the test equipment capabilities, the instrument may be able to compensate for frequency response in amplitude and phase, optionally taking reflections into account.



OTA setups also have to be calibrated. Like every other component, the OTA link has a certain frequency response, typically with much higher attenuation compared to a

conducted setup. Additionally, while a cable of a certain length has fixed attenuation, the OTA measurement distance can easily and inadvertently change, causing differences in attenuation and especially phase. Deviations occur even for small positioning errors or mechanical imperfections of the test fixture when rotating the DUT. Therefore, stable measurement distance and high positioning accuracy are of great importance.

Since at least one interface of the DUT or AUT will be in the air, a typical port calibration or scattering parameter measurement cannot be conducted. While individual parts of the system may be characterized this way and the free space path loss can be calculated, a straightforward measurement of the system frequency response must use a different methodology.

The easiest process to determine the gain of any AUT is to compare the unknown antenna to a known reference antenna, called gain transfer method. By measuring once the full setup with both antennas and comparing the results, the realized gain of the unknown antenna can be determined:

$$L_{sys} = P_{TX,ref} + G_{ref} - P_{RX,ref}$$

$$G_{AUT} = P_{RX,AUT} + L_{sys} - P_{TX,AUT}$$

With  $P_{TX} = P_{TX,ref} = P_{TX,AUT}$  and inserting the system loss  $L_{sys}$ :

$$G_{AUT} = G_{R,ref} + P_{RX,AUT} - P_{RX,ref}$$

All values are in dB and dBm.  $L_{sys}$  is the overall system loss,  $P_{TX}$  is the transmitter power for the AUT and reference antenna.  $P_{RX,ref}$  and  $P_{RX,AUT}$  are the power received with the system reference and AUT antennas, respectively.  $G_{ref}$  is the known reference antenna realized gain, and  $G_{AUT}$  is the unknown AUT antenna realized gain.

Following the same principle, the frequency response of the measurement system can be determined by measuring the transmission coefficient of the system with the reference antenna in place and then subtracting the known reference antenna gain from the transmission. Only the peak gain of the reference antenna has to be known and measured as long as the direction of maximum gain is pointing in the direction of the probe antenna. The distance of the OTA link must be identical for the reference and AUT measurement. To measure the antenna pattern, a positioning system is required to move, rotate, pan or tilt the DUT and the reference antenna phase center must be aligned to the rotation center of the positioner (see Chapter 3.1.2).

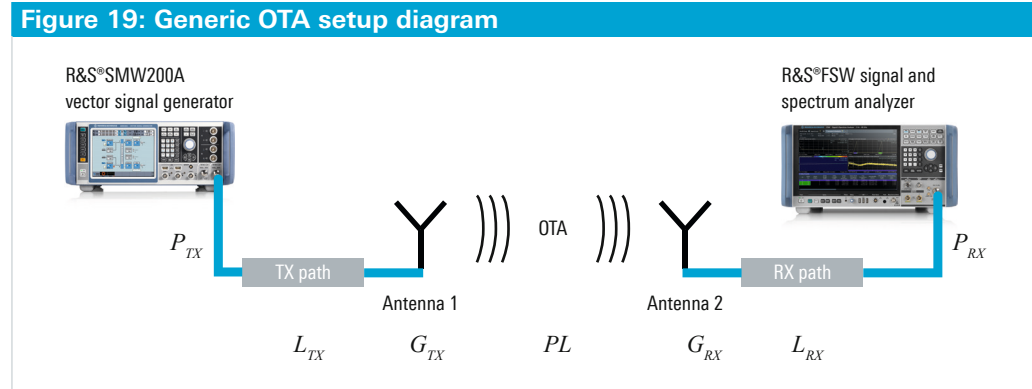
Establishing the absolute attenuation of the complete system is called a path loss calibration. This calibration type can be used for all FF and IFF measurements. For all successive measurements with arbitrary DUTs (or AUTs), the known system loss can be removed from the measurement value to obtain the DUT gain or EIRP, depending on the antenna and measurement type.

The calibration data can either be handled by external automation software controlling the setup or can be applied directly to the test equipment, if supported.

Whether to calibrate only for amplitude, including phase information, depends on the required measurement and used system and devices. For characterization of antenna parameters in FF, calibration of phase is not required. When conducting

NF measurements, transformation of the measurement data requires phase information. For all other DUT measurements, it is up to the user to decide which information is of interest and chose a calibration method accordingly.

### 3.1 OTA system components and challenges



As with every measurement setup, the OTA test system can be characterized either as a whole or separated into components. Figure 19 shows a generic OTA setup. With regard to OTA testing, the DUT (AUT) will replace either "Antenna 1" or "Antenna 2". Depending on the DUT position, it can operate in transmit or receive mode, respectively. Regardless of the operation mode, the simplest approach for calibrating the full system is to measure the cable to the DUT first and the OTA path with the remaining cable afterwards. For simplification of the description, the DUT is assumed to be in place of "Antenna 1", with all measurements applying for receive mode as well.

If the DUT features baseband processing, the direct cable connection to the DUT is not required for operation, but still for the calibration. First,  $L_{TX}$  is determined to achieve a certain known power level at the reference antenna (Antenna 1). Then, the remaining system is calibrated in an additional step and only this data is used during measurement of the DUT.

For simplification of the block diagram, a single black box represents the combined frequency response of the connection from the measurement devices to the respective antenna. It may consist of multiple passive or active components and can also contain switchable paths depending on the setup.

#### 3.1.1 Free space path loss

When performing a DFF measurement in free space without reflections, the frequency-dependent attenuation of a signal transmitted over the air can be calculated using the free space path loss (FSPL),

$$FSPL = \left( \frac{4\pi df}{c} \right)^2, \quad FSPL(dB) = 20 \cdot \log_{10}(d) + 20 \cdot \log_{10}(f) - 147.55,$$

where  $d$  is the distance between the antennas,  $f$  is the frequency,  $c$  the speed of light, and  $d \gg c/f$ , at least such that both antennas are in FF of one other. In general, the OTA path is treated like any other component in the system. Similar to how two coax cables with different connectors require an adapter for connection, the connection from the coax to the air must be "adapted" using antennas. Both the OTA path and the antenna will introduce frequency-dependent attenuation and gain.



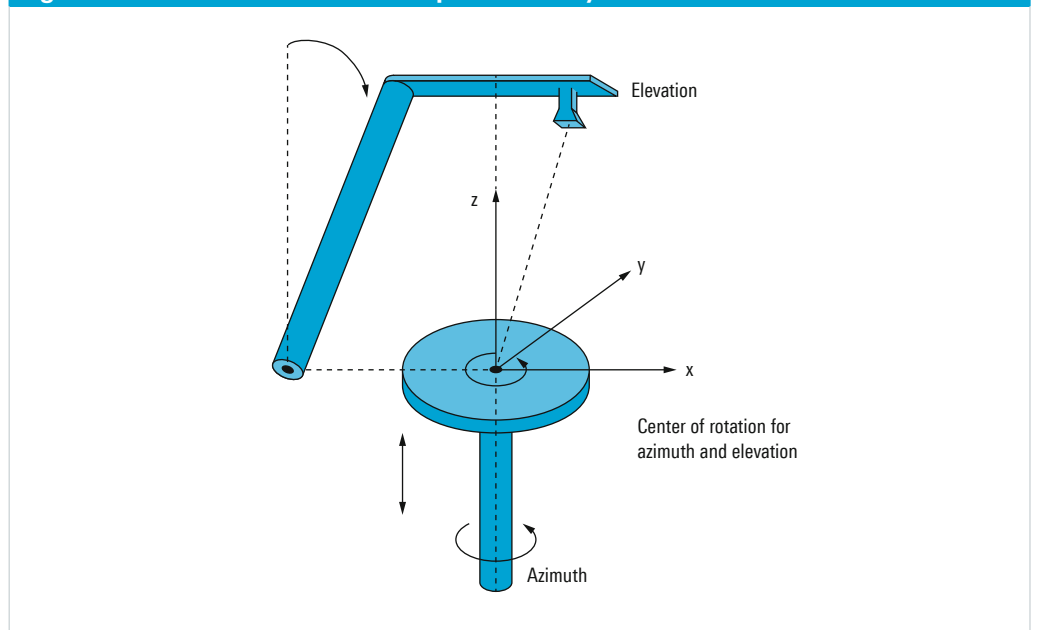
Compared to cable attenuation, FSPL has much higher path loss at typical measurement distances. For example, the attenuation of a 5-meter cable at 1 GHz is typically below 2 dB, while the free space path loss for the same distance and frequency is about 46.4 dB. At 40 GHz, the attenuations are about 13 dB and 78.5 dB, respectively. Therefore, even at small distances and across all frequencies, significant attenuation is introduced into the system.

As mentioned, the OTA loss will make up the majority of the losses in the system. However, measurements with mm-waves in large chambers require long cables with significant additional losses even for the conducted part of the setup, further reducing the received signal level. Therefore, OTA applications in general and mm-wave applications in particular require a high dynamic range in the test equipment.

### 3.1.2 Positioning system

If the test range features some kind of positioning devices, the phase center of the DUT must be placed in the rotation center of the positioning setup. This way, the distance between the DUT and probe antenna stays constant, independent of the measurement angle. Therefore, path loss calibration only has to be conducted for a single direction, as all directions exhibit the same path loss and phase shift. With increasing frequency, the correct positioning in the phase center becomes more important as the wavelengths get shorter. The mechanical setup will add measurement uncertainty depending on the accuracy of positioning and the used frequency range.

**Figure 20: Center of rotation in a positioner system**



### 3.1.3 Specifics of different types of test ranges

Different types of test ranges, e.g. DFF in FAC, CATR, PWC or NF, require additional precautions for correct use of these chambers.

For measurements in FACs, the absorber quality is one key component in creating accurate measurements. The absorber material and shape as well as the chamber size limit the useable frequency range of individual chambers.

With a CATR system, the alignment of the reflector or lens and feed antenna is especially important. For the best performance, the feed antenna must be in the focus point. Additionally for reflector-type CATR, interference caused by the feed to the quiet zone must be mitigated using additional absorbers around the feed antenna.

With plane wave conversion setups, the calibration and accuracy of the amplitudes and phases of all antenna elements of the measurement array define the quality of the quiet zone. Therefore, on top of the typical path loss calibration as performed on all FF systems, calibration of the measurement array itself is key. Typically, a dedicated calibration antenna array is used for this task.

For NF, high positioning accuracy is necessary including stringent requirements for the mechanical alignment, especially in case of high frequency measurements.

Generally, when determining the relevant precautions for a certain type of test range, it is important to consult with a local specialist.

### 3.2 Path loss calibration

To compensate for the OTA losses, a simple path loss calibration is the most straightforward way to calibrate the OTA setup. Since the DUT replaces at least one of these antennas after calibration, a reference antenna with known gain used in place of the DUT is required for a path loss calibration. Note the difference between **gain** and **realized gain**, as described in Chapter 2.2.5.

As discussed in Chapter 3.1.2, the calibration measurement is only required for a single angle of the positioning system. Still, calibration of both polarizations is required in case of a cross-polarized probe antenna, as the two polarized antennas have different characteristics and are attached to different signal paths.

During path loss calibration, the main beam direction (direction of peak gain) of the reference and measurement antenna must be aligned, facing directly towards each other and with matching polarization. Additionally, the phase center of the reference antenna is positioned in the rotation center of the positioning system (see Figure 20). If no positioning system is used, a fixed point in space is determined as the calibration location. For subsequent measurements, the phase center of the DUT is positioned at the exact same location.

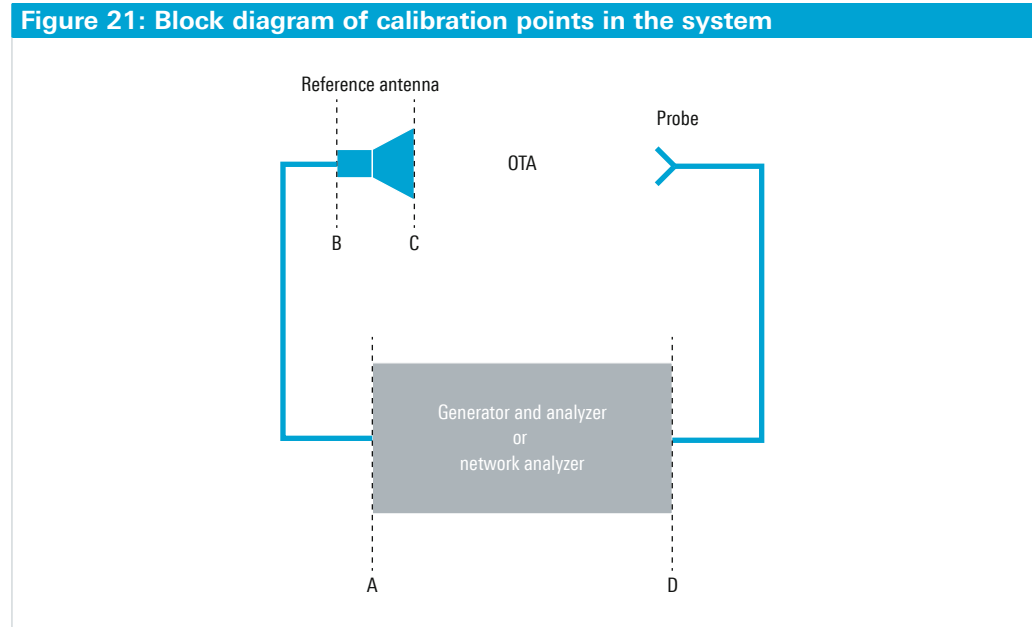


Figure 21 shows the different calibration planes of interest in a typical OTA system. Typically, correction values for either side of the reference antenna are determined. Depending on the type of DUT/AUT, knowledge of the two individual losses  $L_{AB}$  and  $L_{CD}$  is

required, while some simpler measurements can also be conducted with knowledge only of the full system loss  $L_{AB} + L_{CD}$ .

When measuring the antenna pattern and realized gain of a fully passive AUT, it is not important whether the signal losses occur at A-B or C-D. The antenna pattern and realized gain will be unchanged, independent of the signal power at point B. However, if the matching of an antenna is to be evaluated, individual calibration of A-B and C-D is required. The same is valid for all DUTs that have a non-linear power response. If the DUT is actively generating or receiving the signal without any RF connection, only  $L_{CD}$  is of interest, while  $L_A$  is required during calibration.

### 3.2.1 Two-step calibration for all DUTs

With regard to Figure 21,  $L_{AB}$  is the loss between A and B, and  $L_{CD}$  is the OTA and cable loss between C and D, also including the probe antenna gain. To determine both  $L_{AB}$  and  $L_{CD}$ , a two-step calibration sequence is conducted in which the cable loss  $L_{AB}$  and the overall system loss  $L_{AD}$  are determined using either a signal generator and analyzer or a network analyzer.  $L_{CD}$  can then be determined as

$$L_{CD}(f) = L_{AD}(f) + G_{ref}(f) - L_{AB}(f) ,$$

with  $G_{ref}$  being the known realized reference antenna gain, and all values assumed in decibels. With the two calibration values known, the reference antenna can be replaced with any unknown AUT.

On top of frequency, more dimensions may be required since the losses can also be influenced by the used power level or even ambient temperature, depending on the types of components used in the test system. Always choose the number of calibration dimensions according to the relevant characteristics of the used components, such as the linearity of a power amplifier used in a signal path.

### 3.3 Near field calibration

When transforming measured NF data into FF, path loss calibration is not always required. Both amplitude and phase information is required for the two orthogonal polarizations to transform the data to FF in postprocessing. The data for both polarizations can be measured either by rotating the measurement antenna (probe) to the orthogonal polarization or by parallel measurement with a dual-polarized probe. Simultaneous measurement of both polarizations effectively halves the measurement time, but requires calibration data to compensate for the difference between the two signal paths. Referring to the two signal paths and their relative difference in amplitude and phase being balanced, this calibration is called "channel balance" calibration.

Note that it is not necessary to know the realized gain of the reference antenna used during calibration for the transformation to far field directivity. However, when performing absolute "path loss" calibration including phase information, this calibration can also be used for NF measurements and NF to FF transformations. With information about the reference antenna gain, the AUT gain and efficiency can also be determined after transformation. When operating an FAC, it is therefore beneficial to always calibrate for phase as well – if possible with the measurement equipment used, since the same chamber can then be used for NF measurements too.

This is especially true if measurements are conducted at the boundary between NF and FF. The quality of measurements in the region of the Fraunhofer distance may be evaluated using NF-FF transformation. Applying the transformation to measurements can be used to identify the differences between pre- and post-transformation data. If NF effects are within the margin of MU or only occur in regions not important for the current

evaluation of the DUT, transformation may not be required for subsequent measurements. The less planar the wave and the more complicated the radiation pattern, the greater the need for NF-FF transformation.

### **3.3.1 Further requirements for near field to far field transformation**

For an NF-FF transformation to yield valid FF data, comparable to a measurement in a DFF chamber, the effects of the measurement probe must also be corrected in post-processing. More precisely, the spatial response of the probe must be compensated. The transformation is based on the assumption that only a single field component is measured in a single point in space. In reality, however, the probe will respond to more than one field component and has a spatial extent over a finite region [8]. The differences cause a deviation between the electromagnetic field radiated by the DUT and the voltage as assessed by the probe. For example, [9] studies the influence of geometrical parameters of open-ended waveguides and pyramidal horn probes on the voltage received by the probe. The effects of compensation are smaller if the NF measurement is already a good representation of the field [10].

### **3.4 Signal source for calibration**

How to decide whether using a CW signal, modulated signal or noise source is the best choice for the calibration? Which power level should be used and what type of receiver is best qualified?

In general, calibration can be performed with different types of T&M equipment. For example, scattering parameter measurements with any network analyzer can determine frequency response in both amplitude and phase as well as the reflection coefficient. With a signal generator and spectrum analyzer, or any test source and power meter, amplitude calibration is possible, while phase and matching calibration generally are not. Calibrations with CW signals require a frequency sweep with a number of measurement points. While network analyzers are typically fast in sweeping CW signals over multiple measurement frequencies, manual sweeps with generator and analyzer can be more time-consuming. Therefore, modulated signals may be used to determine the frequency response over a given bandwidth. Here, the limiting factor is the baseband bandwidth of the generator and analysis bandwidth of the analyzer. Also, the exact characteristic of the modulated signal must be known and the signal should exhibit a flat signal bandwidth.

In the end, it comes down almost exclusively to which devices are available or planned to be used for later measurements. If a device is to be used for measurements, it should also be used for correction of the setup. Otherwise, the measurement uncertainty can rise due to additional adaptation between instrument connectors, additional switching or other calibration overhead being required on top of the combined measurement uncertainty of both instruments.

For passive antenna measurements, a network analyzer is the most obvious choice as it can quickly sweep with high accuracy over a large bandwidth; it can determine all scattering parameters and is accurate in both amplitude and phase. Port calibration can be used to move the calibration planes easily and the OTA calibration can be used on top. For active antenna measurements, VNA might still be a valid option due to individual use of receiver and/or transmitter as well as the possibility to perform a power calibration to the DUT reference calibration plane. When introducing modulated signals and/or if the DUT features baseband processing, signal generators and analyzers may take the lead position.



Figure 22: R&S®ZNA used for antenna measurements

When deciding the power level for calibration, the type and quality of the chamber must be considered. For chambers with sufficient absorption, it makes sense to calibrate the system at the power level that yields the lowest measurement uncertainty with the T&M equipment used. If nonlinear components with different frequency responses or different power levels are used in the system, the calibration values must be valid for the range of powers where the DUT will be operated. If it is expected that reflections inside the chamber might introduce unwanted interference to the calibration value, the power should be as low as possible, operating the receiver close to the noise floor. This way, the noise level of the instruments and inside the chamber may also be determined.

### 3.5 Chamber verification

On top of the link calibration for a given setup, the used chamber must fulfill certain criteria in order to qualify for correct measurements with limited measurement uncertainty. In general, it is important to verify the shielding and reflection absorption quality of the chamber.

For electromagnetic compatibility (EMC) testing, different calibration and verification methods are defined and standardized. Examples are site voltage standing-wave ratio (sVSWR) measurements, normalized site attenuation (NSA) measurements or field uniformity measurements as defined by CISPR, ANSI, IEC and EN.

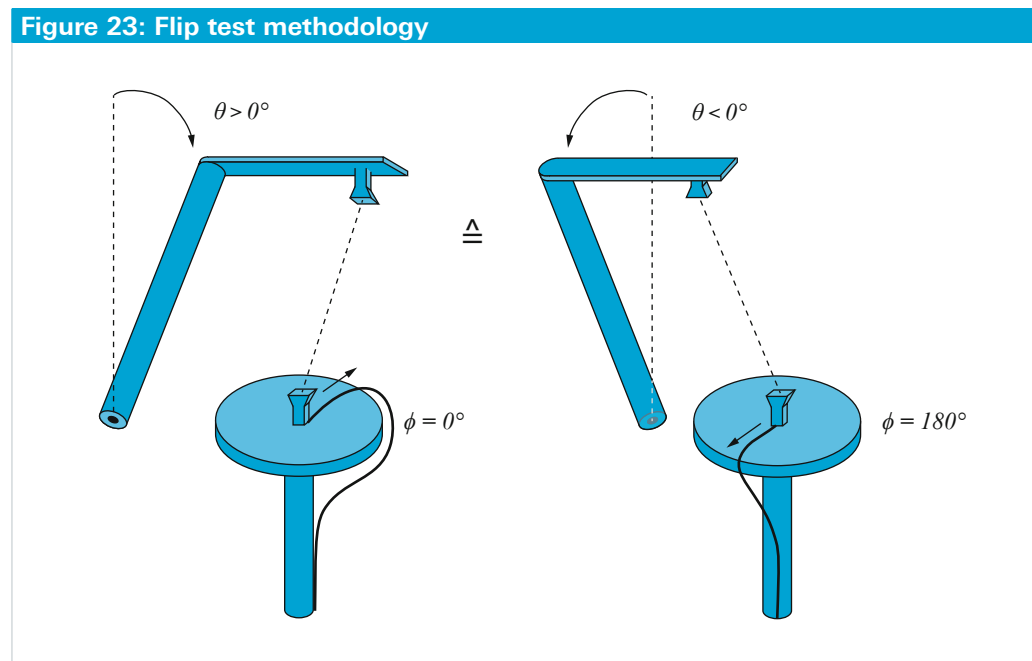
For antenna testing, the QZ quality and the accuracy and reproducibility of measurements are of high interest. As moving or interchangeable parts are involved, the mechanical quality of the setup will also influence the resulting measurement accuracy.

#### 3.5.1 Mechanical alignment

The mechanical alignment of the DUT and positioner setup are especially important when measuring phase information, for example to perform an NF-FF transformation. At short wavelengths, a few millimeters of mechanical misalignment can have a significant impact on the phase deviation in the measurement.

The alignment of both rotation axes to meet in the center of rotation must be verified during site acceptance. For aligning the DUT phase center at this position, additional help, e.g. laser guidance or automated positioning, may be used.

When the phase center and rotation center are aligned, the accuracy along the elevation axis of conical-cut positioners can be confirmed electrically by performing a flip-test. During this test, multiple elevation cuts are measured over the elevation in the positive and negative direction for pairs of azimuth orientations, offset by  $180^\circ$ . For each pair, the amplitude measured at positive elevation with the first azimuth orientation is identical to the amplitude measured at negative elevation of the second orientation, and vice versa. For example, a measurement at  $0^\circ$  azimuth,  $10^\circ$  elevation is identical to  $180^\circ$  azimuth,  $-10^\circ$  elevation. The phase will experience a  $180^\circ$  shift. If the azimuth and elevation rotation center are not aligned perfectly, differences will occur in the measurement.



### 3.5.2 Quiet zone verification

For all types of chambers, the quiet zone (QZ) defines the area in which deviation of the amplitude and phase from the plane wave criteria is limited. For DFF measurements, predominantly the phase will deviate continuously towards the edges of the QZ. This cannot be mitigated due to the layout of the test range, as it is inherent in the test range layout. Unwanted residual reflections in the chamber may create standing waves causing ripples in amplitude and phase that should be minimized by using appropriate absorber material. The amplitude can experience a taper over the quiet zone caused by the radiation pattern of the probe antenna. For CATR systems, amplitude taper is also caused by the non-uniform antenna pattern of the feed that is translated to non-uniform field strength in the reflected QZ. Ripples can be observed in both amplitude and phase. They are mainly caused by imperfections in the reflector.

In any case, the quality of the QZ must be established by measurements in both amplitude and phase over the area the QZ encompasses. Using the same antenna and preferably an automated positioning system, measurements at different locations in the QZ are conducted to compare the relative amplitude and phase offsets and characterize the taper and ripple in the QZ.

### 3.5.3 Golden device measurement

A golden device, or golden sample, is a DUT with known characteristics. It is an easy but reliable way to verify measurements or calibrate a setup.

Such a device can be used to compare the measurement results in a setup with the known ideal values. The use of a reference antenna during path loss calibration therefore also qualifies as a golden device. The actual measurement is corrected to fit the known antenna gain. If repeated multiple times, identical results within the margin of measurement uncertainty are expected for a stable setup.

On top of usage during calibration, where only a single direction is evaluated, the 3D pattern of the amplitude and phase can be of interest in order to evaluate the quality of measurement in the given setup. Deviations over the pattern may be caused by positioning errors or unwanted reflections in the test range, for example.

When dealing with higher product integration than simple antenna characterization, a golden device is used as the reference to which all other devices of the same type can be compared. In this scenario, a system calibration might even be unnecessary as the comparison to the golden device has a comparable purpose, like the gain of an unknown antenna is compared to the gain of the reference antenna used during calibration for antenna characterization.

In summary, a golden device can be used to identify any deviation of other (similar) devices from the "golden standard" but also to identify deviations of the test setup from the expected results, e.g. for calibration, verification or repeatability tests.

### **3.6 Measurement uncertainty**

The measurement uncertainty itself is defined by the European Telecommunications Standards Institute (ETSI) as "a parameter, associated with the result of a measurement that characterizes the dispersion of values that could reasonably be attributed to the measurand" [11]. Calculating the measurement uncertainty is very complex and requires extensive knowledge of all components used in a test system as well as knowledge about the performance of the DUT for which a measurement is to be done. The type of measurement equipment, test range, methodology of calibration and verification and DUT itself can and will have an effect on the overall measurement uncertainty.

ETSI has compiled extensive material on the definition and calculation of measurement uncertainty with regard to radio spectrum matters [11] [12], which will not all be covered in this paper.

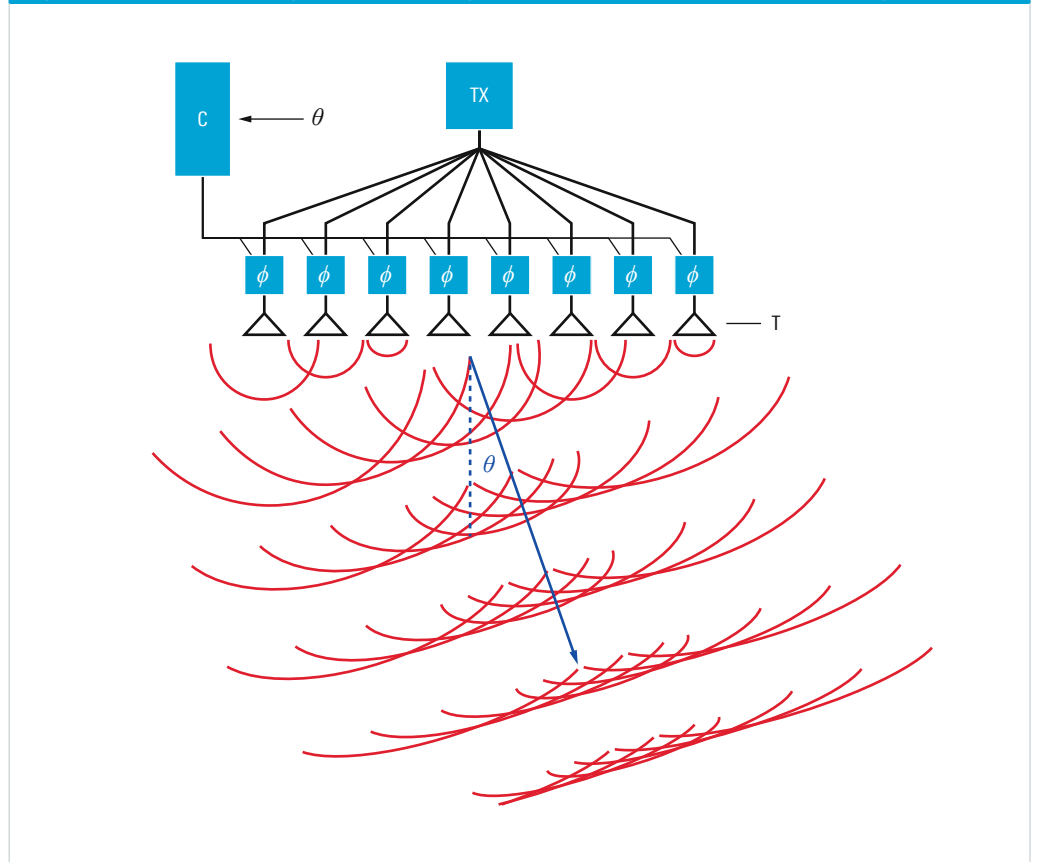


## 4 Array antennas and beamforming

With the increased usage of mm-wave signals in communications systems, higher signal attenuation and decreased antenna size have led to the necessity of using multiple antennas that are combined to form an array antenna. Array antennas allow the use of beamforming and beamsteering to focus the energy in certain directions. This leads to higher signal power counteracting the attenuation due to path loss and enables spatial multiplexing of users since interference for users in different directions is significantly reduced by the directed wave.

Antenna arrays can make use of beamforming by transmitting the signal on multiple elements at a time and applying a relative amplitude and phase difference between those elements. The wave fronts of all individual elements overlap to form constructive interference in the desired direction. For reception, signals from different directions are received with a certain phase difference and by summation of all signals with the respective phase offset, only signals from the desired direction are recovered.

**Figure 24: How analog beamforming is used to steer the beam to angle  $\theta$**



In addition to the desired direction, the array will also create side lobes that result in constructive interference in undesired directions. This can be mitigated through various methods for side lobe reduction, for example by using non-uniform element spacing [13], genetic algorithms [14] [15], or by applying an amplitude taper over the array, leveraging windowing techniques already known from designing finite impulse response (FIR) filters.

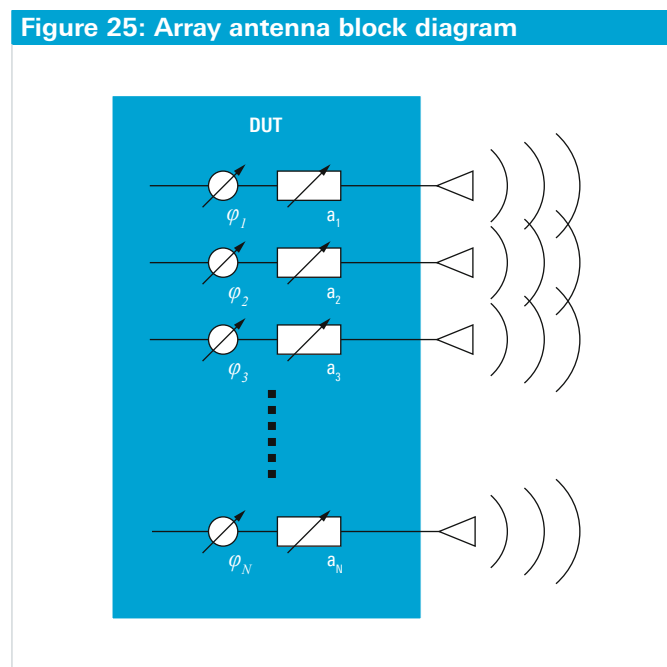
Figure 24 shows the concept of analog beamforming. The RF signal is phase adjusted per antenna element in the RF domain, for a single signal after DAC in transmit mode. Analog beamforming can only apply a spatial filter on a single signal. Analog beamforming is relatively cheap to integrate and allows better coverage of a system.

In contrast, digital beamforming applies amplitude and phase variations in the digital domain, before DAC in transmit mode. Every element requires an individual DAC/ADC and baseband processing. With digital beamforming, parts of the same signal can be radiated in different directions, or signals from different directions can be received simultaneously and extracted individually, or interference from certain directions can be mitigated. It also allows frequency-selective beamforming.

Digital beamforming is more flexible and can improve the capacity of a system. However, it is more costly and power consuming compared to analog beamforming.

On top of analog and digital beamforming, hybrid forms are possible as well. Then, each ADC/DAC of the digital beamformer is connected to multiple elements featuring an analog beamformer on top. Hybrid beamforming can be used to leverage the power of digital beamforming without requiring a transceiver chain for each antenna element.

#### 4.1 Calibration of array antennas



Since the amplitude and phase of each element are used to steer the resulting beam, calibration is required for the individual elements of the array antenna. While the design and verification of beamforming antenna arrays pose test and measurement challenges on their own [16], performing fast and accurate calibration of these arrays is especially important in production.

Array calibration can either be performed conducted or OTA, depending on the ability to connect to the antenna layer. For conducted measurements, measurement of the amplitude and phase difference is trivial and can be performed per element individually. With OTA, the applicable calibration techniques depend on the type and capabilities of the DUT.

With at least one RF input, calibration can be performed using external signal generators and analyzers or a network analyzer. If the array has multiple RF ports, multiport network analyzer solutions may be applicable. If the DUT has internal signal processing, the calibration type depends on the capability and number of transceivers in the DUT.

For **parallel** calibration, if possible, some or all elements are stimulated with signals at different frequencies and the combined multitone signal is used to determine the amplitude and phase relative to one defined reference element in a single measurement. Frequency division is applied to separate signals from individual elements in the receiver, similar to the frequency division multiple access (FDMA) technique. Similarly, code division multiple access (CDMA) may be used to differentiate signals from individual elements at the receiver, determining amplitude and phase offsets in a single measurement. Sufficient baseband processing or RF connectors for signal generators must be available to send different signals on different elements at the same time.

Fully **sequential** calibration, or a time division multiple access (TDMA) based determination of amplitude and phase, is straightforward if the generator and receiver share a common reference clock and are phase-coherent over time. If phase coherence is not possible, frequently switching back to the reference element makes it possible to establish the common phase error that can be removed from the measurement in post-processing. This technique requires  $N$  measurements for a phase-coherent setup and up to  $2 \cdot N + 1$  measurements for a setup without phase coherence, where  $N$  is the number of elements.

During a power-level calibration, pairs of elements are active at a time and a receiving antenna is positioned in boresight of the array. The phase shift of all elements relative to a defined reference element is determined by sequentially setting the phase shifter of one element to different values and measuring the combined power of the two elements. Maximum power is achieved in boresight when the signals from two elements are phase-aligned. Compared to the maximum, the null ( $180^\circ$  phase shift between elements) is more distinct, making calibration for null easier and faster. Without using logic to reduce the search space, phase calibration requires  $(N - 1) \cdot M$  measurements, where  $M$  is the number of possible phase shift settings. The amplitude offset per element is measured for each element individually, adding  $N$  measurements.

## 5 Summary

Modern highly integrated chipsets, frontends and antenna systems require new techniques for over-the-air measurements in a multitude of development steps. Integration of the antenna or antenna array into the chipset pose challenges in beamforming verification and chipset or amplifier testing. With the use of state-of-the-art test and measurement equipment in lab environments, shielded boxes or large anechoic chambers, the challenge of OTA testing largely comes down to understanding key challenges in antenna measurement and chamber setup. This white paper delivered an introduction to both topics, getting engineers new to OTA tests up to speed with key terminology and tools to solve measurement issues.

Array calibration was touched upon in order to summarize the key challenges in this related field of work. With massive MU-MIMO and dynamic beamforming ready for deployment at larger scale in the immediate future, more developments in this field are sure to come.

With our expertise in cellular and wireless technology, EMC and OTA testing, Rohde&Schwarz is your trusted partner for solving the test and measurement challenges ahead.



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