Antenna Array Testing - Conducted and Over the Air: The Way to 5G

White Paper

Products:

- R&S®ZVA
- R&S®ZNB
- R&S®ZNC
- R&S®ZNBT
- R&S®ZVT
- R&S®TS8991
- R&S®TS7124
- R&S®NRPM3

- R&S®ZN-Z84
- R&S®ZN-Z85
- R&S®SMW200A
- R&S®SMBV100A
- R&S®FSW
- R&S®FSVA
- R&S®DST200
- R&S®NRPM-A66

5G networks will need to offer more capacity and flexibility while lowering the operational expenses of the system. Two new technologies can simultaneously address both the increase in capacity and the increase in energy efficiency: Virtualization & Massive MIMO. This white paper provides an overview of test solutions addressing current and future requirements for antenna verification including both conducted and over-the-air (OTA) test methods, which result from applying Massive MIMO antenna technology.

This white paper complements the "Millimeter-Wave Beamforming: Antenna Array Design Choices & Characterization" white paper (1MA276) from Rohde & Schwarz [9], which introduces fundamental theory behind beamforming antennas and provides calculation methods for radiation patterns, a number of simulation results as well as some real world measurement results for small linear arrays.

Note:

Please find the most up-to-date document on our homepage

http://www.rohde-schwarz.com/appnote/1MA286

ROHDE & SCHWARZ

1 Introduction: What is 5G?

5G carries different meanings for different segments, ranging from new use cases of massive Machine Type Communications (mMTC) and Ultra-Reliable & Low Latency Communications (URLLC) in addition to the increase of capacity to new ultra-high frequency bands in the millimeter wave region. From a business perspective, the new 5G networks will need to offer more capacity and flexibility while lowering the operational expenses (OPEX) of the system. The simplest method to increase capacity is to increase the numbers of base stations in the network, but due to the cost of real estate and energy consumption, the expenses will scale at almost the same rate of capacity improvement. Since revenues do not scale at the same rate, this method will have limited implementation; rather it is better to use new technology that targets both an increased capacity while lowering the energy consumption of a base station. As illustrated in Figure 1-1, the bulk of the base-station OPEX is energy consumption and real-estate rental. Two new technologies can simultaneously address both the increase in capacity and the increase in energy efficiency: Virtualization & Massive MIMO.
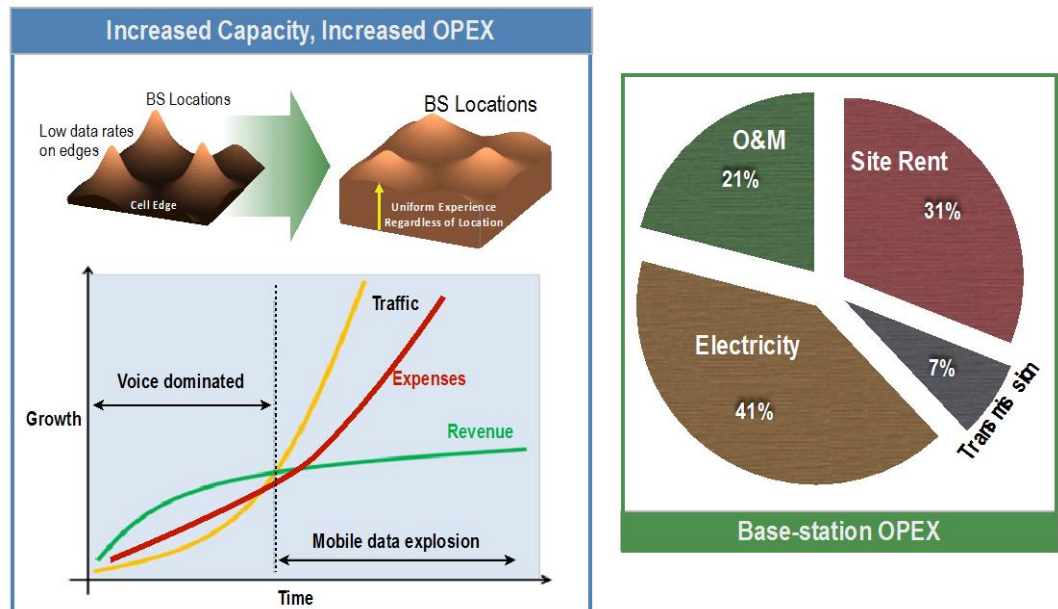
Figure 1-1: Revenue and Expenses of Cellular Networks

By centralizing the base-band processing into a data center using Centralized-Radio Access Network (C-RAN) technology, the air conditioning costs can be reduced significantly, leading to a reduction in OPEX of up to 50% [6]. Each base station becomes a virtual machine inside the data center, leading to enhanced capacity gains using Coordinated Multi-Point (CoMP) and coordinated radio (Figure 1-2). This concept can be further extended to additional network components to form a software-defined network (SDN).

MIMO increases cell capacity without modification of waveforms, multiple access schemes, etc. by transmitting parallel data streams. Current 4G systems use single user MIMO where the user equipment (UE) calculates the inverse channel matrix in order to extract the separate data streams (Figure 1-3). The system complexity resides in the UE, leading to shorter battery lifetimes when MIMO processing is used. Multi-
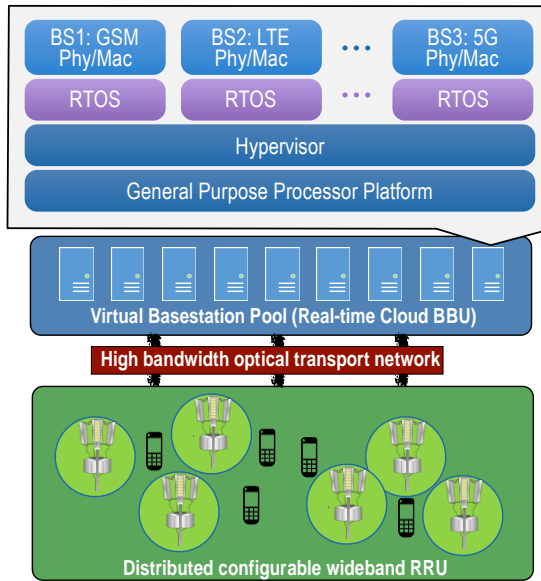
Figure 1-2: C-RAN Virtualization

user MIMO (MU-MIMO) moves the complexity from the UE into the base station by using a pre-coding matrix such that each data stream is received independently by separate receivers. In order to transmit different power levels to different users (generalized case) in an MU-MIMO scheme, beamforming is required.

In addition to facilitating the adoption of MU-MIMO to increase the cell capacity, beamforming can significantly reduce the energy consumption as well by targeting individual UEs with their assigned signal. In a normal base station without beamforming, the extra energy that is not received by the UE gets absorbed into the environment or creates interference for adjacent UEs.
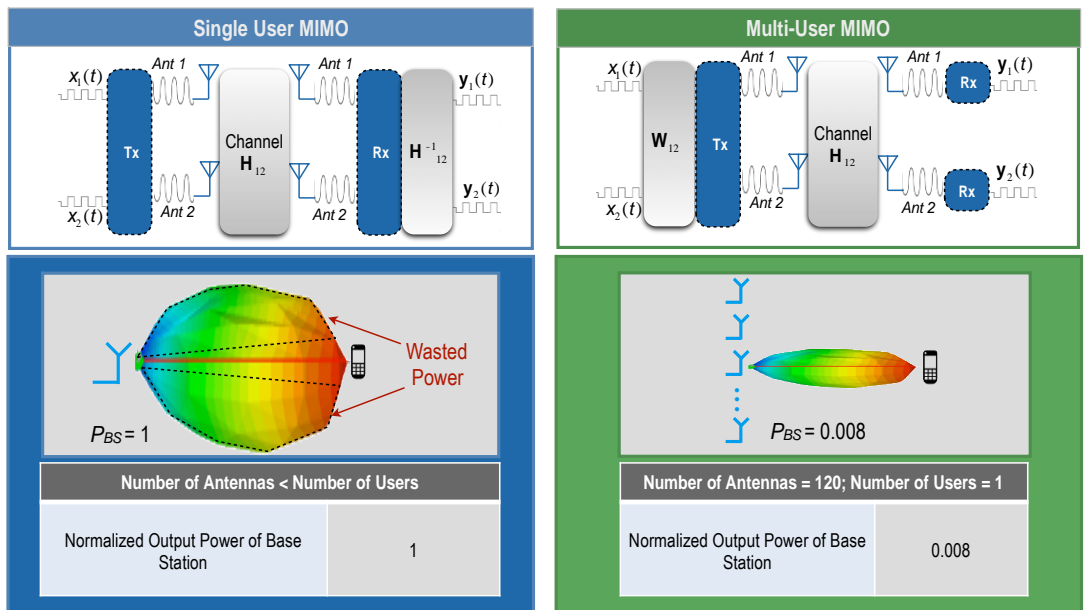

Figure 1-3: MU-MIMO with Beamforming

This white paper provides an overview of test solutions addressing current and future requirements for antenna verification including both conducted and over-the-air (OTA) test methods.

2 Background

2.1 Radiated Fields

The electromagnetic fields from any antenna can be described and measured in two different regions: the near field and the far field. In the near-field region of the antenna, defined as less than twice the square of the antenna aperture divided by the wavelength of operation (Figure 2-1) the field consists of both reactive and radiated components; whereas the far field of an antenna has only the radiated component. For an OTA system, this means that in order to characterize the antenna radiation performance, the measurement can be performed in either the near-field or the far-field region. In the near-field region, a precise measurement of both the phase and the magnitude of the received electromagnetic field is required for mathematical transformation to the far-field region, resulting in the antenna 2D and 3D gain patterns. A measurement in the far-field region only needs the magnitude of the field in order to calculate the beam pattern of the antenna.

$$0.62\sqrt{D^3/\lambda} = 0.6 \text{ m} \qquad 2D^2/\lambda = 4.5 \text{ m}$$

Antenna Aperture: $D = 0.5$ m
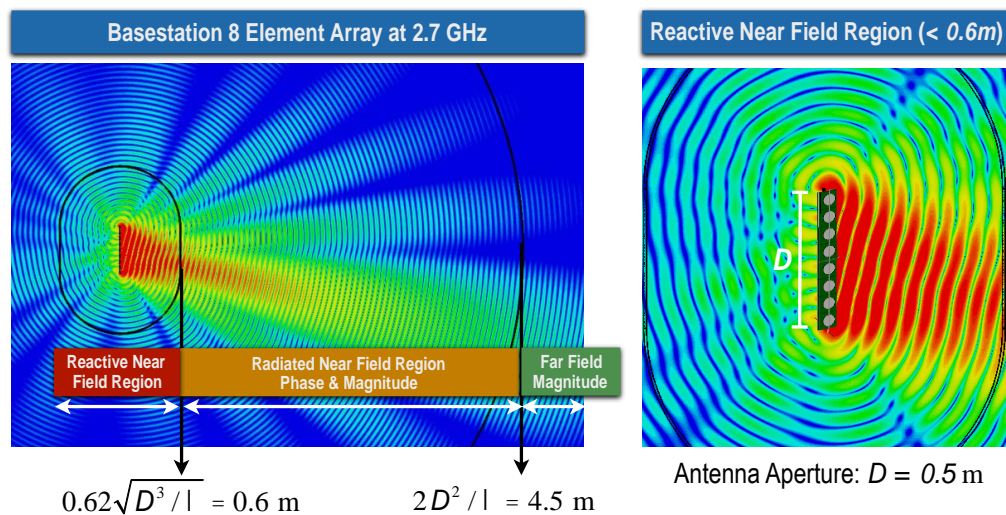
Figure 2-1: Electromagnetic fields outside a basestation antenna array of eight circular microstrip antenna patches at 2.70 GHz with uniform excitation D is the maximum antenna aperture or size [5]

Table 2-1 lists the distances of the boundary between near and far fields for different devices (UE terminal equipment and basestations) for both traditional cellular frequencies and the new millimeter wave (mmWave) frequencies being considered for 5G. For lower frequencies and smaller devices, it is possible to measure in the far-field region, consequently only requiring a magnitude or power measurement. In the mmWave region, the size of the device dominates over the smaller wavelength and it becomes impractical to measure in the far field for anything larger than a small device under test (DUT).

Table 2-1: Far Field Distances (meters)

DUT	DUT Size (m)	Cellular @ 2.7 GHz (m)	mmWave @ 28 GHz (m)
UE	0.13	0.3	3
Laptop	0.36	2	24
Small Cell Base Station	0.50	4.5	47
Macro Cell Base Station	1.00	18	187

2.2 Active Antenna Systems

The critical difference between passive and active antenna systems is that from a measurement standpoint a passive antenna system contains RF I/O ports that allow conductive measurements where a cable directly connects the passive antenna to the measurement system (Figure 2-2).
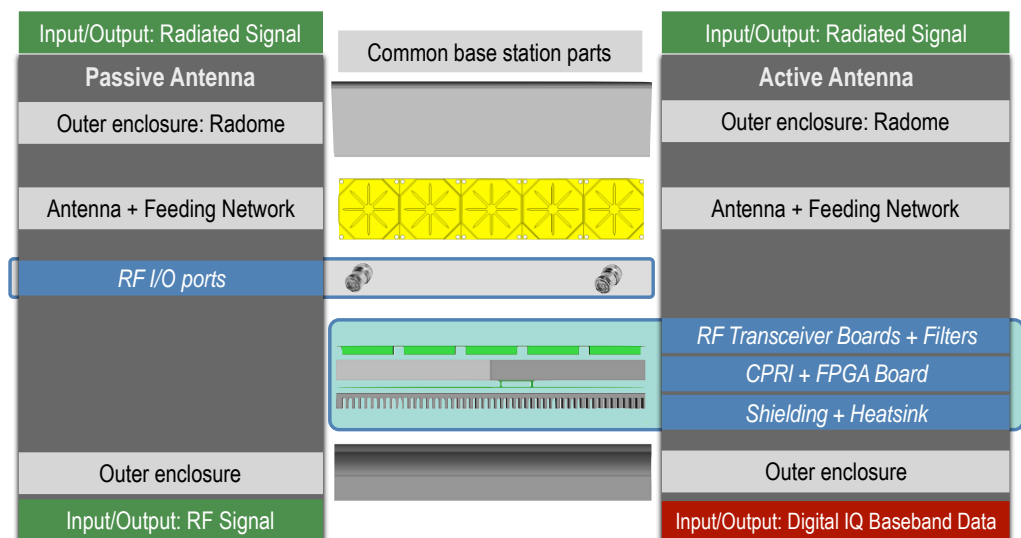

Figure 2-2: Passive (conducted) vs. Active Antenna System

In an active antenna system, the remote radio head (RRH) is directly integrated together with the antenna array. The traditional RF I/O ports are replaced by a fiber interface for the digital I/Q data. Currently the fiber interface uses a protocol called CPRI (common public radio interface, [7]) though this is expected to change for 5G systems due to the capacity bottleneck in CPRI. Although the CPRI protocol is based on an open interface, it also contains proprietary signaling information. Direct and real-time access for external measurement companies to the vendor's digital I/Q data port is difficult and sometimes impossible. This will usher in a paradigm change in RF measurements where all transceiver and RF tests need to be performed over the air. In addition, with restricted access to the digital I/Q data, the phase information in a near-field measurement cannot be as easily obtained as before; giving rise to new and innovative CPRI-free radiation measurements for active antenna systems.

2.3 Antenna Arrays

It is desirable for an antenna system to be able to focus its energy in a particular direction in order to maximize the signal power towards a particular device. Using a half-wavelength dipole as an example, the gain can be increased using two methods (Figure 2-3):

● Antenna aperture: By increasing the aperture (or size of the antenna), the larger antenna becomes more directive due to the periodic current distribution across the antenna. Although this method does not require external circuitry for control, the direction of the beam is fixed and the number of sidelobes increases. Examples include electrically long dipoles, horns, and waveguides.

● Antenna array: If the single dipole element is instead repeated according to the periodicity of the current distribution, an antenna array is created. The amplitude and phase of the signals to individual elements can be adjusted to control both the beam direction and sidelobe levels, creating a "phased array". This results in a significantly more complex feeding network with higher losses than the first method. Examples include RADAR for automotive, aircraft, ships, and satellites.

Single Element

$l = 5\lambda/2$

Phased Array
Feeding Network

Antenna Array

Five $\lambda/2$ antennas
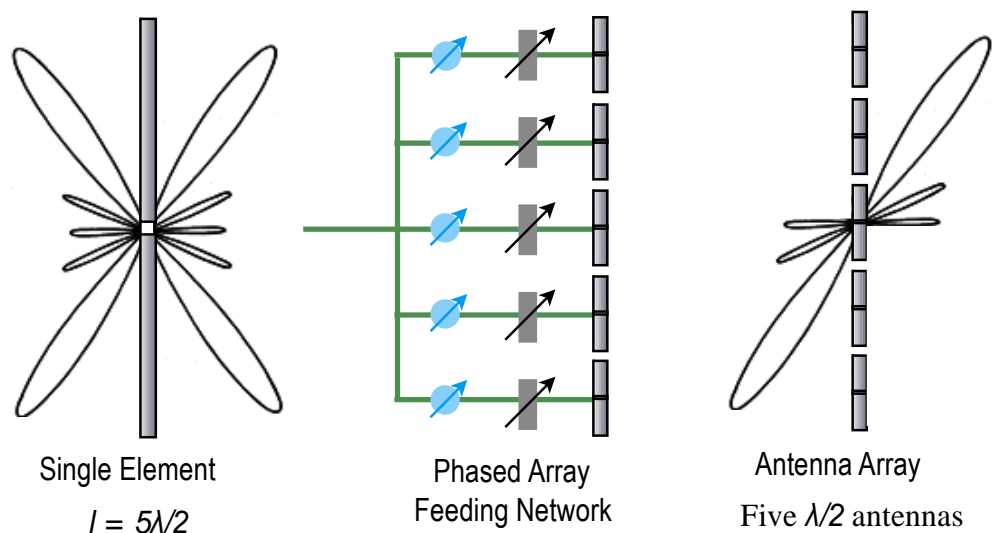
Figure 2-3: Antenna Arrays

Figure 2-4 illustrates the basic mechanism of a phased antenna array with M antenna elements. The antenna elements are usually separated by a distance of half-wavelength in order to minimize mutual coupling. Larger separations result in higher grating lobes. In order to form a beam pointed in a particular direction of θ, the phase differences between antennas are set to particular values. Figure 2-5 shows that by setting a 90 degree phase difference between 8 dipoles separated by half-length, then the beam direction is steered 30 degrees. The resulting main beam has a 0.5 degree broader 3 dB beamwidth and a reduction of peak gain by 0.5 dB.
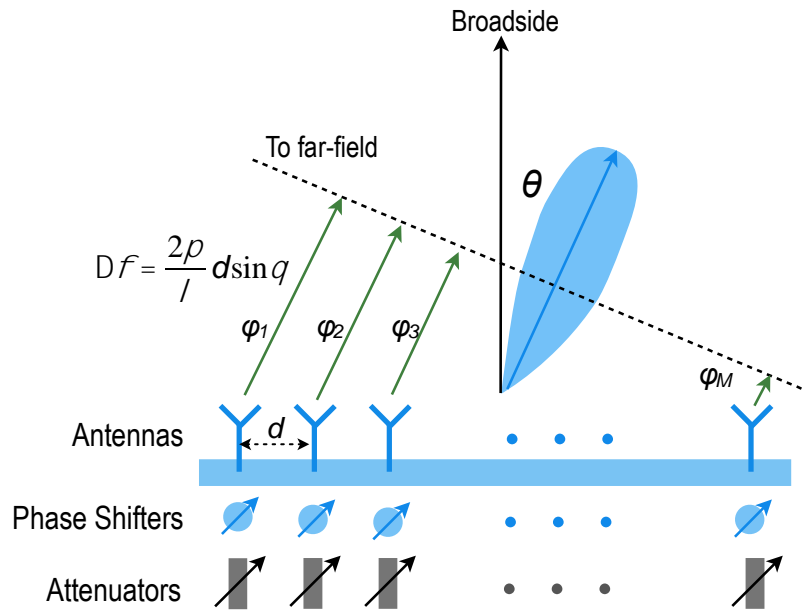
Figure 2-4: Phased Antenna Array

The beam steering capabilities of an antenna array can create both a high gain beam towards a specific direction as well as creating a null in a specific direction in order to mitigate interference in a MU-MIMO system. Therefore, in addition to phase shifting, weighting of the signal amplitude is applied to reduce the side lobes (Figure 2-5). For example, a symmetric linear tapering of the signal amplitudes in the array results in sidelobes that are 10 dB to 15 dB lower, but in a broader beamwidth of the main lobe (5 degree increase).
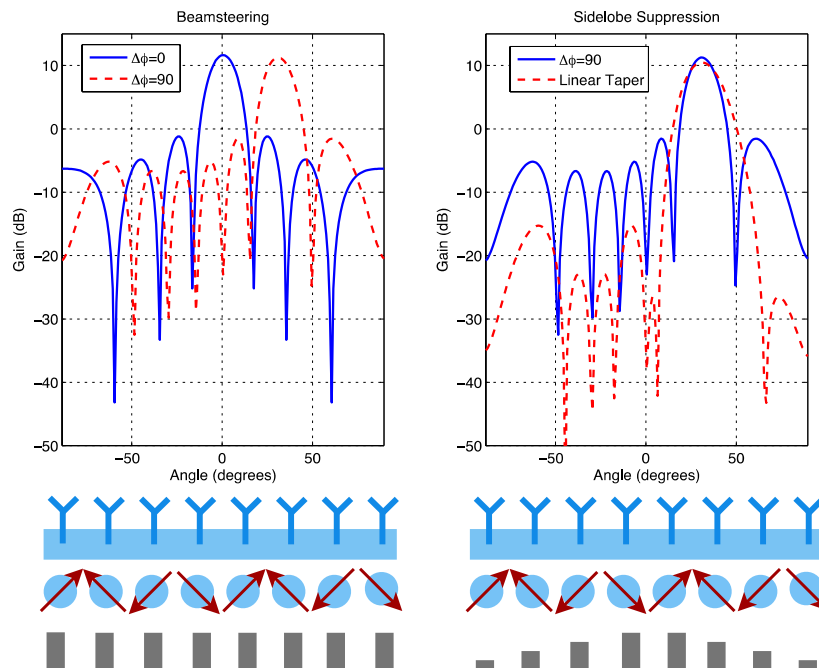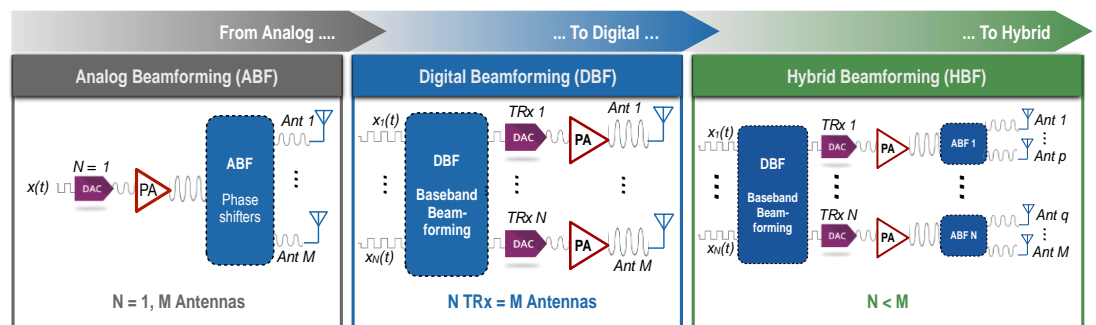

Figure 2-5: Phase and Amplitude Weighting for Antenna Arrays (simulated using CST Microwave Studio)

2.4 Beamforming Architectures

Figure 2-6: Beamforming Architectures for Active Antenna Systems

There are three types of beamforming architectures used for antenna arrays (Figure 2-6):

- Analog beamforming (ABF): The traditional way to form beams is to use attenuators and phase shifters as part of the analogue RF circuit where a single data stream is divided into separate paths. The advantage of this method is that there is only one RF chain (PA, LNA, filters, switch/circulator) required. The disadvantage is the loss from the cascaded phase shifters at high power.

- Digital beamforming (DBF): Digital beamforming assumes there is a separate RF chain for each antenna element. The beam is then "formed" by matrix-type operations in the baseband where artificial amplitude and phase weighting is performed. For frequencies lower than 6 GHz, this is the preferred method since the RF chain components are comparatively inexpensive and can combine MIMO and beamforming into a single array. For frequencies of 28 GHz and above, the PAs and ADCs are very lossy for standard CMOS components. If exotic materials, such as gallium arsenide and gallium nitrate are used, the losses decrease at the expense of high cost.

- Hybrid beamforming (HBF): Hybrid beamforming combines digital beamforming with analog beamforming in order to allow the flexibility of MIMO plus beamforming while reducing the cost and losses of the beamforming unit (BFU). Each data stream has its own separate analog BFU with a set of M antennas. If there are N data streams, then there are NxM antennas. The analog BFU loss due to phase shifters can be mitigated by replacing the adaptive phase shifters with a selective beamformer such as a Butler matrix. One proposed architecture uses the digital BFU to steer the direction of the main beam while the analog BFU steers the beam within the digital envelop (Figure 2-7).
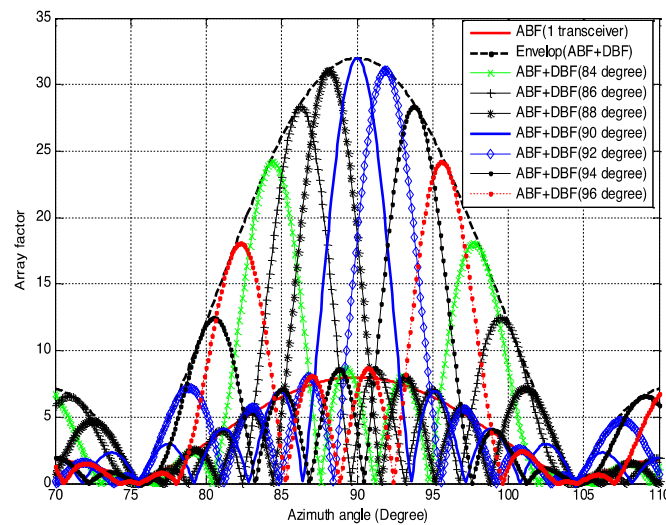
Figure 2-7: Comparison between Analog, Digital, and Hybrid Beamforming [10]

2.5 Array Calibration
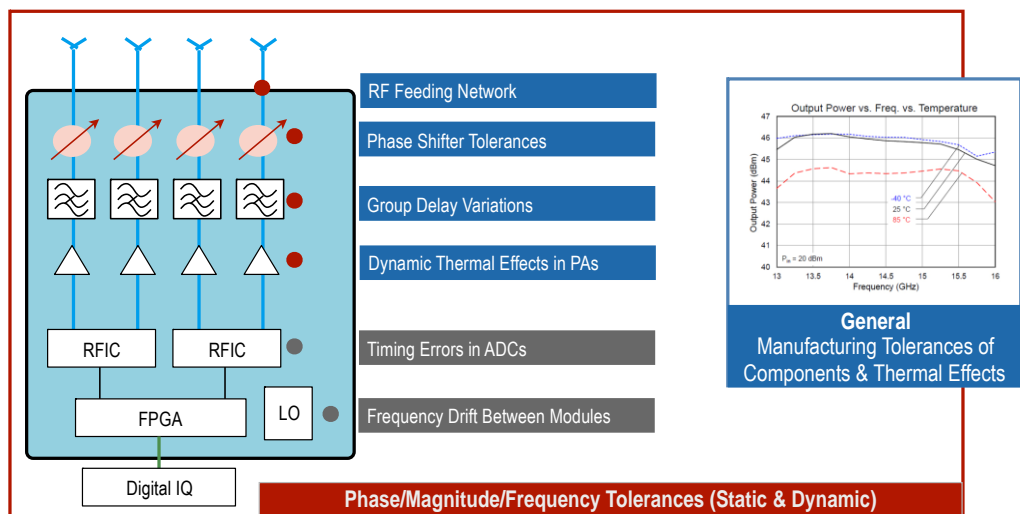
Figure 2-8: Static and dynamic tolerances in antenna arrays

Due to the sensitivity of the antenna array beamsteering to the phase differences between the antenna elements, each array must be calibrated for the following tolerances (Figure 2-8):

● Phase: Phase error can have a large effect on the antenna beam depending on its statistical properties. If the phase error is uniformly distributed across the array, then the main beam direction does not change. Instead, the nulls that are often used to block interference are severely affected, losing 10 dB to 20 dB. If there is a more deterministic phase error distribution, then this will steer the beam in a different direction. Phase error can be caused by manufacturing tolerances in the RF feeding network, thermal effects in the PAs and LNAs, and group delay

variations in the filters. It is recommended to keep the phase error between antenna elements below ±5° (commercial specification for AAS).

● Amplitude: Amplitude error does not affect the direction of the beam, but rather the peak gain and the sidelobe levels and is generally due to the thermal effects on the active components (PA and LNA). Recommended error should be below ±0.5 dB (commercial specification for AAS).

● Timing/Frequency: Depending on the circuit architecture, if a common LO network is not used between modules, there will be frequency drift in addition to the timing errors in the ADCs. Recommended level of frequency drift is 0.5 ppm (commercial specification for AAS).

2.6 Development Process of an Antenna Array

Figure 2-9 shows the simplified typical product development process of an antenna array for an infrastructure supplier. The different phases in this product development process require different measurement and verification methods, thereby using various approaches to measure a Massive MIMO system will require different test interfaces to both the complete antenna array and individual antenna elements.
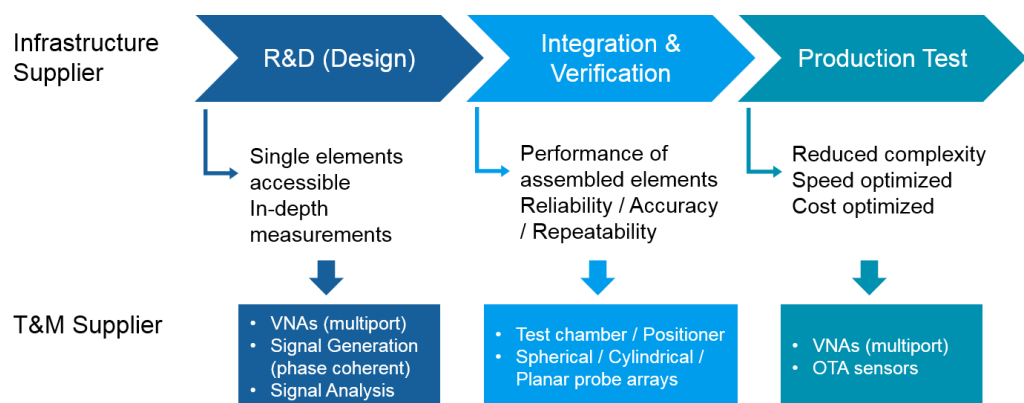
Figure 2-9: Product development process of an antenna array

Antenna arrays with 64 or more elements (corresponding to an 8x8 cross-polarized antenna array) may not provide any individual antenna connectors in the final assembly. In earlier phases of the product design, however, antenna elements are typically accessible with connectors to verify the S-parameters of individual antennas.

Verification and qualification of antenna arrays is required in all product development process phases from initial R&D design to final production test. Mutual coupling (S_{21}) between antenna elements has an adverse effect on network capacity. Therefore simultaneous multiport passive (conducted) measurements for accurate characterization are required.

3 Conducted Antenna Measurements

In the design phase, when antenna connectors are still accessible, a vector network analyzer is used as described in Section 3.1. The VNA, together with a switch matrix, can be used to measure the S-parameters of antenna arrays up to 288 elements.

3.1 Measurements using Vector Network Analyzers

For antenna arrays, the most common measurement with a vector network analyzer are the S-parameter measurements (both transmission and reflection coefficients). The S-parameters contain magnitude and phase information which can be used to measure both near-field and far-field quantities.

▪ Reflection coefficient: $= S_{11} = b_1/a_1$ (reflected power at antenna 1 / injected power at antenna 1)

▪ Transmission coefficient: $= S_{21} = b_2/a_1$ (transmitted power at antenna 2 / injected power at antenna 1)
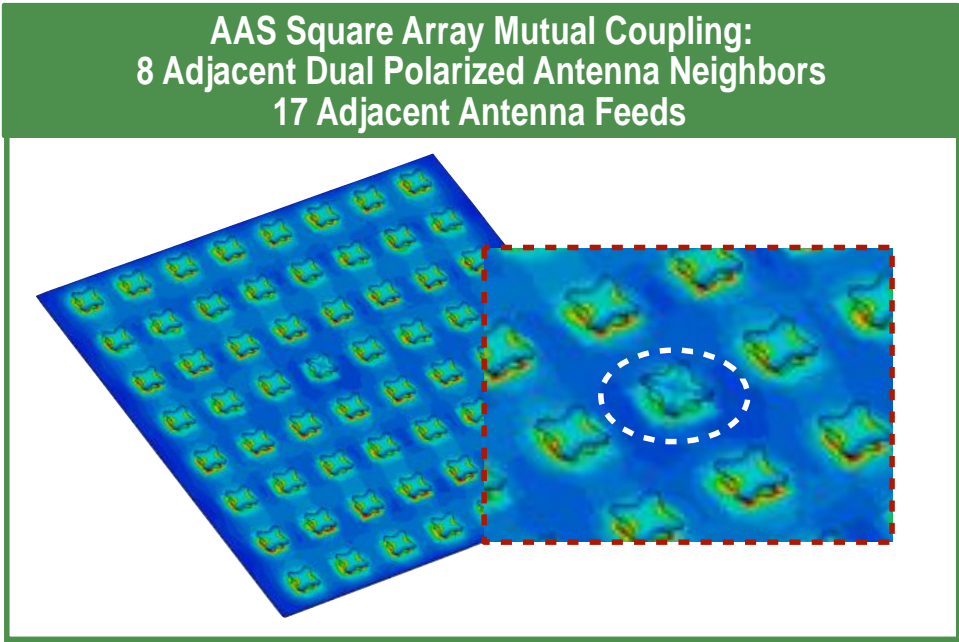
Figure 3-1: Planar antenna array DUT of 64 elements & Mutual coupling between array elements

An example of an antenna array is shown in Figure 3-1 with 64 dual-polarized antennas and 128 antenna ports. Due to the high number of ports, connecting cables and subsequent calibration of the VNA is difficult and time consuming. There are two methods to measure the S-parameters of this array:

1. VNA with two or four ports and a switch matrix

   The VNA is attached to a switch matrix that is connected to the DUT. This method, however, can only measure two to four simultaneous ports. This is not enough ports to accurately measure the total mutual coupling (one antenna element has eight co-polarized neighbors and 17 co-/cross-polarized neighbors).

2. Multiport VNA with multiple ports

   Multiport VNAs simultaneously measure all ports in order to reduce the test duration and perform a complete mutual coupling measurement between one antenna element and its surrounding neighbors. If the number of antenna elements is higher than the number of simultaneous ports (e.g. higher than 24 for the R&S®ZNBT8), switch matrixes can also be added. An additional benefit is that specific tests like "active return loss" (S_{11}, S_{22}, S_{33}, …, S_{2424}) can be measured in parallel with many ports stimulated simultaneously. This method provides deeper insights into antenna array in the design phase which has an effect on the real world operation case in terms of network capacity.

Figure 3-2 illustrates the effect of antenna mutual coupling on the capacity of the cell. Comparing a uniform linear array (ULA) with a uniform square array (USA), it is shown that the element spacing between elements on a USA needs to be three times greater than between elements on a ULA to maintain the same network capacity.
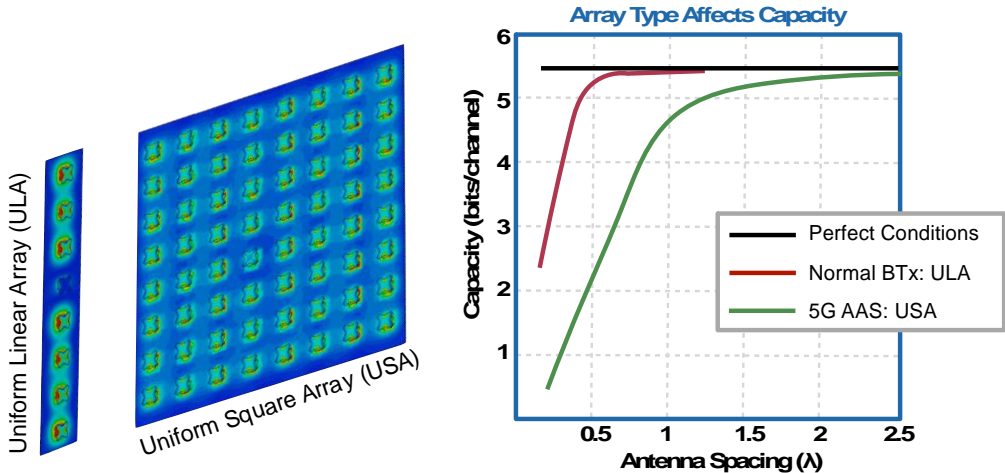

Figure 3-2: Network capacity as a function of mutual coupling [8]

3.2 R&S Solutions for Conducted Measurements

Vector network analyzers from Rohde & Schwarz offer optimum performance and functionality for use in antenna measurement systems with a wide range of solutions for multiport network analysis. The solutions are flexible, allowing for the choice of either a true multiport vector network analyzer or a switched-matrix solution (optional R&S switch matrices) as summarized in Table 3-1.

Table 3-1: R&S Multiport Vector Network Analyzers

R&S Vector Network Analyzer	Frequency Range (model dependent)	Number of Ports	Maximum Ports with Switch Matrix
R&S®ZVA	300 kHz to 110 GHz	Up to 4	Custom Solutions
R&S®ZNB	9 kHz to 40 GHz	2 or 4	48 with R&S®ZN-Z84 12 with R&S®ZN-Z85
R&S®ZNBT8	9 kHz to 8.5 GHz	4 to 24 (in groups of 4)	288 with R&S®ZN-Z84
R&S®ZNBT20	100 kHz to 20 GHz	8 to 16 (in groups of 4)	48 with R&S®ZN-Z85

4 Over-the-Air (OTA) Antenna Measurements

An antenna array applying massive MIMO in both the sub-6 GHz and mmWave frequency range will not provide antenna connectors due to added complexity and cost, physical size limitations, and resulting insertion loss. Consequently, OTA tests are required. OTA tests measuring the three-dimensional antenna pattern can be performed either in near field or in far field. Measurements in near field allow smaller anechoic chambers for the measurement, but require an additional near-field to far-field transformation for antenna gain patterns. Section 4.1 describes the status of 3GPP standardization with respect to OTA tests of Active Antenna Systems (AAS).

OTA measurement parameters can be divided into two general categories: R&D for more complete investigation of the DUT radiated properties, and production for calibration, verification, and functional testing as summarized below:
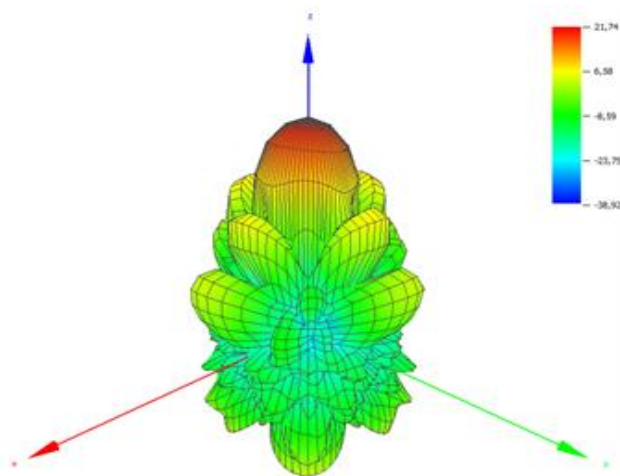
- R&D Measurements

  – Gain patterns: Gain patterns are either 2D from one of the three principal planes (E1, E2, or H-plane) or a complete 3D pattern. For antenna arrays with one or more beams, the 3D gain pattern is more useful (Figure 4-1). Additional information on pattern characterization is available with [8] including an example of a radiation pattern measurement at 28GHz.

  – Radiated power: The effective radiated power (ERP) or effective isotropic radiated power (EIRP) is used to measure an active antenna system either as a UE or a basestation. For UE testing, total radiated power (TRP) is used instead where TRP is the weighted integral of the ERP values over a sphere.

  – Receiver sensitivity: Receiver sensitivity is characterized by the parameter effective isotropic sensitivity (EIS) and measures the block error rate as a function of the receive power equal to the specified receiver sensitivity.

  – Transceiver and receiver characterization: Each individual transceiver in the active antenna system needs to be verified through an OTA interface. This includes a range of measurements for both the transmitter and the receiver as listed in Table 4-1. It is assumed that each transceiver will turn on for individual verification.

Table 4-1: Transceiver and receiver tests

Transmitter Test	Receiver Test
Maximum Output Power	Sensitivity
EVM	Dynamic Range
ACLR	Band Selection
Spurious Emissions	Blocking (IBB, OOB, NBB)
Intermodulation	Adjacent Channel Selectivity

  – Beam steering & beam tracking: Due to the high path loss and limited range of a mmWave wireless system, precise beam tracking and fast beam acquisition is required for mobile users. Whereas with antenna implementation for existing cellular technologies static beam pattern characterization was sufficient, mmWave systems will require dynamic beam measurement systems.

● Production Testing

– Antenna/relative calibration: In order to accurately form beams, the phase misalignment between RF signal paths needs to be below ±5°. This measurement can be performed for both passive and active antenna systems using either a phase-coherent receiver to measure the relative difference between all antenna elements. This is then compiled into a lookup table for the AAS to use as a reference for beam generation or to calibrate the internal self-calibration circuits inside the AAS unit.

– Transceiver calibration: Due to the lack of RF ports on some Massive MIMO systems, the individual transceivers will need to be calibrated using OTA techniques. This includes both transmitters and receivers.

– Five point beam test: The AAS manufacturer specifies a reference beam direction, maximum EIRP, and accordingly EIRP values for each declared beam. For conformance the maximum EIRP point, and four additional points corresponding to the most extreme steering positions are measured (as further discussed in Section 4.1).

– Functional tests: This is the final test performed on the completely assembled unit in production. It can consist of a simple radiated test, a five point beam test, and aggregate transceiver functionality, such as an EVM measurement of all transceivers.

Figure 4-1: Example 3D antenna pattern for a small antenna array (16 elements) at 2.1GHz

OTA measurement systems can be classified into three distinct types depending on which part of the radiated field is being sampled (Figure 2-1). The field regions are separated according to the power distribution of the electromagnetic field. In the reactive near-field region, determining the power requires knowledge about magnitude and phase of the electromagnetic field whereas the radiated field in the far-field region allows determining power only based on the magnitude of the electromagnetic wave. The region between these two extremes is the radiated near field where both the phase and magnitude of the field need to be measured.

For small devices (in terms of wavelengths), such as UEs, the device size is small enough such that the required chamber size for far-field conditions is dominated by the measurement wavelength. For larger devices, such as base stations or Massive MIMO, the required chamber size becomes very large. Huygen's principle in

electromagnetics states that if the tangential electric and magnetic fields are known on an arbitrary surface enclosing the antenna, then the equivalent far-field radiation properties can be calculated using Fourier transforms. Chamber sizes can be reduced significantly as long as the measurement system accurately samples the phase and magnitude of the electromagnetic field on the entire enclosing surface.
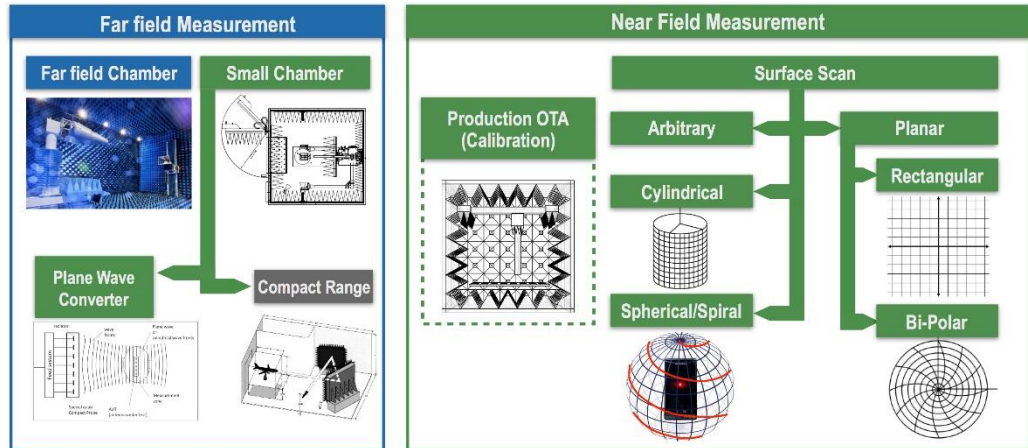

Figure 4-2: Types of OTA Measurement Systems

Most measurements take place either in the radiated near field or in the far field of the DUT due to the difficulty in measuring the reactive near field without coupling to the DUT as summarized below and in Figure 4-2:

● Far field

– Far-field chamber size: Measuring in the far-field region only requires a direct measurement of the field magnitude of the plane waves. Such chambers are generally quite large where the length is set by a combination of the DUT size and the measurement frequencies.

– Near-field chamber size: Although the far field is generally measured at a suitable distance from the DUT, it is possible to manipulate the electromagnetic fields such that a near-field chamber can be used to directly measure the plane wave magnitudes. There are two possible techniques:

i) Compact range chambers: The simplest method to form a planar wave at the surface of the DUT is to extend the path of the electromagnetic fields by using reflectors, similar to optical reflectors. Due to the expense in constructing accurate reflectors, this technique is used mostly for large DUTs such as aircrafts and satellites.

ii) Plane Wave Converter (PWC): A second method to create a planar wave at the DUT is to replace the measurement antenna with an antenna array. Similar to using lenses in an optics system, the antenna array can generate a planar far field at a targeted zone in the region of the DUT (Figure 4-3).
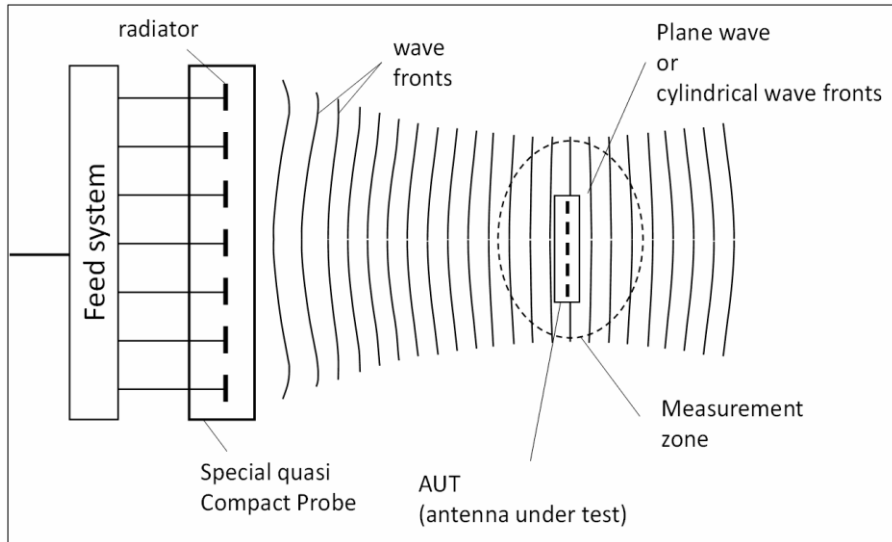
Figure 4-3: Plane Wave Converter 3GPP Submission

● Radiated near field: Measurements in the near-field region require both the field phase and magnitude sampled over an enclosed surface (spherical, linear, or cylindrical) in order to calculate the field magnitude using Fourier spectral transforms.

This measurement is usually performed using a vector network analyzer with one port at the DUT and the other port at the measurement antenna. For active antennas or Massive MIMO, there are often no dedicated antenna or RF ports, so the OTA measurement system must be able to retrieve the phase in order to complete the transformation into far field. There are two methods of performing phase-retrieval for active antenna systems (Figure 4-4):

– Interferometric: This method uses a second antenna with a known phase used as a reference. The reference signal is mixed with the DUT signal with unknown phase. Using post-processing, the phase of the DUT signal can be extracted and used for the near-field to far-field transformation.

– Multiple surfaces or probes: Instead of using a second antenna for the phase reference, this method uses a second surface volume as the phase reference with at least one wavelength separation between the two measurement radii. As an alternative to the measurement of multiple surfaces, two probes with different antenna field characteristics can be used instead over a single measurement surface. The two probes need to be separated by at least half-wavelength to minimize mutual coupling.
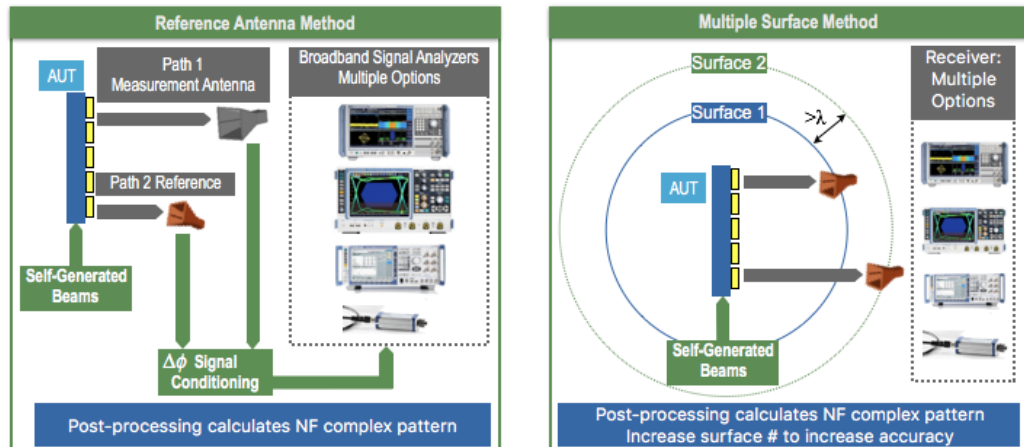
Figure 4-4: Near-field phase retrieval techniques

4.1 Base Station OTA Measurements in 3GPP Release 13/14

3GPP created a dedicated technical report [1] on RF requirement background for Active Antenna Systems (AAS). The study and work item phase contains a list of radiated requirements as well as a list of conducted requirements based on the identified representative deployment scenarios. In conclusion, requirements for transmit and receive measurements applicable to AAS were approved. An AAS is defined as a base station system, which combines an antenna array with a transceiver unit array and a radio distribution network.
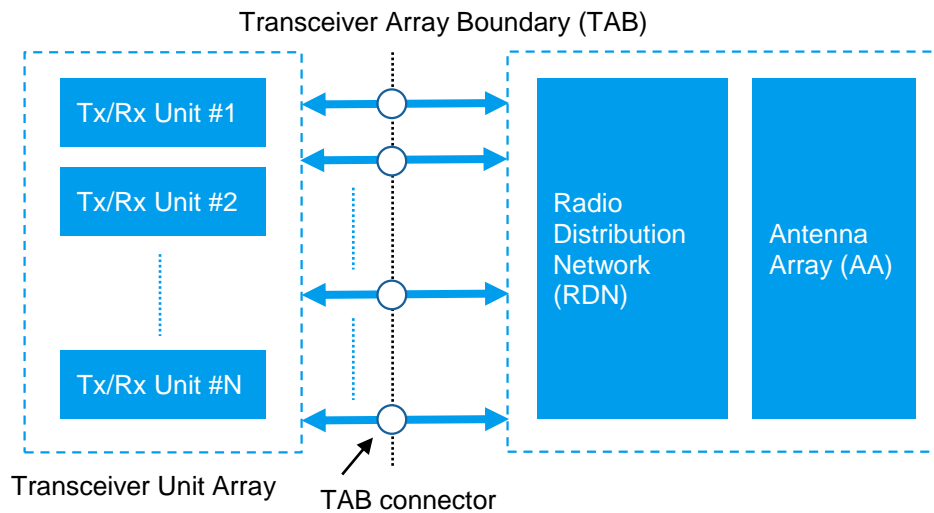
Figure 4-5: General AAS Radio Architecture

Figure 4-5 defines the general AAS BS RF architecture. The point where a transmitter unit or a receiver unit connects with the radio distribution network (RDN) is equivalent to an "antenna connector" of a non-AAS BS and is called "Transceiver Array Boundary connector" (TAB connector). The TAB connector is defined as the conducted reference point. The transmitted signal per carrier from one Tx Unit appears at one or more than one TAB connector(s), and the received signal per carrier from one or more than one TAB connector(s) appears at a single Rx Unit. For AAS BS capable of supporting

applications employing beamforming, all or subgroups of TAB connectors can be configured with designated amplitude and phase weights such that one or more beams are radiated from the antenna array (analog, digital, or hybrid beamforming). Note that from testing perspective requirements are defined with respect to a point of reference in the far field.

4.1.1 Radiated Requirements

3GPP defines the OTA requirements in terms of electromagnetic and spatial parameters. The electromagnetic parameters are specified either in terms of power (dBm) or field strength (dBµV/m). The spatial parameters are specified in a Cartesian coordinate system (x, y, z) using spherical coordinates (r, θ, φ), see Figure 4-6.
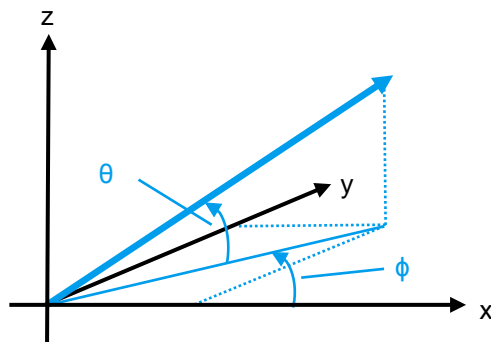

Figure 4-6: Orthogonal representation of coordinate system

The chosen method requires the manufacturer to declare the number of beams intended for cell-wide coverage. Requirements are then to be verified per declared beam. The vendor declares the location of the coordinate system origin in reference to an identifiable physical feature of the AAS BS enclosure. A few basic definitions apply: The declared beam direction pair is associated with the beam center direction and a beam peak direction. A beam center direction and a beam peak direction characterize the capability of the AAS to create a beam. The center direction equals to the geometric center of the -3 dB EIRP contour of the beam. The beam peak direction is the direction where the maximum EIRP is to be found (Figure 4-7).
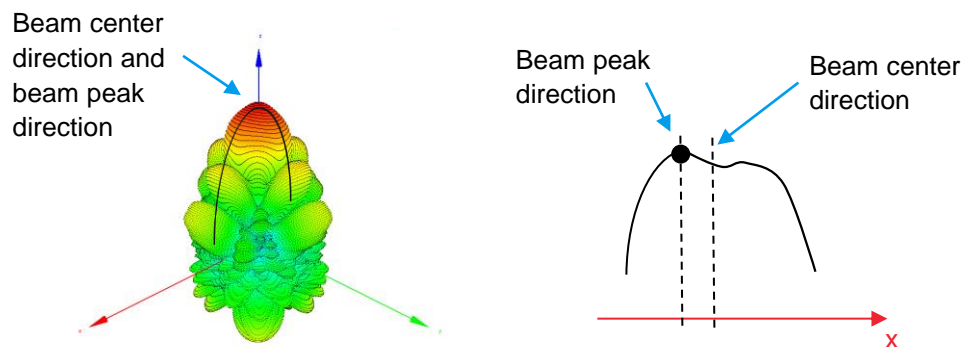

Figure 4-7: Examples of beam direction pairs (left: peak at the 3dB contour center, right: peak not at the 3dB contour center)

The reference beam direction is the declared beam direction pair achieving the intended maximum EIRP. The beamwidth of a beam is defined as the angles describing the major and minor axes of an ellipsoid closest fit to an essentially elliptic half-power contour of the beam. Each beam supported is defined with a unique beam identifier. With respect to characterizing each supported single beam, the manufacturer declares highest intended EIRP including narrowest and widest intended beamwidth in both azimuth and elevation (θ, ϕ).

Note that the reference beam direction is used for describing the beam steering capabilities. The manufacturer of the AAS will declare both the number of beams and the steering capabilities, which may be continuous (top right and bottom right in Figure 4-8) or not continuous (top left and bottom left in Figure 4-8). Compliance is tested at the declared extreme beam directions (e.g. top left in Figure 4-8). The maximum radiated transmit power of the AAS BS beam is the mean power level measured at the declared beam peak direction at the RF channels B (bottom), M (middle) and T (top). The RF channels supported by the AAS BS are also declared by the manufacturer. For conformance declaration of EIRP values is only required for the reference beam direction and the maximum extreme steering directions. Consequently we use the term five point beam test.
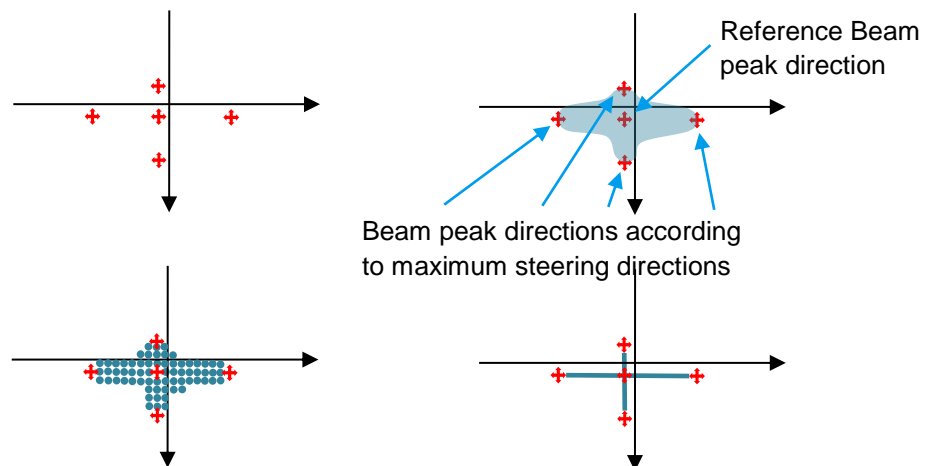

Figure 4-8: 5-Point beam declaration [1]

Note that the complete list of manufacturer declarations is defined in [4] in section 4.10. It includes 29 different parameters (D9.1 "Coordinate system reference point " to D9.29 " OTA contiguous and non-contiguous parameters identical ") for the transmitter and 11 different parameters (D.10.1 " OSDD identifier " to D.10.11 " Conformance test directions") for the receiver of the base station.

4.1.2 Radiated Transmitter Characteristics

The number of beams supported by the AAS is left to the manufacturer to declare where both continuous and non-continuous beam declarations are possible. Radiated transmit power is defined as the EIRP level for a declared beam at a specific beam peak direction. The claimed EIRP level (blue and red crosses in Figure 4-9) is to be achieved for all claimed beam peak directions [4]. However, for compliance only the declaration of the extreme directions are sufficient to be measured (marked with red crosses in Figure 4-9). The potential beam directions are not confined to a square and

can be specified according to any arbitrary surface by the manufacturer. Those beam directions that are compliant are included in the EIRP accuracy compliance specifications.
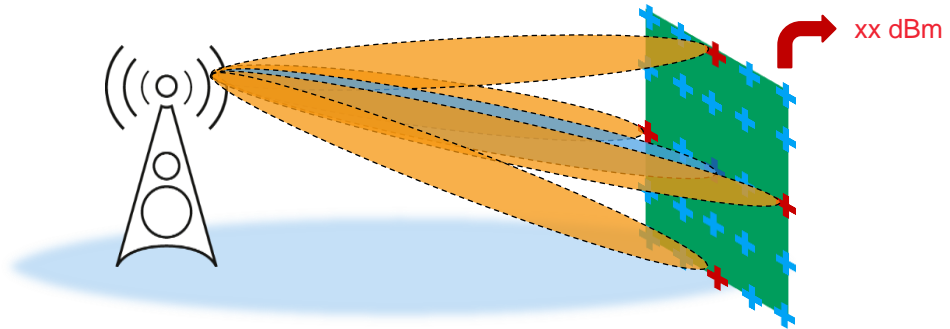

Figure 4-9: Simplified example of AAS non-continuous beam declarations

The requirement defined in [4] reads

For each beam, the requirement is based on declarations (see table 4.10-1) of a beam identifier (D9.3), reference beam direction pair (D9.7), rated beam EIRP at the beam's reference direction pair (D9.8), EIRP accuracy directions set (D9.10), the beam direction pairs at the maximum steering directions (D9.11) and their associated rated beam EIRP (D9.12) and beamwidth(s) for reference beam direction pair and maximum steering directions (D9.13).

And references the requirement defined in [2] including a specific accuracy as follows:

"For each declared beam, in normal conditions, for any specific beam peak direction associated with a beam direction pair within the EIRP accuracy directions set , a manufacturer claimed EIRP level in the corresponding beam peak direction shall be achievable to within +2,2 dB and -2,2 dB of the claimed value."

Additionally [4] defines acceptable uncertainties of the test system according to Table 4-2. Consequently the requirement tested against during the test procedure comprises the minimum requirement and this test uncertainty.

Table 4-2: Maximum Test System uncertainty for transmitter tests

Subclause	Maximum Test System Uncertainty	Derivation of Test System Uncertainty
6.2 Radiated transmit power	±1.0 dB, f ≤ 3.0 GHz	See 3GPP TR 37.842 [1], subclause 10.3.2.2.
	±1.2 dB, 3.0 GHz < f ≤ 4.2 GHz	

4.1.3   Radiated Receiver Characteristics

Similar to the power measurement in downlink direction, in uplink a sensitivity requirement is defined based on the declaration of one or more OTA sensitivity directions declarations (OSDD). The receiver is required to achieve a certain data throughput at a particular OTA sensitivity power level.

The effective isotropic sensitivity (EIS) is defined as the power level relative to an isotropic antenna that is incident on the AAS array from a specified azimuth/elevation direction (angle of arrival) in order to meet the specified receiver sensitivity requirement where the angle of arrival can be described as a combination of Φ and Θ (Figure 4-10).

The AAS may support multiple RoAoA (Range of Angles of Arrival), which describe the overall redirection range capabilities of the antenna. For sensitivity testing the stimulus signal is the same as the fixed reference measurement channel (FRC) for target throughputs in non-AAS requirements [3]. The OTA sensitivity requirement applies per polarization, under the assumption of polarization matching. It is up to the manufacturer to declare whether or not dual polarization is supported by the AAS. As in the downlink case, conformance is to be demonstrated at the extreme directions marked with red crosses in Figure 4-10.
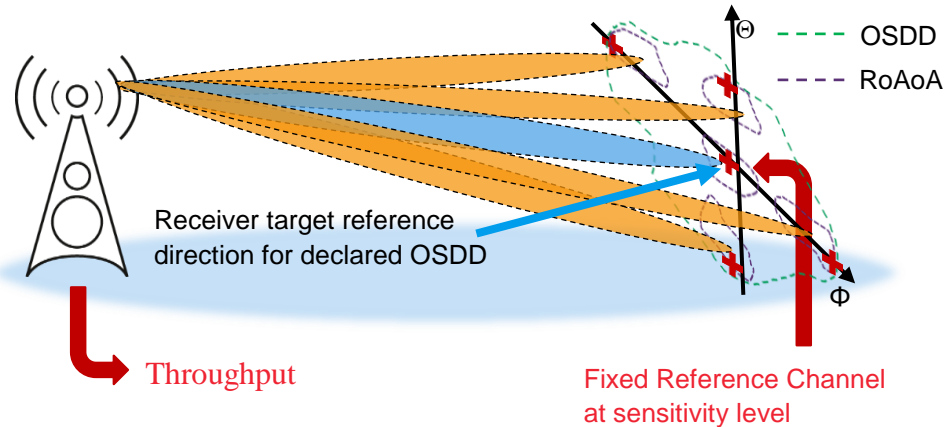

Figure 4-10: Five different directions of a sensitivity Range of Angles of Arrival (RoAoA - purple) comprising the target redirection range (green contour) of an OSDD

The received signal level can be represented as a field-strength or EIS power level. The relation between field-strength and EIS is [1]

$$EIS(\Theta,\phi) = E(\Theta,\phi) - 20\log_{10}(f) + 77.2 \quad \text{[dBm]}$$

4.2 R&S Solutions for OTA Measurements

R&S has a wide selection of chambers, absorbers, measurement equipment, and positioners as part of its integrated solutions for OTA measurements. The OTA products range in size from benchtop systems to large anechoic chambers and with measurement capabilities in frequency bands from 400 MHz to over 90 GHz.

Depending on the antenna array layout/design, there are two modes that require different sets of measurement equipment (but can both use the same chamber, absorbers, and positioner):

1. If the antenna system is passive (DUT has external RF ports for direct RF signal transmission and reception) → use a vector network analyzer with one port at the DUT and the other ports for measurement antennas. Rohde & Schwarz offer two- or four port network analyzers such as the R&S®ZVA, R&S®ZNB and R&S®ZNC. Additionally multiport network analyzers such as the R&S®ZNBT and R&S®ZVT are available.

2. If the system comprises of a remote radio head integrated together with an antenna array with no external RF ports (AAS) → perform an active antenna measurement with a combination of a vector signal generator R&S®SMW200A or R&S®SMBV100A and a signal and spectrum analyzer R&S®FSW or R&S®FSVA.

There are four types of R&S products for OTA for both passive and active antenna systems:

▪ Compliance Systems (R&S®TS8991): These include a series of turnkey solutions for OTA measurements of UEs compliant to CTIA, 3GPP, and other wireless standards and test cases, using far-field measurement techniques; see Table 4-3.

Table 4-3: Wireless Performance Test Chamber (WPTC) Turn-key Solutions

Specification	DST200	WPTC XS	WPTS S	WPTC M	WPTC L	WPTC XL
Application	UE	UE, Small DUT	UE, Small DUT	UE, Medium DUT	UE, Large DUT	UE, Large DUT
Dimensions (L x W x H)	77x70x76cm	2.4x2.4x2.4m	3.5x3.0x3.0m	4.6x3.7x3.45m	5.2x4.3x4m	5.8x5.2x5.2m
Frequency Range (GHz)	0.7-6; 6-90 (ver2)	0.7-18	0.7-18	0.7-18	0.4-18	0.4-18
Range Length	30 cm	62 cm	102 cm	130 cm	138 cm	183 cm
CTIA Compliant	No	No	No	Yes	Yes	Yes
CTIA Test Cases (BH, HHH)	No	Yes	Yes	Yes	Yes	Yes

▪ R&S spiral scanner: The spiral scan can be used for both near-field and far-field measurements. Traditional near-field measurements use a single probe stepping through a uniform grid (typically on a spherical or cylindrical surface). This approach results in long measurement times for higher frequencies (smaller grid spacing in order to have sufficient samples) with almost 3 hours to measure a DUT at 6 GHz. The speed can be improved by distributing the probes across an arc for a spherical system or along a line for a rectilinear system. While this can significantly reduce measurement times, the use of multiple probes introduces two new problems: increased calibration times and mutual-coupling effects between probes.

R&S combines two new technologies into its near-field scanner system in order to address the problems of speed, calibration, and mutual coupling: Fast Irregular Antenna Field Transformation Algorithm (FIAFTA) and the spiral scan. FIAFTA is a new near-field to far-field transformation that allows the use of arbitrary grids instead of uniform grids in the OTA measurement system. Figure 4-11 shows the algorithm accuracy of a FIAFTA near-field measurement compared to a far-field measurement in an accredited external laboratory.
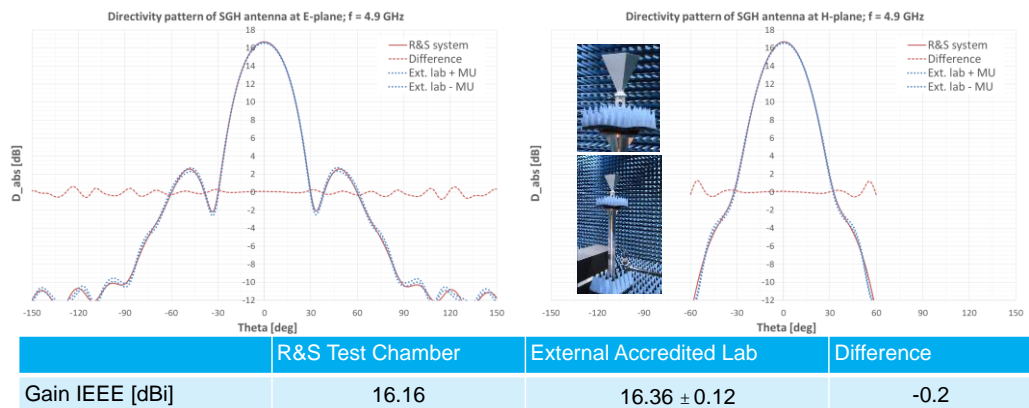

	R&S Test Chamber	External Accredited Lab	Difference
Gain IEEE [dBi]	16.16	16.36 ± 0.12	-0.2

Figure 4-11: FIAFTA Near-field accuracy

The near-field scanner has a single dual-polarized probe (faster calibration and no mutual coupling) that rotates along the measurement surface at the same time as the DUT rotates at a faster speed. This combination of two rotating axes results in a spiral scan that reduces the measurement time for a DUT at 6 GHz to below 6 minutes (Figure 4-12).
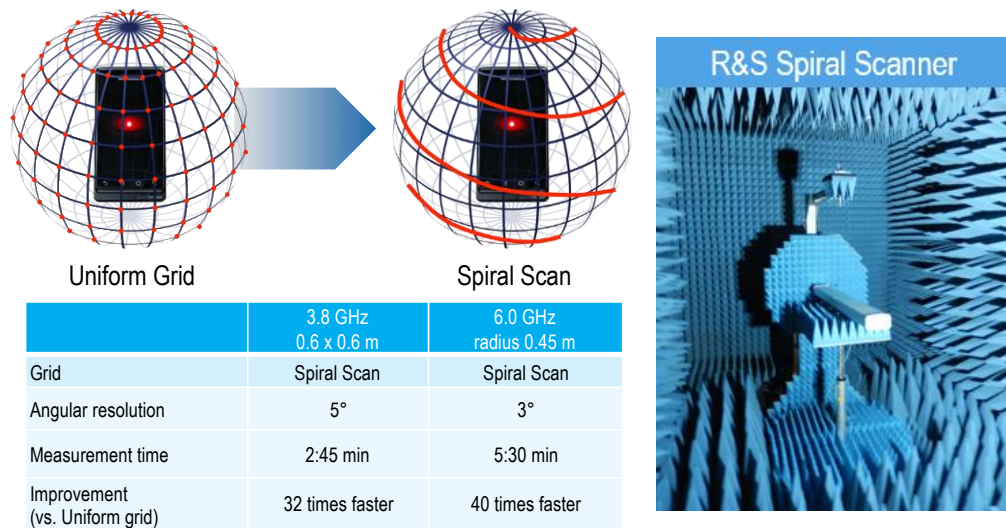

	3.8 GHz 0.6 x 0.6 m	6.0 GHz radius 0.45 m
Grid	Spiral Scan	Spiral Scan
Angular resolution	5°	3°
Measurement time	2:45 min	5:30 min
Improvement (vs. Uniform grid)	32 times faster	40 times faster

Figure 4-12: R&S spiral scanner

● Benchtop chambers & probes: Benchtop chambers are often used for rapid antenna design and prototyping. R&S offers two benchtop systems for small DUTs that can either measure the 3D beam pattern in a passive or active antenna system or measure the real-time beam steering and beam acquisition capability of the DUT. In a production line, the emphasis shifts from comprehensive DUT analysis to calibration and faster functional testing. R&S production verification systems are based on benchtop systems with some customization for specific measurements. A functional test to measure the entire AAS unit can consist of beam-pattern verification using the five point 3GPP method and/or simultaneous excitation of the transceivers for joint transmitter or receiver tests (subset of the test items listed in Table 4-1). For production, it is expected that the 5G DUTs will follow a multi-step process for calibration and verification performed within the near-field region of the DUT in Figure 2-1.

▪ R&S®DST200: This is the larger of the two benchtop systems with a size of 770 mm x 760 mm x 695 mm that can measure the 3D radiation patterns of UE-sized devices from 1 GHz to 77 GHz (Figure 4-13). There is a space at the top of the box to insert the measurement antenna (either horn or an R&S wide-band Vivaldi antenna). The shielding effectiveness is over 100 dB for frequencies below 18 GHz and over 75 dB up to 77 GHz. Automated positioners allow a two-axis rotation of the DUT. The DST200 has many applications and is used for automotive radar and 5G (both sub-6 GHz and mmWave). It can also be used for antenna and transceiver calibration measurements in production lines (as described in more detail below).

Figure 4-13: R&S®DST200 Benchtop 3D Radiation Pattern System

▪ R&S®TS7124: This chamber is smaller compared to the R&S®DST200 with a size of 450 mm x 400 mm x 480 mm. It is designed as a rack-mountable solution (19" rack integration) with both an automatic pneumatic version for production lines and a manual version for R&D measurements. It supports a wide frequency range, providing shielding effectiveness of over 65 dB up to 67 GHz. This shielded box is designed such that the DUT is surrounded by several stationary measurement antennas or probes (see Figure 4-14). A typical setup places probes surrounding the DUT in order to perform and monitor real-time beam steering and beam tracking for devices in the mmWave region. Alternatively, the shielded box can be used at lower frequencies for UE functional testing in production lines.

▪ R&S®NRPM: At higher frequencies in the mmWave region, received signals suffer from high attenuation, and the measurement system becomes very sensitive to mechanical arrangements, requiring frequent calibrations of the system. R&S has an option to replace the antennas with OTA power sensor probes (R&S®NRPM OTA power measurement solution). By placing the power sensor diode directly on the wide-band Vivaldi antenna, the system only requires a low frequency cable between the measurement probe (R&S®NRPM-A66) and the power meter, thereby alleviating the attenuation and frequent calibration issues for mmWave measurements.
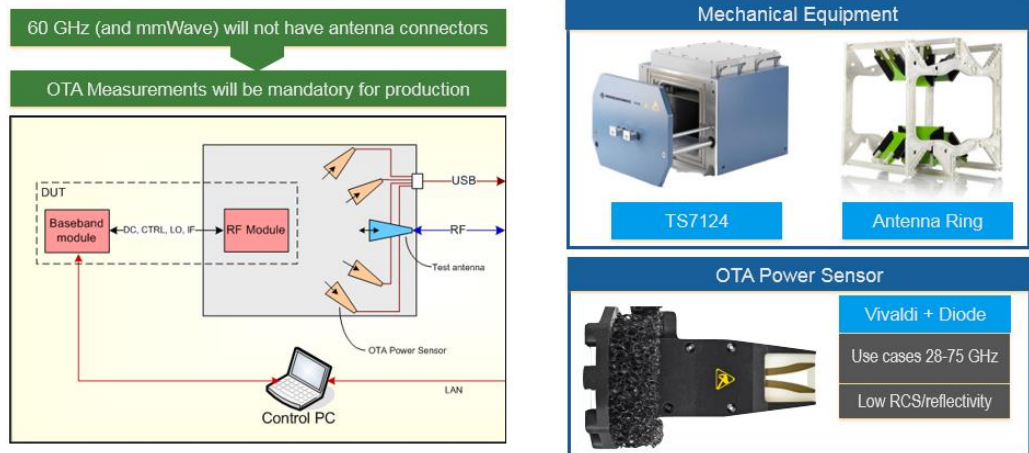
Figure 4-14: R&S®NRPM OTA power measurement solution & R&S®TS7124

5 Conclusion

In summary, due to the elimination of RF test ports and the use of frequencies in the centimeter and millimeter wave length region, OTA will become an essential tool for characterizing the performance of not just the antenna arrays of an Active Antenna System of a Massive MIMO array, but the internal transceivers as well. For this reason there will be a high demand for OTA chambers and measurement equipment to not only measure the strict radiative properties of antennas, but substituting traditional conducted transceiver measurements as well. Rohde & Schwarz with its wide range of anechoic chambers and measurement equipment expertise is well situated to deliver solutions even for future customer requirements.

6 Literature

[1] **3GPP** TR 37.842 v13.1.0 TSG RAN E-UTRA and UTRA; Radio Frequency (RF) requirement background for Active Antenna System (AAS) Base Station (BS). - 2016.

[2] **3GPP** TS 36.105 v13.3.0 TSG RAN Active Antenna System (AAS) Base Station (BS) transmission and reception.

[3] **3GPP** TS 36.141 v13.3.0 TSG RAN E-UTRA; Base Station (BS) conformance testing. - 2016.

[4] **3GPP** TS 37.145-2 v. 13.1.0 TSG RAN; Active Antenna System (AAS) Base Station (BS) conformance testing; Part 2: radiated conformance testing. - 2016.

[5] **Balanis Constantine** Antenna Theory: Analysis & Design [Book]. - New Jersey : John Wiley & Sons, 2005.

[6] **China Mobile Research Institute** C-RAN: The Road Towards Green RAN // Whitepaper. - 2013.

[7] **Ericsson AB, Huawei Technologies Co. Ltd, NEC Corporation, Alcatel Lucent and Nokia Networks** CPRI Specification V7.0 (2015-10-09) [Report]. - [s.l.] : www.CPRI.info, 2015.

[8] **F. Rusek et al** Scaling Up MIMO: Opportunities and Challenges with Very Large Arrays [Journal]. - 2013. - Vols. IEEE Signal Processing Magazine, vol. 30, no. 1.

[9] **Lloyd, Reil** Millimeter-Wave Beamforming: Antenna Arrays and Characterization (1MA276). - 2016.

[10] **Shuangfeng Han et al** Large-Scale Antenna Systems with Hybrid Analog and Digital Beamforming for Millimeter Wave 5G [Journal] // IEEE Communications Magazine. - 2015.

7 Ordering Information

Designation	Type	Order No.
Vector Network Analyzer	R&S®ZVAx	1145.1110.xx
Vector Network Analyzer	R&S®ZNBx	1311.6010.xx
Vector Network Analyzer	R&S®ZNC	1311.6004.12
Vector Network Analyzer	R&S®ZNBT8	1318.7006.24
Vector Network Analyzer	R&S®ZNBT20	1332.9002.24
Vector Network Analyzer	R&S®ZVT8	1300.0000.08
Vector Network Analyzer	R&S®ZVT20	1300.0000.20
Switch matrix	R&S®ZN-Z84	1319.4500.02
Switch matrix	R&S®ZN-Z85	1326.4777.03
Vector Signal Generator	R&S®SMW200A	1412.0000.02
Vector Signal Generator	R&S®SMBV100A	1407.6004.02
Three-Channel Sensor Module	R&S®NRPM3	1425.8563.02
Single-Polarized Antenna Module	R&S®NRPM-A66	1425.8740.02
Signal and Spectrum Analyzer	R&S®FSWxx	1312.8000.Kxx
Signal and Spectrum Analyzer	R&S®FSVAxx	1321.3008.xx
OTA Performance Test System	R&S®TS8991	
RF Diagnostic Chamber	R&S®DST200	1510.9047.02
RF Shielded Box	R&S®TS7124M	1525.8564.xx
RF Shielded Box	R&S®TS7124AS	1525.8587.xx

Rohde & Schwarz

The Rohde & Schwarz electronics group offers innovative solutions in the following business fields: test and measurement, broadcast and media, secure communications, cybersecurity, radiomonitoring and radiolocation. Founded more than 80 years ago, this independent company has an extensive sales and service network and is present in more than 70 countries.

The electronics group is among the world market leaders in its established business fields. The company is headquartered in Munich, Germany. It also has regional headquarters in Singapore and Columbia, Maryland, USA, to manage its operations in these regions.

Regional contact

Europe, Africa, Middle East
+49 89 4129 12345
customersupport@rohde-schwarz.com

North America
1 888 TEST RSA (1 888 837 87 72)
customer.support@rsa.rohde-schwarz.com

Latin America
+1 410 910 79 88
customersupport.la@rohde-schwarz.com

Asia Pacific
+65 65 13 04 88
customersupport.asia@rohde-schwarz.com

China
+86 800 810 82 28 |+86 400 650 58 96
customersupport.china@rohde-schwarz.com

Sustainable product design

◾ Environmental compatibility and eco-footprint

◾ Energy efficiency and low emissions

◾ Longevity and optimized total cost of ownership

Certified Quality Management
ISO 9001

Certified Environmental Management
ISO 14001
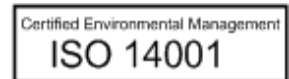
This white paper and the supplied programs may only be used subject to the conditions of use set forth in the download area of the Rohde & Schwarz website.