# Antenna Beam Characterization of 5G Mobile Devices and Base Stations Using the R&S®NRPM Over-the-Air (OTA) Power Measurement Solution

## Application Note

**Products:**

- R&S®NRPM3
- R&S®NRPM-A66
- R&S®NRPM-ZD3
- R&S®TS7124
- R&S®TS-F24-AR
- R&S®TS-F24-AH1
- R&S®TS-F24-AH2
- R&S®TS-F2X-VH4


Radio frequencies in bands around 28 GHz are being discussed as candidates for mobile communications of the fifth generation (5G). Beam steering will be a key feature in the context of 5G. It will be a major challenge to test the beam steering capabilities of base stations and user equipment in every phase from research and development through production. Conducted measurements will be mainly replaced by over-the-air measurements of electromagnetic radiation. Rohde & Schwarz offers the R&S®NRPM Over-the-Air (OTA) Power Measurement Solution that perfectly fits such measurement needs.

Part of this solution are the R&S®NRPM-A66 antenna modules. They have integrated diode detectors. Thus, there are no cables between the antenna and the detector as in traditional setups. This avoids high and potentially unknown RF losses. The R&S®NRPM-A66 antenna modules with their integrated diode detectors are factory calibrated, which means that the user does not have to calibrate them to achieve highly accurate measurement results.

This application note contains theoretical background on OTA power and pattern measurements. It gives step-by-step instructions for the verification of the power level and the radiation pattern of a device under test (DUT) in comparison to a golden device, and it presents an approach for verifying the accuracy of beam steering.


**Note:**

Please find the most up-to-date document on our homepage http://www.rohde-schwarz.com/appnote/1GP118

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# 1 Note

The following abbreviations are used in this application note for Rohde & Schwarz products:

- The R&S®NRPM3 Three-channel sensor module is referred to as NRPM3 sensor module.
- The R&S®NRPM-A66 Single polarized antenna module is referred to as NRPM-A66 antenna module.
- The R&S®NRPM-ZD3 Filtered cable feedthrough is referred to as NRPM-ZD3 feedthrough.
- The R&S®TS7124 RF shielded box is referred to as TS7124 RF shielded box.
- The R&S®TS-F24-AR antenna ring is referred to as TS-F24-AR antenna ring.
- The R&S®TS-F24-AH1 half antenna ring is referred to as TS-F24-AH1 half antenna ring.
- The R&S®TS-F24-AH2 antenna holder is referred to as TS-F24-AH2 antenna holder.
- The R&S®TS-F2X-VH4 adapter is referred to as TS-F2X-VH4 adapter.

# 2 Introduction

Radio frequencies in bands around 28 GHz are being discussed as candidates for mobile communications of the fifth generation (5G). As frequencies are increasing, components and systems are shrinking. In order to minimize losses and the susceptibility to influences from outside, the level of integration is increasing. As a consequence, test points such as in the signal path from the output of a power amplifier to the input of an antenna will no longer exist. Conducted measurements, i.e. measurements that are done while the device under test (DUT) is connected to the measurement equipment via cables, will be mainly replaced by over-the-air (OTA) measurements, i.e. measurements of electromagnetic radiation.

Besides that, antenna elements and thus their effective areas are shrinking as frequencies are getting higher. Accordingly, the so-called path loss between transmitting and receiving antennas is increasing. To overcome this issue, antenna elements can be arranged in arrays that yield higher gain than a single antenna element. However, this does not mean that the overall transmitted power increases, but that the available power is focused to certain directions.

In mobile communications, the relative positions of a mobile device and a base station vary over time. In order to receive sufficient power, the beam directions of the transmitting and/or the receiving antenna are adjusted. This is accomplished by means of beam steering. Therefore, beam steering is a key feature in the context of 5G. It will be a major challenge to test the beam steering capabilities of base stations and user equipment in every phase from research and development through production.

Rohde & Schwarz offers the NRPM Over-the-Air (OTA) Power Measurement Solution that perfectly fits such tests. As sketched in Figure 1, the solution essentially consists of NRPM-A66 antenna modules and an NRPM3 sensor module.

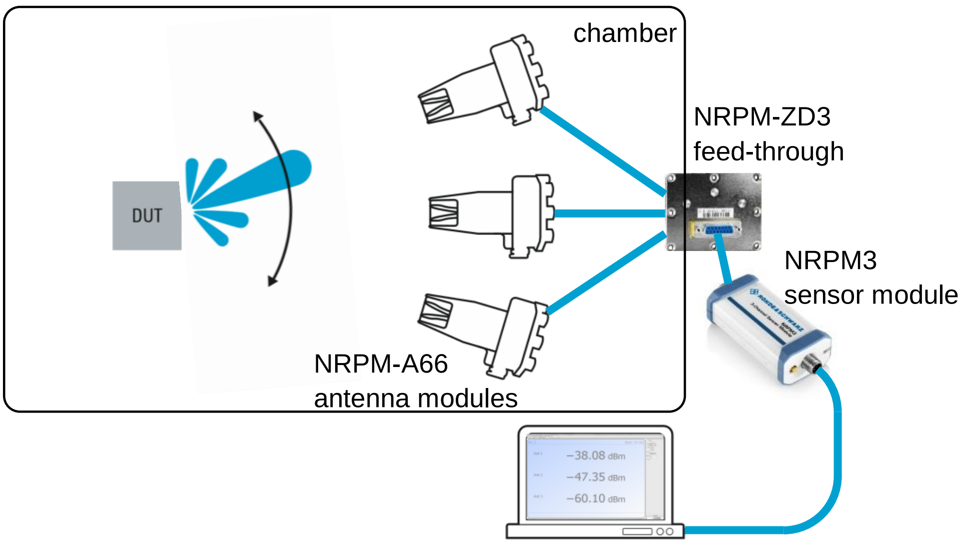


**Figure 1: Sketch of the NRPM Over-the-Air (OTA) Power Measurement Solution used to characterize the spatial distribution of the power radiated by the DUT**

A variety of antenna holders are available. Together with the NRPM-ZD3 feedthrough, the solution can be perfectly integrated into a TS7124 RF shielded box.

The R&S®NRPM-A66 antenna modules have integrated diode detectors. Thus, there are no cables between the antenna and the detector as in traditional setups. This avoids high and potentially unknown RF losses. The R&S®NRPM-A66 antenna modules with their integrated diode detectors are factory calibrated, which means that the user does not have to calibrate them to achieve highly accurate measurement results.

This application note contains theoretical background on OTA power and pattern measurements. It gives step-by-step instructions for the verification of the power level and the radiation pattern of a device under test (DUT) in comparison to a golden device, and it presents an approach for verifying the accuracy of beam steering. It also gives ideas for modifying those procedures in order to cope with special requirements, as well as points to consider before implementing a particular setup.

# 3 Theoretical Background on Power and Antenna Pattern Measurements

The RF power $P_{\mathrm{DUT}}$ radiated by a DUT distributes in space according to its gain function $G_{\mathrm{DUT}}(\theta_{\mathrm{DUT}}, \phi_{\mathrm{DUT}})$, where $\theta_{\mathrm{DUT}}$ is the elevation angle and $\phi_{\mathrm{DUT}}$ is the azimuth angle as seen from the DUT. A receiving antenna accepts radiation from different directions in space according to its gain function $G_r(\theta_r, \phi_r)$, where $\theta_r$ is the elevation angle and $\phi_r$ is the azimuth angle as seen from the receiving antenna. Each of the gain functions can be split into the product of their maximum values, $G_{\mathrm{max,DUT}}$ and $G_{\mathrm{max},r}$, and the spatial distribution functions $C_{\mathrm{DUT}}(\theta_{\mathrm{DUT}}, \phi_{\mathrm{DUT}})$ and $C_r(\theta_r, \phi_r)$ according to

$$G_{\mathrm{DUT}}(\theta_{\mathrm{DUT}}, \phi_{\mathrm{DUT}}) = G_{\mathrm{max,DUT}} \cdot C_{\mathrm{DUT}}(\theta_{\mathrm{DUT}}, \phi_{\mathrm{DUT}}) \quad (1)$$

and

$$G_r(\theta_r, \phi_r) = G_{\mathrm{max},r} \cdot C_r(\theta_r, \phi_r). \quad (2)$$

$C_{\mathrm{DUT}}(\theta_{\mathrm{DUT}}, \phi_{\mathrm{DUT}})$ is the radiation pattern of the DUT, while $C_r(\theta_r, \phi_r)$ is the radiation pattern of the receiving antenna.

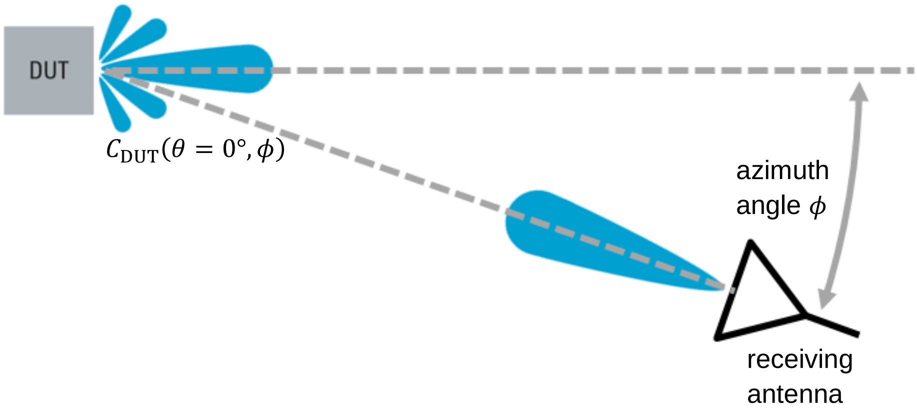


**Figure 2: Arrangement of DUT and receiving antenna. $\phi$ is the azimuth angle. $\theta$ is the elevation angle.**

The equation that describes the received power as a function of the transmitted power is named the Friis equation [1]. In case

- the antennas are complex conjugate matched to the source and load,
- the receiving antenna is oriented such that its maximum gain is in the direction of the DUT, as indicated in Figure 2,
- the distance between the antennas is sufficient (s. 3.1),
- there are no unwanted echoes or interfering signals (s. 3.2) and
- the antennas are polarization matched (s. 3.3) to each other

the Friis equation can be written as

$$\frac{P_r}{P_{\mathrm{DUT}}} = \left(\frac{\lambda}{4\pi R}\right)^2 \cdot G_{\mathrm{max,DUT}} \cdot C_{\mathrm{DUT}}(\theta, \phi) \cdot G_{\mathrm{max},r} \quad (3)$$

and eventually as

$$C_{\mathrm{DUT}}(\theta,\phi) = P_r(\theta,\phi) \cdot \frac{1}{P_{\mathrm{DUT}} \cdot G_{\max,\mathrm{DUT}} \cdot G_{\max,r}} \cdot \left(\frac{4\pi R}{\lambda}\right)^2. \quad (4)$$

$R$ is the distance between the antennas, $\lambda = c/f$ the wavelength of the transmitted signal of frequency $f$, and $c$ is the speed of light.

According to (4), samples of the radiation pattern of the DUT, $C_{\mathrm{DUT}}(\theta,\phi)$, can be determined by measuring the power $P_r$ received by receiving antennas placed in the respective spatial directions $(\theta,\phi)$. As long as the wavelength, the transmitted power and the distance between the antennas are kept constant, the antenna pattern of the DUT and the received power are interrelated by

$$C_{\mathrm{DUT}}(\theta,\phi) = P_r(\theta,\phi) \cdot k, \quad (5)$$

where $k$ is a constant that accounts for the constant terms in (4).

The pattern can be sampled by either moving a single receiving antenna to the relevant angles one after another or by placing multiple antennas in the relevant spatial directions.

The equivalent isotropically radiated power of a DUT, $\mathrm{EIRP}_{\mathrm{DUT}}$, is defined as

$$\mathrm{EIRP}_{\mathrm{DUT}}(\theta,\phi) = P_{\mathrm{DUT}} \cdot G_{\mathrm{DUT}}(\theta,\phi). \quad (6)$$

Using (3), it can be rewritten as

$$\mathrm{EIRP}_{\mathrm{DUT}}(\theta,\phi) = P_r(\theta,\phi) \cdot \left(\frac{4\pi R}{\lambda}\right)^2 \cdot \frac{1}{G_{\max,r}}. \quad (7)$$

It can be determined from measurements of the power $P_r$ received by antennas placed in particular directions $(\theta,\phi)$ and pointing to the DUT. NRPM-A66 antenna modules are factory calibrated such that the power reading corresponds to a gain of 1 for radiation that comes from the boresight direction of the NRPM-A66 antenna module. In case the NRPM-A66 antenna module is pointing to the DUT, the $\mathrm{EIRP}$ can therefore be determined according to

$$\mathrm{EIRP}_{\mathrm{DUT}}(\theta,\phi) = P_r(\theta,\phi) \cdot \left(\frac{4\pi R}{\lambda}\right)^2. \quad (8)$$

## 3.1 Distance between the antennas

The space around an antenna can be divided into the near-field and the far-field region. The far-field is characterized by two essential properties. First, the power density is inversely proportional to the square of the distance from the antenna operating in transmit mode. Second, the angular power distribution is independent of distance. A very commonly assumed inner boundary of the far-field region–for an antenna with dimensions larger than the wavelength–is at distance $R_{\min}$ according to

$$R_{\min} = \frac{2D^2}{\lambda}, \quad (9)$$

where $D$ is the largest lateral dimension of the antenna. In case of an aperture antenna, its largest lateral dimension is the size of its diagonal. In case the antenna is embedded in a device, parts of the device itself might contribute to the overall radiation and have influence on the radiation characteristics. If so, $D$ has to be chosen according to the size of the radiating structure rather than the size of the antenna alone.

In order to determine the far-field pattern of a DUT from power measurements according to (5), the power measurements have to be done with the DUT and the receive antenna in each other's far-field, since the pattern generally changes with distance within the near-field. In this case, the sum of largest lateral dimensions of both antennas has to be chosen as the value of $D$.

However, depending on the type of the DUT and the information that is to be extracted from such a measurement, it might be justified to choose a distance smaller than $R_{\mathrm{min}}$. This is especially true in case of relative measurements, where the values obtained for the DUT are compared to values obtained for a golden device.

Equation (9) is also a criterion for the accuracy of the Friis equation. The Friis equation is an approximation that is correct to within a few percent when the antennas are spaced by at least $R_{\mathrm{min}}$, determined using the largest lateral dimension of either antenna as the value of $D$ [2].

For closer spacings, the Friis equation might not predict the received power very well, but violating the criterion might be justified especially in the case of relative measurements.

## 3.2 Multipath propagation and interference by other signal sources

The Friis equation is valid only for the line of sight without any additional signal paths between the transmit and the receive antenna. Such additional paths result from echoes as they might occur when objects are in the vicinity of the measurement setup. Those echoes are superimposed on the signals of the desired signal path. This may yield a change of the electromagnetic field at the location of the receive antenna and thus a biased estimation of the properties of the transmit antenna.

The Friis equation assumes that there are no interfering signals. In case the frequency of an interfering signal is inside the range of frequencies to which the power sensor is sensitive, this signal contributes to the measured power and thus yields a biased estimation of the properties of the transmit antenna.

Therefore, the measurements have to be performed in the absence of echoes and interferers. Section 5.3.2 gives hints on suitable environments.

## 3.3 Polarization matching

The Friis equation in the form presented above assumes that the receive antenna's polarization matches the polarization of the incoming wave. If this is not the case, the power delivered to the receive antenna's load is less than it would be in case of polarization matching. Then, measurements would have to be taken for two orthogonal polarizations, and the obtained powers would have to be added prior to determining the pattern according to (4).

# 4 Measurement Setup

The setup that will be used for the applications described in the next section is shown in Figure 3. It is common to all of the applications that the DUT operates in transmit mode.

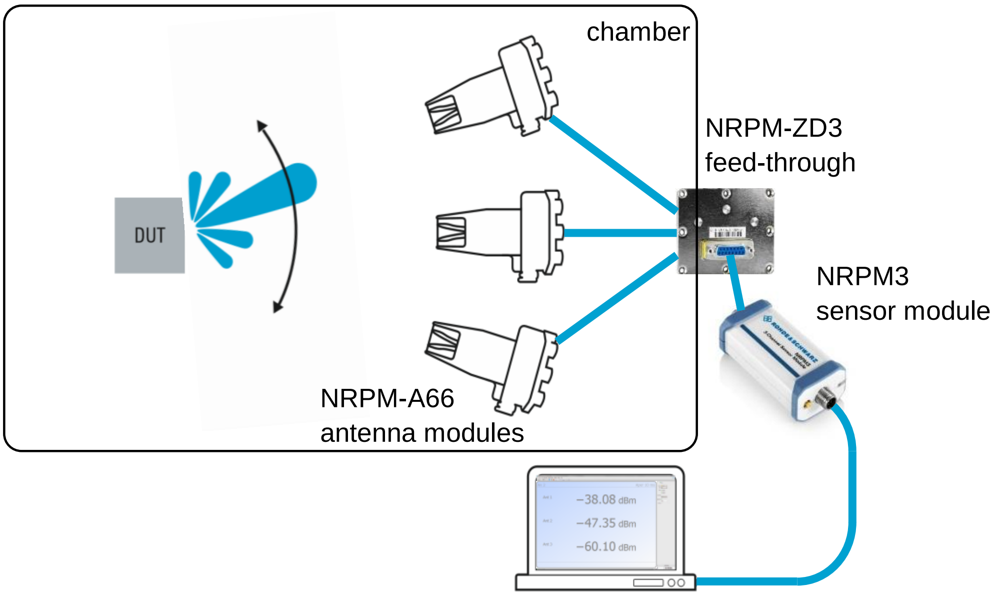


**Figure 3: Block diagram of the setup**

The setup consists of the DUT and

- 3 NRPM-A66 antenna modules
- 1 NRPM-ZD3 feedthrough
- 1 NRPM3 sensor module
- 1 TS7124 RF shielded box with absorber material
- 1 TS-F24-AH1 half antenna ring with TS-F2X-VH4 adapters
- 1 PC for acquiring data from the NRPM3 sensor module via USB

The beam steering capability of a 5G device is simulated using a rotatable horn antenna transmitting a signal generated by a signal generator. Figure 4 shows how the horn antenna and the NRPM-A66 antenna modules are arranged geometrically.

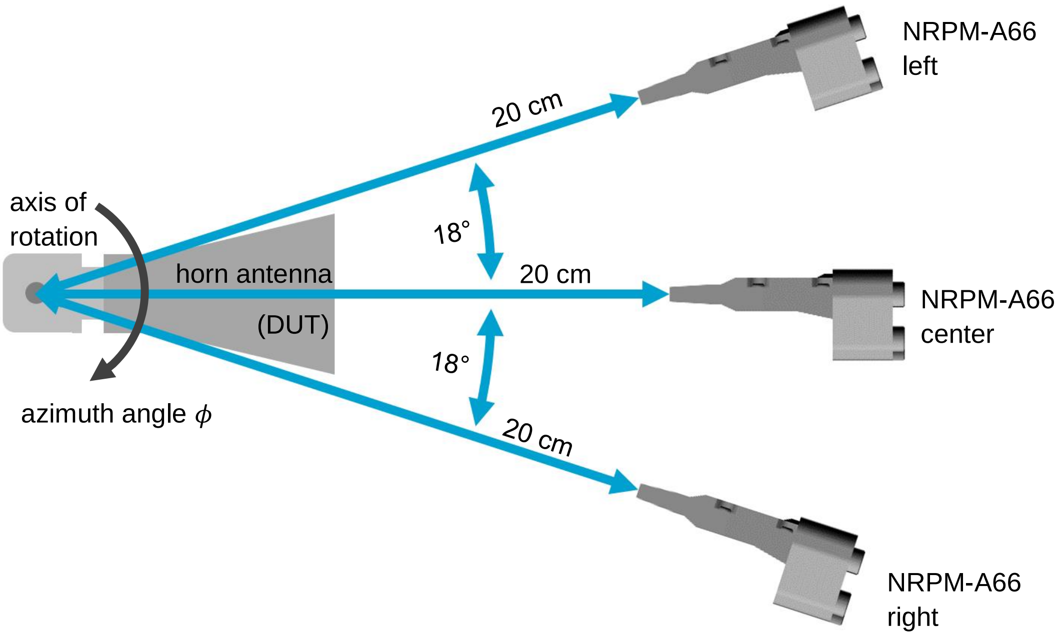


**Figure 4: Relative positions of the NRPM-A66 antenna modules with respect to the horn antenna's axis of rotation**

The NRPM-A66 antenna modules are pointing towards the horn antenna's axis of rotation. They are oriented such that they are polarization-matched to the horn antenna.

The NRPM-A66 antenna modules are placed at azimuth angles of -18°, 0° and 18° as counted from a line connecting the DUT and the center NRPM-A66 antenna module.

The distance between the axis of rotation and the closest point of the NRPM-A66 antenna modules is approximately 20 cm on average with only minor deviations among the NRPM-A66 antenna modules. As a consequence, the path losses between the DUT and each of the NRPM-A66 antenna modules can be considered identical. This is not a requirement for the application described in 5.1, but it can be very convenient in order to compare the radiation to different spatial directions without having to account for potentially unknown individual path losses.

The measurements are performed using a continuous wave (CW) signal at 28 GHz. In general, the presented setup and procedures are applicable to arbitrary frequencies within the extremely large frequency range (27.5 to 75 GHz) of the NRPM-A66 antenna modules.

The horn antenna's aperture has a diagonal of 6.5 cm length. According to criterion (9) the far-field starts 80 cm from the horn antenna at 28 GHz. As can be seen from Figure 4, this criterion is not met with the chosen setup. This is, however, no limitation for the presented applications, since they are based on the comparison of the DUT and a golden device. The presented applications prove the excellent capabilities of such a compact setup.

Figure 5 shows a photograph of the setup.

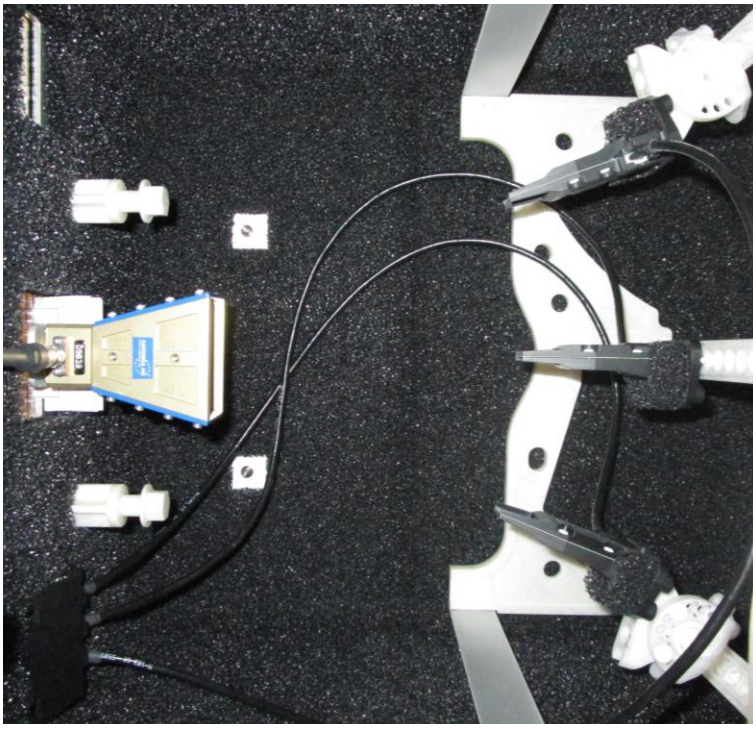

**Figure 5: TS7124 RF shielded box, horn antenna and 3 NRPM-A66 antenna modules, mounted on a TS-F24-AH1 half antenna ring and TS-F2X-VH4 adapters.**

To give a first and illustrative impression on possible measurements, Figure 6 shows the powers received by individual NRPM-A66 antenna modules as the horn antenna is steered to various directions. For angles around -18°, the left NRPM-A66 antenna module (red curve) shows the highest received power. As the horn antenna is steered towards 0° and eventually to positive angles, the center NRPM-A66 antenna module (green curve) and eventually the right NRPM-A66 antenna module (blue curve) receive the maximum power.

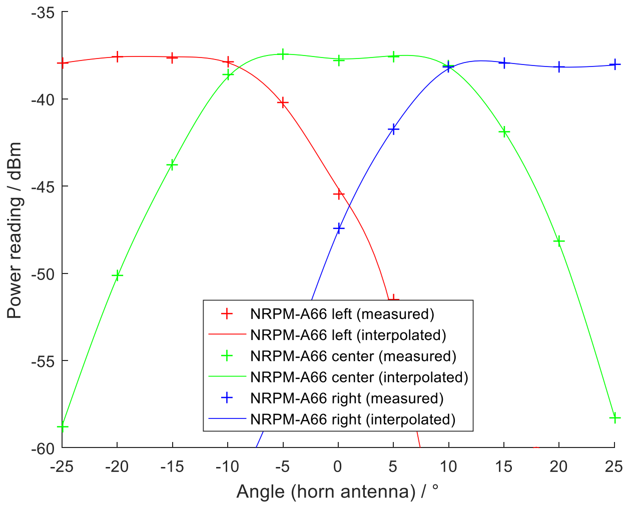


**Figure 6: Power readings obtained with the NRPM-A66 antenna modules arranged for polarization-matching**

The NRPM-A66 antenna modules are expected to be co-polarized to the waves that are radiated by the horn antenna. The left plot in Figure 7 shows the same measurement data as the plot in Figure 6 but with the y-axis extended to lower powers as compared to Figure 6. The right plot in Figure 7 shows the power received by the NRPM-A66 antenna modules rotated by 90° and thus expected to be cross-polarized with respect to the horn antenna.

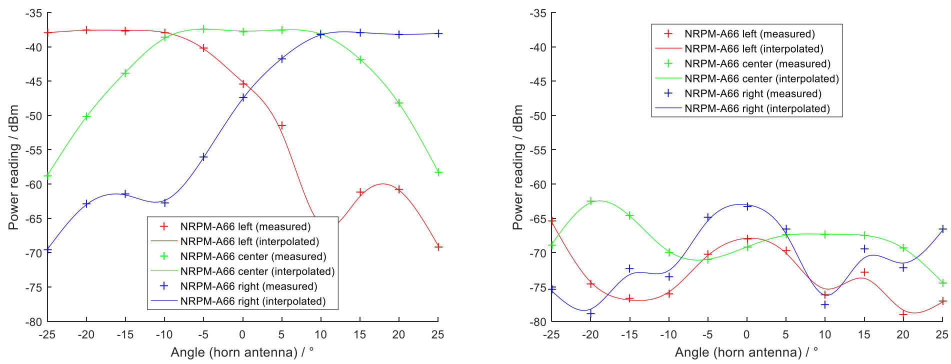


**Figure 7: Power readings obtained with the NRPM-A66 antenna modules arranged to be co-polarized (left) and cross-polarized (right) with respect to the horn antenna.**

# 5 Applications

In this section, two applications are described. The first one is the verification of the power level and the radiation pattern of a DUT in 5.1.

The second one is the verification of the accuracy of beam steering in 5.2.

In 5.3, points are discussed that should be considered before implementing a particular setup.

## 5.1 Verifying the power level and the radiation pattern of a DUT

**Properties of the DUT**

- The DUT operates in transmit mode.
- The beam of the DUT can be steered to different azimuth angles.

**Task**

- Verify that the power level and the radiation pattern of the DUT are within the defined boundaries

**Approach**

- Use a golden device to obtain reference values
- Measure the radiation of the DUT and compare the readings to the reference

### 5.1.1 How to measure the golden device?

1. Put the golden device in place.
2. For each of the defined beam directions:
   a) Steer the beam to the defined direction.
   b) Record the power readings of all NRPM-A66 antenna modules.
3. Remove the golden device.

### 5.1.2 How to measure the DUT?

1. Put the DUT in place. Make sure that the location and the orientation are the same as with the golden device.
2. For each of the defined beam directions:
   a) Steer the beam to the defined direction.
   b) Record the power readings of all NRPM-A66 antenna modules.

### 5.1.3 How to evaluate the measured data?

The data obtained for the DUT is compared to the respective reference data obtained using the golden device. Depending on the deviations, the test is considered as passed or failed.

### 5.1.4 Measurement results

Each of the following figures contains an illustration of the direction to which the horn antenna is pointing and the corresponding display in the R&S®Power Viewer Plus software.

As the horn antenna points towards the left NRPM-A66 antenna module (beam is directed to -18°, Figure 8), the corresponding power reading is maximum. As expected, the reading of the center antenna is lower, and that of the right antenna is minimum.

The opposite is true for the case when the horn antenna points to the right NRPM-A66 antenna module (beam is directed to 18°, Figure 10).

Rotating the horn antenna towards the center NRPM-A66 antenna module (beam is directed to 0°, Figure 9) results in the maximum power reading for the center NRPM-A66 antenna module and lower readings for the left and the right NRPM-A66 antenna module.

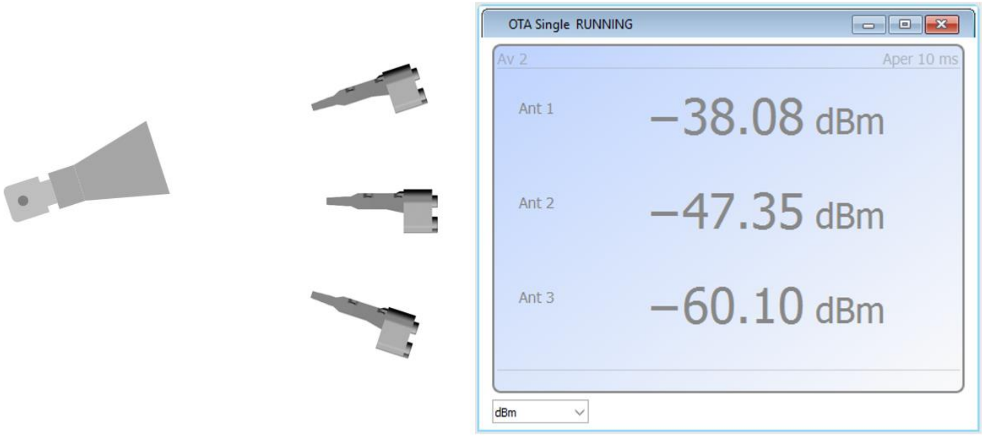


**Figure 8: Horn antenna directed to the left NRPM-A66 antenna module**

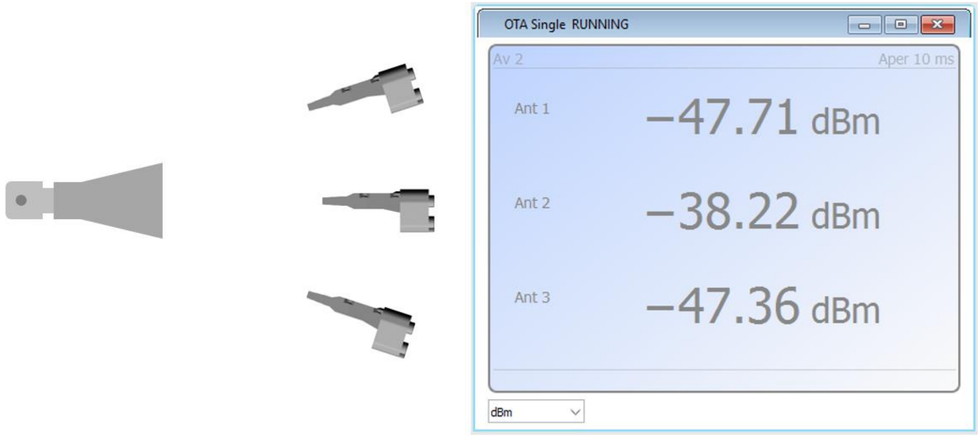


**Figure 9: Horn antenna directed to the center NRPM-A66 antenna module**

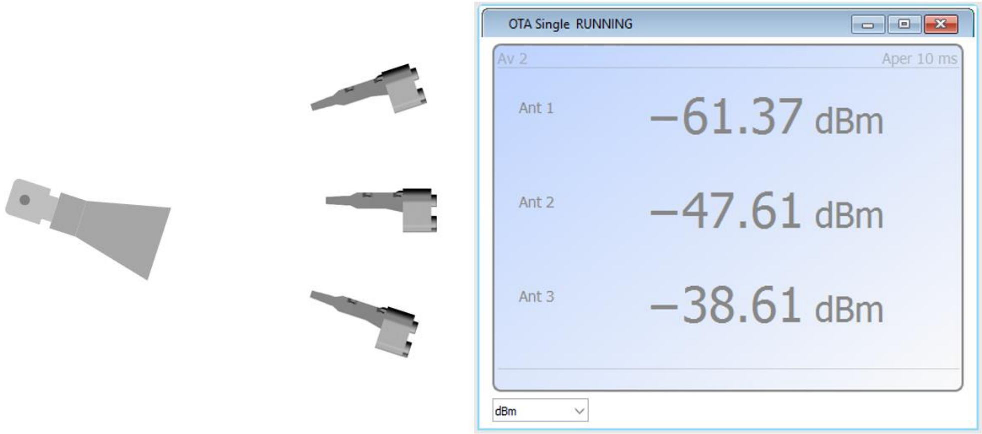


**Figure 10: Horn antenna directed to the right NRPM-A66 antenna module**

### 5.1.5 Prerequisites

It is advisable to consider the points mentioned in 5.3.

### 5.1.6 Ideas for modifications

- If more spatial samples with respect to azimuth are desired, additional NRPM-A66 antenna modules can be used.
- If information on the power distribution with respect to elevation is desired, additional NRPM-A66 antenna modules can be placed below or above the existing NRPM-A66 antenna modules.
- Up to 4 NRPM3 sensor modules and thus 12 NRPM-A66 antenna modules are supported by the R&S®Power Viewer Plus software. This limit does not apply when communicating with the NRPM3 sensor modules via VISA.

## 5.2 Verifying the accuracy of beam steering

**Properties of the DUT**

- The DUT operates in transmit mode.
- The beam of the DUT can be steered to different azimuth angles.

**Task**

- Verify that the beam of the DUT points to the intended direction (even when this direction is not in line with one of the 3 NRPM-A66 antenna modules).

**Approach**

- Obtain a reference pattern using a golden device.
- Put the DUT in place, take a single set of power measurements and determine the beam direction by fitting the reference pattern to the measured powers.

The prerequisites given in 5.2.5 have to be fulfilled.

### 5.2.1 How to measure the golden device?

The golden device–horn antenna A in this case–is put in place. It is steered to different azimuth angles. For each of those angles, the power reading of the center NRPM-A66 antenna module is recorded. Those power readings, when processed according to (4), yield samples of the reference radiation pattern. For the horn antenna, angles between -25° and 25° in steps of 5° have been chosen. The measured values and the result of an interpolation are shown in Figure 11.

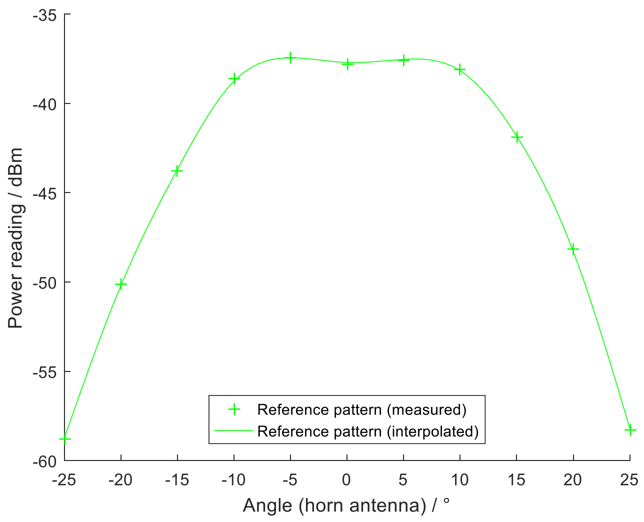


**Figure 11: Reference pattern obtained with horn antenna A and the center NRPM-A66 antenna module**

Note that the horn antenna is not rotated about its phase center, which is the point from which the radiation is said to emanate. Note also that the NRPM-A66 antenna modules are not in the far-field of the horn antenna, which begins in a distance of approximately 80 cm from the horn antenna at a frequency of 28 GHz according to (9). Therefore, the obtained radiation pattern is not necessarily the horn antenna's far-field radiation pattern, but a characteristic pattern that allows to find the horn antenna's beam direction.

### 5.2.2 How to measure the DUT?

1. Put the DUT in place. Make sure that the location and the orientation are the same as with the golden device.
2. For each of the defined beam directions:
   a) Steer the beam to the defined direction.
   b) Record the power readings $P_1$, $P_2$ and $P_3$ of the left, the center and the right NRPM-A66 antenna module, respectively.

### 5.2.3 How to evaluate the measured data?

The evaluation is identical for all of the considered beam directions of the DUT. $P_1$, $P_2$ and $P_3$ denote the powers measured by the three NRPM-A66 antenna modules located at equal distances and at azimuth angles $\phi_1$, $\phi_2$ and $\phi_3$ as seen from the DUT. $P_{\text{ref}}(\phi)$ denotes the reference pattern (the green solid curve in Figure 11).

An estimate of the beam direction of the DUT is that angle $\phi_{\text{est}}$ that minimizes the cost function

$$f = (P_1 - P_{\text{ref}}(\phi_1 - \phi_{\text{est}}))^2 + (P_2 - P_{\text{ref}}(\phi_2 - \phi_{\text{est}}))^2 + (P_3 - P_{\text{ref}}(\phi_3 - \phi_{\text{est}}))^2, \qquad (10)$$

i.e. that best fits the reference pattern to the measured values in a least squares sense.

The minimization is carried out with respect to the physical quantity power in (milli)watts (and not for instance in the logarithmic unit dBm). A power level $P_{\text{dBm}}$ stated in dBm can be converted to the corresponding power $P$ in milliwatts according to

$$P = 10^{P_{\text{dBm}}/10}\ \text{mW}. \qquad (11)$$

Once the actual beam direction is determined, it is compared to the defined beam direction. Depending on the deviation, the test is considered passed or failed.

### 5.2.4 Measurement results

Each of the plots in the following figures corresponds to a particular beam direction (azimuth angles of -10°, -5°, 0°, 5° and 10°).

Each plot shows the identical reference pattern obtained with the golden device–horn antenna A–in green.

The red diamonds represent the power readings $P_1$, $P_2$ and $P_3$ of the left, center and right NRPM-A66 antenna modules, respectively, obtained when the DUT–horn antenna B–was steered to a certain azimuth angle.

The red curves are copies of the green reference curves, shifted by those angles $\phi_{est}$ that best fit the reference pattern to the powers measured by the three NRPM-A66 antenna modules for the different beam directions.

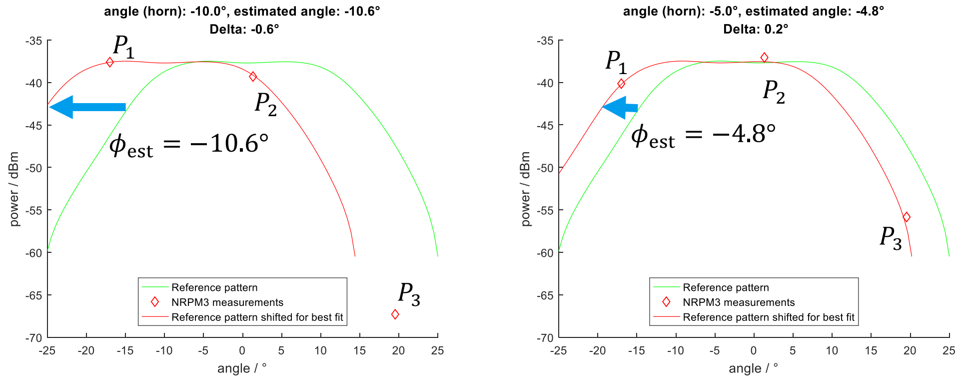


**Figure 12: Estimates of the angle of rotation for the DUT rotated to the left by 10° (left plot) and 5° (right plot)**

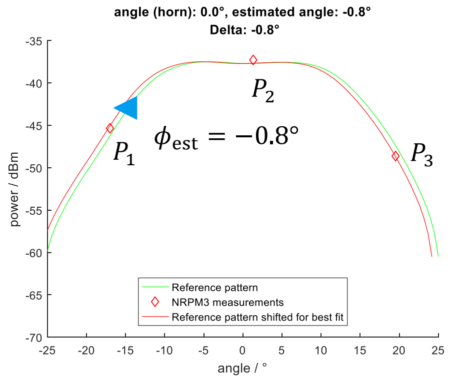


**Figure 13: Estimate of the angle of rotation for the unrotated DUT**

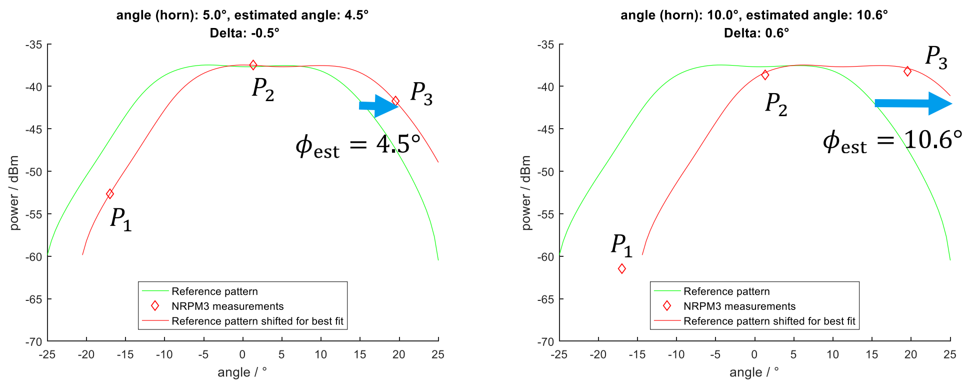


**Figure 14: Estimates of the angle of rotation for the DUT rotated to the right by 5° (left plot) and 10° (right plot)**

As can be seen from the plots, the estimation of the beam direction of the DUT, based on a single set of measurements with three spatially separated NRPM-A66 antenna modules, is in very good agreement with the true beam direction of the DUT.

### 5.2.5 Prerequisites

- In equation (10), the only degree of freedom is $\phi_{\mathrm{est}}$. The estimation of the beam direction might degrade as the radiated power differs between the golden device and the DUT. It has to be ensured that the power levels are sufficiently similar. In case this is not possible, the ideas given in 5.2.6 might help to overcome this issue. The maximum tolerable deviation depends on the particular pattern and the desired accuracy of the estimation of the beam direction.

- The presented approach is based on best-fitting a known pattern to a set of measured values. For the used DUT–a horn antenna–the pattern is invariable irrespective of what angle the horn antenna is rotated to. The only feature that varies as the horn antenna is rotated is the beam direction.
For antenna arrays it is common that while the beam is steered off the direction normal to the antenna elements, the beamwidth increases and the maximum gain decreases. That means that not only the beam direction changes, but also other characteristics of the pattern. In such a case it might be advantageous to apply one of the ideas given in 5.2.6.

- The number of NRPM-A66 antenna modules and their locations have to be chosen appropriately with regard to the number of unknowns to be estimated and the particular pattern of the DUT. It has to be ensured that a sufficient number of NRPM-A66 antenna modules is covered by the DUTs beam so that there are enough measured values to obtain robust fitting. The number of unknowns is 1 in case of applying equation (10), but it might be greater than 1 when other ways of estimating the beam direction are applied (s. 5.2.6).

- The power reading of an NRPM-A66 antenna module is influenced by the impinging power as well as the calibration of the NRPM-A66 antenna module. In order to maximize the accuracy of the angle estimation, the power readings of all used NRPM-A66 antenna modules have to be sufficiently similar for equal impinging powers. The maximum allowable difference depends on the actual pattern of the DUT. The similarity of the power readings can be checked by mounting the relevant NRPM-A66 antenna modules at identical positions with identical orientations one after the other. For each of the NRPM-A66 antenna modules, the power reading is recorded while the DUT is radiating, enabling a comparison of the NRPM-A66 antenna modules. In case the deviation is too high for a given application, the differences can be used as offsets for a relative calibration. Due to the extraordinary linearity of the NRPM-A66 antenna modules, the offsets are valid for the entire power measurement range of the NRPM-A66 antenna modules. In order for the mentioned procedures to be meaningful, it is necessary to provide each of the NRPM-A66 antenna modules with identical signals and identical powers. It is therefore advisable to place the NRPM-A66 antenna modules in such a region relative to the DUT where a slight variation of the actual positions of the NRPM-A66 antenna modules yields only a small variation in the received power.

### 5.2.6 Adaptations for 5G devices

- In case it is necessary to obtain resolution with respect to elevation, additional NRPM-A66 antenna modules can be placed below or above the existing NRPM-

A66 antenna modules. Then, the reference pattern has to be determined in two dimensions (azimuth and elevation), and the evaluation of the elevation angle has to be incorporated into the cost function.

- Depending on the expected variation of the power radiated by individual DUTs, it might be necessary to increase the number of degrees of freedom in the cost function (10) in order to obtain the highest estimation accuracy. This can be accomplished by incorporating a factor $a$ into (10) that is applied to the reference pattern. The cost function then reads as
$f = (P_1 - aP_{\mathrm{ref}}(\phi_1 - \phi_{\mathrm{est}}))^2 + (P_2 - aP_{\mathrm{ref}}(\phi_2 - \phi_{\mathrm{est}}))^2 + (P_3 - aP_{\mathrm{ref}}(\phi_3 - \phi_{\mathrm{est}}))^2$
and is a more realistic representation of the measurement situation in case the power level varies between individual DUTs. Therefore, minimizing this cost function–with respect to $a$ and $\phi_{\mathrm{est}}$–yields higher accuracy in estimating the beam direction. The resulting value of $a$ is an estimation of the power radiated by the DUT with respect to the power radiated by the golden device.
- There are several ways to cope with patterns whose characteristics change as the beam is steered to different beam directions.
One of them is to record a set of reference patterns for different beam directions and approximate them by a two-dimensional analytical expression, where the two dimensions are the beam direction and the observation angle. Useful characteristics for the analytical description of the pattern might be the maximum gain and the beamwidth. Both parameters generally change as an antenna array is steered to different angles. The estimation of the beam direction is done by formulating a two-dimensional cost function and minimizing it with respect to the beam direction. In order to determine the reference patterns, the beam of the DUT has to be steered to different directions. For each direction, the pattern is determined by either rotating the DUT or orbiting the used NRPM-A66 antenna around the DUT.
Another option is using a higher number of NRPM-A66 antenna modules. When arranged with sufficiently small angular spacing, the maximum value and thus the beam direction can be determined immediately or if necessary after an interpolation. Proceeding this way renders the use of a golden device unnecessary.

## 5.3 Points to consider

Before choosing a setup for a particular application, at least the following aspects should be considered in order to get the maximum benefit from the measurements. Those aspects are strongly related to the theoretical considerations in section 3.

### 5.3.1 Appropriate distance between DUT und NRPM-A66 antenna modules

In order to obtain the radiated power or far-field characteristics of the DUT as e.g. the far-field pattern of the DUT according to (4), the DUT and the NRPM-A66 antenna modules have to be located in each other's far-field.

For short distances between the DUT and the NRPM-A66 antenna modules, the Friis equation might not predict the path loss very well. In order to have equal–even though unknown–path losses between the DUT and each of the NRPM-A66 antenna modules, it is advisable to choose equal distances.

In the presented applications, the measurements are done in the near field. This is no limitation, since the measured values are compared to those obtained with a golden device in the same setup.

In case of doubts about the proper distance between the DUT and the NRPM-A66 antenna modules, it is advisable to start with a large distance and check whether the same conclusions can be drawn from measurements that are taken with smaller distances. Further discussion on this topic can be found in [3].

### 5.3.2 Appropriate environment

If the NRPM-A66 antenna modules are used to measure how much power is radiated by the DUT to particular spatial directions, the measurements are degraded as

- not only the line-of-sight signal but also echoes from other objects or
- interfering signals with frequencies for which the NRPM-A66 antenna modules are sensitive

reach the NRPM-A66 antenna modules, as also addressed in 3.2. Therefore, it must be ensured that the levels of echoes and interfering signals are sufficiently low. This can be accomplished using absorbers and shielding.

The level of interfering signals can be determined by measurements with a turned-off DUT. Depending on the level of interference, it might be necessary to shield the test setup from interfering signals. The TS7124 RF shielded box is a perfect solution for this problem.

Echoes can be avoided by placing the measurement setup inside an anechoic chamber or by removing objects not needed for the measurement sufficiently far from the test setup. Those objects that are necessary parts of the setup may have to be covered with absorbing material appropriate for the relevant frequencies. A TS7124 RF shielded box shields the setup from interferers and suppresses unwanted echoes.

### 5.3.3 Orientation of the NRPM-A66 antenna modules

The NRPM-A66 antenna modules are linearly polarized. It has to be kept in mind that the power reading of the NRPM sensor module refers to only that part of the incident wave that is associated with the polarization direction of the NRPM-A66 antenna. Figure 7 clearly shows the effect of rotating the NRPM-A66 antenna modules by 90° about their boresight on the power readings.

The NRPM-A66 antenna modules have to be oriented such that they are co-polarized to the desired polarization of the incident wave. The NRPM-A66 antenna module has maximum sensitivity when the E field vector of the incident wave is parallel to the substrate of the NRPM-A66 antenna module.

In order to obtain consistent results when measuring multiple DUTs, the relative locations and orientations of the golden device, the DUTs and the NRPM-A66 antenna modules have to be kept fixed.

A versatile means for fixing the NRPM-A66 antenna modules are the TS-F24-AR antenna rings or the TS-F24-AH1 half antenna rings, if necessary with TS-F2X-VH4 adapters (s. Figure 15) to adjust the NRPM-A66 antenna module's tilt angle. Apart from that, TS-F24-AH2 antenna holders (s. Figure 15) are available that can e.g. be directly attached to the front and back walls of a TS7124 RF shielded box.

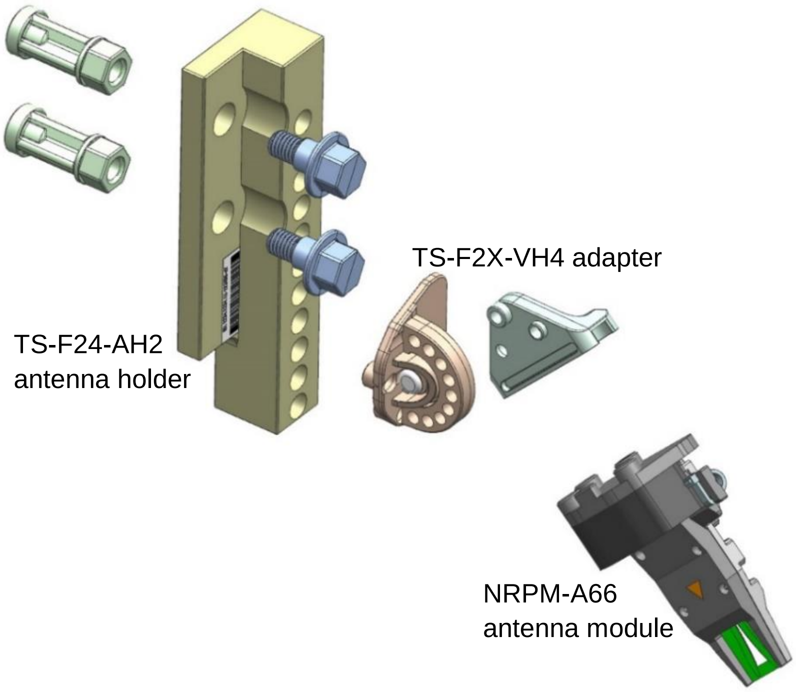


**Figure 15: TS-F24-AH2 antenna holders, TS-F2X-VH4 adapter and NRPM-A66 antenna module**

### 5.3.4 Influence of modulated signals

Measurements can be done with CW signals as well as with modulated signals. In order to obtain the most reliable and comparable results, the signals of the golden device and the DUTs should be identical.

### 5.3.5 Ways of controlling the NRPM sensor module

There are several ways of controlling the NRPM sensor module from a computer. One particularly convenient way is using the R&S®Power Viewer Plus software [4]. However, any programming language that supports VISA can be used. Detailed information on controlling the NRPM sensor module can be found in the NRPM User Manual [5].

# 6 References

[1] **Balanis, Constantine A.**, *Antenna Theory*, Wiley, 2005

[2] **Friis, Harald T.**, "A Note on a Simple Transmission Formula", *Proceedings of the I.R.E. and Waves and Electrons*, May 1946

[3] R4-1706859 “Minimum Measurement Distance at 28GHz”, Rohde & Schwarz, 3GPP TSG RAN WG4 Meeting NR#2 AH

[4] https://www.rohde-schwarz.com/software/nrpm/

[5] **Rohde & Schwarz**, *NRPM OTA Power Measurement Solution User Manual*

# 7 Ordering Information

Please visit the product websites at www.rohde-schwarz.com for comprehensive ordering information (“Options”) on the following Rohde & Schwarz products:

- R&S®NRPM3 (1425.8563.02)
- R&S®NRPM-A66 (1425.8740.02)
- R&S®NRPM-ZD3 (1425.8786.02)
- R&S®TS7124 (1525.8564.02 / .12, 1525.8587.02 / .12)
- R&S®TS-F24-AR (1525.8906.02)
- R&S®TS-F24-AH1 (1525.8887.02)
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- R&S®TS-F2X-VH4 (1525.8758.02)

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