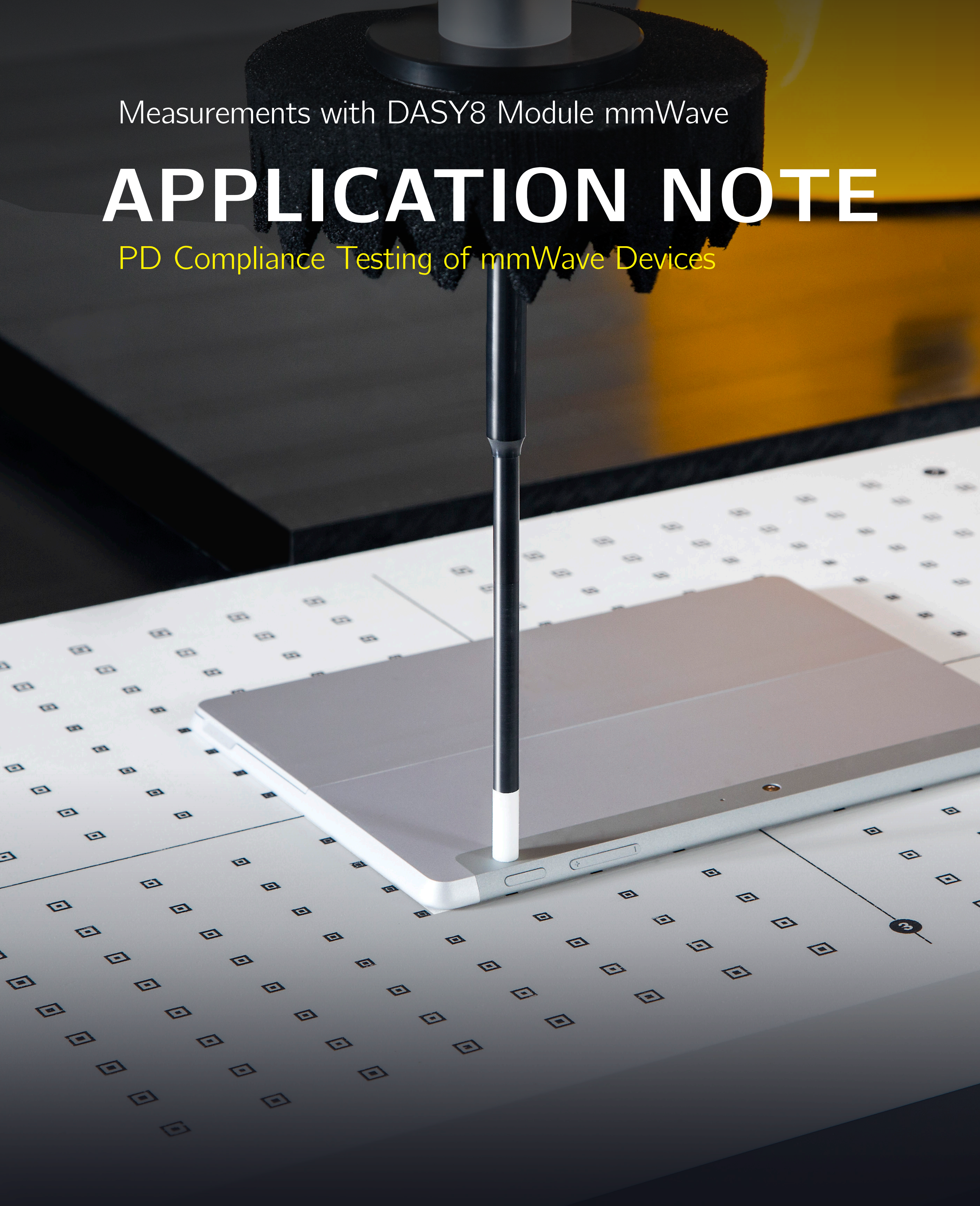
Measurements with DASY8 Module mmWave

APPLICATION NOTE

PD Compliance Testing of mmWave Devices



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Power Density Testing of mmWave Devices

1 Introduction

Fifth generation technologies brings communication systems that operate at millimeter-wave frequencies (i.e., 5G NR FR2) into mobile devices. This leads to new requirements on test systems for assessment of compliance with electromagnetic (EM) safety guidelines. The solution described here is based on a novel non-disturbing millimeter wave near-field probe and a total-field and power-density reconstruction algorithm. The applicability of the solution to test device safety has been validated for millimeter wave sources at distances from the transmitting source as small as 2 mm.

2 EUmmWVx Probe Description

2.1 Probe Design

The EUmmWVx probe is based on the pseudo-vector probe design, which not only measures the field magnitude but also derives its polarization ellipse. This probe concept also has the advantage that the sensor angle errors or distortions of the field by the substrate can be largely nullified by calibration. This is particularly important as, at these very high frequencies, field distortions by the substrate are dependent on the wavelength. The design entails two small 0.8 mm dipole sensors mechanically protected by high-density foam, printed on both sides of a 0.9 mm wide and 0.12 mm thick glass substrate. The body of the probe is specifically constructed to minimize distortion by the scattered fields.

The probe consist of two sensors with different angles (γ_1 and γ_2) arranged in the same plane in the probe axis. Three or more measurements of the two sensors are taken for different probe rotational angles to derive the amplitude and polarization information. These probes are the most flexible and accurate currently available for measuring field amplitude.

The probe design allows measurements at distances as small as 2 mm from the sensors to the surface of the device under test (DUT). The typical sensor to probe tip distance is 1.5 mm. The exact distance is calibrated.

2.2 Probe Handling

EUmmWVx probes must be operated with specific care to avoid any damage:

- the probe must be used only in air; it is not designed to be immersed in liquids
- the protective probe cap should be removed – by sliding it carefully along the probe axis – only to make measurements
- the application of lateral force to the probe tip should be strictly avoided
- a dummy probe should be used to test scanning or any robot movement before measurements are made

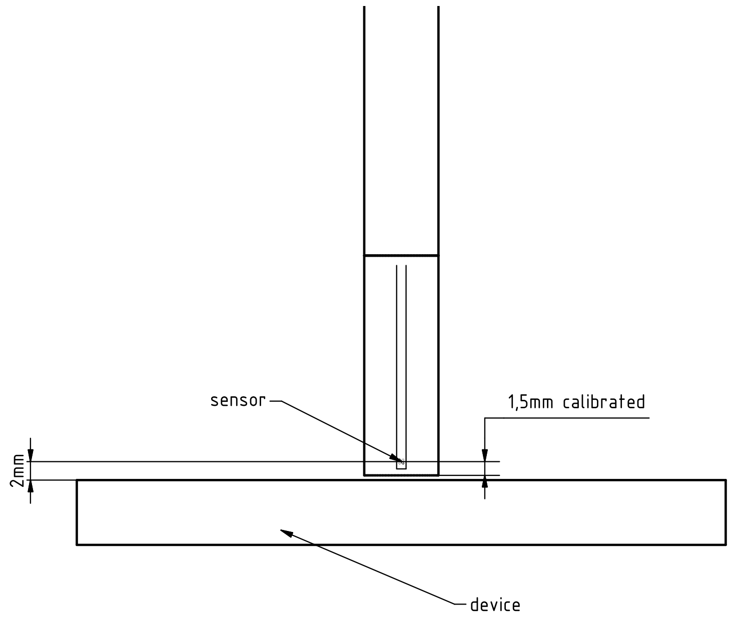


Figure 1.1: Illustration of distance sensor to DUT surface.

3 mmWave Phantom

The mmWave phantom can be used as test bed when measuring power density for any of the 6 faces of wireless devices. It approximates free-space conditions, allowing to evaluate not only the antenna side of the device but also the front (screen) side or any opposite-radiating side of wireless devices without distorting the RF field. It consists of a 40 mm thick Rohacell plate used as a test bed which has a loss tangent ($\tan \delta$) ≤ 0.05 and a relative permittivity (ϵ_r) ≤ 1.2 according to the latest standard draft. High-performance RF absorbers are placed below the polystyrene foam. Measurements have demonstrated that the reflection coefficient is better than -20 dB at any frequencies above 10 GHz.

4 mmWave Device Holder

The mmWave Device Holder is designed to ease positioning of the DUT of various size when measuring power density along an edge. It is made of low loss Rohacell material and meet the standard requirements. It is provided with an additional spacer to accommodate devices with smaller form factor.

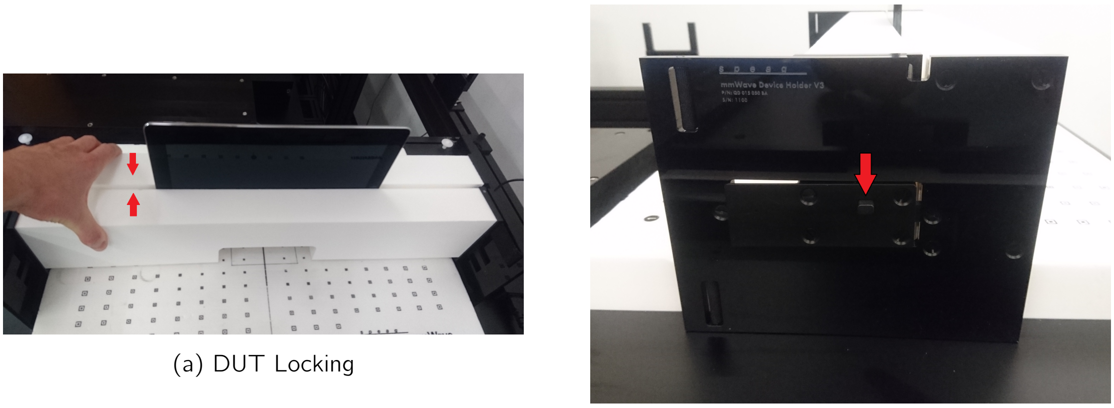
Figure 1.2 shows a DASY8 system setup for Power Density compliance testing at mmWave frequencies. The DUT is held with a mmWave Device Holder placed on top of the mmWave phantom.

The DUT positioning procedure with mmWave Device Holder is described below:

- Mount the mmWave DUT Holder on top of the mmWave Phantom.
- Place the DUT between the two Rohacell bars and, with both hands, gently squeeze the two bars together until the DUT is fixed. The DUT is intended to be placed at the center of the holder with the lowest edge touching the mmWave phantom. For smaller devices, the provided spacer can be used to raise the DUT.
- To release the DUT, press the two small levers on each side simultaneously.
- Make sure that the setup is stable and will not move during scanning. Also make sure that the probe will not hit any of the holder edges.

Figure 1.2: Test Setup with mmWave Holder.

Figure 1.3 illustrates the locking and releasing mechanism of the DUT in the mmWave Device Holder.

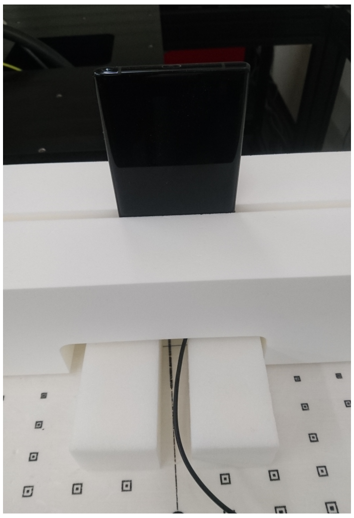


(a) DUT Locking

(b) DUT Releasing

Figure 1.3: DUT Locking / Releasing in mmWave Device Holder

Figure 1.4 shows the positioning of a small form factor device (smartphone) with the mmWave Device Holder when testing a short and long edge. The spacer is used to raise the device and allow to connect a cable. Figure 1.5 show the setup for testing a laptop positioned with the mmWave Device Holder.



(a) Short Edge

(b) Long Edge

Figure 1.4: Setup for Testing a Short / Long Edge of a Smartphone

Figure 1.5: Setup for Testing a Laptop.

5 Measurements

5.1 Prerequisites

The following system configuration is required to perform power density measurements:

- DASY8 system
- EUmmWVx probe
- mmWave phantom
- DASY8 Module mmWave with a valid license

5.2 Software Configuration

First, the hardware configuration must be specified in the software, as described in the following steps:

- under Application Preferences » Inventory » Phantom, import the mmWave phantom
- under Application Preferences » Inventory » Mediums, import Air
- under Application Preferences » Inventory » DAEs, import the DAE configuration file
- under Application Preferences » Inventory » Probes, import the EUmmW probe configuration file
- under Hardware Setup View, place the mmWave phantom in the slot to be used for measurement and select Air as medium
- under Hardware Setup View, specify the DAE, probe, and platform slot to be used for the measurements

Figure 1.6 shows the hardware setup view configured for mmWave measurements.

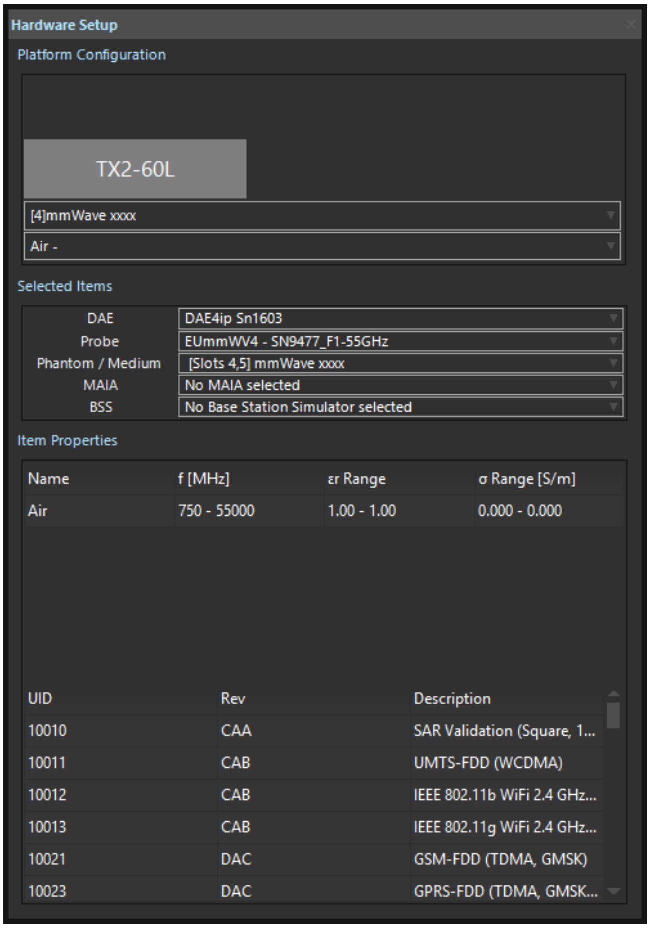


Figure 1.6: Hardware Setup view configured for mmWave measurements.

5.3 Hardware Configuration

After the mmWave phantom is inserted into one of the slots of the DASY8 system platform, the "Teach Phantom" entry in the context menu of the 3D view is used to teach the phantom. The procedure, which is identical to that for teaching SAR phantoms, defines the inclination of the measurement plane.

The last step consists of teaching the DUT, by a single point that defines the DUT height. For this, press the "Teach DUT" tool and move the probe tip as close as possible to the DUT surface without colliding to it. The measurement planes with be then parallel to the mmWave phantom at the height given by the DUT taught point, to which the measurement distance is added. The measurement grid is by default centered on the point taught for the DUT, additional offsets can be configured in the software if needed.

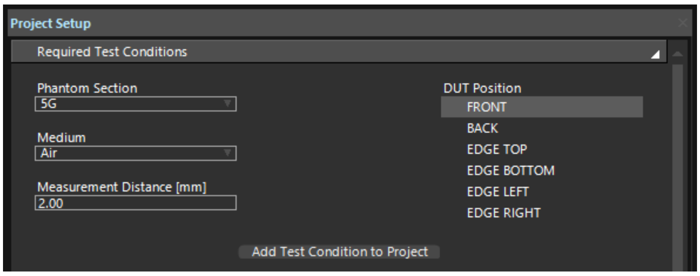
Please note that the teaching process is always performed with a dummy probe

5.4 Project Generation

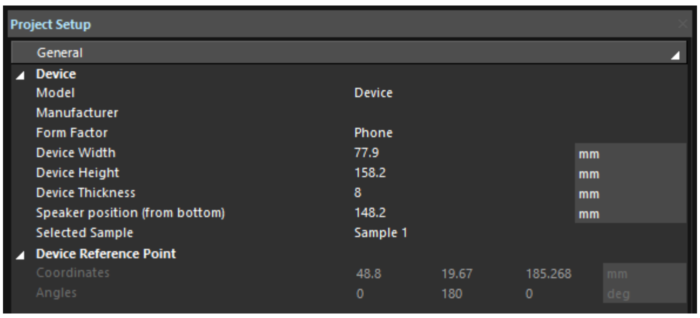
Measurements can be added to the current project as described below:

- under Setup mode, select Project Setup view
- under Device Settings, enter the dimensions of the DUT
- under Test Conditions, enter the desired measurement distance and click on “Add Test Condition to Project"; multiples test conditions can be added to the same measurement file; the measurement distance corresponds to the distance from the probe sensor to the DUT
- under Communication Systems, select the desired communication system, band, and channel

Figure 1.7 shows the Test Conditions and Device Settings views.



(a) Test Conditions view



(b) Device Settings view

Figure 1.7: Test Conditions and Device Settings views

5.5 Scan Selection

DASY8 Module mmWave supports two different scan types:

- Fast Scan – a measurement scan where sensor voltages are sampled continuously while the robot is moving – is used to determine the radiation pattern and the maximum location
- 5G Scan – a fine resolution scan performed on two different planes – is used to reconstruct the E- and H-fields as well as the power density; the average power density is derived from this measurement
- Forward Transform Scan – a fine resolution scan performed on three different plane – is used to reconstruct the E- and H- fields as well as the power density. In addition to the 5G Scan, the power density can be evaluated on any surface in the half space above the measurement plane. Forward Transform Scans are also used as input of the MEO (Maximum Exposure Optimizer) option which assesses the worst case power density for phased array antennas with complex codebook from a reduced set of measurements.
- Time-Averaged Scan – a measurement scan where sensor voltages are sampled continuously at a fixed probe location – is used for compliance testing of devices that can monitor the transmitted power during a certain time interval.
- Generic Scan – a measurement scan performed on a single 2D plane – is used to measure the E-field. The power density, valid in the far-field only, is calculated as $S = \frac{E^2}{120 \cdot \pi}$. DASY8 Module mmWave estimates Dmax, the maximum dimension of the radiation source for which S is valid, according to recent research (https://ieeexplore.ieee.org/document/8393926).

The scan settings (grid steps / extents, anchor point...) can be edited in the Measurement Properties.
Figure 1.8 shows a project that includes measurements in the 5G NR FR2 n257 band. At 30 GHz, Fast Scan and 5G Scan are selected; at 60 GHz, measurements are disabled.

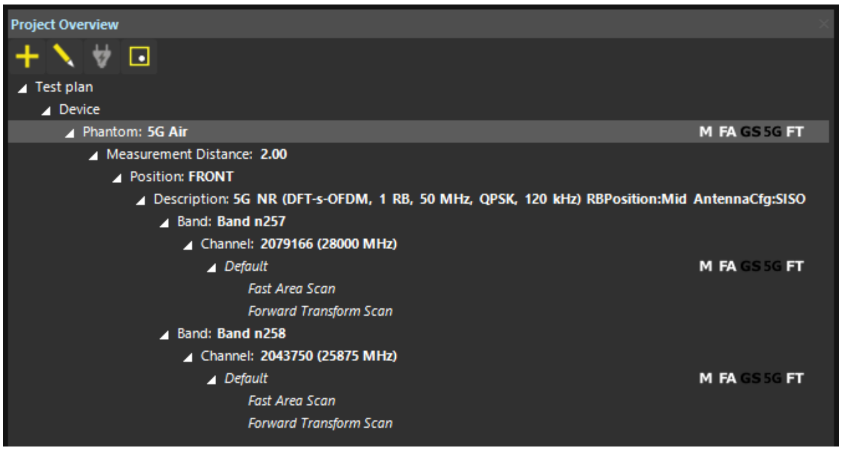


Figure 1.8: Project Overview showing measurements for 5G NR FR2 bands n257 and n258. Fast Area Scan and Forward Transform Scan are selected for measurement.

5.6 Verification Source Measurement

The measurement of a verification source is started by opening the corresponding predefined file and saving it under a different name. An EUmmW dummy Probe is installed, and the phantom is taught (unless already performed). The verification source is placed on the mmWave phantom, connect power supply and grounding cable and let the verification source warm up for at least 40 minutes. Then, "Teach DUT" is selected from the context menu of the 3D view, and the probe is moved to the the corner of the verification source housing. When the probe is almost in contact with the black surface, the Z-coordinate is read from the "Teach DUT" window in the software (SW). The probe is moved up a bit and back to the center of the source, then slowly down until the same Z-coordinate is displayed in the SW window. The DUT point is taught by clicking "Confirm". For safety reasons, the DUT cannot be taught at any point higher than the mmWave phantom home point. Figure 1.9 shows the probe position during teaching of a verification source.

The probe is moved up either manually or by means of the "Robot" - "Move to Home" command, and the real probe is mounted on the Data Acquisition Electronics (DAE) unit. The correct probe is selected in the SW. The correct settings of all other hardware (HW) components in the SW are verified. Due to the internal distance from the horn to the outer surface of the verification source, the measurement distance set in the software should be offset by −4.45 mm; e.g., for measurement of the verification source at 10 mm, the measurement distance set in the software should be 5.55 mm (10 mm − 4.45 mm).

The recommended settings for measurement of verification sources listed in Table 1.1 have been applied in the predefined files.

Frequency [GHz]	Grid step	Grid extent X/Y [mm]	Measurement points
10	0.125 ($\frac{\lambda}{8}$)	60/60	18 × 18
30	0.25 ($\frac{\lambda}{4}$)	60/60	26 × 26
45	0.25 ($\frac{\lambda}{4}$)	42/42	28 × 28
60	0.25 ($\frac{\lambda}{4}$)	32.5/32.5	28 × 28
90	0.25 ($\frac{\lambda}{4}$)	30/30	38 × 38

Table 1.1: Recommended settings for measurement of verification sources.

Note: The verification sources should always be grounded. The standard DASY8 grounding cable is compatible with the verification source.

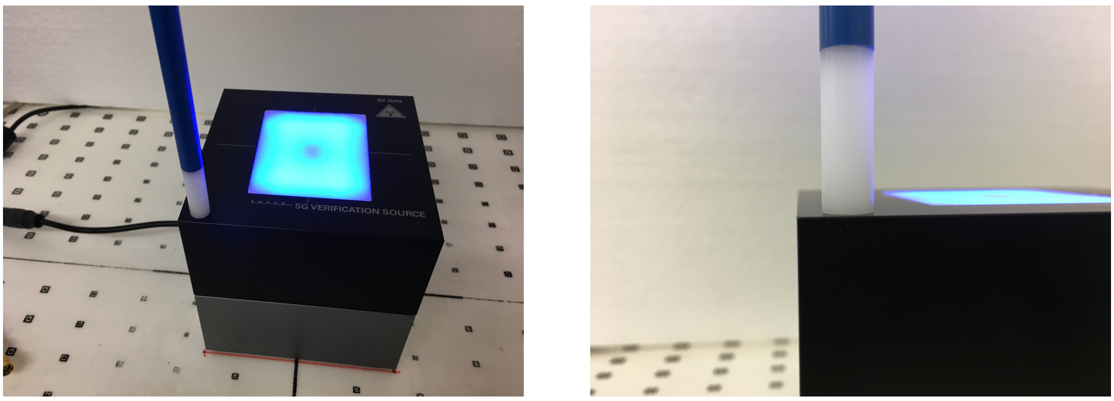


Figure 1.9: Positioning of the probe during teaching of the verification source.

6 Post Processing

6.1 Computation of the Electric Field Polarization Ellipse

For the numerical description of an arbitrarily oriented ellipse in three-dimensional space, five parameters are needed: the semi-major axis (a), the semi-minor axis (b), two angles describing the orientation of the normal vector of the ellipse (ϕ, θ), and one angle describing the tilt of the semi-major axis (ψ). For the two extreme cases, i.e., circular and linear polarizations, three parameters only (a, ϕ, and θ) are sufficient for the description of the incident field.

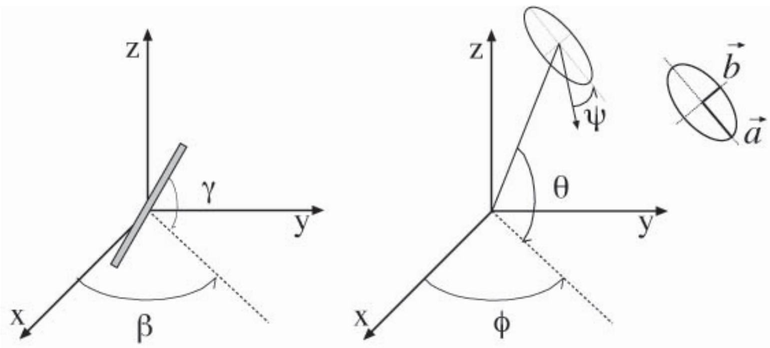


Figure 1.10: Illustration of the angles used for the numerical description of the sensor and the orientation of an ellipse in 3-D space.

For the reconstruction of the ellipse parameters from measured data, the problem can be reformulated as a non-linear search problem. The semi-major and semi-minor axes of an elliptical field can be expressed as functions of the three angles (ϕ, θ, and ψ). The parameters can be uniquely determined towards minimizing the error based on least-squares for the given set of angles and the measured data. In this way, the number of free parameters is reduced from five to three, which means that at least three sensor readings are necessary to gain sufficient information for the reconstruction of the ellipse parameters. However, to suppress the noise and increase the reconstruction accuracy, it is desirable that the system of equations be over-determined. The solution to use a probe consisting of two sensors angled by γ_1 and γ_2 toward the probe axis and to perform measurements at three angular positions of the probe, i.e., at β_1, β_2, and β_3, results in over-determinations by a factor of two (see 1.11. If there is a need for more information or increased accuracy, more rotation angles can be added.

The reconstruction of the ellipse parameters can be separated into linear and non-linear parts that are best solved by the Givens algorithm combined with a downhill simplex algorithm.

To minimize the mutual coupling, sensor angles are set with a shift of 90° ($\gamma_2 = \gamma_1 + 90°$), and, to simplify, the first rotation angle of the probe (β_1) can be set to 0°. More details can be found in [1].

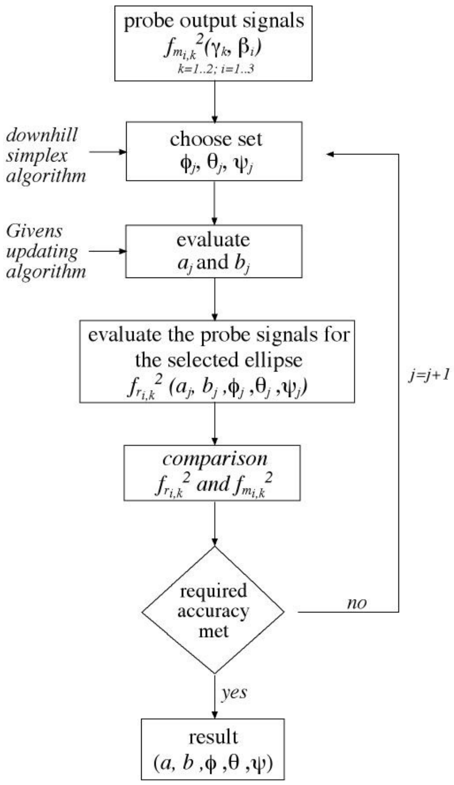


Figure 1.11: Numerical algorithm for reconstructing the ellipse parameters.

6.2 Total Field and Power Flux Density Reconstruction

6.2.1 Plane To Plane (PTP) Reconstruction Algorithm

Computation of the power density in general requires knowledge of the electric (E-) and magnetic (H-) field amplitudes and phases in the plane of incidence. Reconstruction of these quantities from pseudo-vector E-field measurements is feasible, as they are constrained by Maxwell's equations. We have developed a reconstruction approach based on the Gerchberg-Saxton algorithm [2, 3], which benefits from the availability of the E-field polarization ellipse information obtained with the EUmmWVx probe. This reconstruction algorithm, together with the ability of the probe to measure extremely close to the source without perturbing the field, permits reconstruction of the E- and H-fields, as well as of the power density, on measurement planes located as near as $\lambda/2\pi$ away [4]. At closer distances, the uncertainty might be larger.

6.2.2 Equivalent Sources Reconstruction (ESR) Algorithm

SPEAG and IT'IS achieved a breakthrough by developing a novel equivalent source reconstruction (ESR) algorithm, that models an unknown and inaccessible transmitter as a set of distributed known auxiliary sources below the surface of the device enclosure. The locations, amplitudes, and phases of these sources are then determined to optimally reconstruct the measured near-fields. As a result, the transmitters inside any enclosure can be replaced with these equivalent sources in any radiation problem, including exposure assessment scenarios. The novel method has been submitted for publication [5] and a first implementation is now available in DASY8 Module mmWave V3.0 and Sim4Life V7.0.

The ESR permits reconstruction of the E- and H-fields, as well as of the power density, on measurement planes located as close as $\lambda/25$ from the source (2 mm at 6 GHz).

6.3 Power Flux Density Averaging

The average of the reconstructed power density is evaluated on the measurement plane. Two averaging geometries are available: a circle and a rotating square. The averaging area is defined by the user; the default values are 1 cm^2 and 4 cm^2. The three variants of the spatial-average Power Density (sPD) defined in the IEC 63195 standard draft are computed by integration of the Poynting vector:

- *sPDn+*: surface normal propagating power flux density into the phantom
- *sPDtot+*: total propagating power flux density into the phantom
- *sPDmod+*: total power flux density into the phantom considering near field exposure

6.4 API Option: Application Programming Interface for Automation

The API (Application Programming Interface) option enables the further automation of the compliance workflow. Users can develop scripts to remote control DASY8 via a set of commands (start a scan, generate a report...). The scripts might also manage any third party equipment.

6.5 FTE Option: Forward Transformation Evaluations on Head/Flat Phantoms

The FTE (Forward Transformation Evaluation) option enables power density assessment on the SAM heads or any other virtual surface from a single planar measurement.
It cuts down compliance costs for mmWave devices operating near the head as PD can be evaluated for all four test positions at the same head (Left / Right, Cheek / Tilt), and for various test distances at the Flat phantom, from one single planar measurement at 2 mm from the device.
Figure 1.12 shows an example of projection on Left Head, Tilt position from a planar measurement performed at 2 mm from the DUT.

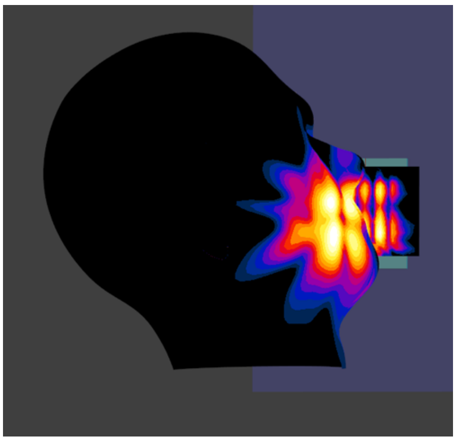


Figure 1.12: Example of Projection on Left Head, Tilt Position.

6.6 MEO Option: Maximum Exposure Evaluations of MIMO Antennas

With the deployment of 5G NR FR2, beam-forming techniques can be implemented in mobile devices for directional signal transmission. This is achieved by controlling the relative phase and amplitude of the signal at each transmitting element of an antenna array. For devices fully utilizing beamforming, the antenna codebook, which represents all possible steering directions, can become very large; therefore, performing measurements for each code would be very time consuming and easily add up to weeks of test time for a single antenna only. In response, SPEAG has developed a robust method to determine the maximum exposure anywhere in space based on a very limited set of planar measurements.
The MEO option determines the maximized spatial averaged power density (mpsPD) on any surface from the same set of planar measurements. The mpsPD can be computed on continuous codebook (relative phases can have any

value), on a discrete codebook (relative phases can have a finite set of values) or on a user-defined codebook. Please note that the MEO option requires the FTE option.

6.7 Visualization of Results

Upon completion, measurement results can be visualized: the peak value of each sPD variant (psPD) is displayed in the Project Overview window (see Figure 1.13).

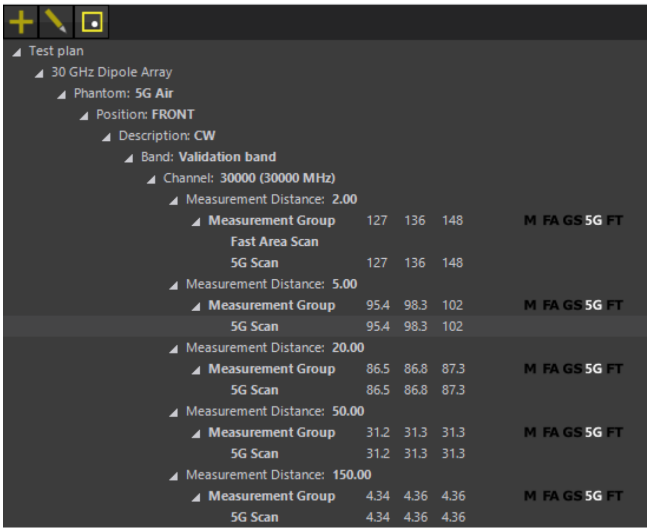
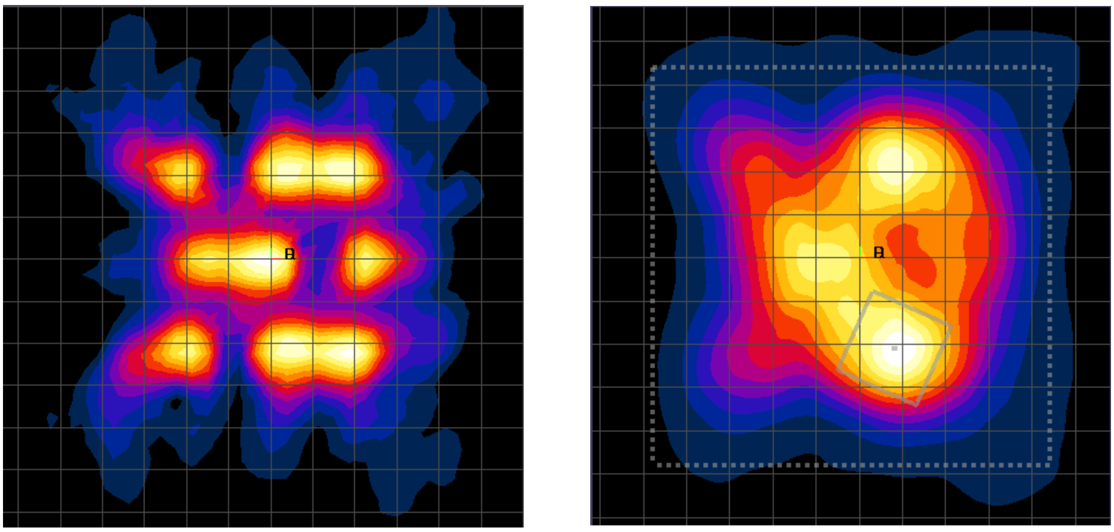


Figure 1.13: Project Overview with average power density results.

The reconstructed E- / H- field, the Poynting vector S and averaged power density (sPD) can be visualized by clicking the eye icon next to the scan. The quantity to be displayed is selected in the Connection drop-down box of the Options window. Figure 1.14 shows the E-field and sPDtot+ for a dipole array at 10 GHz.



(a) Measured E-field (b) sPDtot+ (4cm2, sq)

Figure 1.14: Visualization of E-field and sPDtot+ (4cm2, sq) from a 10 GHz dipole array at 5 mm distance

7 Reporting

7.1 Measurement Printout

Measurement printouts can be generated as described below:

- under Measurement Mode, click on the Measurement Group to be exported in the Project Overview view to enable the Report tool
- under Report tool, select the desired reporting format, then select the template file in the file selection dialog and click Open

A printout of the selected measurement group, located in the same folder as the template file, is now available. Two export formats, Word and HTML, are currently supported. The layout can be customized by the end user.

7.2 Summary Table

The summary table is a convenient tool to use to have an overview of the measurement results. The different psPD, as well as the E- and H- fields and the power drift can be visualized for each measurement. The table can be exported in various formats. An example is shown in Figure 1.15

Description	Measurement Distance	Channel	Frequency	UID	Revision	Measurement Group Name	Job Name	Avg. Area [cm2]	psPDn+ [W/m2]	psPDtot+ [W/m2]	psPDmod+ [W/m2]	Emax [V/m]	Hmax [A/m]	Power Drift [dB]
CW	2.00	10000	10000.000	0	–	Measurement Group	Fast Area Scan	1	N/A	N/A	N/A	N/A	N/A	N/A
CW	2.00	10000	10000.000	0	–	Measurement Group	Forward Transform Scan	1	43.4	45.4	58.9	229	0.594	0.44
CW	5.00	10000	10000.000	0	–	Measurement Group	Forward Transform Scan	1	28.2	34.3	36.1	142	0.411	0.03
CW	10.00	10000	10000.000	0	–	Measurement Group	5G Scan	1	19.4	20.5	21.5	97.5	0.335	0.02
CW	20.00	10000	10000.000	0	–	Measurement Group	5G Scan	1	19.1	19.6	20.3	99.8	0.232	0.21
CW	50.00	10000	10000.000	0	–	Measurement Group	5G Scan	1	20.2	20.3	20.3	93.2	0.228	0.05
CW	150.00	10000	10000.000	0	–	Measurement Group	Fast Area Scan	1	N/A	N/A	N/A	N/A	N/A	N/A
CW	150.00	10000	10000.000	0	–	Measurement Group	5G Scan	1	7.13	7.19	7.20	53.8	0.145	–0.16

Figure 1.15: Example of summary table for measurements at different distances.

8 Conclusion

This application note provides insights in SPEAG's solution for Power Density compliance testing at mmWave frequncies. Additional information is available in the DASY8 Module mmWave system handbook and the validation report.

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