Motorola Model: MD1005G
FCC ID: IHDT56XL1

Power Density Simulation and Measurement Report

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1. Table of Contents

2. Summary

This document provides an overview of the methodology used by Motorola and its test partner to characterize MPE compliance of the 5G mm-wave Mod mobile device model MD1005G when attached to a host phone mobile device. At a high level, the discussion is grouped into the following topics:

- Brief review of the device configuration and operation, as they pertain to MPE characterization
- Explanation of the approach to demonstrate MPE compliance in a mobile device, using simulation and measurement
- Detailed description of the simulation methodology and results, as applicable to the MPE measurement

Note on Right-Left Convention: Throughout this Simulation Report document, references to “right” or “left” side of the Mod device are given from the perspective of viewing the device from the back.

3. Brief Description of the Device

The 5G Mod is a Moto Mod device that contains 4G and 5G radio transceivers, capable of functioning in EN-DC mode. It functions only when it is snapped onto a 5G Mod-compatible smartphone device, such as the Moto Z3 Pro. The 5G Mod does not contain a WiFi/BT transceiver function. Transmissions are coordinated between the host phone and the 5G Mod, but there are cases where both the cellular modem in the phone and the cellular modems in the 5G Mod are transmitting simultaneously, and/or WiFi/BT in the phone is transmitting simultaneously with the cellular radios in the phone and/or Mod.

Figure 1 below shows exterior views of the 5G Mod, and Figure 2 shows an edge view of how the Mod attaches to the host smartphone (Mod is red, phone is blue).

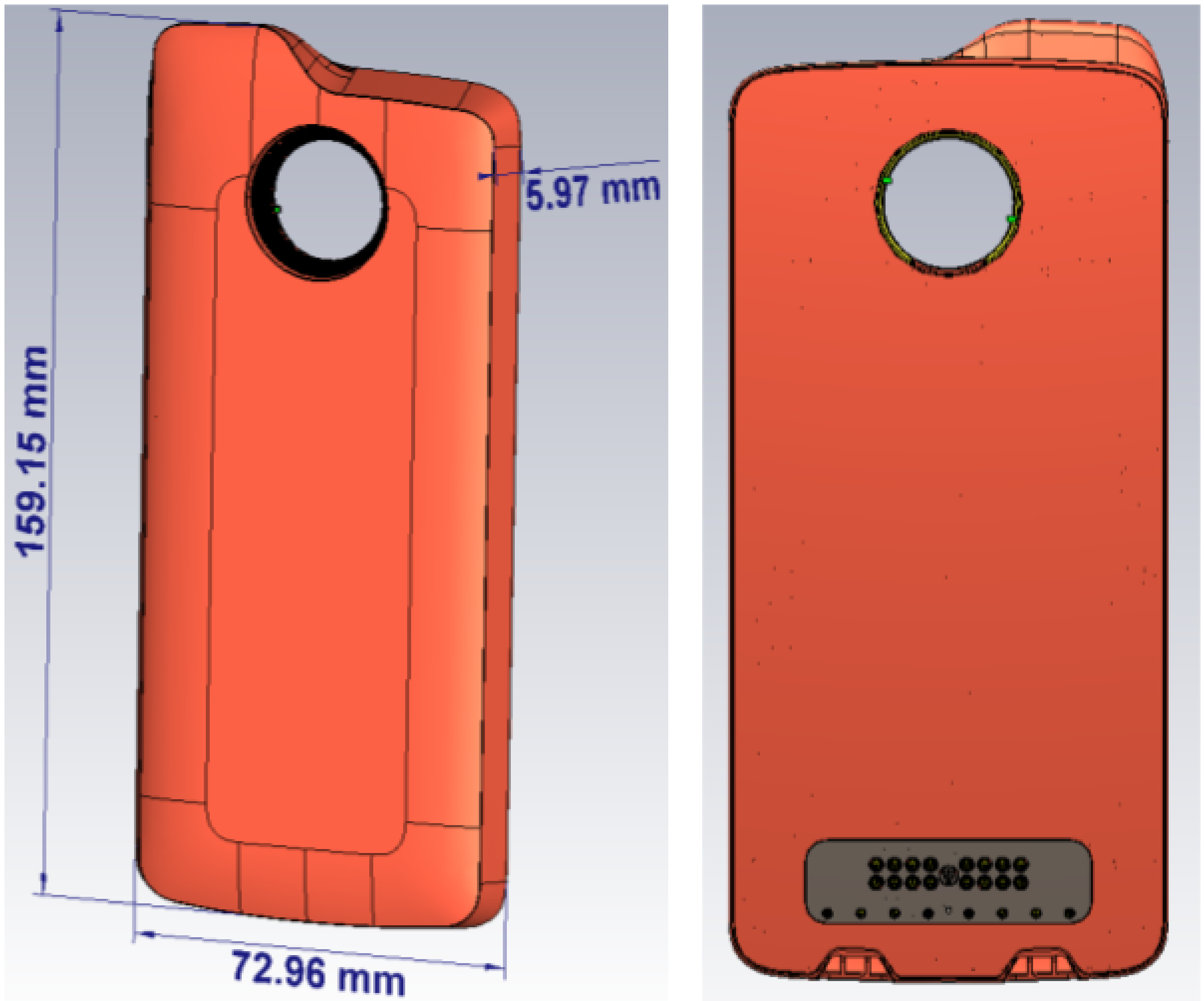

Figure 1: Exterior views of the 5G Mod

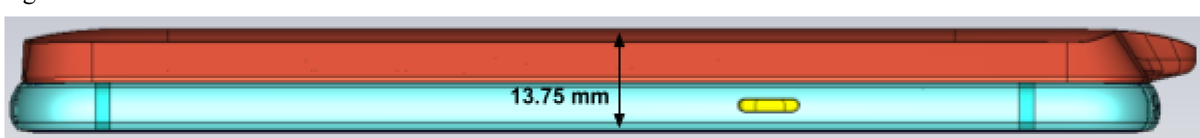

Figure 2: Edge view of the 5G Mod assembled to the host smartphone.

Figure 1-4-3 in the Operational Description shows a ghost view of the 5G Mod assembled to the host smartphone, from the rear side of the Mod. The 4G LTE and 5G mm-wave antenna arrays are shown in that figure.

The antennas labeled Ant1, Ant2, Ant3, Ant4, Ant5, and Ant6 are the transmit and receive antennas for the LTE bands, as enumerated in the figure. The Array Modules labeled Left, Right, Front, and Back are the four 5G mm-wave antenna array modules on the device. For the LTE antennas, the abbreviations in the figures correspond to the bands as follows:

LB: B13, B5

MB: B2, B4, B66

UHB: B48

LAA: B46

Each of the four 5G mm-wave array modules is an identical part containing a 1 X 4 element array of dual-polarization patch antennas. Only one antenna array module is in use by the modem at any one time, i.e. the modem selects one array module at any one time for both transmission and reception operation. Within an array each of the two linear polarizations of the patch antennas is excited by one of the MIMO paths of the modem. Hence, during MIMO operation, two independently controlled beams are formed and pointed by the modem, one in each polarization. Generally, a module can form beams that illuminate a partial hemisphere oriented in the broadside direction orthogonal to the face of the module. Three of the mm-wave array modules are arranged generally on the back side of the device. The Back module is located near the top end of the device and is oriented flat to the PCB, hence illuminating the rear hemisphere of the device. The Left and Right modules are located midway along the two edges of the device, canted at an angle relative the edge or the PCB, so that each of them partially illuminates both toward the side and the back of the device. (The Right and Left modules are illustrated more clearly in a perspective view in Figure 1-4-4 in the Operational Description) The fourth mm-wave module, the Front module, is located in an extension of the housing out of the top of the device, and faces forward, i.e. illuminates the display-side hemisphere to the front of the phone.

As described in the Operational Description there are multiple proximity sensors co-located with the antennas to aid the power-management algorithm.

4. Background & Operation

This section discusses device operation as it relates to MPE compliance measurement and simulation..

4.1. Block Diagram

The figure 5.1.1 in the Appendix A shows the RF/IF block diagram of the 5G Mod device. The modem and transceiver connect directly to the 4G antennas at their respective RF frequencies. The modem is connected to each of the four mm-wave antenna array modules via two IF lines, one for each of the two MIMO layers of operation. Each antenna array module contains up/down-conversion and signal-conditioning circuitry to convert the IF signal to/from the RF (mm-wave) signal transmitted/received by the antenna array, as well as the phase-shifting means whereby the complex weights assigned by the modem to form a desired beam are applied to the ports of each element of the array. Further detail of the mm-wave antenna array modules are given in the accompanying long-term-confidential document "QTM052 5G/NR FR2 MILLIMETER WAVE ANTENNA ARRAY REGULATORY INFORMATION - APPLICATION NOTE." Each IF line (MIMO layer) is associated with one polarization of a 1x4 array of patch antennas in the module. The modem selects one of the four mm-wave antenna array modules for operation at any point in time. In other words, only one module is active for transmit and receive at any point in time. Since 5G mm-wave is a TDD system, the T/R switching means for each module is also included within the module, and under control of the modem.

4.2. Operation

4.2.1. 5G NSA EN-DC Operation

The 5G Mod supports 5G NSA EN-DC operation under the 3GPP standard. This means that the Mod contains both LTE and 5G mm-wave transceivers. The transceivers necessarily operate simultaneously, according to the standard, whenever 5G mm-wave is active. Hence sub-6 GHz SAR exposure and mm-wave power density exposure must be considered together when assessing aggregate MPE compliance. To the extent possible with the respective measurement systems, mm-wave power density is measured on the same exposure planes as are used for SAR, as appropriate to a mobile device, to enable this aggregate assessment. This document focuses on the mm-wave portion of the assessment only, while the sub-6 GHz and aggregate exposure are treated in a separate document.

4.2.2. TX Duty Cycle in TDD System

5G in the mm-wave bands supported by this device is a Time-Division-Duplex system. Under the standard, there is no fixed limitation on uplink/downlink ratio for this system. Although it is understood that initial network deployments may limit the uplink/downlink ratio to some value, it cannot be guaranteed, under the standard which this device must support, for all future network deployments in the lifetime of the device. For this reason, in order to capture worst-case power density conditions, an uplink duty cycle of 100% is assumed for all simulations and measurements.

4.2.3. Beamforming

The 5G mm-wave system employs electronic beamforming in the user equipment. Each mm-wave antenna array module contains a 1x4 array of dual-polarized patch antenna elements. Each MIMO layer from the modem is transmitted on a respective one of the polarizations of the array. For each polarization (MIMO layer), the modem directs the antenna module to apply a specific set of complex weights to the signal copies applied to each of the four antenna element input ports, in order to form the desired antenna beam.

Although a large number of independent phase profiles, and hence antenna beams, is hypothetically possible in each polarization of each module, in practice in this device the modem limits the number of independently selectable beams to a small number. Within a module, each polarization supports only 16 distinct beams from which the modem can select; furthermore, beams are paired between polarizations, i.e., beams cannot be selected independently between polarizations. These beams and beam-pairs are defined at design-time for the device. The net result is that each module only supports 16 predefined beam-pairs, from which the modem selects one beam-pair for operation at any instant in time. Additionally, the modem can only select one of the device's available modules for use at any instant in time. Hence, considering 4 modules with 16 beam pairs defined for each, 64 beam pairs form the basis for searching the worst-case beams via simulation and measuring them.

Each polarization of the array, i.e. each MIMO layer, is also referred to as an "antenna group." An antenna group is comprised of one feed on each of the four patch antennas, all four of which excite the same polarization of radiation. Hence, the antenna group AG0 is formed of the four excitations (feeds), one on each patch element, that excite the linear polarization parallel to the long axis of the antenna module (when observed in the broadside direction); these are the four antenna feed ports labeled as "H1, H2, H3, and H4" in the Operational Description. Similarly, the antenna group AG1 is formed of the four excitations (feeds), one on each patch element, that excite the linear polarization orthogonal to the long axis of the antenna module (when observed in the broadside direction); these are the four antenna feed ports labeled as "V1, V2, V3, and V4" in the Operational Description. A beam pair consists of one beam formed in the AG0 antenna group and one beam formed in the AG1 antenna group.

A module is capable of steering beams (or beam pairs) in the hemisphere that is in the broadside direction to that module. (The broadside direction is the direction orthogonal to the front surface of the module and pointing away.) Very roughly, the portion of space that can be illuminated by a module consists of a cone centered on the module's broadside direction, with a total angular spread of about 70 degrees (that is, +/- 35 degrees from the boresight direction) in the plane parallel to the module's short axis, and about 120 degrees (that is, +/- 60 degrees from the boresight direction) in the plane parallel to the module's long axis. Hence, each module can illuminate a portion of the spherical space around the device. The front module (module 2) illuminates a portion of the hemisphere on the display side of the phone+Mod assembly. The back module (module 3) illuminates a portion of the hemisphere on the back side of the Mod. And the two side modules (modules 0 and 1) illuminate a portion of the respective hemispheres toward each side of the Mod (tilted slightly toward the back as well).

The codebook defined at design time contains a codeword for each beam in the defined set of beam pairs, which is the list of magnitude and phase weights applied to each antenna group's four feeds to cause the desired beam to be formed. The normalized amplitude weights (normalized to the maximum per-port maximum power for the modulation/transmission mode in operation) can range from 0 to 1, while the phase weights can range from

0 to 360 degrees (i.e., any phase value as needed). For purposes of assessing worst-case power density, only beams having normalized magnitude weights of 1 on all four feeds of the antenna group are of interest. The corresponding actual power per port, for the worst-case modulation case for PD analysis, is nominally 8 dBm. But, as explained in Appendix B of the simulation & measurement report, the port power applied to the simulation results are adjusted uniformly so that the simulated EiRP result matches the measured EiRP result for each beam analyzed. An example of how a codeword is entered into HFSS for simulation is shown in figure Figure 7.1.1-2 in Appendix B1.

Considering a nominal per-port power of 8 dBm, the total transmitted power for one antenna group, with a beam with four ports excited, can be approximately calculated as 8 dBm + 6 dB = 14 dBm. (The 6 dB factor represents the 4x multiplier of applying the same power to four antennas in the array.) For a beam pair where two such full-power beams are excited, the total transmitted power in the beam pair can be approximately calculated as 14 dBm + 3 dB =17 dBm. (All power calculations in this paragraph are approximations; actual power should only be considered from the standpoint of measured EiRP as described in the appendices.)

In practical operation, the modem continually attempts to select the mm-wave module and beam pair that give the best communication link with the base station. Hence, in practice, if the user's tissue is close to a given module, the mm-wave path for that module will be blocked and the modem will select a different module and/or beam to avoid the user's blocking effect. In this way, in practice, it is unlikely that the user would be exposed to long-duration full-power transmission as is assessed in this study. However, since this beam-avoidance mechanism is not a fully deterministic guarantee of avoiding user exposure, it is not assumed for the compliance assessment of this device. This exposure assessment is conservatively based on a worst-case assumption that any module/beam may point at the user, except as limited by the device's proximity-detection scheme designed for this purpose.

4.2.4. Proximity Detection Scheme and Excluded Regions

As mentioned in the device description, capacitive and proximity sensors are used to disable transmission from a given mm-wave antenna array module when a user may be located in close proximity to the module and in a direction in which the module may transmit. The control mechanism is a simple one in which, if proximity detectors indicate the potential presence of the user within a roughly conical region in front of the module where power density may approach the MPE limit, that module is disabled from use by the modem. This terminates and prevents transmission from the module in question until the condition is cleared.

For this reason, for each module's testing, portions of the measurement planes around the device are excluded from measurement, since the proximity detection system would prevent transmission if the user occupied those regions. For each module, a principal plane (the plane directly in front of the module, e.g. the backplane for the back module) is excluded entirely, and portions of the other measurement planes, which overlap the detection "cone" of the proximity detection system, are also excluded. Hence the measurements (and simulations) are limited to these reduced measurement planes about the device, defined for each module, which do not enter into the proximity detection regions. However, for each of the principal plane directions, the PD is measured at a conservative distance of 70 mm where the proximity sensor may stop detecting the presence of user.

The figures 5.2.4.1 to 5.2.4.4 in the Appendix A illustrate these reduced measurement planes employed for all the four modules.

5. Simulation and Measurement Approach for MPE

This section details the approach taken to identify and measure the worst-case beam pairs for each mm-wave antenna array module on each measurement plane around the mobile device.

5.1. General Approach

The concept of beamforming adds an additional dimension to the test matrix, effectively increasing the number of the exposure test cases to be checked, by a factor equal to the number of beams that the device can form.

This makes it impractical to measure every beam in every measurement plane. Because the mm-wave power density measurement is time-consuming per beam and measurement plane, it is necessary to identify a-priori the worst-case beams for each measurement condition (plane) via simulation, so that these beams can then be measured to characterize the worst-case power density of the device.

The Ansys HFSS simulation tool (HFSS 19.2) was used for the simulation of near-field power density for this process.

5.2. Finding Worst-Case Near-Field Results

The simulation results are considered across both domains of beam configuration and physical location. At each x-y-z location on each of the reduced measurement planes defined in section 5.2.4, the simulated PD for each full-power beam from each of the four modules is assessed. As described previously, this means that the worst beam from each module is found in the measurement planes around the device, for every x-y-z position that is *not* excluded via operation of the proximity detection system. The worst case of all of these PD results in a measurement plane is then identified, and that module and beam configuration is selected for the measurement of PD on the measurement plane in question. This process thus constitutes *an exhaustive direct search across both location and beam configuration domains*.

More details of finding the worst-case near field results is described in Appendix B.

5.3. Simulation Tool

5.3.1. Tool Description

For the mm-wave power density simulations, the commercially-available ANSYS Electronics Desktop 2018 (HFSS) is used. The ANSYS HFSS tool is used in the industry for simulating 3D, full-wave electromagnetic fields. Motorola uses this EM simulation tool for mm-wave problems due to its established accuracy, advanced solver, and high-performance computing technology capabilities for doing accurate and rapid characterization of high-frequency components.

5.3.2. Solver Description

HFSS' solver employs the Finite Element Method, which operates in the frequency domain. The HFSS simulation employed a direct solver with first order basis functions.

5.3.3. Convergence criteria and power density calculations

HFSS uses a volume air box containing the simulated area to calculate the EM fields. The box is truncated by an Absorbing Boundary Condition. The simulation uses the adaptive mesh technique to meet the exit criteria of delta S < 0.02. The delta S is the change in the magnitude of the S-parameters between two consecutive passes; if the magnitude and phase of all S-parameters change by an amount less than the Maximum-Delta-S-per-Pass value from one iteration to the next, the adaptive analysis stops. Otherwise, the mesh is refined in higher energy areas, according to proprietary Ansys algorithms, and an additional solution pass is taken. An example of a fully refined mesh through one cross-section of the device is shown in the figure below.

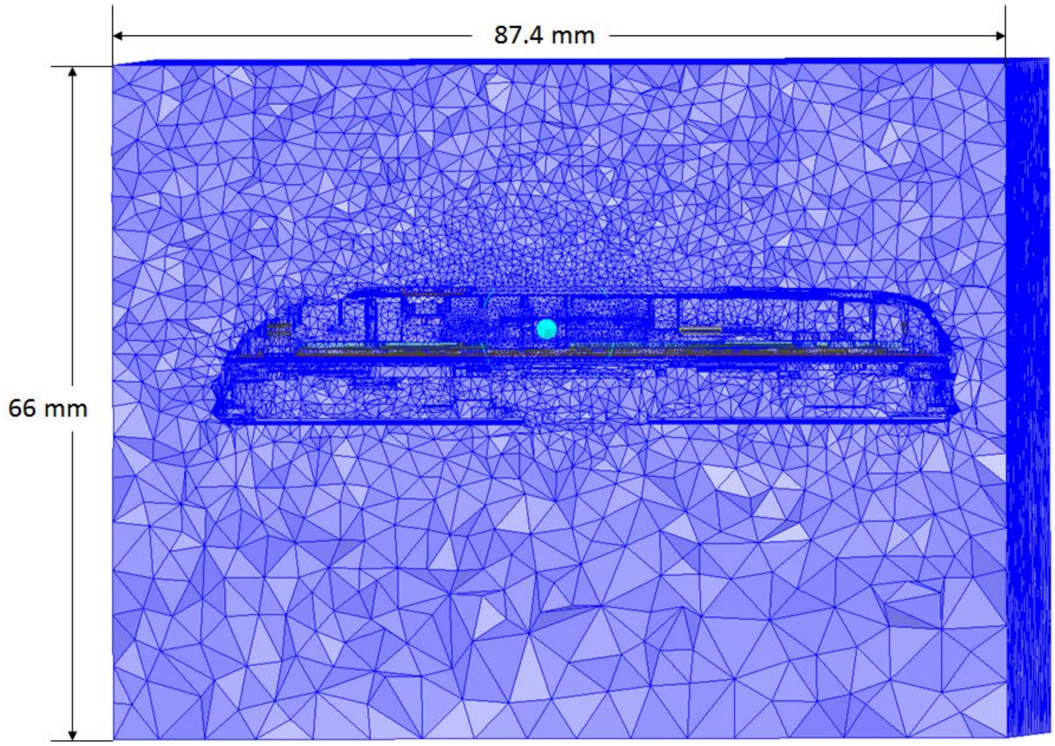

Figure 6.3.3-1: The HFSS mesh in a model of the device.

After finding the simulated electric and magnetic (E and H) fields, the Poynting vector is calculated based on "peak" (i.e. non-RMS) field values in a grid with a 1 mm step, on the appropriate measurement planes as defined in previous sections. The Poynting vector at each spatial point is readily available in HFSS through the "Field Calculator" navigation option. The magnitude of the real part of the Poynting vector (all X, Y, Z components) at each spatial point i.e. the point power density is exported from HFSS to do the averaging. The spatially averaged power density at each point on a given surface is then calculated by taking the average of the point power density over a 4 square cm area. Thus the total power density (all X, Y, Z components) through any given surface is used to calculate the averaged power density.

Hence the spatially averaged power density on a given surface is calculated as the surface integral of the Poynting vector over a 4 square cm averaging area A:

$$P_{av} = \frac{1}{2A}\int_A \left|Re(\vec{E} \times \vec{H}^*)\right| \cdot dS$$

Note that E and H are the complex field vectors, and the calculation thus leads to the total power density average.

5.3.4. 3D Models Used in the Simulations

The 3D model simulated consist of the full CAD model of the 5G Mod attached to the host phone device. A slightly different version of this CAD model is used for the simulations for each of the measurement planes, since inclusion of the measurement planes necessitates growth of the air box in a given direction and it is necessary to optimize the model accordingly so that it solves in a reasonable time on available compute resources. A view of the 3D model variant used in each of the various module simulations is shown in the figures 6.3.4.1 to 6.3.4.4 in Appendix A. The proximity sensor collocated with respective module is also inclined in the same way as the array module.

5.3.5. Simulated and Measured Results

In this section, the worst-case simulated power densities in the respective overall measurement planes, as found in the process described above, are shown in comparison to the measured results.

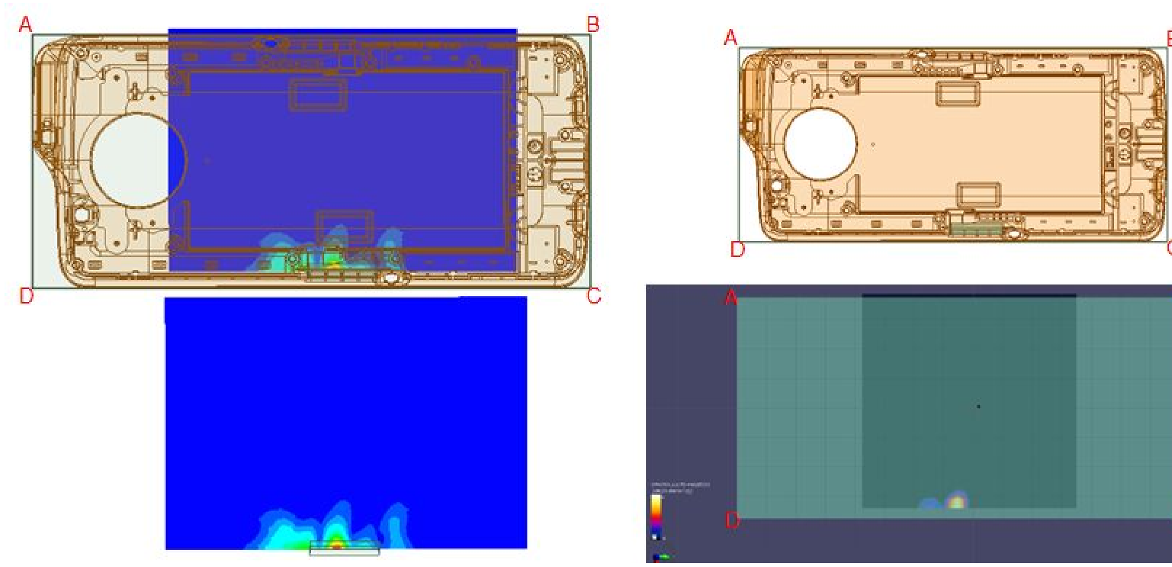

Figure 6.3.5-1 Simulated (left) and measured (right) peak power density distributions for the worst case found in the back surface measurement plane **(Module 0, beam 49&177, back surface)**. Note that the measurement plane is truncated to correspond to the exclusion area of the proximity detection system as explained in Appendix A, which is appropriate since the mm-wave transmitter would be disabled if tissue occupied the exclusion area.

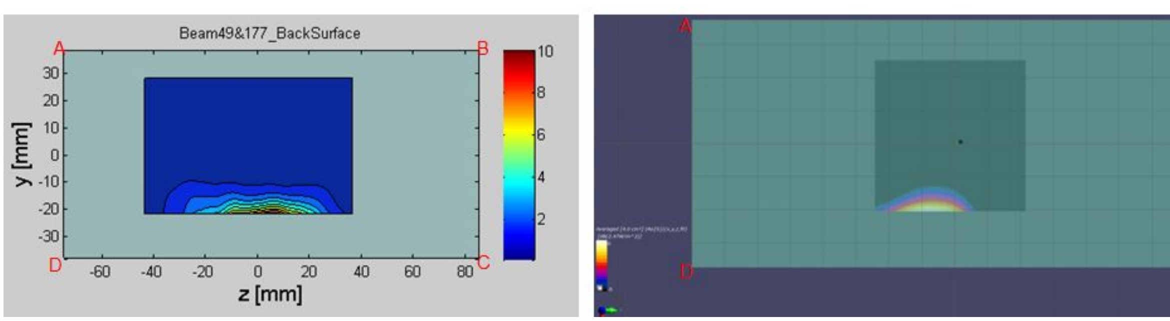

Figure 6.3.5-2 Simulated (left) and measured (right) average power density distributions for the worst case found in the back surface measurement plane **(Module 0, beam 49&177, back surface)**. Note that the measurement plane is truncated to correspond to the exclusion area of the proximity detection system as

explained in Appendix A, which is appropriate since the mm-wave transmitter would be disabled if tissue occupied the exclusion area.

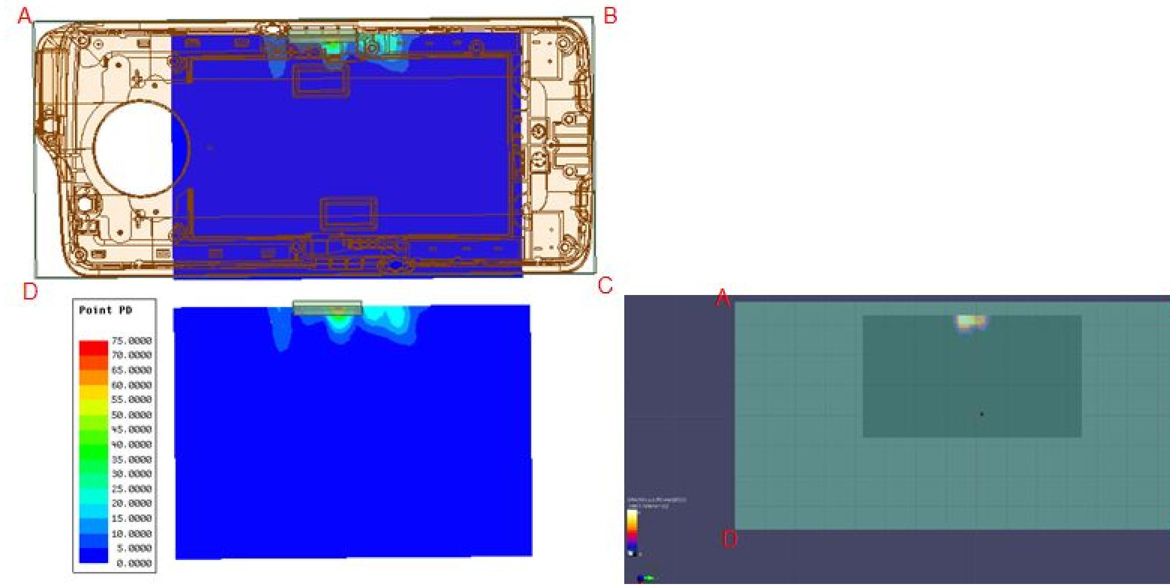

Figure 6.3.5-3 Simulated (left) and measured (right) peak power density distributions for the worst case found in the back surface measurement plane **(Module 1, beam 26&153, back surface)**. Note that the measurement plane is truncated to correspond to the exclusion area of the proximity detection system as explained in Appendix A, which is appropriate since the mm-wave transmitter would be disabled if tissue occupied the exclusion area.

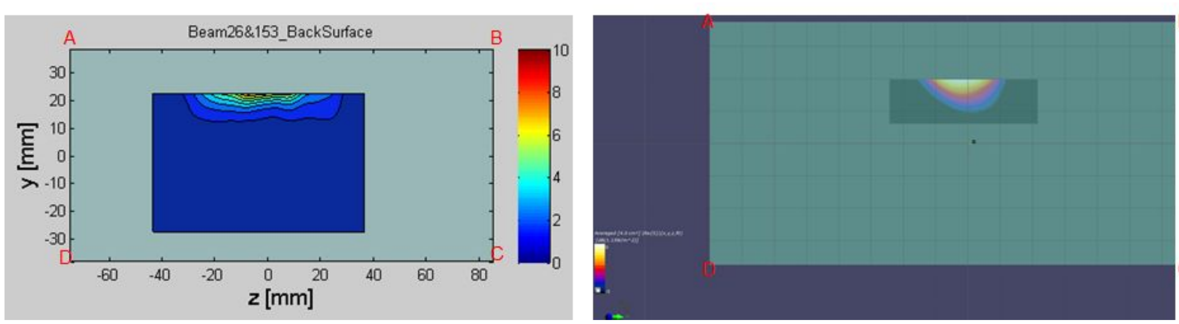

Figure 6.3.5-4 Simulated (left) and measured (right) average power density distributions for the worst case found in the back surface measurement plane **(Module 1, beam 26&153, back surface)**. Note that the measurement plane is truncated to correspond to the exclusion area of the proximity detection system as explained in Appendix A, which is appropriate since the mm-wave transmitter would be disabled if tissue occupied the exclusion area.

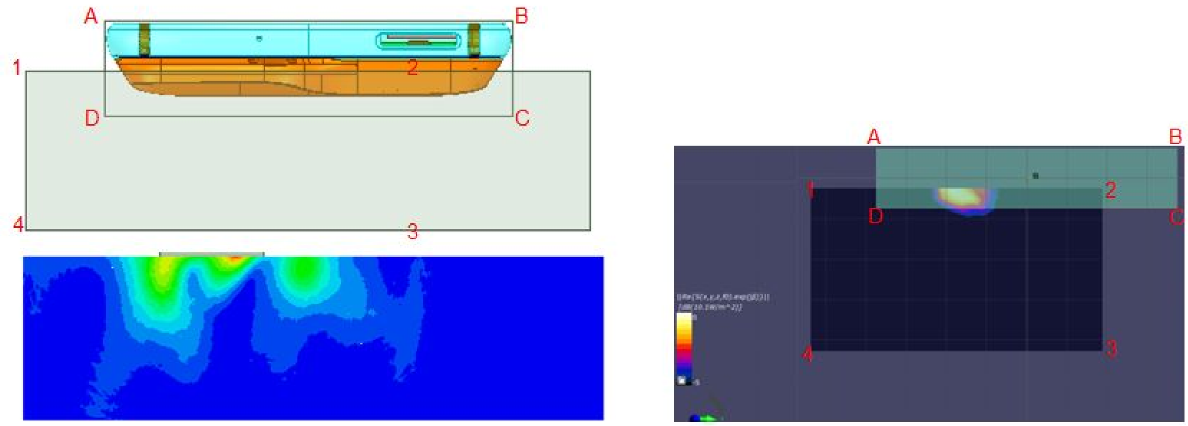

Figure 6.3.5-5 Simulated (left) and measured (right) peak power density distributions for the worst case found in the top surface measurement plane **(Module 2, beam 41&168, top surface)**. Note that the measurement plane is truncated to correspond to the exclusion area of the proximity detection system as explained in Appendix A, which is appropriate since the mm-wave transmitter would be disabled if tissue occupied the exclusion area.

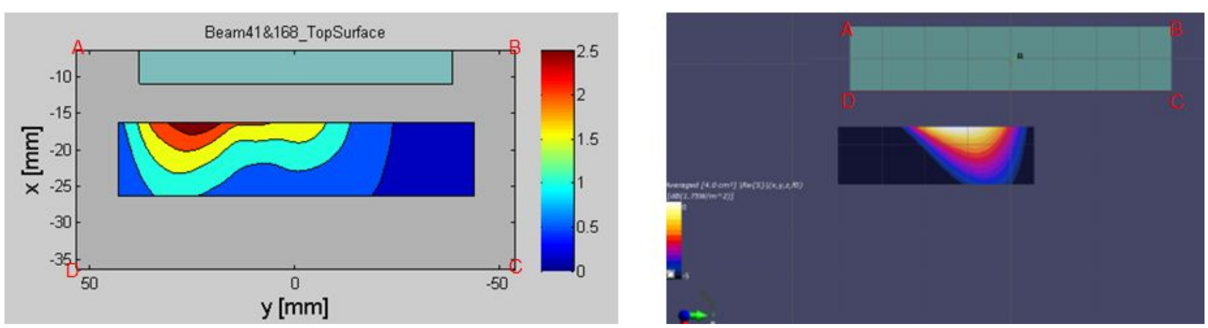

Figure 6.3.5-6 Simulated (left) and measured (right) average power density distributions for the worst case found in the top surface measurement plane **(Module 2, beam 41&168, top surface)**. Note that the measurement plane is truncated to correspond to the exclusion area of the proximity detection system as explained in Appendix A, which is appropriate since the mm-wave transmitter would be disabled if tissue occupied the exclusion area.

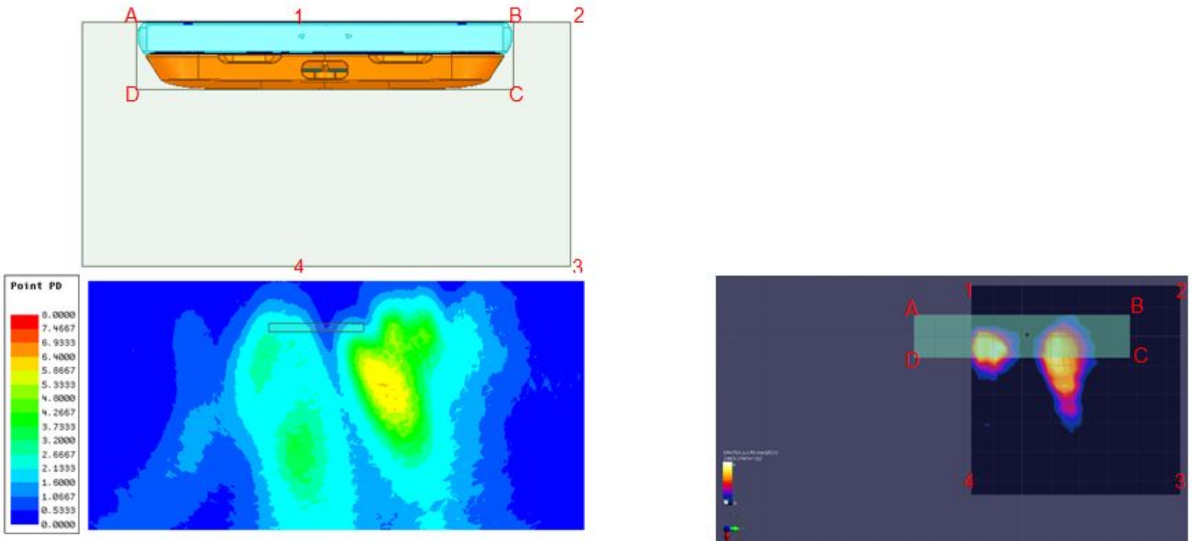

Figure 6.3.5-7 Simulated (left) and measured (right) peak power density distributions for the worst case found in the top surface measurement plane **(Module 3, beam 37&166, top surface)**. Note that the measurement plane is truncated to correspond to the exclusion area of the proximity detection system as explained in Appendix A, which is appropriate since the mm-wave transmitter would be disabled if tissue occupied the exclusion area.

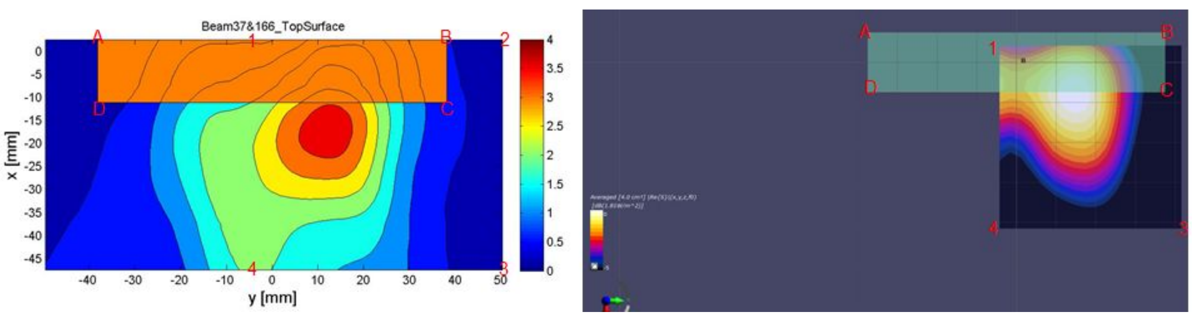

Figure 6.3.5-8 Simulated (left) and measured (right) average power density distributions for the worst case found in the top surface measurement plane **(Module 3, beam 37&166, top surface)**. Note that the measurement plane is truncated to correspond to the exclusion area of the proximity detection system as explained in Appendix A, which is appropriate since the mm-wave transmitter would be disabled if tissue occupied the exclusion area.

Based on the comparison of simulated and measured power density point and average distributions, we find good correlation of the distribution between simulation and measurement. Therefore, although the absolute values may not match between the simulation and measurement, the rank ordering of worst beam pairs from simulation can be used to select the worst case beam pairs for measurement of Power density. The simulated average power density for all the beampairs in each of the modules is presented in Tables 6.3.5.1 to 6.5.3.4 in Appendix C. The Tables 6.3.5.5 to 6.3.5.8 below list the beampairs used for power density measurement.

Note that for some modules and measurement planes, where the simulated power density values of the worst two beams were similar, both of the two worst beam pairs were measured.

Test Config	Beam ID 1	Beam ID 2	Exposure Conditions	Test separation
Module 0 (Right Array)	33	157	Front Surface	2 mm
	49	177	Front Surface	2 mm
	49	177	Back Surface	5mm
	33	157	Right Surface	**70 mm**
	49	177	Left Surface	5mm
	31	161	Left Surface	5mm
	49	177	Top Surface	5mm
	61	189	Bottom Surface	5mm

Table 6.3.5-5 Beampairs used for Measurement of power density for Module 0 (Right Array)

Test Config	Beam ID 1	Beam ID 2	Exposure Conditions	Test separation
Module 1 (Left Array)	26	153	Front Surface	2 mm
	26	153	Back Surface	5mm
	26	153	Right Surface	5 mm
	28	155	Left Surface	**70 mm**
	44	172	Top Surface	5mm

Table 6.3.5-6 Beampairs used for Measurement of power density for Module 1 (Left Array)

Test Config	Beam ID 1	Beam ID 2	Exposure Conditions	Test separation
Module 2 (Front Array)	59	186	Front Surface	**70 mm**
	41	168	Front Surface	5 mm
	43	167	Back Surface	5 mm
	42	169	Right Surface	5 mm
	56	187	Left Surface	5 mm
	41	168	Top Surface	5 mm
	43	167	Top Surface	5 mm

Table 6.3.5-7 Beampairs used for Measurement of power density for Module 2 (Front Array).

Test Config	Beam ID 1	Beam ID 2	Exposure Conditions	Test separation
Module 3 (Back Array)	36	164	Front Surface	2 mm
	52	180	Back Surface	**70 mm**
	62	190	Back Surface	**70 mm**
	35	163	Back Surface	**70 mm**
	54	182	Right Surface	5 mm
	53	181	Right Surface	5 mm
	54	182	Left Surface	5 mm
	38	165	Left Surface	5 mm
	62	190	Top Surface	5 mm
	34	162	Top Surface	5 mm
	37	166	Top Surface	5 mm

Table 6.3.5-8 Beampairs used for Measurement of power density for Module 3 (Back Array).

6. References

[1] none