Power Density Characterization Report

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Innovative Product R&D Group 1

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Power Density Characterization

1. Exposure Scenarios

At frequencies > 6 GHz, the total peak spatial averaged power density (psPD) is required to be assessed for all antenna configurations (beams) from all mmWave antenna modules installed inside the device. This device has a patch antenna arrays (L Patch).

As showed in Figure 1, the surfaces near-by each mmW antenna module for PD characterization are identified and listed in Table 1.

Table 1. Evaluation Surfaces for PD Characterization

Band	Antenna Module	Front	Back	Left	Right	Top	Bottom
n261	L	O	O	X	O	O	X
n260	L	O	O	X	O	O	X

DUT size : 158.2 x 76.8 x 8.45

Rear View

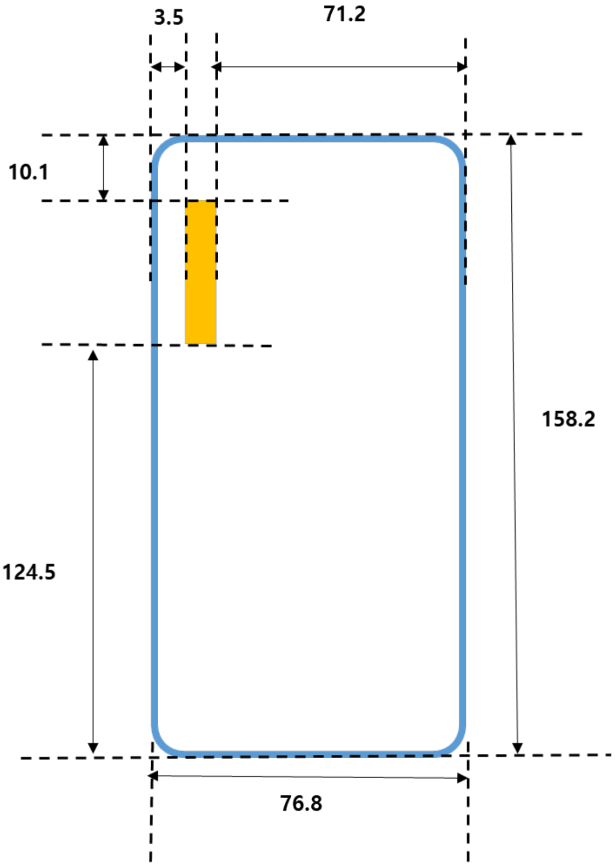
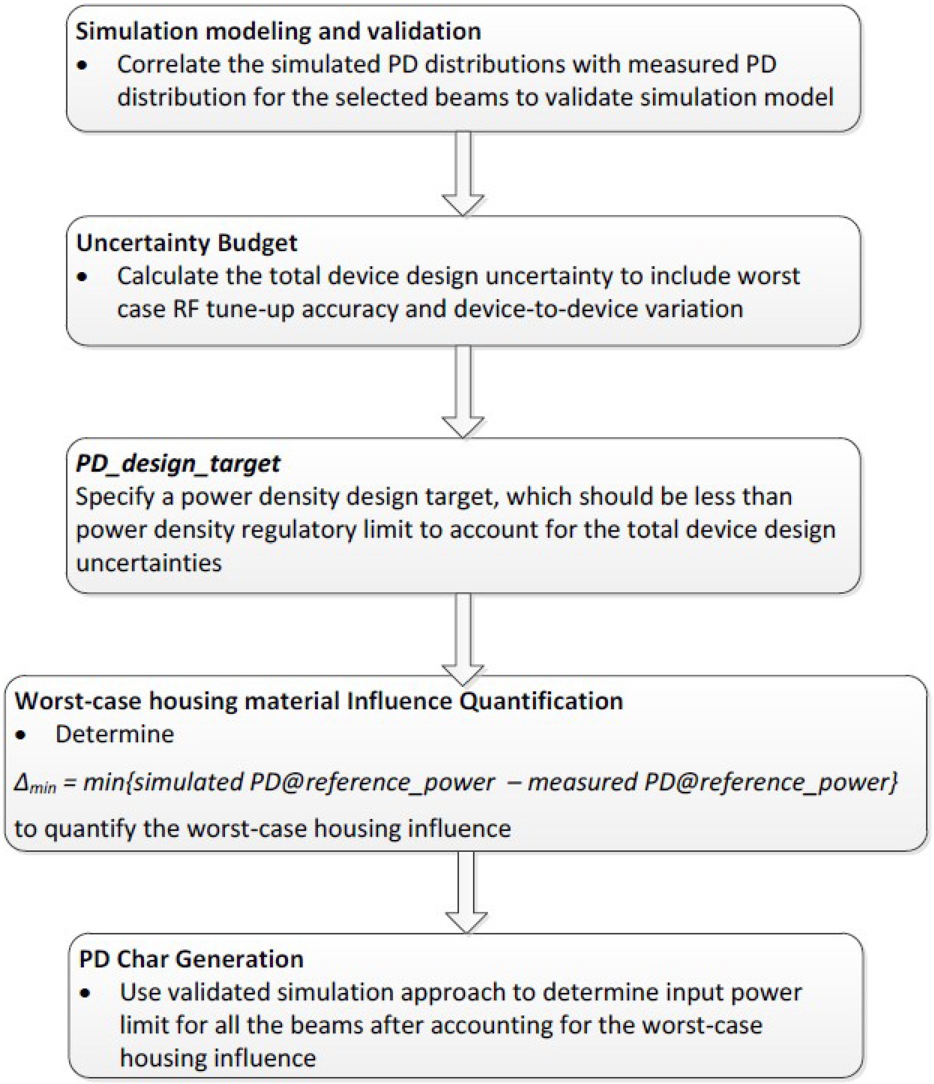


Figure 1: Location of mmW antenna modules looking from back of the DUT

2. Power Density Characterization Method



Simulation modeling and validation

- Correlate the simulated PD distributions with measured PD distribution for the selected beams to validate simulation model

Uncertainty Budget

- Calculate the total device design uncertainty to include worst case RF tune-up accuracy and device-to-device variation

PD_design_target

Specify a power density design target, which should be less than power density regulatory limit to account for the total device design uncertainties

Worst-case housing material Influence Quantification

- Determine

$\Delta_{min} = min\{simulated\ PD@reference\_power - measured\ PD@reference\_power\}$

to quantify the worst-case housing influence

PD Char Generation

- Use validated simulation approach to determine input power limit for all the beams after accounting for the worst-case housing influence

3. Codebook for all supported beams

Table 2. 5G mmW NR Band n261 Ant L Codebook

Module	Type(P or D)	Beam ID_1	Bema ID_2	Feed no.
L	Patch	0		5
		1		5
		2		5
		3		5
		4		5
		5		5
		6		5
			7	5
			8	5
			9	5
			10	5
			11	5
			12	5
			13	5
		0	7	10
		1	8	10
		2	9	10
		3	10	10
		4	11	10
		5	12	10
		6	13	10

Table 3. 5G mmW NR Band n260 Ant L Codebook

Module	Type(P or D)	Beam ID_1	Bema ID_2	Feed no.
L	Patch	0		5
		1		5
		2		5
		3		5
		4		5
		5		5
		6		5
			7	5
			8	5
			9	5
			10	5
			11	5
			12	5
			13	5
		0	7	10
		1	8	10
		2	9	10
		3	10	10
		4	11	10
		5	12	10
		6	13	10

4. Simulation and Modeling Validation

Power density simulations of all beams and surfaces were performed. Details of these simulations and modeling validation can be found in the Power Density Simulation Report. Table below includes a summary of the validation results to support worst-case housing influence quantification in power density characterization for this model.

With an input power of 18 dBm for n261 band and 18 dBm for n260 band, PD measurements are conducted for at least one single beam per antenna module (L) on worst-surface(s). PD measurements are performed at mid cannel of each mmW band and with CW modulation. ALL measured PD values are listed in table below along with corresponding simulated PD values for the same configuration.

PD value will be used to determine worst-case housing influence for conservative assessment.

Table 4. Simulated and Measure PD

Band	Channel	Module	Type	Side	Beam ID	Tx input power (dBm)	Sim. PD (mW/cm2)	Meas.PD (mW/cm2) *Circle AVG
n261	Mid Ch. 2077891 (27923.5 MHz)	L	Patch	Rear	0	18	0.124	0.237
					7		0.632	0.666
				Front	2		0.45	0.879
					11		0.166	0.151
				Right	6		0.479	0.938
					7		0.749	0.562
n260	Mid Ch. 2253331 (38449.9 MHz)	L	Patch	Rear	0	18	0.332	0.324
					8		0.579	0.419
				Front	2		0.343	0.176
					8		0.157	0.086
				Right	2		0.618	0.678
					8		0.723	0.484

5. PD design target

Table 5. PD design target

<table>
<tr><th colspan="2">PD_design_target</th></tr>
<tr><td colspan="2">$\text{PD\_design\_target} < \text{PD\_regulatory\_limit} \times 10^{\frac{-Total\ Uncertainty}{10}}$</td></tr>
<tr><th colspan="2">psPD over 4 cm2 Averaging Area (mW / cm2)</th></tr>
<tr><td>Total Uncertainty</td><td>2.3 dB</td></tr>
<tr><td>PD_regulatory_limit</td><td>1.0 mW/cm2</td></tr>
<tr><td>PD_design_target</td><td>0.442 mW/cm2</td></tr>
</table>

6. Δmin

For non-metal material, the material property cannot be accurately characterized at mmW frequencies to date. The estimated material property for the device housing is used in the simulation model, which could influence the accuracy in simulation for PD amplitude quantification. Since the housing influence on PD could vary from surface to surface where the EM field propagates through, the most underestimated surface is used to quantify the worst-case housing influence for conservative assessment.

Since the mmW antenna modules are placed at different locations, only surrounding material/housing has impact on EM field propagation, and in turn power density. Furthermore, depending on the type of antenna array, i.e., dipole antenna array or patch antenna array, the nature of EM field propagation in the near field is different. Therefore, the worst-case housing influence is determined per antenna module and per antenna type.

For this DUT, the below procedure was used to determine worst-case housing influence,

Δmin :

1. Based on PD simulation, for each module and antenna type, determine one or more worst-surface(s) that has highest 4cm2 PD for all the single beams per antenna module and per antenna type in the mid cannel of each band.
2. For identified worst surface(s) per antenna module and per antenna type group,
    a. First determine min based on identified worst surface(s), and derive plimit
    b. Then prove all other near-by surface(s), i.e., non-selected surface(s), is not required for housing material loss quantification(in other words, these non-evaluated surfaces have no influence on the determined plimit) by:
        i. re-scale all simulated 4cm2 PD at plimit to identify the worst-PD beam per each non-evaluated surface
        ii. Measure 4cm2 PD at plimit on identified worst-PD beam per each

non-evaluated surface

iii. Demonstrated all measured 4cam2 PD values are below PD_design_target

3. If any of the above surface(s) in Step(2.b.iii) have measured 4cm2 PD > PD_design_target, then those surfaces must be included in the min determination in Step(2.a), and re-evaluate plimit with these added surfaces.

Following above procedure, based on Table 2 ~ Table 3 in Samsung PD simulation report, the worst-surface(s) having highest 4cm2 PD for all the single beams per each antenna type and each antenna module group in the mid cannel of n261 and n260 bands are identified as:

a. for L patch: Back (S2) & Right (S4)

Thus, when comparing a simulated 4cm2--averaged PD and measured 4cm2-averaged PD for the identified worst surface(s), the worst error introduced for each antenna type and each antenna module group when using the estimated material property in the simulation is highlighted in bold numbers in Table 8. Thus, the worst-case housing influence, denoted as Δmin = Sim. PD − Meas. PD , is determined as

Table 6. Δmin for Ant L

Band	Antenna	Δmin (dB)
n261	L-Patch	-2.92
n260	L-Patch	-0.4

Δmin represents the worst case where RF exposure is underestimated the most in simulation when using the estimated material property of the housing. For conservative assessment, the Δmin is used as the worst-case factor and applied to all the beams in the corresponding antenna type and antenna module group to determine input power limits in PD char for compliance. The detail plimit derivation is described in Section 7.

Simulated 4cm2 PD values in Table 2 ~ Table 3 in Power Density Simulation Report are scaled to plimit and are listed in Tables 7 ~ 8 for all single beams for all identified surfaces, when assuming the simulation is performed with correct housing influence.

Table 7. n261/mid channel, L Patch simulated 4cm^2 PD at PD_design_Target (if simulation performed with correct housing material properties) (Δmin)

No.	Module	Beam ID	Simulated 4cm2 PD (mW/cm2) Corresponding to PD_design_target if the simulation was performed with correct No.Module Type housing material properties					
			S4(Right)	S3(Left)	S5(Top)	S6(Bottom)	S1(Front)	S2(Rear)
1	L	0	0.203	0.003	0.025	0.003	0.154	0.054
2		1	0.203	0.005	0.030	0.002	0.189	0.048
3		2	0.200	0.004	0.039	0.002	0.192	0.035
4		3	0.191	0.005	0.020	0.003	0.129	0.044
5		4	0.196	0.007	0.047	0.002	0.151	0.070
6		5	0.170	0.008	0.040	0.002	0.140	0.066
7		6	0.195	0.003	0.020	0.001	0.165	0.034
8		7	0.202	0.001	0.019	0.001	0.022	0.170
9		8	0.201	0.001	0.043	0.004	0.021	0.179
10		9	0.206	0.001	0.037	0.003	0.033	0.176
11		10	0.198	0.001	0.025	0.002	0.033	0.174
12		11	0.202	0.001	0.024	0.011	0.068	0.201
13		12	0.185	0.001	0.051	0.006	0.058	0.121
14		13	0.192	0.001	0.043	0.003	0.032	0.158

Table 8. n260/mid channel, L Patch simulated 4cm^2 PD at PD_design_Target (if simulation performed with correct housing material properties) (Δmin)

No.	Module	Beam ID	Simulated 4cm2 PD (mW/cm2) Corresponding to PD_design_target if the simulation was performed with correct No.Module Type housing material properties					
			S4(Right)	S3(Left)	S5(Top)	S6(Bottom)	S1(Front)	S2(Rear)
1	L	0	0.209	0.003	0.012	0.002	0.119	0.129
2		1	0.252	0.005	0.014	0.002	0.113	0.129
3		2	0.230	0.005	0.016	0.001	0.127	0.108
4		3	0.206	0.003	0.045	0.003	0.101	0.081
5		4	0.239	0.004	0.076	0.007	0.098	0.100
6		5	0.194	0.002	0.026	0.004	0.108	0.095
7		6	0.246	0.004	0.012	0.002	0.106	0.133
8		7	0.253	0.001	0.024	0.001	0.047	0.193
9		8	0.251	0.001	0.040	0.002	0.054	0.201
10		9	0.214	0.001	0.021	0.001	0.037	0.167
11		10	0.250	0.001	0.023	0.001	0.055	0.185
12		11	0.236	0.002	0.011	0.001	0.049	0.180
13		12	0.251	0.002	0.024	0.001	0.052	0.190
14		13	0.250	0.001	0.058	0.003	0.049	0.190

7 PD Char

7.1 Single Beams

To determine the plimit at each antenna port, simulation was performed at low, mid, and high channel for each mmW band supported, with 18 dBm input power per active port for n261 band and 18 dBm input power per active port for n260 band:

Obtained PDsurface value (the worst PD among all identified surfaces of the DUT) at all three channels for all single beams specified in the codebook.

Derived a scaling factor at low, mid and high channel, $s(i)low\_or\_mid\_or\_high$, by:

$$s(i)_{low\_or\_mid\_or\_high} = \frac{PD\ design\ target}{sim.PD_{surface}(i)},\ i \in single\ beams \qquad (1)$$

Determined the worst-case scaling factor, $\boldsymbol{s(i)}$, among low, mid and high channels:

$$\boldsymbol{s(i)} = min\{s_{low}(i), s_{mid}(i), s_{high}(i)\},\ i \in single\ beams \qquad (2)$$

and this scaling factor applies to the input power at each antenna port.

7.2 Beam Pairs

Per the manufacturer, the relative phase between beam pair is not controlled in the chipset design and could vary from run to run. Therefore, for each beam pair, based on the simulation results, the worst-case scaling factor was determined mathematically to ensure the compliance. The worst-case PD for MIMO operations was found by sweeping the relative phase for all possible angles to ensure a conservative assessment. The power density simulation report contains the worst-case power density for each surface after sweeping through all relative phases between beams.

Once the power density was determined for the worst-case $\emptyset$, the scaling factor was obtained by the below equation for low, mid and high channels:

$$s(i)_{low\_or\_mid\_or\_high} = \frac{PD\ design\ target}{total\ PD\ (\emptyset(i)_{worstcase})}, i \in beam\ pairs \qquad (3)$$

The total PD ($\emptyset worstcase$) varies with channel and beam pair, the lowest scaling factor among all three channels, $s(i)$, is determined for the beam pair i:

$$s(i) = min\{s_{low}(i), s_{mid}(i), s_{high}(i)\},\ i \in beam\ pairs \qquad (4)$$

7.3 PLimit Calculations

The PD Char specifies the limit of input power at antenna port that corresponds to PD_design_target for all the beams.

Ideally, if there is no uncertainty associated with hardware design, the plimit, denoted as plimit (i), for beam i can be obtained after accounting for the housing influence (Δmin) determined in Table 8, given by:

For n260 and n261

$$plimit(i) = 18\ dBm + 10 * \log(s(i)) + \Delta min,\ I \in all\ beams \qquad (5)$$

where 18 dBm is the input power used in simulation for n261 and n260, respectively; $s(i)$ is the scaling factor obtained from Eq. (2) or Eq. (4) for beam i; Δmin is the worst-case housing influence factor (determined in Table 8) for beam i.

If simulation overestimates the housing influence, then Δmin (= simulated PD - measured PD) is negative, which means that the measured PD would be higher than the simulated PD. The input power to antenna elements determined via simulation must be decreased for compliance.

Similarly, if simulation underestimates the loss, then Δmin is positive (measured PD would be lower than the simulated value). Input power to antenna elements determined via simulation can be increased and still be PD compliant.

In reality the hardware design has uncertainty which must be properly considered. The device design related uncertainty is embedded in the process of Δmin determination.

Since the device uncertainty is already accounted for in PD_design_target, it needs to be removed to avoid double counting this uncertainty.

Thus, Equation 5 is modified to:

If - TxAGC uncertainty < △min < TxAGC uncertainty,

plimit(i) = 18 dBm + 10 * log(s(i)) + △min, I ∈ all beams (6)

else if △min < - TxAGC uncertainty,

plimit(i) = 18 dBm + 10 * log(s(i)) + (△min + TxAGC uncertainty), I ∈ all beams (7)

else if △min > TxAGC uncertainty,

plimit(i) = 18 dBm + 10 * log(s(i)) + (△min - TxAGC uncertainty), I ∈ all beams (8)

Following above logic, the plimit for this DUT can be calculated using Equations (6), (7) and (8), i.e.,

Table 9. $plimit$ **Calculation**

Band	Antenna	△min	TxAGC Uncertainty	plimit	Notes
		(dB)	(dB)	(dBm)	
n261	L(patch)	-2.92	1	plimit(i) = 18 dBm + 10 * log(s(i)) + (△min + TxAGC uncertainty), I ∈ all beams	Using Eq.7
n260	L(patch)	-0.4	1	plimit(i) = 18 dBm + 10 * log(s(i)) + △min, I ∈ all beams	Using Eq.6

Table 9. 5G NR n261 L Patch *plimit*

No.	Module	Beam ID_1	Bema ID_2	plimit (Sim. + Meas.)
1	L	0		14.4
2		1		14.9
3		2		14.3
4		3		15.3
5		4		15.8
6		5		15.6
7		6		14.1
8			7	12.3
9			8	13.9
10			9	13.8
11			10	12.6
12			11	14.1
13			12	13.9
14			13	13.1
15		0	7	10.9
16		1	8	11.9
17		2	9	11.2
18		3	10	10.8
19		4	11	11.7
20		5	12	12.7
21		6	13	11

Table 10. 5G NR n260 L Patch p_{limit}

No.	Module	Beam ID_1	Bema ID_2	plimit (Sim. + Meas.)
1	L	0		13.9
2		1		14.2
3		2		13.7
4		3		14
5		4		14.9
6		5		14.1
7		6		14.2
8			7	13.5
9			8	13.4
10			9	13
11			10	13.7
12			11	13.2
13			12	13.7
14			13	13.8
15		0	7	11
16		1	8	11.1
17		2	9	10.6
18		3	10	11.1
19		4	11	11.1
20		5	12	11.1
21		6	13	10.8