

Spherical coverage with 2 and 3 1x5 ULA, 2x10 URA antenna module redundancy in 6G multi form factor UE at 140 GHz and 300 GHz freq range.

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Abstract—Sub THz UE requiring a broader full spherical coverage with a narrow wavelength with a constraint 2 or 3 reduced antenna modules yet with higher power at CDF 10 percentile is a challenge. Moving one module from the rear panel to a left side edge reduces the 10th percentile EIRP by approx 0.8 dB to 1.1 dB in the evaluated three module layouts, compared with 6.2 dB to 6.6 dB in the two module layouts. Optimization of this process, indicates an estimate of coverage penalty dependencies on whether the remaining modules serve opposite faces, rather than on side mounting alone, the corresponding tablet form factor vs mobile handset configurations differ by less than 0.2 dB, consistent with orientation dominating coverage under the adopted model rather than chassis dimensions. In the evaluated codebook comparison, 30 gap directed beams achieve a 10th percentile EIRP within 0.3 dB of a 165 beam dense codebook. A jointly optimized single beam per module falls 16.7 dB below the dense reference. These results motivate using a common codebook design method when comparing module layouts.

Index Terms—6G, sub-THz, UE antenna placement, dual band shared aperture, beam codebook, spherical coverage, EIRP CDF, module redundancy.

I. INTRODUCTION

UE operating in mmW requires broad spherical coverage from a limited number of compact antenna modules [1]. Earlier work in this series provides two foundations for this study. First, a gap directed codebook approaches the lower percentile coverage of a dense uniform codebook using substantially fewer beams [2]. Second, a three module tablet study shows that module orientation, rather than position on a mounting face, determines coverage under the adopted ideal model [3]. This modeling validates how practical placement constraints affect coverage. The display limits available front mounting space, so the evaluated layouts restrict front modules to the bezel next to the front facing camera. The bottom edge is excluded under the assumed usage conditions, where a hand, stand, or nearby surface may obstruct the radio LOS path. Left side edges provide only 8 mm to 9 mm of depth as primary factor but not ruled out in case 2x5 element antenna module. Combination of ten different layouts are evaluated across two device form factors, two array sizes, and two module counts. A common beam management method is used to isolate layout effects, with coverage differences in CDF 10 percentile. The results validate the modeled coverage tradeoffs associated with these placement constraints, rather than the attenuation caused by the antenna behind the display, chassis, or surrounding objects.

Contributions. (i) Quantification of the coverage penalty from moving a module to a left side edge, showing how it depends on the number and orientations of the remaining modules. (ii) Comparison of corresponding tablet and handset layouts, whose results differ by less than 0.2 dB, supporting the importance of angular coverage rather than chassis dimensions under the adopted model. (iii) A consistent comparison of three beam management methods across ten layouts, distinguishing the effects of module geometry from those of codebook design.

II. SYSTEM MODEL

Each module uses an array with 0.5 mm element spacing, approx half a wavelength at 300 GHz and 0.233 wavelengths at 140 GHz. Two configurations are evaluated: a 2×5 uniform rectangular array and a 1×5 uniform linear array. The element pattern adopts the angular attenuation form of 3GPP TR 38.901 [4], extended here as a modeling approx. Peak gain is estimated from beamwidth using an approx directivity relation and ideal radiation efficiency [5], [6]. For the shared radiating element, beamwidth is assumed to scale with wavelength. A beamwidth of 65° at 300 GHz therefore gives 139.3° at 140 GHz, with estimated peak gains of 9.90 dBi and 3.28 dBi, respectively. Input power per element is fixed at 4 dBm at 140 GHz and 0 dBm at 300 GHz. Codebook comparisons therefore use unchanged power settings. However, the ten element array has twice the total input power of the five element array when all elements are equally driven.

For each observation direction, switched selection chooses the module and beam providing the highest EIRP. Coverage is evaluated over 6000 approximately uniform spherical directions and reported as EIRP CDF percentiles, following the spherical evaluation approach used in 5G FR2 OTA testing [7], [8]. Layouts are ranked by the lower of the two bands' 10th percentile EIRP, emphasizing the weaker band. Under these assumptions, translating a module without changing its orientation leaves the calculated coverage unchanged. Mounting faces therefore matter through their assigned module orientations and placement constraints, rather than through position alone. This separates orientation effects from physical device interactions that require further evaluation.

Geometry and constraints. Front antenna module located on the top bezel of the screen-facing side, next to the camera, with boresight along $+z$ is the reference of the front facing

followed by the edges form the left and right left side edges. The layouts use the following module locations:

- **M1:** Front bezel beside the camera, with boresight along $+z$.
- **M2:** Rear panel or left left side edge, depending on the layout.
- **M3:** Tilted rear module, when included.

Antenna placement beneath the display and along the bottom edge is avoided, as the display or desk may obstruct the radio path when the UE rests on a desk.

III. BEAM MANAGEMENT METHODS

Three methods are evaluated over the same steering range. The discrete candidate pool uses long axis angles from -90° to $+90^\circ$ in 10° steps. For the 2×5 array, short axis angles use 15° steps. The dense method instead determines beam spacing from its crossover criterion.

Dense crossover spaced codebook. Beams are arranged on a grid with spacing calculated by bisection of the array factor response, targeting a crossover level 3 dB below each beam's peak, i.e., approximately half its peak power. If the crossover falls below this level, the spacing is reduced to improve overlap. Stronger overlap generally requires more beams to cover the same scan range. The scan range and selected crossover level therefore determine the required beam count.

Gap directed sequential beam selection codebook. Starting with an empty codebook, beams from all modules are evaluated one at a time. At each step, the beam that gives the highest combined 10th percentile EIRP when added to the existing codebook is retained. Coverage is calculated by selecting the strongest available beam in each observation direction. This approach targets improvements in weaker coverage regions rather than spacing beams uniformly. Selection continues until the total budget of 30 beams per band across all modules is reached.

Joint Single Beam Selection. Each module uses one beam, and the beam combination is optimized for the overall 10th percentile EIRP. For three 2×5 modules, the unfiltered candidate grid contains 247^3 combinations. To reduce computational cost, cyclic coordinate ascent optimizes one module's beam while holding the others fixed, repeating this process across all modules until no further improvement is obtained. Multiple random starting configurations are evaluated, and the best solution is retained. This method may not provide best CDFs for all possible beam combinations.

TABLE I
BEAM-MANAGEMENT METHODS, TABLET, THREE MODULES, 2×5

Method	Beams	p10 (dBm)	
		140 GHz	300 GHz
Dense crossover-spaced	165/15	22.7	14.1
Gap-directed greedy max-min	30	23.6	13.8
Joint-optimal, one beam per module	3	14.5	-2.9

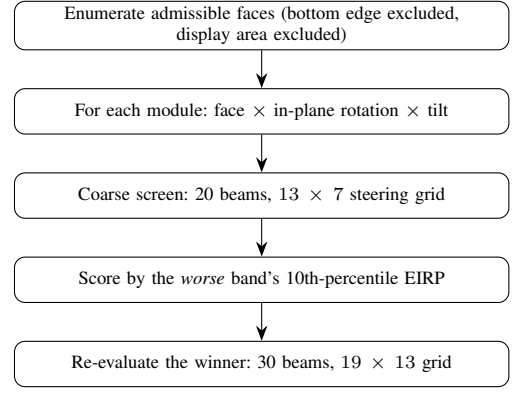


Fig. 1. Placement search. Orientation is searched; front facing on screen and bottom panel excluded.

IV. PLACEMENT SEARCH

The placement search precedes the comparison of selected layouts. Each module is defined by its mounting face, rotation about its boresight, and tilt relative to the face normal. front facing screen area and bottom edge panel is excluded, Five mounting regions are considered: the front bezel, rear panel, top edge, left rail, and right rail. Rotations of $\{0, 60, 120\}^\circ$ and tilts of $\{0, 20, 40\}^\circ$ give 45 candidate configurations per module and approximately 1000 unordered pairs.

Each pair is screened using a coarse 13×7 steering grid and a budget of 20 beams per band. The best candidate is then evaluated using a finer 19×13 grid and 30 beams per band. Candidates are ranked by the lower of the two bands' 10th percentile EIRP. The ten highest ranked two module configurations differ by only approx 0.08 dB. All use zero tilt and modules on opposite faces. The bezel constrained configuration scores 0.04 dB below the unconstrained reference, indicating a small difference in the evaluated search.

V. RESULTS

A. Three Modules: Rear and left side edge placement

Table II compares the M1, M2, M3 three module for tablet form factor with both rear modules against the alternative of one rear module and one on the side edge rail (Fig. 2). The below 2 CDF plots, at 300GHz with the 2×5 , the rear arrangement leads at p10 (13.8 against 12.6) but the side arrangement leads at p80 (22.4 against 22.0) and at p100 (28.6 against 25.6). Antenna modules on the edges helped have improved spherical coverage with improved CDF power at around 75 percentile and with a drastic depreciation around 20 percentile CDF. Scoring on p10, as a link budget does, favors the rear arrangement; scoring on peak EIRP would favor the other.

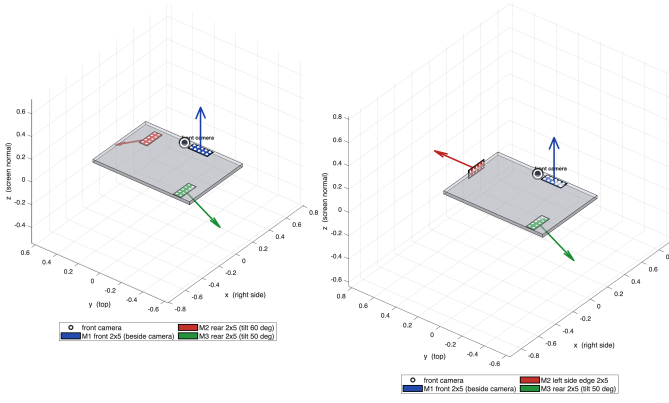


Fig. 2. Three module tablet layouts. Left: M2 and M3 on the rear panel. Right: M2 on the left side edge rail and M3 on the rear panel. M1 remains on the front next to camera in both layouts.

TABLE II
THREE MODULE TABLET: 10TH PERCENTILE EIRP (dBm).

Array	M2 location	140 GHz	300 GHz
2×5	Rear panel	23.6	13.8
2×5	left side edge	23.4	12.6
1×5	Rear panel	17.9	8.3
1×5	left side edge	17.6	7.2

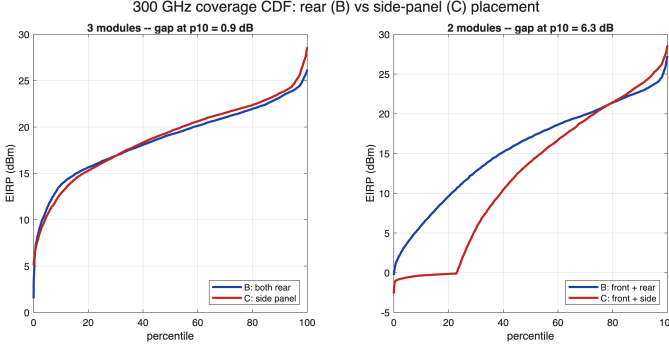


Fig. 3. 300 GHz EIRP CDFs for rear (B) and left side edge (C) placement. Left: the three module layouts show a crossover between lower and higher percentiles. Right: the two module layouts show a larger separation, particularly at lower percentiles. (This indicates 300GHz drastic CDF plot at around 20 percentile for 2 vs 3 Antenna modules)

B. Two modules: opposite faces are mandatory

This config with only two modules, moving M2 from the rear panel to the left side edge reduces the evaluated 10th percentile EIRP by 6.2 dB for the 2×5 array and 6.6 dB for the 1×5 array (slight change), with front and rear modules have opposing boresights and provide complementary spherical coverage, moving M2 to the left side edge places its boresight 90° from M1, leaving rearward directions more dependent on weaker off-axis and backlobe responses (i.e., even though slight change at CDF 10 percentile, a huge change at CDF 75 to 90 percentile, an increased value). And In the three module layouts, M3 retains rearward coverage, reducing the penalty from relocating M2. Within this evaluated

TABLE III
TABLET, TWO MODULES. 10TH-PERCENTILE EIRP (dBm)

Array	M2 location	140 GHz	300 GHz
2×5	rear panel	21.9	5.9
2×5	left side edge	17.6	-0.3
1×5	rear panel	16.1	0.4
1×5	left side edge	11.6	-6.2

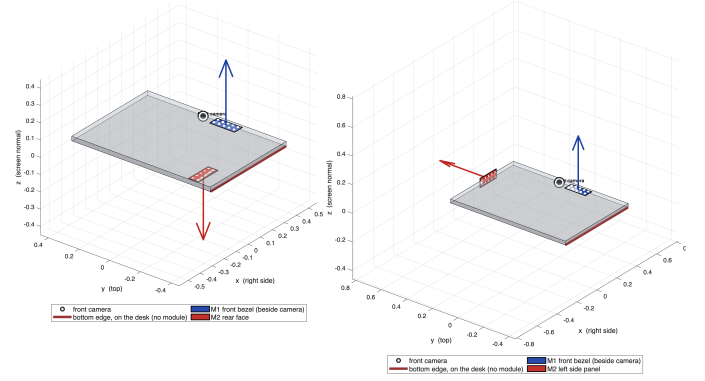


Fig. 4. Two-module tablet geometry: M1 front, M2 on the rear panel (left) against M2 moved to the left side edge rail (right). With the third module removed, the rear hemisphere depends entirely on M2's placement.

layouts, a third module certainly indicate greater placement flexibility by maintaining coverage in directions that would otherwise be poorly served.

C. Array size: the second element row

Table IV validates the impact of adding a second element row across the four layouts in Tables II and III. Replacing each 1×5 array with a 2×5 array improves the 10th percentile EIRP by 5.7 dB to 6.0 dB at 140 GHz and 5.4 dB to 5.9 dB at 300 GHz. These improvements are similar across the evaluated module counts and M2 locations. Under ideal coherent excitation with unchanged power per element, doubling the element count doubles the field amplitude in the aligned direction, giving a peak EIRP increase of $20 \log_{10}(2) = 6.02$ dB [5], [9].

This includes the increase in total input power and lead to increase in directivity power (beams focused). The simulated percentile improvements also depend on element patterns, steering, and beam allocation. The benefit of a third module differs substantially between bands. In the evaluated rear panel comparison, it improves the 10th percentile EIRP by approximately 7.9 dB at 300 GHz, compared with 1.7 dB at 140 GHz. Adding a second element row provides average improvements of approximately 5.6 dB and 5.8 dB, respectively.

Starting with two 1×5 modules, adding the second element row and then the third module raises the 10th percentile EIRP from 16.1 dBm $\rightarrow$ 21.9 dBm $\rightarrow$ 23.6 dBm at 140 GHz, and from 0.4 dBm $\rightarrow$ 5.9 dBm $\rightarrow$ 13.8 dBm at 300 GHz. Thus, the additional row provides the larger improvement at 140 GHz, while the complementary third module provides the larger improvement at 300 GHz. This is consistent with the

TABLE IV

ARRAY SIZE. GAIN FROM A SECOND ROW ELEMENT ($1 \times 5 \rightarrow 2 \times 5$), p10 (dB)

Modules	M2 location	140 GHz	300 GHz
Three	rear panel	5.7	5.5
Three	left side edge	5.8	5.4
Two	rear panel	5.8	5.5
Two	left side edge	6.0	5.9

broader assumed element pattern at the lower band. The results demonstrate a band dependent hardware tradeoff, rather than a universal advantage of module count over array size.

D. Form Factor: UE Handset vs Tablet

Under the adopted model, orientation based design principles apply to both form factors. Corresponding layouts differ by at most 0.4 dB at the 10th percentile, as shown in Table V. Mounting space, side panel options, and user blockage require separate practical evaluation.

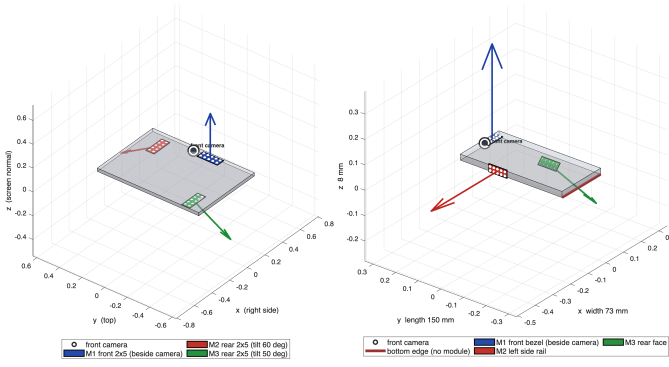


Fig. 5. Selected three module layout on a tablet (left) and a handset measuring 150 mm $\times$ 73 mm $\times$ 8 mm (right).

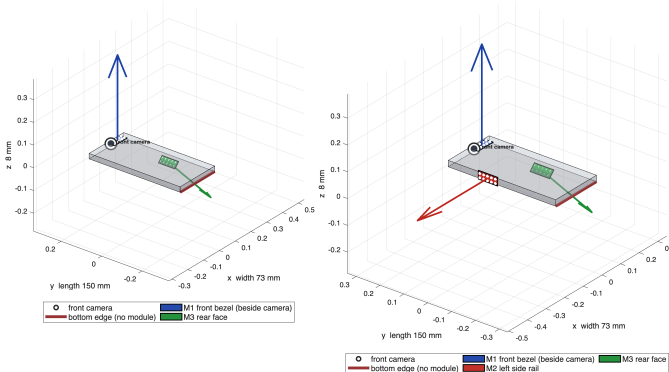


Fig. 6. Handset layouts: two modules (left, M1 front and M3 rear) and three modules (right, M1 front, M2 left left side edge, and M3 rear).

TABLE V

THREE MODULE HANDSET AND TABLET: 10TH PERCENTILE EIRP (DBM).

Array	M2 location	Tablet		Handset	
		140 GHz	300 GHz	140 GHz	300 GHz
2×5	Rear panel	23.6	13.8	23.6	13.8
2×5	left side edge	23.4	12.6	23.4	13.0
1×5	Rear panel	17.9	8.3	17.9	8.3
1×5	left side edge	17.6	7.2	17.7	7.6

VI. DISCUSSION AND LIMITATIONS

Three design rules fall out, and their relative importance is band-dependent.

Module count first at 300 GHz. A third module is worth approx 7.9 dB at 300 GHz but only 1.7 dB at 140 GHz (Tables II, III), and separately makes the second module's placement negotiable.

Opposite faces second. With two modules, moving M2 to a left side edge costs 6 dB+ at 300 GHz and 4.3–4.5 dB at 140 GHz; with three modules this drops to about 1 dB and 0.3 dB respectively (Tables III, II) – the smallest of the three effects at 140 GHz.

Array size third. A second element row is worth 5.6–5.8 dB on both tablet and handset, in both bands (Table V), close to the 6.02 dB theoretical bound. At 140 GHz this exceeds the third module's own gain, so the true 140 GHz ranking is array size, then module count, then opposite faces.

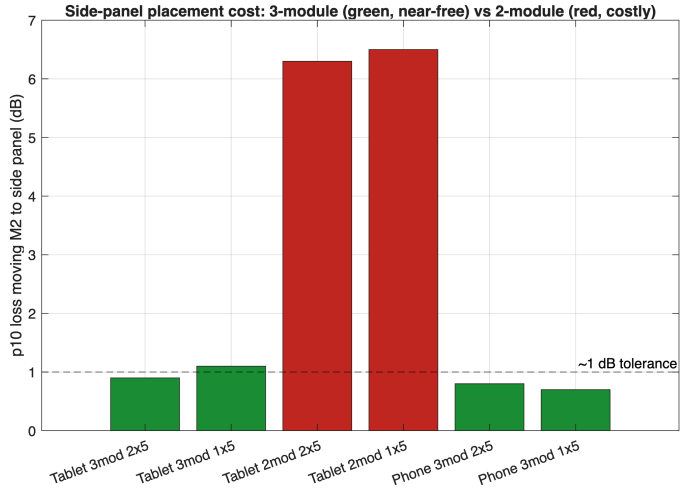


Fig. 7. Reduction in 10th percentile EIRP at 300 GHz when M2 moves from the rear panel to the left side edge. Across the six evaluated cases, the loss is approximately 1 dB with three modules (green) and exceeds 6 dB with two modules (red)

VII. CONCLUSION

At 300 GHz, moving a rear module to the side edge reduces the 10th percentile EIRP by approximately 1 dB with three modules, but by more than 6 dB with two, highlighting the importance of widespread front and rear coverage, observing similar consistency values in tablet and handset scenario. A 30 beam gap directed codebook approaches the 165 beam dense reference within 0.3 dB, while the evaluated single beam

method falls more than 16dB below it. For these layouts, adding a third module provides the larger benefit at 300 GHz, whereas adding a second row element row provides the larger benefit at 140 GHz.

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