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**Millimeter wave antenna module
placement: A quantitative
framework for Smartphones**

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Abstract

Good antenna module placements that are robust to hand blockage are essential for enhancing the user experience at millimeter wave carrier frequencies (and beyond). At this moment of millimeter wave system commercialization, this problem is addressed in a *qualitative* manner based on tradeoffs in terms of user equipment (UE) layout/form factor considerations, a qualitative assessment of likely hand holding modes, available real estate for antenna module placement optimization, etc. In this study, we propose a *quantitative* modeling of this problem by considering statistical models for the likelihood of being in different hand holding modes and the angles of arrival in azimuth and zenith (AoA/ZoA) of the dominant multipath components (MPCs)/clusters in the channel between the base station and the UE. By incorporating these statistical models with a candidate set of locations for the antenna modules, we can compute the *effective* spherical coverage of signal strengths for the determination of good antenna module placements. The effective part of the spherical coverage corresponds to the set of directions of AoA/ZoA likely to be seen for the dominant MPCs/clusters and weighted by the likelihood of observing a blockage/no blockage scenario in the relevant directions. We propose tests on the weighted effective isotropic radiated power (EIRP), uplink outage and uplink throughput to determine the goodness of a UE design from an antenna module placement perspective. With these tests, we show that the use of *only* one antenna module in the UE can lead to *significantly* poor coverage and *significantly* increased throughput losses and outages. With the usage of a pair of antenna modules at the UE side, our studies show that a good placement corresponds to placing one of the modules on the middle of the top edge to provide robust coverage for Portrait-type orientation and another module on the middle strip of the back face or in the middle portion of one of the long edges to provide robust coverage for Landscape-type orientation. Other antenna module placements can lead to significant increases in outage and/or throughput loss.

1 Introduction

The increased path, penetration and blockage losses at millimeter wave carrier frequencies relative to systems standardized for Long-Term Evolution (LTE) and for operation at sub-7 GHz frequencies means that millimeter wave systems rely on beamforming to meet the link budget requirements. Given the reduced inter-antenna element spacings at these frequencies, multiple antenna elements can be controlled by a single radio frequency integrated circuit (RFIC) chip. The integrated set of antenna elements along with the radio frequency (RF) components in the RFIC chip (e.g., phase shifters, gain control stages, etc.) is typically called an *antenna module*. Beamforming over these antenna elements can be performed at the RF level.

The optimal number of antenna feeds that can be supported by a single antenna module is a function of the process node technology used in the manufacture of the RFIC chip and the carrier frequency range supported by it. Thus, a large number of antenna elements (with significantly enhanced array gain proportionate to the antenna elements) cannot be realized with a single antenna module to meet the link budget requirements. Further, antenna elements at millimeter wave carrier frequencies are inherently *directional* in terms of their elemental gain properties with a significant degradation in performance beyond $\pm 45^\circ$ of the boresight direction(s) [that is, the intended coverage directions of the antenna module]. In contrast to sub-7 GHz frequencies where the channel structure and propagation is dominated by scattering, propagation over the channel at millimeter wave frequencies is dominated by reflection

from smooth surfaces such as glass or metallic objects. Thus, the channel structure becomes specular or sparse at these frequencies.

With this channel structure, directional beamforming with a hierarchical set of beamwidths can lead to a robust protocol focusing on reduced latencies in initial acquisition, with the initially acquired beam leveraged and refined for peak gain performance via beamwidth optimization [1]. However, with the coverage provided by a single antenna module limited in terms of the spatial coverage region, multiple antenna modules are necessitated for good coverage over a sphere around the UE since the protocol design must remain *a priori* oblivious to the AoA/ZoA of the dominant reflections in the channel. Thus, stringent network level requirements on *spherical coverage* around the UE on the EIRP in the transmit mode and effective isotropic sensitivity (EIS) [or equivalently, the reference signal received power (RSRP)] in the receive mode are met with the use of two to three antenna modules, which are appropriately and strategically placed on the UE's surface.

The use of more antenna modules leads to increased cost and area/real-estate consumed at the UE side, as well as increased power and thermal considerations. Further, with competition across antenna elements designed for different applications (e.g., WiFi, BlueTooth, near field communications, etc.), optimal antenna module placement at millimeter wave frequencies is a heavily contested issue. Thus, many original equipment manufacturers (OEMs) are considering the use of a small number of antenna modules to meet millimeter wave performance requirements. With this background, we note that single antenna module designs can be quite onerous in meeting network level spherical coverage requirements, especially at the tail (e.g., 20th percentile). Thus, we assume that a hypothetical OEM uses two millimeter wave antenna modules and for such a design, we propose the best antenna module locations.

To motivate this proposal, we develop a *quantitative/maximum likelihood (ML)* framework to estimate good millimeter wave antenna module placements that lead to robustness with hand blockage. In this framework, a candidate pair of antenna module locations is selected and multiple hand holding grips addressing different use-cases in Portrait, Landscape and other modes of operation are studied. Based on user experience (UX) surveys, a probability is attached to the blockage of neither, only one, and both antenna modules corresponding to the selected pair of antenna module locations. From the use of spherical coverage data with/without blockage, we can then estimate the *effective* spherical coverage computed as the spherical coverage weighted with the probabilities associated with being in a blockage/no blockage scenario. Using data from practical network deployment considerations, we then localize the spatial attention to that part of the sphere corresponding to the AoA/ZoA of the dominant reflections in the non-line-of-sight (NLOS) channel or the line-of-sight (LOS) direction (that is, the dominant MPCs). From this localized estimate of the weighted spherical coverage, good antenna module locations are identified based on empirical metrics of KPIs such as uplink outage or uplink throughput at different percentile points.

The main observations from our studies are as follows:

1. While the use of *only one* antenna module to obtain good performance at millimeter wave frequencies is being increasingly considered, such devices can:
 - a. Fail to meet the existing EIRP requirements under blockage conditions,
 - b. Lead to enhanced blockage relative to no blockage operating conditions (over 15%), and

- c. Lead to significant median throughput losses relative to no blockage operating conditions (over 50%).
2. In the context of the use of a pair of antenna modules in the UE, good antenna module placements correspond to robust coverage for both Portrait-type UE orientations as well as Landscape-type UE orientations. With this intuition, we observe that a pair of antenna modules placed one on the middle of the top edge and another on the middle portion of the back face, or middle portion of the left or right long edge can lead to considerable robustness in performance.
3. Further, the cost associated with a relatively poorer antenna module placement can also be quantified in terms of relative outage increase or relative throughput losses. Our estimates show that up to a 35% relative increase in outage can be seen with poorer placements, and throughput losses can be significant (over 75%). These quantifications vindicate the importance of antenna module placement as an important component in millimeter wave system design and optimization (unlike sub-7 GHz systems where discrete antenna elements are spaced as far apart as possible to minimize correlation across antenna elements and enable higher rank transmissions for peak performance).
4. While the use of two antenna modules cannot be mandated as it is UE implementation, good network-level performance of UEs at millimeter wave frequencies can be guaranteed via a simplified set of conformance test enhancements that can capture the deleterious effect of hand and/or body blockage. We propose one such simplified tests in this white paper.

2 Millimeter Wave Performance Quantification: A Background

2.1 UE Antenna Modules

The wavelength λ associated with operation over 28 GHz is ≈ 10.71 mm. At the UE side, antenna elements are typically placed at $\lambda/2$ (≈ 5.36 mm) inter-antenna element spacings to allow the packing of as many antenna elements within a fixed aperture without incurring deteriorated performance from mutual coupling of antennas (associated with closer inter-antenna element spacings). Thus, 4 to 5 dual-polarized antenna elements can be accommodated in a practical antenna module aperture at the UE side (which is often less than 25 mm) allowing the co-phasing of energy (and the associated array gain increase) over these elements to meet the link budget. In Figure 2-1, we provide a pictorial illustration of a typical antenna module that supports a 1x5 dual-polarized linear antenna array and a 2x5 dual-polarized planar antenna array.

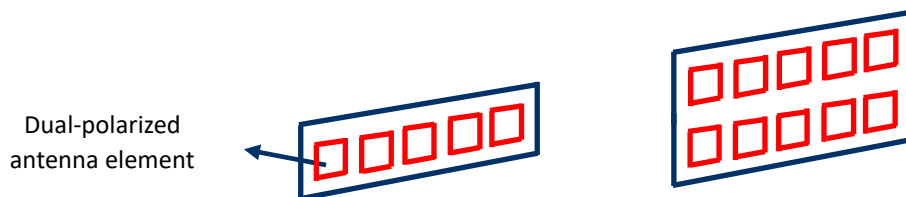


Figure 2-1: Pictorial illustration of antenna modules supporting 1x5 linear and 2x5 planar arrays with each square illustrating a dual-polarized antenna element.

2.2 Spherical Coverage

At millimeter frequencies, propagation is dominated by material reflection in contrast to scattering, which is the dominant propagation mode at sub-7 GHz frequencies. Thus, the channel structure can be geometrically decomposed into individual MPCs with the number of dominant MPCs being small (relative to the ambient antenna dimensions). This sparse nature of propagation can be fully leveraged via *directional* beamforming where a number of beams (each of which steers energy along different directions over the sphere) can be used for capturing the energy from the dominant MPCs.

In many practical deployments, the dominant MPCs can correspond to reflections from a glass or metallic object, or other smooth materials at these frequencies. These MPCs can also correspond to ground bounces. Thus, the AoA/ZoA of the dominant MPCs can be random. To avoid any presupposition or addition of priors on the AoA/ZoA, good coverage over the *entire* sphere around the UE becomes important. Spherical coverage performance of the EIRP in the transmit mode and EIS/RSRP in the receive mode are often used as metrics to study the practical performance in millimeter wave systems [2].

In this context, the antenna elements at millimeter wave frequencies can only provide *directional* coverage. Thus, the antenna modules designed for good performance over a certain frequency range can be placed at different strategically chosen locations of the UE to provide robust coverage over the entire sphere. Depending on the array dimensions (e.g., planar arrays at say, 28 GHz), some antenna module placements are relatively easier than other placements [2]. In Figure 2-2, we illustrate two typical antenna module placement configurations for a pair of antenna modules. In the first configuration, an antenna module is placed on the right long edge (as seen from the front of the UE) and another antenna module is placed on the back face in a vertical placement and closer to the left long edge (also as seen from the front). In the second configuration, an antenna module is placed on the top short edge and another antenna module is placed on the back face in a horizontal placement and closer to the left/middle of the back face.

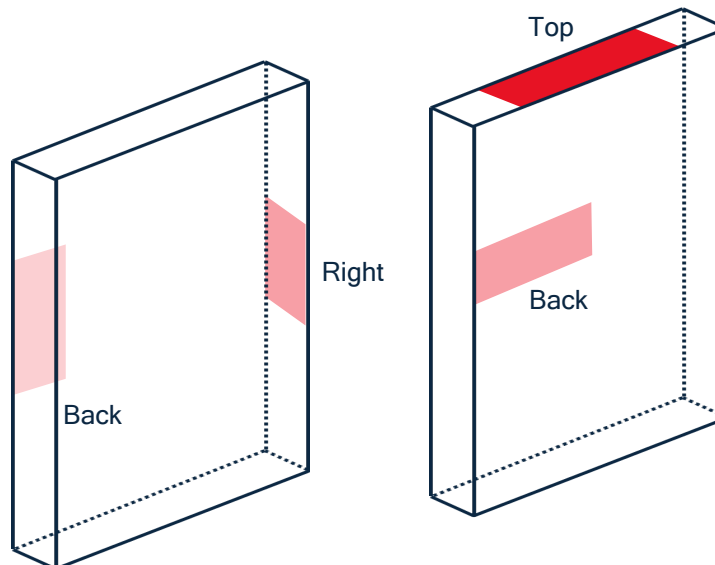


Figure 2-2: Illustration of two typical antenna module placement configurations.

For the two antenna module configurations described above, Figure 2-3 plots the spherical coverage of the RSRP (or equivalently, a shifted version of the EIS), assuming that neither antenna module is blocked.

The plots are over the sphere¹, but illustrated over a two-dimensional (θ, ϕ) plane. From Figure 2-3, we observe that the two antenna module configurations cover different regions of the sphere and can therefore lead to different performance metrics when practically deployed in the same network, depending on the channel structure, hand holding grips, etc.

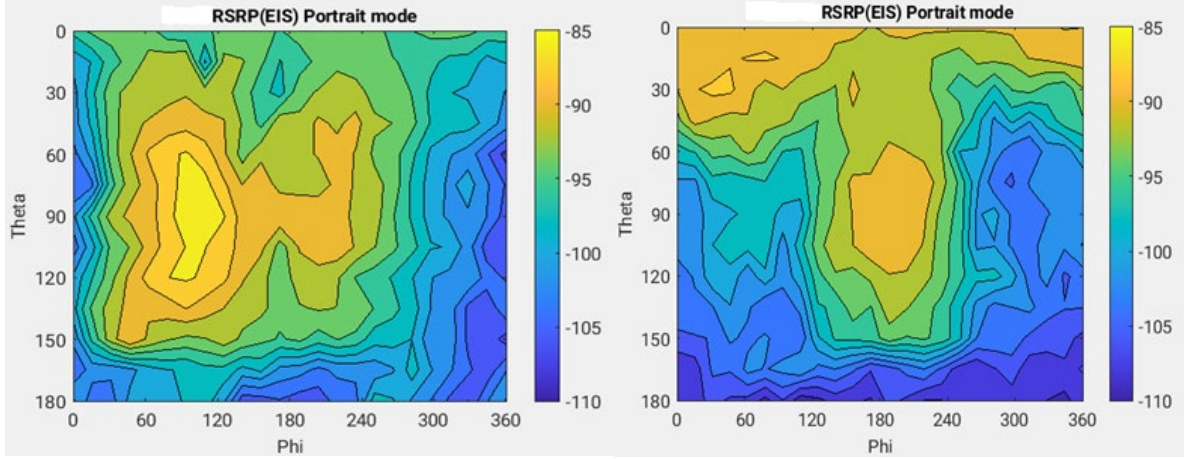


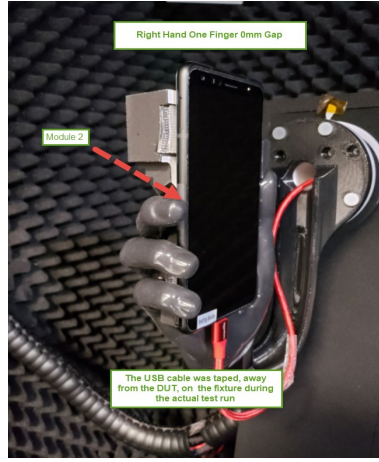
Figure 2-3: Spherical coverage over (θ, ϕ) illustrated over a two-dimensional plane for the two antenna module configurations illustrated in Figure 2-2.

2.3 Impact of Blockage on Performance

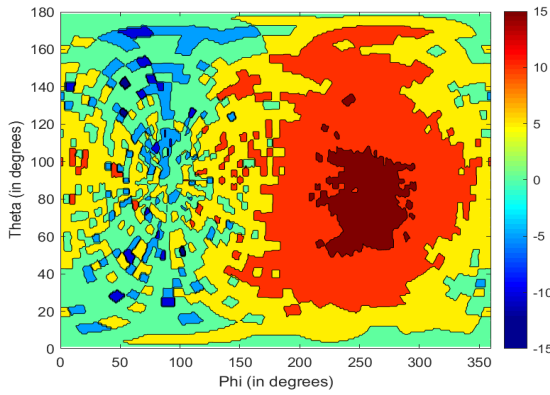
Hand blockage can significantly deteriorate performance at millimeter wave frequencies [3]. This deterioration in performance happens since the wavelength of interest is comparable with the dimensions corresponding to indentations on the hand surface/palm, body parts, etc. Constructive/destructive addition of signals due to reflection from and penetration into different parts of the hand/body can lead to significant signal degradation over certain angles and some enhanced signal strength over different angles [3]. In general, the distortion induced by the hand corresponds to an amplitude/gain component and a phase component over every direction (θ, ϕ) for each antenna element.

In Figure 2-4(a), a hand phantom that is used to hold the UE and which covers one of the antenna modules in the UE is illustrated. Figures 2-4(b)-(c) illustrate the gain pattern of a single representative antenna element with this antenna module in no blockage conditions and with the hand phantom which induces a blockage setting, respectively. These gain patterns are based on measurements in a chamber and correspond to transmitted power from a channel sounder and received power observed over a sphere around the UE. From this figure, we observe that in the no blockage case, the antenna element covers a boresight direction of $(\theta = 90^\circ, \phi = 270^\circ)$ with good coverage over the neighboring directions to the boresight. On the other hand, the hand can induce significant signal distortion around the boresight direction. This behavior in the gain pattern can lead to a drop in signal coverage if a certain direction of the dominant MPC/cluster sees a drop in performance due to presence of the hand.

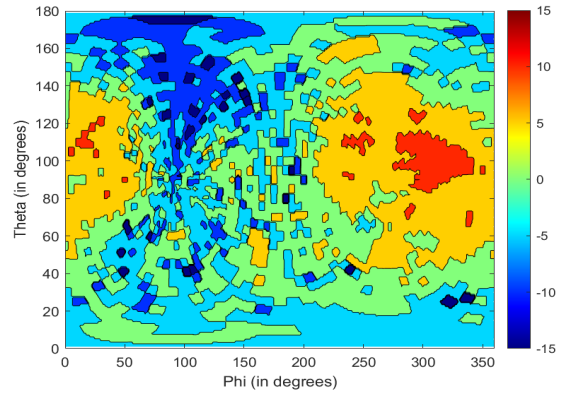
¹ Note that any point on the sphere is captured as a dyad (θ, ϕ) where θ denotes the zenith angle from the Z axis to the XY plane and ϕ denotes the azimuth angle from the X axis to the Y axis. Here, (θ, ϕ) satisfy the constraint that $0^\circ \leq \theta \leq 180^\circ$ and $0^\circ \leq \phi \leq 360^\circ$. The north pole and south pole correspond to $\theta = 0^\circ$ and $\theta = 180^\circ$, respectively, whereas the equator corresponds to $\theta = 90^\circ$.



(a)



(b)



(c)

Figure 2-4: (a) Hand phantom holding the UE and covering one of the antenna modules. Gain pattern over the sphere plotted on a two-dimensional plane with (b) no blockage and (c) blockage.

2.4 Network Level Performance Metrics

We are interested in computing the network level KPIs as described in the pictorial illustration of Figure 2-5 and in determining the best antenna module placements to optimize these KPIs.

In this direction, we first note that the uplink signal-to-noise ratio (SNR) is given as

$$UL_{SNR} = P_{bump} + Array\ gain - Path\ loss - Noise_{gNB},$$

where P_{bump} denotes the total power available at the RFIC chip bump (assuming a ball grid array construction) of the UE corresponding to contribution from the power amplifiers at all the antenna elements across both polarizations, $Array\ gain$ denotes the beamforming array gain over the desired direction corresponding to the dominant clusters in the channel, $Path\ loss$ captures the loss in signal

strength due to propagation from the UE to the base station and $Noise_{gNB}$ captures the noise level observed at the base station upon reception of the transmitted signal from the UE.

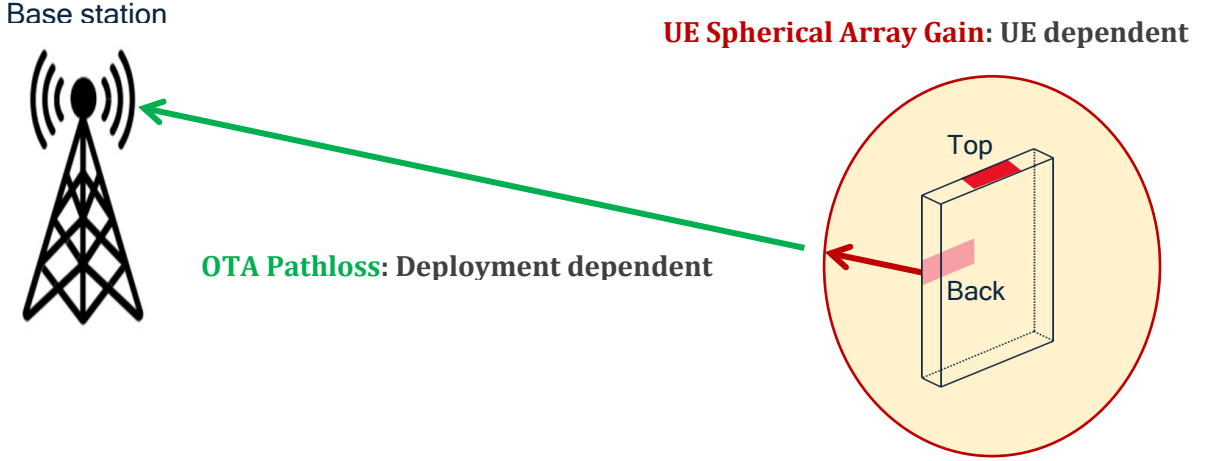


Figure 2-5: Setup describing the uplink KPIs described in this white paper.

The uplink outage corresponds to the scenario where the uplink SNR falls below an appropriately configured $SNR_{threshold}$:

$$UL_{Outage} = P(UL_{SNR} < SNR_{threshold}).$$

A typical value for $SNR_{threshold}$ used in practical deployments is -6 dB which is when the lowest modulation and coding scheme (MCS) cannot be decoded at the base station end with a low error probability. Another important KPI is the achievable uplink throughput, which for 2-port polarization-based transmissions can be written as:

$$Throughput = W \cdot \max(\min(\log_2(1 + snr), 6), \min(2 \log_2(1 + snr/2), 12)).$$

For this computation, we assume that the MCSs are limited on the uplink to 64-Quadrature Amplitude Modulation (64-QAM) per layer, or equivalently, 6 bps/Hz/layer with full coding rate. The above formula considers the best of rank-1 and rank-2 achievable rates with snr indicating the per-layer SNR. Further, it uses a simplified rate metric assuming good cross-polarization discrimination – which is a reasonable assumption for millimeter wave antenna module designs at both the base station and UE sides. Such an assumption needs to be revisited when multi-band antenna modules are considered, where such a cross-polarization discrimination may not be possible across all bands.

At this point, it is important to note that assumptions of a uniform prior on the AoA/ZoA in the spherical coverage metrics ignore the practical deployment scenario that biases the AoA/ZoAs of the dominant MPCs/clusters in the channel to certain angles. For example, in an outdoor deployment with the base station on a high-rise building which is typical of a millimeter wave base station deployment co-located with a sub-7 GHz macro base station, certain AoA/ZoA angles are more likely to be observed than other angles. Similarly, in an indoor deployment with the base station on the ceiling of an office building with a number of metallic or glass reflectors in the building, AoA/ZoA angles have a non-uniform distribution of

observability. Thus, it is important to consider spherical coverage, but localized and weighted by the non-uniform distribution of the AoA/ZoA of the dominant MPCs/clusters in the channel.

3 ML Framework for Optimal Antenna Module Placement

With the background from Section II, the scope of this work is on the characterization of good antenna module placements and a head-to-head comparison between different possible placements in blockage settings. For this, in terms of the evaluation setup, we consider a UE at a certain distance from the base station and described in a local coordinate system (LCS), as illustrated in Figure 3-1. The signal corresponding to the LOS path or the dominant MPC/cluster of the non-LOS path is indicated in Figure 3-1 as the “incoming signal.” This signal corresponds to a certain angle of arrival in azimuth and zenith (the zenith angle is denoted as θ_{zenith} in Figure 3-1). The UE is placed at a certain orientation (corresponding to a tilt angle of $\theta_{orientation}$ relative to the horizontal plane of a global coordinate system).

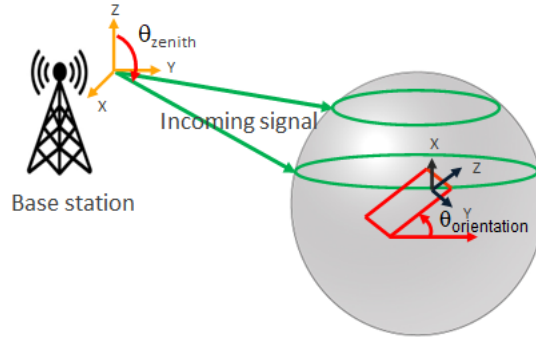


Figure 3-1: Illustration of arrival of path corresponding to the dominant MPC/cluster in the channel between the base station and UE in the LCS of the UE.

We now describe a ML problem formulation to optimize antenna module locations by capturing the impact of blockage on performance:

$$(Location_1^*, Location_2^*) = \underset{Ant \text{ mod } 1 \text{ in } Loc \ 1, \ Ant \text{ mod } 2 \text{ in } Loc \ 2}{argmin} P(UL_{SNR} < SNR_{threshold})$$

subject to priors on AoA, ZoA, UE orientation and Path loss.

The above problem formulation can be described with *Throughput* used as the metric instead of UL_{outage} .

The proposed ML framework that addresses these questions consists of six steps and is pictorially illustrated in Figure 3-2.

3.1 Step 1 (Candidate Antenna Module Location(s))

We begin by partitioning the UE’s surface into different candidate locations, where a distinct antenna module (controlled by an RFIC chip) can be located. In a simplified example as illustrated in Figure 3-3, the top and bottom short edges of the UE can be partitioned into K_1 disjoint regions, whereas the left and right long edges can be partitioned into K_2 disjoint regions. Similarly, the front and the back faces of the UE can be partitioned into K_3 disjoint regions. Since the front face of a typical UE is fitted with glass through which millimeter wave transmissions can incur a significant penetration loss [4] and antenna module placement can lead to significant manufacturing difficulties, we can ignore the front face as a viable

location for an antenna module. To further simplify our study, we consider the case where $K_1 = K_2 = 3$ (illustrated as “Top i” and “Bottom i” for $i = 1, 2, 3$ in Figure 3-3) and $K_3 = 6$ (illustrated as “Back face Top Right, Back face Top Left, Back face Middle Right, Back face Middle Left, Back face Bottom Right and Back face Bottom Left” in Figure 3-3) leading to a total of $N = 2K_1 + 2K_2 + K_3 = 18$ partitions/regions of the UE. Each potential antenna module location is indexed by a number from 1 to 18 and the convention used in this work (in the subsequent plots) is listed in Table 3-1 as well as displayed in Figure 3-3. For a UE equipped with a single antenna module, we have $L_1 = \binom{N}{1} = 18$ possible candidate locations and for a UE equipped with two antenna modules, we have $L_2 = \binom{N}{2} = 153$ possible location pairs. With K antenna modules in the UE, we have $L_K = \binom{N}{K}$ possible location K -tuples. Note that as N increases, the number of possible antenna module location K -tuples (L_K and in particular, L_2) grows significantly leading to a more complicated analysis that is not commensurate with the insights gleaned from such a complicated study. Thus, we focus on the above choices as a representative set for K_1, K_2 and K_3 in this study.

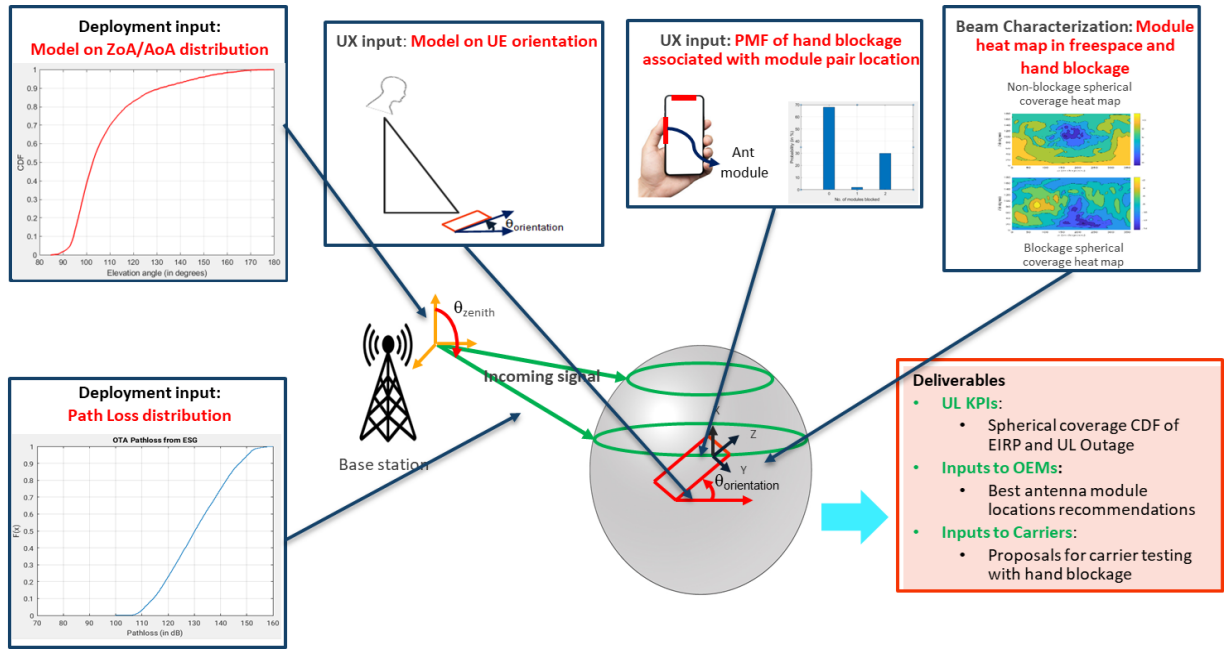


Figure 3-2: Pictorial illustration of proposed ML framework of incorporating priors on hand holdings, UE orientation, path loss and angle of arrivals on performance.

3.2 Step 2 (Representative Hand Holding Grips)

Antenna module location	Plot axes index
Top left, middle and right (T1, T2, T3)	1 to 3
Bottom left, middle and right (B1, B2, B3)	4 to 6
Left top, middle and bottom (L1, L2, L3)	7 to 9
Right top, middle and bottom (R1, R2, R3)	10 to 12
Back face, top right and top left (BTR, BTL)	13 and 14
Back face, middle right and middle left (BMR, BML)	15 and 16
Back face, bottom right and bottom left (BBR, BBL)	17 and 18

Table 3-1: Indexing used for different antenna module locations in the axes of subsequent plots.

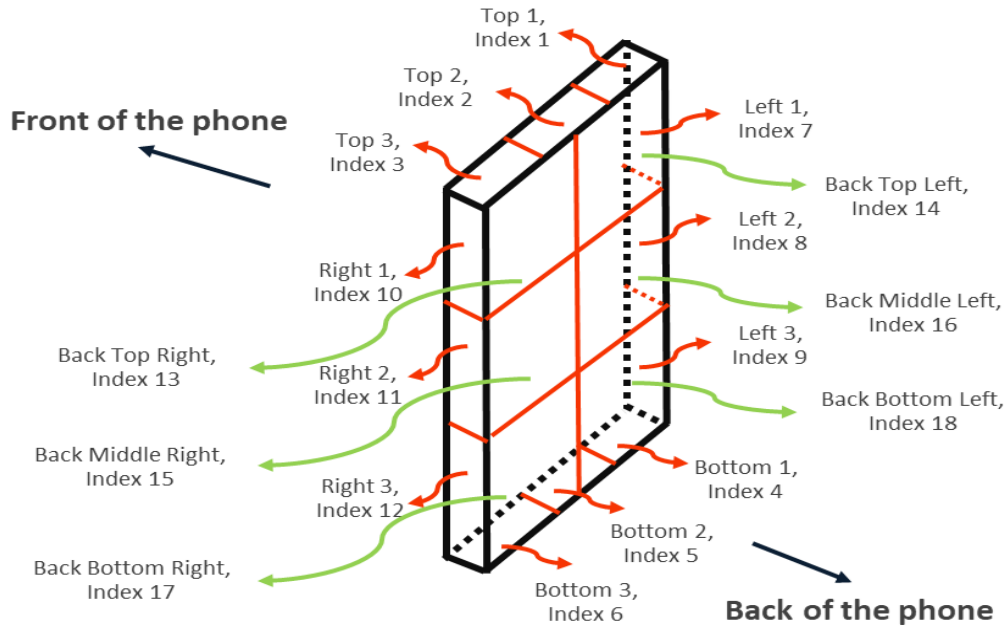


Figure 3-3: UE's edges and back face partitioned into 18 possible locations for the placing of a single antenna module.

We then consider many example/illustrative hand holding grips/use-cases adopted by users and which are representative of usage with the current generation of UEs sustaining communications over millimeter wave carrier frequencies. These hand holding use-cases encompass the Portrait mode, the Landscape mode, as well as non-Portrait/non-Landscape (or miscellaneous) modes of operation. In particular, in Appendix A, we present the $P = 16$ hand holding use-cases that are considered in this study encompassing 5 grips corresponding to different applications in the Portrait mode, 8 grips corresponding to different applications in the Landscape mode and 3 use-cases in the miscellaneous mode. The representative scenarios in Appendix A encompass the practical use-cases employed by users in a practical/real-life setting and any unforeseen use-cases in this study can be augmented to the data described in Appendix A. Further, note that each hand holding use-case blocks different locations/parts of the UE and thus has different impacts on the design of the UE based on the antenna module locations.

3.3 Step 3 (Distribution Function of Phone Orientation and Likelihood of Each Hand Holding Grip)

We look at UX studies on how users typically hold their phones [5], [6]. The UX studies typically involve survey sampling a large user base/population and its behavior in terms of:

- Hand positions and grips (left- or right-handed?, how many fingers envelop each side?, which part(s) of the phone are best suited for sensor locations?, etc.)
- Modes of usage (Portrait, Landscape, etc.)
- Application types used (voice call, video downloading/viewing, gaming mode, etc.)
- Angle between the plane of the phone and the global horizontal plane, etc.

From these survey studies, we can estimate a likelihood/probability that a random user will hold the UE in these different hand holding grips.

In Table 3-2, we present the probability of a random user holding the phone in each of the $P = 16$ hand holding use-cases in either a Portrait-heavy mode or Landscape-heavy mode of operation. In a Portrait-heavy mode of operation, the UE is held vertically up for a significant fraction of the time (e.g., applications such as Instagram, Internet surfing, voice calls, etc.) and the fraction of the use-cases in the Portrait mode sum to 85%, whereas the fraction of the use-cases in the Landscape mode sum to only 10% (with the miscellaneous mode accounting for the remaining 5%). In a Landscape-heavy mode of operation, the UE is tilted by 90° for a significant fraction of the time (e.g., applications such as gaming, watching videos on YouTube, etc.) and the fraction of the use-cases in the Portrait mode sum to 10%, whereas the fraction of the use-cases in the Landscape mode sum to 85%. A third mode of operation appropriates equal weightage to both the Portrait use-cases and Landscape use-cases (both sum to 47.5%). Another survey of the user's holding of the phones provides a distribution function for $\theta_{orientation}$ (the angle between the plane of the phone's screen and the horizontal plane in the global coordinate system) as illustrated in Figure 3-4. This survey shows that the following model is useful in many practical applications:

$$\theta_{orientation} \sim 30^\circ + \text{Uniform}(-15^\circ, 15^\circ).$$

	Portrait-heavy mode	Landscape-heavy mode	Equal weightage between Portrait and Landscape
Portrait use-case 1	18%	2%	10%
Portrait use-case 2	18%	2%	10%
Portrait use-case 3	18%	2%	10%
Portrait use-case 4	6%	1%	3%
Portrait use-case 5	25%	3%	14.5%
Landscape use-case 1	2%	16%	9%
Landscape use-case 2	0.9%	8%	4%
Landscape use-case 3	0.9%	8%	4%
Landscape use-case 4	2%	16%	9%
Landscape use-case 5	2%	15%	9%
Landscape use-case 6	2%	15%	9%
Landscape use-case 7	0.1%	4%	2%
Landscape use-case 8	0.1%	3%	1.5%
Miscellaneous: On a table	2%	2%	2%
Miscellaneous: Placed on a table upside down	2%	2%	2%
Miscellaneous: Credit card holder	1%	1%	1%

Table 3-2: Probabilities of the UE being in different use-cases based on Portrait-heavy, Landscape-heavy, or equal weightage modes of operation.

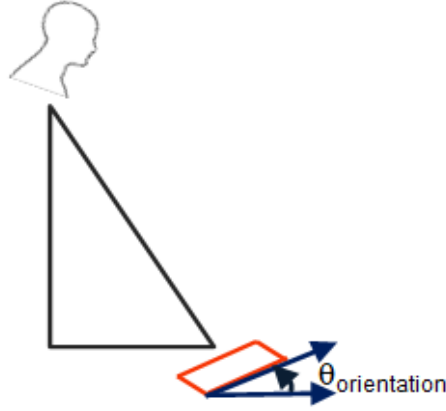


Figure 3-4: Illustration of user's phone orientation with respect to the global horizontal plane.

3.4 Step 4 (Array Gain in No Blockage/Blockage Scenarios)

For each one of the L_1 candidate locations for a single antenna module, we can compute the array gain coverage over the sphere in a no blockage scenario corresponding to no blockage (or Freespace)-based electric field vectors and capturing only the UE's housing effects, and in a blockage scenario corresponding to the presence of a hand which can distort the phases and the amplitudes of the observed electric field vector over the antenna elements in the module. This computation can be either based on measurements from an offline beam characterization procedure in an anechoic chamber, or based on simulations from a high-frequency electromagnetic simulator with a hand blockage model used to capture the impairments of blockage.

3.5 Step 5 (Priors on Path Loss and AoA/ZoA)

We generate statistical models for the AoA/ZoA of the dominant cluster's paths between the base station and the UE along with their path loss from representative deployment studies of practical networks in outdoor and indoor settings. These deployment studies correspond to practical base station placements (e.g., stand-alone or co-located with a sub-7 GHz macro base station) and inter-site distances (capturing densification of the network) also capturing the impact of physical blockages in the network (e.g., buildings, vehicles, humans, etc.). The dominant path could correspond to a LOS scenario or an NLOS scenario capturing reflection from a metallic or glass object and is hence deployment-dependent.

In an illustrative outdoor deployment scenario capturing a downtown San Francisco setting with multiple high-rise buildings, Figures 3-5(a)-(b) describe the CDF of the azimuth and zenith angles of the dominant path between the base station and the UE. From this figure, we observe that the azimuth angle is uniformly distributed over the 0° to 360° range. On the other hand, the zenith angle is above 80° (corresponding to a pre-dominant upwards tilt of the UE) with most of the observations concentrated between the 85° and 130° range. Figure 3-5(c) plots the CDF of path loss observed in this outdoor deployment.

3.6 Step 6 (Computing the Effective Spherical Coverage)

Based on the statistical models for the AoA/ZoA and the models on the likelihood of the different hand holding grips (in either Portrait-heavy, Landscape-heavy or equal weightage mode), for each candidate antenna module location pair, we compute the effective spherical coverage and the corresponding uplink SNR as described below.

Let p_i denote the probability of the user being in the i -th hand holding grip and for this grip, we can define indicator functions $I_i^{11}, I_i^{10}, I_i^{01}$ and I_i^{00} such that $I_i^{11} + I_i^{10} + I_i^{01} + I_i^{00} = 1$ with the convention that

$$I_i^{11} = 1 \text{ if neither module is blocked}$$

$$I_i^{10} = 1 \text{ if the first module is not blocked, but the second module is blocked}$$

$$I_i^{01} = 1 \text{ if the second module is not blocked, but the first module is blocked}$$

$$I_i^{00} = 1 \text{ if both modules are blocked.}$$

In other words, I_i^{kl} partitions the observed scenarios into one of 0, 1 or 2 antenna modules being blocked. Let $G_{unb,unb}(\theta, \varphi)$, $G_{unb,b}(\theta, \varphi)$, $G_{b,unb}(\theta, \varphi)$ and $G_{b,b}(\theta, \varphi)$ denote the array gain observed at an angle pair (θ, φ) with the use of the two antenna modules (in the specific location pair considered here) over these four scenarios: neither module is blocked, first module is not blocked but second module is blocked, second module is not blocked but first module is blocked, and both modules are blocked. Then, the effective array gain seen at an angle pair (θ, φ) is given as:

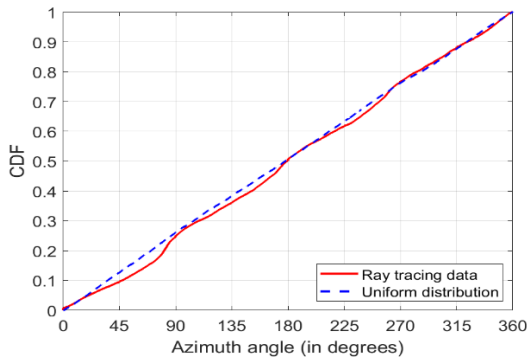
$$G_{eff}(\theta, \varphi) = \sum_{i=1}^{P=16} p_i \cdot \left(I_i^{11} G_{unb,unb}(\theta, \varphi) + I_i^{10} G_{unb,b}(\theta, \varphi) + I_i^{01} G_{b,unb}(\theta, \varphi) + I_i^{00} G_{b,b}(\theta, \varphi) \right).$$

The uplink SNR is then given as

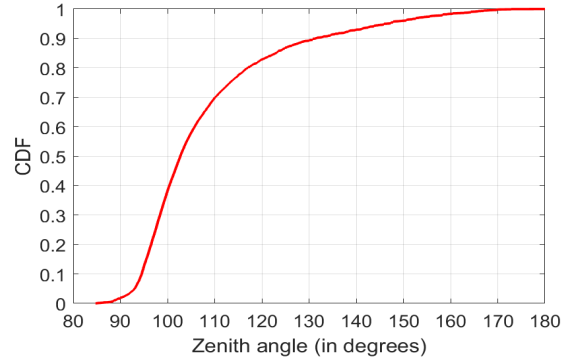
$$UL_{SNR} = P_{bump} - Noise_{gNB} + \iint_{(\theta, \varphi) \in \mathbf{R}} [G_{eff}(\theta, \varphi) - Path\ loss(\theta, \varphi)] \sin \theta d\theta d\varphi,$$

where $\mathbf{R}$ corresponds to the region of interest for the AoA/ZoA of the dominant cluster in the channel based on the UE orientation and network deployment.

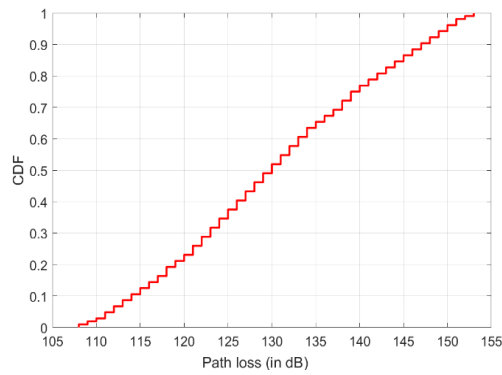
From the pictorial illustration of the evaluation setup in Figure 3-1, to characterize $\mathbf{R}$, first note that since the azimuth angles are uniformly distributed for the dominant cluster's AoA, they are also uniformly distributed in the UE's LCS in the Portrait mode. For the elevation/zenith angle, note that when the UE is vertically aligned with the base station, the dominant cluster's ZoA (θ_{zenith}) impinges a zenith angle of $180^\circ - \theta_{zenith}$ at the UE in its LCS. In general, a path at an angle θ_{zenith} impinges a zenith angle of $|180^\circ - \theta_{zenith} + 90^\circ - \theta_{orientation}|$ in the UE's LCS. Similarly, in the case of a Landscape orientation, the azimuth angle in the UE's LCS can be seen to be $\pm(180^\circ - \theta_{orientation})$ depending on the UE's orientation with respect to the horizontal plane. The zenith angle in the UE's LCS can be seen to be $180^\circ - \theta_{zenith}$. Thus, we consider the statistical distribution of $\{\theta_{zenith}, \theta_{orientation}\}$ and with this distribution estimate the UE's array gains over the angles of interest in either the Portrait or Landscape orientations for an estimate of the uplink SNR.



(a)



(b)



(c)

Figure 3-5: CDF of (a) azimuth angles, (b) zenith angles, and (c) path loss in a typical outdoor deployment.

Percentile value	Loss between no blockage and blockage conditions (in dB)
90	8.6
80	10.6
50	12.2
20	17.2

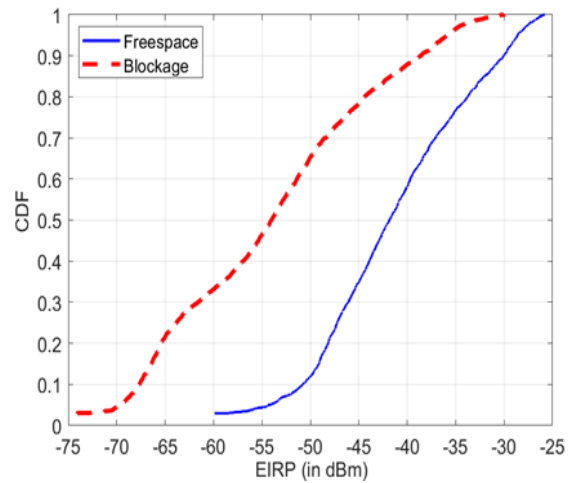


Figure 4-1: Illustrative example of a hand blockage transformation.

4 Conformance Testing Methodologies to Study Hand Blockage Performance

To address the UE design and antenna module placement problem for a device under test (DUT), we propose the following methodology to OEMs and network operators:

1. Retain the EIRP/EIS specifications across bands provided by the network operators at the 100th, 50th and 20th percentile levels for Freespace/no blockage conditions and use these specifications to measure good on-field performance with hand holdings/grips.
2. **Test 1 (EIRP test):** As is done currently, EIRP/EIS data is measured over the sphere in Freespace/no blockage conditions with *only one* of the (potentially many) antenna modules in the UE being turned ON. With an agreement between network operators and OEMs on the impact of hand blockage (e.g., signal strength losses in dB at different percentile points), the Freespace EIRP/EIS metrics for each antenna module in the DUT can be translated to the corresponding hand blockage-based EIRP/EIS metrics for that module. An illustrative example of a hand blockage transformation is given in Figure 4-1 below.

Another agreement between network operators and OEMs are used for a representative set of hand holdings to capture real-world performance. The corresponding priors that are agreed are such that an equal weightage is placed between Portrait and Landscape modes of operation. An illustrative example of such a representative set is Appendix A and the priors listed in Table 3-2, column 3. In terms of the AoA/ZoA and UE orientation priors, a third agreement is made and an illustrative example is provided in Figure 4-2. With the agreed priors, we can cumulate the EIRP/EIS metrics under no blockage and/or blockage over the sphere and then test these metrics with the prescribed EIRP/EIS specifications. Mathematically, the proposed test can be described as:

$$\text{Pass if } HB \text{ prior} - \text{cumulated EIRP} > EIRP_{threshold} \\ \text{Fail otherwise.}$$

3. **Test 2 (Outage test):** To capture the outage performance, an agreement is made between network operators and OEMs for the path loss (possibly as a function of the spatial coverage/direction of interest). With this information and the description in Section II, it is checked whether the DUT's outage level in the deployed hand blockage test condition is within an agreed threshold of the outage observed in the no blockage condition for the same device. Representative thresholds could be 5% or 10% (but could be further optimized). The DUT passes the outage test if the outage level with the device is below the agreed outage level in the deployed test condition. Mathematically, the proposed test can be described as:

$$\text{Pass if } Outage_2 \text{ in HB} - Outage_1 \text{ in FS} < Outage_{threshold} \\ \text{Fail otherwise.}$$

A DUT and the associated antenna module design are acceptable to be admitted into the network if it passes both Tests 1 and 2. The proposed tests are pictorially illustrated in Figure 4-3.

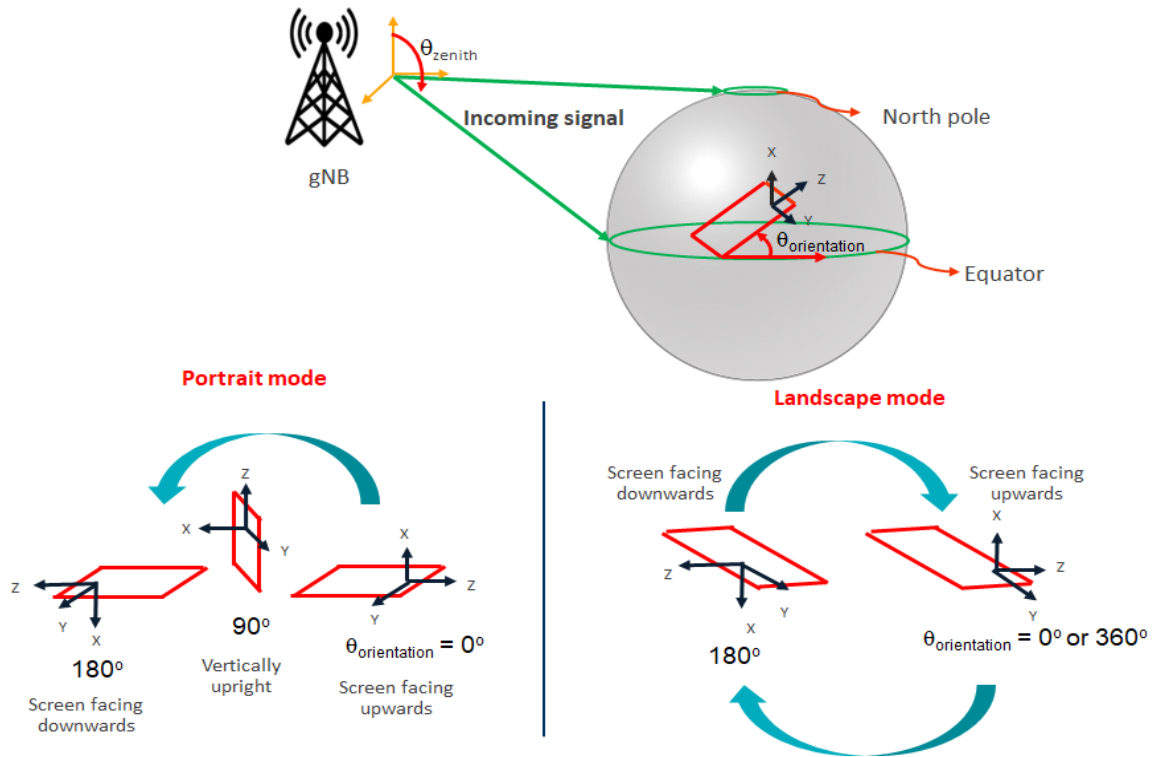


Figure 4-2: Illustrative example of AoA/ZoA and UE orientation priors.

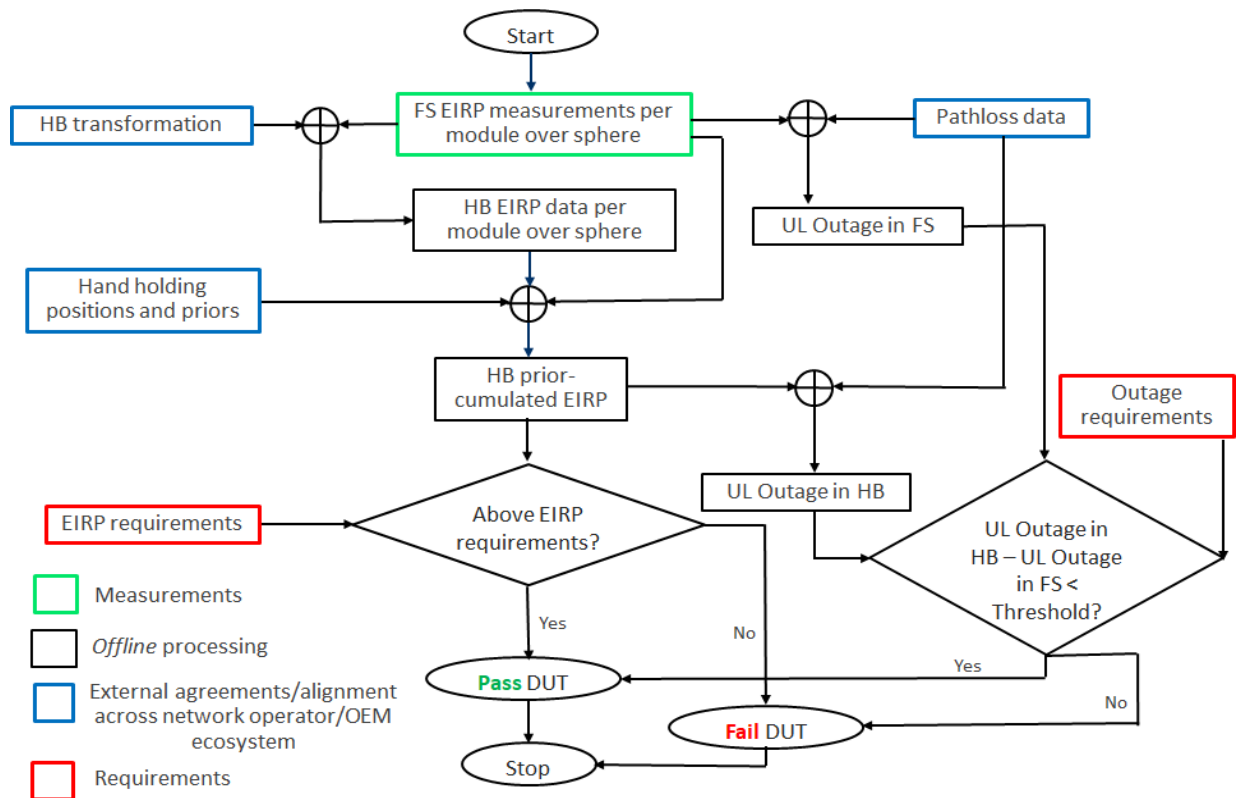


Figure 4-3: Algorithmic description of proposed conformance tests.

5 Recommendations to OEMs and Network Operators

We now provide illustrative results from the proposed ML framework for the study on the best pair of antenna module placements.

5.1 Recommendations to OEMs

	EIRP specifications over both polarizations for n261 (in dBm)
100 th %tile or peak	27.5
50 th %tile	21.0
20 th %tile	14.5

Table 5-1: EIRP requirements (in dBm) for n261 proposed by one network operator.

From an OEM perspective, the basic question in terms of millimeter wave UE design begins with whether good performance can be guaranteed with the use of *only* one antenna module. For good performance, network operators typically impose a requirement on the EIRP/EIS metrics at the peak, 50th percentile and 20th percentile levels that UEs need to meet to be admitted into the network. For example, consider an illustrative EIRP requirement table from a representative network operator in Table 5-1 for n261 (corresponding to 27.5 to 28.35 GHz) at the peak, 50th and 20th percentile levels. Similar tables exist for other bands (e.g., n257, n258, etc.) as well as corresponding metrics for EIS.

In our study, each antenna module consists of a 5x1 dual-polarized linear antenna array. For the beamforming gain, we consider a size-9 analog beamforming codebook with the beam weights in the codebook designed to steer energy towards the boresight direction and its neighborhood ($\pm 45^\circ$).

To compare the performance with the use of only one antenna module at the UE side, we consider two representative hand holdings described in Appendix A (Portrait use-case 1 and Landscape use-case 6) to capture performance in Portrait and Landscape modes of operation. With these representative hand holdings, we study the EIRP for UEs that are designed with single antenna modules corresponding to different single locations and weighted with priors for different arrival angles and UE orientations. With the UE partitioning as described in Figure 3-3, there are $L_1 = \binom{18}{1} = 18$ possible locations for antenna modules and correspondingly, 18 CDF curves for weighted EIRP in any hand holding mode. In Figure 5-1(a), we consider the weighted EIRP CDF for the 18 single antenna module locations under the assumption that the UE is held in the Portrait mode with the representative hand holding in Figure 5-1(a). These are presented as red curves in these figures. Similarly, Figure 5-1(b) illustrates the weighted EIRP CDF with the representative hand holding in the Landscape mode of Figure 5-1(b), and Figure 5-1(c) illustrates the CDF with a 50% Portrait and 50% Landscape mode holding, respectively. In addition, we also display the EIRP specifications at 100th, 50th and 20th percentile from Table 5-1 in black crosses. The same set of CDF curves for Freespace operational mode are presented as blue curves in these figures.

From Figures 5-1(a) and (b), we note that many of the locations for a single antenna module fail the EIRP specifications in both Portrait and Landscape modes, especially at the 50th percentile. At the 20th percentile, however, almost all the single antenna module locations fail the EIRP specifications for both the Portrait and Landscape modes. Those few antenna module locations that do pass the EIRP

specifications in Portrait and Landscape modes turn out to be *mutually exclusive*. This observation is clear from Figure 5-1(c) where in the 50th percentile, only three single antenna module locations pass the EIRP specifications.

Furthermore, we consider the outage increase for all single antenna module devices relative to the outage level observed with the same device under Freespace condition. This relative outage increase (in percentage) is plotted in Figure 5-2(a) showing that most of the single antenna module locations (except antenna modules at the Top edge) result in a significant increase in outage. Even for the Top edge module locations, outage increase is over 15%. These observations suggest the need for the use of two antenna modules at the UE to enable good coverage. The median throughput loss for all single module devices relative to the best two module device is plotted in Figure 5-2(b) and this plot shows a significant degradation in performance with the use of single module devices.

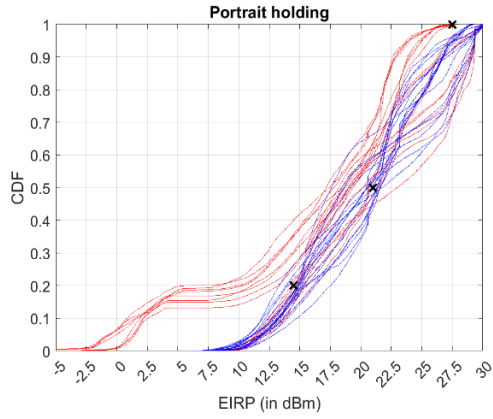
From a UE design perspective, when there is a degree of freedom associated with the use of a pair of antenna modules, placing them proximate to each other is a *bad* idea since both modules can be simultaneously blocked with certain types of hand holdings/use-cases. On the other hand, separating them as far apart as possible, akin to the design of sub-7 GHz UE design is also a *bad* idea since the main determinant of good performance is not the separation between modules, but their relative orientation in mitigating the effect of different hand holdings. This study showed that ensuring that one of the two modules provides good coverage for Portrait-type hand holdings and another module provides good coverage for Landscape-type hand holdings is a *better* design idea. One such example is the use of the top edge for one of the modules and the middle strip of the back face (including perhaps the middle portion of the left/right long edge) for the other module.

In the two module case, Figure 5-3(a) illustrates the EIRP with priors on UE orientation, AoA/ZoA, hand holdings, etc. for all the $L_2 = \binom{18}{2} = 153$ antenna module location pairs. From this figure, we observe that the EIRP specifications *eliminate* some of the poor antenna module placements which are to the left of the EIRP specifications, but a significant number of antenna module placements are useful in meeting the EIRP specifications. Thus, the study of on-field performance and comparing them with the existing EIRP specifications implicitly lead to the use of two antenna modules in good placements at the UE side without such a requirement being explicitly mandated by network operators. Figure 5-3(b) plots the outage increase in blockage condition relative to the outage with the same device under Freespace condition. This plot shows that many two module devices (e.g., one module on the top edge and another module on the left or right edges) can lead to only a small increase in outage (<10%).

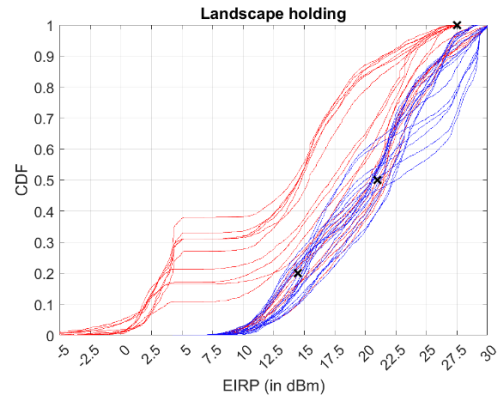
In Figures 5-4 and 5-5, we provide a **pass-fail** bitmap of all antenna module location pairs that lead to the EIRP passing the specifications in Table 5-1 at the 100th, 50th and 20th percentile points and the relative outage increase being less than a threshold of 10%. These bitmaps clearly show that the diagonal corresponding to the use of *only* one antenna module fails the EIRP test as well as the outage test.

5.2 Recommendations to Network Operators

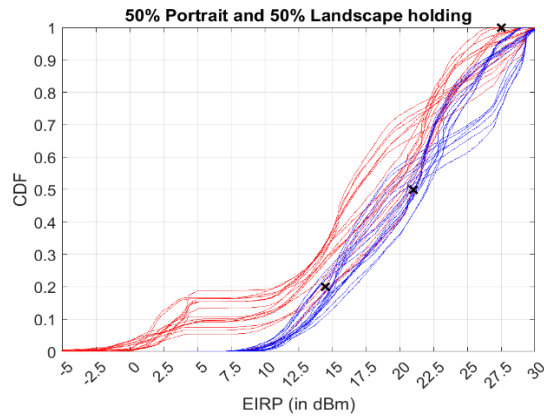
From a network operator perspective, it is difficult to mandate the use of two (or more) antenna modules at the UE side for good millimeter wave network coverage since the number and capability of antenna modules used is left to UE implementation.



(a)

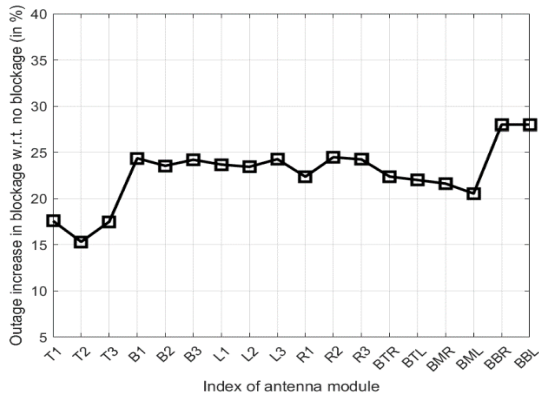


(b)

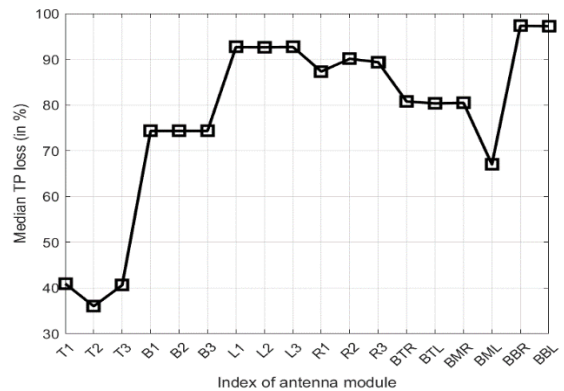


(c)

Figure 5-1: EIRP comparison with (a) one representative Portrait hand holding, (b) one representative Landscape hand holding and (c) with the above two hand holdings used 50% of the time. EIRP specifications from Table 5-1 are in black crosses.



(a)



(b)

Figure 5-2: (a) Relative outage increase and (b) median throughput loss for all single antenna module devices.

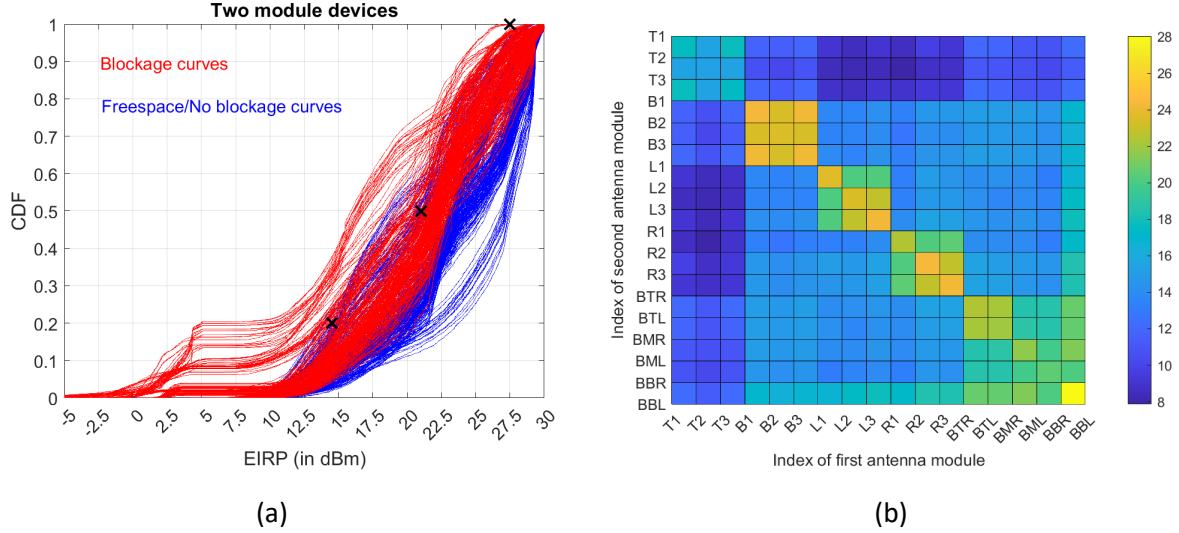


Figure 5-3: (a) EIRP with blockage and no blockage along with EIRP specifications in black crosses for all the $L_2 = 153$ UE antenna module placement. (b) Relative outage increase for all two antenna module devices.

One possibility to enable robustness of the UE design to address hand blockage impairments is to enhance Table 5-1 to incorporate the required EIRP/EIS values for hand and body blockage. Such requirements have a precedence in sub-7 GHz systems where antenna efficiency specifications are made for Freespace as well as for blockage conditions such as “hand left/right” (HL/HR) scenarios and “besides head and hand left/right” (BHHL/BHHR) scenarios. Generalizing such requirements to millimeter wave systems would require multiple considerations such as:

1. The need for a standardized set of hand and body phantoms for measurements at millimeter wave frequencies.
2. Agreements in terms of precise hand holdings and positioning for the phantoms to be used in measurements.
3. A representative set of measurements under diverse conditions that lead to an acceptable set of requirements, etc.

Such an approach is expected to be time-consuming and could be considered as the millimeter wave ecosystem further evolves. As an alternate possibility, the simplified test methodology for conformance testing of devices at millimeter wave frequencies proposed in Section IV can be implemented.

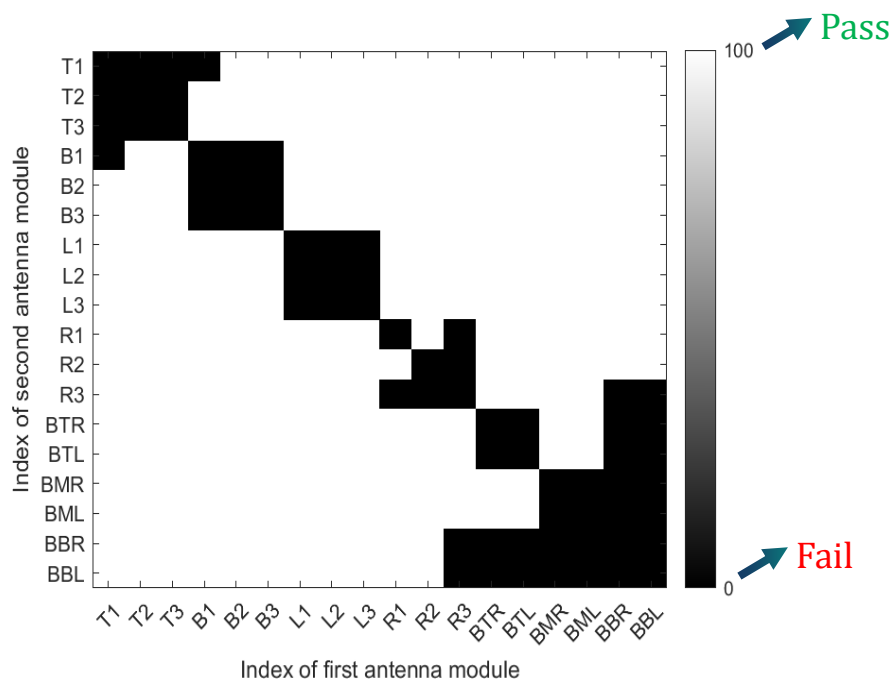


Figure 5-4: Bitmap of UE antenna module location pairs that **pass** or **fail** the EIRP test.

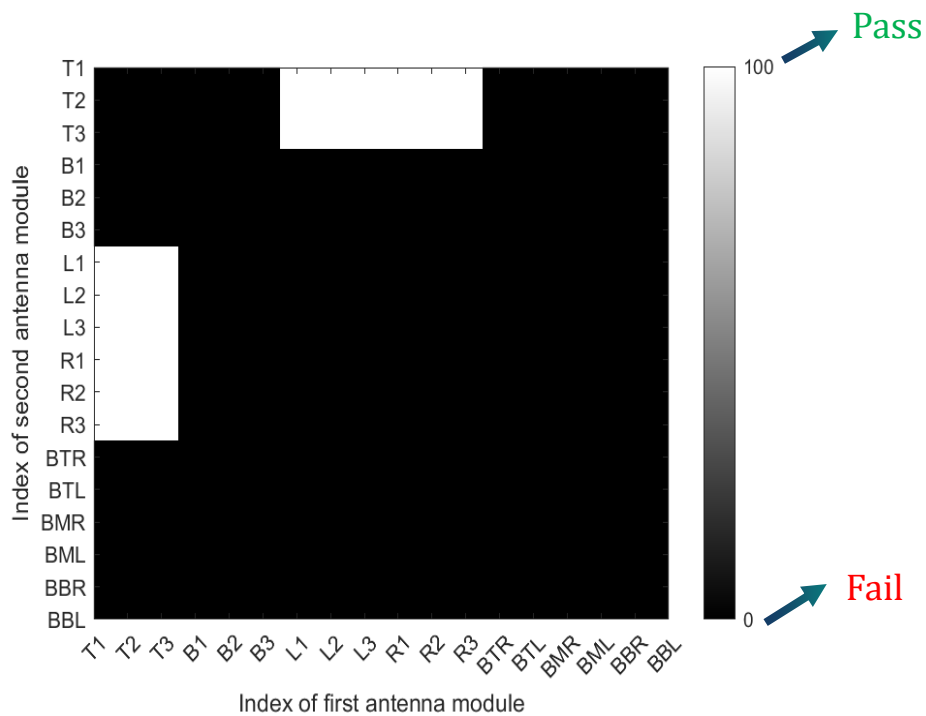


Figure 5-5: Bitmap of UE antenna module location pairs that **pass** or **fail** the outage test.

6 Concluding Remarks

This study considered antenna module placement as an optimization problem and proposed a ML framework to address this issue to enhance the robustness of performance with hand/body blockage. From an innovation perspective, by incorporating disparate data points such as priors on the angles of arrival in azimuth and zenith, path loss, UE orientation and likelihood of hand holdings/use-cases, in this study, we could characterize good and relatively poorer antenna module placements. In this direction, this study established a systematic framework with which any antenna module placement can be quantified and captured in terms of network level KPIs of interest. Since the evolution of the millimeter wave ecosystem is an ongoing process and one of commercial importance, this study motivates the need for enhancing the capability of millimeter wave modems via optimization of antenna module placements and an enabling ecosystem of specifying network level KPI requirements that could assist with the migration/enhancement of capability features of these modems. In particular, this work proposed a test methodology for admittance of good UE designs into the network to capture their on-field performance instead of only capturing their performance in a lab environment.

All this said, it is important to note the caveat that this study has incorporated priors on different design components (e.g., AoA/ZoA, UE orientation, etc.) in a certain way. As millimeter wave deployments are expected to mature with time, there is likely to be a better understanding of these design components that may bring into question the conclusions made in this study. In that scenario, the proposed ML framework in itself is still a valid and useful tool with the appropriate replacement of the different distributions used in this study with more refined estimates. Addition of further components to the ML framework to better capture practical deployments would be a worthy initiative to pursue in this context. In particular, the proposed approach can be further generalized to indoor deployments, across bands (e.g., 28, 39 and 60 GHz), with incorporation of beam management considerations such as latencies in beam acquisition, power and thermal considerations, fading, etc.

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Appendix A: Hand Holding Grips Representative of Usage Modes

We consider five different hand holding grips in Portrait mode (as described below). For example, Type 1 grip consists of one hand holding the UE with thumb on one long edge and other fingers of the same hand holding the other long edge. In this hand holding grip, blockage is induced by the hand on the left and right long edges in the middle and bottom partitions. Blockage is also seen in the back face along Back middle left, Back middle right, Back bottom left and Back bottom right partitions.

Hand holding position	Description	Which parts of the UE are blocked?
Portrait use-case 1	Case 1: One hand holding phone with thumb on one side and other fingers on the other side; Case 2: One hand holding phone on both sides with other hand operating the phone	Blockage in Left middle, Right middle, Left bottom and Right bottom Blockage also seen in Back middle left, Back middle right, Back bottom left and Back bottom right
Portrait use-case 2	Symmetric holding: One hand holding phone on one side with other hand operating the phone	Blockage in Left middle, Left Bottom, Back bottom left and Back bottom right
Portrait use-case 3		Blockage in Right middle, Right bottom, Back bottom left and Back bottom right
Portrait use-case 4	Symmetric holding: Both hands holding phone with only a few fingers blocking either side	Blockage in Left middle, Right top, Back bottom left, Back bottom right and Back middle left
Portrait use-case 5		Blockage in Right middle, Left top, Back bottom left, Back bottom right and Back middle right
Landscape use-case 1	Both hands holding phone with air gaps between fingers on both sides	Blockage in Top left, Top right, Bottom left, Bottom right, Back top left, Back top right, Back bottom left and Back bottom right
Landscape use-case 2	Symmetric holding: One hand holding phone with air gaps on that side	Blockage in Bottom left, Bottom right, Left bottom, Right bottom, Back bottom left and Back bottom right
Landscape use-case 3		Blockage in Top left, Top right, Left top, Right top, Back top left and Back top right

Landscape use-case 4	Case 1: One hand holding phone with no air gaps on that side;	Blockage in Bottom left, Bottom middle, Bottom right, Left bottom, Right bottom, Back bottom left and Back bottom right
Landscape use-case 5	Case 2: Both hands holding phone with air gaps between fingers on only one side	Blockage in Top left, Top middle, Top right, Left top, Right top, Back top left and Back top right
Landscape use-case 6	Both hands holding phone with tight grip on both sides	Blockage in Top left, Top middle, Top right, Bottom left, Bottom middle, Bottom right, Back top left, Back top right, Back bottom left and Back bottom right
Landscape use-case 7	Symmetric holding: A few fingers holding phone in the center of one of the long edges	Blockage in Left middle and Back middle left
Landscape use-case 8		Blockage in Right middle and Back middle right
Miscellaneous use-case 1	UE lying on a table	Blockage in Back top left, Back top right, Back middle left, Back middle right, Back bottom left and Back bottom right
Miscellaneous use-case 2	UE placed on a table upside down	Essentially Freespace in performance
Miscellaneous use-case 3	UE with a credit card holder/pop stick on the back face	Blockage in Back bottom left, Back bottom right, Back middle left and Back middle right



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