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Modeling User’s Body Effects on 5G Millimeter-Wave Cellphone Antenna Array

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Abstract—5G millimeter-wave (mmW) wireless communication is an important study hotspot in recent years. Human blockage has been a part of multipath radio channels, and its extra losses to received powers of wireless links are modeled in different works. This manuscript aims at establishing an analytically tractable and hence fast way to estimate user body effects on radiations of cellphone antennas at mmW frequencies. Mathematical operators are first defined to represent the user-body effects on cellphone antenna radiation where shadowing and backscattering are modeled through knife-edge diffraction and geometrical optics. Next, the proposed operators are tested for a cellphone antenna array which is held in landscape and portrait modes. Agreement of radiation pattern cuts and spherical coverage statistics is observed between full-wave simulations with complex human body models and our proposed mathematical operators. Finally, compared with full-wave simulations, the proposed model has a clear computational advantage in predicting user body effects on cellphone radiations without the need for a complex human body model, while maintaining a decent level of accuracy. The proposed operators, therefore, contribute to expediting the calculation of antenna-body interaction in mmW cellphone-communication channel simulations.

Index Terms—Cellphone antenna array, millimeter-wave, user-effect modeling, mathematical model, channel simulations.

I. INTRODUCTION

MILLIMETER-WAVE (mmW) wireless communication is a significant research highlight in recent years. When studying radio links of mmW bands, ensuring robust connectivity in dynamic electromagnetic scenarios is a key issue. Human blockage is an influential part of the wireless communication environment that affects mmW connectivity. There are studies on this issue, including loss models [1]–[12] and relevant measurements [4], [5], [10], [13]–[16]. In these studies, the human blockage is a part of the radio environment and hence multipath propagation channel, where theories of diffraction are used to model the additional losses to the received power. When a human is the user of a cellphone, researchers generally consider their effects as a part of antennas. The effects have been evaluated in [17]–[25] because they are also essential for link connectivity studies. However, the evaluations are through measurements of a cellphone prototype or electromagnetic simulations including the full human body, which are laborious and time-consuming due to the electrically-large human body at mmW frequencies. A faster way to predict the radiation patterns of a cellphone antenna array in the presence of a user would therefore be useful. This paper develops an analytical model to evaluate the body effects of a cellphone user on cellphone antenna radiation. The model is formulated as mathematical operators applied to radiation patterns of a cellphone antenna array, held in users’ hands, such that radiation patterns of a cellphone antenna array with the presence of the entire body of a user are obtained. Required inputs to the operator are the dimensions of a referential human body along with the phone orientation, with which the shadowing and backscattering effects on the radiation of a cellphone array due to the user body are calculated. No complex body model, let alone dimension measurements of a body are required in defining the operator, allowing us to predict the user body effects more accurately than the present state-of-the-art in [26] where the self-blockage model in Section 7.6.4.1 adopts binary attenuation levels. The efficacy of the operator has been verified against full-wave simulations using a complex user body model, which were verified against measurements in our previous paper [19], [21]. The innovations reported in this paper are summarized as follows.

1) Showing that the absorbing knife-edge diffraction (KED), which is traditionally used to model user’s body effects on the Fraunhofer region of wave propagation, can be used to predict shadowed region of the radiation patterns of the cellphone antenna due to a user body in the Fresnel region;

2) Applying the geometrical optics (GO) to a simple human body structural model, consisting of cylinder and spheres, to model user backscattering effects on the lit region of the radiation patterns of the cellphone antenna;

3) Verifying correctness of the mathematical operators to describe shadowing and backscattering of radiated fields from a cellphone antenna array; the fields with the user’s body effects are compared to the ground truth of complex full-wave simulations, showing that realistic user’s body effects can be considered in radio link and system simulations with much less computational efforts than full-wave simulations.

It must be noted that the mathematical operator does not cover the influence of cellphone user’s hands on the radiation of cellphone antennas. Different from body effects, hands modify current distributions and near-fields of antennas, which are too complex phenomena to model analytically. The operator, therefore, needs radiation patterns of a cellphone with the
influence of user hands as inputs, or it needs radiation patterns of a cellphone in free space when there is no hand effect.

The rest of the paper is arranged as follows: Section II introduces the principles of modeling user’s body effects on radiation patterns, and then shows the mathematical operators to model user body effects. The evaluation metric, i.e., spherical coverage, is introduced. After introducing the user hand models to define inputs to the operator, section III compares radiated fields calculated with the referential complex numerical human model and with the proposed operator. Time costs of the calculation are given. Finally, conclusions are summarized in section IV, followed by Appendix illustrating some essential mathematical formulas to understand the proposed mathematical operator.

II. MODELING BODY EFFECTS ON ANTENNA RADIATION PATTERNS

In this section, we bring in an operator to represent user body effects on radiations of cellphone antennas. Then, a metric to compare body-influenced radiation patterns is illustrated.

A. Definition of the Operator Representing the User Body Effects

Radiation patterns of a cellphone antenna with the user’s whole body effect are related to those with only hand effects by

\[ G_{\text{body}}(\Omega, f) = F_{\text{body}}(\Omega, f)G_0(\Omega, f), \]  

(1)

where \( F_{\text{body}}(\Omega, f) \) is an operating function representing user body effects at a spatial angle \( \Omega = [\theta, \phi] \) over a sphere and at a frequency \( f \); \( G_{\text{body}}(\Omega, f) \) indicates an antenna’s realized gain with user’s whole body effects and \( G_0(\Omega, f) \) indicates an antenna’s realized gain with user’s hand effects. For brevity, we omit \( f \) in the following since we discuss antenna gains at a specific frequency \( f_0 \). This work aims to derive \( F_{\text{body}}(\Omega) \) analytically.

B. From Full-Wave Simulations to Analytical Calculations

When using full-wave simulations to solve the user’s head and torso effects on cellphone antenna radiation, cylinder-like structures have been popularly used to represent user [19], [20]. They showed an excellent agreement of radiated fields with empirical statistics at 5G mmW frequencies. Following them, we use cylinders and spheres to represent the human body. At mmW frequencies, it is sufficient to study skin effects instead of including internal structures of a human [19], [27] since the skin depth of electromagnetic fields is shallower than 2 mm for human skin. Most human bodies are electrically large in size at mmW, diffracted fields from body edges are much weaker than reflected fields in the lit region, especially where the backscattering is prevalent. When analyzing wave reflection, incident electromagnetic waves on a medium interface usually assume far fields of a plane wave source. In contrast, in our case, the incident wave on the human body are like spherical waves since the antenna source is in the user’s hands. Therefore, curvature-based GO with a spherical source is applied. In our analytical model to estimate the backscattered fields, a user body is simplified by a combination of several elliptical cylinders shown in Fig. 1. Apart from these cylinders, a semi-sphere is used to model the region above the head top. The arms are a part of the torso. The body’s dimensions are summarized in TABLE I, which are identical to later calculation of fields in the shadowed region. In addition, depths are defined for the cylindrical head, torso and legs as illustrated in Fig. 1. Given the mobile antenna location and far-field angle \( \Omega_{\text{lit}} \), the Fermat principle determines reflection points on the body [30]. Let us define \( E(\Omega) = [E_\theta(\Omega), E_\phi(\Omega)]^T \) to be a polarimetric electric field vector in the spherical coordinate system where \( ^T \) is the transpose operator. When knowing the locations of the radiating antenna source and a field observation point, we can define an operator \( F_{\text{body}}(\Omega_{\text{lit}}, d_0) \) by

\[ F_{\text{body}}(\Omega_{\text{lit}}, d_0) = \frac{\|E_\text{Ref}(\Omega_{\text{lit}}, d_0) + E_\text{inc}(\Omega_{\text{lit}}, d_0)^2\|_2^2}{\|E_\text{inc}(\Omega_{\text{lit}}, d_0)^2\|_2^2}, \]  

(2)

where \( d_0 \) is the distance between the source and field observation points; \( \|\|_2 \) is 2-norm operator. \( \Omega_{\text{lit}} \) is the solid angle corresponding to the lit region of the mobile antenna source; \( E_\text{R}(\Omega_{\text{lit}}, d_0) \) is the reflected complex electric far-field defined by

\[ E_\text{R}(\Omega_{\text{lit}}, d_0) = T_e(d_{\text{Ref}})C_{\parallel}R_C_{\perp}E_\text{inc}(\Omega_{\text{inc}}, d_{\text{IN}}), \]  

(3)
where the incident angle and distance of the reflected field on the body, $\Omega_{\text{inc}}$ and $d_{\text{IN}}$, define the reflection-point coordinates; $d_{\text{Ref}}$ is the distance between the reflection point and the field observation point; $C_{lg}$ and $C_{gl} \in \mathbb{R}^{2 \times 2}$ define field conversion matrices between global spherical coordinate system and local curvature coordinate system on the body where the reflection point is located [29], [31]; $R_1 \in \mathbb{C}^{2 \times 2}$ is the reflection coefficient matrix defined by

$$R_1 = \begin{bmatrix} \Gamma_r & 0 \\ 0 & \Gamma_v \end{bmatrix},$$  

where $\Gamma_r$ and $\Gamma_v$ are for the parallel and perpendicular polarizations on body surfaces [32], Chapter 1.8. Any incident fields at an observation location $E_{\text{inc}}(\Omega, d)$ can be written as

$$E_{\text{inc}}(\Omega, d) = \frac{\lambda_0 E_0(\Omega)}{4 \pi d} \exp \left( -j 2 \pi \frac{d}{\lambda_0} \right),$$

where $j = \sqrt{-1}$, $\lambda_0$ is the operating wavelength in free-space; $E_0(\Omega)$ represents far-field complex magnitude at a source and $d$ is the distance between the source and observation locations. Now $T_c(d_{\text{Ref}})$ in (3) can be written as

$$T_c(d_{\text{Ref}}) = \sqrt{\frac{\rho_{r,1} \rho_{r,2}}{(\rho_{r,1} + d_{\text{Ref}})(\rho_{r,2} + d_{\text{Ref}})}} \exp \left( -j 2 \pi \frac{d_{\text{Ref}}}{\lambda_0} \right),$$

where $\rho_{r,1}$ and $\rho_{r,2}$ are the principal radii of body curvature at the reflection point, which are defined in the Appendix. In (3), possible multiple reflections between user’s hands, arms and torso are neglected to simplify our model since 1) multiple-bounce rays are produced by hands, the cellphone, and forearms that are smaller than the torso, making their power contribution not as significant as those single-bounce rays from torso, and 2) every reflection leads to a larger than 3 dB loss at mmW frequencies [33]. Hence, our model only includes the line-of-sight (LOS) and the single-bounce reflected signals.

In order to derive $F_{\text{body}}(\Omega_{\text{lit}})$ which aims at representing the measured and simulated observations of $F$ defined in section II-A, we can assume that the field observation point is far enough from the body, i.e., $d_0 \to \infty$, leading to $d_{\text{Ref}} \approx d_0 \gg \rho_{r,1}$ and $\rho_{r,2}$. Now (2) yields

$$F_{\text{body}}(\Omega_{\text{lit}}) = \lim_{d_0 \to \infty} F_{\text{body}}(\Omega_{\text{lit}}, d_0)$$

$$= \frac{\|K_r C_{lg} R_l C_{gl} E_0(\Omega_{\text{inc}}) + E_0(\Omega_{\text{lit}})\|_2^2}{\|E_0(\Omega_{\text{lit}})\|_2^2},$$

where $K_r = \sqrt{\rho_{r,1} \rho_{r,2}} \exp \left( -j 2 \pi \frac{d_\Delta}{\lambda_0} \right)$, and $d_\Delta = d_{\text{IN}} + d_{\text{IN}} \cdot s$ is the extra propagation distance of the reflection path compared with the LOS path; $s$ is the unit vector of the angle $\Omega_{\text{lit}}$.

D. Shadowed Region

1) Existing Human Blockage Models in the Fraunhofer Region of Antennas: When establishing mathematical models to discuss the body effects for the shadowed region, a cylinder or an elliptical cylinder is used [1], [3] to model a human. They work in two-dimensional (2D) cases but not always for three-dimensional (3D) scenarios. Some others used a model based on conducting and insulating screens and wedges [4], [6], [34]. The other papers mainly adopted KED models to describe the shadowed region where a human body is considered as an absorbing screen, e.g., [9]. It is worth noticing that the formulas of KED assume infinitely long edges/wedges. However, it still is a good approximation also for short edges [2], [5], [9], [13], [29], [35] representing, e.g., the right and the left of the torso, leading to multiple-KED models. These KED-models evaluate human blockage effects in a plane-wave multipath channel, which are usually defined as far fields of antennas. However, in our case, mobile antennas are in user’s hands, and moreover, they illuminate the human body through spherical waves. We examine if the KED models, defined in theFraunhofer region, are applicable to the Fresnel region of radiated fields from mobile antennas in typical use cases of portrait and landscape hand grip modes.

2) The Proposed Body Effect Model in the Fresnel Region of Antennas: A user body is modeled as a combined absorbing screen shown in Fig. 2. The rear arms are a part of the torso. The parameter values of the absorbing screen are summarized in TABLE I, which are identical to those of the body model used for the lit region in the previous section. For simplicity, thighs are modeled as a part of the torso and calves are modeled as separate legs. Then, similar to the lit region, the mathematical operator $F_{\text{body}}(\Omega_{\text{shadow}}, d_0)$ is represented by

$$F_{\text{body}}(\Omega_{\text{shadow}}, d_0) = \frac{\|E_T(\Omega_{\text{shadow}}, d_0)\|_2^2}{\|E_{\text{inc}}(\Omega_{\text{shadow}}, d_0)\|_2^2},$$

where $E_T$ and $E_{\text{inc}}$ represent the transmitted and incident fields, respectively.

<table>
<thead>
<tr>
<th>TABLE I</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DIMENSIONS OF THE HUMAN MODEL</strong></td>
</tr>
<tr>
<td>Shadow Lit values [cm]</td>
</tr>
<tr>
<td>Head width ($W_h$) ✓ ✓ 14.8</td>
</tr>
<tr>
<td>Head height ($H_h$) ✓ ✓ 26.0</td>
</tr>
<tr>
<td>Head Thickness ($T_h$) ✓ ✓ 14.8</td>
</tr>
<tr>
<td>Torso width ($W_t$) ✓ ✓ 52.0</td>
</tr>
<tr>
<td>Torso height ($H_t$) ✓ ✓ 80.0</td>
</tr>
<tr>
<td>Torso Thickness ($T_t$) ✓ ✓ 25.0</td>
</tr>
<tr>
<td>Leg width ($W_l$) ✓ ✓ 15.0</td>
</tr>
<tr>
<td>Leg height ($H_l$) ✓ ✓ 69.0</td>
</tr>
<tr>
<td>Leg Thickness ($T_l$) ✓ ✓ 15.0</td>
</tr>
<tr>
<td>Semi-sphere radius ($R_s$) ✓ ✓ 7.4</td>
</tr>
</tbody>
</table>

Fig. 2. The schematic of the proposed knife-edge model of a human body for the shadowed region; coordinate origin: $O = (0, 0, 0)$.

---

Footnotes:

1. These values are taken from [32], Chapter 1.8.

2. KED models evaluate human blockage effects in a plane-wave multipath channel, which are usually defined as far fields of antennas. However, in our case, mobile antennas are in user’s hands, and moreover, they illuminate the human body through spherical waves.

3. This assumption is valid for short edges, as discussed in [2], [5], [9], [13], [29], [35], where the formulas of KED assume infinitely long edges/wedges.

4. Conducting and insulating screens and wedges are used to model absorbing screens.

5. Parameters such as head width, head height, and head thickness are given in [9].

6. In the previous section, the lit region was discussed, where the field is received from the visible part of the human body.

7. The rear arms are a part of the torso, as shown in the figure.

8. The mathematical operator for the shadowed region is derived similarly to the lit region, where $E_T$ and $E_{\text{inc}}$ represent the transmitted and incident fields, respectively.
where $\Omega_{\text{shadow}}$ is the spatial angle of antennas’ radiation patterns in the user-shadowing region; $E_{\text{Inc}}(\Omega_{\text{shadow}})$ is given in (5); $E_T(\Omega_{\text{shadow}}, d_0)$ can be obtained by the sum of diffraction fields due to $N$ knife edges, written as

$$E_T(\Omega_{\text{shadow}}, d_0) = \sum_{i=1}^{N} E_{\text{Diff},i}(\Omega_{\text{shadow}}, d_0) \exp \left( -j 2\pi \frac{\Delta d_i}{\lambda_0} \right),$$

where $\Delta d_i$ is the extra propagation distance of the $i$-th diffraction path compared with the LOS path; $E_{\text{Diff},i}(\Omega_{\text{shadow}}, d_0)$ is a diffracted field where $C_{\text{Diff},i} = C_{\Omega_{\text{shadow}}, d_0}$ is a diffracted field where $C_{\text{Diff},i} = C_{\Omega_{\text{shadow}}, d_0}$ and $S(\omega)$ correspond with cosine and sine Fresnel integrals represented by, e.g., the formula (4) in Appendix A of [9]. It must be noted that KED provides a polarization-independent diffraction coefficient. Let us denote $p_0 = [p_x, p_y, p_z]$ a coordinate on the body where a ray path launched from the mobile antenna location $p_{\text{ant}}$ to a user-shadowing angle $\Omega_{\text{shadow}}$ hits, as defined in Fig. 2; $p_{\text{lit}}$ is the field observation location. Another coordinate on a knife edge $p_{\text{diff}}$ represents a diffracted point of a path on the body. Then, we can obtain

$$\Delta d_i = \| p_{\text{diff}} - p_{\text{ant}} \|_2 - \| p_0 - p_{\text{ant}} \|_2 + \| p_{\text{diff}} - p_{\text{lit}} \|_2 - \| p_0 - p_{\text{lit}} \|_2.$$

In our model, we consider the multiple-KED model with $N = 8$, representing diffracted fields due to (1) right and left sides of the user torso, (2) top of the user head, (3) bottom of the user torso, (4) right and left sides of the user head, and (5) two inner sides of the user legs. Each diffracted path in our model has its applicable angle range. The path from the head top is considered for user-shadowing angles fulfilling $-W_h/2 \leq p_x \leq W_h/2$. While the path from the head left is applied for user-shadowing angles with $H_1 + H_3 \leq p_z \leq H_1 + H_3 + H_h$. By using (8), our analytical model of the operator $\tilde{F}_{\text{body}}(\Omega_{\text{shadow}})$ can be finally written as

$$\tilde{F}_{\text{body}}(\Omega_{\text{shadow}}) = \lim_{d_0 \to \infty} \tilde{F}_{\text{body}}(\Omega_{\text{shadow}}, d_0) = \sum_{i=1}^{N} C_{\text{Diff},i} \exp \left( -j 2\pi \frac{\Delta d_i}{\lambda_0} \right).$$

where $\tilde{F}_{\text{body}}(\Omega_{\text{shadow}})$ is an operator to obtain the absolute value; $\Delta d_i = s \cdot (p_{\text{diff}} - p_{\text{ant}}) + \| p_{\text{diff}} - p_{\text{lit}} \|_2 - \| p_0 - p_{\text{ant}} \|_2$ is the extra propagation distance when $d_0 \to \infty$ in (10); $s$ is the unit vector of the user-shadowing angle $\Omega_{\text{shadow}}$. It is worth noticing in (11) that the shadowing losses are independent of the antenna’s gains.

### E. Near-shadowed Region

We define a set $U = \{ \Omega \in [0^\circ, 180^\circ], \phi \in [0^\circ, 360^\circ] \}$ to represent angles over a sphere. Fig. 3 defines three angular regions, i.e., lit region $U_{\text{lit}}$, shadowed region $U_{\text{shadow}}$ and near-shadowed region $U_{\text{near}}$. The union $U_{\text{near}} \cup U_{\text{lit}}$ fulfills the condition that both powers of reflection and diffraction fields are similar and 10 dB weaker than the LOS field. Fig. 3. The lit, shadowed and near-shadowed regions for the mathematical operators defined from the top view of a human body.

### F. Spherical Coverage

The spherical coverage, which is an empirical statistic of the maximum gains for each angle over a sphere [19], [21], is evaluated to compare the radiation patterns from full-wave simulations and those derived from our mathematical operator. The former is the ground truth while the latter is a computationally lighter alternative. The comparison shows whether the proposed operator successfully reproduces the antenna array’s coverage performance reasonably as compared to the full-wave simulations. Pattern syntheses of a cellphone antenna array are based on equal gain combining for each polarization. CDF plots of spherical coverage are calculated to make the comparison [19], [21]. When deriving the spherical coverage statistics, 10000 solid angles are spaced uniformly over a sphere.

### III. TESTING THE MATHEMATICAL OPERATORS

In this section, numerical human models for full-wave simulations are introduced, which are employed as the ground truth to make a comparison with our proposed mathematical operators. Then, the hand models with a linear antenna array on the cellphone chassis are introduced, which serve for deriving the inputs for the operators. Finally, the performance of the operators is evaluated by comparing its outputs with full-wave simulations.

### A. Numerical Human Models

Our proposed operators, i.e., (7) and (11) for the lit and shadowed regions, are tested by two kinds of user modes, namely landscape and portrait modes, at 28 GHz radio frequency. Their numerical models are generated by open-source software, i.e., Makehuman, as shown in Fig. 4. The permittivity of human skin, $\varepsilon_r = 16.55$ and $\sigma = 25.82$ S/m [21], is used to model the whole body of humans [19], [21] due to the shallow skin depth at 28 GHz. Although the skin permittivity is not homogeneous for a real person, its influence on the radiation patterns is negligible [33]. Therefore, the skin
is modeled by homogeneous impedance boundaries in full-wave simulations. The full-wave simulation is implemented in CST Studio Suite, and the relevant setup is detailed in [18], which was verified against measurements [19].

B. Inputs for the Proposed Operators

For the lit region, $E_0$ needs to be derived as the inputs for (7), so the radiation patterns with hand effects were obtained by full-wave simulations at 28 GHz. The two-hand model and one-hand model with cellphone chassis, composing Fig. 4, are shown in Fig. 5(a) and 6(a). The antenna-hand interaction simulation is detailed [21], including experimental verification. Two four-element dual-polarized linear patch antenna arrays on the cellphone-sized copper box are excited by discrete ports as illustrated in Fig. 5(b) and 6(b). The radiation patterns of selected ports of the two antenna arrays are respectively shown in Fig. 7. There are some ripples in the radiation patterns due to reflections from palms for the two-hand model in the landscape mode while finger-shadowing effects appear in the plots for the one-hand model in the portrait mode.

C. Mathematical Operators Applied to Cellphone Modes

When using the mathematical operators, the same human skin’s permittivity at 28 GHz, $\epsilon_r = 16.55$ and $\sigma = 25.82$ S/m, is used as the full-wave simulations. The same dimensions of the human body are considered for the full-wave simulations and operators as found in TABLE I. In the following plots, the step of angles along both $\theta$ and $\phi$ is 1°.

1) Cellphone in Landscape Mode: The spacing $d_y$ between cellphone antennas and the user body along the $y$-axis is 35.0 cm. Array’s center location $O = (0, 0, 0)$ cm is 10.0 cm below the shoulder top along the $z$-axis. For the proposed operator, we define $\Omega_{\text{shadow}} \in \{\Omega|\theta \in [32\degree, 180\degree], \phi \in [40\degree, 140\degree]\}$ and the rest is the lit region $\Omega_{\text{lit}}$ in the spherical coordinate system.
We can obtain \( F_{\text{body}}(\Omega) = \frac{G_{\text{body,full}}(\Omega)}{G_{\text{hand,full}}(\Omega)} \) by full-wave simulations. Their comparison with the operators \( \tilde{F}_{\text{body}}(\Omega) \) is shown in Fig. 8. We choose Port 3 and Port 7 shown in Fig. 8(a) and (d) as examples since all the ports’ field distributions are very similar to each other. The operator reproduces the full-wave simulations with the complex human model to a large extent. The hemisphere defined in Fig. 1 reproduces the field fluctuations above the user’s head (Fig. 8(a) and (d)) as shown in Fig. 8(f) and (c). Still, discontinuities can be seen in Fig. 8(b) and (c) since the human model assumed in the operator is a combination of planar, cylindrical and spherical structures, each of which has its working angle ranges when using KED and GO. Compared with full-wave simulations, the shadowing angular width and losses are similar for two cuts at \( \theta = 50^\circ \) and \( 90^\circ \), which can be seen in Fig. 8(c). When it comes to the lit region, the reflected power levels are predicted with a less than 2 dB difference at \( \phi \) close to \( 270^\circ \) on average. A similar trend can be found in Fig. 8(f). The spherical coverage of the whole antenna array is calculated as shown in Fig. 8(g) and Fig. 8(h) by using (1) for the full-wave simulations and the proposed operator, respectively. We can find that the proposed operator has higher reflections in \( \theta \in [90^\circ, 135^\circ] \) than the full-wave simulations. This is because the operator assumes a simplified human body that has smooth curvatures, which bring about slightly higher reflection coefficients. The CDF curves in Fig. 8(i) show that their statistical characteristics have a close agreement. The difference is 0.8 dB at CDF = 0.8 level and up to 1.4 dB at CDF = 0.05 corresponding to the shadowed region.

2) Cellphone in Portrait Mode: In order to further verify the proposed operator, another user mode of portrait cellphone posture is studied. The dimensions of the user body are the same as landscape mode, shown in TABLE I. In addition, \( d_y = 30 \text{ cm} \) along \( y \)-axis, and array’s central location \((70, 0, 0) \) cm is \( 15.0 \text{ cm} \) below the shoulder top along the \( z \)-axis. It is worth noticing that Port 1-4 of the dual-polarized antenna array were shadowed by a finger in the normal direction of the antenna as shown in Fig. 6(a). For the proposed operator, we define \( \Omega_{\text{shadow}} \in \{\Omega | \theta \in [21^\circ, 180^\circ], \phi \in [40^\circ, 150^\circ]\} \) and the rest belongs to \( \Omega_{\text{lit}} \).

The full-wave simulations and the proposed operator are compared in Fig. 9. We only choose Port 3 and Port 7 to show user effects in Fig. 9(a) and (d) since all the ports’ field distributions are very similar to each other. Similar to the landscape mode, the proposed operator reproduces the full-
wave simulations to a large extent, and similar discontinuities can also be seen. The pattern cuts in Fig. 9(c) show about 3.2 dB (4.5 dB) difference in the lit region at angles, $\theta = 45^\circ (90^\circ)$ and $\phi$ close to $270^\circ$ on average, while the difference in the shadowed region is smaller. The differences are attributed to constructive and destructive interference of reflected waves from various parts of the body. The fluctuation is a stochastic process similar to small-scale channel fading of received signal strength in mobile channels. A similar trend can be found in Fig. 9(f). The statistical characteristics of antenna patterns, i.e., the spherical coverage, are therefore more important in practical link evaluation [19]. The spherical coverage of the whole antenna array is calculated for the full-wave simulations and the proposed operator as shown in Fig. 9(g) and Fig. 9(h). We can find that the proposed operator has higher reflections in $\theta \in [90^\circ, 135^\circ]$ than the full-wave simulations, similar to the landscape mode. However, the CDF curves show that their statistical characteristic has a close agreement. The major difference is around 1.0 dB at CDF = 0.2 level, corresponding to the green color region in Fig. 9(h).

3) Other Cases: After testing the two vital user modes, we also applied our proposed operator to more cases: 1) we set $d_y = 50.0$ cm and $d_x = 20.0$ cm for the landscape mode; 2) we changed the orientation of the cellphone chassis by $\pm 20^\circ$ along $\theta$ for the landscape mode; 3) we put cellphone antennas in front of a human without hand holding, emulating the case that the user holds a selfie stick for cellphones; 4) we changed operating frequency to 39 GHz for the landscape mode; 5) we applied the operator to a different size of the human model for the landscape mode. The obtained spherical coverage CDF shows a difference of less than 1.2 dB for all these cases. Because of brevity, those results are not shown here.

4) Applicability of the Mathematical Operator: The proposed operator primarily models scenarios where a user stands and uses a cellphone operating at 5G mmW frequencies. In Section III-C, we conducted tests in various conditions and found that the operator can adapt to different antenna positions and orientations. Even at higher 5G mmW frequencies, it maintains good accuracy for statistical characteristics, indicating robustness in scenarios involving a standing user using a cellphone.

However, for other human postures such as sitting, running, or answering a phone call, the operator requires modification and further testing in future studies. Regarding frequency-dependency, the shadowing part can be extended to different frequencies because the knife-edge model includes frequency-
based diffraction and has been used in many papers for human-blockage modeling [2], [5], [9], [13], [29], [35]. Nevertheless, the backscattering part of the model exhibits frequency dependency, considering it includes only the first bounce of reflection and the high-frequency assumption nature of GO. As discussed in Section II-C, high-order reflections at 5G mmWs are usually negligible due to human skin properties. However, when these reflections become significant, the operator’s accuracy decreases. Additionally, the operator assumes the user is within the Fresnel region of the cellphone antenna array; it may not be effective if the user is within the reactive near-field region.

5) Impacts of Human Body Dimensions: To assess the impact of input human dimensions on the statistical characteristics of human-affected antenna patterns, we employ the landscape mode model to calculate the CDF of spherical coverage. We keep the input human sizes unchanged shown in the TABLE I, except for the torso width ($W_t$) and head width ($W_h$). Then, we can obtain the CDF curves depicted in Fig. 10. It can be seen that the maximum difference 0.3 dB happens at CDF = 0.3 level when $W_h$ is from 14 cm to 16 cm. In addition, the $W_t$ mainly influences the CDF $\approx 0.1$ and $\approx 0.8$ level. When it changes from 46 cm to 54 cm, the major difference is around 1.7 dB at CDF = 0.07. Hence, we conclude that a roughly realistic representation of human dimensions suffices when our emphasis lies solely on the statistical characteristics of human effects on 5G mmW mobile antennas.

![CDF curves](image)

Fig. 10. (a) CDF of spherical coverage for different torso widths ($W_t$); (b) CDF of spherical coverage for different head widths ($W_h$).

D. Comparisons of Computational Load

TABLE II compares a computational load for full-wave simulations and our proposed operators at 28 GHz. The operating computer’s CPU is Intel Xeon(R) E3-1230 and the RAM is 16 GB. The inputs are antenna radiation patterns with hand effects for our testing cases, which were derived from full-wave simulations. Calculation of the inputs took 380 minutes on our operating computer. The table shows that the proposed operator can save much time when reproducing body effects on antenna radiations.

<table>
<thead>
<tr>
<th>Input information</th>
<th>Proposed model</th>
<th>Full-wave simulations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Antenna patterns</td>
<td>1) Antenna patterns</td>
<td>1) Antenna patterns</td>
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<tr>
<td>2) User dimensions</td>
<td>2) Three-dimensional human model</td>
<td>2) Derivation of body effects [380]</td>
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<tr>
<td>3) Phone orientation</td>
<td>2) Derivation of body effects [0.6]</td>
<td>2) Derivation of body effects [2100]</td>
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</tbody>
</table>

IV. Conclusion

This manuscript proposes an approach to model user body effects on radiations of cellphone antennas in the 5G mmW band. By implementing full-wave simulations, the antenna gains with hand effects are obtained as inputs for our proposed operators, consisting of KED and GO. Comparisons between the proposed operator and the full-wave simulations with referential complex human models show a good agreement for the statistical characteristic of spherical coverage and cuts of radiation patterns, meaning that the statistical characteristic of the 5G mmW radio channels for the user body effects is modeled properly. They indicate that 1) the KED model, defined in the Fraunhofer region, is applicable to the Fresnel region of radiated fields from mobile antennas in typical use cases; 2) GO can reproduce the statistical characteristic of antenna array’s radiations to a large extent; 3) the proposed model has a clear advantage in deriving user effects on mmW cellphone communications. It can be used in simulations of indoor and outdoor mmW cellphone communication channels. Even when lacking practical human models, the proposed operator allows us to predict the antenna array’s statistical characteristics within a reduced time.

APPENDIX

Here the mathematical and physical principles for reflection rays on arbitrary curvatures are summarized.

Spherical-wave reflection on a curvature is described in Fig. 11. For an incident spherical wavefront, $\rho_{r,1}$ and $\rho_{r,2}$ can be obtained by

$$\frac{1}{\rho_{r,1}} = \frac{1}{s_1} + \frac{1}{f_1},$$  (12)

and

$$\frac{1}{\rho_{r,2}} = \frac{1}{s_1} + \frac{1}{f_2},$$  (13)
where \( s_i \) is the travel distance of the incident wave from the source to reflection point \( Q_i \); \( f_{1,2} \) can be written as

\[
 f_{1,2} = \frac{1}{\cos \theta_1} \left[ \sin^2 \theta_2 \frac{a_1}{a_2} + \sin^2 \theta_1 \frac{a_2}{a_1} \right] \pm \sqrt{\frac{1}{\cos^2 \theta_1} \left[ \sin^2 \theta_2 \frac{a_1}{a_2} + \sin^2 \theta_1 \frac{a_2}{a_1} \right]^2 - \frac{4}{a_1 a_2}}, \tag{14}
\]

where the plus sign corresponds to \( f_1 \) and the minus sign to \( f_2 \): \( \theta_1 = \cos^{-1} (-s_1 \cdot \mathbf{U}_1) \) and \( \theta_2 = \cos^{-1} (-s_1 \cdot \mathbf{U}_2) \) where \( s_i \) is the unit vector of incident direction; \( \mathbf{U}_1 \) and \( \mathbf{U}_2 \) are the orthogonal unit vector on the reflection plane and \( \mathbf{n}_0 = 0, i = 1, 2 \); \( \mathbf{n}_0 \) is the normal vector of the curvature at \( Q_i \); \( a_1 \) and \( a_2 \) are the curvature radii at \( Q_i \). For an elliptic cylinder for backscattering field calculation due to a body, the coordinate of any points on the surface can be represented by \([a \cos \phi, b \sin \phi, z]\). Therefore, \( a_1 = +\infty \) and \( a_2 = a^2 b^2 \left( \frac{\cos \phi}{a} + \frac{\sin \phi}{b} \right)^2 \). Therefore, \( a_1 = a \sin \theta \) and \( a_2 = a^2 b^2 \left( \frac{\sin^2 \theta}{a} + \frac{\cos^2 \theta}{b} \right)^2 \).

Fig. 11. The schematic of the spherical-wave reflection at a curvature

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