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# Self-user shadowing effects of millimeter-wave mobile phone antennas in a browsing mode

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**Abstract**—In this paper a simulation method for estimating the shadowing effect of a human at millimeter-wave frequencies is presented. The shadowing effect is studied at 28 GHz and at 60 GHz for the case when a user holds a mobile phone. Both single-hand grip and two-hand grip browsing scenarios are studied with a dual-polarized mobile phone antenna. We use the integral equation method combined with a surface-impedance-based material model for the human. It is found that at 28 GHz the human body causes shadowing of up to 22 dB behind torso and head of the human, while at 60 GHz shadowing is up to 30 dB. On the other hand, in some other directions the human body effectively increases radiation by up to 5-10 dB through scattering and reflection. The novel method using a detailed human shadowing model is useful in evaluating mm-wave mobile terminal antenna performance in realistic multipath propagation environments.

**Index Terms**—Millimeter waves, mmWave, 60 GHz, 28 GHz, human shadowing.

## I. INTRODUCTION

In the new fifth generation (5G) mobile communications systems, frequencies above 6 GHz are used to exploit broader bandwidths and thus higher data-rates in the access link between the user device and the base station [1]. Especially millimeter-wave frequencies at 26 GHz in Europe and 28 GHz in the US have been set for 5G usage and the networks are in active testing phase [2]. Additionally, the WiGig (802.11ad) operating at 60 GHz is already implemented commercially for multi-gigabit wireless LAN communication. Such 802.11ad capability is found in the newest mobile processors predicting rapid increase of mmWave implementations in future handheld user devices [3].

At mm-waves, the far-field shadowing due to different objects e.g. humans, has been noted to be significant. The shadowing of a human can be modelled with simple models, e.g. with a cylinder [4]. Full-wave simulation of the whole human becomes a difficult problem as total model size can be as large as  $340\lambda \times 100\lambda \times 100\lambda$  at 60 GHz. In [5], a human shadowing model was presented at 28 GHz using finite-difference time-domain (FDTD) simulation method with human shadowing measurements. This paper presents a detailed surface-based human shadowing model usable with an integral equation (IE) solver to significantly reduce the simulation time compared to FDTD method. Thus simulation at even higher frequency of 60 GHz is feasible with a detailed human model. The accuracy of the surface-based model is verified against a volume-based FDTD model. The realistic analysis of human shadowing at 28 GHz and 60 GHz provides valuable

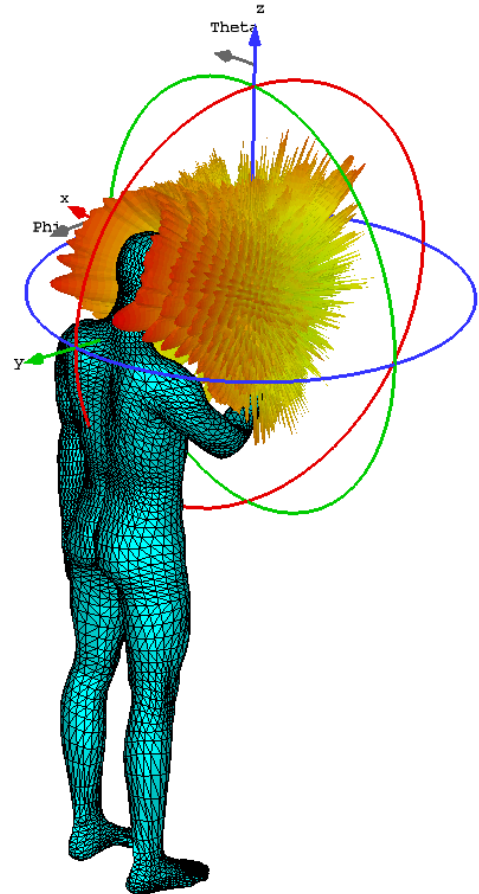


Fig. 1. Radiation pattern of a human holding a 28 GHz mobile phone antenna.

information which can be used to evaluate the mobile phone system operation under practical condition together with a radio channel model, e.g., [6].

## II. STUDY APPROACH

First, a human model was obtained for the simulations. The model was obtained from a program called MakeHuman which provides human models with realistic proportions [7]. A human male model with standard parameters and a height of 170 cm was created. The model was highly detailed with over 14000 polygons. Two cases of mobile phone use were considered, one is the most typical case when a user is holding the mobile phone in a data browsing stance with one hand in

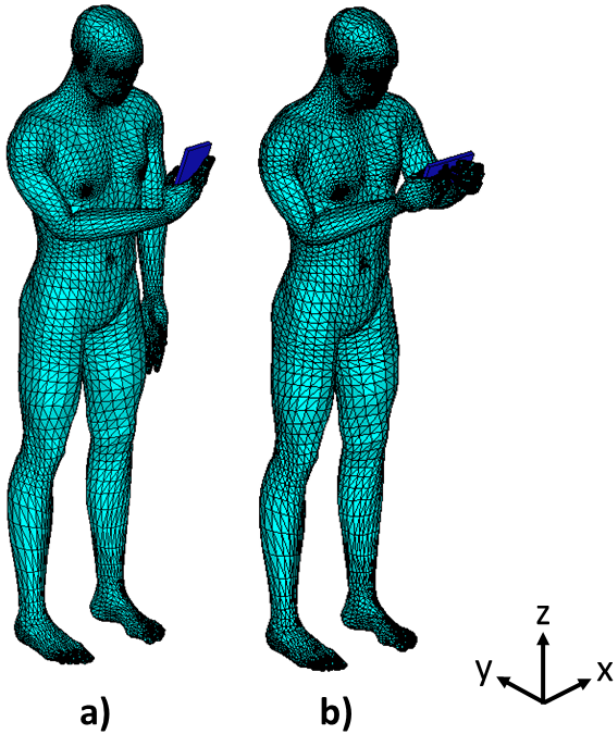


Fig. 2. The two grips for the human holding a mobile phone: a) one-hand grip where the phone is oriented vertically, b) two-hand grip where the phone is oriented horizontally.

Fig. 2a. Second is a data browsing stance with the user holding the phone with both hands in Fig. 2b, e.g. when watching a video. In both cases, the mobile phone antenna is pointing directly towards the user, leading to blockage of the radiated or received field at the antenna due to a body in front, which we call self-use shadowing.

For the mobile phone, a simple dual-polarized patch antenna placed on the top left corner of mobile phone was used. A typical mobile phone chassis size of  $150 \times 75 \times 8 \text{ mm}^3$  was selected. 0.127 mm thick Rogers 5880 substrate was used for the antenna with relative permittivity of 2.2 and metal thickness of  $17 \mu\text{m}$  for possibly straightforward and cost-effective fabrication in the future. The orientations of the mobile phone in the two antenna grips and the dimensions of the antenna elements are shown in Fig. 3 for 28 GHz and 60 GHz. The phone is placed symmetrically with the respect to the center of the head and the mobile phone is tilted  $20^\circ$  away from the z-axis in both grips as is seen in Fig. 2. When feeding ports 1 and 2, the antenna radiates mainly with vertical and horizontal polarizations respectively, given the mobile phone is oriented upright in the one-hand grip shown in Fig. 3a. When the mobile phone is oriented sideways in the two-hand grip, ports 1 and 2 respectively radiate with horizontal and vertical polarizations mainly.

Discrete ports were used for the two dual-polarized feeds seen in Figs. 3c and 3d. The mobile phone was simulated separately with a volume based mesh with FDTD simulation method and the near fields were saved as a near-field source

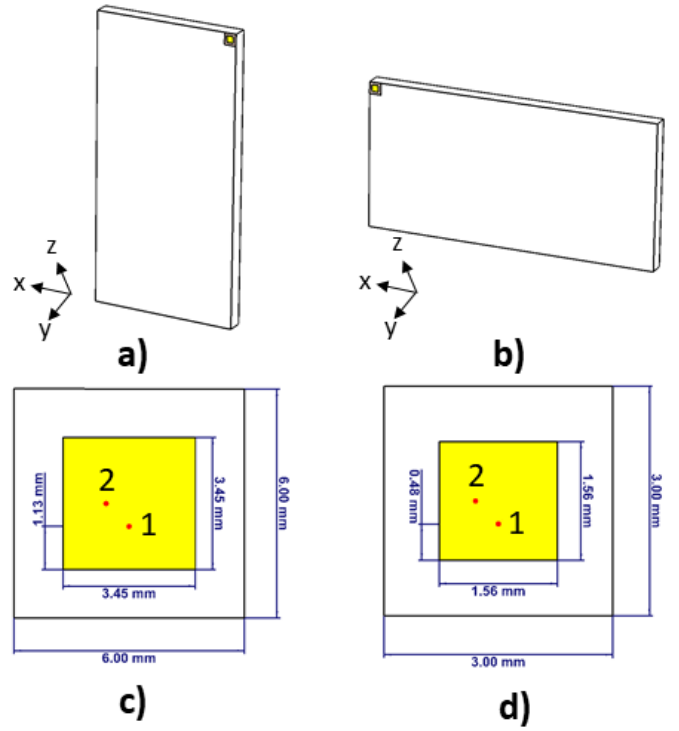


Fig. 3. Orientations and dimensions of the mobile phone antennas: a) 28 GHz mobile phone at one-hand grip, b) 28 GHz mobile phone at two-hand grip, c) 28 GHz antenna element, d) 60 GHz antenna element.

for the body scattering simulation. The reflection coefficient of the patch antenna for both polarizations were  $-18 \text{ dB}$  at 28 GHz and  $-27 \text{ dB}$  at 60 GHz. The maximum free-space gains of the antennas were 6.6 dBi for port 1 and 6.7 dBi for port 2 at 28 GHz, while they are 7.3 dBi for port 1 and 7.4 dBi for port 2 at 60 GHz.

The complete human model was too large for volume-meshing especially at 60 GHz, so a surface mesh with a surface impedance model is more preferable in terms of computational load. The human skin material parameters were considered to be  $\epsilon_r = 16.55$  and conductivity of  $\sigma = 25.82 \text{ S/m}$  at 28 GHz and  $\epsilon_r = 7.98$  and conductivity of  $\sigma = 36.38 \text{ S/m}$  at 60 GHz [8]. The skin depth of human skin is roughly 1 mm at 28 GHz and 0.5 mm at 60 GHz [8]. Therefore, it was deemed accurate enough to model only the skin of the human model.

The human body was modeled as a metal object with a coating of skin material. The surface impedance of the skin material was calculated to be  $Z_{\text{skin}} = \sqrt{\frac{i\omega\mu_0}{\sigma + i\omega\epsilon_r\epsilon_0}} \approx 71.7 + j29.8 \Omega$  at 28 GHz and  $Z_{\text{skin}} \approx 91.4 + j46.4 \Omega$  at 60 GHz.

The mobile phone antennas were placed in the hand of the human as a near-field source obtained from the separate FDTD simulation. This was because exciting the real antenna structure with the substrate material in the IE solver would have increased the simulation time greatly. CST Microwave Studio was used for both FDTD and IE simulations.

The correctness of the scattered fields derived from the surface based integral equation solver was verified by simulating

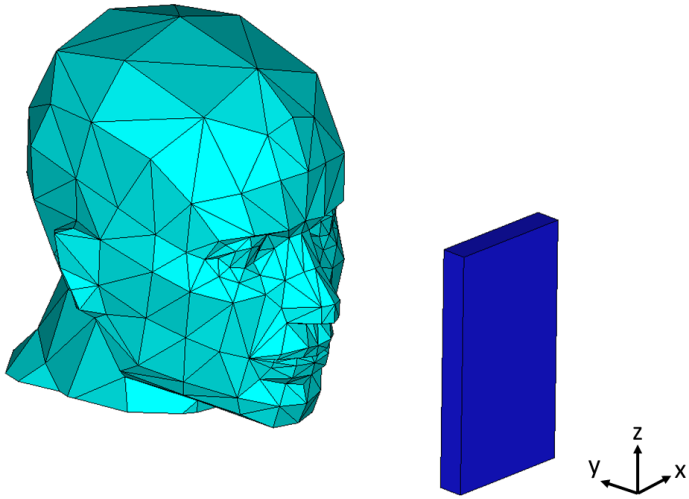


Fig. 4. The model used to verify the surface based impedance model by comparing FDTD with IE.

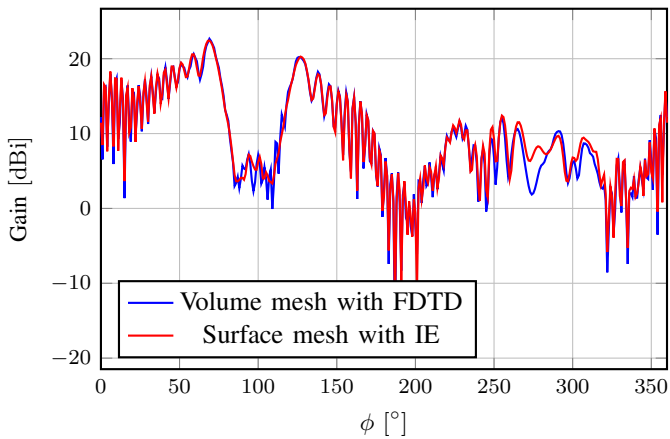


Fig. 5. Gain in the azimuth plane at 28 GHz, comparing FDTD simulation with integral equation simulation for head-only case shown in Fig. 4 for  $\theta = 90^\circ$ .

scattering of only the head of the human shown in Fig. 4. The simulation was run both with a full volume-based mesh with FDTD and with surface based mesh with IE solver. In FDTD, a dielectric solid skin material was used for the head, whereas in IE the skin surface impedance model was used. FDTD method required a mesh size of 57 million cells to achieve accurate results whereas with IE method 100000 surfaces were enough. The comparison between the methods is presented in Fig. 5 and shows a relatively good match between the methods. The surface based model works with fairly small error due to the shallow penetration depth into human skin being just 1 mm at 28 GHz [8]. The use of integral equation method reduced the simulation time from 30 minutes with FDTD to 3 minutes with IE solver in case of simulating only the head.

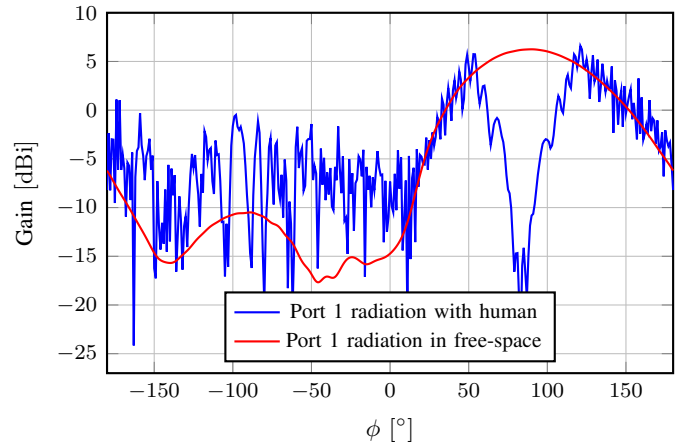


Fig. 6. Gain in azimuth plane at 28 GHz for port 1 active, with human holding the phone with one hand vs. in free-space.

### III. RESULTS

#### A. Shadowing range and magnitude at 28 GHz and 60 GHz

Figs. 6 and 7 show the gain pattern in the azimuth plane when feeding port 1 of the antennas in free space and with human holding the phone in one-hand grip. The whole human body was included in the simulation and the results are shown for 28 and 60 GHz. The maximum attenuation due to self-user shadowing is 22 and 30 dB, respectively. The self-user shadowing effects are seen for azimuth angles between  $\phi = 56^\circ$  and  $116^\circ$  at 28 GHz, and between  $62^\circ$  to  $126^\circ$  at 60 GHz.

The radiation pattern on the YZ-plane is seen in Fig. 8 at 28 GHz. On the YZ-plane, the radiation is attenuated 15 to 20 dB for polar angles  $\theta > 45^\circ$ , i.e. for the angles below the head of the user. At 60 GHz, the shadowing range is similar with attenuation level of 20 to 25 dB for angles  $\theta > 45^\circ$ .

The maximum attenuation of the far-field radiation at 60 GHz is 5 to 10 dB higher than at 28 GHz. This is likely due to reduced diffraction around the human at the higher frequency. The shadowing angular range is similar at the two frequencies with mainly the attenuation level increasing as the frequency increases.

Interestingly, the human body increases the radiation to the other directions, due to scattering and reflection on the human body. This is seen from angles  $\phi < 0^\circ$  in Fig. 6 and angles  $\theta < 0^\circ$  in Fig. 8 where the reflection increases the radiation by 5 to 10 dB.

#### B. Effect of polarization

The radiation patterns when port 1 and port 2 are active at 28 GHz are presented in Figs. 6 and 9, respectively. For horizontally polarized source of port 2, the radiation is attenuated at most 22 dB, and spans for angles from  $\phi = 54^\circ$  to  $\phi = 119^\circ$ , i.e a span of  $65^\circ$ . These are similar values as for the vertically polarized source port 1 in Fig. 6. Also, the attenuation behind the head of the user is similar for the fields created by the two feeds. There was no significant

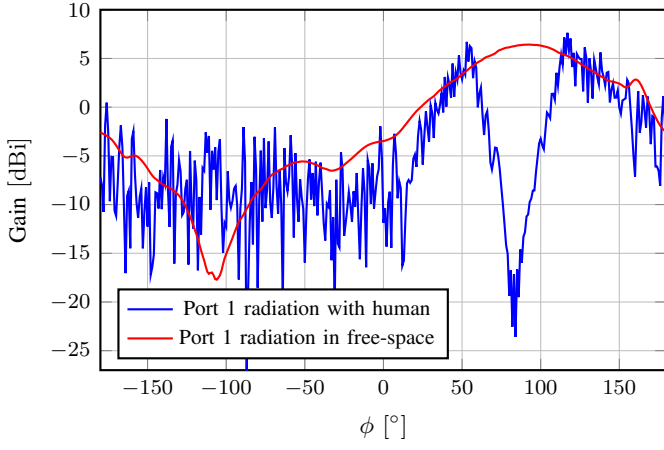


Fig. 7. Gain in azimuth plane at 60 GHz for port 1 active, with human holding the phone with one hand vs. in free-space.

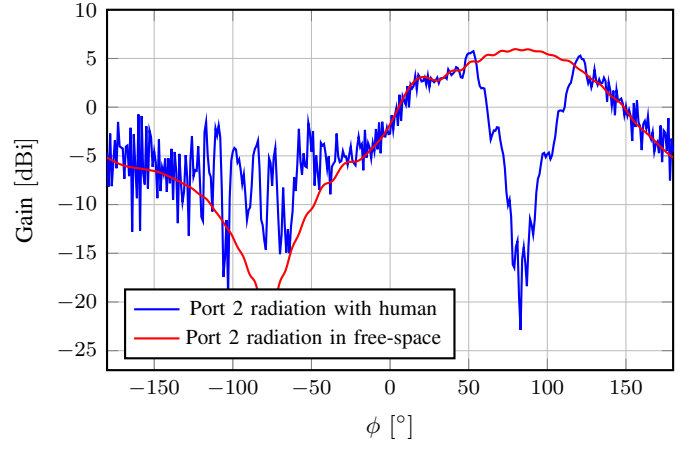


Fig. 9. Gain in azimuth plane at 28 GHz for port 2 active, with human holding the phone with one hand vs. in free-space.

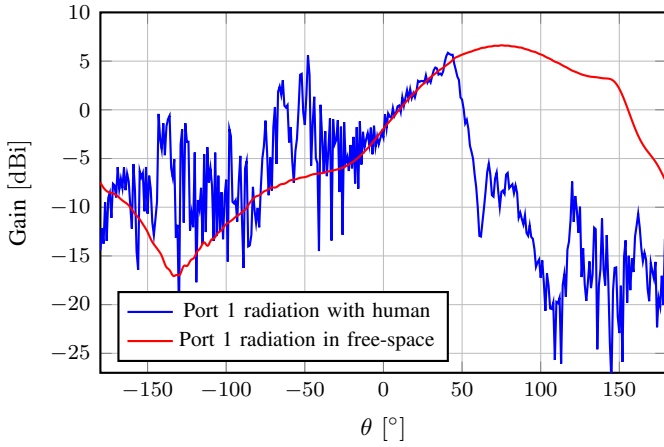


Fig. 8. Gain in YZ-plane at 28 GHz for port 1 active, with human holding the phone with one hand vs. in free-space.

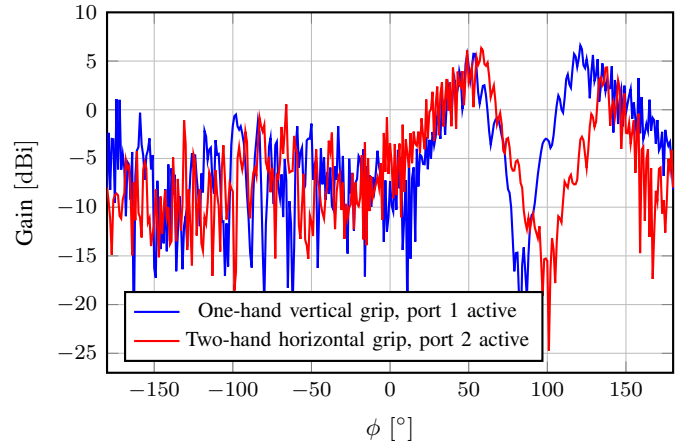


Fig. 10. Gain in azimuth plane at 28 GHz, with human holding the phone with one hand vs. with two hands.

difference of the total scattered power from the body due to the polarization of the illuminating fields.

### C. Effect of the hand grip

Figs. 10 and 11 compare the self-user shadowing effects of the two-hand grip illustrated in Fig. 2b. Port 2 is with two-hand grip and port 1 in the one-hand grip, so that the radiated polarization in the two cases is the same. With the two-hand grip, the human shadowing ranges from from  $\phi = 60^\circ$  to  $\phi = 137^\circ$  spanning a range of  $77^\circ$ . The deepest shadowing dip is shifted to the side  $20^\circ$  due to the antenna element being shifted 37.5 mm from the centerline of the human with respect to the one-hand grip in Fig. 10. The span of the shadowing is increased in the azimuth plane from  $60^\circ$  of one-hand grip to  $77^\circ$  with the two-handed grip. This is due to the antenna element being lower when it's held in the two-hand grip with respect to the body. In the lower position, the wide torso shadows more whereas in the one-hand grip the  $\theta = 90^\circ$

direction is towards the shoulders more as seen in Fig. 2.

On the YZ-plane, the radiation pattern with body scattering for the two grips is shown in Fig. 11. The radiation is increased by 9 dB towards  $\theta = 75^\circ$ . This is caused by the antenna being offset more from the centerline of the human body, leading to the increase of the radiation around the left side of the neck of the human.

## IV. DISCUSSIONS AND CONCLUSION

The human shadowing effect at 28 GHz and 60 GHz was investigated for two typical hand grips of a mobile phone. We used a new integral equation based human model for efficient calculation of the self-user shadowing effects. It was found that in a one-hand grip, the human shadows the radiation up to 22 dB for a  $60^\circ$  sector behind the human in the azimuth plane at 28 GHz. At 60 GHz, the maximum shadowing is increased to 30 dB with the shadowing sector remaining as wide.

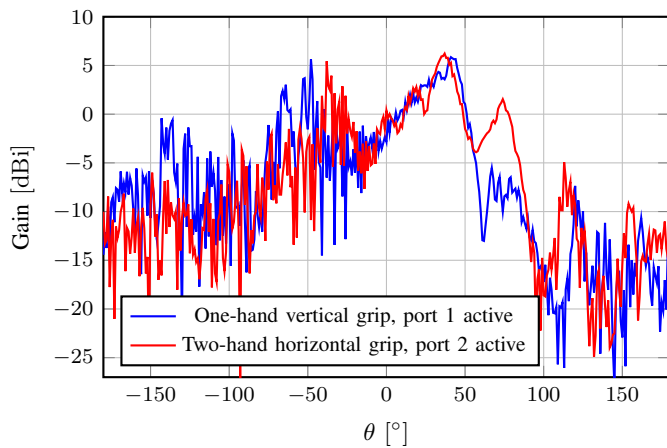


Fig. 11. Gain in YZ-plane at 28 GHz, with human holding the phone with one hand vs. with two hands.

In the elevation plane, the radiation is attenuated up to 20 dB for 28 GHz and 25 dB for 60 GHz for angles  $\theta > 45^\circ$ , i.e. behind the human. Both shadowing in the azimuth and elevation planes was similar for two orthogonal polarizations of the illuminating field created by a dual-polarized patch antenna. It is found that the total scattering power due to a human body did not depend on polarization.

When the hand grip was changed to a two-hand browsing grip, the shadowing sector increased to  $77^\circ$  behind the human. The increased shadowing range is due to the antenna being slightly lower with respect to the body when the mobile phone is held horizontally.

Interestingly, the human body increases the radiation outside the main lobe due to reflection and scattering of fields on the human body. The increase in far-field gain is up to 5 to 10 dB behind and to the sides of the mobile phone, compared to free-space case.

The method presented here is useful in evaluating the performance of mm-wave mobile phone antennas in real operational conditions. The total shadowing pattern can be used in a simulation where the user moves through a real radio channel to calculate e.g. the total array gain for the antenna which enables the comparison of antenna arrays [6].

Further work includes studying the effect of clothing on the shadowing patterns. A thin layer of clothing is expected to increase the power absorption in the skin due to acting as a impedance transformer and thus decreasing the scattering [8]. Field depolarization due to scattering is another important aspect of future study. Also, we will validate the simulation method with experimental data e.g. from measured radiation patterns of a mobile phone antenna array with self-user shadowing effects [9].

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