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# Antenna/Human Body Coupling in 5G Millimeter-Wave Bands: Do Age and Clothing Matter?

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(Invited Paper)

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**ABSTRACT** With the fast development of 5th generation (5G) mobile networks and prominence of the personal area networks and human-centered communications, people of all ages are increasingly exposed in the upper part of the microwave spectrum. In some exposure scenarios, presence of a textile between the radiating source and skin can affect the power absorption. This study investigates, for the first time, the effect of ageing and impact of textile on the power deposition in a skin-equivalent model under near-field exposure induced by multi-beam radiating structures at 26 GHz and 60 GHz. An array of four Yagi antennas has been used as a representative example of 5G reconfigurable antennas. The maximum increase of the averaged absorbed power density with respect to the averaged value for adults is observed at 70 year (8.8% at 26 GHz and 6.9% at 60 GHz). The strongest decrease is for 5-years-old children (−4.5% at 26 GHz and −3.7% at 60 GHz). In presence of a textile, the absorbed power density can increase or decrease depending on the textile properties (thickness and permittivity) and on the thickness of the air gap between textile and skin. With cotton and wool (considered as representative textile materials) the maximum increase of the averaged absorbed power density is about 40% compared to the bare skin.

**INDEX TERMS** 5G, ageing, electromagnetic dosimetry, millimeter waves (MMW), textile.

## I. INTRODUCTION

The increasing need for exchanging high amounts of data and more secured communications has resulted in the shift of operating frequencies towards millimeter waves (MMW) [1], [2]. At these frequencies, channel capacity is enhanced compared to sub-6 GHz bands, and larger bandwidths are available for high data rate communications.

Nowadays, with the wide spread of mobile devices, more and more children and seniors are exposed to radiofrequency radiation sources. At microwave frequencies, the difference in exposure levels between children and adults was investigated [3]–[5]. It was demonstrated that, up to 5.6 GHz, the whole-body-average specific absorption rate (SAR) in children can go beyond the exposure limits [6], [7] by 40%–45% whereas remaining below these limits for adults (given

the same incident field) [5], [8]. A more recent study [9] investigated the whole-body average SAR using the child models specified by the Commission on Radiological Protection (ICRP) instead of the scaled adult phantoms. In this case, the SAR increase in children was of the same order of magnitude as the numerical calculation uncertainties. At MMW, the interaction between human tissues and antennas was discussed in [10]–[13]. Refs. [10], [11] mainly focused on the antenna performance rather than on the exposure assessment. In [12], [13], a dosimetric study in presence of a radiating device is described. The age effect on exposure at MMW was analyzed in [14] considering a plane wave as source. However, age-dependent variations of the absorbed power density have never been studied for MMW antennas.

The exposure is typically assessed considering bare skin. In practice, several exposure scenarios involve the presence of textile interposed between a radiating source and skin (e.g., browsing when using gloves or making a phone call when wearing a hat). Under these conditions, the textile could act as a matching layer affecting the power absorption in the tissues [14]–[16]. The effect of clothing at MMW was previously investigated for a plane wave illumination. To the best of our knowledge, no data related to exposure to realistic sources in presence of textiles have been reported.

With the 5G of mobile networks new frequency ranges are explored. In Europe, the bands allocated for 5G are *n257* (26.5–29.5 GHz), *n258* (24.25–27.5 GHz), *n260* (37–40 GHz), and *n261* (27.5–28.35 GHz) [17]. The 60 GHz band (57–66 GHz in Europe [18]) is also identified as promising, in particular for small cells. This shift towards the upper part of the microwave spectrum impacts the antenna design for emerging wireless devices. Due to the elevated path losses at MMW, a high antenna gain is required. For this reason, directive multibeam phased arrays are increasingly used [19]–[30]. At these frequencies, end-fire antennas are usually preferred to broadside ones for user terminals [21], [27], [31], [32]. Indeed, if the antenna is positioned at the edge of a wireless device, the user shadowing affects less the antenna performance.

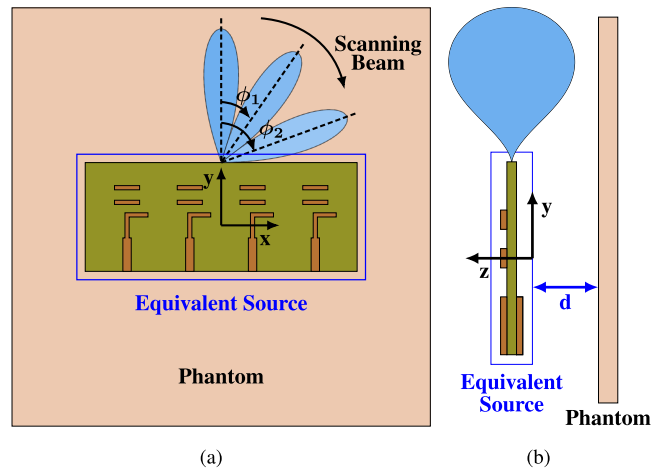
This study deals with the electromagnetic exposure under near-field conditions considering typical reconfigurable antennas at 26 GHz and 60 GHz. For the first time, the analysis is performed taking into account biological tissue permittivity variations with age and presence of a textile in proximity or in contact with skin. Since the power dissipation in the human body at 26 GHz is similar to the one in the lower part of the MMW band, in the rest of the paper we refer to this frequency as MMW for the sake of simplicity.

**II. MATERIALS AND METHODS**

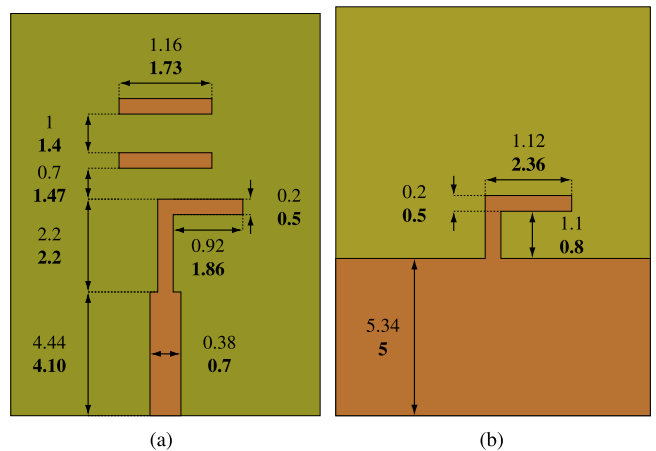
To simulate the exposure scenario of a phone call—i.e., when the phone is placed close to the head—the configuration represented in Fig. 1 was considered.

**A. GENERIC MULTIBEAM ANTENNA**

Two Yagi antennas with parallel polarization are considered as representative radiating structures at 26 GHz and 60 GHz. The design is inspired by recently reported antennas for 5G applications [22], [23]. The antenna topology and dimensions are reported in Fig. 2. Each radiating element is composed on the top layer by a driven element and two directors used to enhance the gain. The currents on the directors are induced by mutual coupling. These currents are almost equal in magnitude to the ones of the driven element but, according to the directors length and spacing, they introduce progressive phase shifts that reinforce the field in the directors direction. On the contrary, the truncated ground plane, acts as a reflector and impacts the front-to-back ratio without almost no modification of the antenna gain [33]. The antennas are designed on a Rogers RO4350B substrate ( $\epsilon_r = 3.48$ ,  $\tan \delta = 0.0037$ ) [34]



**FIGURE 1.** Exposure scenario: (a) front view and (b) lateral view. The dimensions are not to scale.



**FIGURE 2.** Yagi antenna geometry: (a) top and (b) bottom. The dimensions are in mm; those in bold refer to 26 GHz and the ones in regular font to 60 GHz.

with a thickness of 0.508 mm at 26 GHz and of 0.254 mm at 60 GHz. The input reflection coefficients of these two antennas are represented in Fig. 3. An array of 4 elements at each frequency is considered to further increase the gain and allow for the reorientation of the main beam. The inter-element spacing equals 5.77 mm at 26 GHz and 2.34 mm at 60 GHz. By changing the phases at the ports of the array elements, the beamsteering performance can be evaluated. Fig. 4 shows the antenna gain for linear phase shifts  $\alpha$  equal to  $0^\circ$  (beam pointing broadside),  $50^\circ$  (beam pointing at  $15^\circ$ ),  $100^\circ$  (beam pointing at  $30^\circ$ ), and  $142.5^\circ$  (beam pointing at  $45^\circ$ ).

**B. SKIN-EQUIVALENT MODEL**

As at MMW the penetration depth is mainly limited to skin, the tissue model is represented by a homogeneous planar skin layer (Fig. 1;  $6\text{ cm} \times 6\text{ cm} \times 2\text{ mm}$  at 26 GHz and  $4\text{ cm} \times 4\text{ cm} \times 1\text{ mm}$  at 60 GHz). For local near-field exposure, the planar approximation is justified by the fact that the typical radius of the body curvature exceeds by about five times

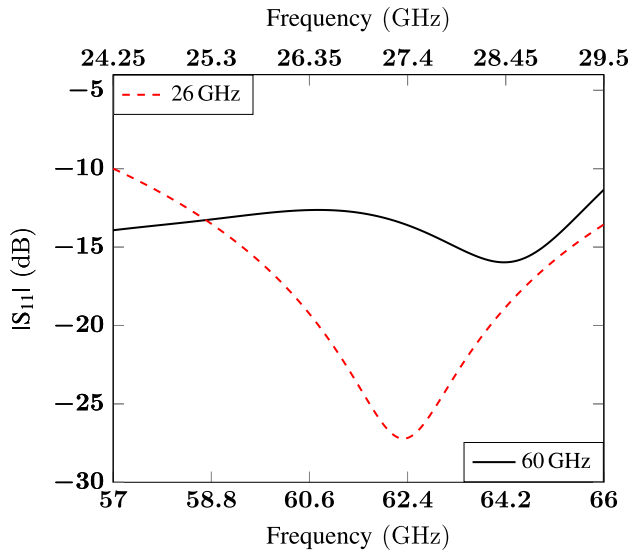


FIGURE 3. Reflection coefficients of 26 GHz and 60 GHz antennas.

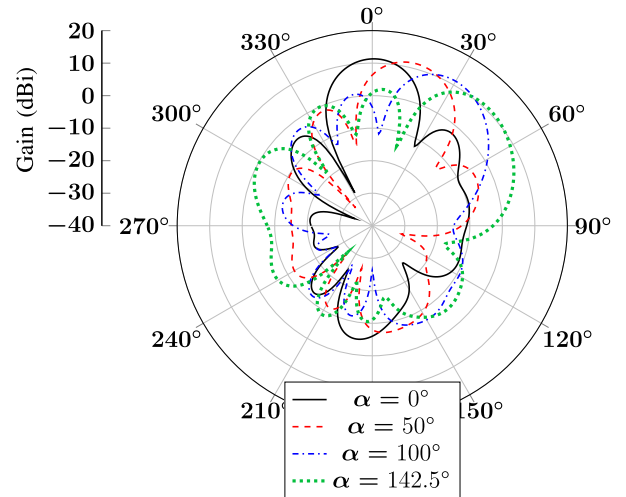
the penetration depth at these frequencies avoiding the wave interference inside the body [35]. The typical permittivity of adult dry skin is  $17.71 - j16.87$  at 26 GHz and  $7.98 - j10.90$  at 60 GHz [36]. Age-dependent permittivity model was introduced in [14] and expresses the complex permittivity of tissues as a function of the TBW, representing the ratio between the amount of water in the human body and the person weight [37], [38]. The age-dependent complex permittivity is calculated as

$$\varepsilon^* = \varepsilon'_W \frac{\alpha - \alpha_A}{1 - \alpha_A} \varepsilon'_A \frac{1 - \alpha}{1 - \alpha_A} \left( 1 - j \frac{\varepsilon''_A}{\varepsilon'_A} \right), \quad (1)$$

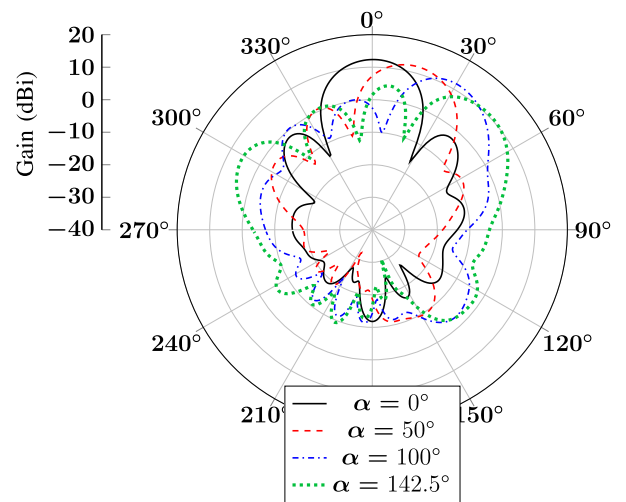
where a  $\varepsilon'_W$  is the real part of the water permittivity [39],  $\varepsilon'_A$  and  $\varepsilon''_A$  are the real and imaginary parts of the adult skin permittivity [36],  $\alpha(\text{age}) = TBW(\text{age}) \cdot \rho$  and  $\alpha_A = TBW_A \cdot \rho$ , where  $TBW(\text{age})$  and  $TBW_A$  are the TBW as a function of age and an average value for an adult [37], [38], respectively, and  $\rho = 1109 \text{ kg/m}^3$  is the skin density [40]. Cotton and wool have been considered as representative commonly used textiles. Their permittivity, measured at 60 GHz [41], is of  $2 - j0.04$  for cotton and  $1.22 - j0.036$  for wool. The permittivity of textile materials is assumed to be constant inside the frequency range considered in this study.

### C. NUMERICAL MODELLING

The exposure scenario was simulated with the time-domain solver of CST Microwave Studio using the finite integration technique (FIT). Perfectly matched layers (PML) were used as exterior boundary conditions. The antenna was simulated separately and replaced by an equivalent source in the final model to speed-up the computation. The currents flowing on this equivalent source were computed in free space on the closed box surrounding the antenna ( $27.33 \times 14.02 \times 2.93 \text{ mm}^3$  at 26 GHz and  $17.05 \times 12.36 \times 1.39 \text{ mm}^3$  at 60 GHz). The equivalent source is then placed in proximity of the phantom



(a)



(b)

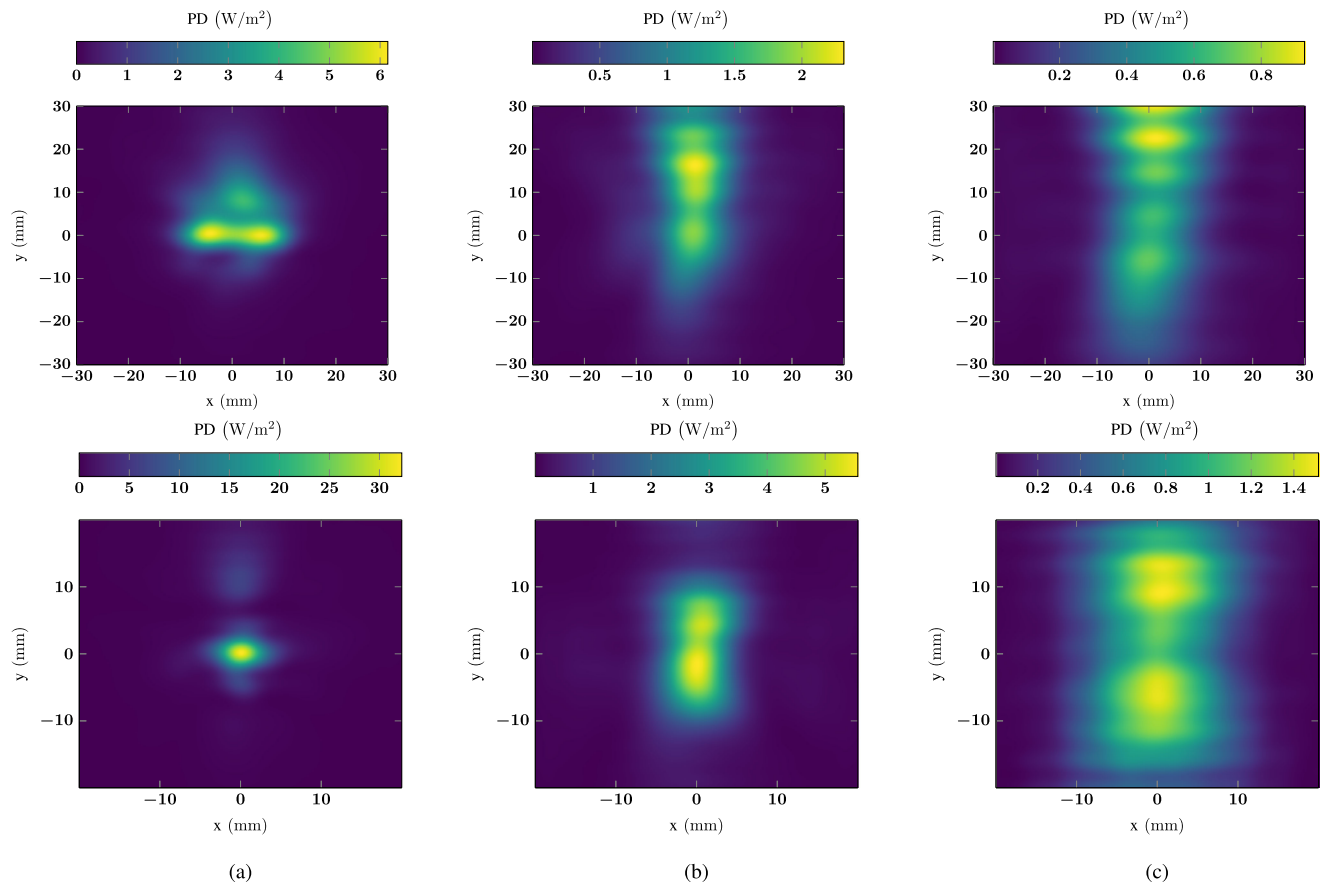
FIGURE 4. Radiation pattern (a) at 26 GHz and (b) 60 GHz for different phase shifts  $\alpha$  between the elements.

to assess the exposure. Analysis of the exposure variation due to the near-field antenna/body coupling at MMW is out of the scope of this study and was presented previously [13]. For the sake of simplicity, we will refer to the equivalent source as the antenna in the paper. The total number of mesh cells reaches about 200 000 000 at 26 GHz and 300 000 000 at 60 GHz. The smallest mesh cell dimension is  $46.5 \mu\text{m}$  at 26 GHz and  $28.6 \mu\text{m}$  at 60 GHz, respectively. It is further reduced in the z direction at the interface between skin and air/textile, and its value is set to  $2.5 \mu\text{m}$  for a total thickness of  $5 \mu\text{m}$ .

### III. RESULTS

The averaged absorbed power density is used as dosimetric quantity in the 6–300 GHz range [6], [7]. It is expressed as

$$PD_{av} = \frac{1}{A} \int_A \frac{1}{2} \text{Re} [\mathbf{E} \times \mathbf{H}^*] \cdot d\mathbf{s}, \quad (2)$$



**FIGURE 5.** PD at 26 GHz (top) and at 60 GHz (bottom) as a function of distance  $d$  between the tissue model and antenna: (a)  $d = 0.5$  cm, (b)  $d = 1.5$  cm, (c)  $d = 3$  cm.

where  $E$  and  $H$  are the electric and magnetic fields, respectively,  $A$  is the averaging area ( $A = 4\text{ cm}^4$  [6]) and  $ds$  is the normal to the surface. The perpendicular to the surface  $A$  component of the time averaged Poynting vector, hereafter referred to as local power density (PD), is expressed as

$$PD = \frac{1}{2} \text{Re} [E \times H^*] \cdot ds. \quad (3)$$

Figure 5 represents the PD distribution as a function of the distance between the antenna and the skin phantom (0.5 cm, 1.5 cm, and 3 cm) when the main beam is pointing at broadside. A distance of 0.5 cm is considered as a typical spacing between the antenna and skin representing the case of a wireless device in contact with skin (e.g., smartphone during a phone call or browsing). In simulations, the antenna input power is set to 10 mW. The distributions are nearly symmetric with respect to the  $y$  axis (the origin of the coordinate system is located in the center of the bottom edge of the source box). As expected, at  $d = 0.5$  cm the exposure is more localized at 60 GHz, and the peak value is higher compared to 26 GHz. The peak value decreases more rapidly with distance at 60 GHz, and at  $d = 3$  cm the maximal values at the two frequencies are approaching.

Figure 6 shows the PD distribution for the antenna beam pointing at  $45^\circ$  from broadside when  $d = 0.5$  cm. At  $45^\circ$ , the

exposure is less localized than at  $0^\circ$ , and the spot produced by the exposure has almost the same extension in the  $y$  direction but is double in the  $x$  one. In addition, at  $45^\circ$  the antenna side lobes contribute separately from the main beam producing some additional spots in the PD distribution.

### A. EFFECT OF AGEING

Figure 7 represents the variations of the  $PD_{av}$  in respect to the value for a 35 year old adult [36] for  $d = 0.5$  cm. The data for Yagi antennas are compared to the plane-wave illumination [14].

For all exposure conditions, the maximum  $PD_{av}$  variations are observed for seniors and are the lowest for youth with a plateau between roughly 20 and 50 year. These variations are mainly due to the fact that the water concentration of skin decreases with age resulting in a decrease of the complex permittivity. This in turn leads to a reduction of the contrast at the skin/air interface and therefore to an increase with age of the power transmission coefficient at this interface.

At 26 GHz, for a 5 year old model the variations are  $-4.5\%$  (Yagi antenna) and  $-2.8\%$  (plane wave). For a 70 year old model,  $PD_{av}$  increases by  $8.8\%$  (Yagi antenna) and  $6.4\%$  (plane wave). Note that the plane-wave approximation results in an underestimation of the  $PD_{av}$  variations. At 60 GHz, the variations are almost identical for the antennas and the plane

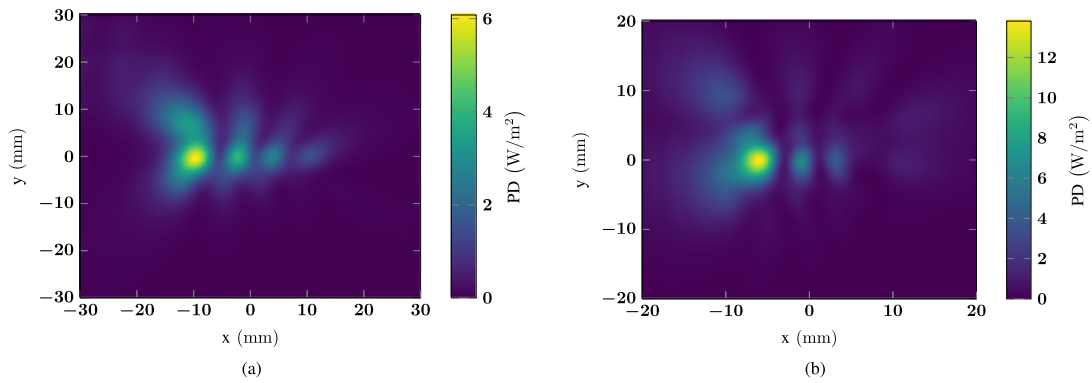


FIGURE 6. PD for  $d = 0.5\text{cm}$  and the beam pointing at  $45^\circ$  from broadside at (a) 26 GHz and (b) 60 GHz.

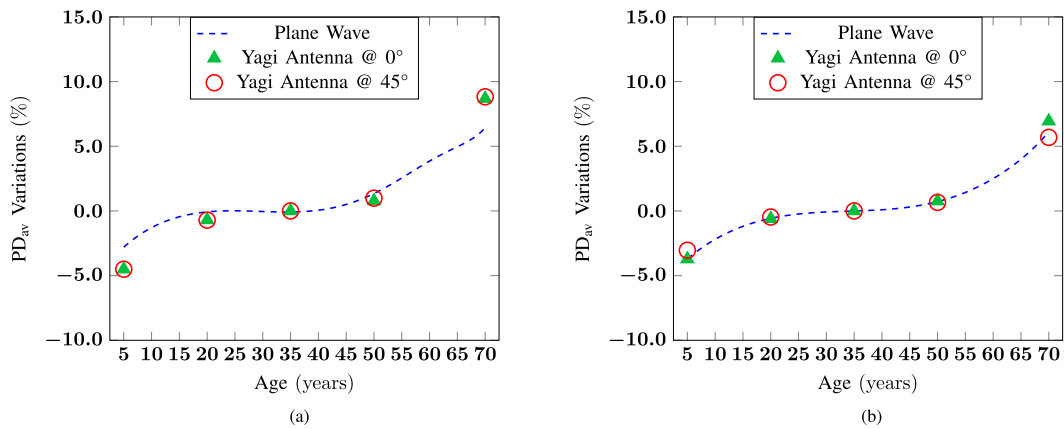


FIGURE 7. Variations of  $PD_{av}$  as a function of age with respect to the reference value at 35 year at: (a) 26 GHz, (b) 60 GHz.

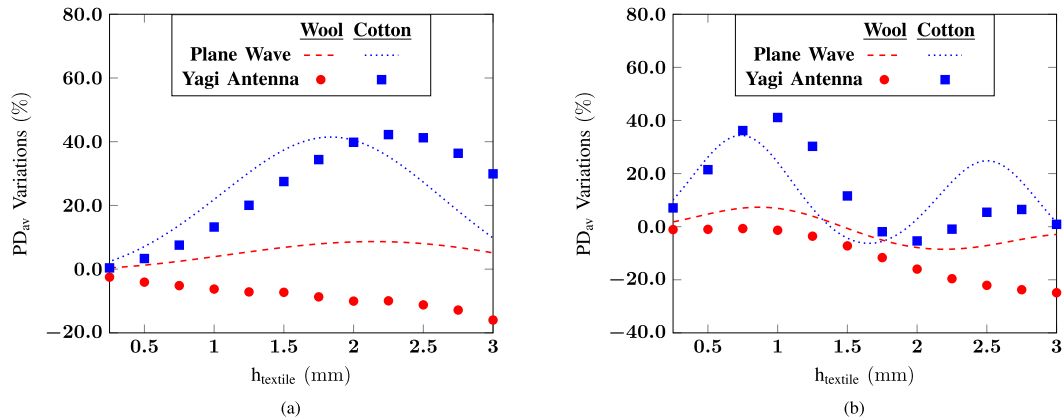


FIGURE 8. Variations of  $PD_{av}$  as a function of the textile thickness with respect to the case of bare skin, when the textile is in contact with skin at: (a) 26 GHz, (b) 60 GHz.

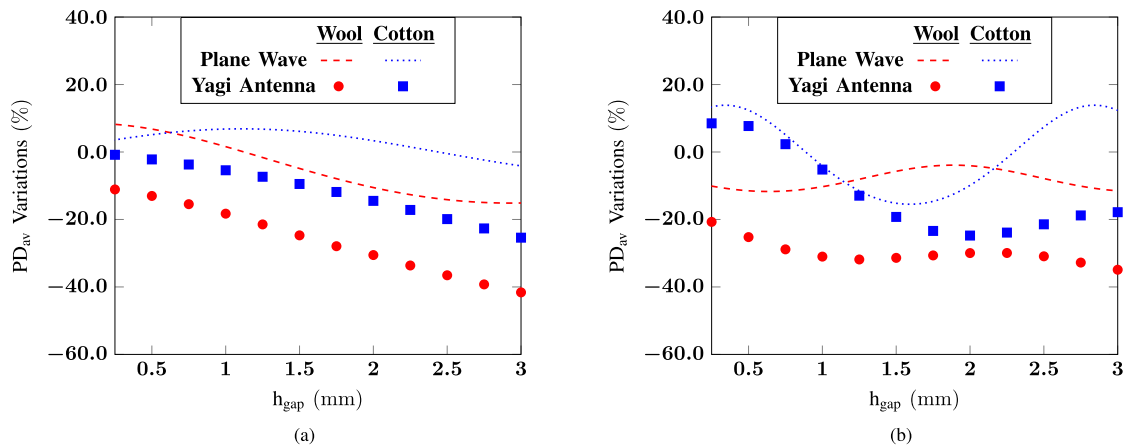
wave  $[-3\%$  to  $-4\%$  (5 year) and  $5.7\%$  to  $6.9\%$  (70 year)] Note that these  $PD_{av}$  changes are of within the typical inter-individual variations.

### B. EFFECT OF CLOTHING

*In contact with skin:* Fig. 8 represents the variations of the  $PD_{av}$  as a function of textile thickness ( $h_{\text{textile}}$ ) for the antennas pointing at broadside and at a distance of 0.5 cm. The data

are compared to the results for plane wave illumination [14]. At both frequencies, presence of a textile material modifies  $PD_{av}$ . In most of the considered scenarios (Yagi antenna/wool, plane wave/cotton, plane wave/wool)  $PD_{av}$  increases with respect to the case of bare skin, except Yagi antenna/wool scenario. The order of magnitude of variations for Yagi antennas is the same as for plane wave. However, the behavior of the curves is different. For a plane wave, the highest  $PD_{av}$





**FIGURE 9.** Variations of  $PD_{av}$  as a function of the thickness of an air gap between the textile and skin with respect to the case of bare skin at: (a) 26 GHz, (b) 60 GHz.

variations are with a 1.84 mm thick cotton layer at 26 GHz (41.5%) and 0.74 mm thick at 60 GHz (34.4%). The exposure scenario with the antenna was simulated considering a textile thickness varying from 0.25 mm to 3 mm with a step of 0.25 mm. Under these conditions, the maximal variation compared to the bare skin at 26 GHz is 42.2% (2.25 mm thick cotton). At 60 GHz, the increment of the  $PD_{av}$  is the highest for 1 mm thick cotton and corresponds to 41.1%.

*With an air gap:* To account for the presence of an air gap between the textile and skin, we added an air layer with the thickness ranging from 0.25 mm to 3 mm with a step of 0.25 mm. The antenna was placed at 0.5 mm from the textile, the main beam pointing towards broadside. The textile thickness was set to a typical value, i.e. 2 mm for wool and 0.2 mm for cotton.

Figure 9 represents the variations of the  $PD_{av}$  compared to the case of bare skin for the antenna and plane wave. At 26 GHz for both textiles,  $PD_{av}$  monotonically decreases with  $h_{gap}$  for Yagi antenna compared to the bare skin or textile in contact with skin ( $h_{gap} = 0$  mm). Note that for the plane wave exposure,  $PD_{av}$  can both increase or decrease depending on the value of  $h_{gap}$ .  $PD_{av}$  reaches the maximum at 0.05 mm (+8.57%) and 1.11 mm (+6.86%) for wool and cotton, respectively. Overall, the plane wave model results in an overestimation of the  $PD_{av}$  variations.

At 60 GHz, and for a 0.2-mm-thick cotton,  $PD_{av}$  can exceed the value for bare skin both for plane wave and antenna source cases. For the plane wave, the highest variation of 13.87% is for  $h_{gap} = 0.34$  mm or  $h_{gap} = 2.84$  mm. For the antenna, the maximal increase of 8.5% occurs for  $h_{gap} = 0.25$  mm. For the 2-mm-thick wool,  $PD_{av}$  is lower than the one for the bare skin, and the plane wave model results in a significant overestimation of the  $PD_{av}$  variations.

#### IV. DISCUSSION AND CONCLUSION

This study analyses the effect of ageing and textile on the power deposition in a skin-equivalent model due to near-field

exposure by a representative multi-beam radiating structure at 26 GHz and 60 GHz.

The  $PD_{av}$  increases with age. The highest value is observed for seniors (+8.8% at 26 GHz and +6.9% at 60 GHz with respect to the reference value at 35 year) and the lowest for youth (−4.5% at 26 GHz and −3.7% at 60 GHz) with a plateau between roughly 20 and 50 year. The plane-wave approximation results in an underestimation of the  $PD_{av}$  variations at 26 GHz. At 60 GHz, the variations are almost identical for the antennas and plane wave. These variations are within the typical interindividual differences and below the safety margins used in guidelines and standards (factor of 10 for occupational exposure and 50 for general public).

When considering the presence of a textile,  $PD_{av}$  can increase or decrease depending on the textile thickness and permittivity as well as on the thickness of the air gap between the textile and skin. For the two considered in this study textiles (i.e. cotton and wool), the maximum increase of the  $PD_{av}$  compared to the bare skin is about 40%. The use of a plane-wave model results in an overestimation of the  $PD_{av}$  variations but the order of magnitude remains the same as for near-field exposure.

Experimental validation of the numerical results would require high-resolution near-field measurements in presence of a tissue-equivalent model. Conventional methods of free-space measurement at MMW are not suited to estimate the power density on the phantom surface [42]. Use of the infrared imaging successfully employed for near-field dosimetry at MMW [43]–[45] is complicated by the presence of textiles. Adaptation of measurement techniques for validation of the numerical results constitutes one of the perspectives of this study.

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