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Numerical Modeling of Electromagnetic Field Exposure from 5G Mobile Communications at 10 GHz

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Abstract—Study on the interactions between electromagnetic fields and biological tissue at high frequency band is an important aspect in the area of wireless communications. The use of millimeter wave frequency band for fifth Generation (5G) devises involves new challenges in terms of Radio Frequency Electromagnetic Field Exposure (RF-EMF) limits and compliance assessment since the basic restrictions for limiting human exposure change from the Specific Absorption Rate (SAR) to the power density. The Electromagnetic Field Exposure to the human head has been studied based on power density by means of numerical simulation for the frequency band of 10 GHz. Study on radio frequency energy absorption has been done based on radiation from a printed monopole antenna at frequency of 10 GHz, transmitting directly towards the human head tissue model. Human head model is constructed from magnetic resonance images with frequency dependent tissue electrical properties. It is shown that at millimeter wave frequency, i.e., 10 GHz, with realistic source (20 mW) and head-source separation distance (10 mm), the amount of power density is in the range of regulatory limits and requirements on EMF exposure. The obtained results might provide valuable information for the design of 5G handheld devices and EMF compliance assessment.

1. INTRODUCTION

By moving to higher generations of mobile communications, i.e., from 1st, 2nd, 3rd, and 4th generations, and to this days 5th Generation (5G), the frequency of operation goes high too. Day-by-day, microwave and millimeter wave regions of spectrum have become considerably more available and manageable. Such high operational frequencies provide advantages in terms of information capacity and speed. The new radio technology, i.e., the 5G, is planning to put together many leading-edge aspects that not taken place yet [1–3]. This new wireless connectivity comes with a number of complexities and technical challenges that need to be addressed, and perhaps one of the key concerns is maximum radiated power and related electromagnetic filed exposure.

Significant and noteworthy volumes of studies and researches have been conducted in the past [4–11], for the 1st, 2nd, 3rd, and 4th generations of mobile communications on health effects, for the whole body and localized tissue heating. At higher frequency bands, such as millimeter wave frequency bands, works need to be done, and studies need to be performed on electromagnetic field exposure. Therefore, the aim of this paper is to investigate, by numerical simulations, the effect of electromagnetic field exposure at frequency of 10 GHz in biological tissues.

Devices emitting Radio Frequency (RF) Electromagnetic Fields (EMF) should be tested to comply with regulatory limits and requirements on EMF exposure. The limits imposed by the international organizations i.e., International Commission on Non-Ionizing Radiation Protection (ICNIRP) [12], Federal Communication Commission (FCC) [13], and IEEE [14] for the current generation of mobile and

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wireless devices are based on Specific Absorption Rate (SAR) with respect to the frequency band of use. SAR shows the amount of the radio frequency energy absorbed in the biological tissues and is expressed in W/kg. Fundamental exposure limits are changing from specific absorption rate to incident Power Density (PD W/m^2), at 10 GHz by ICNIRP, 6 GHz by FCC, and 3 GHz by the IEEE. It is because at high frequency, penetration depth is less into tissue, and energy absorption becomes closer to the surface of skin, hence, exposure over the entire body mass or over averaged 10 g of body tissue is not relevant.

The power density limits above 10 GHz were developed mainly assuming far-field conditions, due to the lack of devices intended to be used near the body in this frequency band. The suitability of these limits for mobile phones, tablets or other handheld devices operated near the body tissues therefore needs to be investigated. Because power density is measured in the free-space, without the presence of the body or a body model, it is of interest to quantify the impact on energy absorption from coupling between the antenna and the exposed body at frequency of 10 GHz.

This paper is organized as follows. A short introduction to the antenna is presented in Section 2. Section 3 presents a head model used for EMF exposure studies. Sections 4 and 5 will present results and conclusions, respectively.

2. ANTENNA

The significance and impact of antenna in the mobile networks drives millimeter wave antennas for 5G devices as one of the key elements for drawing together the 5G mobile networks. The use of millimeter wave frequencies will affect current mobile antenna configurations, along with a number of other antenna associated challenges [15].

A monopole antenna at frequency of 10 GHz with input power of 20 mW is used as a source of radiation. The proposed antenna is designed in free space and in the present of a bulk muscle tissue to avoid any mismatch that could affect the output power. The antenna characteristics in close proximity to the head tissue model are tested, to make sure that the antenna resonates at 10 GHz, as head tissue close to the antenna might affect the input impedance of antenna and hence disturb the antenna scattering parameters.

Numerical simulations were conducted using High Frequency Structure Simulator (HFSS), based on the Finite Element Method (FEM) [16]. The simulations were performed when antenna was placed at a distance of 1 cm from head tissue and radiating directly towards the human head model.

Antenna configuration and dimensions are provided in Fig. 1. The antenna is a two-layer structure, substrate and single side metalized, where radiating element and ground plane are placed on the same side. The antenna is made on an FR4-Epoxy substrate with thickness of 1.6 mm. It has relative permittivity of $\varepsilon_r = 4.4$ and dielectric loss tangent of $\tan\delta = 0.02$. The copper cladding has thickness of 0.036 mm. The antenna port is excited with 20 mW magnitude of power as an input source. The antenna overall size is $21 \times 17 \times 1.636\,\text{mm}^3$.

The return loss of antenna in close proximity to the biological tissue is presented in Fig. 2. It shows that the antenna has an impedance bandwidth of -10 dB in the frequency range of 9.7–14.2 GHz. However, our frequency band of interest is 10 GHz. The antenna is well matched to reference impedance, which is 50 Ω.

The 3D total realized gain pattern of antenna, which is the ratio of the antenna radiation intensity to the total input power to the antenna port is shown in Fig. 3. It displays that the antenna has maximum 7 dB of gain at 10 GHz.

3. HEAD MODEL

In order to realistically predict the energy absorption due to RF-EMF exposure to the human head for very short separation and at millimeter wave frequency band, accurate numerical models are needed. Many computational human body models and experimental phantoms have been used for the RF-EMF exposure assessments. In the computational assessment, the geometrical characteristics of human tissues are represented either in the form of voxels or tetrahedras that are assigned with realistic electrical

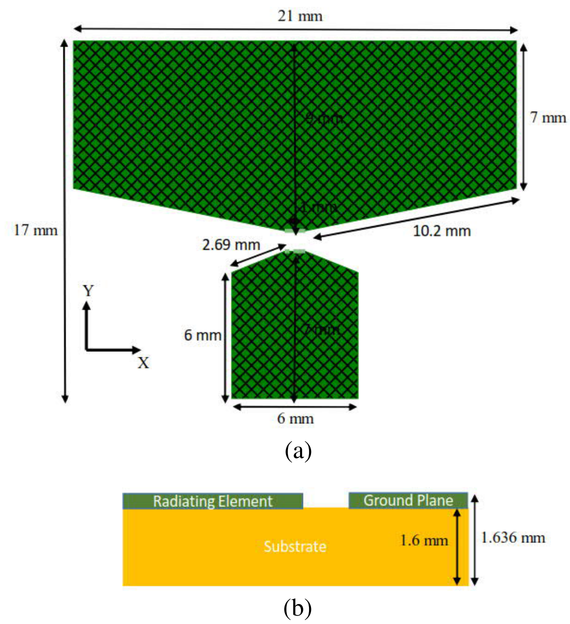

Figure 1. Antenna configuration and dimensions, (a) top view, (b) side view.

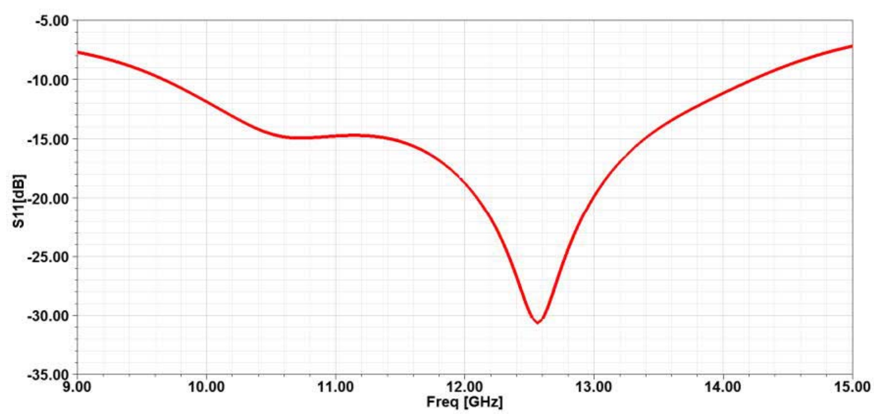

Figure 2. The antenna return loss at distance of 1 cm from head model.

properties of human tissues. Computational models can simulate the amount of RF energy transmitted to the biological tissues and provide details of the effect on tissue from deposited RF energy.

In order to achieve accurate RF field exposure studies, a realistic 3D geometry model of the human head is needed. In this study, magnetic resonance images of an adult male subject were used to construct an anatomical head model as shown in Fig. 4. The methods for constructing the head model have been described in [17]. The ethics committee of Aalto University has approved the study on the head model.

The analysis on human head tissues has been carried out using tissue material properties from [18]. Due to the shallow penetration depth of the RF field in the studied frequency band, only the surface tissues show significant power absorption. The penetration depth at 10 GHz for wet skin is 3.5 mm, while for muscle it is 3.3 mm [18]. Because of the similar dielectric characteristics of muscle and skin at this frequency and because the head skin has a thickness of approximately 2 mm, the head was modelled as a homogenous muscle tissue. Furthermore, due to the shallow penetration depth, tissues deeper than approximately 10 mm were excluded from the analysis (treated as air) to reduce the need

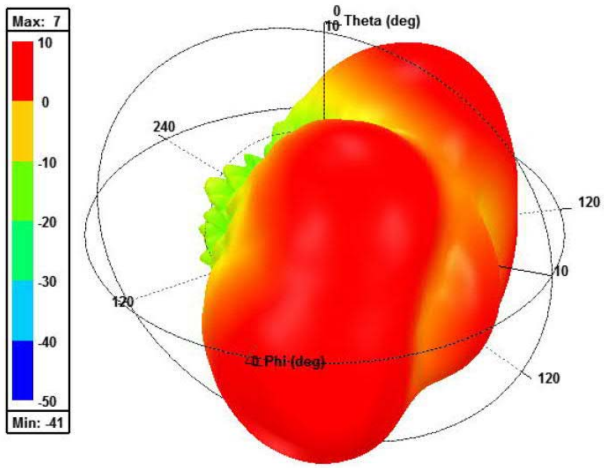

Figure 3. The 3D total realized gain pattern of antenna at 10 GHz.

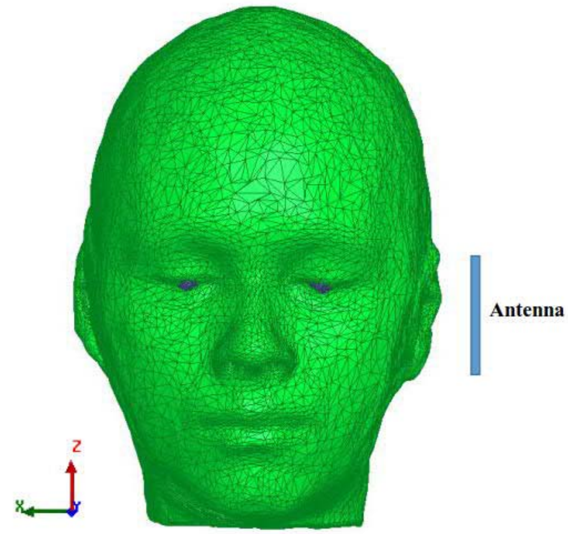

Figure 4. Head model for RF-EMF exposure studies.

for computational resources. To further decrease the required time for calculation on a computer with 128 GB RAM, the number of tetrahedras on the human head was reduce to keep the matrix size to 6×10^6.

4. RESULTS AND ANALYSIS

The millimeter wave handheld devices will be used in very close proximity to the body tissues. Hence, the 5G mobile handset will bring new challenges and issues on EMF compliance assessments. According to the FCC, if a handheld device operates at a distance closer than 5 cm from a person's body, power densities may be computed using numerical modeling techniques, e.g., Finite Different Time Domain (FDTD) or Finite Element Methods (FEM) to determine compliance [19]. In this paper, the FEM is used for numerical studies and analysis.

Millimeter wave antennas will generally have higher gain in some directions, which causes radiation energy to focus in certain directions. Fig. 5 shows antenna total radiation pattern when angle φ changes from $0°$ to $180°$.

Since the antenna is very close to the head tissue, reflection and diffraction of transmitted power could produce the constructive/destructive electric field. The amount of electric field on the surface of the head tissue with phase changes from $0°$ to $90°$ is presented in Fig. 6.

Figure 6 shows that the peak value of electric field is changed from 24.18 V/m to 27.58 V/m for phase angle between $0°$ and $90°$ with maximum amplitude at $60°$ and minimum level at $30°$.

The guidelines on EMF exposure imposed by the ICNIRP [12] specify a maximum power density of $10\,\mathrm{W/m^2}$ averaged over any $20\,\mathrm{cm^2}$ area and with the spatial maximum power density of $200\,\mathrm{W/m^2}$ averaged over any $1\,\mathrm{cm^2}$ area for the frequency range between 10 GHz and 300 GHz. The FCC [13] frequency range limits lie between 6 GHz and 100 GHz with maximum power density of $10\,\mathrm{W/m^2}$ with averaged area over any $1\,\mathrm{cm^2}$. The IEEE [14] EMF exposure limits on power density are $10\,\mathrm{W/m^2}$ in the frequency range of 3–30 GHz over averaged area of $100\lambda^2$ where λ is the free space wavelength in cm and in the frequency range of 30–100 GHz with the averaging area of $100\,\mathrm{cm^2}$.

The maximum power density in this paper is calculated based on the peak value of electric field intensity on the surface of head tissue at frequency of 10 GHz for the averaged area of $1\,\mathrm{cm^2}$. Table 1 provides comparison of power density between current study and the limits provided by ICNIRP, FCC, and the IEEE. Table 1 also shows that the maximum power density is in the range limits imposed by the international organizations.

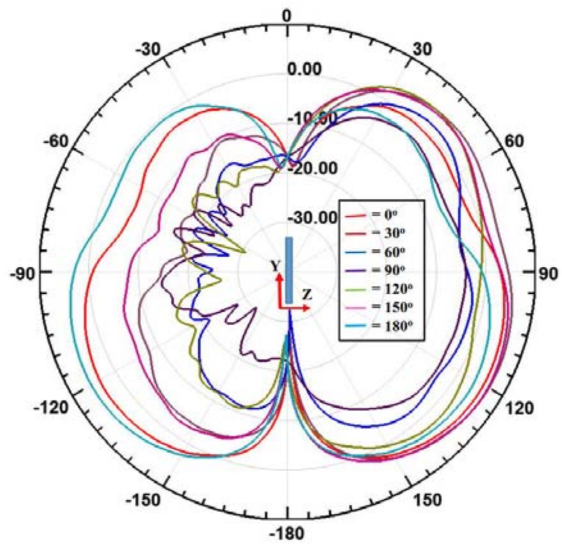

Figure 5. Antenna gain pattern for different φ angles.

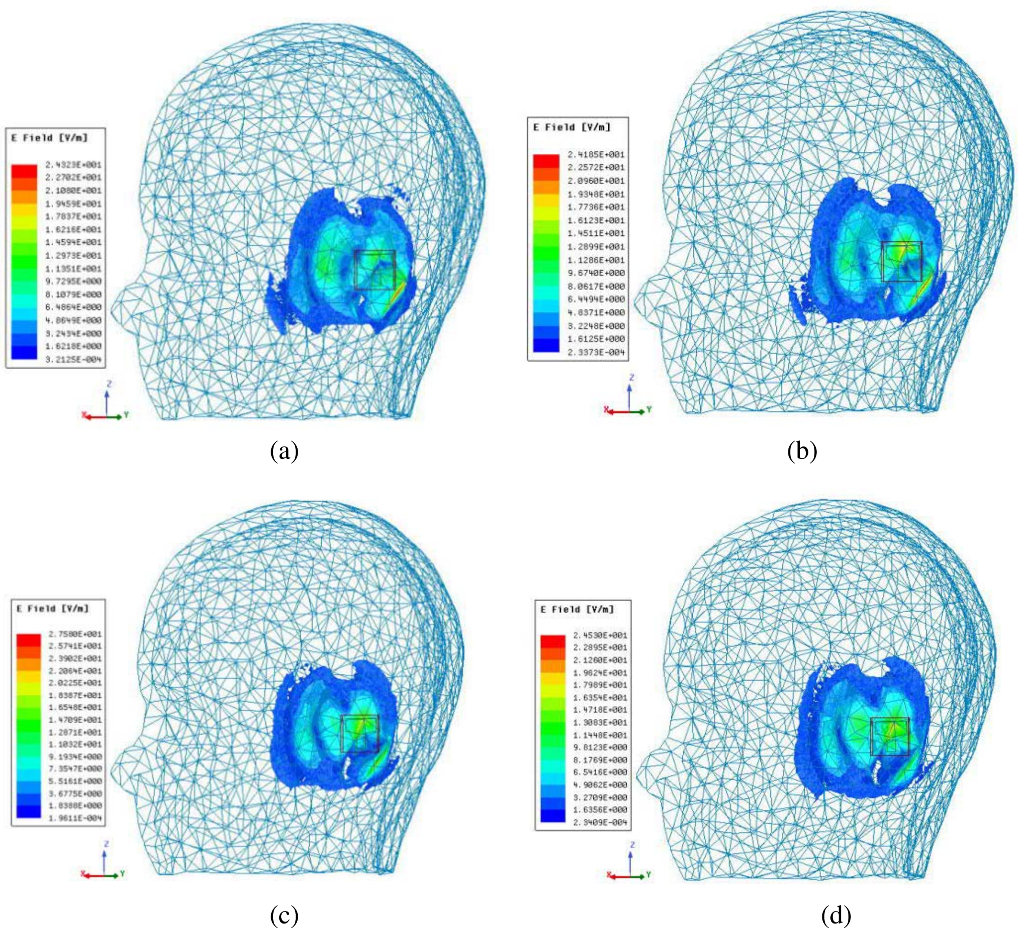

Figure 6. Electric field on the surface of head tissue at frequency of 10 GHz with different phase angle (a) phase = 0°, (b) phase = 30°, (c) phase = 60° and (d) phase = 90°.

Table 1. Comparison of maximum power density at 10 GHz between current study and limits provided by international organizations. The antenna input power for this study is 20 mW. (Av: Averaging Area).

	This Study	ICNIRP	FCC	IEEE	
f (GHz)	10	10–300	6–100	3–30	30–100
PD (W/m^2)	5.291 (Av: 1 cm^2)	10 (Av: 20 cm^2) 200 (Av: 1 cm^2)	10 (Av: 1 cm^2)	10 (Av: 100 λ^2)	10 (Av: 100 cm^2)

5. CONCLUSIONS

Radio frequency electromagnetic field absorption to the human head tissue by a monopole printed antenna was studied at frequency of 10 GHz for the 5th generation of mobile communications.

The results in this paper have been obtained for a monopole antenna with a small form factor of $21 \times 17 \times 1.636\,\text{mm}^3$. The antenna shows good impedance matching at frequency of 9.7 GHz to 14.2 GHz. It has gain of 7 dB at 10 GHz, with very compact size. Hence, it could be easily fitted in the current mobile handsets.

Different regulatory requirements with different standards will result in different restriction limits. Therefore, we considered the average area of 1 cm^2 which is common between different standards, with the limit of 10 W/m^2 of power density. Moreover, the RF-EMF was studied with respect to the power density at a distance of 1 cm from radiation source. It was shown that at frequency of 10 GHz with an antenna (input power of 20 mW) directly radiating to the head tissue, the maximum available power density is in the range limits of the ICNIRP, FCC, and the IEEE.

5G is progressing and developing fast, although the biological effects of 5G communications systems are very scarcely investigated. Using this head model and studies, the ability to process and investigate the RF-EMF exposure of 5G devices by mean of simulation could help the development of 5G. Therefore, the obtained results might provide valuable information for the design of 5G devices and EMF compliance assessment.

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