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ELECTRIC FIELD DISTRIBUTION IN THE HUMAN HEAD: COMPUTATIONAL MODELING ACROSS 1–3 GHZ FOR 5G APPLICATIONS

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Abstract

The deployment of fifth-generation (5G) mobile networks, particularly in the millimeter-wave (mmWave) band, has raised questions regarding human exposure to radiofrequency electromagnetic fields (RF-EMFs). Unlike lower frequencies, mmWave signals penetrate only 1–2 mm into tissue, leading to predominantly superficial absorption. This study investigates electric field (E-field) distribution within the human head using computational electromagnetic modeling. A simplified spherical head model with layered tissue properties was simulated across 1–3 GHz. Results showed a progressive reduction in E-field strength with increasing frequency, with localized hotspots forming near the surface, while brain tissues exhibited consistently lower intensities. These findings support the premise of superficial energy deposition but highlight limitations in current compliance metrics, which rely on averaged absorbed power density. The study underscores the need for refined dosimetric models and regulatory frameworks that account for spatial variability and localized hotspots in 5G mmWave exposures.
KEYWORDS: 5G, Concept-II, Electromagnetic wave, Electric field, Human head model,

Introduction

The rapid evolution of wireless communication technologies, particularly the deployment of fifth-generation (5G) mobile networks, has intensified research into human exposure to radio frequency electromagnetic fields (RF-EMFs). Unlike previous generations, 5G utilizes higher carrier frequencies, including sub-6 gigahertz (GHz) and millimeter-wave (mmWave) bands, which interact with biological tissues differently than lower frequencies (Akyildiz et al., 2015; Ashraf et al., 2024). At frequencies between 1 and 3 GHz, electromagnetic waves can penetrate the superficial layers of the human head, raising concerns about localized absorption and potential health effects (Stanković et al., 2015). Current safety metrics, such as the Specific Absorption Rate (SAR), may not adequately capture localized “hot spots” of absorption, particularly in complex anatomical regions like the ear and eye socket.

Computational electromagnetic (CEM) modeling provides a powerful approach for analyzing electric field (E-field) distribution under such conditions. Methods including the finite element method (FEM), boundary element method (BEM), and hybrid BEM/FEM models enable simulations of induced fields in anatomically realistic head structures (Cvetković et al., 2024). Likewise, the finite integration technique (FIT) and multiphysics models that couple electromagnetic and bio-heat equations have demonstrated effectiveness in estimating E-field strength, SAR, and thermal effects across layered tissues (Kaburcuk & Elsherbeni, 2018; Stanković et al., 2015). Findings consistently show that higher frequencies result in greater attenuation and surface localization of energy, while deeper brain regions exhibit reduced field intensity (Turgut & Engiz, 2023). These outcomes have significant implications for the adequacy of international safety guidelines, such as those of the International Commission on Non-Ionizing Radiation Protection (ICNIRP, 2020), which typically rely on averaged exposure metrics rather t

han localized distributions.

Given the increasing reliance on 5G-enabled devices in daily life, understanding spatial variations in E-field distribution within the human head is crucial for refining safety assessment frameworks. This study develops and validates a computational model to simulate E-field distribution across 1–3 GHz, aiming to provide insight into how 5G signals interact with head tissues and to evaluate the sufficiency of current exposure limits in capturing localized variations.

Methodology

This study employed a computational modeling approach to investigate the distribution of millimeter-wave electric fields within the human head. The methodology comprised the following steps:

Human Head Model

The human head was modeled as a sphere (radius = 0.2 m) representing different tissue layers—muscle, skin, bone, fat, blood, and brain matter (gray and white). These tissues, each with distinct dielectric properties, were averaged for simulation purposes. The midsagittal plane

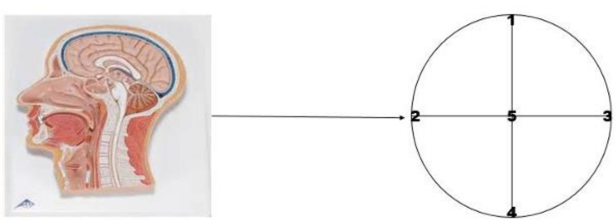

Figure 1: Sphere representing the Sagittal Plane of the Human Head Model. Source: anatomywarehouse.com

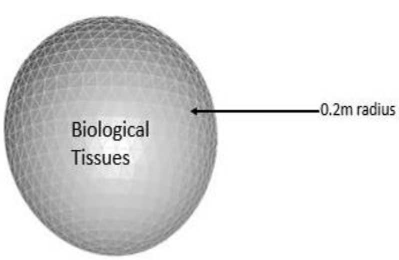

Figure 2 : Human Head Model Using CAD Tools

Simulation Setup

The computational model was discretized with a mesh density of 8–12 patches per wavelength, incorporating symmetry along the XZ-plane to optimize computational efficiency. Excitation was applied using a plane wave field defined by θ = 270°, Φ = 0°, and ψ = 0°, across frequencies ranging from 1 to 3 GHz. Appropriate boundary conditions were enforced to guarantee the continuity of tangential electric (Etan) and magnetic (Htan) fields, as well as the normal component of the displacement field (Dn).

Results: The model analysis was done using the post-processing, which displays and analyze the numerical results. The surface current distributions was visualized, using the 2D field distribution for the numerical results of the electric field. Also, for better representation of the vector, the scaling of the field vector was achieved through color scaling.

Figures 3 to 8 shows the electric field (E-field) penetration at different frequencies.

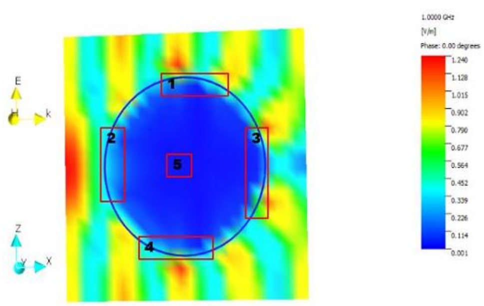

Figure 3: Distribution of the E Field in the Human Head Model at 1GHz

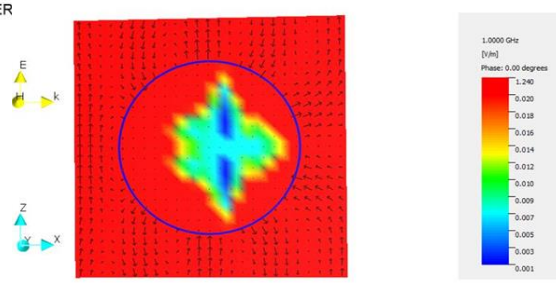

Figure 4: Scaling of the Colour of Distribution of the E Field in the Human Head Model at 1GHz

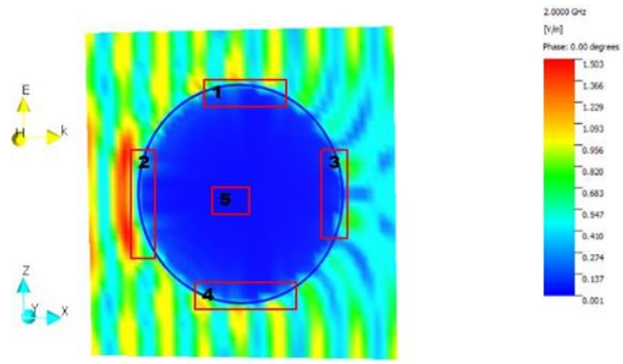

Figure 5: Distribution of the E Field in the Human Head Model at 2GHz

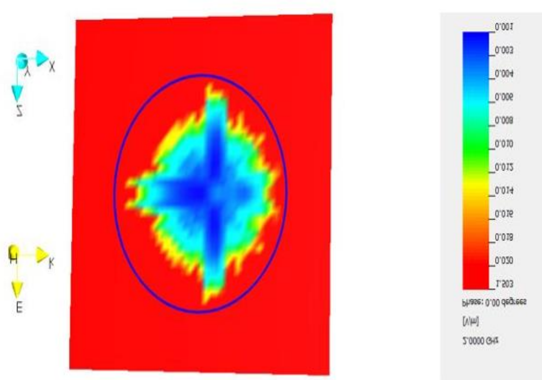

Figure 6: Scaling of the Colour of Distribution of the E Field in the Human Head Model at 2GHz

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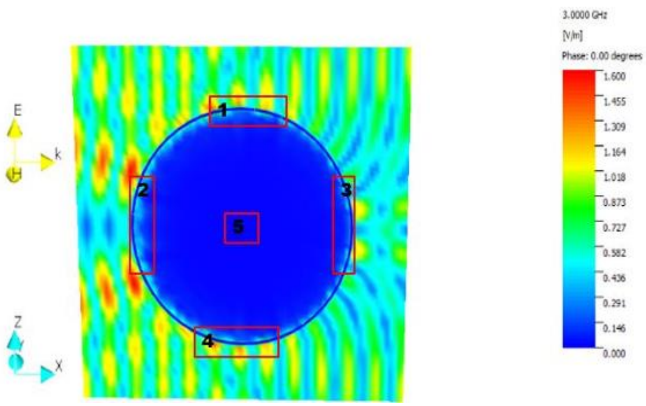

Figure 7: Distribution of the E Field in the Human Head Model at 3GHz

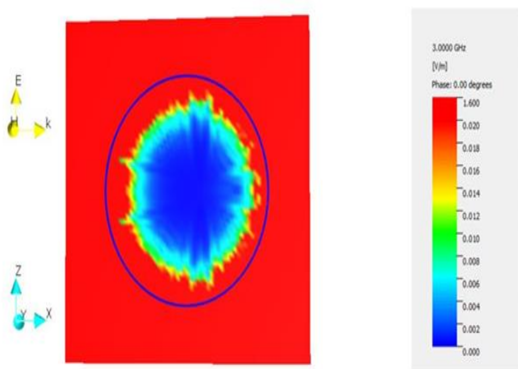

Table 1: E-Field Strength inside Human Head Model at Different Frequencies

Frequency	E-Field Strength Inside Model (V/m)
1 GHz	0.001
2 GHz	0.001
3 GHz	0.000

Discussion: Across the investigated frequency range, a progressive decrease in electric field strength within the head model was observed. At 1 GHz, the distribution exhibited the lowest overall intensity, occupying the largest spatial area, with blue regions dominating the color scale and cyan indicating partial penetration into tissue as indicated in figure 3. As the frequency increased to 2 GHz, the field strength further diminished, with cyan regions becoming negligible and red zones, corresponding to a maximum of 0.02 V/m, emerging along the sides of the model; however, the brain field intensity remained generally low with slight variation as shown in figure 4 . At 3 GHz, this trend continued with a further reduction in field strength, where the red regions at the sides persisted but brain tissue consistently exhibited low-intensity fields, reflecting only minor variations.

Findings

This study demonstrated a significant finding in this regard: "the field vectors close to the interface between free space and the human head model tends to fulfilled the boundary condition that is $Etan^1=Etan^2$, $Dn^1=Dn^2$" This crucial point was further reinforced by the observation that "All the results in figure 3, 4 & 5 fulfil boundary condition at the interface between the free space and the model. The successful adherence to these fundamental electromagnetic boundary conditions—the continuity of the tangential electric field (Etan) and the normal electric displacement field (Dn) across material interfaces—is a strong indicator of the simulation solver's correct implementation of electromagnetic physics and its reliability in modeling wave propagation across different media. Beyond boundary conditions, the simulations also validated a key quantitative trend: the consistent decrease in E-field strength inside the model with increasing frequency. Specific numerical values illustrate this attenuation: "the E field strength inside the model decrease from 0.002V/m, 0.001V/m and 0.000V/m as the frequency is increasing. This provides concrete data supporting the general qualitative trend of attenuation observed. The physical basis for this observation lies in the nature of electromagnetic wave propagation through lossy dielectric materials like biological tissues; higher frequencies typically lead to greater energy absorption and, consequently, increased attenuation of the propagating field within the material. To further enhance the clarity and impact of this validation, the specific numerical values for the E-field strength inside the human head model at each simulated frequency are presented in Table 1. This allows for immediate visual comparison of the attenuation trend, providing concrete evidence that supports the claim of decreasing field strength and reinforces the physical realism of the simulation results in terms of wave attenuation within a lossy medium.

Conclusion

This study provides foundational insights into the interaction of electromagnetic fields with simplified human head models, particularly concerning E-field distribution and penetration. The simulations consistently demonstrated that electromagnetic fields successfully penetrate human head tissues, and critically, that E-field intensity, consistently decrease as the frequency increases across the 1-3 GHz range. A significant observation was the consistent finding that the brain region exhibited a lower E-field intensity compared to other parts of the head model, suggesting a differential absorption or shielding effect. Furthermore, the successful fulfillment of fundamental electromagnetic boundary conditions at the interface between free space and the human head model served as a key validation of the simulation methodology's underlying physical accuracy. While these simulations offer valuable qualitative insights into the general behavior of EM fields within the human head, particularly regarding frequency-dependent attenuation and the apparent "brain shielding" effect, it is important to recognize that the quantitative accuracy of the results is significantly constrained by the simplified anatomical models used. The study's primary contribution lies in reliably demonstrating qualitative trends in EM field behavior within the head, such as frequency-dependent attenuation and differential brain exposure. However, the quantitative accuracy is limited by the simplified anatomical models, necessitating further research for precise estimations. The importance of the observed differential penetration into the brain is re-emphasized as a critical area for future, more detailed investigations using more anatomically faithful representations. Overall, this study serves as a crucial preliminary step in understanding the complex interactions of electromagnetic fields with biological tissues. It successfully identifies key trends and validates fundamental simulation principles, while simultaneously providing a clear roadmap for future research to overcome current limitations and achieve greater anatomical and quantitative accuracy.

Recommendations for Further Studies

To significantly enhance the accuracy, realism, and applicability of future electromagnetic field interaction studies with human head models, several key recommendations are proposed:

Software and Frequency Range Expansion: It is strongly recommended to acquire and utilize a "License version of the software" for future computational studies. The primary rationale for this is to enable simulations at significantly "higher frequency like 24GHz to 60GHz. This expansion is crucial because these higher frequencies are increasingly relevant for cutting-edge wireless communication technologies, such as 5G millimeter wave bands, and other emerging applications. Licensed software typically offers superior computational power, more sophisticated algorithms, and advanced features necessary to accurately model complex electromagnetic phenomena at these higher frequencies, where wave behavior, including skin depth and scattering, becomes more intricate and requires higher fidelity modeling. Also, to use the MIDA model from ITS foundation computation. The MIDA model is recognized as "one of the most detailed image-based anatomical head models available for computational life science (correct representation of the human anatomy) for accurate results" technologies.

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