Modulation of the Antenna-Head Interaction inside a Closed Environment Using MOM-GEC Method

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Abstract **─** The interaction between human head and GSM antenna evaluations are usually conducted in free-space situations but wireless communication devices are frequently used in enclosed environments, such as vehicle, that consist of metallic boundaries. In such fully enclosed or semi-enclosed spaces, human exposure in terms of SAR is closely related to the EM field, which is multiplied, reflected and scattered by the metallic walls of the enclosure. This could lead to complicated resonance effects and affections in the antenna performances. This possible argument of an EM field inside an enclosure has raised serious concerns among the general public. This paper will therefore focus on the impact of dipole antenna modeling the handsets on the SAR distribution inside a cavity modeling the vehicle. Theoretical formulation and simulations are used to study this phenomenon but there is a lot of limitations. Despite, modulation using numerical method are used. A MoM-GEC modeling approach is applied to study the behavior of a dipole antenna resonating at 1.8 GHz. First of all, we are interested in studying the convergence of the input impedance. The current and the electric field distribution are simulated. The specific absorption rate (SAR) is examined for several different tissues.

Index Terms **─** Cavity, dipole antenna, human head, MOM-GEC, SAR.

I. INTRODUCTION

With the recent explosive increase of the use of mobile communication handsets, there has been a growing concern about possible hazard to a human body, especially head part. The influence of these devices on the environment and in particular their interaction with biological tissue must be investigated. Whether or not the presence of the human head affects the antenna performances in a partially closed environment which could be, the interior of a car, a condition of exposure that is largely diffused nowadays. Certainly, the presence of the handset user's influence on the antenna parameters (gain, radiation pattern and input impedance) is an issue which deserves a detailed investigation. Furthermore, growing concerns over the health effects of tissue exposed to electromagnetic energy motivates an effort to understand the power absorption distribution in the tissue when a GSM antenna is used inside a car.

These constraints must be modeled very precisely. Current efforts using numerical methods are aimed to define human head models, phone models, and environment that allow the comparison between numerical and experimental procedures [1], [2] involve practical details like rotating the head model to maintain the cell phone model oriented along the computation axis, to be able to obtain meaningful results.

However, actual exposure in real life is not always produced in a free-space like in our case.

Partially closed environments, like vehicle, are especially rough scenarios for many reasons, the structure is large compared to the wavelength, the metallic structures produce large reflections and the near field effects must be considered. This case of exposition could be characterized by measurements, but the procedure can be very complex. Numerical computation methods constitute an attractive alternative way for those scenarios. Popular numerical techniques currently used for electromagnetic interaction computations are the finite difference time domain (FDTD) method [3-5], the method of moment (MoM) [6] and the finite element method (FEM).

The most popular technique is the FDTD method because of its computational flexibility in modeling complex antenna geometries and the nearby biological tissues. However, it requires significant computer sources for thin layer and at high frequencies. Using the MoM method only the structure in question, not free space as is the case for FDTD is discretized, and boundary conditions do not have to be set. However, method of moments (MoM) cannot be used alone to calculate fields and currents inside lossy dielectrics such as people or phantoms, due to the memory requirements scale in proportion to the size of the problem in question and the required frequency.

These limitations can be offset by parallelization and by hybridization techniques. Approaches in which

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MoM method is hybridized with other methods such as finite difference time domain (FDTD) [6-8] or finite elements method (FEM) [9-10] are attractive for dosimetry problems such as exposure from base station antennae since the need to discretize the free space region between antenna and the exposed dielectric body is avoided.

Actually, few studies to evaluate the effects on SAR arising from reflecting walls located near to a head model have been made [11]. The influence of the metallic structures of a car body frame on the SAR produced by a cell phone when a complete human body model is placed at different locations inside the vehicle was analyzed in [12].

In [13], the scenarios of passengers using different wireless communication devices inside a vehicle was studied. Also, the effects of the devices with different operational frequencies 900 MHz/1.8 GHz/2.4 GHz, and different seating locations on the SARs were investigated. All those studies are based on a simulation using FDTD method.

This paper tries to investigate the EM interaction of a handset antenna and user's head inside a car using the MoM-GEC method. This can be achieved by evaluating the handset antenna performance affection and the amount of the SAR induced in the user's head. The methods and results we present in this paper are the first step in such a process and provide some insight into the expected changes on power deposition for a particular environment that will help in directing subsequent approximation steps.

II. DESIGN MODELS

A simple metal frame was used to simulate the vehicle. A block model for the head were used. The generic phone was used in a vertical position and placed in close vicinity to head (d=1 cm). In our study the user head is reperesnted as a heterogenous and lossy dielectric with rectangular side walls aligned with the cavity walls, this choice of geometry is mainly for sake of simplicity in data management. We trait a case of a head model consisting of four layers modeling, whose macroscopic electrical properties are described in Table 1.

Table 1: Dielectric properties of the head tissue used in our study for f=1.8 GHz

	Permittivity ε_r	Conductivity σ (S/m)	Mass Density ρ (Kg/m^3)	Thickness δ (mm)
Skin	41.36	1.21	1010	2.5
Fat	5.35	0.078	920	5
Skull	16.4	0.45	1810	5
Brain	43.22	1.29	1040	80.5

III. NUMERICAL MODULING

To model the interaction phenomena, there is a set of methods that solves a number of problems. The integral ones are the most suitable to achieve an electromagnetic study of microwave structures.

The integral method used in our study is the method of moment (MOM) combined to the equivalent circuit method (GEC) [14-15]. The concept of generalized equivalent circuit is based on the representation of integral equations by an equivalent circuit in order to alleviate the resolution of Maxwell's equations, which presents a true electric image of the studied structures for describing the discontinuity and its environment [16-19].

In Fig. 1 we represented the advantage of our method which consists of modelling all the problem (structure) using the same formulation which is detailed in Section 5.

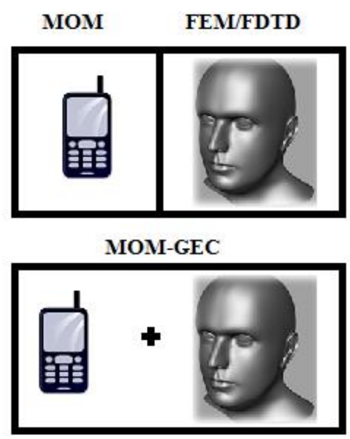


Fig. 1. Advantage of the MoM-GEC method.

IV. PROBLEM FORMULARTION

In this section, we are going to present our formulation to modulate our structure Fig. 2.

Considering the circuit example shown in Fig. 3. We can determine the current density lying in the metal part including the source domain and its associated field to verify the boundary conditions. Next, the integral equation is solved by applying the MOM method using Galerkin procedure.

The cavity used is a waveguide section closed by electrical walls (Fig. 2).

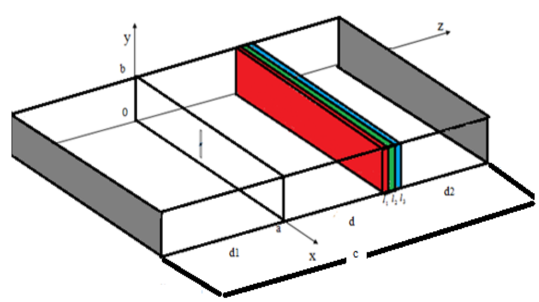


Fig. 2. Dipole antenna in presence of multilayered model inside a cavity.

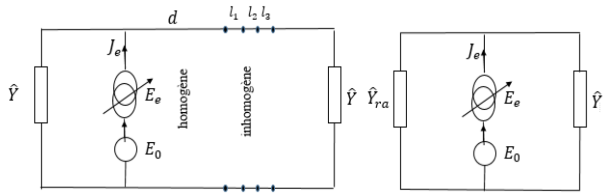


Fig. 3. Representation of dipole antenna in presence of dielectric model with finite thickness using an equivalent circuit.

A particular choice of the trial functions which describe the unknowen current density is defined on the metallic part of the dipole antenna:

$$g_p = \cos(\frac{(2p-1)}{l}\pi(y-\frac{b}{2})\,. \quad (1)$$

Let $f_{mn(m\in\{0,1,2,...,M\}}$ be the local modal basis corresponding the waveguide with electric walls [10]:

$$f_{mn}^{TE,TM} = \begin{cases} N_x^{TE,TM}\cos(\frac{m\pi x}{a})\sin(\frac{n\pi y}{b}) \\ N_y^{TE,TM}\sin(\frac{m\pi x}{a})\cos(\frac{n\pi y}{b}) \end{cases}. \quad (2)$$

Two sources, a virtual and a real one being involved in the formulation process. We trait the case where the virtual source is of current type and the real one is of electric field type.

The real source $E_0 = V_0 F_0$ represents the excitation term associated to feeding element. The function F_0 acts as the shape function, which ensures reliable expression for the voltage and current case of rectangular source $F_0 = \frac{1}{\delta}$.

J_e is the virtual source defined on the metallic domain of the discontinuity surface and it is the problem unknown.

It is expressed as a series of known test functions g_p weighted by unknown coefficients x_p :

$$J_e = \sum_{p=1}^{N_p} x_p g_p\,. \quad (3)$$

Then the equivalent circuit of the studied structure is completed by addition the terminating operator. The admittance operator $\hat{Y}^{cav}_{\left\{\begin{smallmatrix}even\\odd\end{smallmatrix}\right\}}$ is given by:

$$\hat{Y}^{cav}_{\left\{\begin{smallmatrix}even\\odd\end{smallmatrix}\right\}} = \sum_{\substack{m=0,n=0\\ \alpha=TE,TM}}^{\infty} \left| f_{mn}^{cav}\right\rangle y_{mn}^{cav}\left\langle f_{mn}^{cav}\right|, \quad (4)$$

where

$$y_{mn}^{cav} = \frac{\gamma_{mn}^{cav}}{j\omega\mu_0}\coth(\gamma_{mn}^{cav}c),$$

and

$$\left(\gamma_{mn}^{cav}\right)^2 = \left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2 - k_0^2).$$

We modulate the human head as a dielectric multilayered model. Every layer will be considered us a transmission line section with γ_{mn} is the propagation constant for the i^{th} transmission line section, l_i the length of each section.

The admittance operator for the reduced admittance $\hat{Y}_{ra}$ of the inhomogeneous line sections representing the head model is defined by:

$$\hat{Y}_{ra} = \sum \left| f_{mn}\right\rangle Y_{ra}^{\alpha}\left\langle f_{mn}\right|, \quad (5)$$

$$Y_{i+1}^{\alpha} = Y_{\varepsilon i}^{\alpha}\frac{Y_i^{\alpha} + Y_{\varepsilon i}^{\alpha}\coth(\gamma_i l_i)}{Y_{\varepsilon i}^{\alpha} + Y_i^{\alpha}\coth(\gamma_i l_i)}, \quad (6)$$

$$Y_{i=4}^{\alpha} = \begin{cases} Y_4^{TE} = \frac{\gamma_{mn}}{j\omega\mu_0} \\ Y_4^{TM} = \frac{j\omega\varepsilon_0\varepsilon_r}{\gamma_{mn}} \end{cases}, \quad (7)$$

$$Y_{\varepsilon i}^{\alpha} = \begin{cases} Y_{\varepsilon i}^{TE} = \frac{\gamma_{mn}}{j\omega\mu_0} \\ Y_{\varepsilon i}^{TM} = \frac{j\omega\varepsilon_0\varepsilon_{r(i)}}{\gamma_{mn}} \end{cases}. \quad (8)$$

In the dielectric domain, the generalized Ohm and Kirchhoff lows applied to the GEC depicted Fig. 3 lead to the equations system:

$$\begin{cases} J_e = J \\ E_e = (\hat{Y} + \hat{Y}_{ra})^{-1} J_e - E_0 \end{cases}. \quad (9)$$

The current J is expressed in modal basis functions $f_{mn(m\in\{0,1,2,...,M\}}$ weighted by unknown coefficients I_m :

$$J = \sum_{m=0}^{M} I_m f_m\,. \quad (10)$$

Therefore, the application of the Galerkin's method and Kirchhoff's theorem leads to obtain the simplified matrix representation as follows:

$$\begin{pmatrix} I_0 \\ 0 \end{pmatrix} = \begin{pmatrix} 0 & [A] \\ -[A]^t & [B] \end{pmatrix}\begin{pmatrix} V_0 \\ X \end{pmatrix}. \quad (11)$$

Thus, from equation (11), we obtain the equation system:

$$\begin{cases} I_0 = [A][X] \\ 0 = [X][B] - V_0[A]^t \end{cases}. \quad (12)$$

A formal relation between sources (real and virtual) and their dual is then deduced:

$$[A] = \begin{pmatrix} < F_0, g_1 > \\ < F_0, g_1 > \\ \vdots \\ < F_0, g_p > \end{pmatrix}, \quad (13)$$

$$[B]=\begin{bmatrix} \langle g_1,(\hat{Y}+\hat{Y}_{ra})^{-1}g_1\rangle & \langle g_1,(\hat{Y}+\hat{Y}_{ra})^{-1}g_2\rangle & \cdots & \langle g_1,(\hat{Y}+\hat{Y}_{ra})^{-1}g_{N_e}\rangle \\ \langle g_2,(\hat{Y}+\hat{Y}_{ra})^{-1}g_1\rangle & \langle g_2,(\hat{Y}+\hat{Y}_{ra})^{-1}g_2\rangle & \cdots & \langle g_2,(\hat{Y}+\hat{Y}_{ra})^{-1}g_{N_e}\rangle \\ \vdots & \vdots & & \vdots \\ \langle g_{N_e},(\hat{Y}+\hat{Y}_{ra})^{-1}g_1\rangle & \langle g_{N_e},(\hat{Y}+\hat{Y}_{ra})^{-1}g_2\rangle & \cdots & \langle g_{N_e},(\hat{Y}+\hat{Y}_{ra})^{-1}g_{N_e}\rangle \end{bmatrix}. \quad (14)$$

The resolution of the equation system (14) leads to calculate the structure input admittance:

$$Y_{in}=[A]^t[B]^{-1}[A]. \quad (15)$$

V. NUMERICAL RESULTS

The electromagnetic interaction was presented by two mutual effects, one is the induced specific absorption rate level inside the head tissues and the second on the handset performance.

In this section, we present a quantitative discussion about obtained numerical results, while the convergence study is firstly achieved. Figure 4 presents the input impedance variation as a function of the mode number for different used basis function number. In the next, we use a test functions number $N_e = 10$ and $N_b = 200 \times 200$ mode number to ensure the convergence.

Figure 5 illustrates the electric field and current density evaluated by the MOM-GEC at f=1.8 GHz. It shows that the boundary conditions are verified.

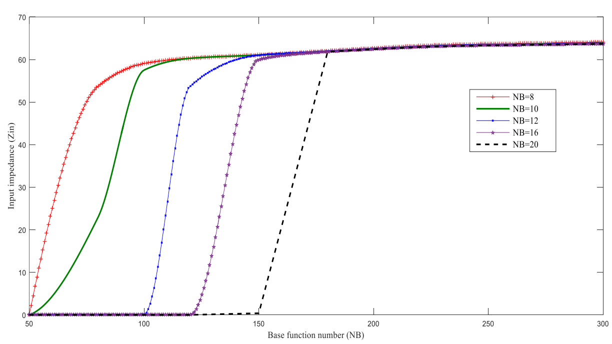
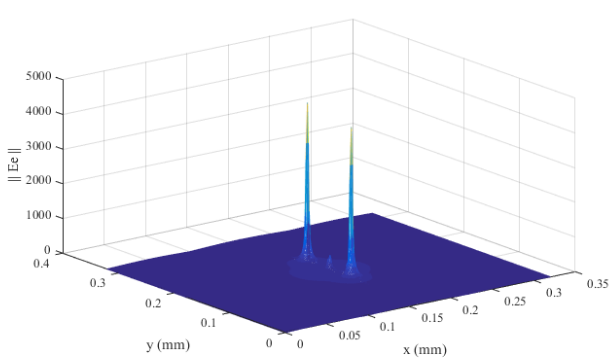
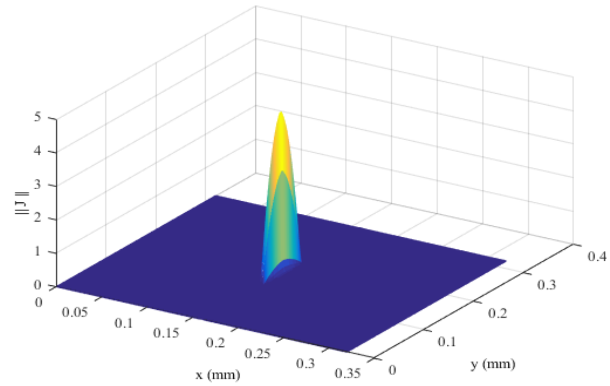


Fig. 4. Variation of the input impedance as a function of the guide modes number for different test functions number at f=1.8 GHz.



(a)



(b)

Fig. 5. (a) 2D representation of the diffracted electric field, and (b) 2D representation of the current density (A.m^{-1}).

A. Modification of the antenna performance

The S parameters has been calculated after convergence from the simulations. The return loss (S_{11}) of the antenna due to a single dipole antenna operated at GSM1, 8 GHz and in presence of the head model are presented in Fig. 6. It was found that the antenna is operating within this semi-enclosed environment with the multilayered head model loadings, the return loss of the antenna is affected, and there is a little shift in the resonant frequency and the shape of the curve in red is also affected by the presence of head model.

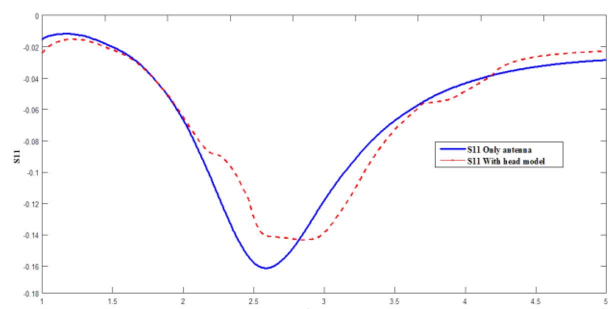


Fig. 6. Current distribution for a dipole antenna in the presence of a layered model inside an infinite waveguide and cavity.

Also, to explain the perturbation of the antenna performance in presence of the head, Fig. 7 shows the current density for a dipole antenna in the presence of a layered model inside a cavity. For a comparison purpose, the response of a single antenna is presented. We conclude that the level of the density of current increased inside a cavity.

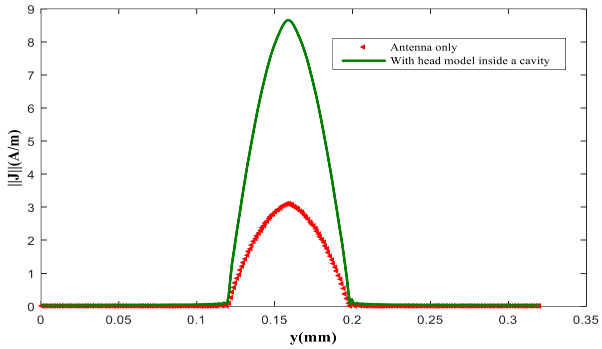


Fig. 7. Current distribution for a dipole antenna in the presence of a layered model.

B. SAR distribution inside several tissues

Inside a cavity (modelling a car), where multipath propagation, reflections and scattering must be accounted for, the SAR distribution undergoes large changes. However, the value of SAR is quite high compared to those in international limiting human exposure [20]. There is a large difference found between free-space and being inside a vehicle.

The SAR value decreases by penetrating into layers. The maximum SAR value is generated at the skin layer. Figure 8 represents the variation in model with four layers. The presence of the "fat" layer reduces the SAR value which increases again in layers of "skull" and "brain", this is due to the low conductivity of the tissue ($\sigma_{Fat} = 0{,}45 S/m$). We can also say that "fat" layer acts as a barrier against penetration of waves.

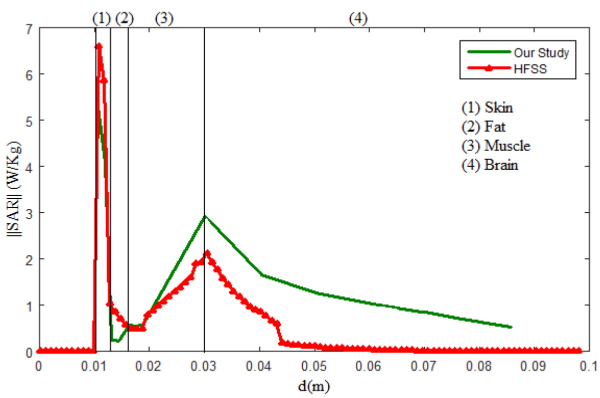


Fig. 8. Specific absorption rate SAR variation inside a four-layered model.

The validation of the SAR calculation was performed by comparison with Simulation using the Ansoft HFSS simulator. Because we are most interested in assessing changes in the SAR distribution rather than in obtaining a figure comparable with the standards.

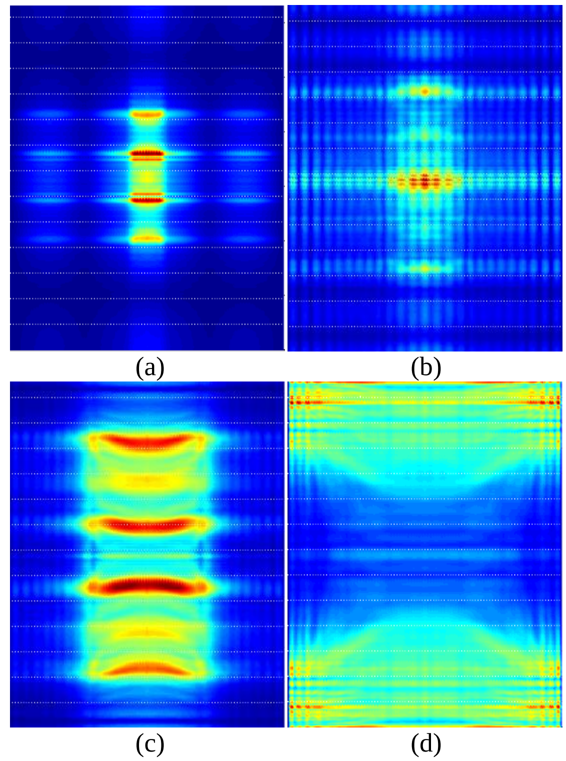


Fig. 9. Specific absorption rate SAR distribution in a four-layered model: (a) skin, (b) fat, (c) skull, and (d) brain inside a car.

The skin (the peripheral layer which is very thin) has a relatively high dielectric permittivity and concentrates the absorbed power (SAR) at the surface of the head. This peripheral layer presents screening effect for the electric component of the incident field. Fat and skull with its lower permittivity act like a barrier for the power penetration.

However, SAR distribution is highly focused in the area proximal to the antenna, and decreases rapidly inside the body, as the penetration depth and SAR distribution shown in Fig. 9 for a four-layered head model inside a cavity.

Table 2: SAR value inside a cavity (four layered head model)

	SAR (W/Kg)
ANSI limit	1,6
Free space	2
Cavity (MOM-GEC)	5.2
Cavity (HFSS)	6.57

As shown in Table 2, exposition inside a partially closed environment will certainly increase the induced SAR in head model. The numerical computations showed a 54% increase of the SAR induced in the tissues while exposed to a dipole antenna inside a cavity, as compared with the obtained in free space. In other words, the exposition inside a car is more hazardous than in free space and the SAR induced in the tissues may cross the ANSI standard limit.

Most of the coupling is in the near field and the most relevant parameters are the distance from the dipole to the head. Table 3 shows that the SAR level decreases with increasing distance from the excitation source. The SAR level is more intense when in an electrical environment.

Table 3: SAR value for different distance inside a cavity

Distance (cm)	SAR (W/Kg)
0,5	8,89
1	5.2
2	3,64
3	1.2

VI. CONCLUSION

The introduction of a realistic partially closed environment would have produced a set of results difficult to interpret. We have taken some decisions about models, complexity results presented, etc. that certainly have some impact on the interpretation of the results.

Instead, for the sake of simplicity we have used a dipole antenna some differences in SAR disposition will arise from that fact. More research and a better understanding of the behavior of actual phones is needed to address this point.

Our results are of comparative nature and are valuable as indicators of the changes expected between the free space widely studied situation and other more realistic exposure conditions, but cannot be directly used for compliance assessment.

The results obtained can also be used to gain knowledge about the influence of user head over the specific absorption rate distribution inside a car, which is of great interest on other research areas, such as electromagnetic compatibility, since the use of electromagnetic sources inside a vehicle is an interesting situation.

We show the feasibility of investigating and obtaining results for the specific absorption rate (SAR) within a complex and large structure (compared to the wavelength) such as a user car. A formulation with the combination between MoM method and GEC method is developed and results compared with those obtained in other works and simulations.

The proposed method can be efficiently used for investigating the effect of the variation of distance on the power absorption by the head as well as the antenna performance. The penetration depth and the specific absorption rate are also computed.

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