A UTD/FDTD Model to Evaluate Human Exposure to Base-Station Antennas in Realistic Urban Environments

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Abstract — **A technique combining uniform asymptotic theory of diffraction and finite-difference time-domain (UTD/FDTD), suitable to characterize human exposure in realistic urban environments at a reasonable computational cost, is presented. The technique allows an accurate evaluation of field interaction with penetrable objects (walls, windows, furniture, etc.) and of power absorption in a high-resolution model of the exposed subject. The method has been applied to analyze the exposure of a subject standing behind a window in a building situated in front of a rooftop-mounted base-station antenna. A comparison of the obtained results with those computed neglecting the presence of the building (free-space condition) evidences that a realistic modeling of field propagation in the actual scenario is essential for an accurate evaluation of absorbed power distribution inside the human body.**

I. Introduction

The steady increase in the number of subscribers of mobile telecommunication systems is pushing towards an enhancement of the capacity of the systems themselves. As a result, more and more base stations are being installed on the rooftop of existing buildings in densely populated areas. These installations are giving rise to widespread concerns among the population about possible detrimental effects to human health deriving from exposure to the electromagnetic (em) fields radiated by base-station antennas.

Safety of base stations, with respect to human exposure, is currently assessed by comparing the exposure field value, averaged on a surface equivalent to the vertical body section, with reference levels suggested by exposure guidelines [1], [2]. However, the exposure field in an urban scenario is far from being uniform, due to the presence of many reflection and diffraction processes. As a consequence, power can be absorbed inside the body in a highly non-uniform fashion and an accurate dosimetric analysis is necessary for a correct evaluation of specific absorption rate (SAR) values inside particular body regions. For example, a subject standing inside a room behind a window facing a base-station antenna is expected to experience higher SARs in the trunk with respect to the lower limbs, while the use of an average field level would mask this effect. In this paper, in order to accurately characterize human exposure in realistic urban environments at a reasonable computational cost, a technique combining uniform asymptotic theory of diffraction and finite-difference time-domain (UTD/FDTD) is proposed.

At present, the most used technique for studying the power absorbed in a subject exposed to em fields is the FDTD method [3]. However, when exposure in a realistic urban scenario has to be modeled, a pure FDTD approach would result in huge computational costs, due to the extremely large dimensions of the region to be studied with respect to the typical wavelength used in cellular telecommunication systems.

To overcome these limitations, a UTD/FDTD technique is proposed, which uses the FDTD method to study a limited region just containing the exposed subject, and a UTD model to evaluate the field propagation in the remaining part of the domain, including the radiating antenna and the reflecting/scattering objects. The implemented UTD model overcomes the limitations of the previous hybrid technique proposed in [4], which was based on a pure geometrical optics (GO) approach and only allowed modeling of infinite planar surfaces with no diffracting edges. The proposed UTD/FDTD technique has been applied to analyze a complex exposure scenario, comprising an indoor environment in which the field penetrates through the room walls and window. More in detail, a typical exposure condition for a subject living in a building in front of a rooftop-mounted antenna, operating in the global system for mobile communications (GSM) 900 MHz band, has been considered and analyzed.

II. Methods and Models

The FDTD method is currently the most used technique in electromagnetic dosimetry problems. In fact, it allows a sufficiently accurate simulation of the field source (antenna) and a detailed modeling of non-homogeneous

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scatterers having arbitrary shape (human body). This method, however, is not efficient to study scattering problems involving large regions (urban environment) due to the huge memory and CPU time requirements. In order to overcome this problem, in this work the FDTD method has been used in conjunction with a UTD model, to characterize very efficiently field propagation in complex large environments.

As a first step, a high frequency UTD model is used to evaluate the incident field on the exposed subject. Such model employs the heuristic diffraction coefficient proposed in [5] to accurately take into account the field scattered from penetrable objects. Higher-order GO reflections and transmissions are computed, while only first-order diffractions are considered. The elements forming the environment are modeled through thin plates of different materials, and the characteristics of the transmitting antenna are taken into account by means of its radiation pattern. In the numerical implementation of the UTD model, a beam-tracing (BT) algorithm [6] has been adopted to derive the ray paths starting from the base-station antenna.

As a second step, the exposure field obtained with the UTD model is employed to derive equivalent currents which, making use of the equivalence principle, are used to excite the field in the FDTD region where the exposed subject is located, as presented in [4]. The FDTD domain is closed applying a five-cell uniaxial perfectly matched layer (UPML) absorbing boundary condition with linear profile and 1% reflection coefficient [3].

It must be observed that, while FDTD is a technique that operates in the time domain, the UTD model works in the frequency domain. This means that the UTD-derived equivalent currents are immediately set to their steady-state value in FDTD. On the other hand, FDTD requires the setting of initial conditions, namely the values of the em field inside the FDTD domain at the initial time step, which are commonly set to zero. This results in the injection of electric and magnetic charges on the equivalent surface during the early transient. As a consequence the final steady-state field distribution is affected by a DC offset, that has been eliminated applying a discrete Fourier transform (DFT), at the frequency of interest, to the em fields computed in the time domain.

III. RESULTS

The above-described UTD/FDTD technique has been used to study a typical exposure situation in an urban scenario as depicted in Fig. 1. A panel antenna is mounted on the rooftop of a building on top of a 3-m high mast, with 6° mechanical tilting. The antenna is supposed to radiate a power of 30 W, typical value for a 4-transmitter base-station in urban environment. A second building, of exactly the same height, is placed in the direction of the main beam of the antenna, at a distance of 45 m (possible width of a metropolitan avenue). A subject is supposed to stand, at the last floor of the second building, behind a 2 m × 1.5 m window (the region where the subject is placed is evidenced by the box in Fig. 1). The geometrical and electrical characteristics of the materials composing the environment are reported in Table I [7].

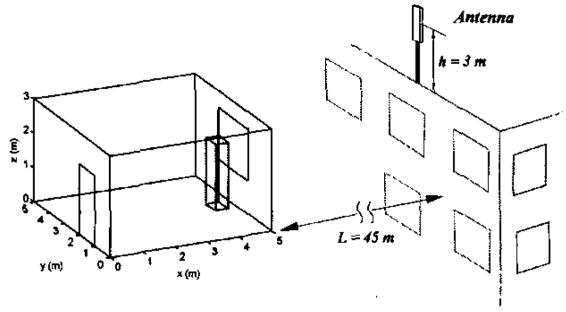

Fig. 1. The considered urban scenario. The region where the subject is located is evidenced by the box.

TABLE I
MATERIAL CHARACTERISTICS (900 MHZ)

Material	ε_r	σ (S/m)	Thickness (cm)
Ceiling and floor	10.0	0.06	25.0
External brick wall	5.1	0.01	22.0
Internal brick wall	5.1	0.01	12.0
Wooden door	3.0	0.00	4.0
Glass window	3.0	0.00	0.5

The considered base-station antenna is a Kathrein 730-691 panel antenna. The three-dimensional radiation pattern of the antenna has been obtained through the method of moments (MoM), employing the NEC code [8]. The obtained -3 dB apertures on the horizontal and vertical planes are about 64° and 8°, respectively; the gain of the antenna is 18 dBi. These data, derived from MoM simulations, are in good agreement with the antenna specifications given by the manufacturer.

The non-homogeneous phantom used to model the exposed subject has been obtained from a tissue-classified version of the "Visible Human Project" data set developed at Brooks Air Force Base laboratories [9] with a 3-mm resolution. The study has been performed at a frequency of 947.5 MHz (central frequency of the GSM900 base-station transmit band). At this frequency, the chosen 3-mm cell dimension corresponds to less than one tenth of the wavelength in the tissue with the highest permittivity, resulting in a good accuracy for the FDTD simulations.

The body model has a total height of 180 cm and 31 different types of tissues/organs have been evidenced. For the electrical characterization of the tissues the data reported in [10] have been used.

Before studying exposure of the subject, the field distribution inside the empty room has been analyzed. The field map predicted by means of the UTD model inside the room on a horizontal plane at a height of 1 m above the floor is reported in Fig. 2. The map shows the field interferences due to the multiple reflection and diffraction processes and evidences that the region behind the window, where the subject will be placed, is the one with the highest field levels.

In order to test the accuracy of UTD/FDTD, the technique has been applied in the absence of the subject (the FDTD domain is left empty) to see if the field distributions predicted by the UTD model were correctly reproduced inside the FDTD domain. To this end, Fig. 3 compares the field maps obtained on the yz-plane passing through the middle of the FDTD domain by means of UTD (a) and UTD/FDTD (b). An optimum agreement between the two maps is observed.

A first question that might arise is whether the use of an enhanced BT algorithm, including UTD-field evaluation, is necessary, or if a pure GO-based approach would suffice. To investigate this issue, a further field map has been calculated neglecting all diffraction effects. The obtained result, reported in Fig. 3(c), indicates that, in such a complex environment, diffraction processes induce significant modifications to the field distribution, and consequently their inclusion in the field propagation model is fundamental in order to obtain realistic field prediction.

After validating the UTD/FDTD approach in the empty room, exposure of the human subject has been studied. The computed whole-body (SAR_{WB}), peak 1-g (SAR_{1g}), and 10-g (SAR_{10g}) averaged SAR values are summarized in the first row of Table II, together with the maximum (E_{max}) and average (E_{av}) rms exposure field values (in the absence of the subject) in the region where the subject has been placed. The reported data indicate that SAR levels in this critical exposure condition (antenna beam directly pointing towards the building facing the base station) are approximately two orders of magnitude lower than the basic restrictions issued by the most recognized international exposure guidelines [1], [2].

In order to understand how crucial a correct characterization of the real exposure scenario is, the previous dosimetric analysis has been repeated in an equivalent free-space condition (the building has been removed, while antenna and subject have been kept in the same positions). The results obtained through this second

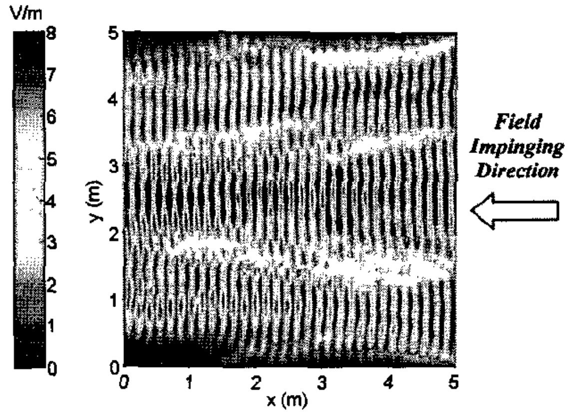

Fig. 2. Field distribution on a horizontal plane inside the empty room (rms values).

TABLE II
EXPOSURE FIELD AND SAR VALUES

Situation	E_{max} (V/m)	E_{ave} (V/m)	SAR_{WB} (mW/kg)	SAR_{1g} (mW/kg)	SAR_{10g} (mW/kg)
Room	7.85	4.62	0.34	11.01	6.13
Free space	5.26	5.25	0.41	12.53	8.45

TABLE III
POWER ABSORPTION IN SOME MAJOR BODY ORGANS

	Room (whole body absorbed power 34.9 mW)		Free space (whole body abs. power 42.4 mW)	
Organ	SAR_{1g} (mW/kg)	Relative power	SAR_{1g} (mW/kg)	Relative power
Brain	2.03	1.71%	1.80	1.45%
Heart	1.06	0.15%	1.29	0.15%
Liver	1.02	0.77%	0.98	0.59%
Testis	1.68	0.06%	3.73	0.11%

study are reported in the second row of Table II. Comparing the two rows, it is possible to note that in the realistic condition the peak exposure is considerably increased, as compared to the free-space situation, due to the many field interactions, while the average exposure is slightly decreased, due to the shielding effect of the room walls and, to some extent, of the closed window. Looking at SAR data, it is evident that in the realistic exposure condition both whole-body and locally averaged values are lower than those obtained for the free-space condition, thus showing a correlation between average exposure field and SAR values. However, since in the studied realistic situation a remarkable alteration of the SAR distribution inside the body, with respect to the free-space condition, is observed, the presence of the environment could have deep implications on power absorption at single organ level. This is confirmed by Table III, where the peak 1-g

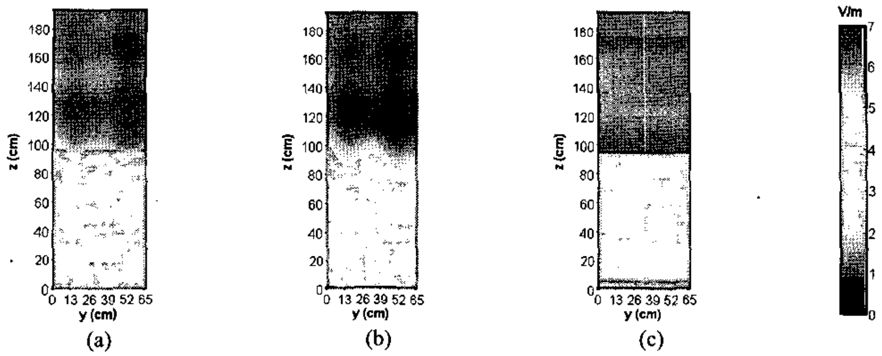

Fig. 3. Field maps on the yz-plane passing through the middle of the FDTD region (rms values). (a) UTD; (b) UTD/FDTD; (c) GO.

averaged SAR and the absorbed power (normalized to the whole-body absorbed power) in some major body organs are reported. The results highlight that in the real scenario, due to the presence of the window, power absorption mainly occurs in the body organs placed above the waist, and SAR in the brain is 13% higher than in the free-space condition.

IV. Conclusions and Discussion

In this paper, a UTD/FDTD model, able to accurately characterize human exposure to electromagnetic fields radiated by base-station antennas in realistic urban environments, has been presented.

The technique has been applied to study indoor exposure for a subject living in a building in front of a rooftop-mounted base-station antenna. The obtained results have shown that in a realistic exposure condition both whole-body and locally averaged SAR values are related to the average exposure field, and that the average field level decreases as compared with the equivalent free-space condition. This could suggest that a free-space model is sufficient for a conservative safety assessment. However, the above conclusion holds for the particular studied condition, and further investigations are needed to verify if other situations exist in which the local SAR values become correlated with the peak exposure field. Moreover, comparison between the real exposure scenario and the more simple free-space situation has revealed that an accurate characterization of the environment is essential for a correct prediction of exposure field levels and for a realistic assessment of power absorption distribution within the exposed body. Although these implications might have little importance for a mere safety assessment, they might prove essential for a correct interpretation of possible epidemiological studies involving exposures in urban environments, and to try to establish a dose-effect relationship.

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