Evaluation of Human Exposure in the Vicinity of a Base-Station Antenna Using the Multiple-Region / FDTD Hybrid Method

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***Abstract* — In this paper, human exposure to the electromagnetic field radiated from a GSM radio-base station antenna operating in the 900-MHz frequency band has been analyzed. A hybrid multiple-region / FDTD method has been used to evaluate the field radiated by the antenna and the power absorbed in an accurate model of the exposed subject. The results show that field levels averaged on a surface equivalent to the left-to-right vertical body section are well correlated with whole-body averaged SAR, while local SAR values are influenced by local peaks in the incident field. A comparison between the computational costs of MR / FDTD and pure FDTD shows that, with the application of appropriate compression techniques, the hybrid method becomes convenient, in terms of memory occupation, when the distance between the subject and the antenna is greater than 80 cm.**

I. INTRODUCTION

The enormous growth in the number of users of mobile telecommunication systems has determined an increased presence of radio base stations in densely populated areas. Consequently a concern for the potential detrimental effects on human health deriving from exposure to electromagnetic (em) fields emitted by the antennas of these systems is raised. This problem is perceived by the general population that can be exposed to the fields emitted by base-station antennas for a long time, also if the exposure levels are expected to be low. Much stronger fields, even though for a shorter time, can be experienced by technical personnel working close to the antennas for the maintenance of the base station apparatuses.

Safety of base stations, with respect to human exposure, is currently assessed by comparing the field value, averaged on a surface equivalent to the vertical body section, with reference levels suggested by exposure guidelines [1]-[2]. However, especially in the vicinity of the base station, the incident field is far from being uniform due to the high directivity of typical base station antennas. As a consequence, it is not obvious that compliance of the average field level with reference levels ensures that basic limits on the power absorbed per unit of mass (SAR) are respected. This is true in particular for local SAR values, which are expected to be influenced by spatial peaks of the exposure field.

To clarify this point, the exposure of a subject placed at various distances from a base station antenna should be studied, and the induced SAR values evaluated and compared with basic restrictions [1]-[2].

For large distances between the antenna and the subject (radiative far field), the characteristics of the incident field are those of a plane wave and the study of human exposure can be efficiently performed by using the FDTD numerical technique applied in the total-field scattered-field formulation [3]-[4]. In this case, the FDTD domain is limited to a region containing the subject, and the plane wave is excited by using the equivalence principle. The FDTD technique can be also applied when the subject is in the reactive near field of the antenna, modeling the antenna geometry inside the FDTD domain. With respect to the previous case, this requires the addition of a small volume hence increasing memory requirements only slightly. For intermediate distances, when the subject stays in the radiative near field, FDTD requirements, in terms of memory occupation and execution time, can become excessive.

A way to overcome this problem is to hybridize FDTD with another technique such as, for example, Kirchhoff integral (multiple-region / FDTD) [5] or ray-tracing (ray-tracing / FDTD) [6]. In particular, in this paper multiple-region / FDTD (MR / FDTD) is considered. This technique uses an FDTD sub-domain to evaluate the field radiated by the base-station antenna and another FDTD sub-domain to study the field induced inside the exposed subject, while Kirchhoff's integral (KI) is used to link the two sub-domains.

Aim of this work is to study the exposure of a subject placed in the radiative near field of a base station antenna and to assess the differences, in terms of whole body and locally averaged SAR, between this situation and uniform plane wave exposure. The advantages and limits of MR / FDTD, as compared to pure FDTD, in treating this kind of problems will be also analyzed.

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II. The Multiple-Region FDTD

In the MR / FDTD method the simulation domain is divided into smaller sub-domains surrounding the em structures to be considered (e.g. sources and scatterers) (see Fig. 1).

The sources that contribute to the field in each sub-domain are both those internal to the sub-domain itself and those external whose effect is taken into account by using the equivalence principle. This principle is applied dividing each sub-domain in two regions separated by an equivalence surface (S in Fig. 1): the inner total-field region and the outer scattered-field region. The discontinuity between total and scattered fields is sustained by equivalent currents flowing on S, which are obtained applying a near-field to near-field transformation to the field scattered from the other sub-domains. This transformation is accomplished by using KI formula computed over a surface (S' in Fig. 1) located in the scattered-field region.

Kirchhoff's integral allows the computation of the generic electric or magnetic field component ($\psi(\mathbf{r},t)$) in a point P outside Kirchhoff's surface (S' in Fig. 1), starting from the knowledge of the same field component and its time and space derivatives on S'.

In the numerical implementation of the MR / FDTD technique, Yee's classic scheme is used for computing the em field inside each sub-domain. The equivalence principle is applied dividing the equivalence surface in square patches corresponding to the external faces of FDTD cells. The field components on these patches are first computed applying Yee's scheme and then modified, starting from the incident em field components ($\mathbf{E}_i$, $\mathbf{H}_i$), through the total-field scattered-field formulation [3]. $\mathbf{E}_i$ and $\mathbf{H}_i$ are evaluated by using a discretized version of KI. To this end, Kirchhoff's surface S' is divided, similarly to the equivalence surface, in square patches and the integral is computed as a summation on all the patches [7].

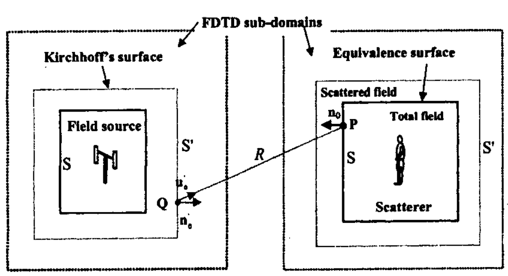

Fig. 1. MR / FDTD: simulation domain.

The above described numerical implementation suffers from high computational costs since at each time step the evaluation of the incident em field on each patch of the equivalence surface requires the computation of a discretized integral on Kirchhoff's surface.

In order to reduce the costs, the solution has been adopted to use for each of the scattered field components one value out of n^2 on Kirchhoff's surface for the integral computation. The value of this component is obtained taking the average field value on a square of n×n patches of the surface. To further reduce computation costs, the patches of the equivalence surface are clustered in groups of m×m and only one incident field component per cluster is computed through KI. This component is evaluated at the center of the cluster and assigned to all the patches of the cluster itself.

III. Antenna and Human Body Models

The antenna considered in this work is a panel antenna operating at 947.5 MHz (central frequency of the GSM base station transmit band [8]) and is depicted in Fig. 2. It consists of four elements aligned on a vertical axis with a uniform spacing of 32 cm. Each element is constituted by a parallel pair of vertical dipoles placed at a distance of 9 cm. All dipoles are fed in phase with the same voltage. At the back of this array is mounted, at a distance of 7 cm, a metallic flat reflector whose dimensions are 25 × 129 cm. For this antenna the Fraunhofer distance is equal to about 5.3 m.

The radiation pattern at 947.5 MHz of the antenna has been obtained with the FDTD method by using a near-to-far-field transformation [3]. The obtained radiation pattern, reported in Fig. 3 in normalized form, shows a -3 dB aperture on the horizontal plane of about 82°, and a -3 dB aperture of about 13° on the vertical plane. The maximum gain is 14.56 dBi.

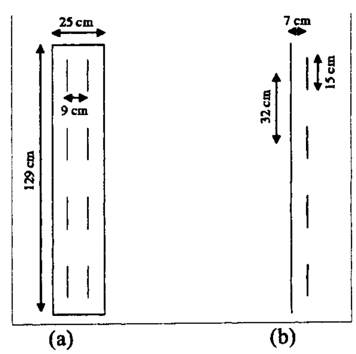

Fig. 2. Panel antenna geometry. (a) Frontal view. (b) Lateral view.

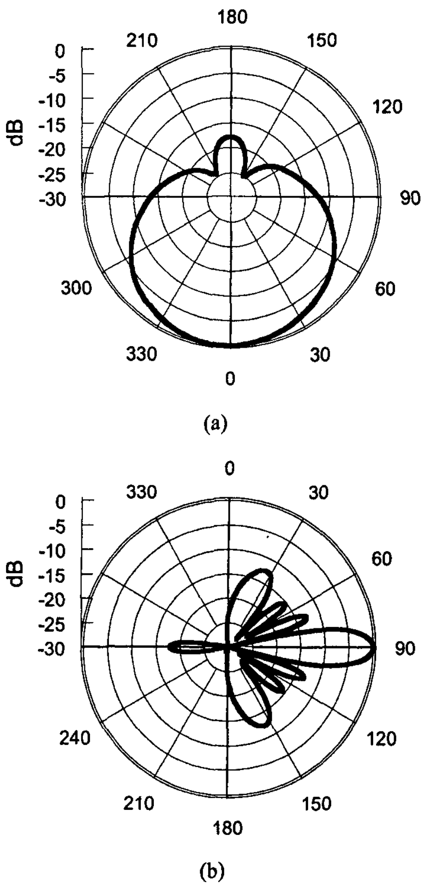

Fig. 3. Normalized radiation pattern of the base station antenna. (a) Horizontal section. (b) Vertical section.

To study the interaction of the radiated field with an exposed subject, a heterogeneous model of man has been used. This model has been obtained from a tissue-classified version of the "Visible Human Project" data set developed at Brooks Air Force Base laboratories [9]. The original model had a 1 mm resolution and has been downsampled to obtain a final resolution of 5 mm. At the considered frequency of 947.5 MHz, in the tissue with the highest permittivity, this cell dimension corresponds to about one tenth of the wavelength, 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. In particular, due to the cell dimension used, the most external layer of the model has been associated with an average tissue made of 1/2 skin and 1/2 fat. For the electrical characterization of the tissues at the considered frequency the data reported in [10] have been used.

IV. RESULTS

The above described hybrid method has been used to evaluate the exposure of a subject placed in front of the base station antenna in the direction of maximum radiation and at a distance of 1 m (radiative near field). The antenna is radiating a total power of 30 W, that represents a typical value for a four-transmitter base station in urban area.

The FDTD sub-domains, in which the antenna and the exposed subject are inserted, have a 5-mm cell size and are closed applying a uniaxial perfectly matched layer (UPML) absorbing boundary condition [11]. The dimensions of the sub-domains containing antenna and subject are 55×90×295 and 110×160×400 cells, respectively. The averaging factor n adopted on Kirchhoff's surface of both the antenna and subject domain is 5; similarly, a clustering factor of 5 has been used on the equivalence surfaces of both the antenna and subject domain. In the simulations, a harmonic excitation has been considered and, once steady state conditions are reached, the amplitude of the three electric field components is determined in the center of each cell of the human body model and the SAR is evaluated. From the SAR distribution the whole-body averaged SAR (SAR_{WB}) and the maximum SAR averaged over body masses of 1 g (SAR_{1g}) and 10 g (SAR_{10g}) have been obtained.

In the considered exposure situation the rms value of the exposure field, averaged over a 40×180 cm surface, equivalent to the vertical left-to-right body section, is 53.8 V/m while the maximum rms field level on the same surface is 77.7 V/m. For comparison purposes, a reference plane wave exposure situation has been also studied. In this case, a rms amplitude of 53.8 V/m, equal to the average value previously found, has been chosen for the incident field. SAR_{WB}, SAR_{1g}, and SAR_{10g} of 0.054, 3.18, and 1.96 W/kg are obtained when the subject is placed 1 m far from the antenna, while 0.042, 1.33, and 0.84 W/kg have been computed in the reference situation. Analysis of the obtained results suggests that, when the field distribution is non-uniform, the whole-body averaged SAR value is still dependent on the field level averaged over a surface equivalent to the vertical body section. On the contrary, local SAR values appear to be more correlated to the maximum field impinging over the exposed subject.

A comparison between pure FDTD and MR /FDTD, in terms of memory occupation and execution times, has been finally performed for different distances D between the antenna and the subject.

TABLE I
COMPARISON BETWEEN PURE FDTD AND MR /FDTD, IN TERMS OF MEMORY OCCUPATION

Distance (cm)	MR / FDTD Memory (Mbyte)	FDTD Memory (Mbyte)
20	716	456
40	732	568
60	751	679
80	773	790
100	797	902
200	942	1459

TABLE II
COMPARISON BETWEEN PURE FDTD AND MR /FDTD, IN TERMS OF EXECUTION TIMES

Distance (cm)	MR / FDTD Time (sec/step)	FDTD Time (sec/step)
20	40	8
40	40	10
60	40	12
80	40	14
100	40	16
200	40	26
350	40	41

Memory occupations in Mbyte and execution times in seconds per time step, obtained with Fortran codes implemented on a PIII 500 MHz computer with 1 GByte of RAM, are detailed in Tables I and II.

The tables show that both the pure FDTD and MR / FDTD require a memory occupation which grows linearly with the antenna-subject distance. However, for MR /FDTD, with the considered compression factors, the memory increase is slower and hence this technique becomes convenient, in terms of memory occupation, at distances greater than about 80 cm. With reference to execution times, MR / FDTD shows values that are independent from the distance and becomes convenient at distances greater than about 350 cm. It must be noted that the compression techniques used play a fundamental role in keeping computational costs at an acceptable level. In fact, without these techniques the MR / FDTD solution of the problem would require about 3 Gbyte of memory occupation and an estimated execution time of approximately 1 hour for each time step.

V. CONCLUSION

In this paper, human exposure to the electromagnetic field radiated from a GSM radio base station antenna operating in the 900-MHz frequency band has been analyzed by using a hybrid multiple-region / FDTD method. The obtained results have shown that field levels averaged on a surface equivalent to the vertical body section are well correlated with whole-body averaged SAR, while local SAR values are influenced by local peaks of the incident field. As a consequence, particular attention should be paid when testing compliance with safety standard on the basis of the average field level.

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