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Wire Antenna Theory Applied to the Assessment of the Radiation Hazard in the Vicinity of the GSM Base Stations

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Abstract: Safety aspects of the GSM base station radiation concerning human health have been analysed. The numerical modelling of the human body was performed by utilizing the antenna theory and BEM numerical procedure. The simplified model of the body represented by thick cylindrical scatterer placed vertically on the perfect conducting ground was used. Measurements of the radiated fields have been done at a few sites, and the results were incorporated in the numerical calculations as an incident field.

Keywords: Antenna theory, Numerical modelling, Radiated field.

1 Introduction

As the demand for new technologies increases, a need to understand more about electromagnetic impact on physical engineering limitations of the equipments and complex systems is also increasing. One important aspect for sure is the safety aspect of the electromagnetic radiation concerning human health. So the issue of product liability is very often the subject of research interest, especially regarding the recent huge growth of communication industry. Study of the wireless communication systems and ubiquitous mobile phone, same as the base station antennas, from the EMC point of view, in order to prevent or attenuate existing electromagnetic interference and protect the humans, became an important task.

Considerable research has been made in the area of bioelectromagnetic interaction design. The extensive experimental and theoretical research particularly regarding health implications of the base station radiation has been carried out [1]-[10]. List of references dealing with this problem is much longer then listed here. In order to assess the possible health risk of the electromagnetic field radiated around the GSM base station a lot of research has been recently done [5]-[8], [10].

The exposure of the human body to the electromagnetic radiation from VLF to RF range results in induced currents and fields inside the body. So the calculation of the induced current is the usual first step in the numerical investigation of the human exposure and then the induced fields and specific absorption rate (SAR) could be obtained. Results for the axial current induced in human body exposed to EM radiation has been reported by many authors using different approaches. In his work Gandhi proposes the finite difference time domain (FTDT) method [3], while King investigates the antenna

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model of the human body in ELF up to RF range, providing the analytical solutions for the current distribution [2], [3].

In this work a human body is considered as a simple cylindrical scatterer placed vertically on the perfect ground. The Pocklington type integral equation with exact kernel is solved by the Garlerkin – Bubnov boundary element technique ensuring stability and satisfactory convergence rate. The excitation function is given in the form of the incident electric field obtained by measurement

2 Assessment of the rf exposure levels

The influence of the EM fields to the human body has been investigated for a long time. Whole electromagnetic spectrum seems to be of interest, although the effects are different and dependent of the frequency range. For the RF range the biomechanisms and related dosimetric quantities are shown in **Table 1**.

Table 1 - *Metrics in exposure standards for RF range.*

Frequency range	Biomechanism	Dosimetric quant.
VLF/LF (3 kHz - 100 kHz)	Neuromuscular stimulation	Current density in excitable tissues
Intermediate RF (100 kHz - 3 GHz)	Tissue heating	Specific Absorption Rate (SAR) in W/kg
Microwaves and mm (3 GHz– 300 GHz)	Surface heating	Power Density in W/m2

Two mostly adopted international documents for RF exposure are: the IEEE Standard C 95.1-1999 issued by the Institute of Electrical and Electronics Engineering (IEEE) [12] and the Guidelines for Limiting Exposure to Time-Varying Electric, Magnetic and Electromagnetic Fields (up to 300 GHz) published by the International Commission on Non-Ionising Radiation Protection (ICNIRP) [13].

According to both guidelines the specific absorption rate (SAR), the time rate of the RF energy absorbed per unit mass, is the primary dosimetric quantity for assessing the human exposure to the base station electromagnetic fields as it is shown in **Table 1**.

The IEEE standard also establishes the limits for rms electric and magnetic fields, so called maximum permissible exposure (MPE) limits and similarly ICNIRP standard is defining the reference limits for the free – space incident fields. These reference levels for exposure are shown in Fig.1 and Fig.2. Meeting these limits SAR compliance should be ensured.

So instead of complex SAR measurements, both standards enable the choice of simpler field measurements (rms electric and magnetic fields) for compliance assessments.

In this work the free space fields incident to the human body was measured and so obtained value has been used as an excitation function for solving the integral equation for current distribution induced in the body and for the calculation of corresponding specific absorption rate.

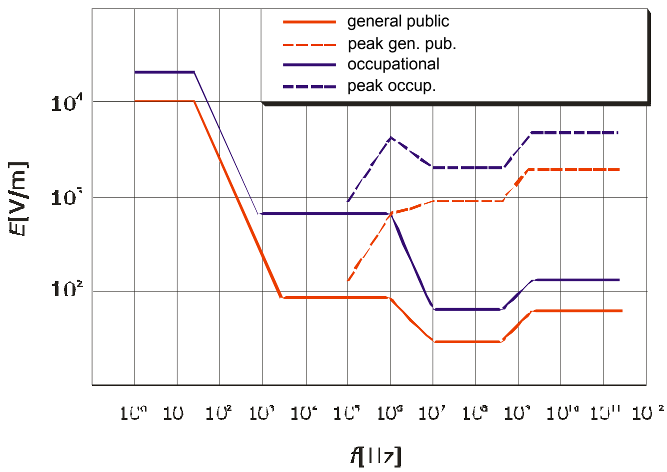

Fig. 1 - *Reference levels for exposure to time varying electric fields.*

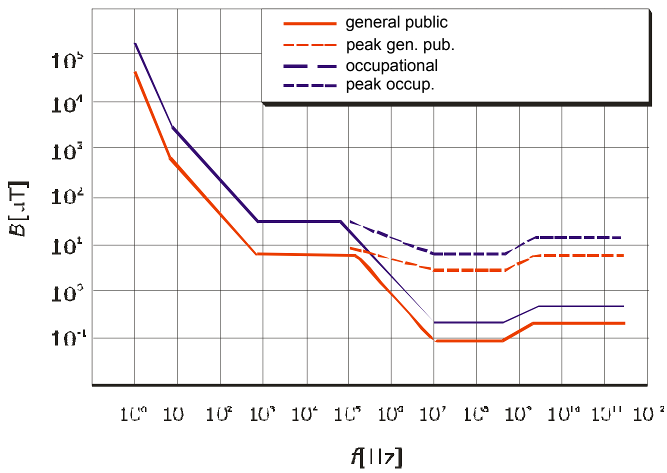

Fig. 2 - *Reference levels for exposure to time varying magnetic fields.*

3 Model of a Human Body

The human body exposed to the electromagnetic field is presented as a thick conducting cylindrical scatterer of the length L and radius a, placed vertically on the perfect ground, as it is shown in Fig.3.

According to the antenna theory and taking into account that the incident electric field is tangential to the body and that the ground is perfectly conducting, scattered field at the antenna surface is given by [4].

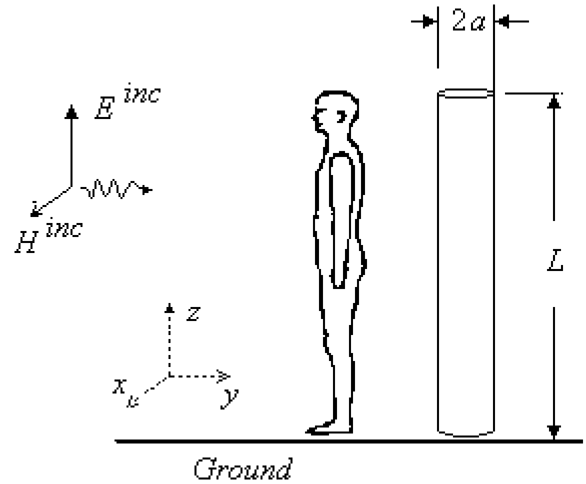

Fig. 3 - *Cylindrical model of a human body.*

$$E_z(a,z)=\frac{1}{j4\pi\omega\varepsilon_0}\int_{-L}^{L}\left(\frac{\partial^2}{\partial z^2}+k^2\right)g_E(z,z')I(z')\,dz' , \tag{1}$$

$$g_E(z,z')=\frac{1}{2\pi}\int_0^{2\pi}\frac{e^{-jkR}}{R}d\phi \quad , \tag{2}$$

where $I(z)$ is the equivalent axial current distribution in the antenna axis while $g_E(z,z')$ denotes the corresponding Green function, k is the free space phase constant, and R is the distance from the source point, (in the antenna axis), to the observation point, (on the antenna surface), of the form

$$R=\sqrt{(z-z')^2+4a^2\sin^2\frac{\phi}{2}} \quad . \tag{3}$$

The total tangential electric field at the antenna surface can be written as the sum of the incident electric field, produced by the RF transmitter E^{inc}, and the scattered field on the antenna surface E^{sct}

$$E_z^{tot}(a,z)=E_z^{inc}(a,z)+E_z^{sct}(a,z) . \tag{4}$$

As the body is imperfectly conducting, loss in the cylinder can be included in the integral equation through the impedance loading the cylinder, as it is proposed by most of the authors [2], [3], [10]. Total tangential electric field so can be expressed by means of the current $I(z)$ and the impedance per unit length of the antenna $Z_L(z)$

$$E_z^{tot}(z)=Z_L(z)I(z) . \tag{5}$$

The Pocklington integral equation for loaded wire mounted on a perfect ground is given by [4],

$$E_z^{inc}(a,z) = -\frac{1}{j4\pi 4\varepsilon_0}\int_{-L}^{L}\left[\frac{\partial^2}{\partial z^2}+k^2\right]g_E(z,z')I(z')dz' + Z_L(z)I(z)\,. \tag{6}$$

According to [3], corresponding impedance per unit length of the cylinder is given by

$$Z_L(z) = \frac{1}{a^2\pi\sigma}\left(\frac{ka}{2}\right)\frac{J_0(j^{-1/2}ka)}{J_1(j^{-1/2}ka)} + Z_c\,, \tag{7}$$

where J_0 and J_1 are the corresponding Bessel functions.

Solving the integral equation (6) yields the axial current distribution induced in the body. When this axial current is once known it is possible to determine the current density, the electromagnetic field and the power density induced in the body [2]. Using King's expression the current density inside the body can be calculated from the equation [3]:

$$J_z(\rho,z) = \frac{I(z)}{a^2\pi}\left(\frac{ka}{2}\right)\frac{J_0(j^{-1/2}k\rho)}{J_1(j^{-1/2}ka)}\,. \tag{8}$$

4 Calculation of the Electric Field and Sar

When the current density is known, the induced electric field at any point onside the cylindrical model of the body can be determined from the expression:

$$E_z(\rho,z) = \frac{J_z(\rho,z)}{\sigma + j\omega\varepsilon}\,, \tag{9}$$

where σ and ε are the electrical properties of the human body.

Specific absorption rate (SAR) is defined as the mass averaged rate of energy absorption in tissue,

$$SAR = \frac{d}{dt}\frac{dW}{dm} = \frac{d}{dt}\frac{dW}{\rho dV} \tag{10}$$

and it is expressed in W/kg.

The absorption of electromagnetic energy causes a temperature rise within a tissue, therefore the SAR is also a measure of the local heating.

The temperature rise is determined with dissipated power density:

$$p(\rho,z) = \sigma\,|E_z(\rho,z)|^2\,. \tag{11}$$

If the tissue would be assumed to have a density of water the specific absorption rate could be defined by (11). For the real tissue density ρ the SAR can be calculated from the expression

$$SAR = \frac{|J|^2}{\sigma\rho} = \sigma\frac{|E|^2}{\rho}\,. \tag{12}$$

According to the investigations done by Balzano and Faraone [5], [6] and [8] another approach to the calculation of the assessment of the human exposure to cellular base station radiation can be performed. Introducing the reference cylindrical configuration for the collinear half-wave resonant dipoles, the predicted average radiated power density P_d at the distance ρ from the array can be expressed in term of the peak antenna gain G_A and radiated power P_{rad} [7], [8],

$$\overline{P_d}(\rho\!\!/|\varphi|<\gamma;L) = \frac{NP_{rad}}{2\gamma\gamma\rho 2\sqrt{1+(\rho\rho\rho_0)^2}}\;,\; \rho_0 = \frac{\gamma}{\pi}G_A\,. \tag{13}$$

If the base station antenna radiation is approximated by plane wave analytical approximation formula proposed in [9] can be can be used

$$SAR = \frac{\sigma}{\rho}\frac{\mu\omega}{\sqrt{\sigma^2+\omega^2\varepsilon^2}}(1+\gamma_{pw})^2\frac{|E^{inc}|^2}{Z_0^{\,2}}\;,\; \gamma_{pw} = \frac{2\left|\sqrt{\varepsilon'}\right|}{\left|\sqrt{\varepsilon'}+\sqrt{\varepsilon_0}\right|}-1\,, \tag{14}$$

where E^{inc} is the root-mean-square (*rms*) value of the incident electric field, and γ_{pw} is the corresponding reflection coefficient and ε' is the complex permittivity of the medium. In this work a new approach to the calculation of the SAR distribution inside the human body is proposed. The integral equation (6) for the axial current distribution was solved. The current density and electric field inside the body was calculated from (8) and (9). Obtained results then were used for calculating SAR from equation (12).

5 Numerical Procedure and Results

The Pocklington integral equation is usually modelled by combining the collocation techniques and finite difference method [1].

In this work the weak Galerkin – Bubnov formulation of the variant of finite element method is used. As the modelled integro-differential equation is defined for the surface of the cylinder, this approach can be referred as the boundary element method (BEM). It is, in fact, a combination of the classical boundary method for solving integral equations and some numerical schemes originated from finite element method (FEM), i.e. finite element technique was used for boundary elements.

In the finite element solution of the free space electric field integral equation, so called "strong" formulation, differentiation over the integral equation kernel must be performed analytically which may result in quasisingularity. This problem then has to be treated by adequate transforms. In proposed numerical calculation the convenient property of the integral kernel was utilized and the weak formulation of the equation (6) was obtained. The term weak used here is taken from the similar finite element procedure for solving partial differential equations.

This approach offers some important advantages:

- The second-order differential operator is replaced by trivial derivatives over basis and test (weight) functions;
- The basis and test functions can be chosen quite arbitrarily (only they have to be order-one differentiable); and
- The boundary conditions are subsequently incorporated into the global matrix of the linear equation system (in MoM basis and test functions have to be chosen so to satisfy the boundary conditions).

According to the well-known finite element algorithm the system of equations arising from equation (6) is obtained [4]:

$$\sum_{i=1}^{M}[Z]_{ji}\{I\}_i=\{V\}_j\,,\quad j=1,2,...,M\,, \tag{15}$$

where $[Z]_{ji}$ is the local matrix presenting the interaction of the i-th source boundary element to the j-th observation boundary element:

$$\begin{aligned}[Z]_{ji}=-\frac{1}{j4\pi\omega\varepsilon_0}\{&\int_{\Delta l_j}\int_{\Delta l_i}\{D\}_j\{D'\}_i^T g_E(z,z')dz'dz+\\ &k^2\int_{\Delta l_j}\int_{\Delta l_i}\{f\}_j\{f'\}_i^T g_E(z,z')dz'dz\}+\\ &+\int_{\Delta l_j}Z_L(z)\{f\}_j\{f\}_j^T dz\end{aligned}\quad, \tag{17}$$

where vector $\{I\}$ contains the unknown coefficients of the solution, matrices $\{f\}$ and $\{f'\}$ contain shape functions $f_k(z)$ and $f_k(z')$, while $\{D\}$ and $\{D'\}$ contain their derivatives. M is the total number of boundary elements, and Δl_i, Δl_j is the width of i-th and j-th boundary element, respectively. Functions $f_k(z)$ are the Lagrange's polynomials.

$\{V\}_j$ is the local right-side vector for j-th observation boundary element:

$$\{V\}_j=-\int_{\Delta l_j}E_z^{inc}\{f\}_j dz\,, \tag{18}$$

representing the local voltage vector. The excitation function in the form of the incident field is obtained by measurement and assumed to be constant along the human body. So the boundary element right - side vector is computed in the closed form (i.e. using the linear approximation)

Since the shape functions have to be differentiable at least once, a family of Lagrange's polynomials should be a convenient choice. So the first order approximation over boundary element was used since it was shown that this choice provides accurate and stable results.

The results for SAR distribution along the human body are shown in Fig.4.

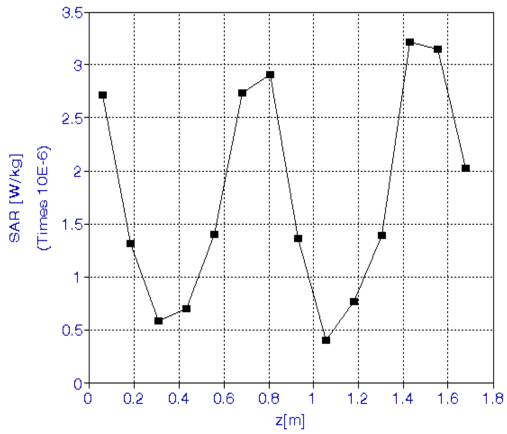

Fig. 4 - *SAR distribution along the human body (f = 900 MHz, measured field E = 2 V/m).*

The incident field of 2 V/m was measured at a 20 m distance from the base station. It can be seen that the maximum value of SAR obtained by the integral equation approach is 3.215 μ W/kg, while the approximation formula (14) gives the value of 2.868 μ W/kg.

6 Compliance with the Exposure Limits

The increasing concern about possible health risks resulting from exposure to electromagnetic fields should keep step with scientific evidence. But despite the enormous amount of research caring out so far and variety of results obtained in many areas of the investigation, some uncertainties are still present (especially concerning some long term effects).

In the last few years a noticeable acceleration in the activities related to the technical standards in the area of the human exposure of electromagnetic fields has been evidenced at the international, European and national levels [11]-[15].

Various theoretical and experimental techniques for radio base station exposure assessment are present in literature. Numerical [1] and analytical [1] approach was utilized.

In order to assess the potential radiation hazard of the electromagnetic field around the GSM base station during the normal operation, measurement of the fields and calculation of the induced currents and SAR at the few defined location in Split has been done on request of Croatian Telecom.

To illustrate the procedure, which was carried out so to be able to compare the field levels in the vicinity of the GSM base station with the corresponding limits given in the guidelines, the measurements and calculation of SAR for one particular three – sectorial base station is described in this paper. Antenna is located on the top roof of a building. Each sector of the base station has installed a Kathrein 739634 transmitting antenna, radiating three carriers (channels) per sector with 10 W per carrier. Fig.5. shows the ground – plan with three defined measurement points. The photo of the base station taken from the measurement point 3 (residential area on the hill) is shown in Fig.6.

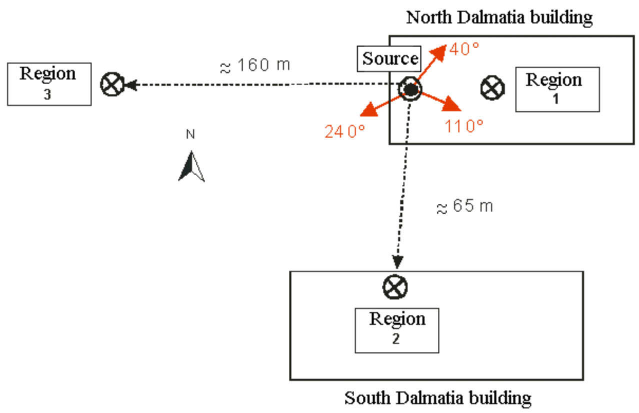

Fig. 5 - Ground plan with the measurement points.

Fig. 6 - *View from the measuring point 3.*

For the wide band (and near field) measurements Holaday Industries HI - 4455 + HI - 4460 isotropic probe was used, and for the narrow band measurements the calibrated electrical dipole (EMCO 3121C DB4) for the electric field and spectrum analyser (Anritsu MS2661C) for the radiated power.

Value of total electric field obtained by the wide band measurement procedure at this site was: E_{tot} = 1.7 V/m.

Results of the electric field obtained by narrow band measurement compared with the permissible limits are given in **Table 2**.

Table 2 - *Comparison with the exposure limits.*

Measured electric field	$\sum E$ =1.531V/m	
Measured power density		$\sum S$ =6.216 mW/m^2
National recommend.	$E_{\lim it}$ =16.82 V/m	
International and European recommend.		$S_{\lim it}$ =4.8 W/m^2
Health risk measure	$(\sum E)^2 / E^2_{\lim it}$ = 0.828 % = - 20.82 dBlimit	$\sum S / S_{\lim it}$ = = 0.129 % = - 28.88 dBlimit

Results of the computed SAR for the measured value of electric field at three defined points are shown in **Table 3** and the basic restrictions for SAR (100 kHz – 10 GHz) according to the recommendation [13] can be seen in **Table 4**.

Table 3 - *Computed SAR for measured electric field.*

Point	*E* [V/m]	*SAR* [μW/kg]
1	0.592	0.25
2	0.867	0.54
3	1.531	1.68

Table 4 - *Basic restrictions for SAR given in [12].*

SAR [W/kg]	Occupational exposure	General public exposure
Whole body average	0.4	0.08
Localized (head and trunk)	10	2
Localized (limbs)	20	4

7 Conclusion

In order to ensure that the requirements for protecting the human beings from hazardous effects, which my be caused by electromagnetic fields emitted by base station antenna, the measurement and calculation of electric field and specific absorption rate has been done.

The analysis of a human being interaction with RF electromagnetic fields based on a simple thick wire antenna model of the body is presented. It is shown that such simple model can be successfully used for predicting the penetration of the electromagnetic field into body. Combining the advantages of the model simplicity and the advantages of applied Galerkin Bubnov variant of the boundary element method in solving the Pocklington integral equation with measured incident field, it is shown that the obtained results can be useful in the assessment of the radiation health risk same as much more demanding calculation for realistic model of a human body performed by FDTD method.

This approach could be useful in terms of monitoring and public information about the level of protection from the exposure to the base station electromagnetic fields.

The proposed procedure for assessing compliance with the exposure limits combine the numerical prediction and simple measurement of the free space field. Measurement of the field is not of the importance only because it is not always possible to predict correctly the value of the incident field, especially in the complex surroundings, but also the important advantage of such approach is the fact that the measured values are usually better accepted in public.

References

[1] O. P. Gandhi, Y. Gu, YJ.Y. Chen, H. I. Bassen: Specific Absorption Rates and Induced Current Distributions in an Anatomically Based Human Model for Plane Wave Exposures, Health Physics, Vol. 63, No 3, Sept. 1992, pp. 281 - 290.

[2] R. W. P. King: Models and Methods for Determining Induced ELF and VLF Electromagnetic Fields in the Human Body: A Critical Study, Proc. of IEEE 23rd Annual Northeast Bioengineering Conference, J. R. La Course, Ed., IEEE Service Center, Piscataway, NJ, 1997.

[3] R. W. P. King: Electric Current and Electric Field Induced in the Human Body When Exposed to an Incident Electric Field Near the Resonant Frequency, IEEE Trans. Microwave Theory and Tech., Vol. 48, No 9, Sept. 2000, pp. 1537 - 1543.

[4] V. Roje, D. Poljak: Wire Antenna Model of the Human Body Exposed to the Low Frequency Electromagnetic Fields, AFRICON 5th IEEE Conf. Cape Tow Sept/Oct. 1999. Proc. Vol. 2, pp. 1045 - 1048.

[5] Q. Balzano, A. Faraone: Human Exposure to Cellular Base Station Antennas, Proc. IEEE Int. Symposium on Electromagnetic Compatibility, pp. 924 - 927, Seattle, Washington, USA, Aug. 2 - 6 1999.

[6] P. Bernardi, M. Cavagnaro, S. Pisa, E. Piuzzi: Human Exposure to Radio Base Station Antennas in Urban Environment, IEEE Trans. MTT, Vol. 48, No 11, pp. 1996 - 2002, Nov. 2000.

[7] A. Faraone: Experimental and Analytical Techniques for Radio Base-Station exposure assessment, Proc. of Int. Symposium on Electromagnetic compatibility, EMC Europe 2002, pp. 485 - 489, Sorrento, Italy, Sept. 2002.

[8] A. Faraone, et al.: Estimation of the Average Power Density in the Vicinity of Cellular Base Station Antenna, IEEE Trans. On Vehicular Technology, Vol. 49, No 3, pp. 984 - 996, May 2000.

[9] N. Kuster, Q. Balzano: Energy Absorption Mechanism by Biological Bodies in the Near Field of Dipole Antennas Above 300 MHz, IEEE Trans. Vehicular Tech., Vol. 41, No 1, Feb. 1992, pp. 17-23.

[10] D. Poljak, V. Roje, A. Šarolić: Human Interaction with the Electromagnetic Field Radiated from a Cellular Base Station Antennas, Proc. of Int. Symposium on Electromagnetic compatibility, EMC Europe 2002, pp. 965 - 968, Sorrento, Italy, Sept. 2002.

[11] J. Wiart, C. Dale, M. F. Wong: EMF Exposure Standard Regarding Base Stations, Proc. of Int. Symposium on Electromagnetic compatibility, EMC Europe 2002, pp. 475 - 483, Sorrento, Italy, Sept. 2002.

[12] IEEE Std. C95.1-1999 Standard for Safety Levels with Respect to Human Exposure to RF Electromagnetic Fields, 3 kHz to 300 GHz.

[13] International Commission on Non-Ionising Radiation Protection (ICNIRP): Guidelines for Limiting Exposure to Time-Varying Electric, Magnetic, and Electromagnetic Fields (up to 300 GHz), Health Phys., Vol. 74, 4, (1998) pp. 494 - 522.

[14] ENV 50166-2: Human exposure to electromagnetic fields – High frequency (10 kHz to 300 GHz), CENELEC, Brussels, 1995.

[15] European Council Recommendation of 12 July 1999 on the limitation of exposure of the general public to electromagnetic fields (0 Hz to 300 GHz) – 1999/519/EC, Official Journal of the European Communities, L 197 of 30 July 1999.