

ESTIMATED AND MEASURED VALUES
OF THE RADIOFREQUENCY RADIATION POWER DENSITY
AROUND CELLULAR BASE STATIONS*

S. MICLAUS¹, P. BECHET²

¹ Land Forces Academy, 3–5 Revolutiei St., 550170 Sibiu, Romania, miclaus@armyacademy.ro

² Communication and Informatics Center, 1–3 V. Milea St., 550325 Sibiu, Romania

Received September 12, 2006

Theoretical and experimental assessment of radiofrequency exposure due to cellular base station antennas is treated. The calculation of the incident power density of the radiation flux is possible by knowing the antenna's technical data from the constructor and by defining the position of the exposed person. The free space propagation model in ideal conditions yet allow just a gross assessment of exposure in the far field region of the antenna, which generally overestimates the real exposure level. Exposure assessment may be also theoretically calculated in near field conditions, with a better agreement with real cases. The compliance distance from the antenna is another important parameter and it can be calculated in accordance to the reference levels stipulated in exposure standards. From experimental perspective, far field in situ measurements of power density level were made in a limited number of locations, by using the frequency-selective method and equipment. The results are discussed, regarding both the obtained values and the factors that influence the measurements. The measured values were well below the maximum permissible exposure levels in the adopted standard in our country.

Key words: radiofrequency, mobile communications, human exposure, power density, base station antenna.

1. INTRODUCTION

In the last decade, the massive proliferation of mobile communications equipment raised a special concern regarding the safety of population and personnel exposed to radiofrequency (RF) radiation emitted by either the cellular phone terminals or the base-station antennas (BSA) [1].

Exposure standards for RF region of electromagnetic spectrum, applicable at national or international level give, for the UHF band of interest, the rms electric field strength (E , in V/m) or power density (S , in W/m²) maximum

* Paper presented at the 7th International Balkan Workshop on Applied Physics, 5–7 July 2006, Constanța, Romania.

accepted values, as reference levels for occupational or population exposure [2–4], in the far field region of the sources.

Besides the continuous research made in the field of biological effects of RF radiation, a secondary debate focuses on the harmonization of the exposure standards throughout Europe. In Romania, the adopted standard limits for human exposure are those given in the ICNIRP guidelines [2] and in the Recommendation adopted by the Working Group “Frequency Management” of the Electronic Communications Committee (ECC) within the European Conference of Postal and Telecommunications Administrations (CEPT), ECC/REC/02/04 [4]. In other countries, like Italy or Switzerland, more strict limits are valid for BSA of mobile communications emissions.

Human exposure is quantified by the distribution of the time derivative of the absorbed electromagnetic energy per unit mass, *i.e.*, specific absorption rate (SAR). The standards give the accepted maximum values for this quantity, in the form of basic restrictions, which are the starting point in the computation of the reference levels given in the standards.

In the present, there are four public mobile communication operators in Romania: Vodafone (GSM 900 MHz and 3G-UMTS 2 GHz), Orange (GSM 900 MHz and 3G-EDGE 2 GHz), Telemobil – Zapp (CDMA and EV-DO 450 MHz) and Cosmote (DCS 1800 MHz).

In order to assess the human exposure and to compare it to the safety limits, there are two possibilities: a) to use computational capabilities in order to simulate the propagation of radiofrequency waves in the space of interest and compute the *E*-field value or the power density *S*-value; b) to measure actual values by using the appropriate system and methodology. In the first case, expensive professional software, that counts on complex environmental conditions in high detail (by taking into account wave propagation mechanisms like reflection, diffraction, absorption, interference) may be used. However, a gross assessment, much cheaper, may be obtained by using simplified analytical calculations, but the computed values are rather orientative. In the second case, either wideband survey meters or frequency-selective receivers/spectrum analyzers with calibrated receptor antennas are needed, for in situ measurements or compliance assessment. To verify compliance with frequency dependent limits and observe the progression of radiofrequency emitters with their signals, technically suited and reproducible measurement methods and instruments have to be established.

Present paper aims to apply and discuss both possibilities of exposure assessment due to RF GSM BSA emissions. It gives an example of simplified calculation of the human exposure next to a BSA (near and far field) and it also discuss the methodology and results of in situ measurements made in some urban locations, both outdoor and indoor, in far field conditions.

The results show that precise experimental measurement of power density of the radiation in a complex and dynamic environment is a difficult task. The measurement equipment technical specifications, its settings, the measurement methodology together with a significant number of external factors that may affect accurate results, all must be carefully studied and setup. As for now, the measured values of RF emissions from BSA are situated well below the standard indicated maximum permissible values.

2. MATERIALS AND METHODS

2.1. THEORETICAL ESTIMATION OF POWER DENSITY LEVELS NEAR A BASE STATION ANTENNA

Power density of the equivalent plane wave is generally expressed as:

$$S = \frac{1}{2} \cdot \text{Re}(\bar{E} \times \overline{H^*}) = \frac{|E_{rms}|^2}{Z_0} = Z_0 \cdot |H_{rms}|^2 \quad (1)$$

The most simple case is the one when a human is exposed to a single BSA, as shown in Fig. 1. In this case, the power density at his position (given by R , θ and φ) may be calculated by the relation:

$$S = 0.08 \cdot \frac{P}{R^2} \cdot 10^{G/10} \quad [\text{W/m}^2] \quad (2)$$

where P is the emitted power emitted by the antenna (in W), and G is the antenna gain (in dB) in the direction where the person is placed relative to antenna.

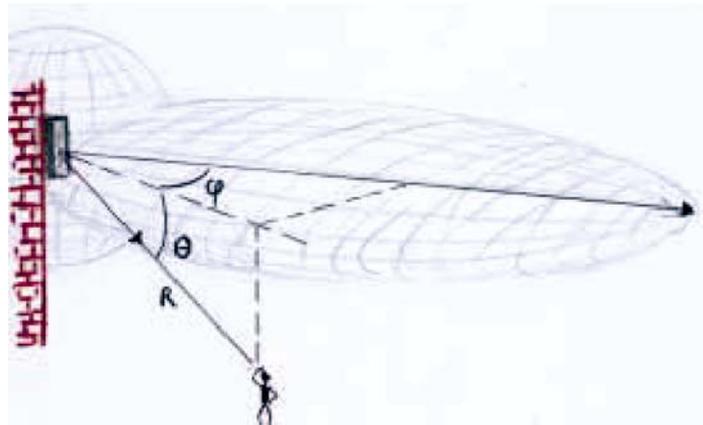


Fig. 1 – Human exposure in the far field of a sector BSA.

In the case when there are simultaneously present a number of N antennas, the total power density is obtained as the sum of the individual S_i from each antenna in the point of interest. This is the simplest way to estimate the exposure in the far field of BSA, but the results are just orientative, since they don't take into account the realistic conditions of exposure and the environment effects.

Prediction formulas were determined for the estimation of the average power density in the close proximity (near field) of a BSA [5] or for the peak power density [6]. It was shown that for a collinear array of antenna elements (either omnidirectional or sectorial), the average power density has a cylindrical decay in the radiative region of the near field ($d > \lambda$) of the antenna and a spherical decay in its far field. An analytical technique allows the analysis of the spatial field distributions and the radiation mechanisms of periodic and nonperiodic linear arrays in the near fields of BSA [7]. The results presented in [7] provide extremely useful information when assessing compliance to RF safety limits especially for occupational exposure, where near field irradiation is inevitable.

Cylindrical character of near (radiative) field converts to spherical character at a distance from a sectorial antenna [6]:

$$\rho_0 = \frac{\overline{\phi_{3dB}}}{6} \cdot D_A \cdot L \quad (3)$$

where $\overline{\phi_{3dB}}$ is the horizontal half power (or -3dB) beam width, D_A is the antenna broadside directivity, L is the antenna height.

In the case of sector antennas, as most of BSA are, the average power density in the near (cylindrical) field, at horizontal distance from the antenna center ρ , and at azimuth ϕ , is [5]:

$$\overline{S}_\rho(\rho, \phi) = \frac{W_{rad} \cdot 2^{-(\phi/\overline{\phi_{3dB}})^2}}{2 \cdot \overline{\phi_{3dB}} \cdot \rho \cdot L \cdot \sqrt{1 + \left(\frac{\rho}{\rho_0}\right)^2}} \quad (4)$$

where W_{rad} is the net radiated power (which can be expressed as $W_{rad} = e_A \cdot W_{fwd}$, where e_A is the antenna efficiency and W_{fwd} is the forward power at the antenna connector).

The compliance distance from BSA then can be calculated as:

$$\overline{\rho} = \rho(\overline{S}) \approx \rho_0 \cdot \frac{q}{\sqrt[4]{1 + q^2}} \quad (5)$$

where:

$$q = \frac{3 \cdot W_{rad} \cdot 2^{-(\phi/\overline{\phi_{3dB}})^2}}{\overline{\phi_{3dB}}^2 \cdot L^2 \cdot D_A \cdot \overline{S}} \quad (6)$$

Relations (4) and (5) offer a simple and accurate way to calculate exposure level and compliance distance for occupational exposure, when needing comparison to the maximum permissible exposure levels, as stipulated by the IEEE standard [8].

As per ICNIRP reference levels, the peak power density needs to be calculated and compared to standardized value. In this case, peak power density in the near field region of BSA is given by [6]:

$$S_{\rho}^{peak}(\rho, \phi) = \frac{W_{rad} \cdot 2^{-(\phi/\bar{\phi}_{3dB})^2}}{\bar{\phi}_{3dB} \cdot \rho \cdot L \cdot \sqrt{1 + \left(2 \cdot \frac{\rho}{\rho_0}\right)^2}} \quad (7)$$

and the afferent compliance distance:

$$\rho^{peak} = \rho(S^{peak}) \approx \rho_0 \cdot \frac{2 \cdot q}{\sqrt[4]{1 + (4q)^2}} \quad (8)$$

where q has the same expression as in (6) with the observation that instead \bar{S} will appear S^{peak} .

2.2. MEASUREMENTS OF FIELD LEVEL AND POWER DENSITY IN THE AREA OF GSM BASE STATION ANTENNAS

Following the requirements of ICNIRP guidelines, the essential features for RF measurement equipment can be derived. The principal need is that the system to be frequency selective, because of frequency dependent limits, and in order to enable the assessment of the worst-case exposure to RF fields emitted by BSA. The equipment must also be sensitive enough, must allow averaging the values over any 6 minutes in time and averaging in space, considering the volume of the human body respectively the interesting areas of it. It is essential to use procedures that allow measurements with low uncertainty and good reproducibility [9, 10].

The portable measurement system that we used was the TS-EMF system by Rohde & Schwarz and it was composed by a spectrum analyser type FSH 3 with its isotropic sensor (Fig. 2), [11]. The system was computer driven, while the R&S RFEX software enables data acquisition and settings management.

A low-scale campaign of in situ measurements was developed in an urban area. Most locations were sited outdoor, but also indoor measurements were made.

One important step is a correct measurement methodology and protocol. In this regard, the ECC Recommendation [4] and the French protocol [12] were strictly followed.

Another crucial and sensitive issue regards the settings of the spectrum analyser. It is of big importance to correctly set the resolution bandwidth (RBW),



Fig. 2 – TS-EMF measurement system for frequency selective measurements.

sweep rate (SR) and detector [13]. The system we used is designed for measurements of the E -field strength or power density. For the major services, measurement packets are predefined through the software (for example GSM packets). This ensures that optimum settings are used and allows evaluation according to single frequencies, complete services and total emission. Since the tri-axis sensor (antenna) has got an isotropic characteristic, the measurement is done independent from direction or polarization of the emitter. This makes measurements easier. In contrast to directional antennas it is no longer necessary to move the antenna for covering all directions and polarization.

Reproducible time averaging method with well known uncertainty estimation can be performed on one single point in the area of interest. Different measurement modes were possible and applied: a) single measurement (*e.g.* for overview); b) average and peak (*e.g.* 6 minutes average); c) long term (*e.g.* determination of time variations in the signals). The most used was the average & peak measurements. To achieve the best accuracy, the system TS-EMF has its individual calibration. The calibration values are stored in the software RFEX and the calibration values are automatically calculated in the measurement result.

To increase the sensitivity of the TS-EMF System, the function Threshold-Calibration can be introduced, and in all measurements this was applied.

In the case of GSM900 pre-defined packet, the RBW = 200 kHz and the trace mode was Max Hold. The dwell time DT = 5000 ms and in the case of average values the measurement period was of 6 minutes. For GSM1800 packet, the RBW = 200 kHz and DT = 10000 ms. All measurements were made fully-automatic using the R&S software RFEX. Not only distance from the source was varied during measurement campaign in one location (in the xOy plane), but also

the height of the sensor, for the same location (in the Oz direction), so as to outline minute variations in the field level.

3. RESULTS AND DISCUSSION

3.1. CALCULATED VALUES AND DISCUSSION

Most of the sector BSA in Romania are Kathrein models. In order to get an idea about the theoretical level of human exposure, in the far and in the near field conditions, we chose for next calculations the Kathrein BSA model 730370 with 4 vertical dipoles. The producer data are for this antenna are: emission frequency is 947.5 MHz, the horizontal half power beam width is $\overline{\phi_{3dB}} = 92.3^\circ$, the gain is 12 dBi, the horizontal directivity is 5.5 dBi and total length of antenna is 1.3 m.

By calculations, the radiative field starts from a distance of $r \approx 5.25$ m, while the far field starts from $r \approx 10.57$ m from antenna panel. The distance at which the cylindrical character of radiation transforms to spherical one is $\rho_0 = 1.92$ m, as given by (3).

If the antenna is placed on a tower at $h = 20$ m above the ground, and has an emitted power of 16 W, then a person positioned on the ground at $(R, \theta, \varphi) = (40 \text{ m}, 60^\circ, 30^\circ)$ under the antenna (see Fig. 1) will face, as for relation (2), a theoretical power density value $S_{theor} = 1.52 \text{ W/m}^2$ while the gain in the mentioned point is $G = -7.2 \text{ dB}$. This power density level is about 1/3 bellow standard limit of ICNIRP.

We calculated the near field exposure in the person's position at $(\rho, \theta, \varphi) = (4 \text{ m}, 60^\circ, 30^\circ)$, that is at $h' = 6.93$ m under the antenna horizontal plane, by using relations (4) and (7). We get the average and peak power densities in this exposure case: $\bar{S} = 0.310 \text{ W/m}^2$ and $S^{peak} = 0.335 \text{ W/m}^2$. Comparing to maximum limits given in the IEEE standard, i.e. $\bar{S}_{max} = 6 \text{ W/m}^2$ for uncontrolled conditions (population) and $\bar{S}_{max} = 30 \text{ W/m}^2$ for controlled conditions (professional) corresponding to $f = 900 \text{ MHz}$, we conclude that the exposure due to this antenna in the afore-mentioned position pose no security problems. Also, comparing the peak calculated value of power density, and compare it to reference values from ICNIRP standard, i.e. $S_{max}^{peak} = 4.5 \text{ W/m}^2$ (population) and $S_{max}^{peak} = 22.5 \text{ W/m}^2$ (occupational), the calculated value is very low at this position.

The compliance distances based on average (IEEE standard) or peak (ICNIRP standard) power densities values, are also calculated on azimuth direction $\varphi = 30^\circ$. We get $\bar{\rho} = 0.43 \text{ m}$ and $\rho^{peak} = 0.76$ from the Kathrein antenna. These are horizontal distances, measured from the centre of the panel.

3.2. MEASURED VALUES AND DISCUSSION

Measurements of GSM900 *E*-field strength or power density took place in urban, extra-urban locations, outdoor and indoor. In situ measurements were made in sensitive areas mostly, tracking both peak and average values (over 6 minutes). Examples of peak values measured in some locations are given here. Locations 1 and 2 are urban locations, while location 3 is extra-urban one. In Fig. 3a, b, c one can see this locations.

An example of GSM900 peak values spectrum and their distribution, for a location near to no. 1, namely on the roof of a school in the same area, is represented in Fig. 4. The settings for this measurement are:



a – Loc. 1



b – Loc. 2



c – Loc. 3

Fig. 3 – Locations of exemplified measurements.

Trace Mode / Detector: Max Hold / RMS
 Res BW / Video BW / Span: 200 kHz / Auto / 30.000 MHz
 Ref Level: 91 dB μ V
 Dwell time: 5000 ms

Power density peak values measured in the 3 locations exemplified in Fig. 3 are:

$$S_1^{peak} = (9.66 \pm 2.73) \times 10^{-5} \text{ W/m}^2$$

$$S_2^{peak} = (23.00 \pm 5.51) \times 10^{-5} \text{ W/m}^2$$

$$S_3^{peak} = (62.00 \pm 13.54) \times 10^{-5} \text{ W/m}^2$$

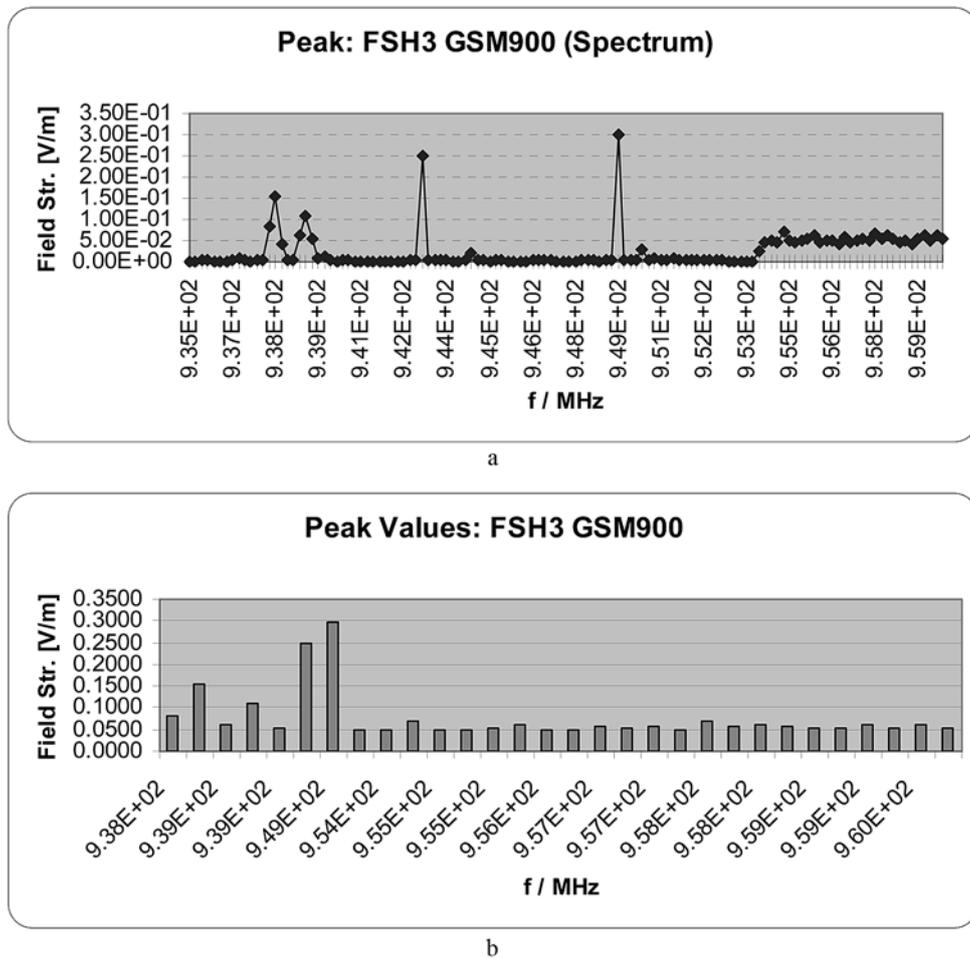


Fig. 4 – Peak E -field strength spectrum (a) and peak values distribution (b) in the GSM900 band for signals measured in location number 1 for a 6 minute long series.

The existence of a large number of scatterers and absorbing objects around leads to a highly nonuniform field distribution in the environment of BSA due to shadowing and fast fading effects. Houses, trees, cars and other objects can lead to field variations that can only be determined by very large measurement campaigns. The buildings cause a strong shadowing effect so the field distribution is very heterogeneous [14–16].

In indoor conditions (inside buildings), the field distribution is even more complicated. It may happen that inside a room volume, the *E*-field strength of a GSM broadcast channel (BCCH) alone, which operates permanently and on the same power, to vary from point to point inside the room as much as +8 to –10 dB from the average value. So a single measurement is completely nonrepresentative for the exposure scenario. Field variations versus time caused by changes of the power of traffic channels, the stability of BCCH's or moving scatterers have to be taken into account in order to determine their contribution to the uncertainty of exposure assessment [17].

The search for maximum field level is a very crucial point, because of the need of comparison to the limits given in exposure standards. The reproducibility of identified maxima is one of the largest problems, due to field variations in time and space. In this context it is important to say that the selection of the location for performing measurements is very important.

4. CONCLUSION

Theoretical methods for *E*-field or power density levels of RF emissions may be applied, in a first instance, for having an idea about the exposure level in the area of a specific BSA. It is possible to assess the power density in the far field of the antenna, in pure ideally conditions and also the power density in the near field – radiative area. However, the agreement between the simple free space propagation calculations and measured peak power density values, especially for indoor situations around a BSA, is rather poor.

Qualitative and quantitative analysis of the results of simple measuring methods compared to more complex methods, based on extensive measurements under realistic conditions, shows that simple methods generally overestimate the average field situation.

During measurement campaign the reproducibility of successive measurements may be low.

The precise experimental determination of power density of RF radiation in a complex environment is a difficult task. This is mainly due to the existence of three fundamental physical properties of electromagnetic waves: reflection, absorption and interference. Under uncontrolled conditions, for instance in a complicated environment, different measurements can lead to quite different

results due to changing conditions. Moreover, the settings of the measurement equipment may affect sensible the measured values. Special attention should be offered to the exposure assessment methodology.

During measurement campaign in a limited number of locations we made up to the present, the maximum power density levels from GSM900 BSA in the far field, never exceeded the reference levels stipulated in the INCNIRP guidelines that are in act in our country.

Acknowledgement: Present work was developed in the framework of a project with contract no. CEx 05-D11-54/10.10.2005 given by the Ministry of Education and Research to Land Forces Academy in Sibiu.

REFERENCES

1. U. Bergqvist, G. Friedrich, Y. Hamnerius *et al.*, *Mobile telecommunication base stations – exposure to electromagnetic fields*, Report of a Short Term Mission within COST 244bis, COST 244bis Short Term Mission on Base Station Exposure, 2001.
2. ICNIRP *Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz)*, Health Physics 74 (4), pp. 494–522, 1998.
4. EUR-OP: *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 J. European Communities, Luxembourg, 1999.
4. ECC RECOMMENDATION (02)04 revised, *Measuring non-ionising electromagnetic radiation (9 kHz – 300 GHz)*, October 2003.
5. A. Faraone, R. Yew-Siow Tay, K. H. Joyner, Q. Balzano, *Estimation of the Average Power Density in the Vicinity of Cellular Base-Station Collinear Array Antennas*, IEEE Trans. on Vehicular Technology, vol 49, no. 3, pp. 984–996, May 2000.
6. R. Cicchetti, A. Faraone, *Estimation of the Peak Power Density in the Vicinity of Cellular and Radio Base Station Antennas*, IEEE Trans. on Electromagnetic Compatibility, vol. 46, no. 2, pp. 275–290, May 2004.
7. R. Cicchetti, A. Faraone, Q. Balzano, *A Uniform Asymptotic Evaluation of the Field Radiated from Collinear Array Antennas*, IEEE Trans. on Antennas and Propagation, vol. 51, no. 1, pp. 89–102, Jan. 2003.
8. IEEE Standard for Safety Levels with Respect to Human Exposure to RF Electromagnetic Fields, 3kHz to 300GHz, IEEE Std. C95.1-1999.
9. S. M. Mann, T. G. Cooper, S. G. Allen, R. P. Blackwell, A. J. Lowe, *Exposure to Radio Waves near Mobile Phone Base Stations*, Chilton, Natl. Rad. Protect. Board Report – 321, 2000.
10. G. Neubauer, D. Papameletiou, T. Samaras, Y. Hamnerius, J. Wiart, K. Lamedschwandner, *Methods to assess exposure of the population next to mobile communication base stations*, 27th triennial General Assembly of the International Union of Radio Science, Maastricht, 2002.
11. Portable EMF Measurement System, User Manual, Rohde & Schwarz, Germany, 2003.
12. Agence Nationale de Frequences, *Protocole de mesure in situ, Visant à vérifier pour les stations émettrices fixes, le respect des limitations, en terme de niveaux de référence, de l'exposition du public aux champs électromagnétiques prévues par le décret n° 2002-775 du 3 mai 2002.*
13. C. Olivier, L. Martens, *Optimal Settings for Narrow-Band Signal Measurements used for Exposure Assessment Around GSM Base Stations*, IEEE Trans. on Instrumentation and Measurement, vol. 54, No. 1, pp. 311–317, Febr. 2005.

-
14. P. Preiner, R. Überbacher, A. Kaczmarczyk, G. Neubauer, *Evaluation of Electromagnetic Field Distributions near Mobile Communication Base Stations*, Proc. COST 281 Workshop: STM Base Station Monitoring, Vienna, 26–27 August 2003.
 15. C. Olivier, L. Martens, *EMF measurements around base stations: some issues*, COST 281-STM Base Station Monitoring Workshop, Vienna, 26–27 Aug. 2003.
 16. G. Neubauer, H. Haider, K. Lamedschwandner, M. Riederer, R. Coray, *Measurement Methods and Legal Requirements for Exposure Assessment Next to GSM Base Stations*, International Zürich Symposium on EMC, pp 143 – 147, February 2003.
 17. H. Lehmann, B. Eicher, P. Fritschi, *Indoor measurements of the electrical field close to mobile phone base stations*, 27th triennial General Assembly of the International Union of Radio Science, Maastricht, 2002.