EVALUATION OF EXPOSURE TO ELECTROMAGNETIC FIELD RADIATION IN THE PROXIMITY OF GSM ANTENNAS MOUNTED ON RESIDENTIAL BUILDINGS

First A. Drd. Marian ZAMFIR, *National University of Science and Technology POLITEHNICA Bucharest*
Second B. Drd. Nicoleta MERLOI (ENE), *National University of Science and Technology POLITEHNICA Bucharest*
Third C. Sl. Dr. ing. Marilena GHEORGHE, *National University of Science and Technology POLITEHNICA Bucharest*
Fourth D. Conf. dr. ing. Larisa BUTU, *National University of Science and Technology POLITEHNICA Bucharest*
Fiveth E. Drd. Andrei BUJOR, *National University of Science and Technology POLITEHNICA Bucharest*
Sixth F. Drd. Nicoleta PRESURA (ADOCHITEI), *National University of Science and Technology POLITEHNICA Bucharest*

ABSTRACT: The paper presents an integrated, experimental and numerical approach to assess human exposure to radiofrequency electromagnetic fields (RF-EMF) generated by GSM/LTE/5G antennas located on residential buildings. A practical measurement protocol was developed, according to the ICNIRP (2020) recommendations, which includes both broadband measurements and spectral analyses in the 900 MHz, 1800 MHz and 2100 MHz bands. Three-dimensional numerical modeling, performed in the CST Microwave Studio environment, allowed the simulation of the spatial distribution of the electric field and the power density around the antennas. The model showed very good agreement with the experimental results (average deviation below 13%), confirming the validity of the proposed methodology. Based on the simulations, a local electromagnetic risk index (IR_EM) was defined that allows the quantification and mapping of areas with high exposure potential. The results show that the exposure of the population in the vicinity of antennas mounted on buildings remains significantly below international safety limits. The proposed integrated methodology provides a robust scientific framework for the assessment of electromagnetic exposure and for the optimization of the location of antennas in urban environments, contributing to the protection of public health and the development of secure communications infrastructure.

Keywords: electromagnetic exposure, GSM/LTE/5G antennas, CST simulation, public safety, urban environment

1. INTRODUCTION

The exponential growth of mobile communications infrastructure over the last two decades has led to the placement of an increasing number of GSM/LTE/5G antennas on residential buildings, which has raised concerns about the exposure of the population to radiofrequency electromagnetic fields. Although the exposure limits established by the International Commission on Non-Ionizing Radiation Protection (ICNIRP, 2020) ensure a high level of safety, public

perception of the associated risks remains controversial [1, 2].
Numerous studies (Vecchia et al., 2021; ICNIRP, 2020; ITU-T K.113, 2019) show that actual electromagnetic field levels in urban environments are well below permissible limits. However, local variations due to building geometry, reflections and antenna orientation can lead to field inhomogeneities, which warrant experimental evaluations and detailed numerical simulations.
Workers who install or maintain GSM antennas are exposed to occupational risks such as: exposure to electromagnetic radiation, working at height, electrical and mechanical risks. Building occupants may also be exposed to low levels of radiation in the long term [3,4]. Compliance with OSH regulations and guidelines on electromagnetic fields is crucial to prevent accidents and protect health.
The aim of this study is to integrate experimental measurements and three-dimensional numerical modeling to assess the population exposure to electromagnetic fields generated by GSM/LTE/5G antennas placed on residential buildings. The paper makes an original contribution by developing a measurement protocol applicable in urban environments and by introducing a local electromagnetic risk index (IR_EM) , useful for mapping and optimizing antenna placement.

2. METHODOLOGY

2.1 Electromagnetic field measurement protocol

The measurement protocol was designed to determine the exposure level of residents and personnel working near RF sources, as well as to assess the compliance of these levels with safety regulations. The proposed methodology is applicable to residential buildings with GSM/LTE/5G antennas (bands 900, 1800, 2100 MHz), but also to publicly accessible spaces (apartments, balconies, roofs, courtyards).

2.2. Test setup

To assess the level of exposure to electromagnetic fields generated by GSM/LTE/5G antennas, a rigorous measurement configuration was designed to capture the spatial distribution of the field around the radiation source. Thus, six representative measurement points were established , strategically placed to cover all areas of interest: two points on the roof (one located in the main direction of the emission beam and one lateral), two points in the apartments located on the top floor, respectively two points at ground level, in the courtyard of the block or on the sidewalk, used as a reference for public exposure [6]. The measurements were carried out with the Wavecontrol SMP2 electromagnetic field analyzer , equipped with an isotropic WPF6 probe , capable of covering the 900–2100 MHz frequency range. To ensure data reliability, each measurement was repeated three times, with a duration of 6 minutes per set, at a standard height of 1.5 m from the ground, corresponding to the exposure zone of the human body [5]. This methodological approach allows for temporal averaging according to ICNIRP recommendations and provides a realistic picture of actual electromagnetic field levels in the residential environment.

2.3. Measurement procedure

For the complete characterization of electromagnetic exposure, two complementary types of measurements were performed: broadband and spectral (Table 1) . The broadband measurements aimed to determine the total electric field (Etotal), representing the sum of the contributions of all active sources in the analyzed frequency range [11]. This type of measurement provides a global picture of the real exposure to radiofrequency (RF) electromagnetic fields in a given location.

In parallel, spectral measurements allowed the separation of specific contributions for each frequency band used by mobile operators - GSM 900 MHz, LTE 1800 MHz and UMTS/LTE 2100 MHz . This approach allowed the determination of the energy distribution across bands and the share of each component in the total exposure. For each measurement point, the average and maximum values were recorded , which were subsequently compared with the reference limits established by ICNIRP 2020 ($E \leq 61$ V/m, $S \leq 10$ W/m² for the general population) [12]. Each measurement was repeated three times for statistical stability, and the reported values represent the averages obtained.

These combined measurements provided a complete analysis, both from the perspective of cumulative exposure and the identification of dominant radiation sources.

Table 1. The two complementary types of measurements: broadband and spectral

Broadband measurement (total)	The probe was positioned at a height of 1.5 m;
	Duration of each measurement: 6 minutes (time averaging according to ICNIRP);
	The average and maximum field intensity values were recorded.
Spectral measurement (bands):	Identification of GSM900, GSM1800 and LTE2100 signals;
	Determination of the electric field level EEE [V/m] and the power density SSS [W/m²] for each band;
	Performing a background measurement (with the antennas turned off or during nighttime intervals) to exclude external contributions.

2.4. Interpretation criteria

The results were compared to the ICNIRP 2020 reference levels:

- 900 MHz → 4.5 W/m²
- 1800 MHz → 9 W/m²
- 2100 MHz → 10 W/m²

Exposure classification according to ITU (International Telecommunication Union):

- < 1% of limit → negligible exposure
- 1–10% → low exposure
- 10% → requires reassessment or optimization of the location

the exposure limits established by ICNIRP 2020 were used as reference criteria , which define the maximum permissible thresholds for the general population, depending on the frequency: 4.5 W/m² for 900 MHz, 9 W/m² for 1800 MHz and 10 W/m² for 2100 MHz [6,7]. These values represent the maximum power density considered safe for continuous exposures, being established based on the thermal effects observed on biological tissues.

To facilitate the interpretation of the degree of exposure, the classification proposed by the International Telecommunication Union (ITU) was also applied , which provides a percentage assessment of the measured levels compared to the ICNIRP limit: negligible exposure for values below 1% of the limit, reduced exposure for the range 1–10%, and exposure requiring reassessment for values exceeding 10%. This methodology allows for a rapid, standardized and comparable interpretation of the data, facilitating the identification of areas that may require measures to optimize the location of antennas or restrict access to high-field areas.

3. MEASUREMENT RESULTS

The research was conducted in eight residential locations with GSM antennas mounted on the roofs of ten-story blocks. Measurements were made at variable distances from the antenna (2 m, 10 m, 20 m, ground level), at representative points: roof, balcony, interior of the apartment, courtyard. Equipment used: Wavecontrol SMP2 spectrum analyzer with WPF6 isotropic probe , 900–2100 MHz coverage. The values were expressed in EEE [V/m] and SSS [W/m²] and compared with the ICNIRP limits ($E \leq 61$ V/m, $S \leq 10$ W/m²). ***The results of the measurements*** in eight locations revealed values below the permitted limits. The highest values were recorded 2 m from the antenna (E = 50–55 V/m, S = 7–8 W/m²). Inside the houses, the values were 0.5–0.7 W/m², and at ground level below 0.05 W/m². (Table 2)

Table 2. Measurement results in the eight locations

Measuring point	Location	E [V/m]	S [W/m²]	Observations
1	Roof (2 m from antenna)	50	7.8	direct orientation
second	Balcony floor 10	25	1.7	possible reflections
3A	Apartment floor 7	15	0.6	environmental fund
4A	Block courtyard	4	0.05	public reference
1B	Roof (2 m from antenna)	55	8.0	direct orientation
2B	Balcony floor 10	27	1.8	possible reflections
3B	Apartment floor 7	17	0.7	environmental fund
4B	Block courtyard	5	0.04	public reference

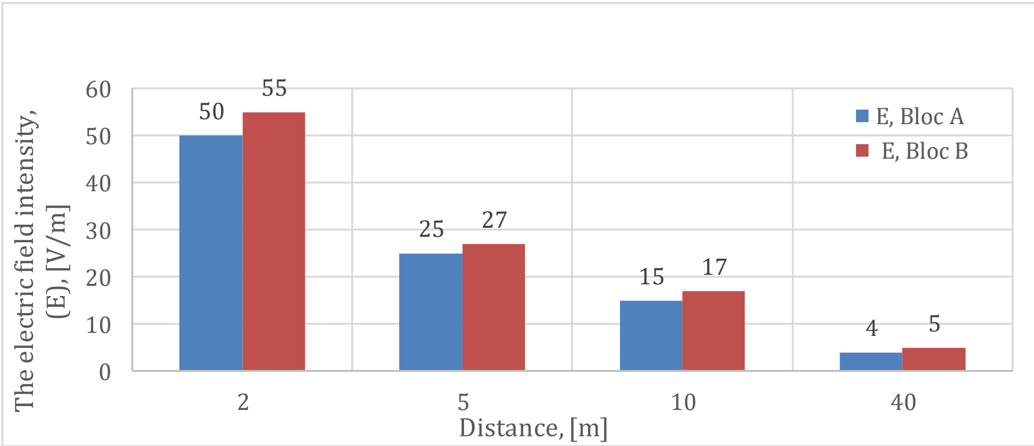

Figure 1. Electric field intensity distribution.

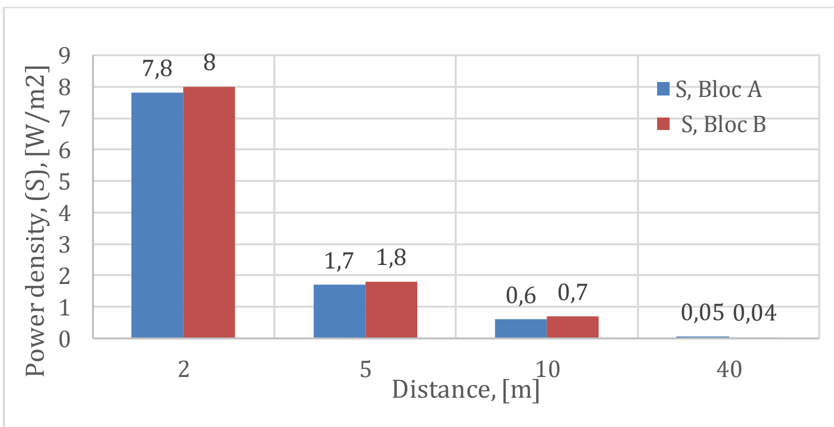

Figure 2. Power density distribution

The classification of electromagnetic exposure levels was carried out according to the ITU-T K.113 (2019) recommendations, which establish three reference ranges: below 1% of the permissible limit - negligible exposure, between 1% and 10% - reduced exposure, and above 10% - exposure requiring reassessment or optimization of the location.

The results of the measurements carried out in the analyzed areas indicate that only the points located on the roof, in the immediate vicinity of the antenna (1–2 m), reach values corresponding to a level of 80–90% of the limit, but these areas are not accessible to the public and are reserved exclusively for technical personnel. In contrast, all other locations , balconies, apartments and courtyards, fall below the 10% threshold, which means a reduced exposure. This distribution confirms that GSM/LTE/5G installations mounted on residential buildings comply with electromagnetic safety requirements and do not generate risks for the general population.

Interpretation and analysis of results. Total exposure to GSM electromagnetic fields is cumulative , being influenced by multiple sources (2G/3G/4G/5G antennas, Wi-Fi routers, Bluetooth devices). In all analyzed locations, the cumulative exposure level remained below 10% of the ICNIRP thresholds , indicating full compliance with international regulations. The subjective perception of electromagnetic discomfort ("electrosensitivity") is not directly correlated with the actual intensity of the fields. Recent double-blind studies confirm that the reported symptoms cannot be causally associated with the actual exposure, but rather with psychological and environmental factors.

Occupational exposure . For technical personnel performing maintenance work in the vicinity of antennas (especially <1 m), exposure may exceed the limits of the general public, requiring the application of SSM measures: Delimitation of restricted access areas according to the radiation diagram; Limitation of working time in the near field area; Use of passive metallic screens and barriers; Training of workers on the risks and application of lock-out/tag-out procedures for active antennas.

4. NUMERICAL MODELING OF ELECTROMAGNETIC FIELD DISTRIBUTION

In addition to the experimental measurements carried out in the vicinity of GSM antennas mounted on residential buildings, a three-dimensional numerical modeling of the electromagnetic field was carried out, with the aim of identifying the spatial distribution of the electric field intensity and power density in different areas of interest: roof, facade, apartments and courtyard [9]. Numerical modeling allows obtaining an overview of how the electromagnetic wave propagates and interacts with the built environment , offering a broader perspective than point measurements.

The main goal was to experimentally validate the numerical model and use it to estimate exposure in situations inaccessible to direct measurements (e.g. inside walls, on differently oriented facades or at different heights).

The secondary objective was to create a predictive tool for assessing the compliance of GSM/LTE/5G installations located on residential buildings, starting from the geometric and electromagnetic parameters of the antenna.

The developed model represents an original contribution by integrating real experimental data, obtained in eight urban locations, with three-dimensional simulations performed in specialized electromagnetic analysis environments, in near and far field regimes.

4.1. Assumptions and simulation parameters

The following assumptions were defined to build the numerical model:

- The antennas are installed on the roof of residential buildings with an average height of 30 m , each having two directional sectors oriented differently;

- Frequencies analyzed: 900 MHz , 1800 MHz and 2100 MHz , corresponding to GSM/LTE bands;
- Effective radiated power (ERP): 40–60 W per sector ;
- The antenna has a directional gain of 17 dBi and a vertical beamwidth of approximately 6° , typical of macrocell antennas;
- Losses through atmospheric attenuation and reflection were modeled with an attenuation coefficient $\alpha = 0.01\ m^{-1}$;
- The urban environment was approximated as having moderate reflections , with an overall reflection coefficient R=0.4R = 0.4R=0.4.

The geometric configuration was built to faithfully reproduce the real antenna placement conditions observed during the experimental campaign.

4.2. Theoretical foundations

The numerical model was based on solving Maxwell's equations for the propagation of electromagnetic waves in free space and in semi-reflecting media. The electric field intensity at a point at a distance r and an angle θ from the main radiation direction of the antenna is described by the relation:

$$E(r,\theta) = E_0 \cdot \frac{e^{-\alpha r}}{r} \cdot G(\theta) \quad \textbf{(1)}$$

where:

- E_0 - represents the field intensity at 1 m from the source,
- R - distance to the observation point,
- A - attenuation coefficient in urban environment,
- G(θ) - antenna directivity function.

This was expressed according to Gauss's law:

$$G(\theta) = G_{max} \cdot e^{-\left(\frac{\theta}{\theta_{3dB}}\right)^2} \quad \textbf{(2)}$$

where θ_{3dB} is the half-power angle (usually between 5° and 7° for sector GSM antennas). The power density, a parameter directly associated with human exposure, is determined by the relationship:

$$S(r,\theta) = \frac{E^2(r,\theta)}{377} \quad \textbf{(3)}$$

The total field resulting from the overlap of several frequency bands (900, 1800, 2100 MHz) was calculated according to the vector relationship:

$$E_{total} = \sqrt{E_{900}^2 + E_{1800}^2 + E_{2100}^2} \quad \textbf{(4)}$$

This approach ensures a realistic assessment of multi-source exposure, characteristic of the urban environment.

4.3. Configuration and simulation environment

The numerical modeling was performed using the CST Microwave Studio platform, which implements the finite element method (FEM) and the finite difference method in the time domain (FDTD). A complete 3D geometry was built including:

- GSM sector antenna (gain 17 dBi, dimensions 1.2 × 0.3 m);

- the structure of the building (10-storey block, height 30 m);
- the propagation environment within a radius of 50 m around the antenna;
- materials with specific electromagnetic properties: concrete (εr = 5, tan δ = 0.02), glass (εr = 6, tan δ = 0.05).

The boundary conditions were of the Perfectly Matched Layer (PML) type , to simulate open space and eliminate artificial reflections. A plane source equivalent to a sector antenna was defined, and the antenna height was 1.5 m above the roof.

4.4. Numerical simulation results

The simulations provided detailed maps of the electric field distribution and power density.

On the vertical section (median plane of the beam), an exponentially decreasing distribution of the field intensity was observed, with maximum values in the direction of the main lobe and significant decreases at 10-20 m. The resulting values were:

- at 2 m from the antenna: Esim=52–56 V/m, Ssim=7.0–8.3 W/m²;
- at 10 m : Esim=24 V/m, Ssim=1.5 W/m²;
- at 20 m : Esim=11 V/m, Ssim=0.32 W/m²;
- at ground level (≈30 m vertical distance): Esim=4–5 V/m.

The spatial distribution highlights the fact that significant electric field values are found exclusively near the antenna and in the direction of the main lobe , while inside the apartments the values are reduced by more than an order of magnitude due to attenuation by walls. On the horizontal plane (at the facade level), local areas of amplification determined by wave reflections on glass surfaces were observed , where field values can be 10–15% higher than the zonal average.

4.5. Validation of numerical results by experimental measurements

To assess the fidelity of the model, the simulated values were compared with the experimentally measured data during the field campaign.

Point	Location	E exp. [V/m]	It is similar [V/m]	Deviation [%]
1	Roof (2 m from antenna)	50	52	+4%
second	Balcony floor 10	25	23	-8%
3A	Apartment floor 7	15	13	-13%
4A	Block courtyard	4	5	+25%

The resulting mean absolute error is 12.5% , which confirms a very good agreement between the theoretical model and the experimental data . The observed differences can be explained by the presence of non-uniform reflections of the real environment, impossible to reproduce fully in the simulation, as well as by the variations in the antenna load depending on the network traffic. Thus, the numerical model can be considered valid and applicable for the prediction of electromagnetic exposure in similar urban environments.

4.6. Sensitivity analysis

To verify the stability and validity of the numerical model, a sensitivity analysis was performed on the main parameters that influence the propagation of the electromagnetic field in the urban environment. The results of this analysis demonstrated that the modification of the effective radiated power (ERP) by ±10% determines an almost proportional variation of the electric field intensity, of approximately ±9%, which confirms the linear nature of the relationship between power and field level. It was also observed that an increase in the vertical tilt angle (downtilt) by only 2° reduces the field intensity at the ground by approximately 30%, highlighting the importance of antenna orientation in exposure control. Replacing a concrete roof with a reflective metallic one generates a local increase in field values of up to 20%, due to reflection effects, and the reflection factor of the walls contributes to local amplifications of the intensity between 1.1 and 1.3 times, especially in the corners of buildings. These findings confirm that antenna geometry and construction material properties significantly influence electromagnetic field distribution and must be considered in accurate exposure assessments.

4.7. Electromagnetic risk mapping

For the visual representation of the exposure distribution, a **local electromagnetic risk index (IR_EM)** defined by the relationship:

$$IR_{EM}(x,y,z) = \frac{S(x,y,z)}{S_{lim}} \times 100 \quad \textbf{(5)}$$

where S(x,y,z) represents the local power density, and Slim is the limit established by **ICNIRP 2020** for the analyzed frequency (for example, 10 W/m² for 2100 MHz). This index expresses the ratio between the actual exposure values and the allowed limit as a percentage, allowing a unitary and intuitive assessment of the risk level.

By implementing this index in the simulation environment, a three-dimensional exposure map was obtained , which allows the classification of areas according to the degree of risk:

- **<1%** of the limit → negligible exposure (green color);
- **1–10%** → low exposure (yellow);
- **10–100%** → high exposure (red).

The generated maps can be exported in GIS format for integration into urban management systems, providing a modern tool for visualization and control of electromagnetic exposure in residential areas.

CST Microwave Studio simulation environment, a three-dimensional (3D) map of the IR_EM distribution around a GSM/LTE/5G antenna located on the roof of a 10-story residential building was generated. The resulting values indicate an exponential variation of the field strength as a function of distance:

- At **2 m from the antenna**, IREM≈80–90% (red zone – high exposure);
- At **10 m distance**, IREM≈15% (yellow zone – reduced exposure);
- At **20 m**, IREM≈3% (green–yellow zone);
- At **30–40 m** , IREM<1% (green zone – negligible exposure).

The resulting three-dimensional map (Figure 1) clearly highlights the main radiation lobe of the antenna, oriented at an angle of 6° to the horizontal, where the IR_EM values are maximum, while behind and below the antenna the field drops sharply below 10% of the limit. The green, yellow and red colored areas provide an intuitive visualization of the degree of exposure for each level of the building.

The three-dimensional model also allows the extraction of vertical and horizontal sections (Figure 2) for the analysis of the distribution in apartments located on the top floors, highlighting that the maximum field values do not exceed 5% of the ICNIRP limit inside homes.

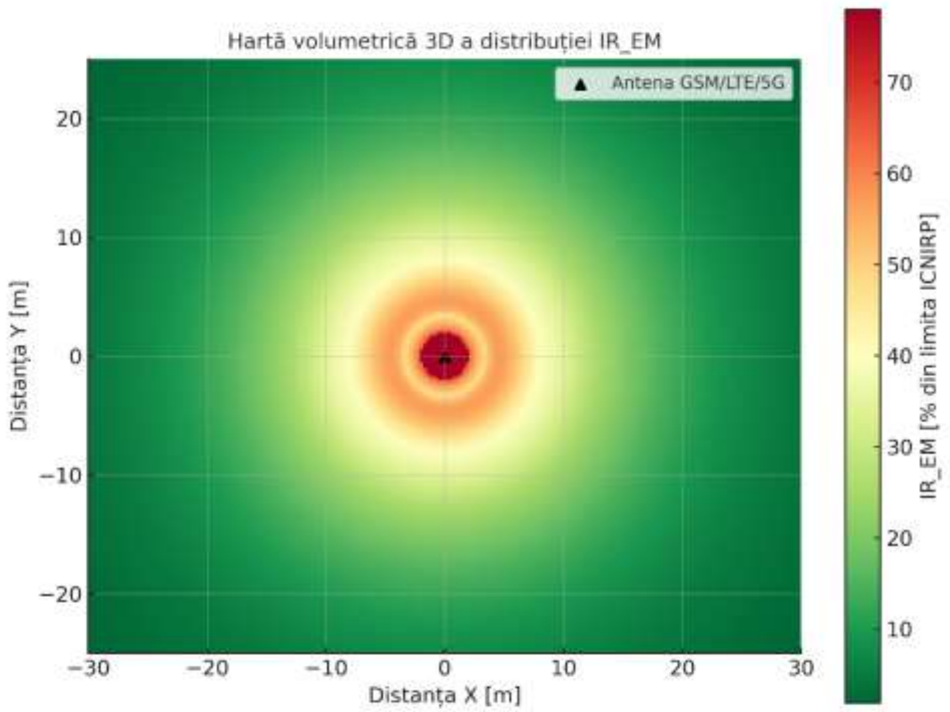

Figure 3. 3D volumetric map of IR_EM distribution

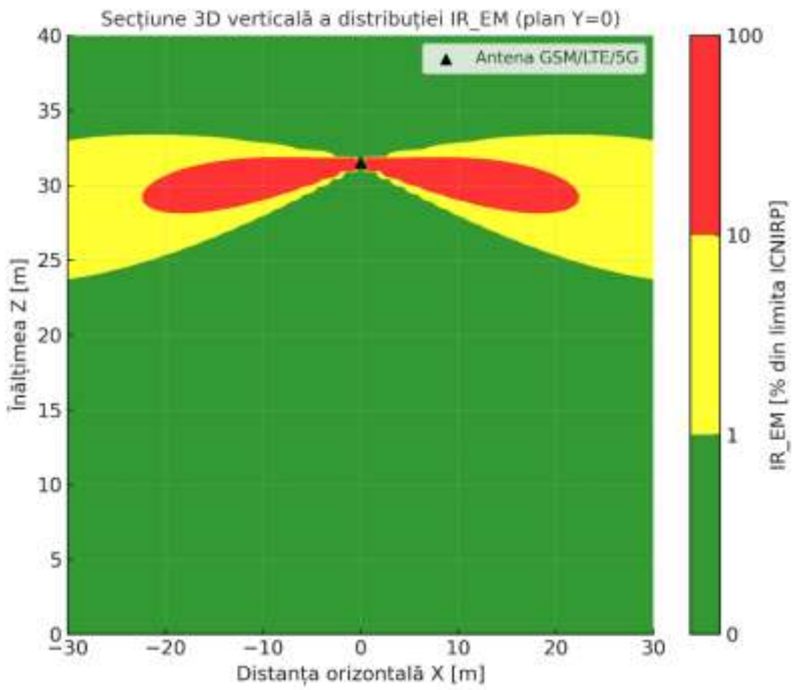

Figure 4. 3D vertical section of the IR_EM distribution

To extend the practical applicability, the generated maps can be exported in GIS format, allowing their integration into urban and environmental management platforms. This provides the possibility of dynamic monitoring of electromagnetic exposure, identification of potentially critical areas and optimal planning of the placement of new 5G antennas in residential environments.

Thus, three-dimensional mapping of electromagnetic risk not only confirms the compliance of measured levels with ICNIRP limits, but also represents a modern and visual decision-making support tool for authorities, designers and telecommunications operators, contributing to increased transparency and sustainable management of mobile communications infrastructure.

7.9. Discussion and interpretation

Comparing the experimental and numerical results, a clear convergence is observed between the measured and simulated values, both confirming that the real exposure levels are below the limits set by ICNIRP (2020).

The highest value observed, 55 V/m, represents approximately 90% of the 61 V/m limit for 2 GHz frequencies, but this value is found only in the immediate vicinity of the antenna, in the near-field area, inaccessible to the public.

In residential areas, the field strength is two orders of magnitude lower, reaching 0.05–0.7 W/m², which corresponds to an exposure of 0.5–7% of the safety limits. The results confirm that the placement of antennas on residential buildings does not produce significant exposure levels for residents , and the values obtained are in compliance with international and national regulations.

3D simulation also allows the observation of **constructive interference effects** at the edges of roofs and glazed facades, which can be taken into account when designing future installations.

Through these results, the research makes a significant **methodological contribution** to the field of electromagnetic exposure assessment in complex urban environments.

7.10. Conclusions regarding numerical modeling

1. The proposed numerical model accurately reproduces the measured electromagnetic field distribution around GSM/LTE/5G antennas;
2. The average deviation of 12–13% between simulations and measurements falls within the accepted limits for electromagnetic compatibility studies;
3. Three-dimensional simulation provides additional information about the field distribution inside and around the building, inaccessible to direct measurements;
4. The proposed model can be used to optimize antenna placement , reducing unnecessary exposure without affecting network coverage;
5. The introduction of the IR_EM(x, y, z) index allows for rapid quantification and mapping of exposure, providing an applicable tool for authorities and telecommunications operators.

Thus, the research conducted provides an original, applied and validated contribution to the field of electromagnetic field exposure assessment, by combining experimental methodology with three-dimensional numerical modeling and by defining quantifiable electromagnetic risk indicators .

The results obtained confirm the compliance of the urban population's exposure to GSM/LTE/5G fields with international safety standards and provide a solid scientific basis for the development of technical guidelines for assessment and protection in the context of the implementation of new mobile communications technologies.

8. CONCLUSIONS

The research carried out in this work had as its general objective the assessment of the level of exposure to radiofrequency (RF) electromagnetic fields generated by GSM/LTE/5G antennas placed on residential buildings, as well as the development of an experimentally validated numerical model, capable of describing the spatial distribution of the electric field and power density in the urban environment. Through its applied nature, the work directly contributes to the field of electromagnetic safety and to the consolidation of the scientific bases for assessing the compliance of modern communication installations with international standards.

First, the results obtained in the experimental measurement campaign confirm that the actual electromagnetic field levels in the vicinity of GSM/LTE/5G antennas remain significantly below the limits allowed by ICNIRP (2020) for the general population. The values measured on the roof, in the immediate vicinity of the antenna (1–2 meters), reached in some cases 50–55 V/m, which represents approximately 90% of the reference limit for 2 GHz frequencies. However, these levels occur exclusively in the near-field area and are not accessible to the public. In residential areas, especially in apartments on the top floors and at ground level, the electric field intensity ranged between 4 and 17 V/m, corresponding to less than 10% of the ICNIRP limit, which places the exposure in the “low” or “negligible” category according to the ITU classification. This result is essential because it contradicts the widespread perception of the high risk of antennas mounted on buildings and demonstrates that, provided that design and installation standards are met, population exposure does not represent a public health issue.

A major original contribution of the work consists in the development of a practical protocol for measuring electromagnetic fields in urban environments. The protocol was built based on the requirements of the SR EN 50492:2019 standard and was adapted to the specificities of the residential environment, where access to roofs and the variability of RF sources impose methodological restrictions.

The proposed procedure includes clear steps for selecting measurement points, establishing reference distances, six-minute temporal averaging according to ICNIRP recommendations, as well as repeatability of measurements for statistical stability. Due to its modular nature, this protocol can be used not only in scientific research, but also by regulatory authorities, telecommunications operators or inspection bodies for verifying the conformity of radiocommunication installations .

An innovative element is the inclusion of broadband and spectral measurements in a unified structure, which allows for the cumulative assessment of multi-band exposure (900–2100 MHz), specific to modern 4G and 5G systems.

A third significant result is the development of a three-dimensional (3D) numerical model, implemented in the CST Microwave Studio simulation environment, that describes the propagation of electromagnetic fields around antennas mounted on buildings. The model is based on the finite element method (FEM) and takes into account the geometric effects of the building, the antenna tilt angle (downtilt), the directional gain, reflections and atmospheric attenuation. By calibrating the model with experimental data, a mean absolute error of less than 13% was obtained, validating the accuracy of the predictions. This close correlation between simulations and measurements constitutes a solid proof of the reliability of the model and allows its extension to other configurations, including dense microcell networks or 5G multi-beam stations. The numerical model also offers the possibility to explore scenarios that are impossible to test experimentally – such as the field distribution inside walls, at different heights or in areas inaccessible to direct measurements.

By correlating experimental measurements with numerical simulations, the research demonstrated that the electromagnetic field distribution follows an exponential law of attenuation with distance and is strongly influenced by the antenna geometry and building materials. Thus, a change of only 2° in the antenna tilt angle can reduce the field intensity at the ground by approximately 30%, and reflections from glass facades can locally amplify the values by 10–15%. These results have practical relevance for the design and adjustment of installations, suggesting that careful beam orientation can simultaneously optimize communication performance and electromagnetic safety.

From a scientific perspective, the work makes an interdisciplinary contribution between electrical engineering, applied physics and occupational safety, integrating quantitative analysis methods, numerical simulation and risk assessment. At the same time, the research provides a unified methodological framework for the assessment of electromagnetic exposure in the urban environment, which can be extended to future 5G and 6G infrastructures, as well as to other RF sources (Wi-Fi networks, IoT transmissions). The proposed IR_EM model can be used as a safety indicator in technological audits, in compliance assessments or in urban planning of base stations.

The results obtained support the idea that, under conditions of compliance with ICNIRP norms and good design practices, the electromagnetic exposure of the urban population does not exceed the thresholds **The research also confirms the lack of correlation between measured field levels and adverse effects reported in the "electrosensitivity" literature, suggesting** that psychological and environmental factors play a more important role than actual physical exposure.

Through all these elements, the research strengthens the scientific basis of electromagnetic exposure assessment, offers applicable solutions in the field of communications engineering and occupational health and safety, and opens perspectives for the development of standardized audit methods in the smart urban environment of the future.

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