POLITEHNICA UNIVERSITY
OF BUCHAREST

Doctoral School of Electronics, Telecommunications
and Information Technology

Decision No. 1049 from 10-07-2023

Ph.D. THESIS SUMMARY

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EFECTUL RADIAȚIILOR ELECTROMAGNETICE PRODUSE DE SISTEMELE DE COMUNICAȚII MOBILE ASUPRA ORGANISMULUI UMAN

THE EFFECT OF ELECTROMAGNETIC RADIATION PRODUCED BY MOBILE COMMUNICATIONS SYSTEMS ON THE HUMAN BODY

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BUCHAREST 2023

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Chapter 1

Introduction

The last decades have shown an unprecedented development of technologies using microwave and radio frequency electromagnetic field sources used for individual, industrial, commercial or medical purposes. These sources also include radio and television transmitters, cellular telephone systems and telephone receivers, microwave ovens, RADAR installations, as well as a multitude of equipment indispensable to the medical system.

The development of these technologies has made life much easier, today we can no longer imagine a modern society without computers, telephones, television or radio. With the help of mobile phones it is possible to communicate by voice, messages, pictures and high-speed data transfer is allowed. RADAR installations help maintain the safety of air, road and rail traffic. Along with the exponential development, these technologies have also brought concerns of the general public about possible adverse effects that electromagnetic field sources could have on human health.

1.1. Presentation of the field of the doctoral thesis

Information on emissions from stations operating in the radio frequency band is often available and can be used to validate compliance; measurements can also be made on site to evaluate the electromagnetic field produced by the existing equipment. This information helps to carry out epidemiological studies.

Such analyzes are still taking place at the present time, but, nevertheless, the use of mobile phones is constantly increasing, especially on the data transfer side, with numerous reports showing that the penetration rate of mobile terminals, at the level of many countries, exceeds 100%, the global average being 111%.

From the perspective of radiation protection, they can be divided into two broad categories: ionizing radiation and non-ionizing radiation. This classification takes into account the fact that when radiation strikes an atom, some of its energy may be transferred to the atom.

If the energy transferred by the radiation is high enough, so that the removal of an electron takes place and ends up with two electrically charged particles, an electron and a positive ion, we say that ionization has occurred and therefore we are dealing with ionizing radiation. The presence of a large number of electrically charged particles can cause tissue damage in living organisms.

Radiation with a low energy level, which does not remove the electron from the atom, is called non-ionizing radiation. In high doses, certain types of non-ionizing radiation can be harmful, but generally when people talk about radiation, they mean ionizing radiation, which is much more dangerous.[1]

The effects of external electromagnetic field exposure on the human body and its cells depend mainly on the frequency and magnitude of the field. At low frequencies the field passes through the body, and at radio frequencies the fields are partially absorbed and penetrate only a small depth in the tissue.

In the radio frequency area, by far the most electromagnetic field emitting applications are in the frequency range from about 100 kHz to several GHz. There are several parameters that influence an individual's exposure. The distance from the source to the individual, along with the emitted power and fill factor are the main determinants of exposure.

In the analysis of exposure caused by mobile communication systems we can imagine two different scenarios. The first concerns the exposure of the human head to near-field electromagnetic emissions from the mobile phone, and the second scenario consists of the exposure of the general public to far-field electromagnetic emissions from antennas installed on base station structures.

The regulations in force limit the maximum power radiated by the mobile terminal, but the diversity of models and the way they are used by the user make it difficult to analyze the individual's interaction with electromagnetic fields, which is why the scenarios in the first category are studied in more detail.

Most of the radio frequency sources that operate close to the human body are mobile phones. Statistics show that there were more than five billion mobile device users worldwide in 2018.

Of the radio frequency sources that operate at a distance from the human body, most are represented by mobile phone base stations and radio broadcasting transmitters. Most European countries provide connectivity for very large areas which makes base stations numerous.

In recent decades, over 25,000 medical studies have been conducted on this topic, and several hundred more are currently underway. There is more accumulated scientific knowledge on this subject than for most chemical compounds, but at the frequencies and power levels used in mobile communication systems no cause-and-effect relationship could be established between exposures to radiofrequency electromagnetic fields and biological reactions adverse. [2]

1.2. Scope of the doctoral thesis

Although studies have shown that the levels at which the electromagnetic fields produced by mobile phone base stations reach the general public are much lower than those generated by mobile phones, people's concern about the presence of these stations has not diminished. An explanation for this fact could be represented by the decision-making power they have in the case of using the mobile terminal, but not in the case of the operation of the base stations. [3], [4], [5]

This work aims to investigate a limited area in the area of non-ionizing waves present in the ambient environment with the aim of establishing the degree of exposure of the population in relation to the norms in force.

The analyzed frequency range is in the radio and microwave range, ignoring the spectrum in the very low range, as well as the infrared and visible light range.

The usefulness of this doctoral thesis, in addition to validating the results obtained from other studies presented in the specialized literature, is justified by the emergence of new technologies, such as 5G (fifth generation), which require new evaluations of the level of the electromagnetic field in different cases of exposure.

1.3. Content of the doctoral thesis

In the first part of the thesis, we want to review the studies related to the possible biological effects on the human body in the electromagnetic field. The electromagnetic field exposure standards and limits of different countries of the world are presented, as well as the procedures and devices for measuring field values.

Chapter 1 provides an introduction to the field and defines the purpose of this doctoral thesis.

Chapter 2 includes several sections, the first part being a synthesis of studies related to biological effects on the human body. Electromagnetic waves are increasingly being used in the medical industry for soft tissue healing and cancer treatment, with common frequencies being 27 MHz, 433 MHz and 2.45 GHz. The chapter concludes by treating the field in an engineering way, presenting the dielectric characteristics of biological media, the coupling relationship between induced fields inside structures and electromagnetic field distributions in free space.

Chapter 3 presents the main protection norms adopted worldwide. The emphasis was placed on the norms recommended by ICNIRP, which have been adopted in almost all of Europe, including our country. The measurements made in the thesis were reported to the limits established by ICNIRP in order to obtain exposure coefficients that give us an overview of the degree of exposure.

Chapter 4 documents the main types of electromagnetic field measuring devices which, moreover, were used during the measurements carried out in this work, as well as the methods of measuring the field components provided in the ECC recommendation (02)04 in order to validate compliance available limits.

Having the theoretical basis from the first part of the thesis, we then proceed to establish the degree of exposure of the general public by referring to the limits provided in the ICNIRP standard.

Chapter 5 highlights the results of an extensive nationwide measurement campaign, mostly carried out by the author, in the vicinity of 1750 fixed mobile phone stations of the Orange Romania operator. The maximum exposure coefficients before and after the activation of 5G technology were estimated.

In chapter 6 and the second part of chapter 7, based on the measurements made by the author, the exposure of the population to electromagnetic fields in special cases, such as stations with distributed antenna systems inside buildings or a site where there are several types of of transmitters.

In the first part of chapter 7, to validate and consolidate the results obtained by the author, the field values measured during one year by 150 fixed sensors placed by the Romanian National Authority for Administration and Regulation in Communications throughout the country, in urban areas with heavy traffic.

Chapter 8 evaluates the average uplink transmit power of mobile terminals in the commercial networks with the highest loads, namely 4G (fourth generation) and 5G. In order to have the clear picture of the main RF field source, a comparison was made between the energy received from the mobile base stations and the energy received from the mobile station.

Chapter 9 highlights the most important conclusions of the analyzes carried out, personal contributions and prospects for the development of the theme in close connection with technological advances.

Chapter 2

The interaction of electromagnetic fields with the human body

After the end of the Second World War, the effects of electromagnetic fields on living organisms began to be intensively studied. Most of the results identify hyperthermia, localized or generalized, as the main cause of electromagnetic field effects on biological environments. Michaelson [6] showed that long enough exposure to a high power level will eventually lead to the breakdown of the thermal regulation system and even to the death of the organism, which is why exposure to very strong electromagnetic fields must be limited.

Numerous reproductive studies [7], [8], [9], [10] have shown that there is no association between exposure to radio waves and adverse effects. Brain cancer studies have also failed to show a cause-and-effect interpretation. [11], [12], [13], [14], [15], [16]

Neurodevelopmental and behavioral studies could not establish clear associations between the presence of mobile phone stations and sleep quality [17] or mobile phone use and cognitive (language skills) or motor development. [18], [19], [20]

During the 1930s, radiofrequency electromagnetic radiation began to be used frequently in medicine by inducing hyperthermia for therapeutic purposes. Since the 1975s, in parallel with the concerns related to the biological effects seen as negative elements of the presence of the electromagnetic field, there is a growing interest in the possible use of electromagnetic waves to treat cancer by gradually inducing hyperthermia. [21]

Commonly used frequencies in the medical industry are 27 MHz, 433 MHz and 2.45 GHz. Therapeutic applications include soft tissue healing devices, hyperthermia to treat cancer, and diathermy. To achieve the desired effects (analgesic, burned cancer cells etc.), patients are exposed to electromagnetic fields that exceed the recommended reference levels. [22]

When studying the interaction phenomena between the electromagnetic field and biological environments, it is necessary to know their electrical and magnetic properties. Electrical properties refer to electrical permittivity and conductivity, while magnetic properties are not of interest to biological matter.

Permittivity reflects the interaction of the medium with the electromagnetic wave what propagates through it. The permittivity of free space is a constant

$\varepsilon_0 = \frac{1}{36\pi} 10^{-9} \frac{\mathrm{F}}{\mathrm{m}} = 8{,}85 \cdot 10^{-12} \frac{\mathrm{F}}{\mathrm{m}}$. For any other medium, the permittivity is a complex quantity of the form $\varepsilon_\mathrm{c} = \varepsilon - \mathrm{j}\varepsilon'$, where ε shows the ability of the medium to store energy, and $\varepsilon' = \frac{\sigma}{\omega}$ highlights the property of the medium to dissipate the energy carried by the electromagnetic field. The "tangent of the loss angle" ("dissipation factor") of the medium is also defined in the literature as $\mathrm{tg}\,\delta = \frac{\varepsilon'}{\varepsilon}$.

2.1 Dosimetry

Electromagnetic dosimetry establishes the relationship between induced fields inside biological structures and electromagnetic field distributions in free space.

The power emitted by mobile communication systems ranges from less than 2 watts in the case of mobile phones, to hundreds and even thousands of watts in the case of base stations. However, under normal conditions of use, base stations generate much lower exposure levels than mobile phones because they are located at much greater distances compared to phones that are placed right next to biological tissue.

Depending on the placement of the subject in relation to the radiation source, the absorption phenomena are different, the subject may be in the reactive near field, radiant near field or far field of the source. In the reactive radiant near-field area, at a distance from the antenna less than λ (λ represents the wavelength that the antenna emits), the field distributions are complicated, there is no single direction of the incident field, the power density is not defined . In this case, the direction of electromagnetic energy propagation is no longer given, as in the case of the far field region, by the direction of the Pointing vector, **p**[W/m^2], defined as the vector product between the electric field intensity vector **E**[V/m] and the magnetic field intensity vector **H**[A/m]. For a correct and complete assessment in the near-field area, the use of numerical methods or near-field probes is necessary.

In a wide range of frequencies, 300 Hz – 300 GHz, two different but interrelated types of quantities are usually used in dosimetry. At very low frequencies (below 100 kHz), most of the biological effects can be quantified by tissue current density, and at high frequencies (above 100 kHz), where most of the interactions are caused by the unit energy deposition rate of mass, the parameters used are Specific Absorption Rate (SAR) and Specific Absorption (SA).

At frequencies above 100 kHz, the human body absorbs the energy of the electromagnetic field, causing an increase in temperature. The dependence of absorption on wave frequency is not uniform. [24]

The external field incident on the biological environment can be expressed in several ways, as power density [W/m^2], as electric field amplitude [V/m] or magnetic field [A/m], but none of the mentioned parameters it is suitable for highlighting the effects induced by the penetration of electromagnetic radiation inside the biological domain. For this purpose, to express the amount of absorbed energy and to define some exposure limits, specific absorption rate and specific absorption have been defined.

Specific absorption rate expresses the time variation of the elementary amount of energy, dW, absorbed or dissipated by a biological domain of volume dV with density ρ and elementary mass dm: [25]

$$\mathrm{SAR}\ \left[\frac{\mathrm{W}}{\mathrm{kg}}\right] = \frac{\mathrm{d}}{\mathrm{dt}}\left(\frac{\mathrm{d}W}{\rho \mathrm{d}V}\right) = \frac{\mathrm{d}}{\mathrm{dt}}\left(\frac{\mathrm{d}W}{\mathrm{d}m}\right). \tag{2.3}$$

The specific absorption represents the total amount of energy absorbed or dissipated, and to calculate this value the SAR value must be integrated over a limited time interval:

$$\mathrm{SA}\ \left[\frac{\mathrm{J}}{\mathrm{kg}}\right] = \frac{\mathrm{d}W}{\rho \mathrm{d}V} = \frac{\mathrm{d}W}{\mathrm{d}m}. \tag{2.4}$$

Knowing the specific absorption rate and specific absorption allows animal-to-animal, animal-to-human, human-to-human, and tissue-to-tissue comparisons and extrapolations. The usefulness of these parameters can also be seen in the analysis of the interdependencies between the different biological effects observed in various experimental models, being clearly superior to the quantities measured only outside the body, not penetrating inside it.

If there were a small-sized, isotropic, sufficiently low-sensitivity induced electric field detector, metrics like SAR could be obtained much more easily: [25]

$$\mathrm{SAR} = \frac{\sigma E^2}{\rho}, \tag{2.5}$$

where σ [S/m] is the electrical conductivity, E [V/m] represents the electric field intensity, and ρ [kg/m3] the tissue density. But this detector does not currently exist, and therefore a common method in experimental dosimetry is based on tracking the rise in temperature over a limited period of time. This time, SAR is expressed through a secondary process, namely, through the rate of temperature increase over time: [25]

$$\mathrm{SAR} = \frac{c\Delta T}{\Delta t}, \tag{2.6}$$

where c [J/kg K] is the specific heat of the irradiated tissue, ΔT [K] is the temperature change, and Δt [s] is the time period over which the temperature rise ΔT is measured.

Chapter 3

Standards and exposure limits

In the world there are several directives approved by governments and international agencies to ensure the protection of the population against exposure to electromagnetic fields.

The first established value for the maximum accepted limit of surface incident microwave power density was 10 mW/cm^2, averaged over any 6-minute period, for frequencies from 10 MHz to 100 GHz [26]. This value was established by the American National Standardization Institute (ANSI) in 1966 through the C95.1 standard and subsequently modified in 1974, 1982, 1991 and 1999. Currently C95 standards are issued and developed as standards IEEE and submitted to ANSI for recognition. [27]

Another working group formed to study problems related to protection against the electromagnetic field and the effects of non-ionizing radiation was founded in 1974 by the International Radiation Protection Association (IRPA). Three years later, the group became the International Non-Ionizing Radiation Commission (INIRC), within IRPA. This group, together with the World Health Organization, created documents that include measurements and measuring devices, sources, applications and also effects of non-ionizing radiation on organisms. In 1992, with the aim of continuing the investigation of the effects of non-ionizing radiation on health, it was decided to separate from INIRC a non-governmental, independent organization, called the International Committee on Non-Ionizing Radiation Protection - ICNIRP), whose main concern is to follow the studies documented in the specialized literature and, starting from their results, to establish the maximum exposure limits. [24]

They laid the foundations for procedures for detailing exposure limits to optical radiation, infrasound, ultrasound and electromagnetic radiation. With the exception of some countries, some of which have already adopted other limits, and others, which invoking the precautionary principle, have imposed much lower limits [28], most European states use these limits for radiation exposure of the general public and those working with radiant systems, mentioned in Recommendation 519/1999 of the European Commission and in EU Directive 40/2004, as an extension of an article in Directive 391/1989.

Studying the effects produced by increasing the temperature of the whole body by more than 1-2°C, changes in the immune system, eye problems, alteration of some neuromuscular and neural functions, hematological changes, reduction of the amount of sperm, changes in cell morphology and others were highlighted. [42]

These effects have led ICNIRP to consider that warming should not exceed 1°C. The SAR value associated with an increase in body temperature of less than 1°C for a 30 minute exposure is 4 W/kg. To protect employees working in an environment where there is an electromagnetic field of radio frequency, ICNIRP established that the basic restriction should be 10 times lower, i.e. 0.4 W/kg. This safety margin was introduced to compensate for situations in which the body's thermoregulation capacity decreases in the case of working conditions at high temperatures or sustained physical exertion.

In 1988 INIRC/IRPA set the 6 minute whole-body averaged SAR limit at 0.4 W/kg [43], but numerous studies have shown that although this whole-body averaged limit is respected, in certain parts of the body, especially at the extremities and in the area of the wrists it shows significant excesses. This led to the introduction of locally calculated SAR limitations, averaged over 6 minutes in 10 g of tissue, at the head and trunk level of 10 W/kg and at the limb level of 20 W/kg in the norms developed by ICNIRP in 1998. [24]

All values discussed above are valid for worker exposure. Considering that workers are generally adults who have a good physical condition and do not have health problems, in order to ensure adequate protection of the entire population, the values of the basic restrictions have decreased 5 times compared to the maximum level established for workers. This margin of protection is not the result of in-depth studies, but was arbitrarily established as a precaution in case data on the existence of non-warming effects should later appear.

Table 3.1 shows the basic restrictions for the general public recommended by the ICNIRP 1998 standard.

Table 3.1 *Basic restrictions for electric and magnetic fields*

Exposure	**Frequency range**	**Head and trunk current density [mA/m^2]**	**Whole body averaged SAR [W/kg]**	**Local SAR in the head and trunk [W/kg]**	**Local SAR in the limbs [W/kg]**	**Power density [W/m^2]**
General public	Up to 1 Hz	8	-	-	-	
	1– 4 Hz	8/*f*	-	-	-	
	4 Hz – 1 kHz	2	-	-	-	
	1 – 100 kHz	*f*/500	-	-	-	
	0.1 – 10 MHz	*f*/500	0,08	2	4	
	0.01 – 10 GHz	-	0,08	2	4	
	10 – 300 GHz					10

where the frequency (*f*) is considered in Hz and the SAR values are averaged over a time interval of 6 minutes.

At frequencies exceeding 10 GHz, the penetration depth of electromagnetic waves is very small, energy absorption taking place mainly in the epidermal and subcutaneous tissues, or in the outer layer of the eyeball. Unlike SAR, power density is a quantity that evaluates energy per surface instead of mass, and is better suited to express the basic restrictions in this frequency domain.

Except for power density, none of the basic restrictions can be measured directly, and verifying compliance with these protection norms would be nearly impossible. As a result, ICNIRP has put them in correspondence with reference levels of easily measurable physical quantities: electric field strength (*E*), magnetic field strength (*H*), magnetic induction (*B*) and power density (*S*).

Table 3.3 shows the reference levels corresponding to the basic restrictions in the case of exposure to electromagnetic waves of the general public. The value of the frequency, expressed in MHz, was noted with *f*.

Tabelul 3.3 *Reference levels for general public exposure*

Frequency range	***E* [V/m]**	***H* [A/m]**	***B* [μT]**	***S* [W/m^2]**
0.065 – 0.15 MHz	87	5	6.25	
0.15 – 1 MHz	87	0.73/*f*	0.92/*f*	-
1 – 10 MHz	$87/f^{1/2}$	0.73/*f*	0.92/*f*	-
10 – 400 MHz	28	0.073	0.092	2
400 – 2000 MHz	$1.375 f^{1/2}$	$0.0037 f^{1/2}$	$0.0046 f^{1/2}$	*f*/200
2 – 300 GHz	61	0.16	0.20	10

Being vector quantities, for the intensity of the electric field, the magnetic field and the magnetic induction, the values in the table represent average values of the modules of the three vector quantities. For fields with frequencies above 10 GHz, the averaging period is $68/f^{1.05}$ minutes, where f is the frequency expressed in GHz. For fields with frequencies below 10 GHz, averaging is done for 6 minutes.

In 2020, the International Commission on Non-Ionizing Radiation Protection published new guidelines for limiting exposure to electromagnetic fields (100 kHz to 300 GHz). [48]

The new guideline takes into account studies in the literature and updates the radio frequency electromagnetic field part of the ICNIRP 1998 guideline and the 100 kHz -10 MHz part of the ICNIRP 2010 low frequency guideline.

ICNIRP 2020 still uses the SAR parameter to set exposure restrictions, but increases the range of frequencies to which it applies; if the 1998 standard provided restrictions up to 10 GHz, now the application range is up to 300 GHz and provides protection also in the case of new technologies that use higher frequencies than current technologies. To better align with the time it takes for the core body temperature to rise, the time over which the whole body reference values are averaged has been changed from 6 minutes to 30 minutes. The SAR values were not changed because research showed that they were anyway more comprehensive than originally thought.

Chapter 4

Measuring devices and procedures in accordance with existing standards

4.1 Devices for measuring the electromagnetic field

Electromagnetic field measuring devices fall into two broad categories: wide-band measuring devices and narrow-band, frequency-selective (possibly also coded) measuring devices.

Devices in the first category have a simple mode of operation, the measuring device indicating the magnitude of the electric or magnetic field integrated over the entire frequency band for which the probe was designed. Typically, this band extends from a few hundred kHz up to 40-60 GHz. Devices in the second category can select a narrow band convenient for making field measurements. They are actually spectral analyzers that process the signal received from the electric or magnetic field probe and extract the values related to each frequency in the analyzed band. The working band of these devices is much smaller than in the case of the devices of the first category; usually this band stretches from a few hundred kHz to 3-5 GHz. Narrowband instruments are used when greater sensitivity is required.

4.2 Measurement methods

In ECC/REC/(02)04 [58] 3 measurement methods were considered that can be used:

- method 1: quick assessment;
- method 2: variable frequency band scan;
- method 3: detailed investigation.

These methods are not useful in the situation where the critical exposure is located in a small area, for example, the mobile phone in relation to the human head.

The "quick assessment" method is recommended when it is necessary to sum up the levels of non-ionizing radiation generated by all sources emitting in a band of several tens of GHz. This method is suitable and applicable for far-field exposure assessment. The rapid assessment is performed with a broadband device and is a first step method to determine if the total level is approaching the decision threshold.

The variable frequency band scan (method 2) is used when it is desired to determine the exposure due to each individual source and is carried out with the help of a spectrum analyzer connected to an electric or magnetic field probe. A very important element in this method is the knowledge of the emission characteristics of the sources, in order to be able to adapt the resolution and display method of the spectral analyzer.

Method 3, of detailed investigation, can be used when neither the first nor the second is applicable. When the field strength is very high or when the measurement is carried out in the near field of the source, a detailed evaluation must be carried out. Another application situation of this method occurs when systems that emit in pulses, discontinuously or in ultra-wideband are involved and require a distinct approach. The equipment used for this type of measurement, as with the previous method, are usually spectrum analyzers.

The exposure coefficient is expressed as a percentage and is calculated by summing up the weighted contribution of each individual source, using formula (4.12), and the value of 100% corresponds to reaching the maximum allowed limit:

$$C_{\text{exp}} = \sum_{i=1}^{N} \left(\frac{E_{i_{\text{măs}}}}{E_{i_{Lim}}}\right)^2 = \left(\frac{E_{1_{\text{măs}}}}{E_{1_{Lim}}}\right)^2 + \left(\frac{E_{2_{\text{măs}}}}{E_{2_{Lim}}}\right)^2 + \cdots + \left(\frac{E_{N_{\text{măs}}}}{E_{N_{Lim}}}\right)^2, \tag{4.12}$$

where $E_{i_{\text{măs}}}$ is the measured intensity, and $E_{i_{Lim}}$ is the limit corresponding to the frequency at which it was measured.

E can be replaced by *H* if the probe used is of magnetic field. For the cases when the power density *S* is measured, relation (4.12) becomes:

$$C_{\text{exp}} = \sum_{i=1}^{N} \frac{S_{i_{\text{măs}}}}{S_{i_{Lim}}} = \frac{S_{1_{\text{măs}}}}{S_{1_{Lim}}} + \frac{S_{2_{\text{măs}}}}{S_{2_{Lim}}} + \cdots + \frac{S_{N_{\text{măs}}}}{S_{N_{Lim}}}. \tag{4.13}$$

Actual measurements made using a spectrum analyzer need some individualized settings for each type of source under investigation. In the case of mobile telephone systems, stations do not transmit at constant power, the transmit power varying with the traffic load and the distances between the station and the mobile terminals it serves. The present thesis aims at an evaluation of compliance with some protection rules and takes into account the situation in which the station transmits at maximum power on all channels. For this, in addition to the measured values, the maximum possible exposure is also estimated. Each mobile phone station is equipped with one or more technologies, in the urban environment most stations are equipped with all three nationally licensed technologies (GSM, UMTS and LTE).

To estimate the exposure in the conditions where a cell emits with maximum power on all channels, the electric field intensity (*E*) or the power density (*S*) on the

BCCH frequency will be measured and multiplied in correlation with the number of emission units /reception (n_{TRX}), using formulas (4.14) or (4.15).

$$E_{\text{est}} = E_{\text{mas BCCH}} \cdot \sqrt{n_{\text{TRX}}} \,, \tag{4.14}$$

$$S_{\text{est}} = S_{\text{mas BCCH}} \cdot n_{\text{TRX}} \,. \tag{4.15}$$

Also in UMTS systems there are control channels that transmit system information and that are emitted with constant, time-invariant powers. Only these channels will be measured and then, to determine the maximum exposure, the measured value will be multiplied by a factor k which is the ratio of the power spectral density under the conditions in which the station would transmit at theoretical maximum power to the measured power density for the component signal invariant.

$$E_{\text{est}} = E_{\text{mas}} \cdot \sqrt{k} \,, \tag{4.18}$$

$$S_{\text{est}} = S_{\text{mas}} \cdot k \,. \tag{4.19}$$

Using modern analyzers that can perform decoding and exclusive measurement of the intensity of the electric field generated by the pilot channel, the estimation of the maximum exposure requires the use of a factor k=10. If it is not possible to decode and measure only the pilot channel, the solution is to measure the maximum exposure generated by each carrier under very low traffic conditions (ideally no traffic load); the measured value will be multiplied by a value corresponding to a factor k=5, the power assigned to all control channels, including the pilot, being approximately 20% of the total theoretical maximum power. There are situations when mobile operators decide to change the weights assigned to the control channels, which will influence the multiplication factor.

Similar to CDMA networks, all base stations in LTE (Long Term Evolution) networks work in the same frequency band. As in the case of GSM, where we have the BCCH channel, or 3G where we have the pilot channel, in the case of LTE systems the time-invariant signals are the reference signals and the signals on the broadcast channel (PBCH - Physical Broadcast Channel). For LTE, maximum exposure analysis can be done in 2 ways, depending on the measuring device being investigated. The first method involves the use of a modern analyzer with a decoder, which measures only the reference signal (Reference Signal - RS) transmitted by the base station at a constant power and then extrapolates to estimate the maximum exposure using relations (4.22) and (4.23), where k is the theoretical extrapolation factor, corresponding to the number of subcarriers and is dependent on the bandwidth of the LTE channel, according to table 4.2.

$$E_{\text{est}} = E_{\text{mas}} \cdot \sqrt{k} \,, \tag{4.22}$$

$$S_{\text{est}} = S_{\text{mas}} \cdot k \,. \tag{4.23}$$

Table 4.2 *The theoretical extrapolation factor, k*

LTE Channel Bandwidth [MHz]	***k***
1.4	72
3	180
5	300
10	600
15	900
20	1200

The second method involves the use of a spectrum analyzer without a decoder, in this case the energy carried by the reference signals can no longer be accurately detected, as they are transmitted on resources spread over time and frequency. To overcome this problem it is taken into account that the PBCH is transmitted with the same characteristics regardless of the service configuration or bandwidth and spans a bandwidth of 1080 kHz (72 subcarriers of 15 kHz) shifted to the center frequency of the LTE channel. Only these subcarriers will be measured and then, to determine the maximum exposure, the measured value will be interpolated by a factor *m* which represents the ratio of the power density under the conditions in which the station would transmit at theoretical maximum power and the measured power density for the invariant component of the signal:

$$E_{\text{est}} = E_{\text{mas}} \cdot \sqrt{m}\,, \tag{4.24}$$

$$S_{\text{est}} = S_{\text{mas}} \cdot m\,. \tag{4.25}$$

The interpolation factor *m* is calculated according to the bandwidth of the LTE channel and taking into account that the PBCH signals are transmitted on 72 subcarriers. The values of the factor *m* can be found in table 4.3.

Tabelul 4.3 *The theoretical extrapolation factor, m*

LTE Channel Bandwidth [MHz]	***m***
1.4	1
3	2.5
5	4.16
10	8.33
15	12.5
20	16.66

Chapter 5

Evaluation of electromagnetic field exposure in the vicinity of fixed mobile telephone stations

The public wants to be informed about the quality of the living environment. Thus, measuring the ambient electromagnetic field is an effective way to determine the general exposure of the general public to electromagnetic waves. In 2018, Orange Romania launched a campaign to measure the power density near each mobile phone station (with macro or micro coverage) whose address is in the inner city [59]. Over the course of a year, the author coordinated the campaign in which the power density was measured in the vicinity of 1750 sites distributed throughout the country. At the beginning of 2021, in Bucharest, with the development of the 5G network in the 2100 MHz and 3500 MHz frequency bands, the author repeated 122 power density measurements in the same coordinates where the initial measurements were made, before the 5G installation. The results were compared with reference levels in Romania which are the same as those provided in the ICNIRP standard. [24]

The measurements were performed with the "quick assessment" method [58], this method being the most suitable in far-field situations. The rapid assessment is performed with a broadband device and is a first step method to determine if the total level is approaching the decision threshold. A Narda NBM-520 broadband electronic module was used to which a Narda RF 1891 electric field triaxial probe with the band 3 MHz – 18 GHz was connected. Since the probe is triaxial, the measurement is independent of the emitter bias, making measurements easier. The averaging time was considered, according to the ICNIRP requirements, to be 6 minutes, and the physical quantity in which the field value was expressed is the power density. The measurement analyzer was set to measure the average of the maximum values recorded during the measurement time interval.

In order to obtain the maximum exposure coefficient, using equation (5.1), the measured values were reported to the lowest reference value provided by national legislation for the general public in the case of mobile phone systems in which Orange Romania company stations operate. Based on the data in Table 3.3, the LTE 800 system operating on the downlink in the frequency band 806 – 816 MHz, determines 4.03 W/m2 as the lowest power density reference value.

$$C_{\text{exp\_max}}[\%] = \frac{S_{\text{mas}}\left[\frac{\text{W}}{\text{m}^2}\right]}{4.03\left[\frac{\text{W}}{\text{m}^2}\right]} \cdot 100\,. \tag{5.1}$$

Figure 5.4 shows the cumulative distribution function of the 1750 values of the maximum exposure coefficients measured. As can be seen, more than 90% of the coefficients are below 0.2% of the ICNIRP limits, i.e. more than 500 times lower, with the average of the coefficient values being about 0.11%. The highest level recorded was 6.667%, but this too is more than 15 times lower than the minimum reference level.

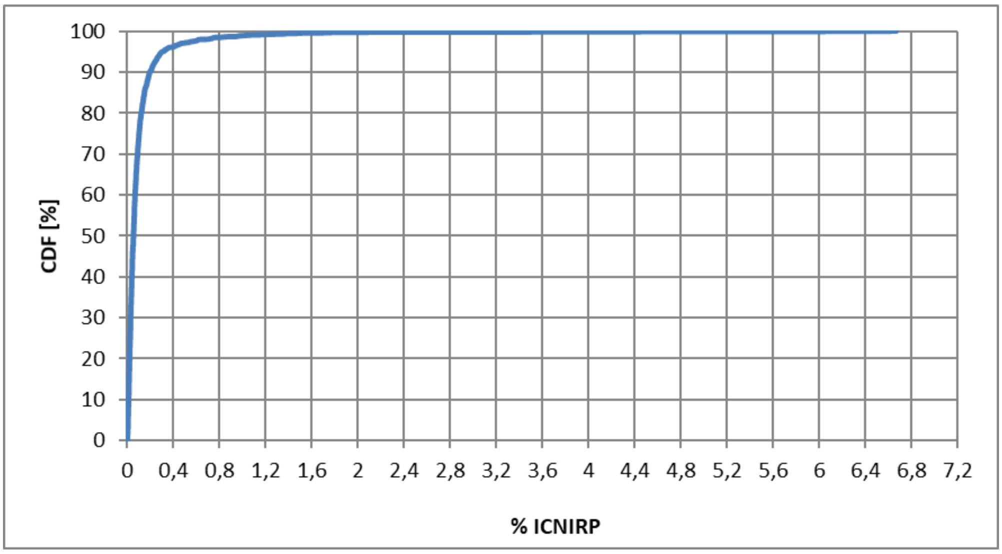

Figura 5.4 *Cumulative distribution function of all measurements*

Based on the coordinates of the sites, they were classified into 1190 urban sites and 560 rural sites. In Figure 5.5, respectively in Figure 5.6, the cumulative distribution functions of the maximum exposure coefficients measured for the urban and rural sites are presented.

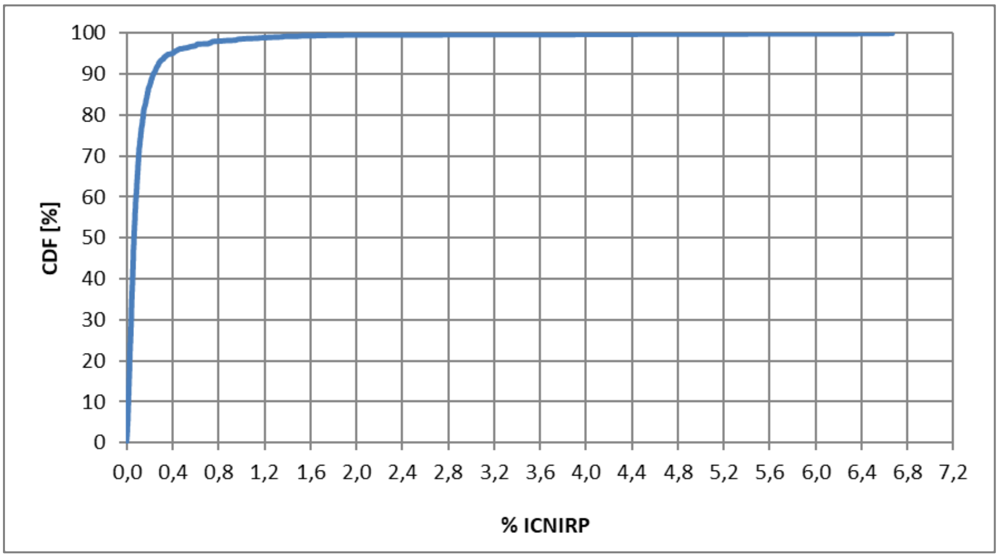

Figura 5.5 *Cumulative distribution function of urban measurements*

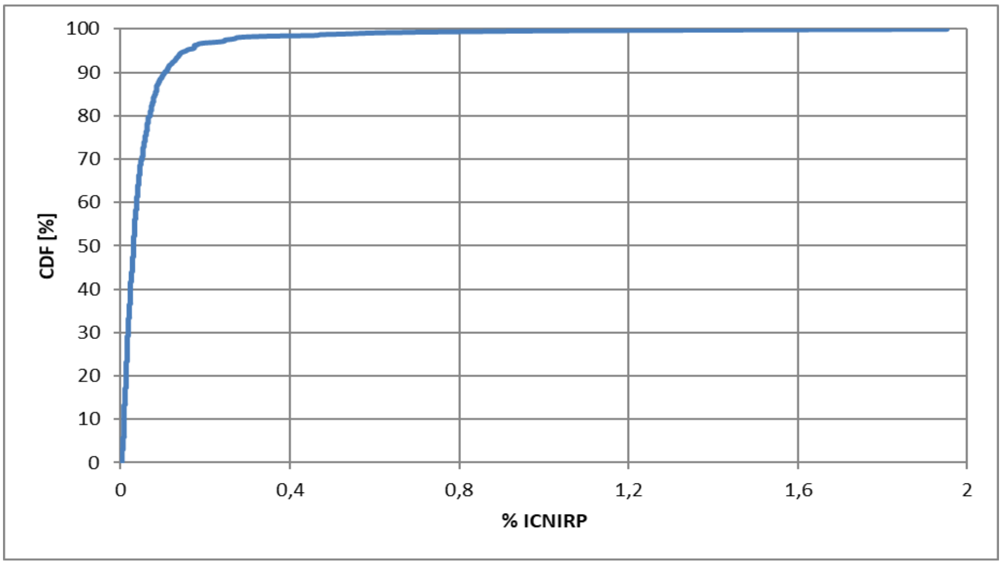

Figura 5.6 *Cumulative distribution function of rural measurements*

Regardless of the environment, the cumulative distribution shows that more than 90% of the coefficients are below 0.2% of the limits provided by ICNIRP, in the case of measurements in the urban environment 4 maximum exposure coefficients having values between 4.2% and 6.67%, in while over 99% of the values were below 2%. Following the point-by-point analysis of these values, it was found that there were buildings in which mobile phone stations were operating near the measurement points.

For each value measured after the start of the 5G network, the same maximum exposure coefficient was calculated, by relating the measured value to the lowest reference value provided by national legislation for the general public in the case of mobile phone systems in which Orange Romania company stations operate, namely 4.03 W/m^2 corresponding to the LTE 800 MHz system. The cumulative distribution shown in Figure 5.7 highlights that 90% of the coefficients are below 0.2% of the ICNIRP limits, while over 99% of the values are below 1%, with only one measured value being 2.4% of the limit. by ICNIRP.

For the 122 measurements taken after the development of the 5G network, the average value of the maximum exposure coefficient was calculated and compared with the value before the advent of 5G technology. The average value of the maximum exposure coefficient before 5G was 0.47% of the lowest reference value provided by national legislation for the general public in the case of mobile phone systems in which Orange Romania fixed stations operate, and after the installation of the 5G network, this value increased to 0.55%, a value almost 200 times lower than the legal limit.

The measurements show that the exposure of the general public to the electromagnetic field produced by macro mobile phone stations is low. Except for 4 values, the maximum exposure coefficients measured were below 2%. Having the 4 values obtained in the vicinity of stations operating inside buildings, we can think that in the case of measurements inside buildings we could obtain higher power density values.

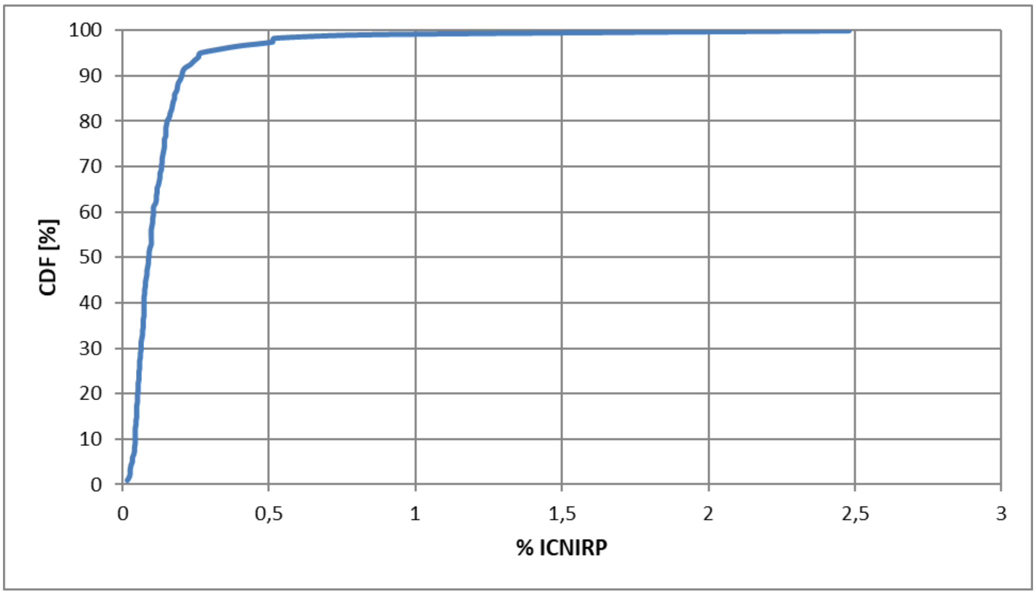

Figura 5.7 *Cumulative distribution function of measurements taken after the development of the 5G network*

Measurements carried out after the installation of the 5G network led to the same conclusions, the average exposure increased by only 17%, in some cases the measured values were even lower, which was attributed to the fact that to start the 5G network in the 2100 MHz band it was necessary to turn off of two UMTS2100 carriers, and 5G network traffic is still low.

Chapter 6

Evaluation of exposure to electromagnetic fields in distributed antenna system sites

In addition to mobile phone stations installed on towers or terraces, there are also a large number of stations with a distributed system of antennas inside buildings, called "indoor" stations. Following the spot analysis of the 4 highest values measured during the nationwide power density measurement campaign near each mobile phone station (with macro or micro coverage) whose address is in the inner city, it was observed that these 4 points they were a few meters from the access doors of some buildings where indoor mobile sites were operating. This has aroused the interest of carrying out measurements in buildings where indoor stations operate with a distributed system of antennas, especially in the context in which Orange Romania wants to expand its 5G network.[60]

In 2019, ambient electromagnetic field exposure was assessed using a broadband power density measurement device inside 60 Orange stores where indoor sites were installed. In March 2021, using a selective measuring device in frequency and in narrowband code, the case of two offices belonging to Orange Romania was analyzed, based on the measured values of the power density, estimating the maximum exposure coefficient in the hypothetical conditions in which all technologies would operate at full load. In each premises there is a passive system consisting of antennas, power dividers and cables. [61]

In the case of the 60 stores, measurements were made according to the "rapid assessment" method [58], and the broadband measurement equipment used consisted of a Narda NBM-520 broadband electronic module connected to a triaxial electric field probe Narda RF 1891 with the 3 MHz - 18 GHz band. For the 2 offices, the "Investigation in the band" method [58] was used, the measurements were carried out based on the previously presented procedures using the SRM-3000 spectrum analyzer and a triaxial electric field probe, with the 75 MHz - 3 GHz band . For all measurements, the measuring device was set to measure maximum values, the measurement time for each point was 6 minutes, and the physical quantity in which the field value was expressed is the power density.

The measuring rig was mounted on a non-conductive tripod with the probe positioned at a height of approximately 1.7 m from the floor.

For each of the 60 Orange stores, measurements were made at a single point at a horizontal distance of 1-1.5 m from the antenna.

For the two offices, the chosen points were divided into two large categories:

- at 1 - 3 m from the antenna in a horizontal plane, considered the area in the immediate vicinity of the antennas. Four measuring points were chosen in the "EH" premises, respectively five points in the "Skanska" premises;
- at 5 - 20 m from the antenna in the horizontal plane, considered the remote area. Four measuring points were chosen in the "EH" premises, respectively five points in the "Skanska" premises.

The frequencies used by the broadcast systems are higher than 800 MHz, which leads to a reactive near field that extends up to 37.5 cm from the antennas, which is why we can consider that all measurements were made in the area where it is possible use the plane wave model.

In the case of measurements in shops, the calculation of the maximum environmental exposure coefficient expressed as a percentage of the regulated limits was made using equation (5.1), by which the measured values were related to the lowest reference value provided by the national legislation for the general public in the case of mobile phone systems in which Orange Romania company stations operate.

Figure 6.2 illustrates the cumulative distribution function (CDF) of the 60 measured maximum exposure coefficient values. As can be seen, more than 90% of the coefficients are below 17% of the ICNIRP limits (where 100% is equivalent to reaching the power density value of 4.03 W/m^2), i.e. more than 5 times lower. The average of the coefficient values is about 6.59%, and 74% of the measurements are below 10% of the reference value. The maximum level recorded was 23.28%, which is more than 4 times lower than the minimum reference level.

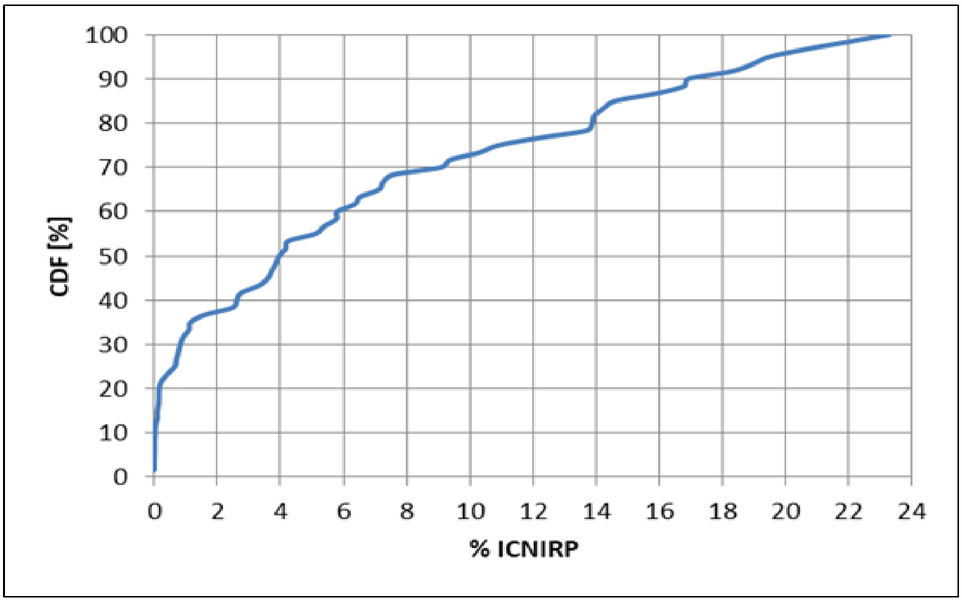

Figura 6.2 *Cumulative distribution function of measurements from shops*

The system in the first premises, hereinafter referred to as "EH" (Europa House), is a medium-sized one, with 8 antennas distributed over two floors (4 antennas on each floor), connected by approximately 500 m of feeder. The second headquarters, named "Skanska", contains 24 antennas and just over 1000 m of feeder. A GSM station with a TRX operating in the 900 MHz band, a UMTS station transmitting on a single carrier in the 2100 MHz band and an LTE station transmitting on two 20 MHz carriers in the 1800 MHz and 2600 MHz bands, respectively.

In addition to the stations present in the buildings, there are also macro GSM, UMTS and LTE stations nearby belonging to Orange, Vodafone and Telekom, but their contribution to the measured value is negligible.

In Figure 6.6 we have the representation of the maximum estimate of the total exposure coefficients for a person near the antenna. For the "Skanska" headquarters, they vary between 5.85% and 13.28%, the latter being almost 8 times lower than the legal limit, the average of these maximum coefficients being 9.18%. The lower values of the coefficients are due to the higher ceiling, higher losses from the radiant system and implicitly a lower apparent radiated power. In the case of the "EH" building, the average of the exposure coefficients near the antennas is 37.48%, but the values of more than 40% of the exposure coefficients make us think that the power inserted into the antenna system should be reduced. The uncertainty of the SRM-3000 device with which the measurements were made is -3.3/+2.4 dB, so insufficient to bring the exposure over 100%. [62]

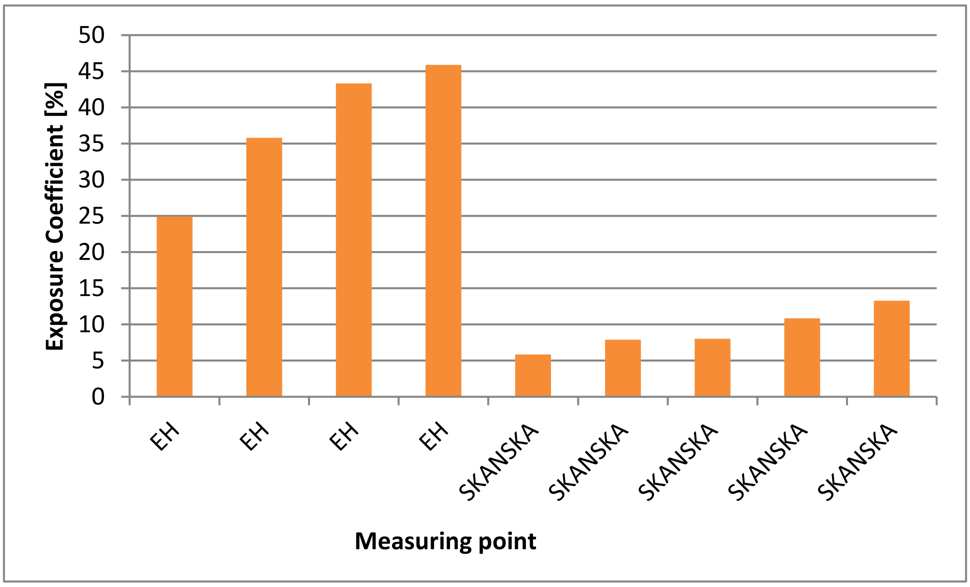

Figura 6.6 *Estimated maximum exposure coefficient for "near area"*

The measurements in the far area of the antennas are also very useful, the field being reduced in that area, but it helps to outline the picture of the average exposure coefficient at building level.

For ease of evaluation of the total maximum exposure in the area far from the antennas, the maximum coefficients estimated at each point were summed and represented in Figure 6.10 the estimated maximum total exposure coefficients for a person located more than 5 m from the antennas.

The differences between the coefficients estimated in the 2 headquarters are no longer significant, because the construction method of the buildings makes its presence felt. If in the measurements in the near area we had higher values in the case of "EH", now due to the compartmentalization of the offices and the kitchen area, the penetration attenuation is much higher in "EH" than in the case of "Skanska", where the building is of open type space.

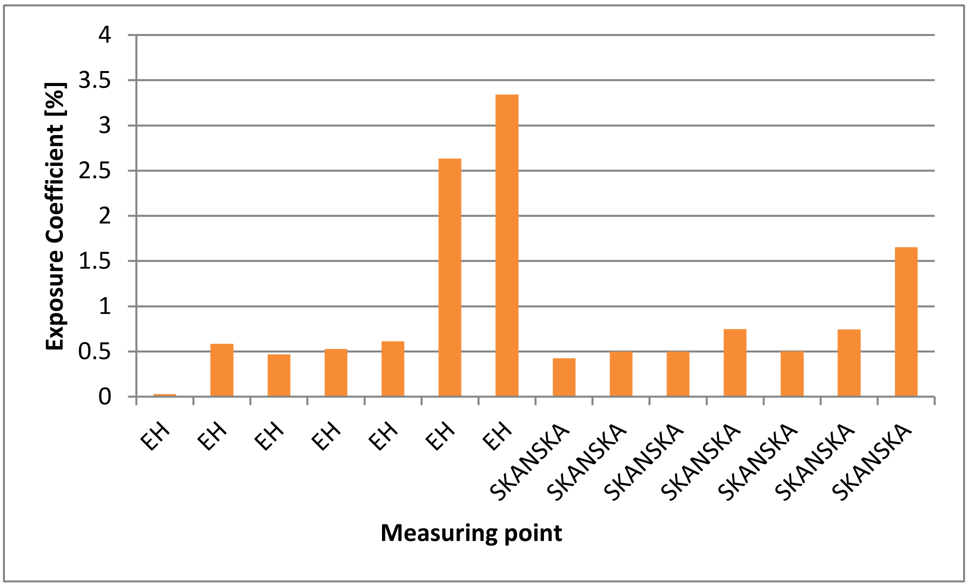

Figura 6.10 *Estimated maximum exposure coefficient for "far area"*

The total coefficients estimated in the remote area have close values in the two premises, they do not exceed 1.65%, except for two points in "EH" located at 10 and 15 m, respectively, but in visibility with the antenna. The average of the coefficients corresponding to the far area in "EH" is 1.17%, that is, 20 times lower than the average near the antennas, and in the case of "Skanska" the average is 0.72%.

If we were to calculate the average exposure coefficients for all measured points in each building, in "Skanska" we would get an average exposure coefficient of 4.24%, and in "EH" 14.37%, about 7 times lower than limit.

Although none of the buildings recorded values of exposure coefficients that we are concerned about, in the context of the addition of 5G technology, which in outdoor measurements we have seen increases the exposure coefficient by about 17% [59], at to which we can add the uncertainty of the device with which the measurements were made (-3.3/+2.4dB), at the point where we obtained the highest total maximum estimated exposure coefficient of 45.88% we could reach a value of the estimated maximum total exposure coefficient of over 90%. For this reason, in the case of the "EH" premises, it is recommended to reduce the transmission powers and install an additional antenna in the kitchen area.

Chapter 7

Evaluation of human exposure to electromagnetic field using data provided by the national autonomous electromagnetic field monitoring system

In order to be able to have technological development and progress from a scientific point of view, it is important how we present people with the dependence of health risks in relation to technological evolution [63]. An important step in reassuring the population has been the emergence of broadband or multi-frequency electromagnetic field monitoring systems that continuously measure the electromagnetic field produced by any of all surrounding sources and transmit the evaluation results to a publicly accessible platform.

Internationally, there is ITU-T Recommendation K.83 "Monitoring of Electromagnetic Field Levels" which outlines how to make and present long-term electromagnetic field measurements in areas of public interest. [64]

In addition to electromagnetic field measurement campaigns conducted by mobile communications network operators, in recent decades several countries have implemented radio frequency electromagnetic field monitoring networks as a means of exposure assessment. [37], [65], [66], [67], [68]

The National Authority for the Administration and Regulation of Communications in Romania makes available to the general public an interactive map that presents the values measured on the territory of Romania of the power density and the intensity of the electric field which they compare with the reference levels adopted by the national legislation. The values of the field levels shown on the interactive map are obtained either by measurements with portable equipment, or by measurements made by the 150 fixed sensors located in 104 localities in our country, installed in the vicinity of areas considered sensitive, such as educational institutions, institutions public buildings, hospitals or public areas in the vicinity of which there are multiple electromagnetic field sources.[65]

To analyze the exposure of the general public to the electromagnetic field, with the help of experts from the Monitoring and Control Executive Directorate within

ANCOM, the data measured by 150 fixed sensors were exported over the course of a year, between August 1, 2021 and July 31, 2022. For each frequency band (100 kHz – 7 GHz, 925 MHz – 960 MHz, 1805 MHz – 1880 MHz, 2110 MHz – 2170 MHz) the maximum and hourly average values of the electric field intensity were taken into account. The starting database totaled over 10 million samples. [72]

In Figures 7.2 and 7.6 respectively, they were represented, for the frequency band 100 kHz - 7 GHz, the histograms of the annual averages of the maximum values, respectively hourly averages of the measured electric field, as well as the cumulative distributions of the annual averages of the maximum values, respectively hourly averages of the measured electric field.

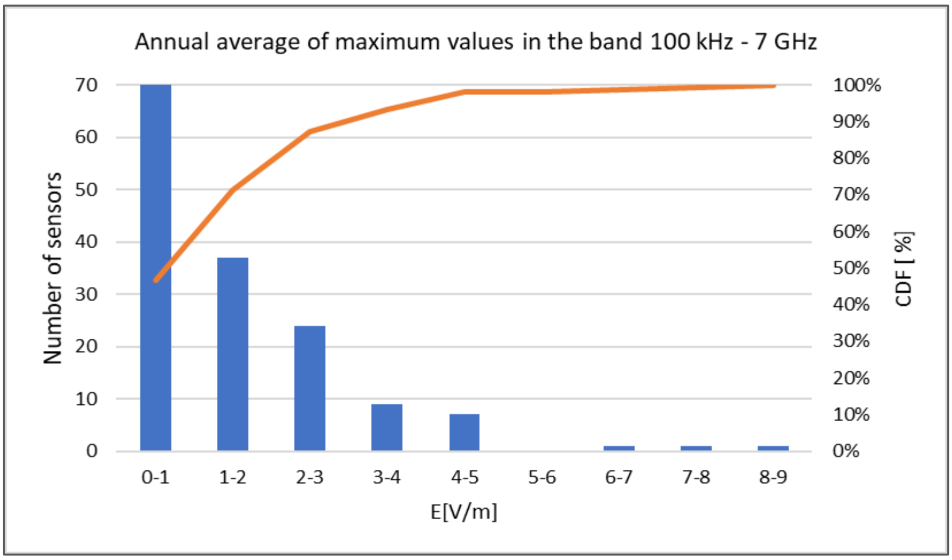

Figura 7.2 *Histogram of the annual averages of the maximum values of the electric field measured in the band 100 kHz - 7 GHz. The cumulative distribution of the annual averages of the maximum values of the electric field measured in the band 100 kHz - 7 GHz*

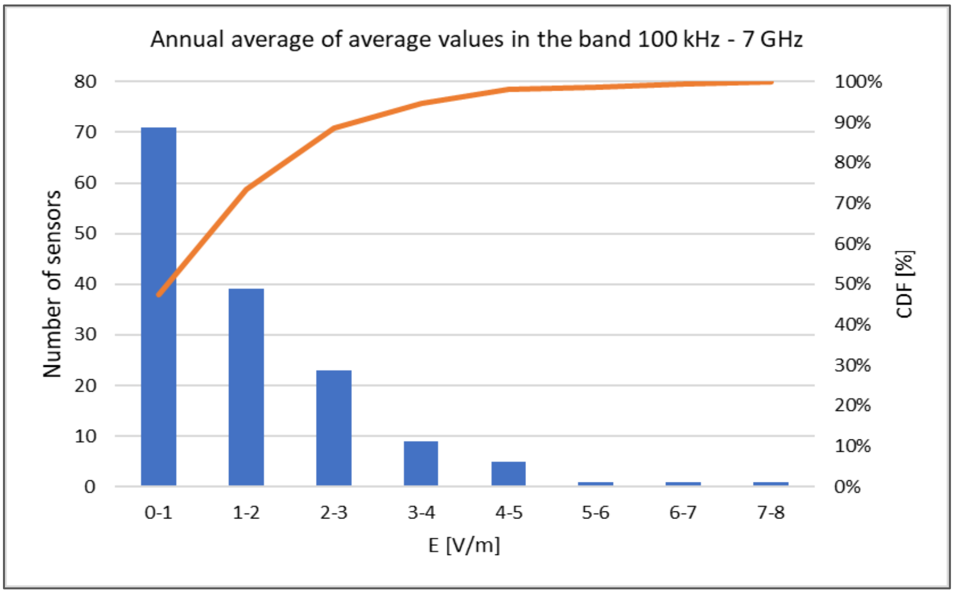

Figura 7.6 *Histogram of the annual averages of the average values of the electric field measured in the band 100 kHz - 7 GHz. The cumulative distribution of the annual averages of the average values of the electric field measured in the band 100 kHz - 7 GHz*

It is observed that for 70 of the 150 sensors the average of the electric field maxima measured in the band 100 kHz - 7 GHz, at the hourly level for 365 days is below 1 V/m, 90% of the values being below 4 V/m which is less than 15% of the reference level intended for the general public.

Regarding the annual averages obtained for hourly average values recorded by sensors in the 100 kHz - 7 GHz band, 97% of these are below 15.5% of the reference level for exposure of the general public.

The measured values show that there is no cause for concern regarding the health effects caused by exposure to the ambient electromagnetic field. The annual average of the maximum values of the electromagnetic field recorded at hourly level, in the band 100 kHz – 7 GHz, by all 150 sensors is 1.57 V/m, being more than 17 times lower than the reference level. The highest values of the field were measured by the sensor located on the terrace of building A of the Faculty of Electronics, Telecommunications and Information Technology, in Iuliu Maniu Boulevard 1-3, Bucharest, where several broadcast stations are known to be located, mobile telephony, data transmissions, radio relays, etc. Even for this location, the highest value of the electromagnetic field in the band 100 kHz – 7 GHz, recorded during the analyzed year was 12.24 V/m, being below 45% of the reference level. For this value, the maximum exposure coefficient of the general public, considering the most restrictive reference level, is approximately 20%.

7.1 Power density measurements on sites where there are multiple types of transmitters

A special case is the sites where there are several transmission or transmission-reception equipment installed. At the national level, more and more such sites are appearing. In 2018, in order to choose such a site in order to carry out electromagnetic field measurements, in addition to the visual choice, the electromagnetic field values measured by the fixed sensors within the network implemented and made available to the population by ANCOM, available throughout the country, were analyzed , installed in the vicinity of areas considered sensitive, such as educational institutions, public institutions, hospitals or crowded public areas in the vicinity of which there are multiple electromagnetic field sources. [73]

In Figure 7.10 we have the terrace plan of building A of the Faculty of Electronics, Telecommunications and Information Technology. To make it easier to understand and identify in the field, I have highlighted the aedicula and the terrace portions on the plan. With Arabic numerals I noted the points where the electromagnetic field measurements were made, and with "X" I positioned the main and most visible electromagnetic field sources.

For the measurements, a Narda NBM-520 broadband electronic module was used to which a Narda RF 1891 electric field triaxial probe with the band 3 MHz – 18 GHz was connected. The measurement process followed the "quick assessment" method, with the probe located 1.5 m above the terrace and approximately

0.5 m from the antennas. There were cases, namely, points 3, 4 and 13, when it was considered necessary to make measurements at smaller distances from the antennas, because they were areas easily accessible to the public, and even to pass other structures people get very close to the antennas.

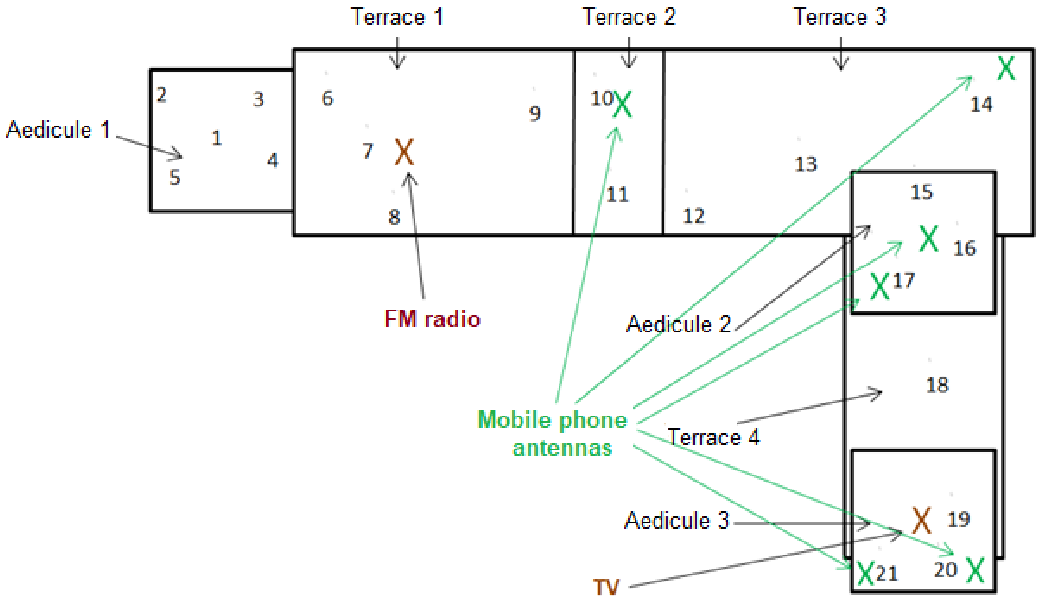

Figura 7.10 Terrace plan building A of the Faculty of Electronics, Telecommunications and Information Technology

For each measurement point, two measurements were made, the first time the average value of the power density during the 6 minutes was retained, and the second time the maximum value was retained.

In Figure 7.16, respectively Figure 7.17, the maximum values, respectively the measured average values of the power density are represented. To note the difference from the statutory reference levels, we have also plotted the audience-specific reference limits for power density for each frequency band. In the case of the frequency band 400 MHz - 2 GHz, where the limit is given as the frequency expressed in MHz weighted by 200, we took the worst case, considering the power density limit $2W/m^2$.

The measured values at any point on the terrace are below the reference levels for the general public specified by the ICNIRP standard, the highest measured value being approximately 10% of the ICNIRP threshold. With the exception of the area in front of the microwave antenna related to measuring point 13, the higher values are recorded on the aedicules, where the visibility with the emission antennas is higher than in the case of the terraces.

The difference between the obtained values of the maximum exposure coefficients, 10% based on the measurements made by the author and 20% the measurements made by the ANCOM sensor, is explained by the fact that the ANCOM measurements were reported at 27.5 V/m which is the minimum reference threshold from the 100 kHz – 7 GHz band, although most antennas on the terrace emit in bands above 2 GHz, where the reference level is 61 V/m, which would lead to maximum exposure coefficients not exceeding 5% of the norms.

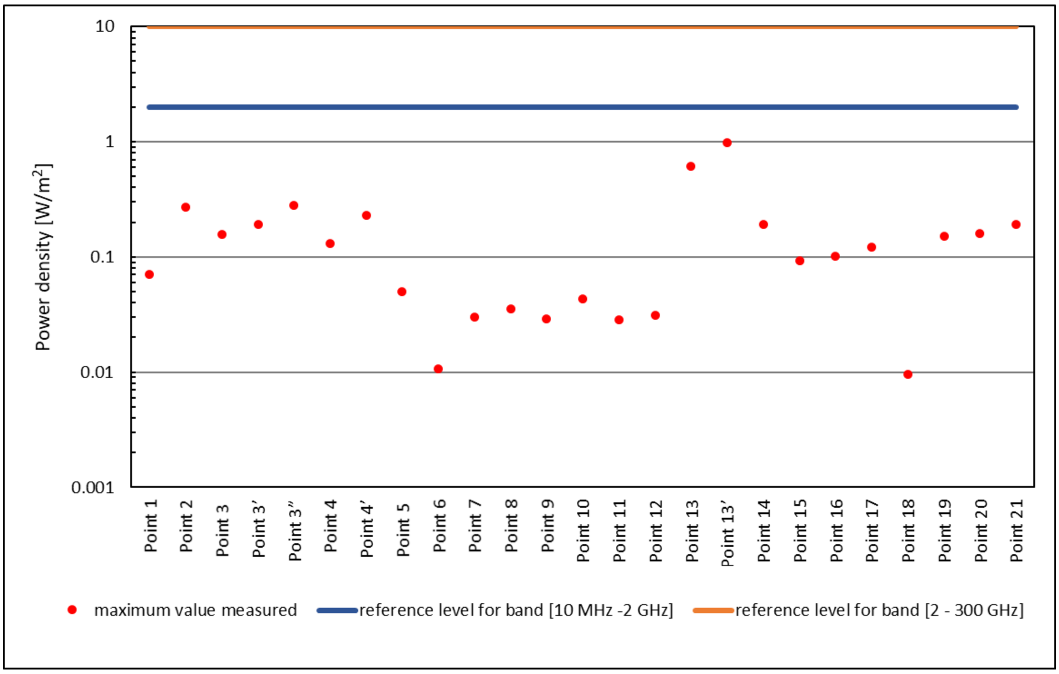

Figura 7.16. *Maximum power density values measured*

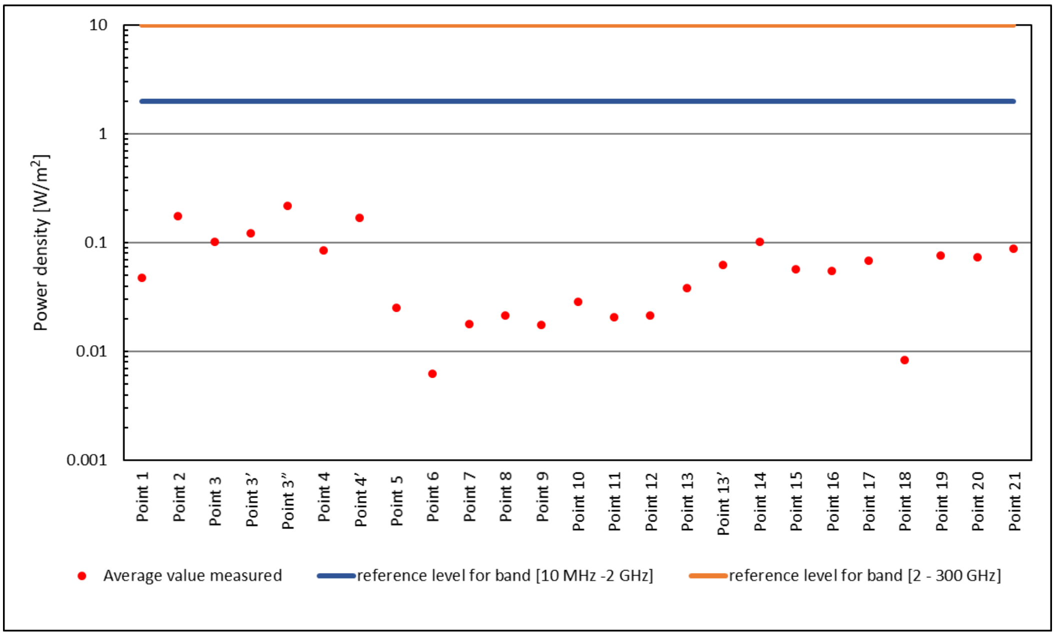

Figura 7.17. *Average power density values measured*

Although the measurements show that there is no cause for concern, it was considered useful to evaluate the field on the top floor of the building, in the hallway just below the terrace where the initial measurements were taken. As expected, due to the attenuation brought by the walls and ceiling of the building, the field level is reduced compared to the one to be recorded on the roof; it would have been even lower if a WiFi router had not been placed on the 8th floor.

Chapter 8

Evaluation of uplink power and energy emitted by mobile equipment in commercial 4G and 5G networks

In order to limit the exposure of people to the electromagnetic fields emitted in the frequency bands allocated to mobile operators, in parallel with the reduction of the ambient exposure produced by the base stations, it is also very useful to reduce the exposure produced by the equipment of the users during use.

Many studies have been done so far to evaluate the time average of the power emitted by mobile terminals in GSM [76], [77], UMTS [78], [79] or LTE technologies [80], which show that for GSM, the time average of the transmitted powers is about 50% of the maximum power, while for UMTS and LTE they are even lower, one of the reasons being the better power control mechanisms.

An in-depth study of the powers and energies emitted by GSM and UMTS terminals, which shows that in good propagation conditions, from the point of view of the emission power of the terminals, the UMTS system is much superior to the GSM system, registering energy values on average about 100 times smaller, can be found in [81].

In order to be able to evaluate the average power with which a terminal emits from the 4G and 5G commercial networks of the Orange Romania mobile operator, data was extracted from the operation and maintenance platform. Recordings were collected on an hourly basis for each cell associated with the base stations. Recordings were carried out over 4 days, from May 24 to May 27, 2021 for all mobile stations connected to 100 urban sites equipped with 5G in the uplink band 3530 - 3630 MHz and 4G in the uplink bands 837 - 847 MHz, 1740 - 1760 MHz and 2510 - 2530 MHz, respectively another 100 rural sites equipped only with 4G. [83]

During the 96 hours, on the approximately 1700 cells associated with the 200 sites, more than 30 billion samples were collected and analyzed.

It has been observed that the average instantaneous powers emitted by a terminal connected to 5G technology are lower than when connected to 4G technology. More than 90% of the instantaneous average powers emitted by the terminal in 5G are below 130 mW, while in the case of 4G technology, these powers can reach 175 mW.

The average value of the power emitted by the mobile terminal in 5G is 92 mW, and in 4G it is 116 mW.

In order to compare the average powers emitted by the EU in 4G in urban and rural areas respectively, in Figure 8.3 the cumulative distribution functions of the instantaneous average powers emitted by the EU were represented, where it can be seen that in rural areas the powers are higher compared to areas urban.

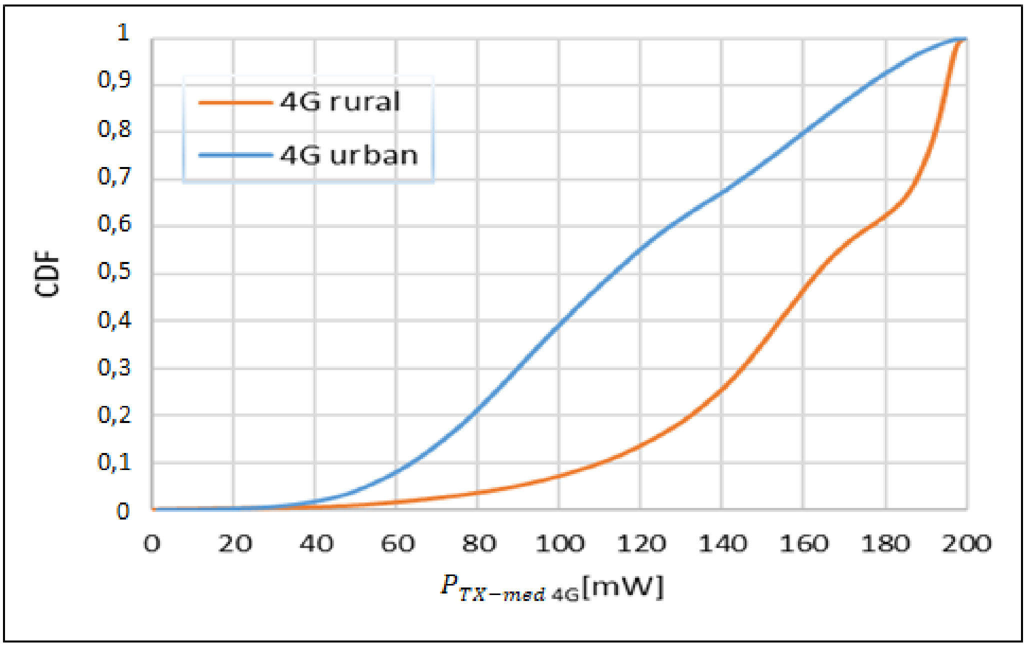

Figura 8.3 *CDF of the average instantaneous powers with which an UE broadcasts in urban / rural 4G*

The calculation of the energy emitted by the terminals in one hour shows that in the case of 5G technology, for 95% of the cases, the average energy emitted by the terminal does not exceed 2.55 J, the average being 1.03 J. In the case of 4G technology, the average energies emitted of user equipment are higher in rural areas, 95% of the average energy values emitted by the EU being below 330 J, while in the urban environment they are below 300 J. In one hour, the average energy emitted by mobile stations in 4G technology installed in the rural environment is 245 J, and in the urban environment this average value drops to 175 J.

Recalling the results obtained in the power density measurement campaign near each mobile phone base station, namely, the average power in the vicinity of the base stations was equal to 4.85 mW when we do not have 5G, respectively 5.73 mW when the site is equipped and with 5G, we get an average energy of 17.46 J when we don't have 5G, and 20.63 J when we also have 5G. If it is considered that the mobile terminal is very close to the user, often touching the person's body, we notice that the energy received from the base stations is significantly lower, by about an order of magnitude, even when the user is in the immediate vicinity of them which is practically the worst case.

Chapter 9

Conclusions

This PhD thesis aims to clarify a relatively long discussion that has been going on for several decades, namely, the exposure of the population to non-ionizing electromagnetic fields, focusing in particular on the assessment of exposure in the frequency range where mobile telephone networks operate.

First of all, it should be pointed out that the erroneous use of names such as "invisible enemy" or "electromagnetic pollution" only leads the public into an area of confusion and incorrectly perceives the electromagnetic field. Sometimes even generating a state of fear. The public must be informed about radiation protection and how it interacts with the human body, radiation being divided into ionizing radiation and neonizing radiation.

Ionizing radiation transfers enough energy to the atom and the removal of an electron from the atom occurs, while non-ionizing radiation has a lower energy level and does not remove the electron from the atom.

The general conclusion, following all the measurements made or interpreted by the author, is that the level of exposure to the ambient field both inside the buildings and outside them is far below the reference levels established by law; in most cases it does not exceed a few percent of them. This conclusion is also reinforced by the bibliography related to the subject.

Another important conclusion is that although fixed mobile phone stations are the main source of exposure in terms of population fear, the closest field source to the human body is the mobile phone, the energy received from it exceeding the energy received from radio base stations.

9.1 Obtained results

Chapter 1 provides an introduction to the field and defines the purpose of this doctoral thesis.

Chapter 2 is divided into several sections. In the first part, a synthesis is made of the studies related to the biological effects on the human body. There is still debate among scientists, with some being more skeptical even in the context that so far we have no study that contains firm and reproducible evidence to unequivocally prove a cause-effect relationship between low-level electromagnetic emissions found within internationally regulated reference limits, and a negative biological effect. Although no adverse effects related to exposure to ambient electromagnetic fields have yet been demonstrated, public concern is motivated by the lack of control over the type and timing of exposure, whereas in the case of using mobile terminals people can choose when and how much to use them.

In the last 30 years, mobile communication systems have experienced remarkable technological progress, spreading almost all over the world. Along with the technological development, a series of recommendations appeared, made by recognized scientific organizations in the field, which, based on the study of the bibliography in the field, established limit values for the exposure of the working personnel and the general public.

Electromagnetic waves are increasingly being used in the medical industry for soft tissue healing and cancer treatment, with common frequencies being 27 MHz, 433 MHz and 2.45 GHz.

The chapter concludes by treating the field in an engineering way, presenting the dielectric characteristics of biological media, the coupling relationship between induced fields inside structures and electromagnetic field distributions in free space.

Chapter 3 presents the main protection norms adopted in the world as well as the arguments that were the basis of their establishment. The emphasis was placed on the norms recommended by ICNIRP, these norms being adopted in almost all of Europe including Romania. The measurements carried out in the thesis were reported to the limits provided by ICNIRP in order to obtain exposure coefficients that give us an overview of the degree of exposure.

Chapter 4 documents the main types of electromagnetic field measuring devices that have otherwise been used during the measurements carried out in this work, as well as the methods of measuring the field components provided in the ECC recommendation (02)04 in order to validate compliance with the available limits.

Chapter 5 presents the results of an extensive campaign to assess the exposure to ambient electromagnetic fields in the vicinity of fixed mobile telephone stations. Power density measurements were carried out in the vicinity of 1750 fixed stations belonging to Orange Romania, distributed throughout the country. Later, after the start of 5G technology, 122 measurements were repeated in the same coordinates to study the differences. The measured values were related to the reference levels provided by ICNIRP, thus obtaining the exposure coefficients. More than 90% of the maximum exposure coefficients calculated for the 1750 values measured before the implementation of 5G technology were below 0.2% of the ICNIRP limits, the average of the coefficient values being about 0.11%; the maximum estimated coefficient was 6.667%, more than 15 times lower than the minimum reference level.

Following the classification of the measurements according to the area, no significant differences were found between the values measured in urban areas compared to those measured in rural areas.

Four of the coefficients stood out, having higher values than the others, but after the spot analysis it was found that the measurement points were in the vicinity of the access ways of some buildings where mobile phone stations were operating.

The evaluation of the maximum exposure coefficients following the start-up of 5G states showed that, except for four of the values, they did not exceed 2% of the ICNIRP, with the average exposure increasing by only 17% compared to previous measurements.

Chapter 6 starts from the observations in the previous chapter when the highest measured values were in the vicinity of buildings with indoor mobile phone stations and investigates the exposure to electromagnetic fields in sites with a distributed antenna system. Ambient electromagnetic field exposure was assessed by measuring with a broadband power density meter inside 60 Orange stores, and subsequently using a narrowband code and frequency selective meter, analyzed the case of two offices belonging to Orange Romania, based on the measured values, estimating the maximum exposure coefficient under hypothetical conditions in which all technologies would work at maximum load.

In the case of the 60 measurements in stores, more than 90% of the values were below 17% of the limits provided by IGNIRP, where 100% is equivalent to reaching the power density value of 4.03W/m^2, the average of all values being about 6, 59%, the maximum level recorded was 23.28%, i.e. more than 4 times lower than the reference value.

In the case of the two offices where we used the band investigation technique, we estimated the exposure in the very unlikely situation when all technologies emit simultaneously at maximum power level, at maximum capacity. The maximum values of the exposure estimate in the proximity of the antennas varied in the case of measurements from the "Skanska" headquarters between 5.80% and 13.28% of the legal limit, while for the "EH" headquarters we had values over 40% of the limit . The average of the calculated exposure coefficients in the area near the antennas is 37.48% in the "EH" building, respectively 9.18% for the "Skanska" headquarters. The measurements in the areas far from the antennas no longer had significant differences, observing the rather large influence of the architecture of the buildings. The total coefficients estimated in the remote area have close values in the two premises, except for two points in "EH", they do not exceed 1.65% of the legal limits. The average of the coefficients corresponding to the far area in "EH" is 1.17%, that is, 20 times lower than the average near the antennas, and in the case of "Skanska" it is 0.72%.

Although we did not record any values that would cause us concern, in order to activate 5G technology, in the EH headquarters it is recommended to reduce the emission powers.

Chapter 7 presents the results of the electromagnetic field measurements performed by the fixed sensors installed by ANCOM, as well as the study of a site where several emission or emission-reception stations are installed. The annual average of the hourly peak values measured by the 150 sensors in the 100 kHz - 7 GHz band is 1.57 V/m, more than 17 times lower than the reference level. The annual averages of maximum field values in the 2110 MHz – 2170 MHz band are below 2 V/m, about 3% of the reference threshold, for 95% of the sensors, while for the 1805 MHz – 1880 MHz band, except for 2 between the sensors, the measured field was below 3 V/m. For the frequency band 925 – 960 MHz, the reference level is 41.81 V/m, with 97% of sensors reporting annual average maximum values below 7.2% of this level.

The annual averages obtained for the measured hourly average values are lower than the annual averages of the maximum hourly values. Relative to the general public exposure reference levels for each frequency band, 97% of the annual averages obtained for the measured hourly average values are below 15.5% for the 100 kHz - 7 GHz band, below 3.2% for the 2110 MHz band - 2170 MHz, below 4.2% for the 1805 MHz - 1880 MHz band, respectively below 6.8% for the 925 MHz - 960 MHz band.

The conclusion is that all measurements reported values well below reference levels. The highest values were measured by the sensor installed on the body A of the Faculty of Electronics, Telecommunications and Information Technology, where the maximum exposure coefficient of the general public, calculated considering the most restrictive reference level, was approximately 20%. The measurements carried out by the author in the vicinity of the antennas on this terrace revealed levels that do not exceed the reference values, the maximum exposure coefficient of the general public being 10% of the ICNIRP threshold. The difference between these values of the maximum exposure coefficients is justified by the fact that the ANCOM measurements were reported at 27.5 V/m which is the minimum reference threshold in the 100 kHz – 7 GHz band, although most antennas on the terrace emit in bands of above 2 GHz, where the reference level is 61 V/m, which would lead to maximum exposure coefficients not exceeding 5% of the norms.

In chapter 8, a comparative assessment of the power and energy emitted on the upward path by the users' mobile equipment in 4G and 5G networks was carried out. The levels of uplink power emitted by user equipment in the 4G network are higher than in the case of the 5G network. The average value of the power emitted by the mobile terminal in 5G is 92 mW, and in 4G it is 116 mW. The power levels emitted by user equipment in the 4G network are higher in rural areas than in urban areas. Uplink transmission times are lower in the 5G network than in the 4G network. The average energy emitted in an hour by 5G terminals does not exceed 2.55 J for 95% of the cases, the average of all values being 1.03 J. in the case of the 4G network, the average energies emitted in an hour by mobile terminals are 245 J in the rural environment, respectively 175 J in the urban environment. The conclusion is that when the mobile terminal is very close to the user, the energy received from the terminal is higher than the energy received from the radio base stations.

9.2 Original contributions

This section reviews the author's main contributions to the analysis of population exposure to electromagnetic fields generated by mobile communication systems.

a) Synthesis of the main national and international rules for protection against electromagnetic field exposure in force in the world, with an emphasis on ICNIRP also adopted in Romania. [2, 3]

b) Presentation of electromagnetic field measurement methods and devices. The measurement method for estimating the maximum exposure in the extreme cases where fixed mobile stations would transmit at full power under full load conditions was detailed. [3]

c) Carrying out an extensive campaign to measure the power density of the ambient electromagnetic field in the vicinity of 1750 fixed mobile telephone stations installed in urban areas throughout Romania and evaluating the ambient field exposure coefficient of the general public. [2]

d) Remeasurement of power density after the activation of 5G technology in 122 points out of 1750 and calculation of the new ambient exposure, as well as assessment of the additional exposure brought by the activation of 5G technology. Specialized literature does not have many studies on this subject at present. [2]

e) Measurements and estimates of exposure coefficients to neonizing electromagnetic fields in order to assess exposure in indoor spaces where base stations with a distributed antenna system operate. [1, 3]

f) Analysis of the emission powers of mobile terminals in 4G and 5G networks and comparison of the powers and energies emitted by the terminals according to technology and environment, as well as comparison of the energy received by the user from fixed mobile telephone stations with the energy received from the mobile terminal own. [4]

g) Analysis and interpretation in relation to the regulated reference levels of the electric field intensity values measured nationally over a period of one year by the 150 fixed sensors installed by ANCOM. Over 10 million samples were analyzed. [5]

h) Evaluation of electromagnetic field exposure in multiple points located in the vicinity of the antennas on the terrace of building A of the Faculty of Electronics, Telecommunications and Information Technology. An exposure map was practically made for a special case of sites where there are several emission or emission-reception equipment installed. [6]

9.3 List of original publications

1. E. Oproiu, C. Costea, **M. Nedelcu**, M. Iordache, I. Marghescu, „*5G Challenges, Requirements and Key Differentiating Characteristics from the Perspective of a Mobile Operator*", Future Access Enablers for Ubiquitous and Intelligent Infrastructures. Third International Conference, FABULOUS 2017: 64-70, doi.org/10.1007/978-3-319-92213-3_10, **WOS:000481658200010, (ISI, IEEE)**.

2. **M. Nedelcu**, T. Petrescu and V. Niţu, "*Evaluation of electromagnetic field exposure in the vicinity of mobile phone base stations*", 2021 IEEE International Black Sea Conference on Communications and Networking (BlackSeaCom), Bucharest, Romania, 2021, pp. 1-5, doi: 10.1109/BlackSeaCom52164.2021.9527794, **WOS:000892556200050, (ISI, IEEE)**.

3. **M. Nedelcu**, V. Niţu and T. Petrescu, "*Evaluation of electromagnetic field exposure in indoor spaces where there are located base stations with distributed antenna system*" 2021 International Symposium on Signals, Circuits and Systems (ISSCS), 2021, pp. 1-6, doi: 10.1109/ISSCS52333.2021.9497401, (**IEEE Xplore**).

4. **M. Nedelcu**, V. Niţu and T. Petrescu, "*Uplink power levels of user equipment in commercial 4G and 5G networks*", 2021 13th International Conference on Electronics, Computers and Artificial Intelligence (ECAI), Pitesti, Romania, 2021, pp. 1-4, doi: 10.1109/ECAI52376.2021.9515027, (**IEEE Xplore**).

5. **M. Nedelcu**, T. Petrescu, "*Evaluation of human exposure to electromagnetic fied using data provided by the National Autonomous Electromagnetic Field Monitor system*", U.P.B. Sci. Bull., Series C, Vol. 85, Iss. 2, 2023, pp. 175-184, ISSN 2286-3540, **WOS:001015488500011, (ISI**).

6. **M. Nedelcu**, T. Petrescu, "*Power density measurements on shared sites*", U.P.B. Sci. Bull., Series C, Vol. 85, Iss. 3, 2023 pp. 297-306, ISSN 2286-3540 (**ISI**)

9.4 Perspectives for further developments

The main direction of further development of the study is the 5G system which is starting to be increasingly implemented in Europe in several frequency bands, in the first phase it is developed in the bands below 6 GHz, then in the second phase we will see deployments in the 24 - 28 GHz bands with 500 - 1000 MHz continuous spectrum channel widths. Sixth generation technology is also already being discussed.

A second direction worth studying is how mobile exposure will evolve. Initially, the terminal was used almost exclusively for voice calls, the head area being the most exposed, and nowadays the terminal is mainly used in the hand, away from the head, but closer to the body. The average usage time is increasing and it is interesting to monitor the average energy absorbed from the terminal.

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