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Simulating the Dispersion of the Energy Flux Density of the Electromagnetic Field Generated by Antennas for Mobile Communications

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Abstract: The last two decades have faced a significantly increased number of telecommunication antennas emitting electromagnetic radiation in residential areas. The theoretical simulation of the dispersion of the energy flux density of the electromagnetic field has been performed applying the physical peculiarities of the waves generating electromagnetic radiation. Having evaluated studies on simulation, the visual representation of the spread of electromagnetic radiation has been carried out according to the results obtained applying the AutoCad package. A comparison of the simulated value of the energy flux density radiated from antennas for mobile telecommunications with the measured one has disclosed an overlap of 30%. The simulation of the energy flux density showed that, in the close proximity zone (under a distance of 30 m), antennas radiate values within the range 10–10,000 $\mu W/cm^2$. At a distance larger than 30 m, the values of energy flux density fluctuate from 10 to 0.001 $\mu W/cm^2$.

Keywords: environmental processes modelling; ionizing and (or) non-ionizing radiation; physical pollution; communications

1. Introduction

Electromagnetic radiation emitted by sources for cell telecommunications can be experimentally measured using a variety of software created for simulating the electromagnetic radiation [1,2]. The simulation of the electromagnetic radiation of mobile telecommunications includes the analysis of a few different antennas emitting electromagnetic radiation, which is difficult in normal conditions, using mathematical models [3,4].

The rapid growth of technologies in this sector is a significant factor in the growth of concentration too [5–7]. A precise model helps with managing the electromagnetic fields of the source and helps in predicting impact factors of practical uses (e.g., impact on other structure or the area) [8–10]. Simulation is required for both the existing and intended objects and provides a possibility of foreseeable conditions under which electromagnetic radiation is of the necessary value but does not exceed the permitted limits [11].

Due to the lack of scientific research on electromagnetic radiation from mobile antenna and public concern, the tendencies of EMF insensitivity parameters in the environment are discussed in this article. The contemporary opinion on the negative effect of mobile phone antennas and electromagnetic radiation from mobile phones does not allow making assumptions about future consequences on the basis of conducted scientific research.

A rapid increase in the level of electromagnetic radiation (many times exceeding original background) that can damage the ecological balance of the environment has been observed; therefore, it should be researched and evaluated by theoretical and experimental methods.

To indicate the impact of electromagnetic radiation on the environment, including on the human body, a specific characteristic, the Specific Absorption Rate (SAR), is used. This is a measure of the amount of electromagnetic fields (EMFs) absorbed by the human body from the radiation source. This rate is measured as the power absorbed within a defined area of body tissue in a standard measurement of watts per kilogram (W/kg).

Simulation must evaluate such parameters as the radiation diagram (direction) of the antenna for mobile telecommunications, amplification, polarization, power, frequency, landscape openness, land relief, the height of buildings, the distance between buildings, the angle of the direction of the dispersed signal, the impact of signal diffraction on rooftops and reflections, operating wavelength and other factors [12–14]. In order to analyze the energy flux density of the electromagnetic field under changing terrain, a number of different environmental factors must be assessed [15,16].

A direct electromagnetic field reflected from the ground surface is emitted to the point B of the monitored area. The intensity of the flux density S depends on the location of location B in respect of directional chart $F(\theta^\circ)$. When an antenna is directional, the intensity of the electromagnetic field decreases if angle θ° increases. This is the reason why the density in P_2 is more powerful than in P_1. L is the range from the A to the ground surface up to the projection of point B showed as the projection of a direct route from A to B. dh is the distance between point B and the line of the directional chart of the antenna. This value depends on a change in landscape altitude according to the base of the antenna. Due to the fact that at each point remote in a certain direction from the antenna at distance L, a change in terrain will be related with that point, angle θ° for the selected direction and land relief depends only on distance L. Thus, the flux density of the electromagnetic field also becomes proportional to L. Establishing such a connection is required for analyzing the density generated by mobile telecommunications under changing terrain (Figure 1) [17].

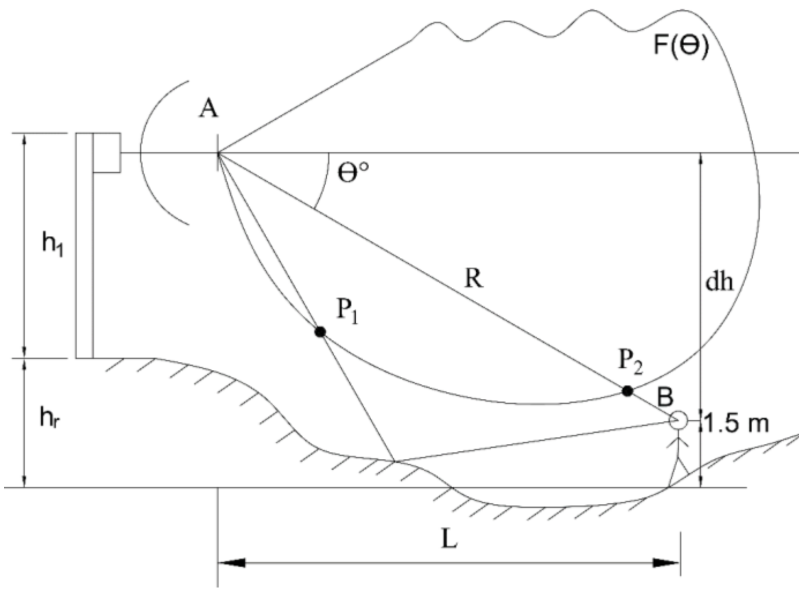


Figure 1. Example of a figure finding the energy flux density of the electromagnetic field generated by antenna A in point B considering terrain: L—distance projection of a direct route from A to B; dh—difference in the altitude between point B and the antenna; θ°—angle; h_1—the height of the physical center of the antenna above the ground; P_1 and P_2—the energy flux density of the electromagnetic field in the measured points; h_r—variations in terrain; R—the distance between the physical center of antenna A and monitored point B Reprinted/adapted with permission from Ref. [17].

When the antenna of mobile telecommunications is elevated higher than the surrounding buildings and forests, the dispersion and diffraction of electromagnetic radiation around obstacles are evaluated according to the heights of buildings, distances between them, street width and orientation, forest density, etc. [18].

In open space, the electromagnetic waves of mobile telecommunications weaken according to the function of inverse square distance. Therefore, the higher the source of the base station is elevated, the weaker the fields reaching the ground. After touching the surface, electromagnetic radiation begins weakening because of terrain or other obstacles on the Earth's surface. The area for dispersion is worse than that in free space [19], because the gap between the source and the customer always encounters obstacles [20].

Electromagnetic radiation is emitted in direct and indirect trajectories (Figure 2). The areas covered by the electromagnetic radiation of mobile telecommunications following direct trajectories are called direct visibility zones. The areas that fail to be reached by electromagnetic radiation emitted through direct trajectories are called indirect visibility zones. Such areas can only be affected by electromagnetic radiation when reflected, diffracted or dispersed from different objects and obstacles. A mobile phone receives dispersed, diffracted or reflected waves due to the barriers present in the way of the emitted radio signal. Where there is a decrease in electromagnetic radiation caused by mobile telecommunications, it is substantially affected by vegetation, wood and concrete structures, etc. [21,22]. In free space, signal suppression is proportional to the squared distance (Figure 3).

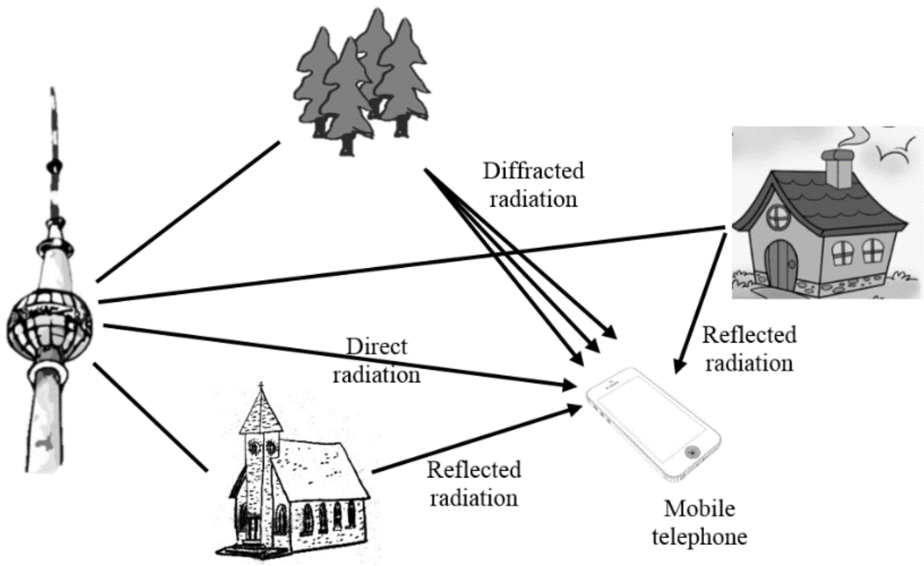


Figure 2. The dispersion of electromagnetic radiation assessing objects present in the environment.

Simulation, as a tool for research, has a number of advantages. Simulation involves repeated experiments and changes in their conditions at the discretion of the researcher. The simulation of electromagnetic radiation dispersion processes evoked by mobile telecommunications taking place around us is applied to establish or evaluate the emission of electromagnetic radiation in the environment and buildings [23].

Theoretical research on the dispersion process of electromagnetic radiation primarily focuses on describing the procedure with reference to differential equations and limited conditions for unambiguousness [24]. Upon solving differential equations, a functional relationship between the variables, which describe the process propagating the electromagnetic fields of mobile telecommunications, is established [25].

Simulation software empowers us to receive results from residential areas, from the buildings used for technical purposes and workplaces and fails to examine separately flux distribution but only focuses on the directions of the required points [26]. The simulation of a specific situation involves a number of variables, including an adjusted reflection coefficient, the impact of a meteorological situation on the suppression of the electromagnetic field, the terrain reflection coefficient for measuring radiation in shadow zones, expanding the sampling sequence of the directional antenna, and changing the height of the antenna [27]. However, not all packages of simulation software allow determining the above introduced parameters, which may result in imprecise simulation results [28,29].

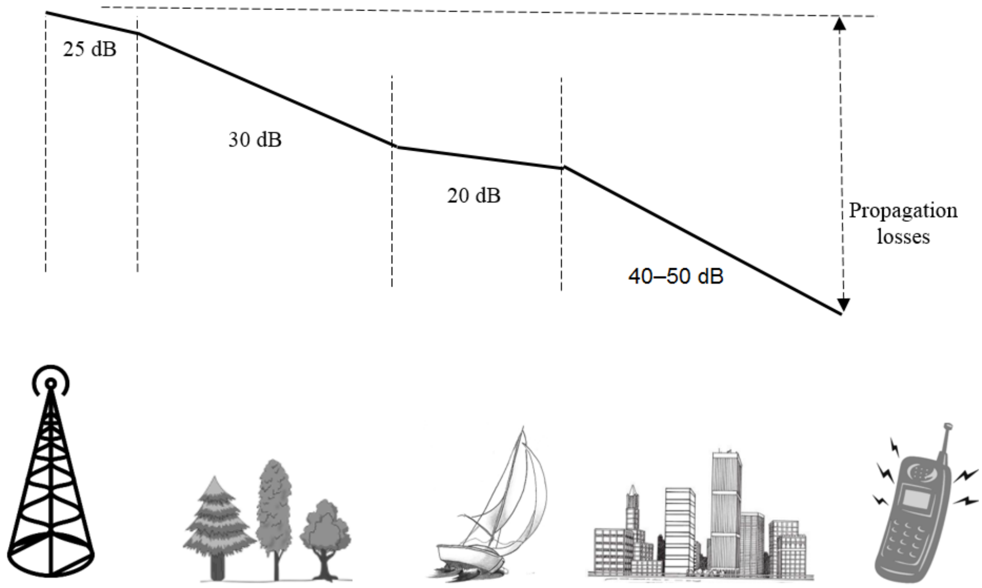


Figure 3. Suppressing the electromagnetic radiation of mobile telecommunications in free space.

The simulation programs of the electromagnetic radiation of mobile telecommunications allow understanding and preliminary estimating of the expected influence of the electromagnetic fields of mobile telecommunications and visually establishing limits to the electromagnetic fields of mobile telecommunications (Figures 4–6).

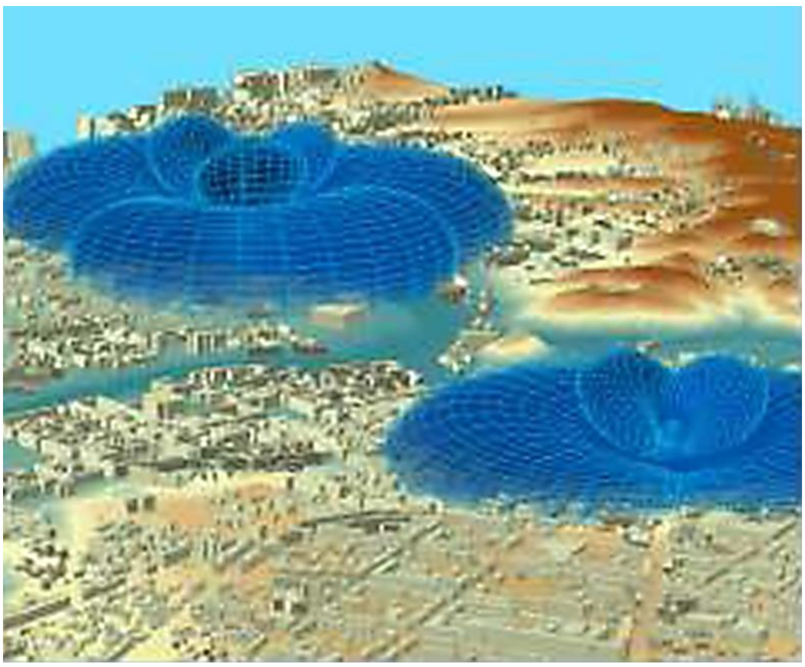
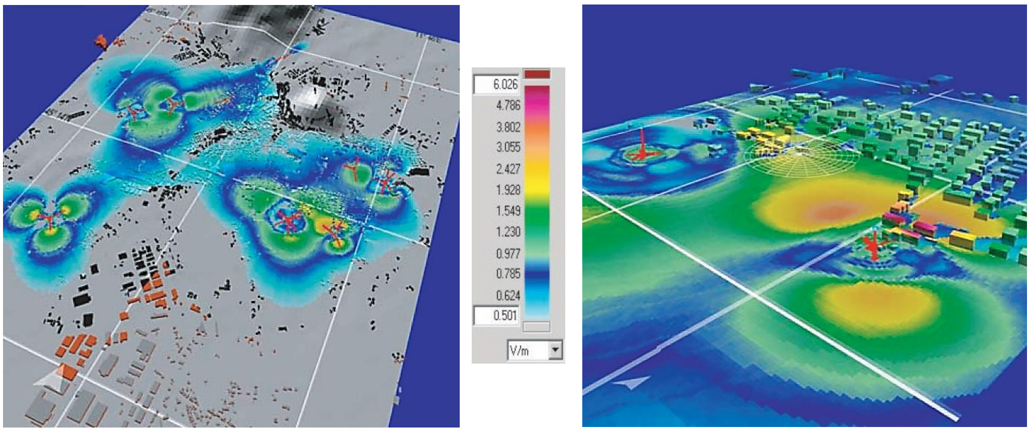


Figure 4. The distribution of the energy flux density simulated by CELLULAR EXPERT software Reprinted/adapted with permission from Ref. [23].



(**a**) (**b**)

Figure 5. The examples of simulation performed using FIDELITY software: (**a**) the distribution of the electrical field around the base stations of mobile telecommunications; (**b**) the distribution of the electrical field around buildings Reprinted/adapted with permission from Ref. [30].

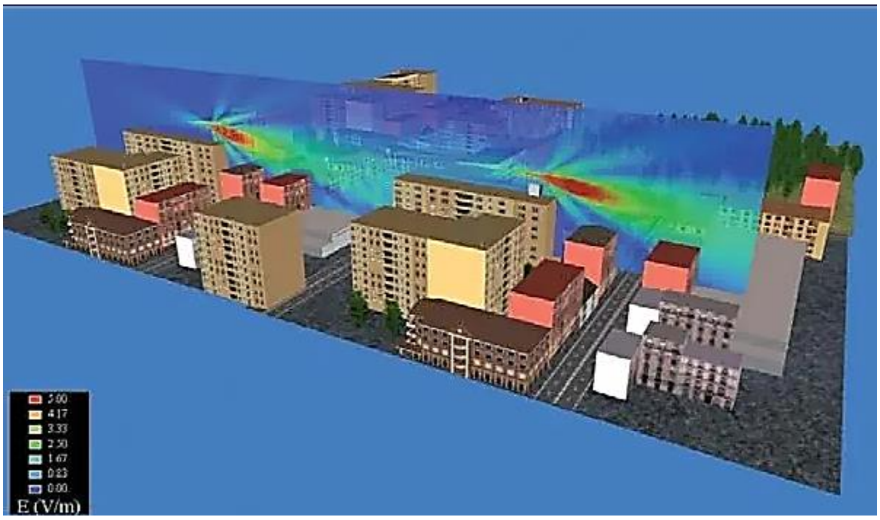


Figure 6. The distribution of the energy flux density in 3D format simulated by SATIMO software Reprinted/adapted with permission from Ref. [31].

A proper computation methodology helps with all estimations performed by the templates of programs written on the basis of the formulae provided in the applied methods [30]. Therefore, computations are performed more precisely and faster, thus leaving a possibility of graphically visualizing the obtained data.

The received numerical values do not need analysis in the form of tables or to be used for additionally applying to rendering programs [32]. The given charts allow effectively evaluating the distribution of the electromagnetic field and determining the zones of maximum radiation.

Additionally, the computations of simulated electromagnetic radiation are conducted. The calculations of the dispersion of the energy flux density are performed applying physical qualities defining the spread of electromagnetic waves. Radiation intensity created anywhere above the Earth's surface (considering the technical specifications of the antenna) and receding from the vertical axis of the antenna is calculated by the Equation (1):

$$S = \frac{1}{3.77} \sum_{i=1}^{N} \frac{\left[F_i(\Delta) F_i(\varphi) K_Z K_H \sqrt{30 P_i G_i \eta_i}\right]^2}{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2}, \quad (1)$$

where S—the energy flux density of the electromagnetic field, μW/cm^2; N—the number of antennas; P_i—the power of the source-transmitter, W; G_i—the antenna gain, dB$_i$; η_i—line loss, dB$_i$; F_i (Δ)—the directivity factor of a vertical diagram; F_i (φ)—the directivity factor of a horizontal diagram; K_H—coefficients measuring the unevenness of the directivity diagram in the horizontal plane (can be chosen including boundaries from 1.26 to 1.41); K_Z—coefficient measuring terrain unevenness in rural areas and the effect of reflective surfaces in a settlement or city (depending on the positions and density of above-ground objects, coefficient K_Z can take values from 1.3 to 1.15); x, y, and z—the coordinates of the measurement point.

Data displayed in the formula, i.e., coordinates x, y, and z of the center of the antenna, the direction (azimuth) of the most intensive radiation, the inclination of the antenna, the power, the amplification, line loss, coefficients, the radiofrequency of the antenna, effective radiated power of the antenna, directivity diagrams in the vertical and horizontal plane, are received from the Communications Regulatory Authority as well as referring to the technical specifications provided by the producers of mobile telecommunication antennas. The directivity factors of vertical and horizontal diagrams are found according to technical diagrams specified by producers [33].

The examination of the upcoming and available antenna assists in calculating the theoretical parameters of the energy flux density taking into account the qualities of the antenna; however, surrounding terrain is assessed as an area having no significant unevenness. Such areas usually have installed antennas, and, although the obtained measurement results are favorable enough, in order to determine safety requirements, the impact of land relief is unnecessarily downgraded [34]. The wave diffused from the antenna is dispersed and, having reflected from terrain at a certain distance, makes a sum with the previous wave, thus creating a maximum [35]. Uneven terrain changes the position of the electromagnetic maximum of mobile telecommunications, and therefore requires a more detailed examination. Hence, if the simulated values are lower than the permitted rates, still, it is advisable to check them experimentally [36].

The novelty of this work is the experimental research of electromagnetic radiation from different mobile communication antennas with low, medium and high effective radiation power. The research methodology of electromagnetic radiation propagation of mobile communication antennas is chosen taking into account the physical and theoretical characteristics of electromagnetic wave propagation.

The goal of simulation is to evaluate the distribution of the energy flux density of the electromagnetic field generated by antennas for mobile communications in the environment. According to the results of the research, it is possible to renew the legal regulatory framework of electromagnetic expertise, that regulates the allowed intensity level of the electromagnetic fields, and to improve evaluation methods and methodologies for electromagnetic radiation.

2. Methodology for Simulating the Dispersion of the Energy Flux Density of the Electromagnetic Field Generated by Antennas for Mobile Communications

The theoretical simulation of the dispersion of the energy flux density is conducted applying the physical properties of emitted electromagnetic waves. The main factors influencing the dispersion of the energy flux density of the electromagnetic field in the area include the power of the transmitter, the coefficient of antenna amplification and the distance between the antenna and the measured point (Figure 7).

$$\mathrm{EIRP} = \mathrm{PG}, \quad (2)$$

where EIRP—Effective Isotropic Radiated Power, W; P—the power of the source, W; G—the coefficient of antenna amplification, dBi.

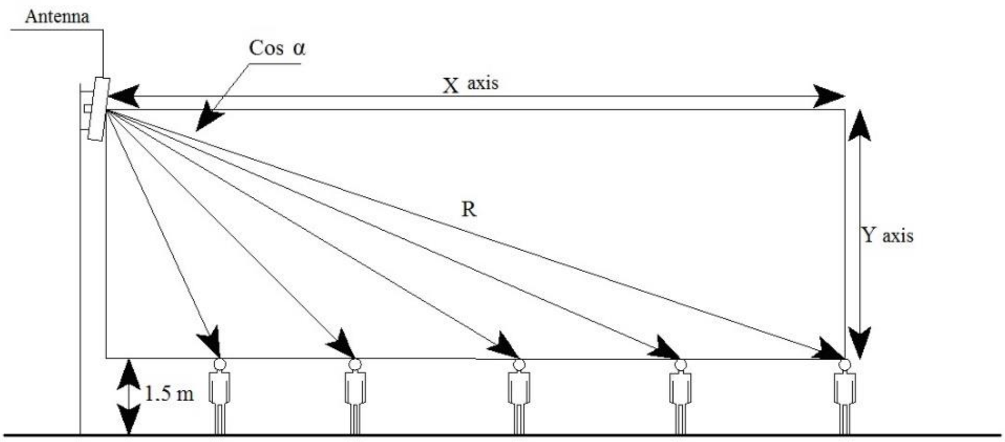


Figure 7. Evaluation scheme for the energy flux density of the electromagnetic field.

Effective Isotropic Radiated Power (EIRP) is the multiplication of the power of radiation (transmitter) supplied to the input of the antenna and the coefficient of antenna amplification. The dispersion of the energy flux density in the area depends on EIRP: the more powerful the antenna is, the higher the values of the energy flux density in the environment. The power of the transmitter in space is constant, whereas the coefficient of antenna amplification changes in the following way:

$$G(\alpha) = G(0) \cdot cos^3\ (\alpha), \tag{3}$$

$$cos\ (\alpha) = \frac{X}{\sqrt{X^2 + Y^2}}, \tag{4}$$

$$R = \sqrt{X^2 + Y^2}, \tag{5}$$

$$cos\ (\alpha) = \frac{X}{R}, \tag{6}$$

$$cos^3\ (\alpha) = \left(\frac{X}{R}\right)^3, \tag{7}$$

$$G(\alpha) = G(0) \cdot \left(\frac{X}{R}\right)^3, \tag{8}$$

where *G* (α)—antenna amplification at a certain angle, dBi; *G* (*0*)—maximum amplification of the antenna, dBi; *X*—the distance between the antenna and the measured point in the x axis, m; *Y*—the distance between the antenna and the measured point in the y axis, m; *R*—the distance between the antenna and the measured point, m.

Figure 7 and Equations (2)–(8) show that the values of the energy flux density depend on the angle between the measured point and the antenna as well as on the distance between the antenna and the measured point. A wider angle between the measured point and the antenna and a larger distance between the measured point and the antenna results in a lower density of energy in the environment.

The energy flux density of the electromagnetic field in free space propagation is calculated according to the Equation (9):

$$W = \frac{P_T G}{4\pi r^2} = \frac{EIRP}{4\pi r^2}, \tag{9}$$

However, the energy flux density in the environment changes in a more complex manner (particularly due to reflections) and can be described applying Equations (10)–(12):

$$W = \frac{E^2}{Z}, \tag{10}$$

$$E = E_T + \Gamma E_A = E + 0.6E = 1.6E, \quad (11)$$

$$W_M = \frac{(1.6E)^2}{120\pi} = \frac{1.6^2\left(\frac{(\sqrt{30}EIRP)}{r}\right)^2}{120\pi} = \frac{2.56\left(\frac{30EIRP}{r^2}\right)}{120\pi} = \frac{2.56EIRP}{4\pi r^2}, \quad (12)$$

where *W*—the energy flux density of the electromagnetic field, W/m^2; *Z*—wave impedance of the space where the wave propagates, Ω; *E*—the strength of the electric field, V/m; E_T—the strength value of a direct electric field, V/m; E_A—the strength value of a reflected electric field, V/m; Γ—reflection coefficient; *r*—the distance between the antenna and the measured point. An effective radiation power (*ERP*) is calculated by Equation (13):

$$ERP = EIRP - 2.15, \quad (13)$$

where *ERP*—effective radiation power, *W*.

For the reason that directivity diagrams in vertical and horizontal planes have a very significant impact on the dispersion of the values of the energy flux density of the electromagnetic field in the environment, the formula is modified and presented as follows:

$$W = \frac{2.56P_T G}{4\pi r^2} = \frac{2.56ERP(G_\alpha)(G_\theta)}{4\pi r^2}, \quad (14)$$

where G_α—the coefficient of antenna amplification in the vertical plane; G_θ—the coefficient of antenna amplification in the horizontal plane.

According to the provided Equation (14), theoretical simulation experiments on electromagnetic radiation generated by antennas for mobile telecommunications have been conducted. In order to compare the results of theoretical simulation and research findings, the following brands of antennas for mobile telecommunications were selected: KATHREIN 742241, KATHREIN 80010292, KATHREIN 742241, KATHREIN 742266, RFS AP 909016 and KATHREIN 741989.

Data, required for conducting simulation experiments, i.e., the height, the azimuth of the maximum emitting, antenna inclination, the power and amplification of the transmitter, radio frequency of the antenna, effective radiated power, directivity diagrams in vertical and horizontal planes are received from the Communications Regulatory Authority as well as from the technical specifications provided by the producers of antennas for mobile telecommunications.

The tests are carried out with the NBM-550 broadband electromagnetic field meter with an isotropic probe. The operating frequency range of 100 kHz–3000 MHz corresponds to the range in which hazardous radiation sources can operate, i.e., mobile base stations, mobile antennas and mobile phones. Measuring of electric field strength is from 0.01 V/m, magnetic field strength from 0.01 mA/m, electromagnetic field energy flux density from 0.001 mW/m^2 or 0.1 nW/cm^2.

An exemplary case of the measurement setup is presented in Figure 8, corresponding to the situation according to the obtained dispersion through the area of 2 Seskines str. in Vilnius. An analogous methodology was adopted in each study area.

Having evaluated simulation research, the visualization of the dispersion of electromagnetic radiation according to the obtained results and using AutoCad software is conducted. The dispersion of electromagnetic radiation from the antenna, according to the current orientation in space, is displayed by a spectral indicator corresponding to the values of the energy flux density in the area.

The overall energy flux density in the selected area was rendered employing AutoCad software and introducing separate dispersions along the entire range of 500 m, thus creating the whole dispersion of electromagnetic waves. The dispersion of each antenna has been rendered independently, later analyzing the effect of the overlapped energy flux density. While simulating the electromagnetic radiation of mobile telecommunications both in close proximity (under a distance of 30 m) and remote areas (at a distance of more than 30 m), all resulting values are displayed as those of the energy flux density.

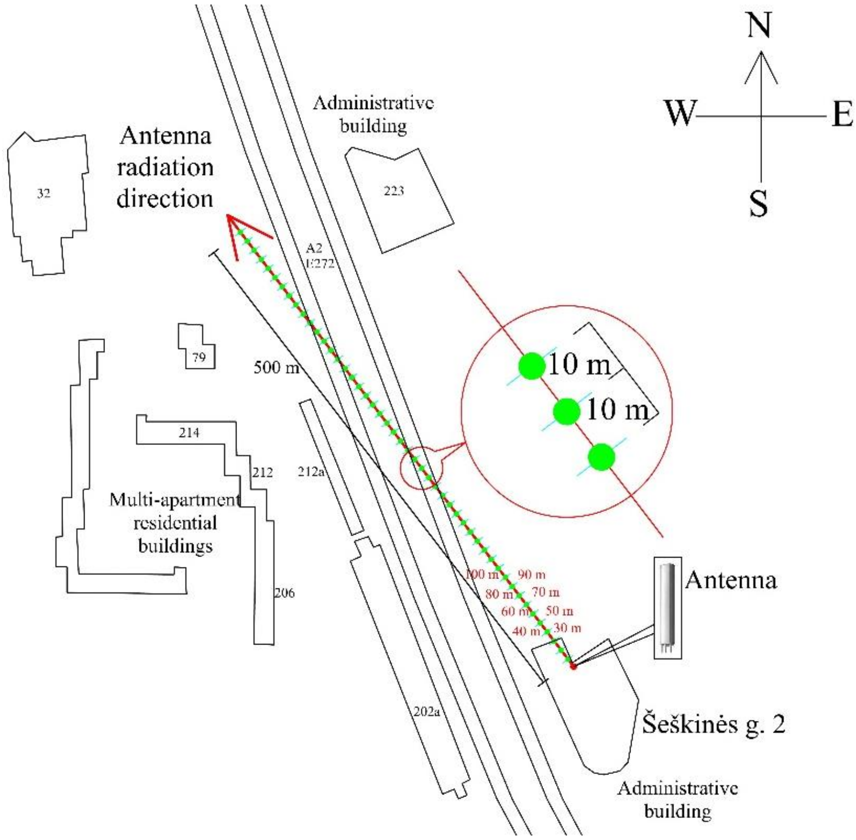


Figure 8. A schematic example of a measurement setup through the area of 2 Seskines str. in Vilnius (coordinates—54°42′21.2″ N, 25°40′32.2″ E).

3. Results and Analysis

Simulating the dispersion of the energy flux density of the electromagnetic field generated by antennas for mobile communications was performed. The simulation of the values generated by sector antennas for mobile telecommunications is conducted in the horizontal plane (overhead view).

Figure 9 shows the simulation of the dispersion of the energy flux density of the electromagnetic field in the area of 5 Rugiu str. in Vilnius. The picture also discloses that the highest values emerge following the most intensive radiation (marked red) emitted by the source. Considering the distance under 20 m, the values of the energy flux density scatter between 50 and 10,000 μW/cm^2.

While moving further away, the values drastically decrease and reach 7 μW/cm^2 in front of the dwelling house (marked yellow). The simulation of the dispersion, along with the measurements taken, has disclosed that the highest values have been recorded at a height of 13.5–22.5 above the Earth's surface. Farther, at a distance of 100 m (marked green), the values are scattered, thus covering the range from 0.5 to 0.1 μW/cm^2. At other distances (marked blue), e.g., 200, 300, 400 and 500 m from the antenna for mobile telecommunications, the values are really low and scattered in the range from 0.1 to 0.001 μW/cm^2—500-fold less than those allowed and provided by HN 80:2015.

The values decrease according to square dependence in free space under larger distances, where interference usually takes place due to reflection from buildings and uneven terrain. In these cases, the energy weakens even faster. The conducted simulation reveals that, when receding from the antenna, the energy flux density gradually decreases.

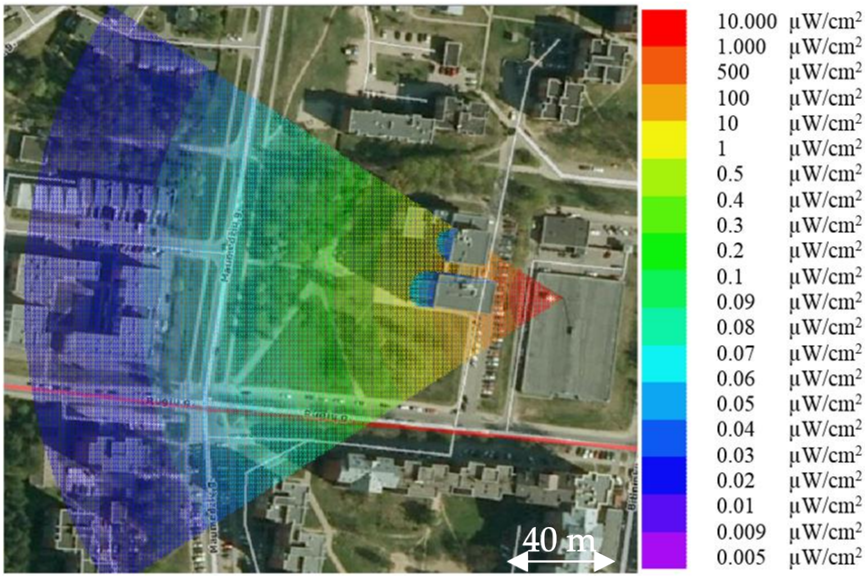


Figure 9. The dispersion of the electromagnetic radiation emitted by the antenna for mobile telecommunications KATHREIN 742241 through the area of 5 Rugiu str. in Vilnius (coordinates—56°20′32.7′′ N, 23°39′57.05′′ E). Occupied area is 0.25 km^2.

Figure 10 presents the dispersion of the energy flux density provided by antennas for mobile telecommunications in the area of 2 Seskines str.

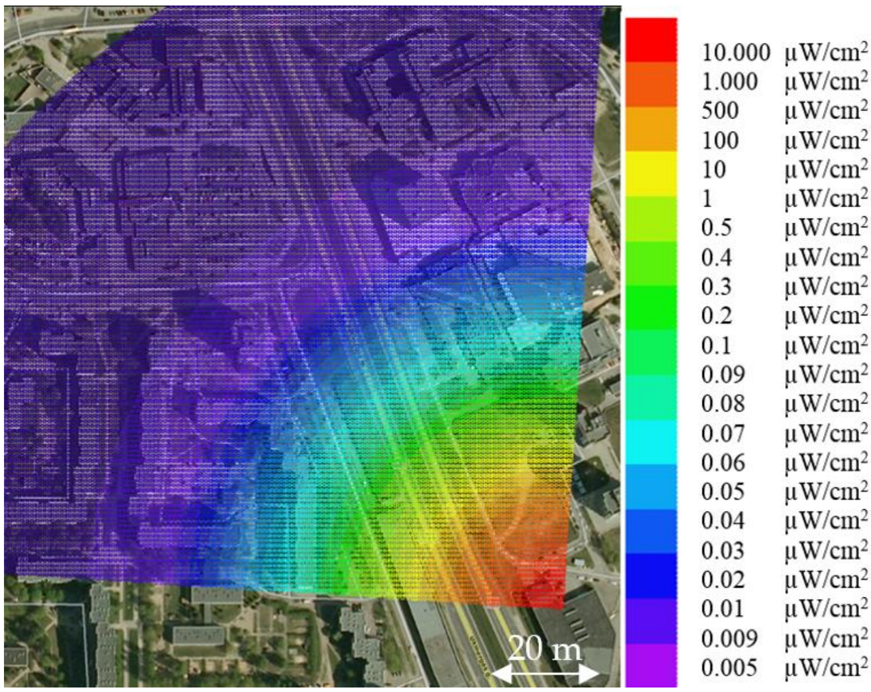


Figure 10. The dispersion of the electromagnetic radiation emitted by the antenna for mobile telecommunications KATHREIN 80010292 through the area of 2 Seskines str. in Vilnius (coordinates—54°42′21.2′′ N, 25°40′32.2′′ E). Occupied area is 0.04 km^2.

The obtained distribution of radiation dispersion shows that the values (marked red) are the highest when the distance from the impact source (antenna) is the shortest. The values of EFD reach a range of maximum values making 10–100 µW/cm^2 when the distance from the antenna is less than 25 m along the direction of the most intensive propagation of radiation. When receding (marked yellow-green) at a distance of 50 m from the antenna, the values are scattered in the range from 0.3 to 10 μW/cm^2. A decrease in the energy flux density of the electromagnetic field (marked blue) is observed at a distance of 80 m from the source. Having reached the residential block and the nearest office building across the street (202A Seskines str.), flux density rates do not exceed 1 μW/cm^2. The dispersion of electromagnetic radiation at a distance of 400 m from the source is represented by an integral distribution, i.e., the values reach a minimum rate of 0.005 μW/cm^2.

The dispersion of the formed energy flux density of the electromagnetic field in the area of 11 Sauletekio Ave is depicted in Figure 11.

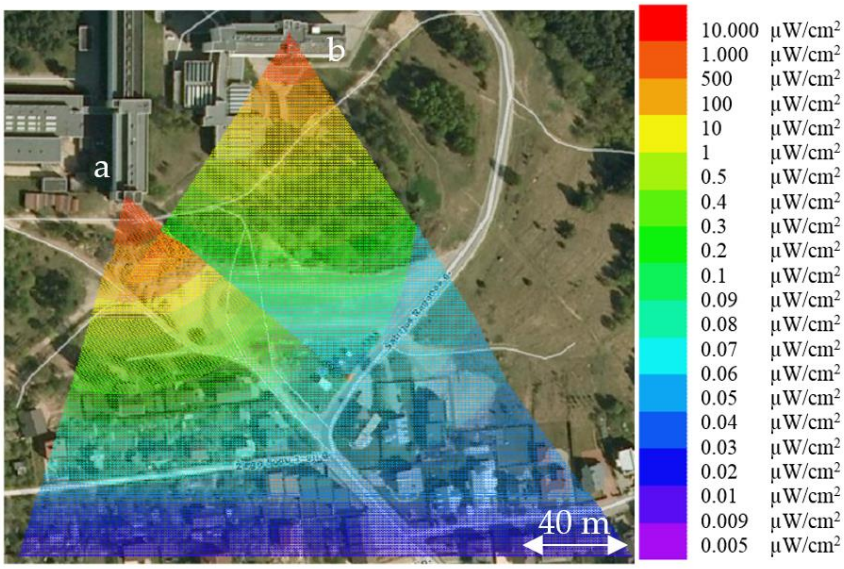


Figure 11. The dispersion of the electromagnetic radiation of two antennas, KATHREIN 742266 (a) and KATHREIN 742241 (b), for mobile telecommunications in the area of 11 Sauletekio Ave (coordinates 54°42′45.78″ N and 25°15′0.56″ E). Occupied area is 0.25 km^2.

The dispersion of two differently oriented antennas for mobile telecommunications falls into three areas. In the first one (marked red), flux density is created due to the exploitation of antenna KATHREIN 742241 directed southward; thus, the highest values of flux density, in the range of 10,000–10 μW/cm^2, are recorded at a distance of 50 m. While moving further away from the antenna (marked green-blue) and approaching a distance of 200 m, the values are scattered in the range of 0.5–0.07 μW/cm^2. The direction of the second antenna KATHREIN 742266 EMF producing the electromagnetic field is redirected at an azimuth of 170°. The highest values of flux density (marked red) of 1000–10 μW/cm^2 are dispersed at a distance of 40 m from the antenna. An important point is that, 20 m from the aforementioned antenna, the second dispersion of flux density is affected by the first one. It can be observed that, at a distance of 15 m, the values of flux density have increased up to 50 μW/cm^2 (marked pink), which is the case when the values in the unaffected areas of the first antenna remain unchanged and reach about 48 μW/cm^2. Within the distances (marked light blue) of up to 150 m, the values significantly drop to 0.5–0.08 μW/cm^2. The last two segments form the second area representing only dispersion attributed to the second antenna. In the third zone, (marked blue) the dispersion of the flux density of both antennas is combined. Within the distances of up to 400 m, because of the double impact of antennas, they remain stable, and the values of the emerged energy flux density of electromagnetic radiation are scattered up to 0.07–0.04 μW/cm^2. Only approaching a distance of 450 m, the values reach minimum rates and, up to the threshold of 500 m, disperse in the range of 0.03–0.005 μW/cm^2. Only the electromagnetic radiation of energy flux density within the range of 0.3–0.1 μW/cm^2 accesses the first private household plots and a possible impact. A further emission decreases to 0.05 μW/cm^2, which is 200-fold less than the value allowed by HN 80:2015.

Figure 12 shows the simulation of the dispersion in the region close to Plikiskiu village of Joniskis municipality where, along road 1611, two antennas, including RFS AP 909016 and KATHREIN 741989 are positioned.

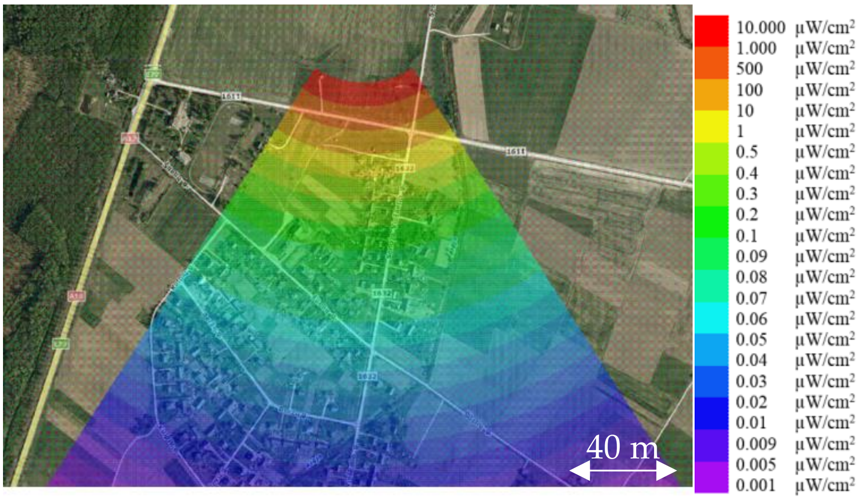


Figure 12. The dispersion of the electromagnetic radiation of two mobile telecommunications antennas, RFS AP 909016 and KATHREIN 741989, in the region close to Plikiskiu village of Joniskis municipality (coordinates—54°44′31.15″ N and 25°16′15.56″ E). Occupied area is 0.25 km^2.

Figure 11 indicates that the highest density areas are concentrated in the elliptic field (marked red)—the segment between two antennas, both having a separate source of radiation in all directions. The maximum values, scattered in the range of 1000–10 μW/cm^2, have been observed in this field. Further (marked yellow) from both radiation sources having reached a distance of 40 m, the values decrease to 10–1 μW/cm^2. At a distance longer than 50 m, dispersion is divided into several segments where a change in flux density is uneven. In the sector closer to the first (Figure 11, left side) antenna (marked green), the highest values are oriented in north-westward and south-westward from the first as well as in north-eastward and south-eastward directions from the second antenna. In the above introduced segments under a distance of 150 m, the values of flux density fluctuate in the range of 0.1–0.2 μW/cm^2. At the same time, in the sectors having flux density emitted north and southward, the values decrease faster and reach 0.1 μW/cm^2 at a distance of 150 m from the source. Other dispersion sectors (marked blue-green) record the values that decrease even faster and reach 0.08 μW/cm^2 at a distance of 150 m from the source. Further changes in flux density become equal in all sectors (marked blue). At a distance of 300 m, the values scatter and fall within the range of 0.08–0.03 μW/cm^2.

While moving even further from the sources of electromagnetic radiation, the values decrease drastically, and the lowest ones fall to 0.009 μW/cm^2. In the last segment of 100 m, the values of energy flux density remain almost the same and reach extremely low rates, i.e., as low as 0.001 μW/cm^2.

Table 1 compares the dispersion values of the measured and simulated electromagnetic radiation generated by different antennas for mobile telecommunications.

The conducted simulation has proved (Table 1) that a properly selected measuring methodology allowed precisely determining the ambient values of the electromagnetic radiation of mobile telecommunications. The precisely and swiftly conducted simulation has suggested graphically presented data. There is no need to analyze the obtained numerical values in tables or use additional separate rendering software. The visually presented simulation results allow effectively estimating the dispersion of electromagnetic radiation and defining the areas of maximum radiation.

Table 1. Comparison of measured and simulated electromagnetic radiation generated by antennas for mobile telecommunications.

The Type of the Antenna and the Location of Installation		Value of the Energy Flux Density of the Electromagnetic Field, μW/cm^2		
		Distance of 50 m	Distance of 100 m	Distance of 200 m
KATHREIN 742241 (coordinates—56°20′32.7″ N, 23°39′57.05″ E)5 Rugių str.	Measured	7.00	0.5 *	0.10 *
	Simulated	6.52	0.44	0.09
KATHREIN 80010292 (coordinates—54°42′21.2″ N, 25°40′32.2″ E) 2 Seskines str.	Measured	0.98 *	0.44 *	0.09 *
	Simulated	0.91	0.12	0.08
KATHREIN 742266 (coordinates 54°42′45.78″ N, 25°15′0.56″ E) 11 Sauletekio Ave	Measured	0.20 *	0.21 *	0.20 *
	Simulated	0.25	0.20	0.22
KATHREIN 741989) (coordinates—54°44′31.15″ N, 25°16′15.56″ E) Plikiskiai str.	Measured	0.03 *	0.05 *	0.04 *
	Simulated	0.02	0.04	0.03

* The dynamic range is 1.66 μW/cm^2.

The highest energy flux density is registered where the main antenna diagram lobe reaches ground level. It is obvious that the maximum created by mobile phone antenna depends on the ERP (effective radiated power) of the antenna and height above the ground level of the antenna (one antenna reaches it at 50 m and another one at 200 m). The mobile connection antenna in the maximum radiation direction creates one maximum. Mobile connection antennas electromagnetic field energy flux density values in ground-level air increase further from the antenna, highest values can be observed at the point where main antenna radiation zone reaches the Earth's surface, further on, it declines.

According to the presented simulation methodology, the distribution and results of electromagnetic radiation flux in residential and technical buildings or other areas of work can be analyzed, thus reflecting the boundaries of sanitary zones if such are required.

A comparison of the simulated and radiated values of the energy flux density of mobile telecommunications with the measured ones discloses that 30% of the findings do not overlap. Compared to other foreign authors [21] and considering the effective radiated power of small and medium-sized antennas for mobile telecommunications, this is a rather precise result, as the simulation of a specific situation requires a number of variables to be included the adjusted ground reflection coefficient (an error margin of 20% emerges when choosing this parameter), the impact of the meteorological situation on the suppression of the electromagnetic field (an error margin under 15%) and the ground reflection coefficient of measuring radiation in shadow zones (an error margin under 20%). Difficulties are encountered when precisely determining landscape openness, calculating the angle of the direction of the emitted electromagnetic radiation and establishing diffraction from rooftops (an error margin under 30%). Foreign researchers [21] applied CONCERTO software to simulate electromagnetic radiation and pointed to an error margin of 35%.

4. Conclusions

The simulation of the energy flux density of the electromagnetic field allows estimating electromagnetic radiation emitted by antennas for mobile telecommunications, which results in the termination of the conducted experiments. A comparison of the simulated value of the energy flux density radiated from antennas for cell telecommunications with the measured one point to an overlap of 30%, because simulation encounters difficulties in precisely measuring a variety of natural and human-made obstacles and reflections. Thus, the properly selected simulation software allows understanding and preliminarily estimating the electromagnetic fields of mobile telecommunications as well as visually determining places where electromagnetic radiation exceeds the established standards.

The simulation of the energy flux density of the electromagnetic field of antennas for mobile telecommunications showed that, in the close proximity zone (under a distance of 30 m), antennas radiate values from 10 to 10,000 $\mu W/cm^2$, whereas the values fluctuate between 10 and 0.001 $\mu W/cm^2$ at a distance larger than 30 m. The values of the energy flux density of the electromagnetic field decrease according to square dependence in free space, while at distances exceeding 100 m fluctuate in the range from 0.01 to 1 $\mu W/cm^2$. The maximum density was equal to 10–100 $\mu W/cm^2$ under the distance less than 25 m from the antenna in the direction of the most intensive radiation.

The examination of the upcoming or available antenna or other powerful source of radio waves includes calculating the theoretical parameters of the density taking into account the qualities of the antenna and accepting surrounding terrain as an area with no significant unevenness. Similar places have most frequently installed antennas, and, although the obtained measurement results are satisfactory enough, in order to determine necessary safety requirements, the impact of land relief is unnecessarily downgraded. The wave propagated outwards the antenna is dispersed and, having reflected from terrain, is summed up with the previous one, thus creating a maximum. Uneven terrain changes the maximum position of this electromagnetic field, which needs further examination. Thus, if the simulated values are lower than the established standard, it is still advisable to check them experimentally.

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