

Electric field calculation for 5G base station with adaptive antenna system

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This paper presents the procedure for calculating the electric field level in the vicinity of base stations (BS) implemented in 5G technology. The specificity of the 5G system is the application of dynamic routing of traffic radiation beams directly towards active users (beamforming). In the paper, the following characteristics are calculated: 1. maximum field level; 2. mean field level without application of power control and 3. mean field level with application of radiated power control in the BS for traffic channels depending on the distance from the BS, taking into account only the field created by the considered BS, not the neighbouring ones. In this calculation, a uniform distribution of user density in the BS cell and an equal traffic load of all users during a sufficiently long-time interval were assumed. The parameters that change in the graphs are the characteristics of the applied antenna (width of its main radiation beam, gain in the main and side radiation beams), BS height and radius of the BS cell. The most interesting result is that the mean level of radiation in the case of application of control of the emitted power can also increase with increasing distance from the BS, whereby the shape of the obtained characteristics depends on the radius of the BS cell. However, in an absolute sense, the level of the electric field in this case is lower than the values allowed by regulations and can pose a danger only through the aggregate value with other sources of radiation.

Keywords: 5G, adaptive antenna system, beamforming, power control, mean electric field level

1 Introduction

The development of the mobile telephony system is based on the ambition to develop new, increasingly advanced services. These new services are characterized by the need for higher data transfer rates, i.e., decreasing transmission delays, which is then connected to the application of various advanced techniques for signal transmission that were not known in earlier generations of mobile systems. The application of new signal transmission techniques brings a whole series of challenges, the adequate solution of which enables the achievement of the established goals in terms of speed and delay in transmission. A technological leap is needed in the implementation of the systems, which is manifested by the introduction of the 5G mobile telephony system into widespread implementation. However, as it usually happens, every significant technological leap is accompanied by many doubts, controversies, and even resistances that primarily relate to potential negative effects on human health and the natural environment. When it comes to 5G mobile systems, the fear of a negative effect is associated with non-ionizing radiation caused by the functioning of both user equipment (UE) and base stations (BS) to an even greater extent than when it comes to mobile systems of previous generations. The results of some research further increase doubts because they indicate the need to review the norms defined by international recommendations [1] considering the effects (appearance of malignant

tumours) caused by an artificially generated electric field [2]. Measurements carried out in an apartment located near the BS antenna in an industrially highly developed country where people's health is traditionally taken care of indicate high (dangerous) levels of the electric field, especially in the children's room [3]. Because of all this, any contribution aimed at resolving such dilemmas is of great practical importance.

There are two basic approaches to insight the level of the electromagnetic field (that is, its electric field component) in the space around the BS. The first approach is entirely computational: the maximum theoretically possible level of the electric field is calculated. The second procedure is based on the realized measurements of the electric field. If it is a purely measuring procedure, the measurement results are based on the current level of traffic. The higher the value of the traffic in a certain time interval, the higher the radiation level, i.e., electric field, will be. Such measurements are then realized in periods of the highest traffic, that is, during the main traffic hour. However, in this way, the highest field levels that can be expected cannot be measured, considering that the highest traffic load does not mean that we are dealing with the maximum potentially possible traffic load. That is why priority is usually given to the combined measurement and calculation procedure when measurements are performed. It is necessary to first measure the level of radiation caused by sending control signals that are constantly present during the

operation of the mobile system, and then the value of the electric field thus obtained is multiplied by an extrapolation factor whose value is theoretically determined for the case that all traffic resources in the mobile system are activated [4]. This paper refers to the first, purely computational procedure to determine the electric field caused by the function of mobile telephony base stations in 5G technology.

Chapter 2 highlights the specifics related to antenna systems for 5G base stations. Related to that, chapter 3 presents several radiation diagrams of antennas for 5G systems that are used to calculate the electric field in this paper. The calculation procedure of the mean field level itself is given in chapter 4. A review of specific situations in the calculation, which include on the one hand the maximum field level and on the other hand the calculation of the field when radiation power control is applied, is presented in chapter 5. The results of calculation are presented in chapter 6. Finally, the conclusion of the paper is found in chapter 7.

2 Specificities of the antenna system for 5G base stations

Antenna systems in base stations of earlier generations of mobile telephony (2G, 3G and 4G) are characterized by fixed radiation patterns. The most common are directional panel antennas that cover part of the space around the BS, so that several antennas with different directions (usually three or more) are needed to cover the entire space. Antennas are usually directed so that the beam of radiation is inclined at an angle of only a few degrees in relation to the horizontal plane (electrical and mechanical tilt). In this way it is achieved that the users who are relatively far away from the base station for which the signal attenuation is greater are under the influence of the main radiation beam, while the closer users are under the influence of the side (weaker) radiation beams [5]. This ensures that these closer users are less exposed to radiation.

When 5G systems are considered, their antennas are characterized by having variable (adaptable) radiation patterns, especially if it refers to systems operating in the 3.4-3.8 GHz frequency range. In this case we are talking about adaptive antenna systems (AAS). However, for 5G systems antennas with fixed radiation patterns may be used, as for 2G, 3G and 4G systems. As for the radiation that transmits information (traffic channels) in the case of AAS application, the main beam of radiation is directed directly towards the active user, i.e. to his UE and tracks his movement. Two strategies are used: beamforming, where a radiation beam is specially

formed for each active user, or beam steering, where an optimal radiation beam is selected for each active user from a predetermined set, whereby one beam can be determined for more than one user. Beamforming is a broader concept and it includes beam steering as one possible of its strategies. Beamforming is applied not only in mobile telephony, but also in other areas as, for example, ultrasound transmission [6].

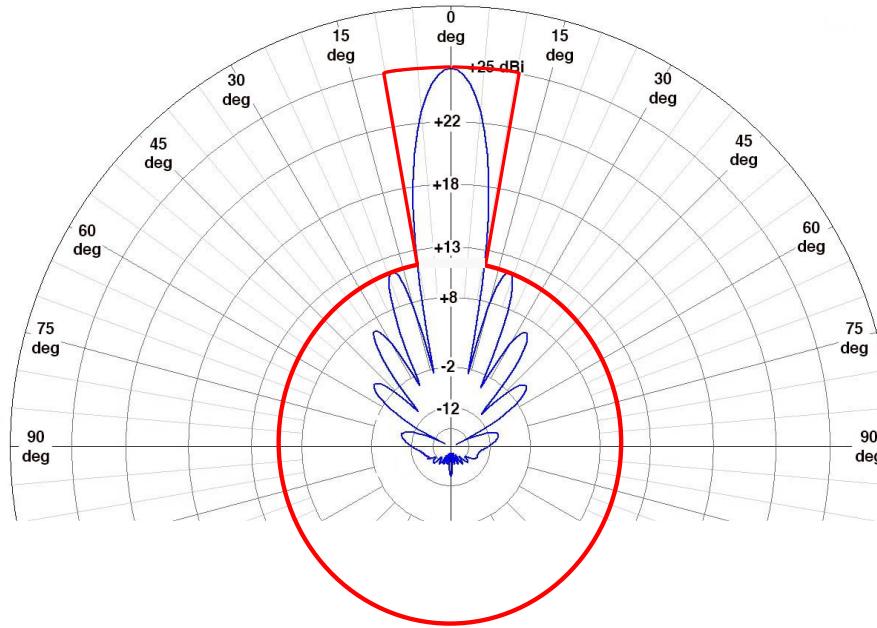
The radiation that transmits the control signals for 5G mobile telephony systems is sent in a similar way as that for the 2G to 4G systems by fixed beams of radiation.

3 Antenna radiation patterns for 5G base stations

The main radiation beam of the antennas intended for sending signals from the traffic channels of the 5G system is characterized by a very small width. Specific data that can be found in the literature are rather scarce. The values stated in literature do not exceed 20° in azimuth, while they are even less in elevation. For this our consideration, the initial reference will be the characteristics presented in [7], where it is stated in Figs. 19-24 that different widths of the traffic radiation beam are used in the connection establishment phase and during the established connection (they are larger during the connection establishment). As an example, we will take the characteristics from the figures 19 and 20 (antenna 1). These figures show that in the phase of the established connection, the width of the main radiation beam is 20° in azimuth and 10° in elevation, while the maximum gain of the antenna in both cases is 25 dBi or $G_1=17.78$ times compared to the unit gain of the isotropic antenna. The signal in the area of the main radiation beam may be completely modelled by the same maximum gain value $G_1=17.78$, while outside this area it is modelled by a unique value corresponding to the maximum level of the signal outside the main radiation beam. The signal level in this case is 14 dB lower than the signal level in the area of the main beam ($G_0=3.54$). This is summarized by the first row in Table 1, i.e., graphically presented in the Fig. 1 for the azimuth plane, where the approximate feature is highlighted in red. In a similar way, values are obtained in the second row of Table 1 that correspond to the characteristics from Figs. 21 and 22 (antenna 2) in [7] as well as in the third row of Table 1 (antenna 3) according to the characteristics in Figs. 23 and 24 in [7]. The analysis according to radiation patterns for the established connection phase (rows 1 and 2) is of greater importance than for the connection establishment phase (row 3), considering that the established connection phase lasts significantly longer than the connection establishment phase.

Table 1. Basic characteristics of radiation patterns for two examples of beams used to send traffic signals

Main beam width		Maximum gain of the main beam		Maximum gain of the side lobes by azimuth		Maximum gain of the side lobes by elevation	
Azimuth 2ε (°)	Elevation 2β (°)	dBi	G_1	dBi	G_0	dBi	G_0
20	10	25	17.78	11	3.54	11	3.54
25	12	25	17.78	13	4.47	13	4.47
40	14	25	17.78	15	5.62	15	5.62

**Fig. 1.** An example of the approximation of the antenna radiation pattern by azimuth

Besides the calculation based on concrete radiation patterns, analysis often use hypothetical radiation patterns that represent envelopes of a large number of characteristics directed to a larger number of users [8]-[10]. The resultant radiation pattern obtained in this way gives an increased ("overestimated") value of the transmitted signal in relation to the actual value, and therefore an increased level of radiation. The procedure for reducing the level of the transmitted signal to realistic limits is presented in [9].

Signal transmission in mobile telephony systems is based on different multiplexing techniques. When speaking about 2G systems, the applied techniques are time and frequency multiplexing (Time Division Multiple Access – TDMA and Frequency Division Multiple Access – FDMA). 3G systems are based on the application of code multiplexing (Code Division Multiple Access – CDMA). Orthogonal frequency division multiplexing (Orthogonal Frequency Division Multiplexing Access – OFDMA) is the basic technique for implementing 4G and 5G systems. As a consequence of the application of beamforming in 5G systems, we can also talk about spatial multiplexing of signals (Space

Division Multiple Access – SDMA) [11] considering that traffic radiation beams may be simultaneously directed towards a larger number of users. SDMA additionally contributes to a significant increase in the speed of data flow in 5G systems compared to the previous generations of mobile telephony systems.

4 Calculation of radiation levels in points around 5G base stations

Let us observe the radiation of the 5G base station antenna located at point ABS according to Fig. 2. The radiation is directed towards the UE whose current position is at point A2. The distance of point A2 from the base of the base station (point BBS) is r_2 , while its distance from the BS antenna (point ABS) is l_2 . The direction of radiation towards the UE overlaps the angle δ in the vertical plane in relation to the antenna height h_{BS} , while in the horizontal plane the direction of radiation is at an angle α in relation to the x -axis. The width of the main radiation beam in azimuth is 2ε , while in elevation it is 2β .

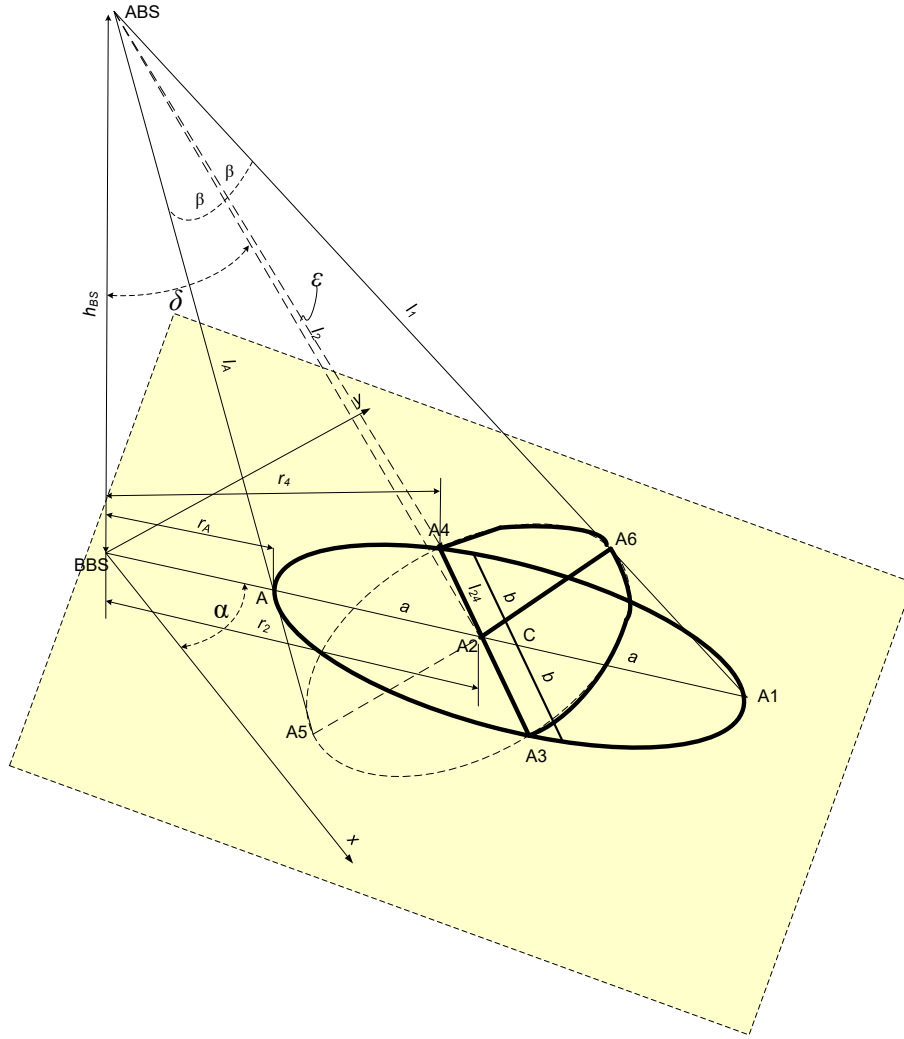


Fig. 2. Radiation influenced by 5G BS, spatial image

As explained in the previous chapter, the antenna radiation pattern may be modelled over two areas. Within the area limited by the angles β and ε , the signal amplification corresponds to the maximum amplification in the area of the main radiation beam, while outside this area the amplification is equal to the maximum signal amplification outside the main radiation beam, as already illustrated in Fig. 1. This model is found in the literature under the label "Cone+Sphere radiation pattern" [12]. The area corresponding to the main beam of radiation represents a cone that in intersection with the surface of the ground gives an ellipse AA3A1A4. The level of radiation on the surface bounded by this ellipse is therefore higher than outside this area. The centre of the considered ellipse is point C, and its semi-axes are a and b . The line A4A5A3A6 shows an ellipse that would represent the base of a straight cone that limits the area of the main

beam of radiation, where A4A2A3 is the straight line of its penetration through the ground plane.

In Figs. 3 and 4, the spatial image of radiation is split down into its presentation in the vertical and horizontal plane.

The level of the electric field at some point in the vicinity of BS may be represented by a formula

$$E = \frac{\sqrt{30 \cdot P \cdot G}}{d} \quad (1)$$

where P is the power of the BS, G is the gain of the antenna in relation to the isotropic antenna (an antenna whose gain is expressed in dBi) and d is the distance of the considered point from the BS. In accordance with the discussion from the previous chapter, G_1 (higher antenna gain level) or G_0 (lower antenna gain level) may be represented as the gain value G .

Thus, the semi-axis of the ellipse has a length

$$a = h_{BS} \cdot \frac{\operatorname{tg} \beta \cdot \left(1 + \left(\frac{r_2}{h_{BS}}\right)^2\right)}{1 - \left(\frac{r_2}{h_{BS}}\right)^2 \cdot \operatorname{tg}^2 \beta} \quad (5)$$

considering that

$$\operatorname{tg} \delta = \left(\frac{r_2}{h_{BS}}\right). \quad (6)$$

The equation of an ellipse centred at point C may be expressed as follows:

$$\frac{((x - x_C) \cdot \cos \alpha + (y - y_C) \cdot \sin \alpha)^2}{a^2} + \frac{((x - x_C) \cdot \sin \alpha - (y - y_C) \cdot \cos \alpha)^2}{b^2} = 1 \quad (7)$$

where $x_C = BC \cdot \cos \alpha$, $y_C = BC \cdot \sin \alpha$ and point B is an abbreviated designation of point BBS from Figs. 2, 3 and 4.

In order to determine the coordinates of point C, it is necessary to start from:

$$\begin{aligned} BC &= BA + AC = h_{BS} \cdot \operatorname{tg}(\delta - \beta) + a \\ &= h_{BS} \cdot \frac{\operatorname{tg} \delta \cdot (1 + \operatorname{tg}^2 \beta)}{1 - \operatorname{tg}^2 \delta \cdot \operatorname{tg}^2 \beta} \end{aligned} \quad (8)$$

Hence, the coordinates of point C are:

$$x_C = h_{BS} \cdot \frac{\operatorname{tg} \delta \cdot (1 + \operatorname{tg}^2 \beta)}{1 - \operatorname{tg}^2 \delta \cdot \operatorname{tg}^2 \beta} \cdot \cos \alpha \quad (9)$$

$$y_C = h_{BS} \cdot \frac{\operatorname{tg} \delta \cdot (1 + \operatorname{tg}^2 \beta)}{1 - \operatorname{tg}^2 \delta \cdot \operatorname{tg}^2 \beta} \cdot \sin \alpha \quad (10)$$

Each point on the ellipse must satisfy the equation of the ellipse, including point A4. To determine the coordinates of point A4, it is first necessary to determine the length of the line A2A4 using Fig. 4:

$$A2A4 = (ABS)A2 \cdot \operatorname{tg} \varepsilon = \sqrt{h_{BS}^2 + r_2^2} \cdot \operatorname{tg} \varepsilon \quad (11)$$

The coordinates of point A4 are now:

$$\begin{aligned} x_{A4} &= r_2 \cdot \cos \alpha - A2A4 \cdot \sin \alpha \\ &= r_2 \cdot \cos \alpha - \sqrt{h_{BS}^2 + r_2^2} \cdot \operatorname{tg} \varepsilon \cdot \sin \alpha \end{aligned} \quad (12)$$

$$\begin{aligned} y_{A4} &= r_2 \cdot \sin \alpha + A2A4 \cdot \cos \alpha \\ &= r_2 \cdot \sin \alpha + \sqrt{h_{BS}^2 + r_2^2} \cdot \operatorname{tg} \varepsilon \cdot \cos \alpha \end{aligned} \quad (13)$$

given that the line A2A4 is normal to the semi-axis a .

Semi-axis b is now calculated from Eqn. (7):

$$\begin{aligned} b &= \\ &= \left| \frac{a \cdot ((x_{A4} - x_C) \cdot \sin \alpha - (y_{A4} - y_C) \cdot \cos \alpha)}{\sqrt{a^2 - ((x_{A4} - x_C) \cdot \cos \alpha + (y_{A4} - y_C) \cdot \sin \alpha)^2}} \right| \quad (14) \end{aligned}$$

The probability that the level of the electric field at point A2 has greater than two values will now be obtained as the ratio of the area of the ellipse with semi-axes a and b that we took into account in this derivation and the area of the BS cell:

$$P_1 = \frac{\pi \cdot a \cdot b}{\pi \cdot r^2} = \frac{(h_{BS} \cdot \frac{\operatorname{tg} \beta \cdot (1 + \operatorname{tg}^2 \delta)}{1 - \operatorname{tg}^2 \delta \cdot \operatorname{tg}^2 \beta})^2 \cdot ((x_{A4} - x_C) \cdot \sin \alpha - (y_{A4} - y_C) \cdot \cos \alpha)}{r^2 \cdot \sqrt{(h_{BS} \cdot \frac{\operatorname{tg} \beta \cdot (1 + \operatorname{tg}^2 \delta)}{1 - \operatorname{tg}^2 \delta \cdot \operatorname{tg}^2 \beta})^2 - ((x_{A4} - x_C) \cdot \cos \alpha + (y_{A4} - y_C) \cdot \sin \alpha)^2}} \quad (15)$$

where r is the radius of BS cell.

The position of point A2 may be such that the entire analyzed ellipse is inside BS cell (ellipse 3 in Fig. 5), or point A2 is located closer to the cell border so that only part of the ellipse is inside BS cell, whereby the condition $r_2 \leq r$ must be satisfied (ellipses 1 and 2 in Fig. 5).

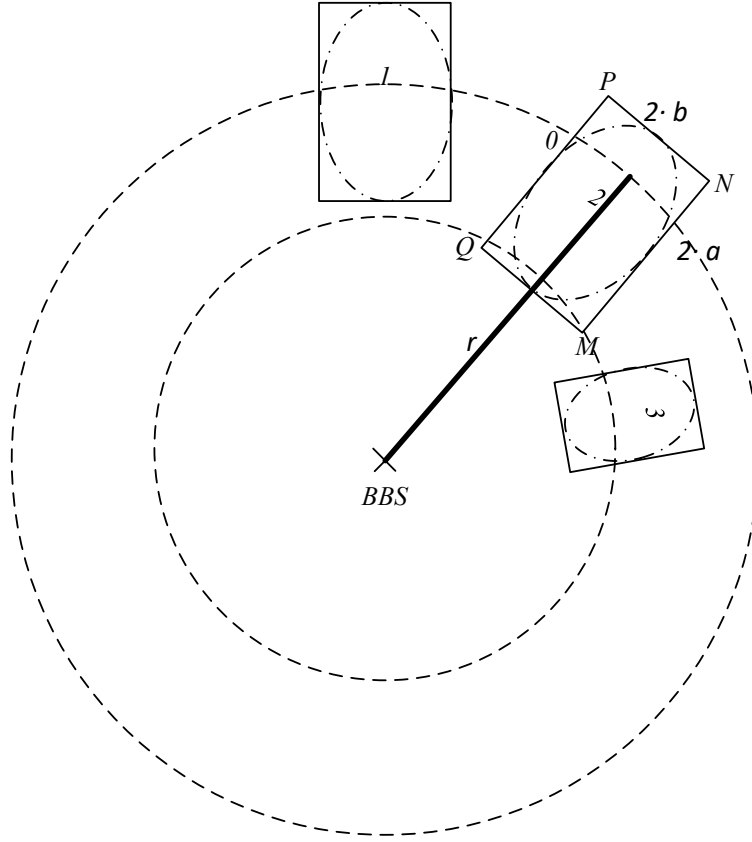


Fig. 5. Possible positions of the ellipse within the BS cell

In this second case, only part of the surface of the ellipse should be taken into account for formula (15). To simplify the calculation, in the formula (15), we will replace the surface of the ellipse with the surface of the described rectangle, whose sides are $2a$ and $2b$ (rectangle PNMQ for ellipse 2). This in any case increases the probability that the level of the electric field has the higher of two values. The value of probability P1 may be now expressed as the value from formula (15)

multiplied by factor $4/\pi$. This is valid for the case that the entire surface of the ellipse is inside the BS cell. If part of the ellipse is outside the BS cell, thus if $2a > r - h_{BS} \cdot \tan(\delta - \beta)$, instead of the entire major axis of ellipse $2a$, inside the BS cell there will be its part with length OQ as shown in Fig. 5:

$$OQ = r - h_{BS} \cdot \tan(\delta - \beta) \quad (16)$$

The probability that the level of the electric field at point A2 has the higher of two values will be in this case:

$$P_1 = \frac{2 \cdot (r - h_{BS} \cdot \tan(\delta - \beta)) \cdot b}{\pi \cdot r^2} = \frac{2}{\pi} \cdot \frac{(r - h_{BS} \cdot \tan(\delta - \beta)) \cdot ((x_{A4} - x_C) \cdot \sin \alpha - (y_{A4} - y_C) \cdot \cos \alpha) \cdot h_{BS} \cdot \frac{\tan \beta \cdot (1 + \tan^2 \delta)}{1 - \tan^2 \delta \cdot \tan^2 \beta}}{r^2 \cdot \sqrt{(h_{BS} \cdot \frac{\tan \beta \cdot (1 + \tan^2 \delta)}{1 - \tan^2 \delta \cdot \tan^2 \beta})^2 - ((x_{A4} - x_C) \cdot \cos \alpha + (y_{A4} - y_C) \cdot \sin \alpha)^2}} \quad (17)$$

The mean level of radiation at point A2 during a longer time interval may now be determined using the formula:

$$E = P_1 \cdot E_1 + (1 - P_1) \cdot E_0 \quad (18)$$

where E_1 is the field level corresponding to the main radiation beam where the antenna gain is G_1 , and E_0 is the field level outside the main radiation beam corresponding to the antenna gain G_0 .

5 Maximum radiation level and impact of power control

The maximum level of radiation at some point is obtained in the case that all available traffic resources are assigned to only one user located at that point. In addition, the allocated BS emission power always corresponds to the maximum available. The field strength in this case is determined using formula (3), where the antenna gain is G_1 .

In all the calculations in this paper, including the calculation of the maximum radiation level, the BS emission power of $P_{max}=200$ W is adopted in accordance to the data from [13] and it is typically more than twice as high as for mobile systems of 2G to 4G generations.

Power control in mobile telephony systems is used to reduce the interference of signals intended for different users, as well as to save energy. The signal power allocated in the BS to each individual active UE depends on several different factors, but mainly on the mutual distance between the BS and the UE [14].

The goal of power control is to provide equal conditions for signal reception to each UE at the point of reception, regardless of its distance from the BS. This primarily refers to equal signal power levels. If we assume that P_{max} is intended for the UE at the edge of the BS cell, i.e. at a distance r from the BS, then UE located at a distance r_2 will require power:

$$P = \sqrt{\frac{r_2^2 + h_{BS}^2}{r^2 + h_{BS}^2}} \cdot P_{max} \quad (19)$$

6 Calculation results

The results of the electric field calculation are presented in the Figs. 6-9. First, Fig. 6 presents the mean level of the electric field depending on the distance from the BS for antenna 1 according to Tab. 1 in conditions without power control in the BS ($E_{mean_no_pc}$), the maximum level of the electric field (E_{max}) as well as the mean level of the electric field in the conditions when power control is applied in the BS (E_{mean_pc}). Then, Fig. 7. presents the mean electric field level depending on the distance from the BS for all three antennas according to Tab.1 when no power control is applied. And, finally, Fig. 8 presents the mean electric field level for all three antennas in the case that power control is applied in the BS. The radius of the BS cell in these graphics is 150 m, and the height of the BS is 30 m.

Based on the graphs in Figs. 6, 7 and 8, several conclusions can be made:

1. The mean level of the electric field in the case when power control is not applied decreases more slowly depending on the distance from the BS (slower relative decrease) than the maximum level of the electric field;
2. The mean level of the electric field is higher if antennas with a wider radiation pattern are used;
3. In the case that power control is applied in the BS, the mean level of the electric field increases with increasing distance from the BS. This is due to the expansion of the area covered by the main radiation beam when the distance from the BS increases. (If it were not present this expansion of the area covered by the main radiation beam, the electric field level would not change depending on the distance from the BS.) The relative increase in the electric field level is greater when antennas with a wider radiation pattern are applied: for antenna 1 the increase is about 5% when the distance changes from the BS to the edge of the base station cell, while for antenna 3 this relative increase is about 20%. This result is at a first glance unexpected, and it shows that it is desirable to perform a cumulative calculation of the electric field strength during a longer time interval in the vicinity of 5G base stations not only in their vicinity, but also with distance from the BS up to the BS cell border. However, the specific calculated values in this case are below the limits of permissible values [1] and may represent a danger only through the cumulative effect with other field power levels.

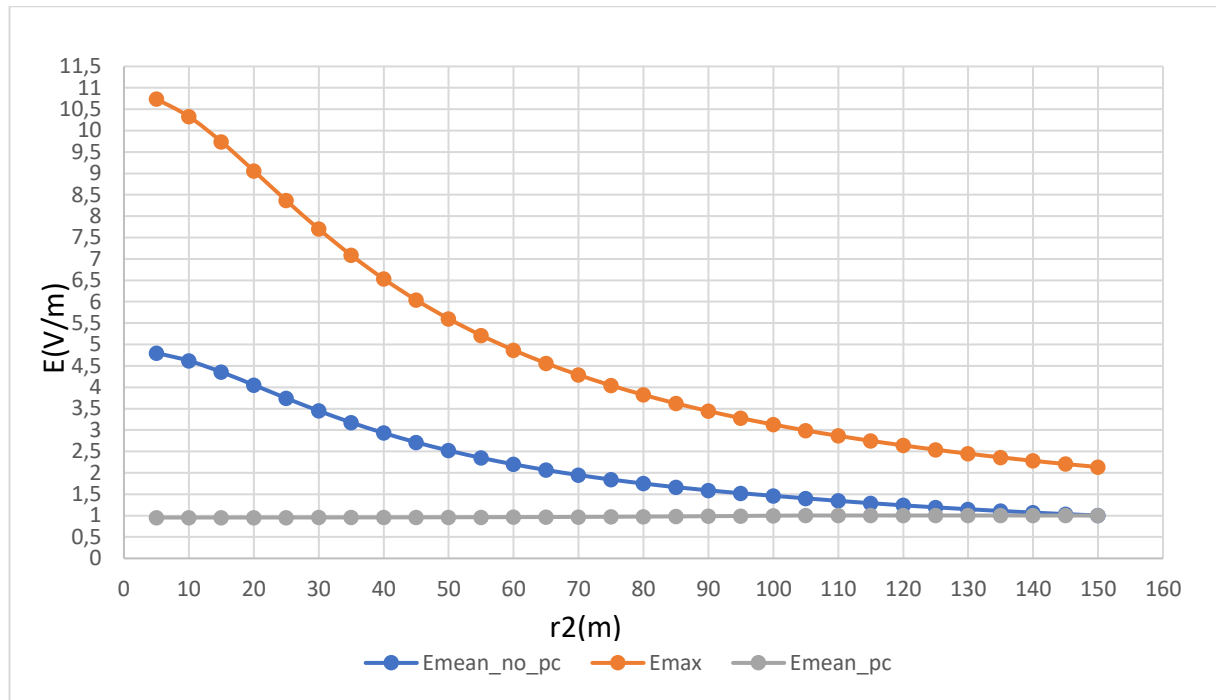


Fig. 6. Mean level without power control, maximum level and mean electric field level with power control in the BS as a function of the distance from the BS for antenna 1

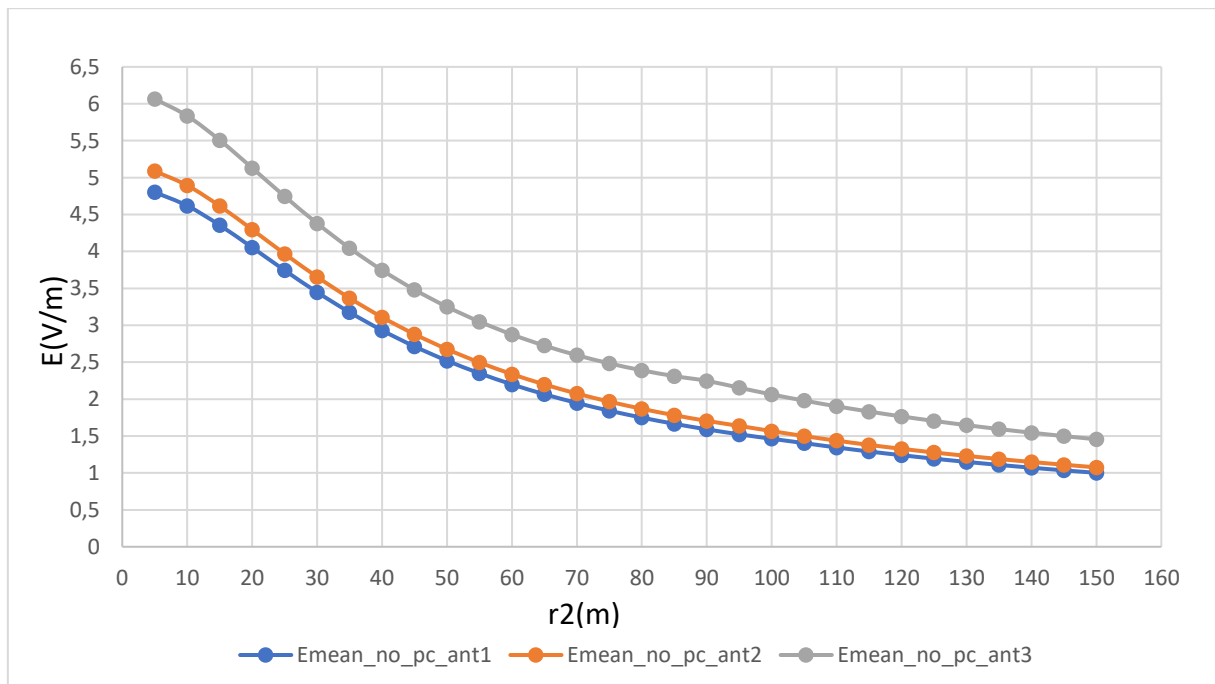


Fig. 7. Mean electric field level without power control in the as a function of the distance from the BS for antennas 1, 2 and 3

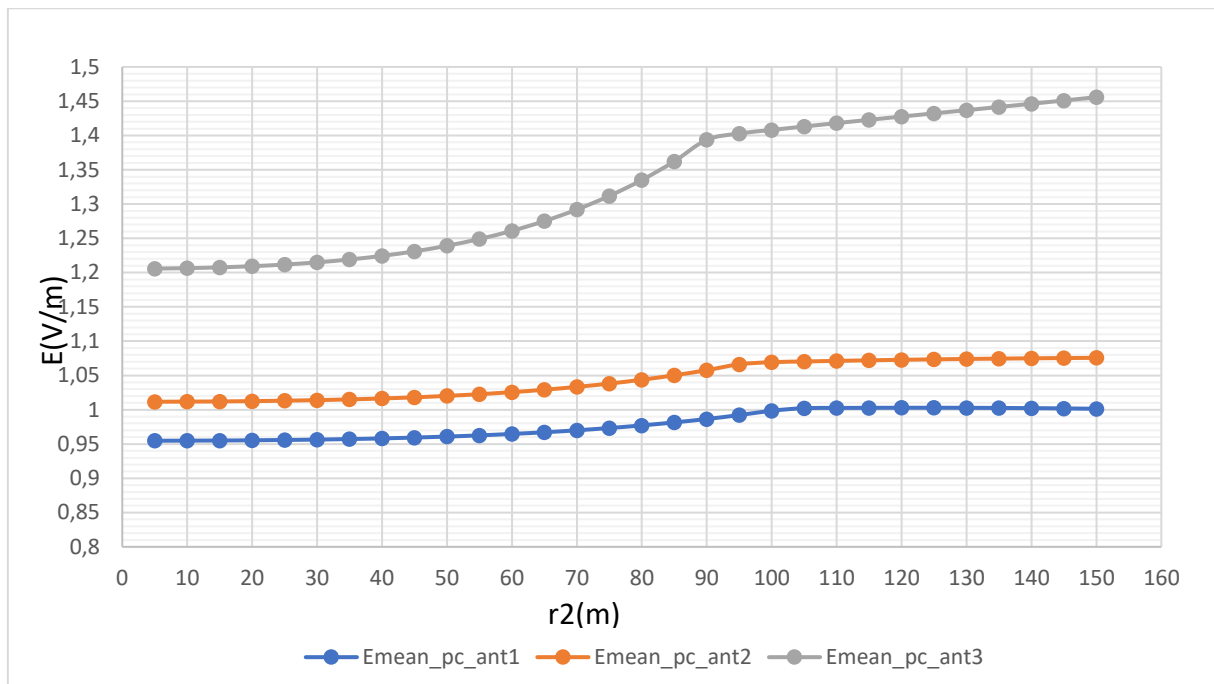


Fig. 8. Mean electric field level with power control in the BS as a function of the distance from the BS for antennas 1, 2 and 3

The influence of the BS height from the ground surface on the value of the maximum electric field is illustrated in Fig. 9. The graph is presented for the BS height $h_{BS}=10$ m, 20 m and 30 m. The smaller the BS height, the higher the level of the electric field, i.e., radiation, so that when the height of the BS is reduced, it is easiest to exceed the limits that define the maximum allowed electric field [1].

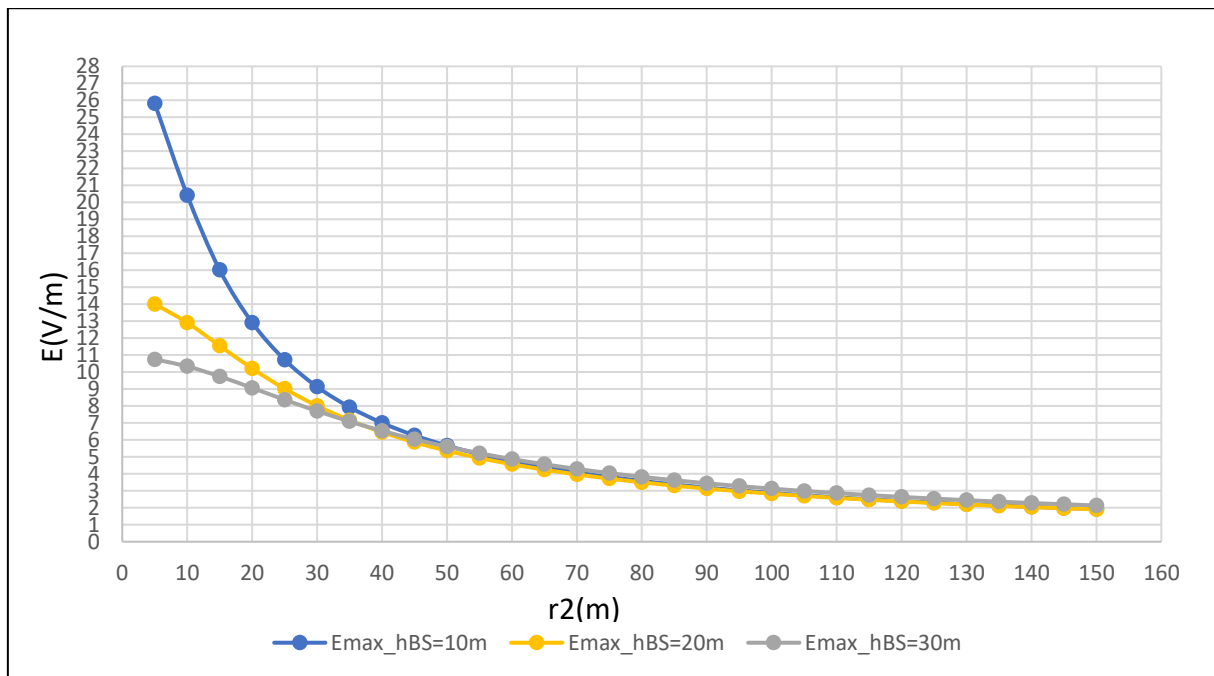


Fig. 9. The maximum level of the electric field as a function of the distance from the BS for different BS heights

The effect of the cell radius may be seen in Fig. 10. The characteristic is presented for antenna 3, and the cell radii are $r=100$ m, 150 m and 200 m. The value of the electric field in all 3 cases has one breaking point when the slope of the increase in the electric field level decreases as a function of the distance from the BS, and for $r=100$ m the level of the electric field starts to decrease starting from the breaking point. The break occurs at the moment when

the ellipse ceases to be completely inside the BS cell. The increase of the electric field is relatively greater with the increase of the cell radius (it is greater for $r=200$ m than for $r=150$ m), while the break is more noticeable when the cell radius is smaller.

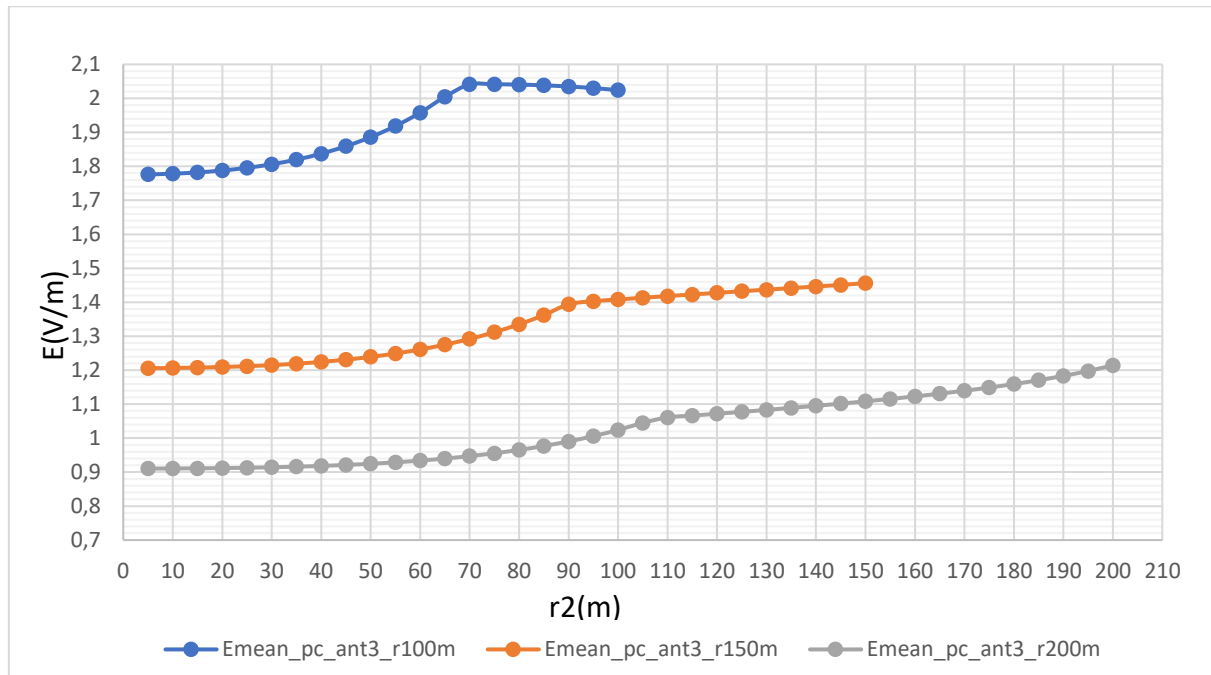


Fig. 10. Mean electric field level for BS with power control as a function of distance from BS for different cell radii

7 Conclusion

This paper presents the procedure for calculating the electric field in the vicinity of base stations implemented in 5G technology. The peculiarity of the 5G system is the directing of the traffic radiation beam (beamforming) towards the active user, which then entails the need for new principles of field calculation compared to earlier generations of mobile systems (2G to 4G). Therefore, with the 5G systems, we can talk about the existence of spatial multiplex (Space Division Multiple Access - SDMA), which did not exist at earlier generations of mobile systems. The applied radiation beams should be as narrow as possible to minimize interference and radiation exposure. In this paper it is proved that the radiation level increases with the increase in the width of the main beam, as well as that the radiation level increases with the increase in the distance of the user from the base station if power control is applied in the base station. For small radiation beam widths this increase in radiation level is insignificant, but when the beam width increases, the increase can become significant and non-negligible.

Simplifications in the paper that do not affect the generality of the obtained results are:

1. Formula (19) is valid in the case of uniform distribution of user density within the BS cell and equal traffic load of all users;
2. In the derivation of the formulas, the wave propagation model is assumed to be as in free space, i.e. the signal power decreases with the square of the distance from the BS;
3. All calculations are made for the case of the maximum possible traffic load when all traffic resources are occupied, i.e. the engaged BS power is equal to the maximum predicted BS emission power;
4. For the antenna radiation pattern, a simplified model was adopted where there are only two levels of radiation: one for the main radiation beam equal to the maximum gain value in this area and the other equal to the maximum gain level in the area outside the main radiation pattern;
5. The area for which the higher level of signal amplification applies is an ellipse in the area around the point for which calculation is performed. By modelling this by means of the circumscribed rectangle around the ellipse, it is achieved that the calculation results of the radiation level are slightly higher than it is in reality.

The calculation for 5G with AAS is complex considering that the intensity of radiation at each point depends on the current arrangement of active users in the base station cell. Unlike 2G to 4G systems, the database with antenna radiation patterns is rather scarce because the radiation patterns are dynamically variable and dependent even on the phase in the connection realization.

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