Estimation of Electromagnetic Background Created by Equipment of Cellular Radio Networks in Urban Areas with High Spatial Density of Subscribers

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***Abstract*—The estimation of electromagnetic background level created by mobile and base stations of cellular communication networks on urban areas with high terrestrial density of subscribers (in places of their gathering) are made. Analysis was executed by behavior simulation of GSM cellular radio network fragment with use of three-dimensional multibeam model of radio wave propagation (X3D Ray model) and three-dimensional topological model of typical urban area fragment with buildings height of 6-20 m at mobile stations allocation inside and out of buildings. Results have been performed for different terrestrial density of subscribers and base stations antenna height. It is concluded that in places of cellular communications subscribers gathering mobile stations electromagnetic radiation can make essential contribution to the total electromagnetic background level created by cellular communication equipment and other electromagnetic radiation sources on business hours. In conditions of shading places of people gathering by buildings and at high level of intranetwork interference (poor intranetwork EMC) the electromagnetic background level created by mobile equipment can exceed maximum permissible level.**

Keywords—Intrasystem EMC; cellular communication base and mobile stations; electromagnetic safety; electromagnetic background

I. INTRODUCTION

At the present time because of increase in cellular communication radio equipment terrestrial density and mass active use of different type of cellular communications services [1] the question about cellular communications electromagnetic safety in places with high spatial density of the population, especially in places of subscribers gathering, on business hours is of the great interest.

The previous studies [2] testifies that electromagnetic radiation (EMR) of mobile stations (MS) in telephone and data transmission mode negatively effects on operation of electronic medical devices of individual use in public places of urban areas with high spatial density of the population. The results of the paper [3] are that one of the prevailing EMR sources by signal level among the studied are the base stations (BS) of cellular communications. The electromagnetic background (EMB) level created by systems of cellular communications depends on quality of intrasystem electromagnetic compatibility (EMC) ensuring (depends on the levels of intrasystem interference that reduce radio receivers sensitivity and respectively constrain to increase MS and BS EMR power for supporting of high service quality).

One of the main criteria of electromagnetic safety estimation of cellular radio networks, and many other sources of EMR, is maximum permissible level (MPL) of power flux density or electromagnetic field (EMF) strength in observation point (OP) created by BS and MS. The MPL value of these electromagnetic environment parameters is various in different countries [3], and the value of ones must not exceed MPL at operating of cellular communications. The power flux density MPL is regulated at the level of 0.1 W/m^2 (EMF strength permissible level is 6.14 V/m or 15.8 dBV/m) for example in Belarus, Russia and other countries.

The goal of this paper is estimation of EMB level created by BS and MS on the territory of urban areas of medium number of building storeys in places of subscribers gathering including conditions of presence of intranetwork interference, and the analysis of cellular communications electromagnetic safety for the population in these conditions.

For this goal the behavior simulation of GSM-1800 cellular radio network fragment is executed with the use of three-dimensional model of typical urban area fragment with buildings height of 6-20 m at MS allocation out of buildings (outdoor) and inside buildings (indoor), it was performed using the three-dimensional multibeam radio wave propagation (RWP) X3D model [4], simplified empirical RWP model into buildings [5] and modified COST building penetration RWP model [4] (outdoor-to-indoor RWP model). During the behavior simulation of cellular network required levels of MS EMR power values for supporting of necessary quality of service are received. Then the estimation of EMF total intensity created by BS and active MS in places of subscribers gathering and inside buildings is executed. The estimates are performed for different terrestrial density of subscribers, BS antenna height and different floor number of buildings. The comparison of estimation results of EMF total intensity created by BS obtained using the behavior simulation of cellular network and using the expressions of technique [6], [7] was also made.

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II. Initial Models and Data

Models and initial data used at behavior simulation of cellular network are given below.

A. The system parameters of simulation.

1) The analysis is performed for BS and MS of GSM-1800 standard.

2) The level of the BS receiver (of GSM-1800 standard) own noise resulted to the receiver input in a frequency band of radio reception 200 kHz is equal to –114 dBm.

3) Quality of intrasystem EMC is defined by "carrier/interference" (*C/I*) value. The typical value of *C/I* for GSM standard radio networks is 15 dB in uplink [8].

4) BS equivalent isotropic radiated power (EIRP) value is 43 dBm/channel.

5) Quantity of duplex communication radio channels assigned to sector cell is 7 at three-sector cell structure.

6) Maximum level of MS EMR power does not exceed the level of 21 dBm.

7) The minimum level of MS EMR power of radio networks of GSM-1800 is regulated at the level of 0±5 dBm during operation of cellular radio network in normal conditions [9]. It is accepted that the minimum level of MS EMR power is 0 dBm.

8) It is assumed that the useful signal received by MS is a signal of prevailing BS for which RWP losses in a point of MS allocation are minimum.

9) The type of MS antenna is isotropic. The value of MS antenna gain is equal to G_{aMS} = 0 dB.

10) The value of BS antenna gain is accepted at the level of G_{aBS} = 17 dB at the estimation of MS EMR power required level.

11) BS antenna height is H_{BS} = 25-35 m.

12) MS height over the earth surface and over the floor of the room is H_{MS} = 1.5 m.

13) OP height over the earth surface is H_{OP} = 1.5 m and is the same value over the floor of the room at estimating of the total level of EMF strength.

14) OP height over the earth surface is H_{OP} = 2 m at estimating of the total EMF intensity using scenario in Fig. 1.

15) Terrestrial density of MS in places of subscribers gathering is ρ_P = 2-4 MS/m^2.

16) Terrestrial density of active MS in telephone mode is ρ_{MS} = 0.16-0.32 MS/m^2 taking into account that traffic intensity in cellular radio networks can reach value of *E* = 0.08 Erl on business hours.

17) It is accepted that quantity of active MS in the room is N_{MS} = 5-10 MS.

18) Terrestrial density of BS is approximately ρ_{BS} = 1-3 BS/km^2.

B. RWP model for urban (city) area.

The three-dimensional X3D model [4] of multipath RWP on urban area is used. It is based on use of three-dimensional SBR (shooting and bouncing ray) algorithm used for determination of RWP rays paths between BS and MS in three-dimensional space. Model has no restrictions on use in the accepted conditions. The parameters of three-dimensional RWP model are shown in [10].

C. RWP model into buildings.

1) The simplified empirical RWP model into buildings is used based on experimental data [5] and assuming the fixed attenuation of radio waves at penetration into buildings: 6.4 -13.4 dB depending on floor number (1-6 floors).

2) The modified COST building penetration RWP model [4] (outdoor-to-indoor model) is used. This model is an enhancement of the empirical outdoor-to-indoor model described in the COST 231 Propagation Prediction Models final report [11]. The building penetration radio receivers set is not account for the floor plan that is in the place and will generate an empirical result using the COST model.

D. Model of urban area.

The topographical computer model of a fragment city housing of part of Minsk, which was described in detail in [10], is used. The following characteristics of the model are accepted at analysis performance:

1) The considered urban area fragment conforms to the territory type of "urban high-rise" [12]. Buildings height is mainly 6-20 m (2-6 floors).

2) The earth surface is assumed as flat. Type of a covering of an earth surface is asphalt.

3) The walls material is brick. The roof material is concrete.

E. Model of the room.

The model of the room represented in Fig. 3 is considered. The size of the room is the following: the length is *L* = 18 m, the width is *W* = 6 m, the height is *H* = 3 m. Materials of the room elements are the following: the wall material is brick, the floor and ceiling material is concrete, the door material is wood.

F. Model of the crowd.

The model of the crowd is gathering of subscribers on territory of considered urban area with average terrestrial density ρ_P mentioned above. Terrestrial allocation of subscribers in the crowd is uniform.

G. Estimation of the total EMF intensity created by BS.

For random mutual allocation of BS antennas and OP near the earth surface it is characteristic division the total EMF intensity from BS in OP on two components ([6], [7]). For BS set with identical EIRP P_{eBS} located randomly with average terrestrial density ρ_{BS} in vicinity of radius $R_{BP\ BS}$ around OP average value of the total EMF intensity $\Pi_{\sum 1BS}$ created by these

BS in OP on height $H_{OP} << H_{BS}$ is defined by the following expression:

$$\Pi_{\Sigma 1BS} = (L_{TBS}/2)\ln(4H_{OP}/\lambda), \quad L_{TBS} = \rho_{BS} P_{eBS} \tag{1}$$

The radius $R_{BP\,BS}$ is defined as follows:

$$R_{BP\,BS} = 4H_{OP}H_{BS}/\lambda \tag{2}$$

For BS set with identical EIRP P_{eBS} located randomly with average terrestrial density ρ_{BS} outside the vicinity of radius $R_{BP\,BS}$ average value of the total EMF intensity $\Pi_{\Sigma 2BS}$ created by these BS in OP on height $H_{OP} << H_{BS}$ is defined by the following expression:

$$\Pi_{\Sigma 2BS} = L_{TBS}/4 \tag{3}$$

The total average intensity Π_{Σ} of EMF created by all BS in OP on height H_{OP} is defined by summing expressions (1) and (3):

$$\Pi_{\Sigma} = \Pi_{\Sigma 1BS} + \Pi_{\Sigma 2BS} \tag{4}$$

H. The estimation of MS EMR power required level.

The estimation of required level of MS EMR power out of buildings (outdoor) for supporting of necessary quality of service at RWP between MS and BS is made by the following expression:

$$P_{MSoutdoor} = S - G_{aBS} + L - G_{aMS} + C/I \tag{5}$$

where S is minimum detectable signal level at the BS receiver input, dBm; G_{aBS} is BS antenna gain, dB; L is signal attenuation at RWP, dB; G_{aMS} is MS antenna gain, dB; C/I is "carrier/interference" ratio at the BS receiver input, dB.

The estimation of required level of MS EMR power in buildings (indoor) for supporting of necessary quality of service with BS is made by the following expression:

$$P_{MSindoor} = S - G_{aBS} + L_{outdoor-to-indoor} - G_{aMS} + C/I \tag{6}$$

where $L_{outdoor\text{-}to\text{-}indoor}$ is attenuation of signal at RWP between BS and MS allocated inside buildings including attenuation of signal through elements of buildings construction, dB.

I. Estimation of the total level of EMF strength created by BS and MS by behavior simulation.

The total level of EMF strength (E_{Σ}, V/m) in OP created by all MS ($E_{\Sigma MS}$, V/m) and BS ($E_{\Sigma BS}$, V/m) is defined by the next expressions:

$$E_{\Sigma BS} = \sqrt{\sum_{i=1}^{M} E^2{}_{BS_M}} \tag{7}$$

$$E_{\Sigma MS} = \sqrt{\sum_{i=1}^{N} E^2{}_{MS_N}} \tag{8}$$

$$E_{\Sigma} = \sqrt{E^2{}_{MS_1} + \ldots + E^2{}_{MS_N} + E^2{}_{BS_1} + \ldots + E^2{}_{BS_M}} \tag{9}$$

where M is BS quantity on considered urban area territory; N is MS quantity on considered urban area territory of radius R_1.

J. Scenarios of modeling.

1) For estimation of the total EMF intensity from BS by behavior simulation of cellular network using X3D RWP model in order to comparison with the results obtained using expressions (1) and (4) the basic scenario represented in Fig.1 is used. BS with antenna height H_{BS} = 30 m are allocated on the territory with an average terrestrial density approximately ρ_{BS} = 1 BS/km^2. OPs are allocated uniformly within the territory of $R_{BP\,BS}$ radius. On the first stage the estimates of the total EMF intensity in OP without taking into account influence of buildings on RWP are received. On the second stage the behavior simulation of cellular network taking into account influence of buildings on RWP with use of urban area model with identical buildings heights (5-25 m) is executed.

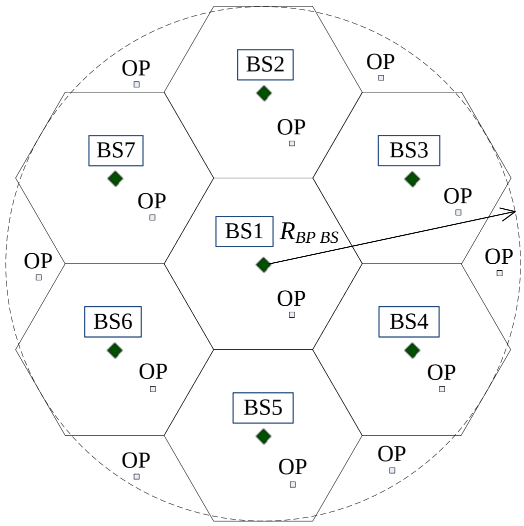

Fig. 1. Scenario for estimation of the total EMF intensity created by BS

2) For estimation of required levels of MS EMR power the basic scenario is used. Seven BSs are allocated close to regular placement with an average terrestrial density approximately ρ_{BS} = 3 BS/km^2 on the considered urban area fragment. MS are allocated out of buildings (outdoor) and in buildings (indoor). On the first stage the values of signal attenuation levels at RWP from prevailing BS by signal level to MS allocated inside and out of the buildings are received. On the second stage the estimates of required MS EMR power levels for supporting of necessary service quality taking into account signal attenuation at RWP and in conditions of intranetwork interference presence were executed.

3) For estimation of the total level of EMF strength in OP created by MS EMR in places of subscribers gathering out of buildings the scenario represented in Fig. 2 is used. Active MS and OP are allocated uniformly on considered territory of urban area in the vicinity of radius R_1 = 5 m. The minimum distance between MS and OP is 0.4 m.

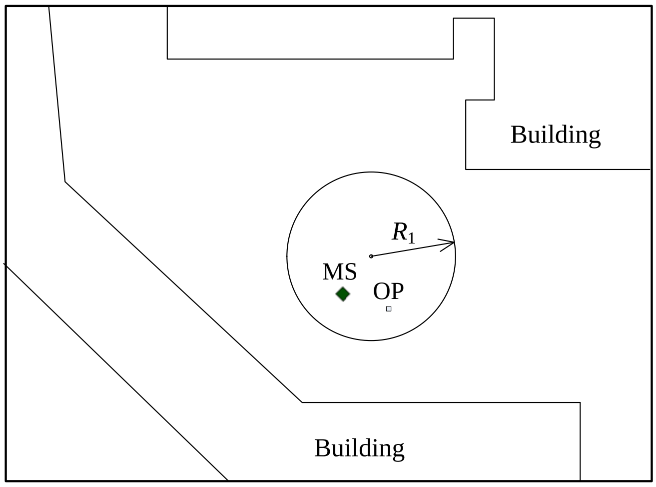

Fig. 2. Scenario for estimation of the total EMF strength in OP created by MS EMR in the crowd out of buildings (outdoor)

4) For estimation of the total level of EMF strength in OP created by MS EMR in building room the scenario (Fig. 3) is used. Active MS are allocated as shown in Fig. 3. OPs are allocated in the room uniformly. The minimum distance between OP and MS is selected equal to 0.4 m.

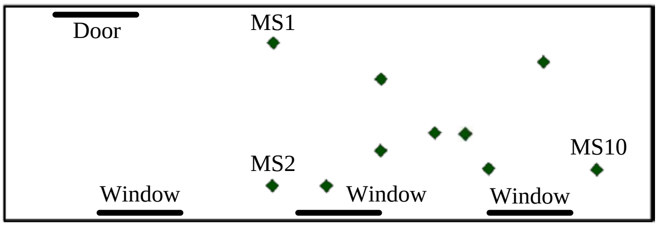

Fig. 3. The scenario for estimation of the total level of EMF in OP created by MS EMR inside the building room

III. The Results of Behavior Simulation and Discussion

A. Comparison of the values of the total EMF intensity in OP obtained by behavior simulation and expressions.

Histograms of distribution of the total EMF intensity Π_Σ in OP created by BS without taking into account influence of buildings on RWP and taking into account this influence with use of urban area model with buildings height of 25 m are shown in Fig. 4-5 below.

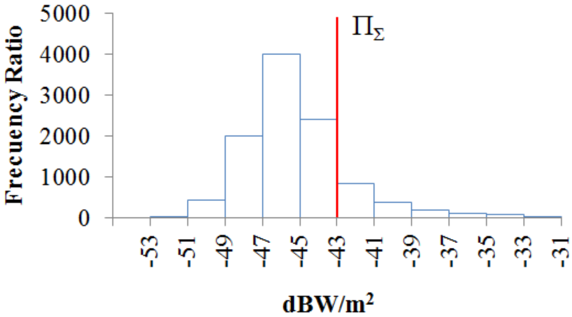

Fig. 4. Histogram of the total EMF intensity distribution in OP created by BS without taking into account influence of buildings on RWP

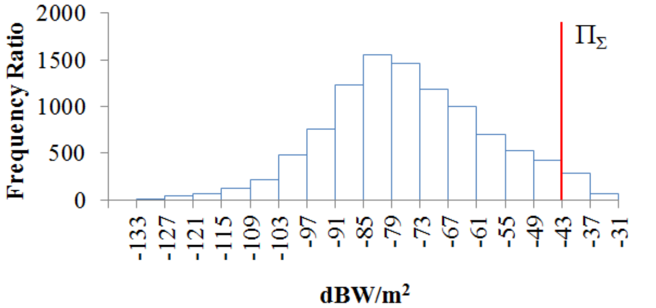

Fig. 5. Histogram of the total EMF intensity distribution in OP created by BS taking into account influence of buildings on RWP with use of urban area model with buildings height of 25 m

The calculation results of OP relative quantity in which the total EMF intensity created by BS does not exceed calculated value obtained by expressions (1) and (4) are shown below in Table 1. Calculated value of the total EMF intensity obtained using expression (1) is $\Pi_{\Sigma 1BS} = -43.5$ dBW/m^2 and using expression (4) is $\Pi_\Sigma = -43$ dBW/m^2 at BS EIRP P_{eBS} of 43 dBm.

TABLE I. Relative quantity of OP, %, in which the total EMF intensity does not exceed calculated values obtained using expressions (1) and (4)

Buildings height, m	**Relative quantity of OP,%, in which the total EMF intensity created by BS does not exceed calculated values of Π_Σ and $\Pi_{\Sigma 1BS}$**	
	Π_Σ	$\Pi_{\Sigma 1BS}$
Without taking into account influence of buildings on RWP	84.5	83.5
5	90.1	88.0
10	92.5	91.5
15	94.0	93.1
20	95.6	95.0
25	96.5	96.1

The results analysis of comparison of the total EMF intensity values in OP obtained using expressions (1)-(4) and using behavior simulation of cellular network testifies to the following:

1) Relative quantity of OP in which the total EMF intensity created by BS on the territory without taking into account influence of buildings on RWP does not exceed calculated Π_Σ value is 84.5 %.

2) Relative quantity of OP in which the total EMF intensity created by BS taking into account influence of buildings on RWP does not exceed calculated Π_Σ value is 90.1…96.5 %.

These results confirm the possibility of use of expressions (1)-(4) for worst-case estimation of EMB level created by BS on urban area territories of medium number of building storeys.

B. Estimation of required levels of MS EMR power.

Relative quantity of MS out of buildings whose EMR power $P_{MSoutdoor}$ exceeds minimal value of 0 dBm and safety level value of 17 dBm is shown in Table 2 below. The safety level value of MS EMR power was obtained taking into account the requirements [13]: the level of power flux density of MS EMR at distance of 370 mm from MS must not exceed MPL of 3 μW/cm^2 in the 800-2400 MHz frequency band.

TABLE II. RELATIVE QUANTITY OF MS, %, WHOSE EMR POWER EXCEEDS MINIMAL AND SAFETY LEVEL

H_{BS}, m	Relative quantity of MS, %, whose EMR power exceeds minimal and safety level	
	$P_{MSoutdoor}$ = 0 dBm	$P_{MSoutdoor}$ = 17 dBm
25	13.5	0.4
30	6.6	0.2
35	3.9	0.03

The maximum value of MS EMR power required levels inside buildings depending on building floor and height of BS antenna are shown in Table 3. These results were obtained taking into account the estimates of useful signal levels at the inputs of MS receivers allocated inside buildings on different floors of buildings [10] at communication probability of 0.99, with use of signal attenuation estimation technique at RWP from BS to MS allocated inside buildings (outdoor-to-indoor) [14] and signal attenuation values at penetration of radio waves into buildings with dependence of building floor number [5].

TABLE III. MAXIMUM VALUES OF REQUIRED LEVELS OF MS EMR POWER INSIDE BUILDINGS ON DIFFERENT FLOORS

Floor No.	$P_{MSindoor}$, dBm	
	H_{BS} = 25 m	H_{BS} = 35 m
1	12.1	2.5
2	7.5	0.8
3	1.0	0
4-6	0	0

The example of histogram of MS EMR power values distribution inside the building room represented in Fig.3 on the first floor at BS antenna height of 25 m obtained using expression (6) at relatively poor conditions of RWP between BS and MS is shown in Fig. 6 below. The values of signal attenuation $L_{outdoor\text{-}to\text{-}indoor}$ were received with use of modified COST building penetration RWP model.

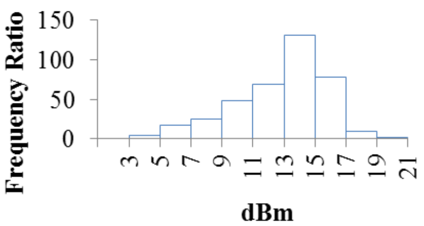

Fig. 6. The example of histogram of MS EMR power values distribution inside the building room on the first floor at BS antenna height of 25 m

C. Estimation of the total level of EMF strength in OP created by BS and MS.

The estimates results of the total level of EMF strength in OP created by MS EMR in places of subscribers gathering out of buildings at different BS antenna height for two cases are shown in Tables 4, 5. The first case is when MS are allocated in place of MS shading by buildings. The second case is when MS are allocated in line of sight of the nearest BS. The values of each MS EMR power depend on RWP losses.

TABLE IV. THE ESTIMATES RESULTS OF THE TOTAL LEVEL OF EMF STRENGTH CREATED BY BS AND MS IN PLACE OF SUBSCRIBERS GATHERING OUT OF BUILDINGS AT DIFFERENT BS ANTENNA HEIGHT (MS ARE SHADING BY BUILDINGS)

H_{BS}, m	$E_{\sum BS}$, dBV/m	$E_{\sum MS}$, dBV/m	$E_{\sum}$, dBV/m
	ρ_{MS} = 0.32 MS/m^2		
25	–62.8…–47.5	4.0…14.8	4.0…14.8
30	–56.2…–39.5	–5.9…6.1	–5.9…6.1
35	–52.2…–32.0	–12.3…2.6	–12.3…2.6
	ρ_{MS} = 0.16 MS/m^2		
25	–62.8…–47.5	–0.6…13.6	–0.6…13.6
30	–56.2…–39.5	–13.0…0.2	–13.0…0.2
35	–52.2…–32.0	–16.3…–1.8	–16.3…–1.8

TABLE V. THE ESTIMATES RESULTS OF THE TOTAL LEVEL OF EMF STRENGTH CREATED BY BS AND MS IN PLACE OF SUBSCRIBERS GATHERING OUT OF BUILDINGS AT DIFFERENT BS ANTENNA HEIGHT (MS ARE ALLOCATED IN LINE OF SIGHT OF THE NEAREST BS)

H_{BS}, m	$E_{\sum BS}$, dBV/m	$E_{\sum MS}$, dBV/m	$E_{\sum}$, dBV/m
	ρ_{MS} = 0.32 MS/m^2		
25	–2.6…2.1	–11.0…–3.9	–1.5…2.6
30	–3.5…1.3	–11.0…–3.9	–2.4…1.9
35	–2.5…–0.2	–11.0…–3.9	–1.5…0.8
	ρ_{MS} = 0.16 MS/m^2		
25	–2.9…2.1	–18.3…–4.5	–2.6…2.5
30	–3.5…1.3	–18.3…–4.5	–3.0…1.7
35	–2.5…–0.2	–18.3…–4.5	–2.1…0.6

The estimates results of the total level of EMF strength in OP created by MS EMR inside the building room on different floors at different BS antenna height are shown in Table 6. Values of each MS EMR power are equal to maximum values according to the Table 3.

TABLE VI. THE ESTIMATES RESULTS OF THE TOTAL LEVEL OF EMF STRENGTH CREATED BY MS INSIDE THE BUILDING ROOM ON THE DIFFERENT FLOORS AT DIFFERENT BS ANTENNA HEIGHT

Floor No.	$E_{\sum MS}$, dBV/m			
	H_{BS} = 25 m		H_{BS} = 35 m	
	N_{MS} = 5	N_{MS} = 10	N_{MS} = 5	N_{MS} = 10
1	–20.5…6.4	–19.1…6.4	–30.1…–3.3	–28.7…–3.2
2	–25.1…1.8	–23.7…1.8	–31.8…–5.0	–30.4…–4.9
3	–31.6…–4.8	–30.2…–4.7	–32.6…–5.7	–31.2…–5.7
4-6	–32.6…–5.7	–31.2…–5.7	–32.6…–5.7	–31.2…–5.7

The analysis of obtained results testifies to the following:

1) In conditions of shading of MS set by buildings at active MS terrestrial density ρ_{MS} = 0.32 MS/m^2 and BS antenna height H_{BS} = 25 m the total level of EMF strength in OP created by MS and BS can achieve 14.8 dBV/m (89.5%

from MPL). At increasing the value of *C/I* ratio up to 16-17 dB the total level of EMF strength created by cellular communication equipment can achieve 15.9 dBV/m and insignificantly exceed MPL that is dangerous for the population. At increasing of BS antenna height up to 30-35 m the total level of EMF strength in OP does not exceed MPL and makes 2.6…6.1 dBV/m. In those conditions of RWP MS EMR make the main contribution, in comparison with BS EMR, to the total EMB level. The total level of EMF strength in OP created by BS with antenna height of 25-35 m is –62.8…–32.0 dBV/m and it is inessential contribution to the total EMB level created by cellular communication equipment in places of subscribers gathering. At decreasing ρ_{MS} up to 0.16 MS/m^2 the range upper bound of the total level of EMF strength in OP created by MS and BS decreases on 1.2…5.9 dB depending on BS antenna height.

2) At allocation of MS in line of sight of the nearest BS at active MS terrestrial density $\rho_{MS} = 0.32$ MS/m^2 and BS antenna height H_{BS} = 25 m the total level of EMF strength in OP created by MS and BS in places of subscribers gathering achieves the level of 2.6 dBV/m and remains acceptable from the point of view of electromagnetic safety. In those conditions of RWP BS EMR make primary contribution, in comparison with MS EMR, to the total EMB level. With increase in BS antenna height up to 30-35 m the total level of EMF strength created by MS and BS is not changed essentially. At decreasing ρ_{MS} up to 0.16 MS/m^2 the range upper bound of the total level of EMF strength in OP created by MS and BS decreases on 0.6 dB.

3) The total level of EMF strength in OP created by EMR of MS set in the room on the first floor at BS antenna height H_{BS} = 25 m and quantity of active MS N_{MS} = 5-10 can achieve 6.4 dBV/m and does not exceed MPL. This value is observed in the nearest OP from MS at distance of 0.4 m and will depend on value of MS EMR power and quantity of active MS inside the room. Increase in BS antenna height up to 35 m decreases essentially the total level of EMF strength created by MS, and MS EMR power levels approach the minimum level. The results in Fig. 6 show that MS EMR power can exceed the safety level of 17 dBm in the room that is dangerous from the point of view of electromagnetic safety.

IV. Conclusion

The results given above testify to the following.

1) The comparison results of the total EMF intensity values in OP obtained by expressions (1)-(4) and by the behavior simulation of cellular network using X3D RWP model showed that expressions (1)-(4) can be applied for worst-case estimation of EMB level created by BS on urban area territory of medium number of building storeys.

2) In conditions of MS shading by buildings in places of subscribers gathering on considered urban area and at high levels of intranetwork interference MS EMR make essential contribution, in comparison with BS EMR, to the total level of EMB created by cellular communication equipment and other sources of EMR. The total level of EMF strength created by MS set can overrate MPL. At allocation of MS in line of sight of BS the EMR of BS on considered urban area make primary contribution, in comparison with MS EMR, to the total EMB level created in the crowded places.

3) The use of cellular communications in buildings on the ground floors can be dangerous from the point of view of electromagnetic safety because at relatively poor conditions of RWP and at high levels of intranetwork interference MS EMR power can exceed safety level in these rooms.

4) Increasing BS EIRP more than 43 dBm/channel does not allow to improve quality of service, this way increases levels of intranetwork interference proportionately, and will lead to growth of EMB level created by BS on considered urban area in places of subscribers gathering.

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