Worst-Case Models of Electromagnetic Background Created by Cellular Base Stations

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Abstract—**The novel "worst-case" mathematical models of electromagnetic background, created by base stations of cellular communications and ground radio transmitters of other services is offered. This model allow to estimate the background total intensity directly on the basis of calculation of the total electromagnetic loading on territory as the total equivalent isotropic radiated power of base stations of cellular communications and other radio transmitters falling to the unit of the area of considered territory. The relationships characterizing restrictions on maximum permissible parameters of radioelectronic environment, created by base stations, at operating restrictions on maximum permissible levels of an electromagnetic field for the population, are resulted.**

Keywords - electromagnetic background, electromagnetic loading, cellular communications, ecology, electromagnetic safety

I. INTRODUCTION

Intensive development of the mobile and fixed radio communication systems and networks in places with high population density is the reason of intensive electromagnetic pollution on urban and suburban territories produced by BS of CC (see Section VII) and wireless broadband access and many other radio transmitters of different radio services covering these territories. This circumstance causes anxiety, that, in particular, is reflected in official memorandum [1] and in earlier works [2,3, et al.], and also in papers devoted to the estimation of intensity of an EMF (see Section VII) generated by mobile phones [4,5,6], and also to the analysis of electromagnetic compatibility, ecology and safety of radio telecommunication systems [7].

Direct estimation of total intensity of set of EMF in some observation point at a ground surface, as a rule, represents extremely difficult and intricate problem connected with calculation of levels of EMF in the considered point generated by all radio transmitters located in a zone of radio visibility. Expected uncertainty of transmitters spatial allocation and parameters of EMR (see Section VII) in most cases impede of it correct performance.

In this paper the original and novel technique of worst-case estimation of total intensity of an electromagnetic background (EMB - see Section VII) in any point near to the ground surface is stated. This technique is based on calculation of integrated system parameter of REE (see Section VII) - the total e.i.r.p. (see Section VII) of BS of CC and other radio transmitters falling to the unit of the area of considered territory, named in [8] as "electromagnetic loading (EML - see Section VII) on territory". This technique in particular can be of interest for designing sensor networks for monitoring of electromagnetic pollution of the human environment.

The paper is organized as follows. In Sections II the main concepts are given. Initial models and relations are described in Section III. Relations for worst-case estimation of EMB and some results of practical application of presented technique are given in Sections IV, V. The main advantages and novelty of presented technique are summarized in Conclusion. Abbreviations are given in Section VII.

II. MAIN CONCEPTS

Solving of many problems of electromagnetic ecology and electromagnetic safety of radio systems of an information service of a human society is connected with the analysis of electromagnetic stress as an integrated system characteristic of electromagnetic environmental pollution. Nevertheless, today the generally accepted definition of the term "EMS" (see Section VII) is absent. As a rule, the concepts described by this term, can be carried to one of two groups: "EMS on a human body" and "EMS on the population (the industrial personnel)".

The term "EMS on a human body", as a rule, is applied to define the following quantities:

a) The total intensity Π_Σ of the EMF ensemble affected on human body; it is determined as the scalar sum of power flux densities Π_i of each of N EMR sources created an EME (see Section VII) in observation point:

$$\Pi_\Sigma = \sum_{i=1}^{N} \Pi_i \text{ , W/m}^2. \quad (1)$$

b) The total radiant exposure W_e of EME impact on human body; it is determined as the product of the total intensity Π_Σ of the EMF ensemble affected on human body and the time duration T of this impact:

$$W_e = \Pi_\Sigma \cdot T, \text{ W·s/m}^2. \quad (2)$$

c) The relative total intensity X of the EMF ensemble affected on human body; it is determined as the scalar

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sum of relative intensities of each of N=M+K EMR sources created the EME in observation point:

$$X = \sum_{m=1}^{M} \left(\frac{E_m}{E_{MPL\,m}} \right)^2 + \sum_{k=1}^{K} \frac{\Pi_k}{\Pi_{MPL\,k}} , \qquad (3)$$

where $E_{MPL\,m}$, $\Pi_{MPL\,k}$ - the accepted maximum permissible levels (MPL) of EMF, expressed in terms of EMF strength [V/m] (for group of M sources for which values of their EMF strength E_m are considered, m=1, … , M), or in terms of power flux density [W/m^2] (for group of N sources for which values of their EMF power flux density Π_n are used, n=1, … , N) depending on a frequency range, kind of radio service (broadcasting, radar, fixed, mobile, etc.), on an EMR modulation and mode (continuous, pulse, pulse narrow-beam with circular scanning, etc.).

The term "EMS on the population (the industrial personnel)" is applied to define the following quantities:

d) Set (matrix) of values of total EMF intensity (1) from the set of EMF sources (REE) located on given territory (in space) and forming a terrestrial map of total EMF intensity at specified height (over a terrestrial surface, above sea level, etc.), or a map of total EMF intensity in plane section of some spatial domain (a zone of high population density, a zone of aircrafts short-range air navigation and landing, etc.).

e) Set (matrix) of values of a total radiant exposure (2) from the set of EMF sources (REE) located on given territory and forming a spatial map of total radiant exposure of an industrial premise, zone, settlement, etc.

f) Set (matrix) of values of relative total EMF intensity (3) forming a terrestrial map of values of relative total EMF intensity produced by the set of EMF sources creating REE on specified territory.

Taking into consideration variants of EMS definition given above, however it is necessary to notice the following:

- For a designation of variants of EMS definition resulted above in normative documents, in the scientific, technical and educational literature the other terms of the concrete physical interpretation are often used, such, as "total EMF intensity, "EMF power exposition", "relative total EMF intensity", etc.
- All characteristics mentioned above are characteristics of EME, i.e. characteristics of EMF ensemble in an observation point (variants $^{a)}$, $^{b)}$, $^{c)}$) or in specified territory (variants $^{d)}$, $^{e)}$, $^{f)}$). It is possible to use these characteristics only indirectly to describe properties of the supreme cause of EME formation - properties of REE on considered territory (space) - power and time characteristics of EMR of total set of radio transmitters of different radio services placed in considered area.

The last can be considered as an inconvenience and disadvantage of the EMS definition "by the field", because power and time characteristics of EMR of transmitters forming REE in considered area are represent the initial information containing in corresponding databases used for spectrum management. This initial information on technical characteristics, modes of EMR and allocation parameters of equipment set in considered area which are the reason of EMS occurrence, in a combination with characteristics of RWP (see Section VII) in considered area is directly used

- for EMS management on separate terrestrial plots by change of EMR power and time characteristics of radio equipment placed on considered area;
- for mathematical modeling and estimations of power characteristics (1), (2), (3) of EME in separate points or in specified territory.

Therefore, at least at the integrated system analysis of electromagnetic compatibility, ecology and safety of modern radio telecommunication system, according to author opinion, the additional consideration of electromagnetic loading on territory (EML) "by EMR power" in the form of the total specific EMR power of ground radio equipment falling to the unit of the terrestrial area is required. Quantitative communication of EML on territory and EMS on the population will be established below.

Particularly the EML on territory $L_{T\,BS}$ created by EMR of BS of CC networks with the identical e.i.r.p. P_e of BS at identical areas S_S of sites (at regular spatial topology of a CC network), or identical e.i.r.p. P_e of BS at it's constant average territorial density $\rho = 1/S_S$ (at generally irregular spatial topology of a network, including random or close to random territorial BS allocation) can be defined as follows:

$$L_{T\,BS} = P_e / S_S , \qquad (4.1)$$

at regular spatial topology of a CC network;

$$L_{T\,BS} = \rho P_e \qquad (4.2)$$

at generally irregular (random) spatial topology of a network.

The goal of this work – to estimate relation between characteristics (4.1), (4.2) of EML on territory created by EMR BS CC, and EME characteristics (1) - (3), used for description of EMS produced by BS of CC.

III. MODELS AND RELATIONS

A. Worst-Case Model of RWP conditions

Conditions of RWP from BS with antennas established at stated height H_{BS} over a surface, to an observation point with cellular phone (human head) near to a ground surface at height H_{OP}, have a following important features [9]:

- On small distance R from BS RWP conditions is equal to this conditions in free space - strength E of EMF BS decreases in inverse proportion to distance to BS, the power flux density Π of EMF BS decreases in inverse proportion to a square of distance R to BS.
- Since some distance R_{BP} ("breakpoint" distance) from BS RWP conditions changes: distance dependence of strength E of EMF become to oscillate because of the

multipath RWP; the envelope of distance dependence of EMF BS strength become to decrease in inverse proportion to a square of distance R to BS, the envelope of distance dependence of EMF power flux density Π decreases in inverse proportion to the fourth degree of distance to BS.

- Distance R_{BP} between BS and MC on which the given changes of RWP conditions occurs, depends on a wavelength λ of BS EMR, height of BS antennas H_{BS} and height H_{OP} of supervision point over a terrestrial surface and is defined by a following relation:

$$R_{BP} = 4H_{BS}H_{OP}/\lambda \,. \tag{5}$$

Consequently for the case $H_{BS} >> H_{OP}$ the worst-case model of RWP conditions between BS and observation point near ground surface on distance R can be represented as follows:

$$\Pi = P_e \Big/ \left(4\pi R^2\right), \quad H_{BS} \le R \le R_{BP} \,, \tag{6.1}$$

$$\Pi = R_{BP}^2 P_e \Big/ \left(4\pi R^4\right), \quad R \ge R_{BP} \,. \tag{6.2}$$

B. Statistical Model of EMF Ensemble (free-space RWP)

At random terrestrial allocation of BS with constant territorial density ρ [BS/m^2] and BS antenna height H_{BS} [m] under the surface in circular domain of radius R_{BP} round a supervision point, the probability distribution of a power flux density of EMFs in observation point from BS of this (1st) group will be the hyperbolic distribution of the order "-2" [4,8]:

$$w(\Pi) = \frac{\Pi_{min}\Pi_{max}}{(\Pi_{max} - \Pi_{min})\Pi^2} \approx \frac{\Pi_{min}}{\Pi^2}, \tag{7}$$

$$\Pi_{min} \le \Pi \le \Pi_{max}, \quad \Pi_{max} >> \Pi_{min}$$

$$\Pi_{max} = \frac{P_e}{4\pi H_{BS}^2}, \quad H_{OP} << H_{BS}\,;$$

$$\Pi_{min} \approx \frac{P_e}{4\pi R_{BP}^2} = \frac{P_e\lambda^2}{64\pi H_{BS}^2 H_{OP}^2}, \quad H_{BS} << R_{BP}\,;$$

average of this distribution is defined by a following relation:

$$m_1(\Pi) \approx \Pi_{min} \ln\left(\frac{\Pi_{max}}{\Pi_{min}}\right) = \\ = \frac{P_e\lambda^2}{64\pi H_{BS}^2 H_{OP}^2} \ln\left(\frac{16H_{OP}^2}{\lambda^2}\right). \tag{8}$$

C. Statistical Model of EMF Ensemble (multipath RWP)

At random terrestrial allocation of BS with constant territorial density ρ [BS/m^2] and identical BS antenna height H_{BS} [m] under the surface in ring domain of inner radius R_{BP} round a supervision point and outer radius mR_{BP}, m>>1 (radius of zone of BS radio visibility), the probability distribution of a power flux density of EMFs in observation point from BS of this (2nd) group will be as the hyperbolic distribution of the order "-3/2" [4,10]:

$$w(\Pi) = \frac{\sqrt{\Pi_{max}\Pi_{min}}}{2\Pi^{3/2}\left(\sqrt{\Pi_{max}} - \sqrt{\Pi_{min}}\right)} \approx \frac{\sqrt{\Pi_{min}}}{2\Pi^{3/2}}, \tag{9}$$

$$\Pi_{min} \le \Pi \le \Pi_{max}\,;$$

average of this distribution is defined by a following relation:

$$m_1(\Pi) = \sqrt{\Pi_{max}\Pi_{min}} = P_e \Big/ \left(4m^2\pi R_{BP}^2\right);. \tag{10}$$

$$\Pi_{min} = \frac{P_e}{4\pi R_{BP}^2}, \quad \Pi_{max} = \frac{P_e}{4m^4\pi R_{BP}^2}\,.$$

D. Model of BS Terrestrial Allocation

BS allocation against an observation point and number of BS of the 1st group (from the zone of free-space RWP between BS and observation point) and of the 2nd group (from the zone of multipath RWP between BS and observation point) are random under the following reasons:

- At classical regular hexagonal terrestrial structure of cellular network (case 1) – under the random allocation of the observation point against BS that make random the minimum distance between this point and the nearest BS (the source of EMF of prevailing intensity) and owing to randomness of hit inside a zone of free-space RWP of BS allocated near to border of this zone.
- At random BS terrestrial allocation on territory (case 2) - owing to the random allocation of BS against the observation point and to randomness of BS appearance inside a zone of free-space RWP.

In both cases the uniformity of average territorial BS density ρ allows to define average BS quantity N_{AV} obviously as follows:

$$N_{AV1} = \frac{S_{BP}}{S_S} = \rho\pi R_{BP}^2 = \frac{16\rho\pi H_{BS}^2 H_{OP}^2}{\lambda^2}, \; S_S = \frac{1}{\rho} \tag{11}$$

in zone of free-space RWP between BS and observation point (S_{BP} is an area of this zone, S_S is an area of cellular site);

$$N_{AV2} \approx 16\rho\pi m^2 H_{BS}^2 H_{OP}^2 / \lambda^2, \; m >> 1 \tag{12}$$

in zone of multipath RWP between BS and observation point.

IV. AVERAGE TOTAL EMF INTENSITY

A. The total EMF intensity from the BS of the 1st group

The total average EMF intensity $\Pi_{\Sigma 1}$ from the BS of the 1st group allocated in a zone of free-space RWP between BS and observation point can be defined evidently as scalar product of average quantity (11) of BS in this zone and average (8) of probability distribution (7) of an EMF power flux density in observation point from BS of this group:

$$\Pi_{\Sigma 1} = N_{AV1} m_1(\Pi) = [\rho P_e/4)\ln\left(16H_{OP}^2/\lambda^2\right) = \\ = \frac{L_{TBS}}{2}\ln\left(\frac{4H_{OP}}{\lambda}\right) \tag{13}$$

This relation is of very great value: it establishes the simple direct dependence between EMS on a human body (1)-(3) in the observation point and EML on territory (4.1), (4.2) in free-space RWP vicinity of this point.

The most important features of (13) are in following:

- The EMS on a human body in observation point formed by EMF of BS allocated inside the vicinity of free-space RWP to this point is defined generally by the EML on the area $\rho P_e = L_{T\,BS}$ of this vicinity created by EMR of these BS.
- Under the condition that $H_{OP} << H_{BS}$ the EMS on a human body in observation point does not depend on BS antennas heights; under this condition the relation (13) is true also for cases, when e.i.r.p. and antenna heights of separate BS are essentially unequal.

If K radio networks of the same frequency range (λ=const) are deployed in considered territory, and generally these networks are of various standards and generations, and appropriately of essentially various e.i.r.p. P_{ek} and spatial densities ρ_k, k=1, … , K of BS, and also of various heights of BS antennas and sizes of a free-space RWP vicinities round the observation point, then on condition that elevation of an observation point is much less than BS antenna heights, the total EMS in this point formed at the expense of free-space RWP between BS and observation point, will be defined by a following relations:

$$\Pi_{\Sigma 1_\Sigma} = \sum_{k=1}^{K} \Pi_{\Sigma 1k} = \frac{L_{TBS\Sigma}}{2} \ln\left(\frac{4H_{OP}}{\lambda}\right), \tag{14}$$

$$L_{TBS\Sigma} = \sum_{k=1}^{K} \rho_k P_{ek} = \sum_{k=1}^{K} L_{TBSk}\ ; \tag{15}$$

here $L_{T\,BS\,k}$ is the EML on territory created by all BS of the 1st group of k-th radio network on considered area, $L_{T\,BS\,\Sigma}$ is the total EML on this area created by BS of the 1st group of all K radio networks.

For the case of different frequency ranges ($\lambda\neq$const) the relation (14) become more complex: it become a weighted sum of the total EML created by BS of the 1st group of each radio network:

$$\Pi_{\Sigma 1_\Sigma} = \sum_{k=1}^{K} \Pi_{\Sigma 1k} = \frac{1}{2} \sum_{k=1}^{K} L_{TBSk} \ln\left(\frac{4H_{OP}}{\lambda_k}\right), \tag{16}$$

B. *The total EMF intensity from the BS of the 2nd group*

The total average EMF intensity $\Pi_{\Sigma 2}$ from the BS of the 2nd group allocated in a zone of multipath RWP between BS and observation point can be defined evidently as scalar product of average quantity (12) of BS in this zone and average (10) of probability distribution (9) of an EMF power flux density in observation point from BS of this group:

$$\Pi_{\Sigma 2} = N_{AV2} m_1(\Pi) = \frac{\rho P_e}{4} = \frac{L_{TBS}}{4} \tag{17}$$

This relation as well as the relation (13) would be of very great importance: it establishes the simple direct dependence between EMS on a human body (1)-(3) in the observation point as a result of the EML (4.1), (4.2) on area out of free-space RWP vicinity of this point, created by distant BS of the 2nd group.

Under the conditions of uniform terrestrial distribution of BS with average density ρ in annular vicinity $R_{BP} < R < mR_{BP}$, m>>1, and $H_{OP} << H_{BS}$ the most important features of (16) are the same as the features of (13):

- The EMS on a human body in observation point formed by EMF of BS of the 2nd group is also defined generally by the EML out of the "breakpoint" vicinity on the area of the multipath RWP to this point.
- The EMS on a human body in observation point does not depend on BS antennas heights and frequency range.
- The relation (16) is true also for cases, when e.i.r.p., antenna heights and EMR frequencies of separate BS are essentially unequal.

Under the generalized conditions accepted at reception of the relation (14), additionally expanded on a case of different frequency ranges of considered radio networks ($\lambda\neq$const), the total EMS in an observation point formed at the expense of multipath RWP between BS and observation point, will be defined by a following relation:

$$\Pi_{\Sigma 2_\Sigma} = \sum_{k=1}^{K} \Pi_{\Sigma 2k} = \frac{L_{TBS\Sigma}}{4} \tag{18}$$

C. *The total average intensity of EMB created by BS*

The total average intensity Π_Σ of EMB created by BS of both groups in observation point located near ground surface, under the condition of uniform terrestrial distribution of BS with average density ρ and $H_{OP} << H_{BS}$ can be estimated using (13)-(18). For BS of the same frequency range (λ=const)

$$\Pi_\Sigma = \Pi_{\Sigma 1} + \Pi_{\Sigma 2} = \frac{L_{TBS}}{2}\left(\ln\left(\frac{4H_{OP}}{\lambda}\right) + \frac{1}{2}\right) = \\ = \frac{L_{TBS}}{2} \ln\left(\frac{4\sqrt{e}H_{OP}}{\lambda}\right) \approx \frac{L_{TBS}}{2} \ln\left(\frac{6.6 \cdot H_{OP}}{\lambda}\right); \tag{19}$$

for BS of the different networks and frequency ranges ($\lambda\neq$const)

$$\Pi_{\Sigma_\Sigma} = \Pi_{\Sigma 1_\Sigma} + \Pi_{\Sigma 2_\Sigma} = \\ = \frac{1}{2} \sum_{k=1}^{K} L_{TBSk} \ln\left(\frac{4H_{OP}}{\lambda_k}\right) + \frac{L_{TBS\Sigma}}{4}\ . \tag{20}$$

V. PRACTICAL APPLICATIONS

A. *Proportion Between EMB Components*

Relations (13) - (20) indicate that EMB in observation point near ground surface is formed substantially by the EMR of BS of the 1st group from the free-space RWP zone. Values of ratio $\Pi_{\Sigma1} / \Pi_{\Sigma2}$ received for H_{OP}=2m accepted in some countries for estimation of electromagnetic safety of the population and for H_{OP}=5m corresponding to height of a window aperture of the second floor of a residential building are given below in Table.

TABLE I. VALUES OF RATIO $\Pi_{\Sigma1} / \Pi_{\Sigma2}$ FOR DIFFERENT H_{OP}

Frequency Range, MHz	**Standard of CC**	**$\Pi_{\Sigma1} / \Pi_{\Sigma2}$**	
		H_{OP}=2m	*H_{OP}=5m*
450	GSM-450, TETRA, APCO-25, IMT-MC (CDMA-450)	5.0	6.8
900	GSM-900	6.4	8.2
1800	GSM-1800	7.7	9.5
2000	UMTS	8.0	9.8
2600	LTE	8.5	10.3

B. Permissible EML on Territory Created by BS CC

Using (13)-(20) it is possible to find potential limitations on EML on territory created by BS of CC implied by requirements of ecology and electromagnetic safety of the population. Taking into consideration different values of maximum permissible level of EMF power flux density Π_{MPL} accepted in different countries it is possible to define the following:

- The maximum permissible EML on territory created by radio networks of the same frequency range (λ=const):

$$L_{TBSmax} = \frac{2\Pi_{MPL}}{\ln(6.6 \cdot H_{OP}/\lambda)}. \tag{21}$$

- The maximum permissible terrestrial density ρ_{max} of BS for fixed Π_{MPL} and fixed e.i.r.p. P_e of BS of the given frequency range:

$$\rho_{max} = \frac{2\Pi_{MPL}}{P_e \ln(6.6 \cdot H_{OP}/\lambda)}. \tag{22}$$

- The maximum permissible e.i.r.p. $P_{e\,max}$ of BS for fixed Π_{MPL} and fixed terrestrial density ρ of BS of the given frequency range:

$$P_{emax} = \frac{2\Pi_{MPL}}{\rho \ln(6.6 \cdot H_{OP}/\lambda)}. \tag{23}$$

Relations (21) - (23) represent the worst-case limitations for an estimation of potentially dangerous levels of EML on territory created by BS CC, and also potentially dangerous levels of BS terrestrial density and e.i.r.p.

It is obvious, that the estimation (23) may be optimistic (overrated) because, as a rule, at BS location in urban area the absence of a sanitary-protective zone should be provided, i.e. at height $H_{OP} \le 2$ m over a surface the total EMB level should be not exceeding the Π_{MPL} (that is partially provided by a BS beam shape in a vertical plane.

Estimations of the maximum permissible EML on territory for GSM 900/1800 network at various Π_{MPL} levels accepted in various countries, regions and time, are given below in Table II. These estimations are received using (20), (21) and taking into account the ratio of three to one between the amount of GSM-1800 and GSM 900 frequency channels [15]: it is accepted that 25 % EMB are created by GSM-900, and 75 % EMB are created by GSM-1800.

TABLE II. VALUES OF $L_{TBS\,MAX}$ FOR DIFFERENT Π_{MPL} AND H_{OP}

Π_{MPL}, **W/m^2**	**Range of Application**	**$L_{TBS\,max}$, W/m^2 (kw/km^2)**	
		H_{OP}=2m	*H_{OP}=5m*
0.001	Recommended [2] as preliminary preventive MPL value for “total general electromagnetic irradiations from all high-frequency equipment with very low pulse modulation”	0.00048 (0.48)	0.00039 (0.39)
0.01	Recommended by [3] as qualified top border of EMB intensity safe for the population. Corresponds to Π_{MPL} for the population earlier accepted in USSR [11]	0.0048 (4.8)	0.0039 (3.9)
0.02	MPL accepted in Moscow for UHF systems [16]	0.0096 (9.6)	0.0078 (7.8)
0.025	MPL accepted in Ukraine [12]	0.012 (12.0)	0.0098 (9.8)
0.024 / 0.095	0.024 W/m^2 (GSM-900) and 0.095 W/m^2 (GSM-1800) accepted in Paris (cited in [2])	0.036 (36.0)	0.0295 (29.5)
0.042 / 0.095	0.042 W/m^2 (GSM-900) and 0.095 W/m^2 (GSM-1800) accepted in Switzerland (cited in [2])	0.038 (38.0)	0.0315 (31.5)
0.1	MPL accepted in Russia and Belarus [13,14]; it is also close to MPL levels accepted in some European countries and regions [2].	0.048 (48.0)	0.039 (39.0)

An estimations resulted above are harmonized with known data concerned an actual EML on urban areas [17]. Particularly the average EML on territory created by BS of 2G/3G CC on urban areas in Belarus, Russia and some other countries come up to 0.015…0.02 W/m^2 (15…20 kW/km^2) for ρ = 5…10 BS/km^2, P_e = 1.5…2.5 kW. This level of average EML on territory created by infrastructure of CC is acceptable for majority of countries and regions, but rather dangerous according to [11,12]. And it also may be dangerous for populous regions where EML on territory created by other EMF sources of different radio services (fixed and mobile) is commensurable or exceed the EML created by BS of CC.

EML on territory and EMB created by BS of CC may be decreased at the expense of high-quality frequency planning and optimization of an infrastructure of networks, considerable reduction of the site’s sizes and wide use of mini / micro BS.

C. Probability to get into a restricted space for building

In respect to modern cities characterized by intensive industrial, office and residential high-rise construction activity on all territory of urban areas, it is of interest to estimate the probability of event that arbitrarily chosen point of ground surface can get into a restricted space with inadmissible level of EMB created by BS CC. This estimation can be executed with use of models resulted above.

At free-space RWP the radius R_{RA} and the area S_{RA} of the restricted space around BS with e.i.r.p. P_e of circular EMR is defined by an obvious relations:

$$R_{RA} = \sqrt{\frac{P_e}{4\pi\Pi_{MPL}}}, \quad S_{RA} = \pi R_{RA}^2 = \frac{P_e}{4\Pi_{MPL}}.$$

It is necessary to expect, that

- restricted spaces of separate BS are not crossed in connection with the tendency to regularization of network spatial structure;
- area of restricted space is much less (10 times and more) then the BS site area.

Therefore probability V_{RA} of that randomly chosen point of urban area gets under the restricted space of nearest BS, can be defined as a relative part of the BS area of service (site area) of CC network coinciding with area of BS restricted space of this network:

$$V_{RA} \approx \rho S_{RA} = \frac{\rho P_e}{4\Pi_{MPL}} = \frac{L_{TBS}}{4\Pi_{MPL}} . \qquad (24)$$

Thus, this probability characterizing potential ecological risks of construction activity in modern urban area, is defined generally by the ratio of total EML on urban area created by BS CC and accepted value of EMF maximum permissible level.

VI. CONCLUSION

In the given paper the concept of EML on territory as an integrated system characteristic of REE in considered area of space is proposed, and original worst-case models for estimation of EMB near ground surface which illustrate the direct coupling between the total average EMB level and the level of EML on territory created by BS are offered.

The main advantages and novelty of results presented above are in following:

- They allow to perform a direct and comparative quantitative estimation of the contribution in total EMB near ground surface of BS from the zone of free-space RWP to the observation point and of BS from the zone of multipath RWP to this point, and testify that BS of the 1st group make a prevailing contribution in EMB formation.
- They point that EMS on a human body in observation point near ground surface substantially specified by the EML level on considered area. EMB level near surface practically does not depend on BS antennas heights and relatively weakly depend on CC frequency range.
- They allow to specify potential limitations on EML on territory created by BS of CC, and also to estimate potential limitations on BS e.i.r.p. or BS average terrestrial density in urban areas implied by requirements of ecology and electromagnetic safety of the population.
- They testify that relations (13)-(15), (17)-(19), (21), (24) are true also for cases, when $^{I)}$e.i.r.p. and antenna heights of separate BS are essentially unequal, and $^{II)}$when fixed EMF sources are transmitters of other radio services. These circumstances additionally confirm the large value of EML on territory as an integrated system parameter of REE electromagnetic ecology and safety which generally determine the EMB level in human environment.
- The worst-case models of EMB created by the radiation of BS CC given above can be of interest for designing sensor networks for monitoring of electromagnetic pollution of the human environment.

VII. ABBREVIATIONS

EMR – electromagnetic radiation of radio transmitter.
EMF – electromagnetic field.
EMB – total electromagnetic background in observation point.
EMS – electromagnetic stress (on human, on population, etc.).
EML – electromagnetic loading
EME – electromagnetic environment
e.i.r.p. – equivalent isotropic radiated power
REE – radioelectronic environment
RWP – radiowave propagation
BS – base station of cellular communications (CC)

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