Worst-Case Estimation of Electromagnetic Background Near Ground Surface Created by Heterogeneous Radioelectronic Environment

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Abstract— **The practical method of worst-case estimation of the total electromagnetic background near ground surface created by different radio systems is offered. This method takes into consideration heterogeneity of radioelectronic environment formed by the full set of stationary and mobile transmitters of different radio services, and peculiarities of radio wave propagation on different distances between transmitters and observation point, and of statistical features of electromagnetic fields in observation point generated by these transmitters. The presented method allow to estimate the fundamental upper bound of electromagnetic background total intensity created by heterogeneous radioelectronic environment, directly on the basis of estimation of the total electromagnetic loading on territory as the total equivalent isotropic radiated power of full set of transmitters of all services falling to the unit of the area of considered territory. The presented results ensure the facilities of EMC diagnostics and design of ultra wide band radio systems using nonsine radio waves, and cognitive radio systems using frequency bands on the secondary basis, and of support of the acceptable electromagnetic environmental conditions in populous areas.**

Keywords—electromagnetic background, electromagnetic loading, heterogeneous radioelectronic environment, cognitive radio, EMC diagnostics, cellular communications.

I. Abbreviations

CDF – cumulative distribution function.
EMB – total electromagnetic background in observation point.
EME – electromagnetic environment.
EMF – electromagnetic field.
EML – electromagnetic loading (on territory).
EMR – electromagnetic radiation of radio transmitter.
EIRP – equivalent isotropic radiated power.
MPL – maximum permissible level.
MTR – mobile transmitter.
OP – observation point.
PDF – probability density function.
PFD – power flux density of EMF.
REE – radioelectronic environment.
RWP – radiowave propagation.
STR – stationary transmitter

II. Introduction

Urban and suburban areas are covered by a great number of different radio services (communication, broadcasting, etc.) [1]. Electromagnetic fields (EMF) radiated by the full set of stationary (STR) and mobile (MTR) transmitters of ground radio systems and networks of these services is a major reason of electromagnetic background (EMB) in places with high population density. EMB created by this equipment may be a reason of EMC problems and harmful interference for wideband and ultra wideband (UWB) wireless sensor networks and cognitive radio systems which are using frequency bands “on a secondary basis” [2]. And also this EMB may be dangerous for population as an electromagnetic stress for people – this EMB impairs electromagnetic ecology of human environment and electromagnetic safety of population [3,4].

Direct calculation of the total EMB intensity near ground surface, as a rule, is an extremely intricate problem connected with calculation of the full set of EMF levels in the observation point (OP) generated by all transmitters located, at least, in a zone of OP radio visibility. Expected uncertainty of MTRs spatial allocation and parameters of electromagnetic radiation (EMR), and also of radio wave propagation (RWP) losses in most cases make these estimations unrealizable.

In [5,6] the concept of an electromagnetic loading (EML) on territory as the total equivalent isotropic radiated power (EIRP) of transmitters set falling to the unit of the area of considered territory, is introduced. EML is the integrated system characteristic defining electromagnetic safety of radioelectronic environment (REE) formed by the full set of radio transmitters allocated on the territory, for operating of radio systems and for people health. Results of [5,6] allow to estimate the fundamental upper bound of EMB total intensity created by homogeneous narrowband REE formed by the set of terrestrially distributed uniform transmitters with undirected EMR, on the basis of calculation of the total EML in the vicinity of OP. But these results are inapplicable directly for complex heterogeneous REE formed by the set of STR (with undirected and directed EMR) and MTR of different radio services and frequency bands, randomly distributed in OP vicinity.

The aim of this paper is to propose on the base of [5,6] the novel applied method of worst-case estimation of the near-ground EMB total intensity created by the full set of STR and MTR of different types, frequency bands and radio services, distributed in the vicinity of OP, acceptable for EMC diagnostics and design of UWB and cognitive radio systems, and for

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proximate analysis of electromagnetic environmental conditions in populous areas.

III. Initial Models and Relations

A. EML on Territory

EML on territory L_T created by EMR of terrestrially distributed transmitters with the average EIRP P_e and average terrestrial density ρ, is defined in [5,6] as follows:

$$L_T = P_e \rho , \text{ [W/m}^2\text{]}. \quad (1)$$

B. Model of EMF sources Random Terrestrial Distribution

Random terrestrial distribution of transmitters of M types traditionally is described by the known Poisson model of surface distribution of point objects:

$$p_k(N_{\Delta S\, m}) = \left(N^k_{\Delta S\, m} \exp(-N_{\Delta S\, m})\right)\Big/ k!, \quad (2)$$
$$N_{\Delta S\, m} = \rho_m \cdot \Delta S, \quad m = 1,2...,M ,$$

where $p_k(N_{\Delta S\, m})$ is a probability that exactly k point objects (transmitters) of m-th type are allocated in area ΔS, if average number of these objects in this area is $N_{\Delta S\, m}$.; ρ_m is an average density of area distribution of the objects of this type. In addition we will consider that antennas of transmitters of considered m-th type are elevated at the height H_m over a surface.

C. Worst-Case Model of RWP conditions

It is appropriate to use the pessimistic or the worst-case model of RWP conditions at worst-case estimation of EMB intensity. Bounding to take into consideration only RWP line-of-site situations within street canyons in the VHF and UHF frequency range, basic RWP losses can be characterized by the well-known "breakpoint" RWP model [7].

This model have a following important features: on small distance R between transmitter and OP the conditions of RWP are equal to free-space RWP: the EMF power flux density (PFD) Π [W/m^2] decreases in inverse proportion to a square of distance R. Since some distance R_{BP} ("breakpoint" distance) between OP and transmitters RWP conditions are changes: the envelope of PFD distance dependence decreases in inverse proportion to the fourth degree of distance R.

Distance R_{BPm} between transmitter of m-th type and OP allocated near ground surface on which changes of RWP conditions occurs, depends on a wavelength λ_m of transmitter's EMR and antenna height H_m , and height H_{OP} of OP over a surface:

$$R_{BPm} = 4 H_m H_{OP} / \lambda_m . \quad (3)$$

Consequently the worst-case model of RWP conditions (as an envelope of values of real RWP losses) between transmitter of m-th type and OP on distance R can be represented as

$$\Pi_m = P_{em} \Big/ 4\pi R^2 , \quad R \le R_{BPm} , \quad (4)$$

$$\Pi_m = \mathrm{R}^2_{\mathrm{BPm}} P_{em} \Big/ \left(4\pi R^4\right), \quad R \ge R_{BPm} , \quad (5)$$

where P_{em} is a EIRP of transmitters of m-th type.

This model, as a rule, gives the underestimated propagation losses at multipath RWP in urban area [7] and therefore provides the worst-case character of estimation procedure for EMB created by REE of urban and suburban areas.

D. Model of Heterogeneous REE

All cases of the mutual placement of OP in relation to transmitters of each type can be divided into following groups:

1) The first group of J cases for which height H_j of antennas of transmitters of each j-th type over a surface is relatively large: $H_j >> H_{OP}$, $j = [1, \ldots , J]$ (base stations of cellular communications, access points of WiMAX and Wi-Fi, broadcasting transmitters, etc.);

2) The second group of K cases, for which the random distribution of transmitters of each k-th type over a surface is close to H_{OP}: $H_k \approx H_{OP}$, $k = [1, \ldots , K]$, $J+K=M$; transmitters of this group are different MTRs: user's stations of mobile communications (cellular, trunking, etc.). For this group the total EMF intensity created in OP by transmitters of k-th type can be divided on following components [6]:

a) EMF generated by the nearest transmitter of k-th type allocated in the "breakpoint" vicinity of OP; intensity Π_k of this EMF in OP is random and essentially prevailing over the EMF intensity created by other transmitters of this type allocated in an OP vicinity of radius R_{BPk}.

b) The total intensity Π_{BGk1} of EMFs created by all other transmitters of k-th type allocated in the "breakpoint" vicinity of OP, which can be considered as quasistationary in relation to the first component.

c) The total intensity Π_{BGk2} of EMFs created by all other transmitters of k-th type allocated out of the "breakpoint" vicinity of OP, which can be considered as stationary in relation to the first and second components.

Let's suppose that heterogeneity of REE in considered territory is defined by the following:

1) By heterogeneity of STR set located here (the first group of J cases considered above in cl. *A*), i.e. by presence in considered territory STRs of many types (base stations of GSM, CDMA, UMTS, LTE, TETRA, APCO25, Wi-MAX; MMDS, etc.; broadcasting transmitters etc.).

2) By heterogeneity of the MTR set distributed on considered territory (the second group of K cases considered above in item *B*), i.e. by presence of MTRs of many types (mobile phones of cellular and trunking systems, modems of wireless broad-band access, manpack and mobile VHF and UHF radio stations of police, utility, emergency, fire prevention service, security services, etc.

3) By heterogeneity of EIRP of STRs and MTRs with respect to OP, including EIRP randomness owing to randomness of fixed orientation of directed EMR of STRs of several groups (Wi-MAX users terminals, radio relay stations, etc.).

4) By heterogeneity of power criteria of electromagnetic safety and EMC for transmitters of various groups and frequency ranges (the accepted values of maximum permissible levels (MPL) of EMF), caused by essential distinctions in gravity of EMR of various systems (pulse or continuous, fixed or variable direction, etc.). In particular, in cases, when REE is formed by several groups of transmitters for which various values of MPL of EMF are accepted, electromagnetic safety is characterized by the total relative intensity X of EMF in OP [8,9]:

$$X = \sum_{i=1}^{I} \Pi_{\Sigma i} / \Pi_{MPLi} \ , \qquad (6)$$

where $\Pi_{\Sigma i}$ – the total EMF intensity in OP created by transmitters of *i*-th group, for which the MPL Π_{MPLi} is accepted.

E. Models of EMB Components

1) For transmitters of the *j*-th type, related to the first group in Item III *D* above, it is specified the following [5]:

a) For transmitters allocated on free-space RWP distances, the average EMB intensity $\Pi_{\Sigma 1j}$ created by these transmitters in OP at height H_{OP} practically independent of their antennas heights $H_j \gg H_{OP}$ over a ground surface and is defined by EML on territory L_{Tj} formed by these transmitters:

$$\Pi_{\Sigma 1j} = \left(\rho_j P_{ej}/2\right) \ln\left(4H_{OP}/\lambda_j\right), \quad \rho_j P_{ej} = L_{Tj} \,. \qquad (7)$$

where ρ_j, P_{ej} and λ_j are terrestrial density, EIRP and EMR wavelength of transmitters of the *j*-th type correspondingly.

b) For transmitters allocated outside the free-space RWP distances the average EMB intensity $\Pi_{\Sigma 2j}$ created by these transmitters in OP at height H_{OP} is frequency independent and also practically independent of their antennas heights $H_j \gg H_{OP}$ over a ground surface, and is defined only by EML on territory L_{Tj} formed by these transmitters:

$$\Pi_{\Sigma 2j} = L_{Tj}/4 \,. \qquad (8)$$

2) For transmitters of the *k*-th type, related to the second group in Item III *D* above, it is specified the following [6]:

a) The EMB intensity produced both by all MTRs of the *k* -th type as from R_{BPk} - vicinity of OP randomly allocated on the surface, and from area outside this vicinity, except the EMF of transmitter of *k* -th type nearest to the OP, is defined by equations:

$$\Pi_{BGk} = \frac{L_{Tk}\left(Z_k+1\right)}{4}, Z_k = \sum_{H=2}^{\mathrm{int}\{N_{Ak}\}} \frac{1}{H-1}, N_{Ak} = \pi \rho_k R_{BPk}^2 \qquad (9)$$

where $int\{N_{Ak}\}$ means an integer part of average number N_{Ak} of transmitters of *k*-th type in R_{BPk} vicinity of OP; $L_{Tk}=\rho_k P_{ek}$ is EML on territory formed by these MTRs.

b) For small tolerance probability *p* of event that PFD created in OP by the nearest MTR of the *k* -th type, will exceed the level $\Pi_{BG\,kn}$, this level depends only on EML on area created by MTRs of this type and do not depend on EMRs wavelength:

$$\Pi_{BGkn} \approx L_{Tk}/4p, \quad p \le 0.1, \quad k = 1,...,K \,. \qquad (10)$$

So, the EMB intensity in OP created by MTRs of the certain *k* -th type allocated in its zone of radio visibility is a sum of quasistationary component (9) and of stochastic component specified by (10). Therefore the total EMB intensity $\Pi_{BG\Sigma k}$ created by MTRs of the *k* -th type depends both on EML on territory L_{Tk} created by these MTRs and on tolerance probability *p*:

$$\Pi_{BG\Sigma k}(p) = \Pi_{BGk} + \Pi_{BGkn} \approx \frac{L_{Tk}}{4}\left(Z + 1 + \frac{1}{p}\right), \; p \le 0.1 \,. \qquad (11)$$

For small levels of tolerance probability and also for random EIRP of MTRs of the *k* -th type (cellular phones with EIRP adjustment, etc.) subject to $Z \le 10$

$$\Pi_{BG\Sigma k}(p) \approx \Pi_{BGkn} \approx \frac{L_{Tk}}{4p} = \frac{m_1(P_{ek})\rho_k}{4p}, \quad p \le 0.01 \,, \qquad (12)$$

where $m_1(P_{ek})$ is assembly average of P_{ek} . Expressions (9), (11) are frequency dependent owing R_{BP} frequency dependence, but with reduction of tolerance probability this dependence become weaker and can be neglected (as in (12)).

IV. Intensity of EMB component created by STRs of the 1st group with nondirectional EMR

Taking into consideration (7), the total average EMB intensity $\Pi_{\Sigma 1J}$ created in OP by transmitters of all *J* types of the 1st group selected above in Item III *D* and allocated in free-space RWP distances, is defined by weighed sum L_{TJW} of EML on territory formed by STRs of these types:

$$\Pi_{\Sigma 1J} = \sum_{j=1}^{J} \Pi_{\Sigma 1j} = L_{TJW}/2, \quad L_{TJW} = \sum_{j=1}^{J} L_{Tj} C_{\lambda j},$$

$$L_{Tj} = \rho_j P_{ej}, \quad C_{\lambda j} = \ln\left(4H_{OP}/\lambda_j\right). \qquad (13)$$

Contribution of STRs of each type in total EMB intensity is frequency-dependent. Values of weights $C_{\lambda j}$ for STRs of some frequency ranges and services, defined for the centre of each frequency range and different H_{OP}, are given in Table 1.

TABLE I. Weighting Factors for Different Services, Systems and Frequency Ranges

Freq. range, MHz	**Service (system, standard)**	**$C_{\lambda j}$ for H_{OP} [m]**		
		1m	***1,5m***	***2m***
146-174	Mobile (APCO-25)	0,76	1,16	1,45
380-470	Mobile (TETRA, APCO-25, MPT-1327, CDMA-450, GSM-450)	1,73	2,14	2,43
470-550	Broadcasting (DVB-T, 21-30 TVC))	1,92	2,32	2,61
550-630	Broadcasting (DVB-T, 31-40 TVC))	2,06	2,49	2,76
630-710	Broadcasting (DVB-T, 41-50 TVC))	2,19	2,60	2,88
710-790	Broadcasting (DVB-T, 51-60 TVC))	2,30	2,71	3,00
935-960	Mobile (GSM-900)	2,54	2,94	3,23
1805-2170	Mobile (GSM-1800, UMTS)	3,28	3,68	3,97
2400-2483,5	Fixed (WiMAX)	3,48	3,89	4,18
2483,5-2690	Fixed, Mobile (LTE, MMDS)	3,54	3,95	4,23

Taking into consideration (8), the total average EMB intensity $\Pi_{\Sigma 1J}$ created in OP by transmitters of all *J* types of the 1st group selected above in Item III *D* and allocated outside the free-space RWP distances, is frequency-independent and defined only by the total EML on territory L_{TJ} formed by STRs of all *J* types:

$$\Pi_{\Sigma 2J} = \sum_{j=1}^{J} L_{Tj}/4 = L_{TJ}/4, \quad L_{TJ} = \sum_{j=1}^{J} L_{Tj}\,. \qquad (14)$$

Sum of (13) and (14) come to the full total average EMB intensity produced in OP by transmitters of all J types which is defined by the EML on territory formed by these transmitters:

$$\Pi_{\Sigma 1J} = \Pi_{\Sigma 1J} + \Pi_{\Sigma 2J} = L_{TJW}/2 + L_{TJ}/4, \qquad (15)$$

$$L_{TJ} = \sum_{j=1}^{J} L_{Tj} \quad L_{TJW} = \sum_{j=1}^{J} L_{Tj} C_{\lambda j}\,.$$

At increase of H_{OP} over a ground surface the contribution of EMB component (14) decreases, and at $H_{OP} \geq 10\lambda_j$, $j = 1, \ldots, J$ it can be neglected.

V. Total Intensity of EMB component created by transmitters of the 2nd group with undirected EMR

Cumulative quasistationary EMB component, formed by transmitters of K types of 2nd group, can be found by direct summation of components (9), each of that is frequency-dependent owing to the frequency dependence of R_{BPk}:

$$\Pi_{BGK} = \sum_{k=1}^{K} \Pi_{BGk} = \frac{1}{4}\sum_{k=1}^{K} L_{Tk}\left(Z_k + 1\right). \qquad (16)$$

As to stochastic components (10), their basic peculiarity is that these components depend not on individual EMR characteristics of the nearest transmitters, but on the integral REE characteristics – EML on territory produced by transmitters of each type in OP vicinity. As a result the tolerance probability p that some level $\Pi_{\Sigma K}$ of cumulative intensity of stochastic EMB component created by transmitters of K types of 2nd group will be exceed, is defined by the total EML on territory $L_{\Sigma TK}$, created by transmitters of this group, allocated in OP vicinity:

$$p \approx L_{\Sigma TK} / \left(4\left(\Pi_{\Sigma K} - \Pi_{BGK}\right)\right) \leq 0.1, \quad L_{\Sigma TK} = \sum_{k=1}^{K} L_{Tk}\,. \qquad (17)$$

At high EMB protection requirements regarded the EMB created by transmitters of 2nd group, the contribution of frequency-dependent components (9) and quasistationary EMB component (16) weakens, and the level of total EMB $\Pi_{BG\Sigma K}$ created by transmitters of 2nd group, expected with probability no more then p, is defined by a following expression:

$$\Pi_{BG\Sigma K}(p) \approx \frac{L_{\Sigma TK}}{4p}, \quad p \leq 0.01\,. \qquad (18)$$

In conclusion it is necessary to underline that transmitters of the considered group are all MTRs - subscriber's radio stations of mobile services (phones of cellular communication, radio stations of business telecommunication, date transmission modems, etc.), and all STRs with small antenna heights, comparable with H_{OP}. Randomness of mutual allocation of transmitters and OPs is caused both by random distribution of transmitters on territory, and by random coordinates of OPs. Last allows to use the stated approach also in cases when in area distribution of transmitters of any separate types (attributed to the 2nd group) features of regularity are watched, and adequacy of Poisson model (2) for transmitters of these separate types give rise to doubt.

VI. Total Intensity of stochastic EMB component created by MTRs with random EIRP

Cumulative distribution function (CDF) $P(\Pi k)$ for probability of PFD Π_k created at free RWP conditions (4) by the nearest transmitter from the set of transmitters of k-th type (2nd group) which are randomly uniformly distributed on territory with fixed EIRP P_{ek} and average density ρ_k according to (2), is following [6]:

$$P(\Pi_k) = \Gamma\left(1, \rho_k P_{ek} / (4\Pi_k)\right) = \exp\left(-\rho_k P_{ek} / (4\Pi_k)\right). \qquad (19)$$

If EIRP of transmitters of k-th type of the 2nd group considered above is random with probability density function $w(P_{ek})$, it is possible to consider all ensemble of transmitters of this type in the form of a composition of set G subgroups of transmitters. In this composition each g-th subgroup (g = 1, …, G) is characterized by EIRP P_{ekg} in a direction on an OP and a terrestrial density $\rho_{kg} = \rho_k w(P_{ekg}) dP_{ek}$. In this case the probability of nonexceeding the level Π_k of EMB intensity produced by transmitters of all g subgroups will be equal to the product of probabilities

$$P(\Pi_k) = \lim_{G\to\infty}\left(\prod_{g=1}^{G} \exp\left(-\frac{\rho_{kg} P_{ekg}}{4\Pi_k}\right)\right) =$$

$$= \exp\left(-L_{TAk} / (4\Pi_k)\right), \quad L_{TAk} = \rho_k m_1(P_{ek}), \qquad (20)$$

where $m_1(P_{ek})$ is assembly average of EIRP P_{ek}, L_{TAk} is an averaged EML on territory produced by transmitters of the k-th type with random EIRP.

It is similarly easy to prove that at presence in OP vicinity of all K types of transmitters of group of similar cases (height of antennas over a surface is close to height of an OP, values of EIRP P_{ek} are random, area distribution of transmitters of each type is uniform and random with average density ρ_k and can be described by model (2)), the probability of nonexceeding the level Π_K of EMB intensity produced by transmitters of all K types will be equal to the following:

$$P(\Pi_K) = \exp\left(-\frac{L_{TAK}}{4\Pi_K}\right), \qquad (21)$$

$$L_{TAK} = \sum_{k=1}^{K} \rho_k m_1(P_{ek}) = \sum_{k=1}^{K} L_{TAk}\,,$$

where L_{TAK} is an averaged EML on territory produced by transmitters of all K types with random EIRP.

Expressions (19)-(21) testify that outcomes of [6], concerning definition of permissible level of EML on territory created by EMR of MTRs of cellular communications for which the probability of excess in a considered OP by EMF intensity of the nearest MTR of prescribed level Π_{max} will not exceed value P, can be applied to a case of heterogeneous

REE for which the random allocation of K types of transmitters of the 2nd group in OP vicinity is representative. The maximum permissible level of EML on territory L_{TAKmax} created by transmitters of all K types, exceeded with probability p, will be defined by the following relations:

$$L_{\max TAK\max} \approx 4p\Pi_{\max},\ p \le 0.01;\quad \Pi_{\max} = \Pi_{MPL} - \Pi_{BG}, \tag{22}$$

where Π_{MPL} is the maximum permissible level of EMF intensity in OP, Π_{BG} is the total intensity of fixed EMB presented in OP.

Randomness of EIRP of EMF sources can be defined by the various reasons: usage of forced EIRP adjustment of MTRs in cellular network, random directivity of STRs with directional EMR, etc. Thus, the results given above allow to calculate the contribution of the set of spatially distributed transmitters with directional EMRs in EMB using (21),(22).

VII. Estimation of relative EMB intensity at heterogeneity of power criteria of electromagnetic safety and EMC for transmitters of various groups

Variants of estimation of the total relative intensity X of EMB in OP, in view of a rule (6) are considered below.

1) For the stationary transmitters with nondirectional antennas lifted over the earth surface (transmitters of J types of the 1st group considered above), if for this group the M values of MPL Π_{MPL1}, Π_{MPL2}, …, $\Pi_{MPL\,M}$ are accepted, the ratio (15) will be transformed to a following type:

$$X_{\Sigma 1J} = X_{\Sigma 1J} + X_{\Sigma 2J} = \sum_{\mu=1}^{M}\left(\frac{L_{TJW\,\mu}}{2\Pi_{MPL\,\mu}} + \frac{L_{TJ\,\mu}}{4\Pi_{MPL\,\mu}}\right), \tag{23}$$

$$L_{TJW\,\mu} = \sum_{j=J_{\mu-1}}^{J_\mu} L_{Tj}C_{\lambda j},\ L_{TJ\,\mu} = \sum_{j=J_{\mu-1}}^{J_\mu} L_{Tj};\ J_0 = 1;\ J = \sum_{\mu=1}^{M} J_\mu,$$

where J_μ - number of types of transmitters in μ–th subgroup of the given group, for which the EMB MPL value $\Pi_{MPL\,\mu}$ is accepted; $L_{TJW\,\mu}$, $L_{TJ\,\mu}$ - the "weighed" and the "absolute" total EML on territory formed by transmitters of μ-th group correspondingly, $X_{\Sigma 1J}$, $X_{\Sigma 2J}$ – the total relative EMB intensity in OP produced by transmitters of all J types, allocated in a zone of free-space RWP and outside this zone correspondingly.

2) For transmitters near earth surface with nondirected EMR (transmitters of K types of the 2nd group considered above), if for this groups K values of MPL Π_{MPL1}, Π_{MPL2}, …, $\Pi_{MPL\,K}$ are accepted, the ratio (16) defining the total EMB intensity, formed by cumulative EMR of transmitters of all K types of this group, except the prevailing EMF of this group in OP, will be transformed to a following type:

$$X_{BGK} = \sum_{k=1}^{K}\frac{\Pi_{BGk}}{\Pi_{MPLk}} = \frac{1}{4}\sum_{k=1}^{K}\frac{L_{Tk}}{\Pi_{MPLk}}\left(Z_k + 1\right). \tag{24}$$

3) Similarly the relative intensity of EMF prevailing in OP and radiated by one of the nearest transmitters of k-th type, will be defined by level of tolerance probability p and "weighed" total EML on territory, created by transmitters of all K types:

$$X_{\Pr K} = \frac{-1}{4\ln(1-p)}\sum_{k=1}^{K}\frac{L_{Tk}}{\Pi_{MPLk}} \approx \frac{1}{4p}\sum_{k=1}^{K}\frac{L_{Tk}}{\Pi_{MPLk}},\ p \ll 1 \tag{25}$$

In particular, for UHF cellular communications with MPL of EMB 0.1 W/m^2, for tolerance probability p = 0,01 [10], we receive the simple expression connecting MPL of EML on territory $(L_{TCT})_{max}$ from cellular MTRs and MPL $(X_{MS})_{max}$ of the relative EMB intensity produced by these devices:

$$\left(L_{TCT}\right)_{\max} \approx 0{,}004\left(X_{MS}\right)_{\max}; \tag{26}$$

the $(X_{MS})_{max}$ value is determining subject to EMB in OP.

Total relative EMB intensity created by transmitters of J+K cases from 2 groups considered above, will be defined by summation of (23), (24) and (25):

$$X_\Sigma = X_{\Sigma 1J} + X_{BG\,K} + X_{\Pr K}. \tag{27}$$

VIII. Total Intensity of EMB created by STRs and MTRs of cellular communications

The terrestrial traffic density equal to terrestrial density ρ_e of "active" MTRs is a base characteristic of cellular communications in places with a high population density. Processing of this traffic by MTRs is performed with an average EIRP P_{em}. Each "active" MTR take up a communication channel with STR (base station), thus the average EIRP of STR traffic channel $P_{ceb} = \Delta_{PBA}P_{em}$ essentially exceeds the EIRP of MTR:

$$P_{ceb}[dBW] = P_{em}[dBW] + G_{Ab}[dB] - G_{Am}[dB] + D_{sb}[dB], \tag{28}$$

where G_{Ab} is STR antenna gain, G_{Am} is MTR antenna gain, D_{sb} is difference in EMR power of "downlink" и "uplink" connections necessary for cellular network operation.

As a rule, in cellular systems STR and MTR antenna gains differs on 12-16 dB, and difference $\Delta_{PBA} = G_{Ab}D_{sb}/G_{Am}$ [units] in average EIRP of STR traffic channel and MTR EIRP may be about 20 dB in 3G networks, and about 25 dB in GSM networks; in last cases STR's EIRP are constant, and MTR's EIRP are adjusted forcedly.

Using (7)-(12), we receive the total EMB intensity $\Pi_{\Sigma CC}$, created both by STRs and MTRs of cellular network:

$$\Pi_{\Sigma CC} = \Pi_{\Sigma B} + \Pi_{\Sigma M} \approx \frac{L_{TM}}{2}\left(\Delta_{PBA}\ln\left(\frac{6.6\cdot H_{OP}}{\lambda}\right) + \frac{1}{2p}\right) \tag{29}$$

Results of estimation of total EMB intensity $\Pi_{\Sigma CC}$ and its separate components for various levels of tolerance probability and terrestrial traffic density ρ_e, performed for GSM-1800 (P_{em} = 0.05 W, H_{OP} = 2 m, Δ_{PBA} = 100), are given on Figure 1.

On this figure five curves are calculated for ρ_e=0.002 MTR/m^2: the black horizontal line 1 corresponds to the level of quasistationary EMB component, the black line 2 corresponds to the level of stochastic EMB component calculated under the (8),(18); the green curve 3 corresponds to cumulative level of quasistationary and stochastic EMB components created by MTRs, calculated under (11); the well-matched red curve 4 and blue curve 5 corresponds to the total EMB intensity $\Pi_{\Sigma CC}$ calculated under the (29), and calculated under the (29) taking into account an improved level (9),(16) of a quasistationary EMB component, correspondingly (the difference between these curves become perceptible at smaller Δ_{PBA}). It is easy to be convinced that at estimations of the total EMB intensity created by cellular communications in whole, it is possible to neglect by the quasistationary component, formed by MTRs.

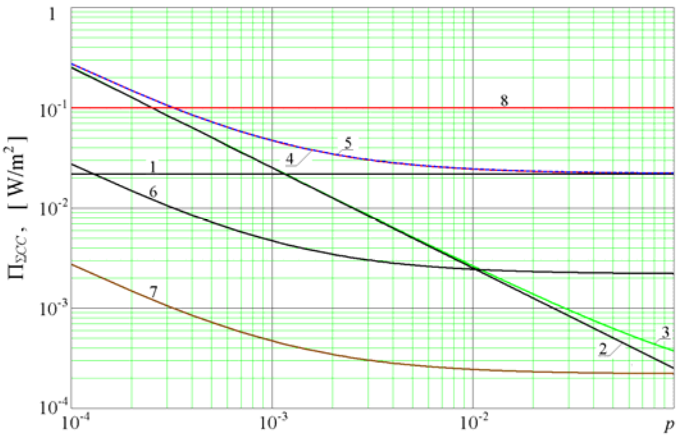

Fig. 1. Dependences of the total EMB intensity created by GSM-1800 radio equipment, on tolerance probability, for various ρ_e

The accepted value ρ_e=0.002 MTR/m^2 is a terrestrial density of MTRs in an active mode, at specific traffic intensity of busyhour E_T=0.04-0.05 Erl., it corresponds to terrestrial density of subscribers $\rho=\rho_e/E_T$ =2.0-2.5·10^4 1/km^2 in severe REE on areas with high population density (urban area with compact planning, speech service on urban pedestrian area [11]).

On Fig. 1 dependences of EMB total intensity for other ρ_e values are also resulted: the black curve 6 corresponds to ρ_e=0.0002 MTR/m^2 (urban vehicular according to [11]), the brown curve 7 corresponds to ρ_e=0.00002 MTR/m^2 (suburban area). The red horizontal line 8 corresponds to MPL 0.1 W/m^2 accepted in [8,9]. Curves 4-8 testify that at high area density of subscribers of cellular communications and at high population safety requirements (p=0.001 … 0.01), the excess of the accepted MPL of total EMF intensity by the total EMB intensity created by all set of radio equipment (STRs and MTRs) of cellular communications is quite probable, although EMF levels created by STRs (base stations) essentially less than MPL.

As a whole, results illustrated by curves on Fig. 1 are appropriate to the real levels of ecological risks in densely populated territories with the mass usage of cellular communications. Evaluations enclosed on Fig.1 (particularly curve 1 with $\Pi_{\Sigma B}$ = 0.022 W/m^2 for $\rho_e = 2\cdot10^{-3}$ MTR/m^2 and corresponding estimations $\Pi_{\Sigma B}$ = 0.0022 W/m^2 for $\rho_e = 2\cdot10^{-4}$ MTR/m^2 on urban area) are agreed with the results [12] of EMB measurements taking on 0.004 … 0.015 W/m^2 for comparable ρ_e values for urban area.

IX. Conclusion

The material resulted above illustrates in full the importance of EML on territory (1) as the REE major system parameter defining in the integral form its electromagnetic safety and EMC. Expressions resulted above allow to connect the total EMB intensity in OP with the total EML on territory created by all set of STRs and MTRs of various types, services and levels of hierarchy, allocated as in R_{BP} vicinities of OP with free-space RWP, and also in zone of interference RWP.

Thus, results presented above allows to develop a practical technique of estimation the electromagnetic safety of people in populous areas, and of estimation the EMC of cognitive and ultra-wide band radio systems functioning in allocated frequency bands on a secondary basis, using the system-level initial data – the database of frequency assignments of different radio services of regional and/or national level, and also data concerned the coverage of populous areas by radiocommunications (cellular communications, mobile communications of industrial, official and municipal services, etc.).

Unlike [5,6], the results given above allow to perform these estimations taking into account various types of REE heterogeneity - variety of types of STRs and MTRs, randomness of antenna orientations of transmitters with directed EMR (EIRP randomness on an OP direction), and also variety of power criteria of electromagnetic safety and EMC for transmitters of various types and frequency ranges.

The similar technique illustrated by the novel results of calculations of the total EMB intensity created by STRs and MTRs of GSM-1800, can be used in spectrum management and proximate diagnostics of electromagnetic safety of people in urban areas and EMC diagnostics of radio systems operating in corresponding frequency bands on a secondary basis.

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