Worst-Case Estimation of Electromagnetic Background Created by Cellular Mobile Stations Near Ground Surface

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***Abstract*—The novel technique of worst-case estimation of near-ground electromagnetic background created by mobile stations (MS) of cellular communications is offered. This technique takes into consideration peculiarities of radio wave propagation on different distances between MS and observation point (OP) and of statistical features of ensemble of MS signals in OP related to the presence of prevaling component. It allow to estimate the fundamental upper bound of electromagnetic background total intensity created by MS directly on the basis of calculation of the total electromagnetic loading on territory as the total equivalent isotropic radiated power of MS set falling to the unit of the area of considered territory, and/or estimation of average terrestrial density of cellular traffic intensity. The given results ensure the facilities of EMC design of cognitive radio systems in frequency bands assigned for mobile communications and of support of the acceptable electromagnetic environmental conditions in populous areas.**

Index Terms—electromagnetic background, electromagnetic loading, cellular communications, cognitive radio, EMC

I. Abbreviations

BS – base station of cellular communications (CC).
CDF – cumulative density function.
EMB – total electromagnetic background in observation point.
EME – electromagnetic environment.
EMF – electromagnetic field.
EML – electromagnetic loading.
EMR – electromagnetic radiation of radio transmitter.
EIRP – equivalent isotropic radiated power.
MPL – maximum permissible level.
MS – mobile station of CC – cellular phone, data set, etc.
OP – observation point.
PDF – probability density function.
PFD – power flux density of EMF.
REE – radioelectronic environment.
RWP – radiowave propagation.

II. Introduction

Electromagnetic fields (EMF) radiated by fixed and mobile radio equipment of cellular communications (CC) is a major reason of electromagnetic background (EMB) in places with high population density (urban and suburban territories). EMB created by this equipment may be a reason of EMC problems and harmful interference for wideband and ultra wideband wireless sensor networks and cognitive radio systems which are using CC frequency bands “on a secondary basis” [1,2]. And also EMB created by base (BS) and mobile (MS) stations of CC 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 intensity of EMF ensemble created by MS near the ground surface, as a rule, represents extremely intricate problem connected with calculation of EMF levels in the considered point generated by all MS located, at least, in a zone of radio visibility. Expected uncertainty of MS spatial allocation and parameters of electromagnetic radiation (EMR), and also radio wave propagation (RWP) losses in most cases prevent from the estimation this total EMF intensity.

The technique of worst-case estimation of the total intensity of near-ground EMB created by BS of CC and other fixed transmitters elevated under ground surface, developed in [5], cannot be used for estimation the total EMB intensity created by near-ground MS on account of the fundamental singularity - presence of prevaling components in ensemble of levels of MS signals in near-ground observation point (OP) [6,7].

The aim of this paper is to propose the original and novel applied technique of worst-case estimation of total intensity of near-ground EMB created by cellular MS which take into consideration the presence of prevaling MS signals and specificity of RWP near ground surface.

The main advantage and practical value of this technique lies in the fact that it is based on determination of integrated system parameter of radioelectronic environment (REE) of considered territory - the total equivalent isotropic radiated power (EIRP) of MS set falling to the unit of area of this territory, named in [5] as “Electromagnetic Loading (EML) on territory”, and/or on direct prediction of the main system-level parameters of CC design and operation, such as the average terrestrial density of CC traffic intensity in busyhour. The results of development of this technique are given below.

III. Main Concepts

The total EMB intensity created by MS in OP is determined as the scalar sum of power flux densities (PFD) Π_i of each of N MS allocated in zone of radio visibility round the OP:

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

The average EML on territory L_{MS} created by N MS with undirected EMR and EIRP $P_{e1}, \ldots, P_{eN}$, allocated on area S, is determined as follows:

$$L_{T\,MS} = \left(\sum_{n=1}^{N} P_{en} \right) \Big/ S \text{ [W/m}^2\text{], [kW/km}^2\text{]}. \quad (2)$$

The EML on territory L_{MS} created by set of MS with average EIRP P_{eMS} and undirected EMR, randomly allocated on territory with average terrestrial density ρ_{MS} (as MS of the real cellular networks), is defined as follows:

$$L_{T\,MS} = \rho_{MS} P_{eMS} \, . \quad (3)$$

The EML (3) on territory created by MS, also can be defined via the parameters of CC personal average traffic intensity in busyhour [8] as follows:

$$L_{T\,MS} = P_{eMS}\rho_{MS}\, , \quad E_P = \lambda_p t_h, \quad \rho_{MS} = \rho_S E_P = E_{PS}\, , \quad (4)$$

where E_P [erlang] is personal traffic intensity, λ_p is personal arrival rate, t_h is average holding time; ρ_S is average terrestrial density of CC subscribers; $\rho_{MS}=\rho_S E_P$ is the average terrestrial density of radiating MS; E_{PS} is the average terrestrial density of CC traffic intensity in OP vicinity of radio visibility.

The goal of this work is to show the direct quantitative relation between characteristics (2)-(4) of EML on territory created by set of terrestrially distributed MS, and average intensity (1) of EMB produced by terrestrially distributed MS.

IV. Models and Relations

A. Worst-Case Model of RWP conditions

It is appropriate to use pessimistic or 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 UHF frequency range, basic RWP losses can be characterized by the well-known "breakpoint" RWP model [9].

This model have a following important features: on small distance R between MS and OP conditions of RWP are equal to this conditions in free space: EMF power flux density Π decreases in inverse proportion to a square of distance R; since some distance R_{BP} ("breakpoint" distance) between MS and OP conditions changes: the envelope of distance dependence of EMF power flux density Π decreases in inverse proportion to the fourth degree of distance R.

Distance R_{BP} between MS and OP allocated near surface on which changes of RWP conditions occurs, depends on a wavelength λ of MS EMR, MS antenna height H_{MS} and height H_{OP} of OP over a surface:

$$R_{BP} = 4 H_{MS} H_{OP} / \lambda \, . \quad (5)$$

Consequently the worst-case model of RWP conditions (as an envelope of curve of real RWP losses) between MS and OP on distance R can be represented as follows:

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

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

This model, as a rule, gives the underestimated propagation losses at multipath RWP in urban area [9] and therefore provides the worst-case character of estimation procedure for EMB created by near-ground MS, presented below.

B. Model of MS Set Random Terrestrial Distribution

Random terrestrial distribution of MS with average density ρ_{MS} [MS/m^2] traditionally can be described by the known Poisson model [6,7,10]:

$$P(k,N) = \frac{N^k}{k!} exp(-N), \quad N = \rho_{MS} S\, ; \quad (7)$$

$P(k,N)$ is a probability that exactly k pointed MS are allocated in area S, if the average number of MS in this area is N.

The most representative case is when the OP height H_{OP} and MS height H_{MS} over the ground surface are equal to the human height (1.5 – 2.0 m). For CC of UHF frequency range

$$H_{MS} = H_{OP} = n\lambda, \ \ n \approx 3 \ldots 12; \quad R_{BP} = 4n^2\lambda \, .$$

Assessed values of "Breakpoint" distance R_{BP} for different frequency ranges and different H_{OP} are given in Table 1.

TABLE I. Typical Dimensions of OP Free-Space RWP Vicinity

H_{MS}, H_{OP} $n\lambda$, m	GSM-900 λ=0.32m		GSM-1800, UMTS λ=0.15m		LTE (2.5-2.7 GHz) λ=0.115m	
	n	R_{BP}, m	n	R_{BP}, m	n	R_{BP}, m
1.0	3.1	12.5	6.7	26.7	8.7	34.8
1.5	4.7	28.1	10.0	60.0	13.0	78.3
2.0	6.2	50.0	13.3	107	17.4	139

All MS allocated in zone of radio visibility round the OP are divided on 2 groups: MS allocated on distances $R \le R_{BP}$ (1st group), and MS allocated on distances $R > R_{BP}$ (2nd group) as shown in Figure 1.

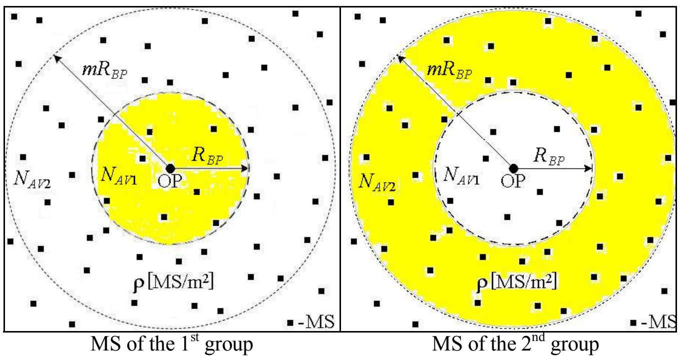

Figure 1. Allocation of MS round the OP in free-space RWP vicinity (left picture) and in zone of multipath (interference) RWP (right picture)

Average quantity of MS of the 1st group allocated in zone of free-space RWP:

$$N_{AV1} = \left(16\rho_{MS}\pi H_{MS}^2 H_{OP}^2/\lambda^2\right) = 16\rho_{MS}\pi n^4\lambda^2 . \qquad (8.1)$$

Average quantity of MS of the 2nd group allocated in zone of multipath RWP:

$$N_{AV2} = \left(m^2 - 1\right)N_{AV1} \approx m^2 N_{AV1}, \quad m >> 1, \rho_{MS} = const . \quad (8.2)$$

C. Statistical Characteristics of EIRP of MS

MS EIRP is random variable owing to randomness of distance between BS and MS and existence of the forced EIRP MS adjustment by BS. Relative terrestrial position of OP vicinity and BS is arbitrary, therefore this adjustment may be performed in different conditions of RWP between BS and MS.

If MS terrestrial distribution is uniform with constant average density ρ_{MS}, and maximal EIRP MS P_{eMSmax} corresponds to the maximal distance between BS and MS (cellular site radius), then probability density function (PDF) $w(P_{eMS})$ and average $m_1(P_{eMS})$ of EIRP MS are [11]

$$w(P_{eMS}) = 1/P_{eMSmax}, \quad m_1(P_{eMS}) = P_{eMSmax}/2, \quad 0 < P_{eMS} < P_{eMSmax} \qquad (9.1)$$

for forced EIRP adjustment in free-space RWP (6.1), and

$$w(P_{eMS}) = 2\sqrt{P_{eMS}/P_{eMSmax}}, \quad m_1(P_{eMS}) = P_{eMSmax}/3, \quad 0 < P_{eMS} < P_{eMSmax} \qquad (9.2)$$

for forced EIRP adjustment in interference RWP (6.2).

D. Statistical Model of EMF Ensemble generated by MS of the 1st group

The PDF of the PFD ensemble of EMF in arbitrary OP, generated by MS of the 1st group with uniform EIRP $P_e=m_1(P_{eMS})$ will be the hyperbolic of the order "-2" [5-7,11]:

$$w(\Pi_1) = \Pi_{min}/\Pi_1^2, \quad \Pi_1 \geq \Pi_{min}, \qquad (10)$$

$$\Pi_{min} = P_e/\left(4\pi R_{BP}^2\right) = P_e/64\pi\lambda^2 n^4 . \qquad (11)$$

Ordinary moments of this distribution is absent, only quantiles of $w(\Pi_1)$ can be calculated. Therefore in ensemble N_{AV1} of EMF generated by MS of the 1st group the dominate component is present, and statistical propertied of prevalent EMF generated by the MS nearest to OP, and of ensemble of other N_{AV1}-1 EMFs, must be analyzed separately.

Method of «thinning» of random points of MS location in OP vicinity permit to deduce the PDF $w(R_{min})$ of the distance from OP to the H^{th} nearest MS (H=K+1, K is a number of excluded nearest MS) and PDF $w(D_\Pi)$ of the dynamic range $D_\Pi=\Pi_H/\Pi_{min}$ in OP of the EMF of the H^{th} nearest MS [6,11]:

$$w(R_{min}) = \left(2G^H/\left(\Gamma(H)\right)\right)R_{min}^{2H-1}\, exp\left(-GR_{min}^2\right); \qquad (12)$$

$$w(D_\Pi) = \left(N_{AV1}^H/\left(\Gamma(H)D_\Pi^{H+1}\right)\right)exp\left(-N_{AV1}/D_\Pi\right); \qquad (13)$$

$$G = \pi\rho_{MS}, \quad R_{min} > 0; \quad D_\Pi = \Pi_H/\Pi_{min} > 0 .$$

Expression for kth order ordinary moment of distribution (13) is

$$m_k(D_\Pi) = N_{AV1}^k\Gamma(H-k)/\Gamma(H), \quad H = K+1 > 0 . \qquad (14)$$

Thereby for the nearest MS (H=1) the 1st-order ordinary moment of D_Π is absent, only quantiles of PDF (13) may be calculated. For all other MS from OP vicinity this moments are exist, and thir total EMF intensity may be calculated using (1).

E. Statistical Model of EMF Ensemble generated by MS of the 2nd group

The PDF of the PFD ensemble of EMF in OP generated by MS of the 2nd group with uniform EIRP $P_e=m_1(P_{eMS})$ will be the hyperbolic distribution of the order "-3/2" [5-7,11]:

$$w(\Pi_2) = \frac{\sqrt{\Pi_{max}\Pi_{min}}}{2\Pi_2^{3/2}\left(\sqrt{\Pi_{max}} - \sqrt{\Pi_{min}}\right)} \approx \frac{\sqrt{\Pi_{min}}}{2\Pi_2^{3/2}}, \qquad (15)$$

$$\Pi_{min} \leq \Pi_2 \leq \Pi_{max}, \ \Pi_{min} = P_e/\left(4\pi R_{BP}^2\right), \ \Pi_{min} = P_e/m^4 .$$

The average of this distribution is

$$m_1(\Pi_2) = \sqrt{\Pi_{max}\Pi_{min}} = P_e/\left(4m^2\pi R_{BP}^2\right). \qquad (16)$$

Models and expressions given above allow to develop a peculiar technique of worst-case estimation of the total EMB intensity created by all MS located round the OP.

V. Estimation of EMB Created by MS

A. General Technique

Taking into consideration the worst-case nature of RWP model (6.1),(6.2), essential difference in RWP conditions for MS of the 1st and the 2nd groups and difference in their average quantity (8.1) and (8.2), and also taking into consideration arguments [6,7,11] related to the proof of a presence of the prevaling component (as a rule from the nearest MS) in OP ensemble of MS signals of 1st group, that demands the special approach owing to absence of the initial moments of PDF of the level of prevaling EMB component in OP, the worst-case estimation of EMB total intensity (1) in OP created by MS can be defined as follows:

$$\Pi_\Sigma(P) = \Pi_{\Sigma MS1} + \Pi_{\Sigma MS2} + \Pi_{MS1}(P), \qquad (17)$$

$$\Pi_{\Sigma MS1} = \left(N_{AV1} - 1\right)m_1(\Pi_1), \quad \Pi_{\Sigma MS2} = N_{AV2}m_1(\Pi_2),$$

where $\Pi_{MS1}(P)$ is a quantile of CDF of EMF intensity of prevaling EMB component in OP for probability P, $\Pi_{\Sigma MS1}$ is a total EMF intensity in OP created by all MS of the 1st group except the nearest one, $\Pi_{\Sigma MS2}$ is a total EMF intensity created by all MS of the 2nd group, $m_1(\Pi_1)$ and $m_1(\Pi_2)$ are average values of EMF in OF radiated by MS of the 1st group except the nearest one and by MS of the 2nd group appropriately.

B. Prevaling EMF created by the nearest MS

Using (8.1),(13) it is possible to prove the dependence of the PDF $w(\Pi_{MS1})$ and CDF $P(\Pi_{MS1})$ of PFD Π_{MS1} in OP from the nearest MS with EIRP P_{eMS} upon the EML on territory $L_{T\,MS}$ created my MS of the 1st group in OP vicinity:

$$w(\Pi_{MS1}) = \frac{L_{T\,MS}}{4\Pi^2_{MS1}} exp\left(-\frac{L_{T\,MS}}{4\Pi_{MS1}}\right), \quad \Pi_{MS1} > 0; \qquad (18)$$

$$P(\Pi_{MS1}) = exp\left(-L_{T\,MS}/(4\Pi_{MS1})\right), L_{T\,MS} = P_{eMS}\rho_{MS}. \qquad (19)$$

In consideration of forced and smooth MS EIRP adjustment by BS in the range [0, P_{eMSmax}], the probability (19) that PFD Π_{MS1} of prevailing EMF created by the nearest MS will not exceed level Π_{max} in OP, is of the following form

$$p(\Pi_{max}) = \int_0^{P_{eMSmax}} exp\left(-\frac{\rho_{MS}P_{eMS}}{4\Pi_{max}}\right) w(P_{eMS})dP_{eMS} =$$
$$= \frac{2}{\nu}\left(\frac{\rho_{MS}P_{eMS\,max}}{4\Pi_{max}}\right)^{-2/\nu} \gamma\left(\frac{2}{\nu}, \frac{\rho_{MS}P_{eMS\,max}}{4\Pi_{max}}\right), \qquad (20)$$
$$\gamma(\alpha, x) = \int_0^x e^{-t}t^{\alpha-1}dt, \quad \rho_{MS}P_{eMS\,max} = L_{TMSP},$$

where $L_{T\,MS\,P}$ is a "peak" EML on territory created by MS with maximum possible EIRP randomly terrestrially distributed with average density ρ_{MS}; ν=2 for MS EIRP adjustment in conditions of free-space RWP, and ν=4 for interference RWP. For free-space RWP conditions of MS EIRP adjustment

$$P(\Pi_{max}) = \frac{2\Pi_{max}}{L_{TMS}}\left(1 - e^{-\frac{L_{TMS}}{2\Pi_{max}}}\right), L_{TMS} = \rho_{MS}m_1(P_{eMS}); \qquad (21)$$

for interference RWP conditions of MS EIRP adjustment

$$P(\Pi_{max}) = \sqrt{\frac{4\Pi_{max}}{3L_{T\,MS}}} \int_0^{\sqrt{\frac{3L_{T\,MS}}{4\Pi_{max}}}} e^{-t^2}dt, L_{TMS} = \rho_{MS}m_1(P_{eMS}). \qquad (22)$$

If in arbitrary OP the maximum permissible level (MPL) Π_{MPL} of EMF is specified, and the external EMB with intensity Π_{BG} is present, then the probability (21) $p(\Pi_{MS1} \le (\Pi_{MPL}-\Pi_{BG})) = P(\Pi_{max}) = P(\Pi_{MPL}-\Pi_{BG})$ that PFD Π_{MS1} of prevailing EMF from nearest MS will not exceed the permissible limit reduced by EMB $\Pi_{MPL}-\Pi_{BG}$ will be

$$P(\Pi_{MPL} - \Pi_{BG}) = \frac{2(\Pi_{MPL} - \Pi_{BG})}{L_{T\,MS}}\left(1 - e^{-\frac{L_{T\,MS}}{2(\Pi_{MPL} - \Pi_{BG})}}\right); \qquad (20a)$$

properly for interference RWP conditions of EIRP adjustment

$$P(\Pi_{MPL} - \Pi_{BG}) = \sqrt{\frac{4(\Pi_{MPL} - \Pi_{BG})}{3L_{T\,MS}}} \int_0^{\sqrt{\frac{3L_{T\,MS}}{4(\Pi_{MPL} - \Pi_{BG})}}} e^{-t^2}dt. \qquad (21a)$$

The external EMB which intensity Π_{BG} is taken into account in (20a), (21a) is formed as a sum of few EMB components created by fixed and mobile radio transmitters of different radio services. The worst-case model of EMB component created by BS of CC and/or other fixed transmitters with nondirectional antennas elevated above ground surface is present in [5]. The corresponding models for EMB components created by MS of the 1st (except the nearest MS) and 2nd groups are given below.

C. EMB created by remainder MS of 1st group

Using (14) for $K \ge 2$ it is possible to find the useful expression for total average intensity $\Pi_{\Sigma MS1}$ of quasistationary component of EMB in OP created by all MS of the 1st group except the nearest one:

$$\Pi_{\Sigma MS1} = \frac{L_{TMS}Z}{4}, Z = \sum_{H=2}^{int\{N_{AV1}\}} \frac{1}{H-1}, L_{TMS} = \rho_{MS}m_1(P_{eMS}); \qquad (23)$$

in this expression $int\{N_{AV1}\}$ means the integer part of (8.1). Computed curve of factor $Z(N_{AV1})$ is presented on Figure 2.

Factor Z depends on MS terrestrial density in OP vicinity. In areas with high population density $\rho_{MS} \approx 10^{-4} - 10^{-1}$ MS/m^2 and for $H_{MS} \approx H_{OP} \approx 1.5 - 2.0$ m we have $R_{BP} \approx 30 - 140$ m and $Z \approx 1 - 8$.

D. Total Quasistationary EMB intensity created by MS

Using (8.2),(16) it is easy to receive a useful worst-case model for estimation of the total average intensity $\Pi_{\Sigma MS2}$ of quasistationary component of EMB in OP created by EMF MS of the 2nd group, directly using the results of estimation of EML on territory created by these MS:

$$\Pi_{\Sigma MS2} = \lim_{m\to\infty}(N_{AV2}m_1(\Pi_2)) = \frac{L_{T\,MS}}{4}, \; N_{AV2} \approx \rho_{MS}\pi m^2 R^2_{BP}. \qquad (24)$$

Using (23) and (24) it is possible to find the total average quasistationary EMB intensity created by MS of 1st and 2nd groups:

$$\Pi_{BG\,MS} = \Pi_{\Sigma MS1} + \Pi_{\Sigma MS2} = \frac{L_{T\,MS}(Z+1)}{4}. \qquad (25)$$

Average intensity (24) of a quasistationary component of EMB in OP created by EMF MS of the 2nd group depends only on EML on territory created by MS of this group. Therefore it is possible to define the external radius $R_{eq}=qR_{BP}$ of equivalent

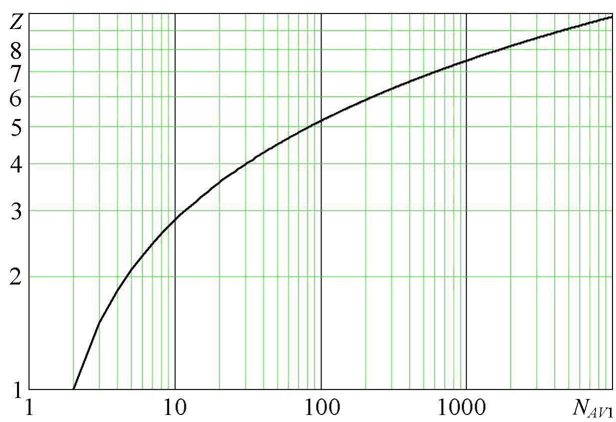

Figure 2. Values of factor Z for different quantity of MS of the 1st group

annular free-space RWP zone round OP with internal radius R_{BP} and similar MS terrestrial density ρ_{MS}, for which the intensity of EMB in OP created by all MS allocated in this zone, will be equal to (25).

Taking into consideration the free-space RWP in this zone the following model closed to (10),(11) may be used [11]:

$$w(\Pi) = \frac{\Pi_{min}\Pi_{max}}{(\Pi_{max} - \Pi_{min})\Pi^2} \approx \frac{\Pi_{min}}{\Pi^2}, \quad \Pi_{min} \le \Pi \le \Pi_{max};$$

$$\Pi_{max} = P_{eMS} / \left(4\pi R_{BP}^2\right), \Pi_{min} = P_{eMS} / \left(4\pi q^2 R_{BP}^2\right), \Pi_{max} >> \Pi_{min};$$

$$m_1(\Pi) \approx \Pi_{min}\, ln(\Pi_{max}/\Pi_{min}) = P_{eMS}\, ln\left(q^2\right) / \left(4\pi q^2 R_{BP}^2\right);$$

$$\Pi_{\Sigma MS2} = N_{eq} m_1(\Pi), \quad N_{eq} = \pi R_{BP}^2\left(q^2 - 1\right)\rho_{MS};$$

$$\frac{\left(q^2 - 1\right)}{q^2} ln\left(q^2\right) = 1 \quad \rightarrow \quad q = 1.964 \approx 2, \quad R_{eq} \approx 2R_{BP}. \qquad (26)$$

Thus, the radius of equivalent circular OP vicinity with free-space RWP and average MS terrestrial density ρ_{MS} which produce the same intensity of the quasistationary EMB as (25), is 2 times greater then “breakpoint” radius.

E. Maximum Permissible Level of EML on territory created by MS

If in arbitrary OP the MPL Π_{MPL} is specified, and the external EMB with intensity Π_{BG} is present, then for the fixed probability (20a),(21a) $P(\Pi_{max}) = P(\Pi_{MPL}\text{-}\Pi_{BG})$ that PFD Π_{MS1} of prevailing EMF from nearest MS will not exceed the permissible limit $\Pi_{MPL}\text{-}\Pi_{BG}$ reduced by EMB (or for the fixed corresponding probability that total EMF intensity will exceed the MPL Π_{MPL}) the MPL of EML on territory created by MS may be determined.

MPL of EML on territory created by MS L_{maxMS} depends on MPL of EMB Π_{MPL}; last may be determined

- by MPL of total interference for secondary radio services generated by MS of primary terrestrial mobile radio service, or
- by Hygienic Regulations for radiotelecommunications; in many countries Π_{MPL} is accepted in in the range 0.02 – 0.1 W/m^2 (2 – 10 µW/cm^2) [11,12].

Curves $L_{maxMS}(\Pi_{max})$ calculated with use of (22) for different levels of $P(\Pi_{max})$ and for interference RWP conditions of MS EIRP adjustment are given on Figure 3.

MPL of EML on territory created by MS can be defined with accuracy comprehensible to practice using the following simplified expressions:

$$L_{max\,MS} \approx 4P\Pi_{max}(1 + p), \quad p = 1 - P(\Pi_{MS1} \le \Pi_{max}) \le 0.1 \quad (27)$$

for MS EIRP adjustment in interference (multipath) RWP, and

$$L_{max\,MS} \approx 4P\Pi_{max}(1 + 2p/3), \quad p \le 0.1 \qquad (28)$$

for MS EIRP adjustment in free-space RWP;

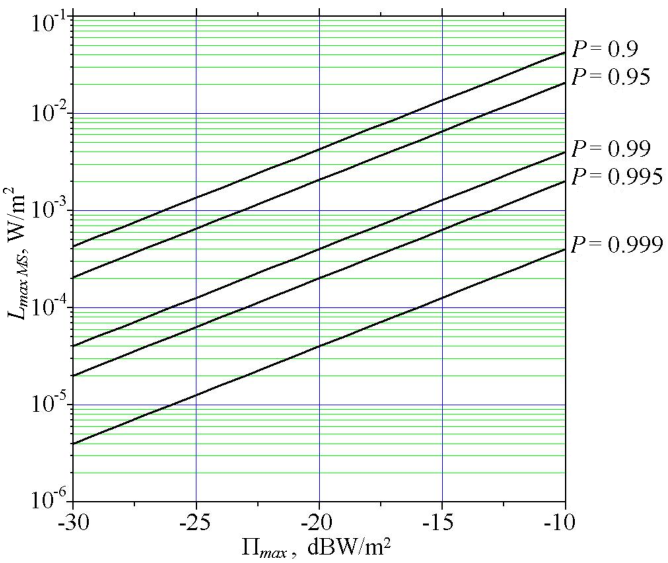

Figure 3. MPL L_{maxMS} dependence on MPL Π_{max} determined with a glance of quasistationary EMB in OP for different levels of $P=P(\Pi_{MS1} \le \Pi_{max})$

For small P MPL of EML on territory created by MS do not depend on RWP conditions:

$$L_{max\,MS} \approx 4p\Pi_{max}, \quad p << 0.1. \qquad (29)$$

F. Total EMB intensity created by MS of CC

Taking into account results presented above, it becomes evident that the EMB intensity in OP created by MS allocated in its zone of radio visibility (17) is a sum of quasistationary component (25) and of stochastic component specified by (18)-(22) and (27)-(29). Therefore the total EMB intensity Π_Σ created by MS depends both on EML on territory $L_{T\,MS}$ created by MS and on tolerance probability $p = 1 - P(\Pi_{MS1} \le \Pi_{max})$:

$$\Pi_\Sigma(p) = \Pi_{BG\,MS} + \Pi_{MS1} \approx \frac{L_{T\,MS}}{4}\left(Z + 1 + \frac{1}{p}\right), p \le 0.1. \qquad (30)$$

Taking into consideration (4) for small levels of tolerance probability subject to $Z \approx 1 \ldots 8$

$$\Pi_\Sigma(p) \approx \frac{L_{T\,MS}}{4p} = \frac{m_1(P_{eMS})E_{PS}}{4p}, \quad p \le 0.01. \qquad (31)$$

This expression correspond to the worst-case model of estimation of EMB intensity in OP created by MS allocated in OP vicinity of radio visibility and illustrate the direct relationship of EMB intensity with EML on territory created by MS and with CC terrestrial density of traffic intensity in OP vicinity.

VI. Estimated Values of EMB Created by MS

Using expressions (30),(31), let us execute the “worst-case” estimations of total EMB intensity and of total level of interference created by MS in GSM-1800 frequency range (1710-1785 MHz) in places with various MS terrestrial density and for various tolerance probability p. At performance of these estimations the following initial data is used:

A) The personal traffic intensity in busyhour $E_P = 0.05$ erlang and approximate data [13,14] concerned an average MS terrestrial density.

B) The average MS EIRP $m_1(P_{eMS}) = 62.5$ mW with a glance of (9.1) and $P_{eMSmax} = 125$ mW [15].

C) Values of probability $p = 10^{-1} – 10^{-3}$ for various levels of protection against EMB influence on EMF receptors in GSM-1800 frequency range.

D) $R_{BP} = 60$ m (Table 1) for $\lambda = 0.15$ m, $H_{OP} = 1.5$ m, in this case the area of R_{BP} – vicinity of OP is 11300 m^2.

E) Receiving antenna of cognitive radio system is the half-wave dipole (gain $G = 1.64$ and effective aperture $A_e = G\lambda^2/(4\pi) \approx 0.003$ m^2).

Estimated values of EMB intensity $\Pi_\Sigma(p)$ in near-ground OP and of total interference power $Q_{DR}(p)$ in output of receiving dipole antenna created by MS of GSM-1800 are tabulated below.

TABLE II. CALCULATED VALUES OF TOTAL EMB AND TOTAL INTERFRENCE INTENSITY IN GSM-1800 FREQUENCY RANGE

ρ_{MS}, MS/m^2, E_{PS}	p=0.1		p=0.01		p=0.001	
	$\Pi_\Sigma(p)$, W/m^2	$Q_{DR}(p)$, W	$\Pi_\Sigma(p)$, W/m^2	$Q_{DR}(p)$, W	$\Pi_\Sigma(p)$, W/m^2	$Q_{DR}(p)$, W
10^{-1}	$29\cdot10^{-3}$	$8.7\cdot10^{-5}$	$17\cdot10^{-2}$	$5.1\cdot10^{-4}$	$16\cdot10^{-1}$	$4.8\cdot10^{-3}$
10^{-2}	$29\cdot10^{-4}$	$8.7\cdot10^{-6}$	$17\cdot10^{-3}$	$5.1\cdot10^{-5}$	$16\cdot10^{-2}$	$4.8\cdot10^{-4}$
10^{-3}	$29\cdot10^{-5}$	$8.7\cdot10^{-7}$	$17\cdot10^{-4}$	$5.1\cdot10^{-6}$	$16\cdot10^{-3}$	$4.8\cdot10^{-5}$
10^{-4}	$29\cdot10^{-6}$	$8.7\cdot10^{-8}$	$17\cdot10^{-5}$	$5.1\cdot10^{-7}$	$16\cdot10^{-4}$	$4.8\cdot10^{-6}$

The data resulted in Table II are quite adequate to the real near-ground EMB intensity in frequency ranges of BS reception and illustrate obviously the relationship of the total EMB level and of the total interference level created by MS, with the average EML on territory created by MS and with the average terrestrial density of CC traffic intensity.

In particular, at moderate requirements to tolerance probability (p=0.1) and moderate MS terrestrial density (the average urban terrestrial density of CC traffic intensity $E_{PS} = \rho_{MS} = 10^2 – 10^3$ 1/km^2), and also at use of a small part of the GSM-1800 frequency range assigned for MS radio transmission, EMB levels are not very great, and levels of interference on the receiving dipole antenna output will not exceed 10^{-9}-10^{-10}W, that allows to consider the given frequency range as conditionally suitable for use by cognitive radio systems. In this case the EMB quasistationary component is an essential part of total EMB intensity because $1/p$ in (30) is small.

At high requirements to tolerance probability (p=0.001) and the high MS spatial density (in buildings, urban pedestrian areas [13], concourse, etc.), levels of EMB created by MS are rather considerable and even can exceed the MPL accepted by hygienic regulations for radiotelecommunications. In this case levels of interference $Q_{DR}(p)$are too great for use of the given frequency range by other systems, and EMB quasistationary component $\Pi_{\Sigma MS1}+\Pi_{\Sigma MS2}$ is only negligible part of total EMB intensity because in (30) $1/p >> Z+1$ and stochastic component Π_{MS1} of total EMB is prevalent.

VII. CONCLUSION

In this paper the concept [5] of EML on territory as an integrated system characteristic of REE in considered area is developed, and original worst-case technique for estimation of near-ground EMB created by MS of CC directly on the basis of prediction of average MS terrestrial density and average terrestrial density of CC traffic intensity is offered.

The main advantages and novelty of approach and results presented above are that they establish the direct quantitative relationships between EML on territory and the fundamental upper bound of EMB intensity created by MS allocated in OP vicinity of radio visibility. This approach allow to define the MPL of EML on territory created by MS in cases when MPL of EMB intensity and tolerance probability are given, and eventually offer simple and useful equations for worst-case estimation of total EMB created by MS of CC.

In whole, the presented approach allow to perform a simple direct and comparative quantitative estimation the upper bound intensity of the total near-ground EMB created by MS.

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