Verification of Worst-Case Analytical Model for Estimation of Electromagnetic Background Created by Mobile (Cellular) Communications

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***Abstract*—Results of experimental verification of the proposed analytical technique for calculation of the average electromagnetic background (EMB) intensity created by base stations of cellular communications, which is based on estimation of the average electromagnetic loading on area (EMLA) created by base stations, are presented. This verification is executed by comparison of the published results of measurements of levels of EMB generated by 2G/3G radio networks in more than 30 countries, with the results of corresponding analytical worst-case estimations of EMLA and average EMB intensity for the real and potential places of EMB measurements. Results of this comparison convincingly confirm the adequacy of the offered analytical technique for worst-case estimation of EMB created by mobile (cellular) communications, and also support its real practical importance for an assessment of electromagnetic ecology of various areas, electromagnetic safety of population and intersystem EMC in conditions of extremely fast development of radio networks and services of 4G/5G/6G.**

Keywords— cellular communications, electromagnetic loading, electromagnetic background, intersystem EMC, electromagnetic ecology, electromagnetic safety

I. Abbreviations

BS – base station.
CC – cellular communications.
EMB – electromagnetic background.
EMLA – electromagnetic loading on area.
EME – electromagnetic environment.
EMF – electromagnetic field.
EMR – electromagnetic radiation.
EIRP – equivalent isotropic radiated power.
OP – observation point.
RFC – radio (frequency) channel
RMS – root mean square
RWP – radio waves propagation.
MS – mobile (subscriber's) station

II. Introduction

In papers [1-3], the following simple formulas were proposed for a pessimistic (worst-case) estimation of the average total intensity of electromagnetic background (EMB) created in the observation point (OP) near the earth's surface by the set of base stations (BS) of cellular communications (CC):

$$Z_{\Sigma BS} = \sum_{i=1}^{N} Z_{BSi} \approx \frac{B_{TBS}}{2} ln\left(\frac{6.6 \cdot H_{OP}}{\lambda}\right), \tag{1}$$

$$E_{\Sigma BS} = \sqrt{120\pi Z_{\Sigma BS}}\,, \quad B_{TBS} = \frac{\sum_{i=1}^{M} P_{eBSi}}{S}\,, \tag{2}$$

where $Z_{\Sigma BS}$ [W/m^2] - the total intensity of EMB created by BS in considered OP (defined as a scalar sum of power flux densities Z_{BSi} of electromagnetic fields (EMF) presented in OP, which are radiated by the set of N BS distributed over the surrounding area of S); H_{OP} - OP height above the surface, λ - wavelength of BS electromagnetic radiation (EMR); B_{TBS} [W/m^2] - the average EMLA created by BS; P_{eBSi} - equivalent isotropic radiated power (EIRP) of circular EMR of corresponding BS; $E_{\Sigma BS}$ [V/m] - the total EMB intensity in units of EMF strength (RMS value). For BS set with omnidirectional EMR and equal EIRP P_{eBS} the average EMLA is defined as $B_{TBS} = \rho_{BS}\, P_{eBS}$, where $\rho_{BS} \approx N/S$ is an average BS area density, [BS/m^2].

Expression (1) is obtained using the following assumptions:

a) OP height above the surface H_{OP} is significantly less than the minimum possible distance between the OP and the antenna of the nearest BS;

b) EMR of BS is close to isotropic with EIRP equal to EIRP in the main beam of BS antenna;

c) minimum possible distance between BS antenna and OP exceeds the radius of the near zone of the BS EMR; radio wave propagation (RWP) conditions between OP and BS corresponds to the lower limit of RWP attenuation in urban area in model [4, eq. (1),(2)];

d) when determining B_{TBS} in (2), P_{eBSi} values are accepted as the BS EIRP registration values. In fact the actual total BS EIRP approaches the registration values only during the business-hours when all BS radio channels are operating at the greatest capacity.

These assumptions determine the generally pessimistic nature of estimations of the total EMB intensity in OP using (1),(2), because, by virtue of the above assumptions, expressions (1),(2) corresponds to the peak loading of the CC network and does not actually take into account the

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shadowing of BS of neighboring sites by buildings, as well as the BS EIRP reduction for OP locations under the BS antennas due to the BS EMR elevation directivity.

On the other hand, the factors that reduce the pessimism of estimations (1) include the fundamental property of electromagnetic environment (EME) in terrestrially distributed sets of EMR sources, which consists in the presence in the OP of the predominant EMF created by the nearest EMR source [5] (RWP conditions for which in OP vicinity, as a rule, correspond to free-space model), as well as the fact that model (1) does not take into account the increase in EMB intensity in OP due to the summation of direct ray and rays reflected from surfaces (ground, building walls and roofs, etc.).

The main restriction of the widespread use of expressions (1),(2) for the estimations of EMB intensity created by CC radio networks, is their insufficient experimental verification. The goal of this paper is to analyze the adequacy of the technique for predicting EMB intensity, proposed in [1-3] and based on (1),(2), with the use of trustworthy published results of EMB measurements, and also of estimations the average EMLA, created by CC BS in places where these measurements were made. Results of verification of model (1), which are based on the analysis of EMB measurement data presented in papers [6-8, 17-24], are given below in Sections IV-VII.

III. Typical Input Data for the EMLA Assessment

Information concerned the conditions of EMB creation, contained in [6-8], as a rule, is not enough to estimate EMLA created by the set of BS in the considered area and to perform estimates using (1). Therefore we will use the following typical CC characteristics based on expert evaluations, networks design experience and research results on high-quality CC radio networks design and frequency planning in urban areas that provide a compromise level of intra-network interference with high quality of wireless services [9,10], as well as known data [11-13, etc.] on the area density of CC subscribers and on the specific traffic intensity G in Erlangs [Erl.] in CC networks:

a) we will assume that in urban areas, mainly three-sector BS with EIRP levels of 50-53 dBm in GSM 900 radio channels, 47-50 dBm in GSM 1800 radio channels and 53-57 dBm in UMTS radio channels are used;

b) in CC networks, the specific traffic intensity of mobile phone service during busy hours over the past 20 years has increased from 0.02-0.04 Erl. [12] to 0.08-0.1 Erl. [13] and for a corresponding measurement period can be estimated using linear interpolation;

c) area density of CC subscribers and mobile stations (MS), which has a determining influence on EMLA created by the BS set in a considered territory, varies over a wide range of 3000-100000 MS/km^2 for urban areas, 300-3000 MS/km^2 for suburban areas and 10-300 MS/km^2 in rural areas [11,13], which requires clarification in each case using reference data on population density and its coverage by cellular services during the measurement period.

Note 1: in some countries and regions an essential limitations in BS EIRP are applied, or in conditions of a large BS area density an essentially lower RFC EIRP are used [14, etc.] that's why for these cases estimations of EMB intensity with the use of (1) and EIRP levels assumed in Cl. *a)* of Section III above, will be considerably overrated.

Note 2: the typical input data adopted above correspond to business-hours of CC, therefore, estimates (1) obtained with its use should, if possible, be compared with the maximum measured values of EMB intensity, since the average values of the EMB intensity are, as a rule, significantly lower than the maximum ones (on 5-20 dB, taking into account [13,19, etc.]).

IV. Verification of (1) Using Data [6]

In [6], the following measurement results and initial data are presented:

a) RMS values of the total strength of EMB generated by the GSM 900, GSM 1800 and UMTS CC systems at a fixed point in the city (Demirtepe-Ankara, Turkey), obtained as a result of automated measurements during 4 months in 2011: average value 1.53 V/m, minimum value 1.18 V/m, maximum value 2.36 V/m; maximum values for measurements during days 1.97-2.09 V/m ([6], Section 4.1) and for measurements during weeks and months 2.13-2.28 V/m ([6], Cl. 4.2, 4.3);

b) the OP (the receiving antenna) was located at a height of 2 m above the surface on the roof of the building. Since this height is significantly less than the minimum possible distance between OP and the antenna of the nearest BS, the conditions for its location are adequate to the conditions for OP location with respect to the BS antennas adopted for model (1);

c) the considered region (Demirtepe-Ankara) is characterized by a high density of BS and a high voice traffic intensity. In the OP vicinity of the radius of 3.5–4 km (40–50 km^2), during the measurement period, there were 1586 single-sector BS (about 530 three-sector BS) with approximately 6000 transceivers, i.e. approximately 4 transceivers (or 4 radio channels) per BS sector. As a result of estimation the average area density of three-sector BS in the considered region, a value of 10-12 BS/km^2 was obtained.

Taking into account the typical input data adopted above, we will assume that in each BS sector there is one GSM 900 radio channel with EIRP 50-53 dBm, two GSM 1800 radio channels with EIRP 47-50 dBm and one UMTS radio channel (2.1 GHz) with EIRP 53-57 dBm (the total BS EIRP will be 0.4-0.9 kW with circular radiation pattern of a three-sector BS). This assumption is based on data presented in Fig. 4 and Table 4 of [6], which indicate the predominance of EMF of 3G CC (UMTS) and allow to estimate the ratio of EMR levels of GSM 900, GSM 1800, and UMTS.

In the vicinity of the measurement point, the BS density is 2–3 times higher than the average in the considered area, which follows from the map of the BS distribution in OP vicinity (Fig.3 in [6]). We assume that an increase in BS area density in the vicinity of the measurement point, which leads to a decrease in the size of sites and the maximum communication range, is accompanied by a corresponding decrease in BS EIRP to reduce the levels of intrasystem interference while preserving the average EMLA created by the BS, at the same level.

Taking into account the "forked" ("interval") nature of the initial data, we perform estimations of EMLA and of EMB intensity created separately by GSM 900 with BS EIRP 50-53 dBm (B_{TBS900}, $Z_{\Sigma BS900}$), by GSM 1800 with BS EIRP 47-50 dBm ($B_{TBS1800}$, $Z_{\Sigma BS1800}$) and by UMTS with BS EIRP 53-57 dBm ($B_{TBS2100}$, $Z_{\Sigma BS2100}$), as well as the total average EMB intensity in units of EMF power flux density ($Z_{\Sigma BS}$=$Z_{\Sigma BS900}$+$Z_{\Sigma BS1800}$+$Z_{\Sigma BS2100}$) and EMF strength ($E_{\Sigma BS}$):

B_{TBS900}=1.0-2.4 kW/km^2, $Z_{\Sigma BS900}$ = 0.0019-0.0044 W/m^2;

$B_{TBS1800}$=1.0-2.4 kW/km^2, $Z_{\Sigma BS1800}$=0.0022-0,0053 W/m^2;

$B_{TBS2100}$=2.0-6.0 kW/km^2, $Z_{\Sigma BS2100}$=0.0045-0.014 W/m^2;

$Z_{\Sigma BS}$ = 0.0086-0.024 W/m^2, $E_{\Sigma BS}$ = 1.80-3.01 V/m.

The lower boundary of the interval of $E_{\Sigma BS}$ values obtained using (1) is 18% (1.4 dB) higher than the average EMB intensity 1.53 V/m given in [6]; this interval covers the values of the maximum measured EMB levels of 1.97-2.09 V/m for measurements during the day, of 2.13-2.28 V/m for measurements during separate weeks and months, and of 2.36 V/m for measurements during the observation period (4 months).

V. Verification of (1) Using Data [7]

In [7], the results of measurements of EMB intensity created by CC (GSM 900, GSM 1800, UMTS) and broadcasting (FM Radio, DAB, TV) systems in outdoor places of urban (Basel city) and rural (Bubendorf, about 16 km away from Basel) areas in Switzerland are presented; the prevalence of GSM 1800 EMB in conditions of Basel urban area, and of GSM 900 EMB in conditions of Bubendorf rural area was detected. Measurements were performed in 2005 at an altitude of 1.5 m above the ground surface; in Basel, the average EMB level was 0.50 V/m (share of GSM 1800 is 0.42 V/m), and the maximum EMB level was 1.50 V/m; in Bubendorf, the average and maximum EMB levels were 0.15 V/m (share of GSM 900 is 0.1 V/m) and 0.50 V/m, respectively.

The input data given in [7] are not enough to estimate the average EMLA created by the BS set in Basel and Bubendorf, and to carry out EMB estimations using (1). Therefore, as in the previous case, we make a number of assumptions related to the EMLA forecast for the considered settlements:

a) part of Basel where EMB measurements were carried out, is characterized by dense mid-rise buildings (3-4 floors); and Bubendorf is characterized by low-rise rural development; so it can be assumed that EMLA in considered urban and suburban/rural areas differs by approximately an order of magnitude, which generally corresponds to the data contained in [7];

b) the specific voice traffic intensity during the business-hour of CC networks in 2005 in central Europe can be taken at the level of $G \approx$ (0.05-0.07) Erl.;

c) the population density in Basel in 2005, according to [15,16], is approximately 5000-7000 people/km^2, in Bubendorf (taking into account considerations given above), the population density can be accepted at the level of 500-700 people/km^2; the CC coverage in Switzerland in 2005 can be accepted at the level of 75-85% of population size, so we can accept the average area density of CC mobile stations (MS) during the measurement period approximately equal to $\rho_{MS} \approx$ 500 MS/km^2 in Bubendorf, and $\rho_{MS} \approx$ 5000 MS/km^2 in Basel.

Hereinafter, we use the following technique for estimating of EMLA in places of measurements of the total EMB intensity created by CC:

a) Using the evaluation data concerned the specific voice traffic intensity in 2005, we estimate the area density of MS in the active radiation mode: $\rho_{AMS} = G \cdot \rho_{MS}$; for Basel we'll get $\rho_{AMS} \approx$ (250-350) MS/km^2, for Bubendorf we'll get $\rho_{AMS} \approx$ (25-35) MS/km^2.

b) After that, we estimate the minimum average number N_C of GSM radio channels (RFC) required to provide radio communication with subscribers over an area of 1 km^2: $N_C \approx \rho_{MS}/8$; for the GSM 1800 network of Basel we get $N_C \approx$ (32-44) RFC/km^2; for the Bubendorf GSM 900 network, we obtain $N_C \approx$ (3-5) RFC/km^2.

c) Using the known technique [12], we estimate the approximate number N_{QoS} of GSM radio channels required to provide the high quality voice communication service for CC subscribers ("grade-of-service" $V \approx 0.99$) during the busy hour $N_{QoS} \approx K_{QoS} N_C$, $K_{QoS} \approx 1.5$ (K_{QoS} value is determined roughly without taking into account the presence of synchronization channels, fragmentation of the network coverage area into separate BS sectors, etc.); for Basel we get $N_{QoS} \approx$ (42-64) RFC/km^2; for Bubendorf, we obtain $N_{QoS} \approx$ (5-9) RFC/km^2.

d) Using the typical values of channel EIRP P_C BS GSM in the considered areas, we estimate the average values of EMLA $B_{TBS} = P_C \cdot N_{QoS}$. For Basel, the average EMLA created by BS of GSM 1800 with the channel EIRP P_C = 47-50 dBm (50-100W) will be $B_{TBS} \approx$ 2.1-6.4 kW/km^2 (2.1-6.4 mW/m^2). For Bubendorf, the average EMLA created by BS of GSM 900 with the channel EIRP P_C = 50-53dBm (100-200W), will be $B_{TBS} \approx$ 0.5-1.8 kW/km^2 (0.5-1.8 mW/m^2).

e) Using (1), for the obtained B_{TBS} values, we'll obtain the following estimated values of EMB intensity in considered areas at a height of H_{OP} = 1.5 m: for Basel B_{BS} = 0.0043-0.013 W/m^2, $E_{\Sigma BS} \approx$ 1.27-2.22 V/m; for Bubendorf $B_{\Sigma BS} \approx$ 0.00085-0.0031 W/m^2, $E_{\Sigma BS} \approx$ 0.57-1.1 V/m.

These evaluated data are in sufficiently good agreement with the published measurement results:

- the maximum measured total EMB intensity in Basel 1.5 V/m (at 1.26 V/m of supposed GSM 1800 share) corresponds to the lowest boundary of estimated range 1.27-2.22 V/m;
- the average measured total EMB intensity in Basel 0.5 V/m (at 0.42 V/m of GSM 1800 share) is 5 dB below the lower boundary of the estimated range of EMB intensity, which reflects the pessimistic nature of estimations (1) based on initial data CC for busy hour,
- the maximum measured total EMB intensity in Bubendorf 0.5 V/m roughly corresponds to the lowest boundary of estimated range 0.57-1.1 V/m, and the supposed GSM 900 share 0.34 V/m of the maximum measured EMB level is only 2 dB below the lowest boundary of this estimated range;

- the average measured total EMB intensity of GSM 900 in Bubendorf 0.1 V/m is 7-8 dB below the lower boundary of the estimated range of EMB intensity, which, on the one hand, reflects the pessimistic nature of the model (1), and on the other hand, may indicate the commuting (daytime migration) of Bubendorf population, which reduces population density and voice traffic intensity during busy hours.

VI. Verification of (1) Using Data [8]

In [8], an overview of the results of measurements of the total EMB intensity, performed in 2006-2012 in 19 European countries, is enclosed. This review summarizes the following generalized data of a comparative analysis of the measurement results in EU countries: average levels of the measured field strength were obtained from 0.08 to 1.8 V/m, less than 1% of the values exceeded 6 V/m, and less than 0.1% of the values exceeded 20 V/m. Authors of [8] also noted the difference in conditions and poor comparability of the measurement results, therefore, to verify the model (1), the data [8] characterizing the EMB created by BS of CC were selected, and estimations (1) were made for the expected EMB levels under the following typical conditions:

– for urban areas covered by GSM 1800 CC with BS channel EIRP 47-50 dBm for H_{OP} = 1.5 m, G = 0.08 Erl. and for the different average terrestrial density of subscribers ρ_{MS} (extreme with $\rho_{MS} = 10^4$-10^5 MS/km^2 (Table 1.1) and most probable with $\rho_{MS} = 10^3$-$5{\cdot}10^4$ MS/km^2 (Table 1.2), taking into account the data [11,13, etc.]);

Table 1.1. **Estimated EMB intensity (urban areas, GSM 1800, RFC EIRP 0.05-0.1 kW)**

ρ_{MS} [MS/km^2]	100 000	25 000	10 000
ρ_{AMS} [MS/km^2]	8 000	2 000	800
N_C [RFC/km^2]	1000	250	100
N_{QoS} [RFC/km^2]	1100	280	120
B_{TBS} [kW/km^2]	55 - 110	14 - 28	6 - 12
$Z_{\Sigma BS}$ [W/m^2]	0.11 - 0.23	0.029 - 0.057	0.012 - 0.025
$E_{\Sigma BS}$ [V/m]	6.4 - 9.2	3.3 - 4.6	2.1 - 3.1

Table 1.2. **Estimated EMB intensity (urban areas, GSM 1800, RFC EIRP 0.05-0.1 kW)**

ρ_{MS} [MS/km^2]	5 000	2 500	1 000
ρ_{AMS} [MS/km^2]	400	200	80
N_C [RFC/km^2]	50	25	10
N_{QoS} [RFC/km^2]	60	32	14
B_{TBS} [kW/km^2]	3 - 6	1.6 - 3.2	0.7 - 1.4
$Z_{\Sigma BS}$ [mW/m^2]	6 - 12	3.3 - 6.6	1.4 - 2.9
$E_{\Sigma BS}$ [V/m]	1.5 - 2.1	1.1 - 1.6	0.7 - 1.0

– for suburban areas covered by GSM 900 CC with BS channel EIRP 50-57 dBm for H_{OP} = 1.5 m, G = 0.08 Erl. and for the different average terrestrial density of subscribers ($\rho_{MS} = 10^2$-10^3 MS/km^2, Table 1.3);

– for rural areas covered by GSM 900 CC with BS channel EIRP 57-60 dBm for H_{OP} = 1.5 m, G = 0.08 Erl. and for the different average terrestrial density of subscribers (ρ_{MS} = 20-80 MS/km^2, Table 1.4).

Table 1.3. **Estimated EMB intensity (suburban areas, GSM 900, RFC EIRP 0.1-0.5 kW)**

ρ_{MS} [MS/km^2]	500	250	100
ρ_{AMS} [MS/km^2]	40	20	8
N_C [RFC/km^2]	5	3	1
N_{QoS} [RFC/km^2]	8	5	2
B_{TBS} [kW/km^2]	0.8 - 4.0	0.5 - 2.5	0.2 - 1.0
$Z_{\Sigma BS}$ [mW/m^2]	1.4 - 7.0	0.85 - 4.3	0.34 - 1.7
$E_{\Sigma BS}$ [V/m]	0.73 - 1.6	0.57 - 1.3	0.36 - 0.8

Table 1.4. **Estimated EMB intensity (rural areas, GSM 900, RFC EIRP 0.5-1.0 kW)**

ρ_{MS} [MS/km^2]	80	40	20
ρ_{AMS} [MS/km^2]	6.4	3.2	1.6
N_C [RFC/km^2]	0.8	0.4	0.2
N_{QoS} [RFC/km^2]	1.2	0.7	0.4
B_{TBS} [kW/km^2]	0.6 - 1.2	0.35 - 0.7	0.2 - 0.4
$Z_{\Sigma BS}$ [mW/m^2]	1 - 2	0.6 - 1.2	0.34 - 0.68
$E_{\Sigma BS}$ [V/m]	0.61 - 0.87	0.48 - 0.67	0.36 - 0.5

The results of comparing the experimental data given in [8] with the data in tables 1.1-1.4, are summarized below in Items 1-9, using the following symbols: E_{max}, E_{min} and E_{av} are maximum, minimum and average recorded EMB levels correspondingly, [V/m]; E_{Uav}, E_{SUav} and E_{Rav} are average EMB levels in urban, suburban and rural areas correspondingly; superlinear references will correspond to the reference number in the bibliography [8].

1. Austria, 2006, Hutter et al.[3]: E_{max} = 1.24 V/m, E_{Rav} = 0.13 V/m, E_{Uav} = 0.08 V/m. Recorded E_{max} value agrees with the estimations for $\rho_{MS} \approx 2500$ MS/km^2 in Table 1.2. The E_{Rav} and E_{Uav} values are significantly lower than the estimated data of the Tables 1.3, 1.4 2, which corresponds to the pessimistic nature of estimates (1) for CC business hours and also can be explained under the assumption that RFC EIRP used in this region is considerably less than typical EIRP values accepted above. The abnormal ratio of E_{Rav} and E_{Uav} is explained most probably by the fact that measurements in rural area were carried out close to the BS, and by the assumption that in rural area RFC EIRP maybe essentially higher than in urban area.

2. Austria, 2009, Tomitsch et. al.[4] (Lower Austria, 85% of OP in open area): E_{max} = 0.42 V/m, E_{av} = 0.39 V/m; these data are in good agreement with the calculated data of Tables 1.3, 1.4.

3. Germany, 2007, Bornkessel et.al.[5] (measurements near BS and in public places - hospitals, schools): E_{max} = 3.88 V/m, E_{min} = 0.03 V/m, E_{av} = 1.31-1.42 V/m;

these data are in good agreement with the calculated data of Tables 1.1, 1.2.

4. Italy, 2008, Troisi et.al.[6] (data from the national radiomonitoring system): <1 V/m (68.8%), 1-3 V/m (22.6%), 3-6 V/m (6.3%), 6-20 V/m (2.2%), >20 V/m (<0.1%). About 98% of these measurement results are in good agreement with the data in tables 1.1-1.4; model (1) does not exclude the EMB intensity at the level of 6-20 V/m (0.1-1.0 W/m^2) or more when measuring in the main lobe of the macro-BS antenna pattern.

5. Spain, 2011, Rufo et.al.[7] (measurements up to 2.2 GHz, 18 outdoor points, the predominant contribution of mobile communications): $E_{av} = 0.17$ V/m. The measured average values of the EMB intensity should be significantly lower than the maximum values at CC busy hour, this is confirmed by comparing the given E_{av} value with the calculated data of the Tables 1.1-1.4.

6. Belgium, Netherlands and Sweden, 2012, Joseph et.al.[8,9] (measurements of EMB created by BS, at 311 points, incl. 68 indoor and 243 outdoor): $E_{max} = 3.9$ V/m; $E_{Uav} = 0.74$ V/m, $E_{SUav} = 0.46$ V/m, $E_{Rav} = 0.09$ V/m. These results are in good agreement with the data in Tables 1.1-1.4 for urban and suburban areas, and 10-14 dB lower than the estimates in Tables 1.3-1.4 for the countryside, which corresponds to the pessimistic nature of the estimates (1) for open areas that do not take into account an attenuation of radio waves in buildings.

7. Greece, 2008, Gotsis et.al.[10] (data from the national radiomonitoring system for 46 different places): $E_{av} = 1.64$ V/m, which are in good agreement with the calculated data of Tables 1.1, 1.2.

8. Great Britain, 2006, Cooper et.al.[11] (public space, about 20 randomly selected GSM micro- and pico-sites): measured EMB values are in the range 0.003-1.8 V/m. The experimental data are in good agreement with the calculated data of Tables 1.1-1.4.

9. 2000-2012; Rowley et.al.[16] (results of measurements of EMB levels from BS of CC over a period of 10-11 years; 173,000 measurements, 20 countries, 5 continents): the presented global average EMB level is $E_{av} = 0.52$ V/m. This analysis covers the years when the level of CC development was significantly lower than the current level, as well as the results of measurements in places with a low density of CC subscribers; in general, the indicated global average EMB level is in good agreement with the data in Tables 1.1-1.4.

VII. Verification of (1) Using Data [17-24]

In [17-24], there is no necessary data for EMLA evaluating at places of EMB measurements, therefore, we can only compare the results of measurements of EMB intensity given in these works with the calculated data in Tables 1.1-1.4.

In [17], the following results of measurements of the maximum EMB intensity created by BS GSM 900 (955-960 MHz), GSM 1800 (1805-1810 MHz), UMTS (950-955 MHz) & LTE (1810-1825 MHz) in different places are presented: in Kosovo 2.82, 1.28, 1.58 & 1.26 V/m correspondingly, in Sweden 1.26, 2.15, 1.41 & 0.76 V/m correspondingly, in UK 2.8, 3.12, 1.03 & 0.47 V/m correspondingly.

In [18], the following measurement results for maximum EMB intensity created by BS CC in 311 locations, 68 indoor and 243 outdoor, over 35 areas in Belgium, The Netherlands and Sweden are given: 3,9 V/m for GSM 900, 2,15 V/m for GSM 1800, 2,67 V/m for DECT & 1,41 V/m for UMTS.

Paper [19] contains EMB measurement results in 23 countries across five continents since 2000 in 173,000 points. Measured EMB levels vary widely in range 0,06-20 V/m, total maximum EMB levels GSM 900/1800 ≈19,7 V/m, WCDMA ≈18,3V/m, GSM 900 ≈7,5V/m, GSM 1800 ≈7,5V/m.

Paper [20] contains EMB measurement results during 11/2002-12/2006 in many areas; more than 4,000,000 electric field strength measurements have been performed. Registered total EMB intensity was 0.2-5 V/m, contribution of GSM 1800 was 0.06-1.1 V/m, contribution of GSM 900 was 0.06-3 V/m.

Paper [21] presents the following results of measurements (Italian national electromagnetic field monitoring network) of the total EMB, created by all radio cervices in November 2006: 68,8% ≤1 V/m, 91,4% ≤3 V/m, 8,6% in the range 3-20 V/m. There is no data on the CC contribution, but it can be assumed that in 2008 it amounted 40-60%, i.e. ≤0,6-0.8 V/m (70%), ≤2-3 V/m (90%), 3-17 V/m (10%).

Paper [22] contains the results of EMB measurements in 2006 in Lower Austria (rural, suburban and urban areas, 226 participants, 154 households in rural areas, 56 in smaller cities (<10000 inhabitants), and 16 in towns); fixed maximum levels: GSM 900 ≈1V/m, GSM 1800 ≈ 1.4 V/m, DECT ≈3.3 V/m. Paper [23] presents the results of EMB measurements in Extremadura, Spain; the highest measured GSM EMB intensity was 0.632 μW/cm^2 (1,54 V/m). Paper [24] contains the results of EMB measurements created by BS of GSM, DCS and UMTS in open urban area: E_{max} = 3,9-4.6 V/m, (2017-2019).

Undoubtedly all these data are in good agreement with the calculated data of Tables 1.1-1.4, especially considering that model (1) does not exclude the presence of EMB intensity at the level of 6-20 V/m and more when measuring near the macro-BS antenna on heights more than 1.5-2 m above the ground surface.

VIII. Computer-Aided Verification [25] of (1)

The results [25] of computer verification of model (1) based on the computer behavior simulation of GSM 1800 CC network in urban areas with different building height (5-25 m) also confirm the adequacy of model (1).

The probability of not exceeding the EMB values near ground surface ($H_{OP} = 1.5$ m) obtained using (1), by estimates of EMB intensity obtained by CC network simulation, correspond to 0.845 for a building height of 5 m, and increase to 0.965 when the building height increases to 25 m. This fact confirms the useful pessimistic nature of the model (1).

IX. Conclusion

Comparison of estimates using (1) with experimental data [6-8, 17-24] indicates the adequacy of model (1) and its great practical significance.

However, taking into account the fact that the presented verification of model (1) is based on the predicting of EMLA created by CC in places of EMB measurements (due to a priori uncertainty of the raw data), this verification cannot be recognized as sufficient. For comprehensive evidence of the adequacy of the model (1), the additional measurements of EMB intensity are required in the conditions of complete accessibility of objective information about the average EMLA created by CC on areas where these measurements will be performed. In particular, more in-depth studies of the adequacy of (1) can be performed using mobile radio monitoring systems and regional databases of EMR sources.

Impact of the use an estimated or supposed typical (not real) values of BS EIRP in GSM and UMTS radio channels, on the objectivity of verification of (1) using data [6-8, 17-24], is significantly weakened due to the relatively weak sensitivity of the estimates of EMB intensity, expressed in units of EMF strength, to the change in the initial data on BS EIRP, since, for example, a 6 dB change in RFC EIRP (4 times) entails a corresponding change in EMF strength only 2 times.

Due to the fact that estimates (1) of EMB intensity are based on estimates of the average EMLA created by the EMR of CC BS, this technique is universal and fundamentally applicable for estimating the average EMB intensity for any ratios of voice and data traffic and for CC of all generations (2G/3G/4G/5G/6G...), as well as for estimating the EMB intensity created by other radio services (broadcasting, etc.).

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