Electromagnetic Background Generated by Mobile (Cellular) Communications

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***Abstract*—A practical technique for the worst-case evaluation of levels of electromagnetic background generated by cellular communication systems is proposed. It is based on the analysis of the average electromagnetic loading on area created by base and mobile subscriber's stations, and on the prediction of the area traffic capacity created by wireless information services supported by cellular communications. Such evaluations are very important for supporting the intersystem EMC, electromagnetic safety and ecological compatibility of 4G/5G/6G systems**

***Keywords*— wireless communications, area traffic capacity, electromagnetic background, EMC, electromagnetic safety, electromagnetic ecology**

I. Introduction

Full-scale implementation of 4G/5G/6G cellular communication (CC) systems with the expected deepest penetration of wireless technologies in all areas of human activity, at a significant expansion of frequency bands of CC radio frequency channels (RFC) up to hundreds MHz, an increase in data rates over these RFC up to 0.01-1 Tbit/s in RFC of BS and up to 0.1-10 Gbit/s over the user interface, a growth of spatial density of sources of EM radiation (EMR) up to 10^6-10^7 devices/km^2, as well as an increase in area traffic capacity (ATC) up to 10-10^3 Mbit/s/m^2 [1, 2] may be the cause of a catastrophic deterioration in electromagnetic (EM) ecology of human environment, an unacceptable decrease in EM safety of population, and also be a reason of harmful interference to other radio systems and services.

Electromagnetic background (EMB) generated by CC systems in places with a high population density can be considered as electromagnetic (EM) pollution of the habitat. Its intensity essentially depends on the quality of providing of intrasystem EMC in CC radio networks. Today EMB is a factor of increasing apprehension; in particular, a correlation between the potential EM pollution level and the danger of COVID-19 has been assumed [3]. Thus, the level of EM pollution of the habitat, along with other factors that worsen its ecology and the human health, may be one of the reasons for the general weakening of the human immunodefence and an increase in population susceptibility to infections like coronavirus. That determines the relevance of developing an effective technique for predicting the levels of environmental EM pollution by EMR of modern and future CC systems.

A direct calculation of the EMB intensity created by EMR of base (BS) and mobile subscriber's (MS) of CC systems is usually impossible due to the prior uncertainty of the source data. In this paper author propose and summarize a methodology elements of which are developed in [4-9], for practical assessment of the EMB intensity near earth surface created by CC, based on an analysis of the integral system characteristics of CC radio networks - the average electromagnetic loading on area (EMLA) created by a BS and MS, and the ATC produced by these systems.

II. Basic Models and Relations

The proposed technique of engineering evaluation of the average EMB intensity created by the set of BS and MS of CC in the observation point (OP) allocated near earth's surface at altitude of human height $H_{OP} = 1\ldots2$ m, is based on the following basic concepts, models and relationships:

1) The total EMB intensity Z_Σ[W/m^2] in OP means the scalar sum of values of power flux densities Z_n of EM fields created by N sources of these fields located in a zone of radio visibility of these sources from the OP:

$$Z_\Sigma = \sum_{n=1}^{N} Z_n \ . \qquad (1)$$

2) The average EMLA B [W/m^2] created by the set of K sources of EM fields, distributed over the area S [m^2], is defined as a sum of covering total radiated powers (CTRP) P_{ek} of these sources per area unit:

$$B = \frac{\sum_{k=1}^{K} P_{ek}}{S},\ P_{ek} = \frac{1}{2\pi}\int_0^{2\pi}\int_0^{\beta_m} P_k(\beta,\alpha) sin(\beta) d\beta d\alpha,\ \beta_m \le \frac{\pi}{2}; \quad (2)$$

P_{ek} is a part of EM radiation power of the k-th source, emitted by its antenna in a solid angle $\Omega \le 2\pi$ covering the underlying terrain S, minus antenna-feeder losses; $P_k(\alpha,\beta)$ is a power radiated by an antenna of this source in direction (α,β); β_m is the maximum angle in the vertical plane corresponding to the horizon (border of the irradiation area).

In cases when sources with the same equivalent isotropic radiated power (EIRP) P_e [W] of non-directional EMR are distributed over the area uniformly with average density ρ, the average EMLA created by these sources will be $B = \rho P_e$. The last, in particular, can be used when evaluating the EMLA created by MS, and also by BS in CC networks of a regular cellular structure.

Definition (2) of CTRP differs from the definition of the total radiated power (TRP) contained in [10] by integrating the radiated power not over the full solid angle 4π, but only in its part $\Omega \le 2\pi$ covering the irradiated surface. This allows us to take into account the influence of the tilt of main beams of BS antennas to the surface.

3) The average total ATC S_{tr} [bit/s/m^2] of CC wireless information services is defined as the volume of downlink traffic over the set J of BS RFC per area unit:

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$$S_{tr} = \sum_{j=1}^{J} V_{tr\,RFC\,j} \Big/ S, \quad J = \sum_{l=1}^{L} k_l , \qquad (3)$$

where S is the area, the wireless information services of which are provided by all of k_l downlink RFCs of each of L operating BS of this area; $V_{tr\,RFC\,j}$ [bit/s] is the traffic volume (data rate) of the j-th servicing downlink RFC.

III. EMB Intensity created by BS

The average total intensity $Z_{\Sigma BS}$ [W/m^2] of EMB created in OP by a set of BS located randomly uniformly (with respect to the OP position) in the area of BS radio visibility from the OP, is determined by the expression [4, 5]

$$\boxed{Z_{\Sigma BS} = Z_{\Sigma BS1} + Z_{\Sigma BS2} \approx \frac{B_{TBS}}{2} ln\left(\frac{6.6 \cdot H_{OP}}{\lambda}\right),\ H_{OP} \geq \frac{\lambda}{4}}, \quad (4)$$

$$Z_{\Sigma BS1} = \frac{B_{TBS}}{2} ln\left(\frac{4H_{OP}}{\lambda}\right),\ Z_{\Sigma BS2} = \frac{B_{TBS}}{4} , \qquad (5)$$

where λ is the wavelength of BS radiation, B_{TBS} [W/m^2] is the average EMLA in area of BS radio visibility (at least, in OP vicinity). The average EMB intensity created by BS consists of two components: frequency dependent component $Z_{\Sigma BS1}$ corresponds to the contribution of BS located in OP vicinity of free-space propagation of radio waves (RWP) between BS and OP, and frequency independent component $Z_{\Sigma BS1}$ corresponds to the contribution of BS located outside this vicinity in the area of interference (multipath) RWP.

IV. EMB Intensity created by MS

The average total intensity of EMB $Z_{\Sigma MS}$ [W/m^2] created in OP by a set of radiating MS located at a height $H_{MS} \approx H_{OP} \approx h$ above the earth's surface and distributed randomly uniformly in area of MS radio visibility from the OP, is determined by the expression [6, 7]

$$\boxed{Z_{\Sigma MS} = Z_{\Sigma MS1} + Z_{\Sigma MS2} \approx \frac{B_{TMS}}{2} ln\left(\frac{13.2 \cdot \pi h^2}{\lambda^2}\right),\ h \geq \frac{\lambda}{2\sqrt{2\pi}}}, \quad (6)$$

$$Z_{\Sigma MS1} = \frac{B_{TMS}}{2} ln\left(\frac{8\pi h^2}{\lambda^2}\right),\ Z_{\Sigma MS2} = \frac{B_{TMS}}{4} , \qquad (7)$$

where λ is the EMR wavelength, B_{TMS} [W/m^2] is the average EMLA created by radiating MS in area of MS radio visibility (at least, in OP vicinity). In (7),(8) the presence of a MS reactive near-field zone (absence of radiation at distances $R \leq \lambda/2\pi$) was taken into account.

The average EMB intensity created by MS also consists of two components: frequency dependent component $Z_{\Sigma MS1}$ corresponds to the contribution of MS located in OP vicinity of free-space RWP between MS and OP, and frequency independent component $Z_{\Sigma MS1}$ corresponds to the contribution of MS located outside this vicinity in area of interference RWP.

The EMB level Z_{MSp} caused by MS radiations, not exceeded with probability p, is related to the average EMLA B_{TMS} created by MS set in OP vicinity, by a simple relation [5, 10]:

$$Z_p \approx \frac{B_{TMS}}{4(1-p)},\ B_{TMS} \approx \rho_{MS} P_{eMS} ;\ p > 0.9 , \qquad (8)$$

where ρ_{MS} is terrestrial density of radiating MS, and P_{eMS} is its average EIRP. For UHF CC systems, the EMB level created by these MS, not exceeded with probability p≈0.99, is approximately equal to $Z_{p\approx 0{,}99} \approx 25B_{TMS}$.

Comparative estimates using (4) and (6) allow us to conclude that at uniform MS distribution over the territory, contribution of their EMR to the total intensity of EMB created by CC, is small and can be neglected. However, in places of mass gathering of MS, where their area density can exceed the average a hundred times or more (shopping and business centers, stadiums, airports, vehicles, etc.), contribution of EMR MS to the total EMB intensity created by CC turns out to be dominating.

V. EMLA Estimation in 4G/5G/6G Networks

Due to the extremely intensive increase in the quantity and spatial density of EMR sources, as well as the significant expansion of wireless information services at CC evolution to 5G/6G, direct EMLA calculation based on (2) to predict EMB intensity using (4), is practically impossible. Alternatively, the technique [9] of estimation of average EMB intensity created by wireless systems in terms of prediction of average ATC, can be proposed.

This technique is based on the following relations obtained on the basis of the well-known Shannon-Hartley theorem under the assumption that properties of the intranet interference in CC RFC are close to the properties of their internal thermal noise:

$$C_{PR} \approx \Delta F_R \cdot log_2(1 + CNIR), \quad CNIR = S_R / N_\Sigma ; \qquad (9)$$

$$W_{EP} = C_{PR} / \Delta F_R = mW_{ER} \approx log_2(1 + CNIR), \qquad (10)$$

$$\boxed{\begin{aligned} B_{TBS} &= \frac{8\pi^2 mkT_0 K_N D_\Sigma \left(2^{W_{EP}} - 1\right) R_{max}^2 S_{tr} Q}{\lambda^2 W_{EP}} = \\ &= \frac{8\pi^2 mkT_0 K_N D_\Sigma CNIR \cdot R_{max}^2 S_{tr} Q}{\lambda^2 \, log_2(1 + CNIR)} ; \end{aligned}} \qquad (11)$$

$$D_\Sigma = (K_{CC} + 1) L_m L_C K_H , \qquad (12)$$

where C_{PR} [bit/s] is the potential RFC capacity, ΔF_R is the RFC bandwidth, [Hz]; S_R is the RFC useful signal power, [W]; N_Σ is the RFC total noise power which is a sum of RFC internal thermal noise power N_0 and intrasystem interference power N_{INT}, [W]; $CNIR$ is the "carrier-to-(noise plus intrasystem interference)" ratio; k=1.38·10^{-23} W/K is Boltzmann's constant, K_N is radio receiver noise factor, T_0 is an ambient temperature (T_0=290K); W_{EP} [bit/s/Hz] is the RFC potential spectral efficiency which is m times greater than the real RFC spectral efficiency W_{ER}; D_Σ is a total necessary reserve in BS EMR power which take into account the losses L_m at RWP into buildings ($L_m \leq$20dB), the losses L_C at RWP in street canyons (which are caused by multipath phenomenon due to the reflection from buildings and earth's surface, and also by diffraction; $L_C \leq$20dB), the necessary margin K_H in levels of receiving signals for the handover implementation ($K_H \leq$10dB), and the factor $K_{CC}=N_{INT}/N_0$ which characterizes the excess of the internal thermal noise level by the intrasystem interference level. K_{CC} value is determined by the quality of the frequency-spatial planning (FSP) of CC radio network and can take values in a wide range from 0 (intrasystem interference is absent) to 100...1000 (20-30 dB) and even more at low FSP quality (at poor intrasystem EMC); R_{max} is a radius of service area (site radius of CC radio network), on the border of which ensuring the required level of useful signal on MS receiver's input needs the maximum BS EMR power.

$Q=P_{AR}/P_{AI}\leq 1$ is the system parameter of EMR BS directivity; in this ratio P_{AR} and P_{AI} are values of BS average radiating power which reaches an observation area near ground surface by the real BS antenna with horizontal and vertical selectivity, and by the ideal isotropic antenna with the same antenna gain, correspondingly. For the k-th EMR source which take part in creating the EMLA (2), $Q=P_{ek}/\max\{P_k(\alpha,\beta)\}$. In particular, if CC radio network is regular with N_S sectors on each BS, then for worst-case estimations $Q\approx 1/N_S$. can be used.

Total necessary reserve D_Σ in transmitting power is different for BS of different hierarchical levels of CC radio network structure: for internal pico-BS (access points in rooms) $D_\Sigma \leq$ 10-30dB, for external macro-BS of dense urban areas it can reach 70-80 dB in radio networks with poor intrasystem EMC (at high K_{CC} levels). Thus, under the requirements for RFC data rates of 4G/5G/6G CC, it is the value of the parameter D_Σ that actually determines the total average EMLA (11) and the total EMB intensity (4) created by CC BS, and accordingly, their EM safety, EM ecology and EMC. In some cases, when determining the D_Σ value, it is advisable to take into account the correlation between its components in (12).

Factor m in (10),(11) reflects both the ratio of potential and real RFC spectral efficiency, and the contribution of MIMO technology in its improvement. In cellular RFCs without the use the MIMO technology $m\approx 2...10$. Thus, the expected increase in CC RFC spectral efficiency due to MIMO technology by 2-8 times actually allows only to compensate approximately for the imperfectness of modulation/demodulation and coding-decoding processes. Therefore, predictable EMB analysis can be performed for $m = 1$ under the assumption that data rates in cellular RFC is close to the potential.

The dependences $Z_{\Sigma MS}(S_{tr})$ for micro-sites with R_{max}=300m calculated using (4), (11) for λ=8cm (3.75 GHz), $L_m L_C K_H$=40dB, Q=0.3, and various levels of intrasystem interference are given below in Figure 1. Figure 2 shows the same dependences, but calculated for pico-sites with R_{max}=30m и $L_m L_C K_H$=20dB. In these figures, the black curve corresponds to K_{CC}=0 (no interference), the blue, green and brown curves correspond to K_{CC}=10, K_{CC}=100, and K_{CC}=1000, respectively.

Figure 3 shows the dependences $Z_{\Sigma MS}(S_{tr})$ for pico-sites with R_{max}=30m, $L_m L_C K_H$=20dB and K_{CC}=10, for indoor wireless information services with different *CNIR* levels: at *CNIR*=10dB (black curve), *CNIR*=20dB (blue curve), *CNIR*=30dB (green curve) and *CNIR*=40dB (brown curve). In Figures 1-3, the red horizontal line corresponds to the level of 0.1 W/m^2, which is accepted in many countries as the EMB maximum permissible level (MPL) for population.

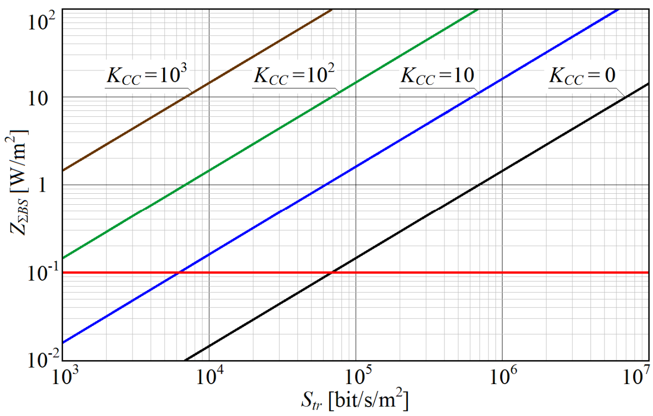

Fig. 1. Dependences of the average EMB intensity created by the CC system of a micro-site structure (R_{max}=300 m) on the average ATC produced by its micro-BS, at different quality of FSP (intrasystem EMC)

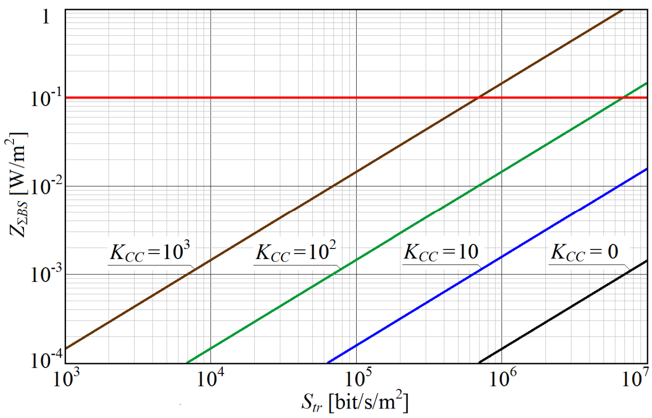

Fig. 2. Dependences of the average EMB intensity created by the CC system of a pico-site structure (R_{max}=30 m) on the average ATC produced by its pico-BS, at different quality of FSP (intrasystem EMC)

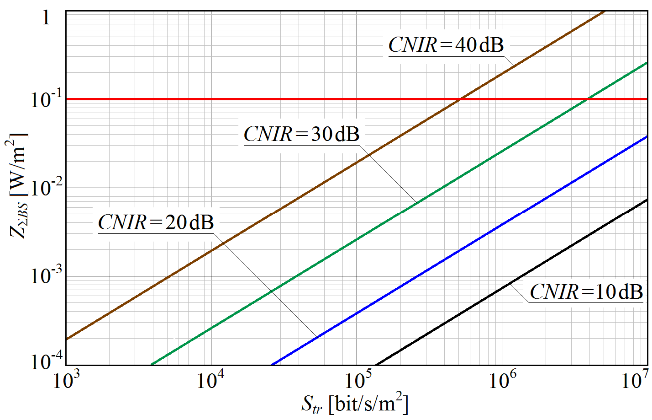

Fig. 3. Dependences of the average EMB intensity created by CC system of a pico-site structure, on the average ATC, at different *CNIR* in downlink RFCs.

Analysis of expressions (4), (11) and curves shown in Figures 1.2 allows us to conclude that operation of the upper hierarchical level of 4G/5G/6G radio networks, which will be safe for the population, even with relatively good quality of intrasystem EMC ($K_{CC}\leq$10) is possible only in cases when its BS, which are serving sites with a radius of hundreds of meters, will be used only for radiotelephony and for relatively low-speed data transmission, for which, as a rule, $S_{tr}\leq 10^3$-10^4 bit/s/m^2.

Safe public wireless information services with very high ATC levels S_{tr}=10^6-10^7 bit/s/m^2, predicted for 4G/5G/6G networks, is possible only in pico sites of pico-BS with maximum communication range of no more than 20-30 m while ensuring high RFC spectral efficiency and devoting much attention to intrasystem EMC.

Analysis of curves in Figure 3 allows us to illustrate the rather obvious conclusion that the safe operation of indoor access points and, in general, the safe operation of pico-BS of 4G/5G networks with the maximum expected ATC levels can be provided at $CNIR \leq$20-25dB.

Figure 4 shows the dependences $Z_{MSp}(B_{TMS})$ (and also curves $Z_{MSp}(\rho_{MS})$ for P_{eMS} = 0.1 W) of EMB level created in OP vicinity by the prevailing MS radiations, not exceeded with different probabilities p; the solid red horizontal line corresponds to the MPL level of 0.1 W/m^2, which is determined taking into account the danger of non-thermal effects of exposure of radio frequency EM fields on the human body; the dash red horizontal line corresponds to the level of 10 W/m^2, allowed by ICNIRP taking into account the thermal effects of EMF exposure on biological tissues.

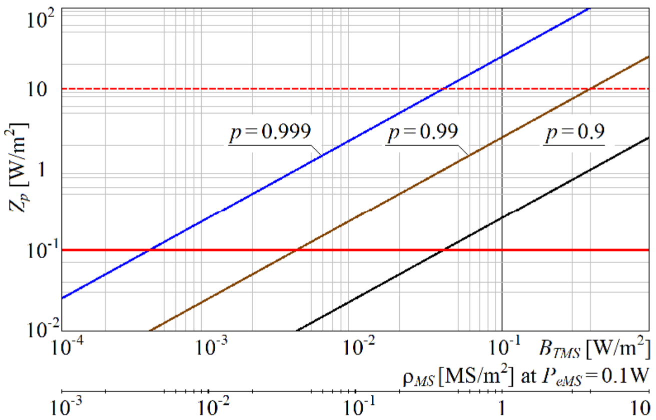

Fig. 4. Dependences of the EMB level threshold not exceeded with different probabilities p in OP by the prevailing MS radiations, on the average EMLA created by radiating MS distributed in OP vicinity.

Plots in Figure 4 illustrate the real danger of the creation of unacceptable EMB levels in places with a high area density of radiating MS (1-10 MS/m^2) declared in [1, 2] for developed 5G/6G networks, even with a relatively small MS EIRP (10-100 mW).

VI. Conclusion

Expression (4) given above provide the possibility of use the technique [4, 5, 9] for estimating the EMB intensity (1) created by the set of BS allocated in CC service area, based both on direct EMLA calculation using (2), and on the forecast of the average ATC (3) created by wireless public information services during busy hours, using (11).

Expressions (6), (8) provide the possibility of use the technique [6, 7, 11] for estimating the total EMB intensity created by the set of MS distributed in OP vicinity.

Since the EMB estimations based on the direct EMLA assessment (2), are in good agreement with the published results of EMB measurements [8], one should also expect a good agreement between the results of experimental EMB analysis and the proposed technique [9] of EMB analysis on the basis of ATC prediction, with the use of (11).

Expressions (11) make it possible to quantify the effectiveness of different ways of reduce the total EMB intensity created by CC, by reducing the reserve D_Σ (12) in BS EMR power, which provides a reserve for fading, for attenuation in buildings, for handover and for intranetwork EMC, and also by decreasing the value of the system parameter Q of the BS EMR directivity.

And, in general, expressions presented above provide the ability to substantiate quantitatively the safe and EMC-compromise scenarios of intensive development of 4G/5G/6G technologies, systems and services in accordance with declarations [1, 2, etc.], assuming a reasonable combination of wireless and wired solutions at different CC hierarchical levels without compromising the volume and quality of information services in all areas of human activity.

The proposed technique for the worst-case estimation of the expected EMB intensity created by CC, based on the forecast of EMLA and ATC, facilitates significantly both the procedures for analyzing the EM ecology of densely populated areas and the EM safety of the population under conditions of extremely intensive development of new generations of CC, as well as the analysis the EMC of radio systems of primary and secondary radio services.

References

[1] IMT Vision – Framework and overall objectives of the future development of IMT for 2020 and beyond, Rec. ITU-R M.2083, 2015.

[2] Z.Zhang et al., 6G Wireless Networks: Vision, Requirements, Architecture, and Key Technologies, IEEE VT Magazine, vol. 14, no. 3, pp. 28-41, Sept. 2019.

[3] V.I. Mordachev, Correlation between the potential electromagnetic pollution level and the danger of COVID-19. 4G/5G/6G can be safe for people. Doklady BGUIR. 2020; 18(4): 96-112. DOI: http://dx.doi.org/10.35596/1729-7648-2020-18-4-96-112.

[4] V.Mordachev, Worst-Case Models of Electromagnetic Background Created by Cellular Base Stations, Proc. of the 9th Intern. Wireless Comm. & Mobile Comp. Conf. (IWCMC 2013), Cagliari, Sardinia, Italy, July 1-5, 2013, pp.590-595.

[5] V.Mordachev, Worst-Case Estimation of Electromagnetic Background Near Ground Surface Created by Heterogeneous Radioelectronic Environment, Proc. of the EMC 2015 Joint IEEE Int. Symp. on Electrom. Compat. and EMC EUROPE, Dresden, Germany, Aug. 16-22, 2015, pp. 1147-1152.

[6] V.Mordachev, Worst-Case Estimation of Electromagnetic Background Created by Cellular Mobile Stations Near Ground Surface, Proc. of Intern. Symp. “EMC Europe 2014”, Gothenburg, Sweden, Sept. 1-4, 2014, pp.1275-1280.

[7] V.Mordachev, System-Level Estimation of Prevaling Levels of EM Fields of Mobile Phones Considering Near-Field Zone Limitations of Their Antennas, Proc. of Intern. Symp. "EMC Europe 2017", Angers, France, Sept. 4-8, 2017, 6p.

[8] V.Mordachev, Verification of Worst-Case Analytical Model for Estimation of Electromagnetic Background Created by Mobile (Cellular) Communications, Proc. of the 2020 Int. Symp. “EMC Europe 2020”, Rome, Italy, Sept. 23-25, 2020, 6 p.

[9] V.Mordachev, Estimation of Electromagnetic Background Intensity Created by Wireless Systems in Terms of the Prediction of Area Traffic Capacity, Proc. of the Intern. Symp. "EMC Europe 2019", Barcelona, Spain, Sept. 2–6, 2019, pp.82-87.

[10] CEPT Report 67, July 6, 2018, p.17.

[11] V.Mordachev, S.Loyka, On Node Density – Outage Probability Tradeoff in Wireless Networks, IEEE JSAC, 27, 7, Sept. 2009, pp.1120-1131.