Estimation of the Electromagnetic Background Created by Low-Earth Orbit Satellites, Based on the Prediction of the Ground Area Traffic Capacity

Vladimir Mordachev, Dzmitry Tsyanenka
EMC R&D Lab, Belarusian State University of Informatics and Radioelectronics, Belarus
mordachev@bsuir.by, tsiond@tut.by

***Abstract* — A technique for analysing levels of the ground electromagnetic background (EMB), created by constellations of low-earth orbit communication satellites (LEOS), based on estimates of the average area traffic capacity generated by them at the earth's surface, and available system characteristics of LEOS and their constellations, such as orbit altitude, characteristics of antenna patterns, limitations on the angle of LEOS antenna main lobe direction to the earth's surface, and features of servicing scenarios for ground subscriber terminals. Obtained estimates of the average EMB levels, corresponding to the expected values of the average area traffic capacity generated by LEOS constellations, are sufficiently higher than the levels of natural microwave EMB on the earth's surface, which agree with estimates obtained earlier using data on the LEOS total radiated power and their quantity in the constellation, and confirms the adequacy of the presented technique.**

***Keywords* — low earth orbit satellites, electromagnetic radiation, area traffic capacity, electromagnetic background.**

I. INTRODUCTION

Creation of mega-constellations of low-earth orbit communication satellites (LEOS) in near-earth space (Starlink, OneWeb, Astra, Kuiper, GuoWang, Sfera, etc.) will increase by several orders of magnitude the number of space sources of microwave electromagnetic radiation (EMR) in the direction of the earth's surface. Such a development, under certain conditions, can lead to an unacceptable complication of the electromagnetic environment (EME) for systems of various radio services operating in the frequency bands of these LEOS constellations on the earth's surface and in airspace on a secondary basis, as well as to a significant increase in the intensity of the electromagnetic background (EMB), which can exacerbate the problems of electromagnetic safety of the population and the electromagnetic ecology of the habitat, especially when integrating these satellite communication systems (SCS), providing high speeds and relatively low delays in the transmission of information to ground subscriber terminals (ST), with global 5G/6G mobile communication systems.

The authors previously developed a method [1] for analyzing the average EMB intensity created by LEOS constellations based on estimates of the number of satellites in the constellation, the LEOS total radiated power and EMR parameters in the main (ML) and side (SL) lobes of radiation patterns of their antennas (AP), the altitude of the LEOS orbit, and restrictions on the angle at which MLs of their antennas can be directed to the earth's surface when servicing the ST. The method allows one to analyze the statistical and integral power EME characteristics, represented as an ensemble of N radio-frequency electromagnetic fields (EMF) created by multitude of N LEOS at an observation point (OP) near the earth's surface and is very useful for the diagnostics of intersystem EMC of LEOS megaconstellations with radio services near earth surface and with population.

A disadvantage of the method proposed in [1] is a certain difficulty in collecting the necessary initial data, sometimes classified as confidential.

The aim of this work is to develop a methodology that allows to analyze the EMB characteristics at the earth's surface created by LEOS constellations, based on estimates of the average total Area Traffic Capacity created by LEOS at the earth's surface – the *ATC* parameter [bit/s/m2], and the available LEOS system characteristics, such as the orbits altitudes, the number of orbital shells, the characteristics of antennas directivity of LEOS and ST, and restrictions on the elevation angle at which the "LEOS-ST" communication channel can be implemented.

II. ANALYSIS TECHNIQUE

When analysing the EMB characteristics at the earth's surface created by LEOS radiations, we will use models [1] and approach [2] to assess the average level of EMB created by mobile communication systems, based on the *ATC* forecast.

A. Required Power of the Useful Signal at the Input of the ST Radio Receiver.

1) According to the Shannon-Hartley theorem, the radio channel potential capacity V_P [bit/s] is determined by the following relationships:

$$\left.\begin{aligned} &V_P \approx \Delta F_R \cdot log_2\left(1+SNIR_P\right), \\ &\upsilon_P = \frac{V_P}{\Delta F_R} \approx log_2\left(1+SNIR_P\right), \\ &SNIR_P \approx p_0/\left(p_N + p_{INT}\right) = 2^{\upsilon_P} - 1 \end{aligned}\right\} , \qquad (1)$$

where υ_P [bit/s/Hz] is the potential spectral efficiency of data transfer in a radio channel with a bandwidth of ΔF_R [Hz], $SNIR_P$ is the "signal-to-noise-plus-interference" ratio; $p_0 \approx const$, $p_N = kT_0K_N \approx const$ and $p_{INT} \approx const$ [W/Hz] are the power spectral densities of the radio signal, the receiver's own noise and interference in the ΔF_R band, respectively; k is the Boltzmann constant, $1.38 \cdot 10^{-23}$ J/K; K_N is the noise figure of radio receiver; T_0 is the ambient temperature, [K] (T_0=290K).

2) The actual data rate V_R of in the communication channel is m times less than the potential channel capacity V_P; the actual data rate spectral efficiency υ_R of in the channel is the same number of times less than the potential spectral efficiency υ_P. Ensuring a data transmission rate equal to V_P at a constant ΔF_R requires an essential increasing the actual ratio $SNIR_R$ in the channel with comparison to the $SNIR_P$ level. In this case

$$\begin{gathered}\upsilon_R = \frac{\upsilon_P}{m} = \frac{log_2\left(1 + SNIR_P\right)}{m} = \frac{log_2\left(1 + SNIR_R\right)^{1/m}}{m} \approx \\ \approx \frac{log_2 SNIR_R}{m^2}; \quad SNIR_R \approx SNIR_P^m.\end{gathered} \tag{2}$$

Parameter m in (2), reflecting the ratio of radio channel potential and actual characteristics, allows us to take into account the contribution of MIMO technology [3] to increasing the spectral efficiency of data transmission over the radio channel and in some cases can be less than one. But in cellular (mobile) communication radio channels without using MIMO technology $m \approx 2...10$ [4], and the achievable increase in spectral efficiency in these radio channels due to MIMO technology by 2–8 times actually allows only to compensate for the imperfection of the modulation/demodulation and coding-decoding processes. Therefore, it is of interest to perform estimates for $m = 1$ under the assumption that the data transmission rate V_R in cellular (mobile) communication radio channels is close to the potential in definition (1): $V_R \approx V_P$.

3) The minimum required power of the useful signal P_0 in radio channel (the actual sensitivity of radio reception), which ensures the capacity V_P of the radio channel with thermal noise of power $P_N \approx p_N \Delta F_R$ and interference of power $P_{INT} \approx p_{INT} \Delta F_R$ is determined by the following relationship (neglecting the differences in the influence of intra-network interference and thermal noise on the radio channel capacity):

$$P_0 = p_{N\Sigma} \Delta F_R SNIR_P,\ p_{N\Sigma} = \left(K_{CC} + 1\right) p_N,\ \frac{p_0}{p_{N\Sigma}} = SNIR_P, \tag{3}$$

where $p_{N\Sigma}$ is the total spectral power density of the internal noise and interference in the radio channel; coefficient $K_{CC} \approx P_{INT} / P_N$ characterizes the excess of the interference level over the thermal noise level; its value is determined by the quality of frequency-spatial planning of communication system, the operation of other communication systems in adjacent radio channels, as well as the presence of systems of other radio services in the same frequency bands on a secondary basis, and can take values in a wide range from 0 (there is no intra-network interference) to 10 or more at the low quality of ensuring intra-system and inter-system electromagnetic compatibility (EMC).

B. Energy Per Bit at Data Radio Reception by ST.

At the minimum required power of the useful signal P_0 at the input of the ST radio receiver, the minimum required signal energy for receiving 1 bit of information at a rate of V_P [bit/s] must not be lower than the following value, [J/bit]:

$$E_{b\,r} = \frac{P_0}{V_P} = \frac{\left(K_{CC} + 1\right) p_N \left(2^{\upsilon_P} - 1\right)}{\upsilon_P} = \frac{\left(K_{CC} + 1\right) p_N \cdot SNIR_P}{log_2\left(1 + SNIR_P\right)}. \tag{4}$$

Since the energy required for the reception of one bit of information by the ST can be calculated through the power flux density (PFD) of LEOS radiation at the earth's surface and the equivalent area of the ST receiving antenna, it is possible to determine this PFD value and the corresponding radiation power in ML of the LEOS antenna, which is necessary for transmitting one bit of information to the serviced ST located on the earth's surface.

For this purpose, we use the following idealized two-level model of the ST AP [1], in which the AP ML has a conical shape with a width of $\Delta\varphi_{ST}$, and the ratio of the powers in the reception mode for the AP main (P_{MST}) and side (P_{SST}) lobes is equal to C_{PST}:

$$\begin{gathered}G_{MST} = \frac{C_{PST}}{\left(1 + C_{PST}\right) sin^2\left(0.25 \cdot \Delta\varphi_{ST}\right)}, \\ G_{SST} = \frac{1}{\left(1 + C_{PST}\right) cos^2\left(0.25 \cdot \Delta\varphi_{ST}\right)},\ C_{PST} = \frac{P_{MST}}{P_{SST}},\end{gathered} \tag{5}$$

where G_{MST} is the ST antenna gain by the ML (the antenna efficiency $\eta = 1$ within the framework of the considered model), G_{SST} is the ST antenna gain by the SL level, assumed to be constant in all directions outside the ML. In this model, with a relatively small ML width ($\Delta\varphi_{ST} \leq 20°$), the SL level depends little on $\Delta\varphi_{ST}$: $G_{SST} \approx 1/(1+C_{PST})$.

The antenna effective area S_{eST} of a ground ST at receiving a satellite signal by a main conical lobe of width $\Delta\varphi_{ST}$ is equal to

$$S_{eST} = \frac{G_{MST}\lambda^2}{4\pi} = \frac{C_{PST}\lambda^2}{4\pi\left(1 + C_{PST}\right) sin^2(0.25\Delta\varphi_{ST})}. \tag{6}$$

Thus, the PFD Z_E [W/m^2] created by LEOS EMR at the earth's surface at the location of the serviced ST, at $m = 1$, can be determined as follows:

$$
\begin{aligned}
Z_E &= \frac{P_0}{S_{eST}} = \frac{4\pi P_0}{G_{MST}\lambda^2} = \frac{4\pi\Delta F_R\left(K_{CC}+1\right)p_N\left(2^{\upsilon_P}-1\right)}{G_{MST}\lambda^2} = \\
&= \frac{4\pi\Delta F_R\left(K_{CC}+1\right)p_N SNIR_p}{G_{MST}\lambda^2}.
\end{aligned}
\tag{7}
$$

C. Estimates of Radiated Energy Per Bit of Information Based on Propagation Losses.

Using a two-level model (5) with parameters P_{MSC}, P_{SSC}, C_{PSC} (radiation powers on the ML and SL; their ratio, respectively), G_{MSC}, G_{SSC} (levels of the ML and SL, respectively) to represent the characteristics of the LEOS radiation, we will determine the required radiated energy per bit of transmitted information, taking into account the radio waves attenuation on the “LEOS–ST” radio link.

In order for the signal at the receiver input to have energy (4), the following conditions must be met:

a) radio signals must be emitted by the LEOS transmitters with a power that compensates for the basic losses at radio wave propagation (RWP) from the LEOS transmitter antenna to the ST receiver antenna [5]; in relation to the case under consideration, we will limit ourselves to taking into account the losses L_{bf} at RWP in free space (since the “LEOS–ST” radio links of SHF and EHF frequency ranges are direct-visibility radio links, only a small part of which covers the atmosphere dense layers and in most cases are implemented at frequencies at which signal attenuation in atmosphere can be neglected, including in the transparency windows of the lower part of the millimeter range);

b) LEOS radiation power can be reduced by using directional antennas of satellites and ST, since the losses L at signal transmission over a radio link are determined by the known relationship [5]:

$$
L = L_{bf}/\left(G_T G_R\right), \tag{8}
$$

where $G_T = G_{MSC}$ and $G_R = G_{MST}$ are gain factors of LEOS transmitting antennas and ST receiving antennas, respectively.

Attenuation at radio frequency transmission with a wavelength λ in free space at a distance R and signal transmission losses over a radio line are determined by the following expression [6]:

$$
L_{bf} = \left(\frac{4\pi R}{\lambda}\right)^2, \quad L = \frac{L_{bf}}{G_{MSC}G_{MST}} = \frac{16\pi^2 R^2}{\lambda^2 G_{MSC}G_{MST}}. \tag{9}
$$

The radiated energy per bit of transmitted data must be provided at a level not lower than $E_{bt} = E_{br}L$:

$$
\begin{aligned}
E_{bt}(R) &= \frac{E_{br}L_{bf}}{G_{MSC}G_{MST}} = \frac{16\pi^2\left(K_{CC}+1\right)p_N\left(2^{\upsilon_P}-1\right)R^2}{\lambda^2 G_{MSC}G_{MST}\upsilon_P} = \\
&= \frac{16\pi^2\left(K_{CC}+1\right)p_N \cdot SNIR_P R^2}{\lambda^2 G_{MSC}G_{MST}\, log_2\left(1+SNIR_P\right)}.
\end{aligned}
\tag{10}
$$

If the data rate over the “LEOS–ST” radio channel with frequency band ΔF_R corresponds to its potential capacity (1), then the power $P_{MSC}(R)$ emitted in LEOS ML and LEOS total radiated power $P_{TRSC}(R)$, $P_{TRSC} = P_{MSC}+P_{SSC}$) can be determined as follows depending on the distance R between LEOS and ST:

$$
\left.
\begin{aligned}
&P_{MSC}(R) = E_{bt}(R)V_P = YR^2,\; P_{TRSC}(R) = P_{MSC}(R)\frac{1+C_{PSC}}{C_{PSC}}; \\
&Y = \frac{16\pi^2\left(K_{CC}+1\right)p_N\left(2^{\upsilon_P}-1\right)\Delta F_R}{\lambda^2 G_{MSC}G_{MAT}} = \\
&= \frac{16\pi^2\left(K_{CC}+1\right)p_N SNIR_P \Delta F_R}{\lambda^2 G_{MSC}G_{MST}}.
\end{aligned}
\right\}
\tag{11}
$$

To obtain the dependence of the total radiated power $P_{TR\,SC}(V_R)$ in a real radio channel “LEOS–ST” on its required real capacity V_R for the given parameters contained in (11), we modify the relation (10) using (1), (2) as follows:

$$
\begin{aligned}
E_{bt}(R) &= \frac{16\pi^2\left(K_{CC}+1\right)p_N\left(2^{M\upsilon_R}-1\right)R^2}{\lambda^2 G_{MSC}G_{MST}M\upsilon_R} = \\
&= \frac{16\pi^2\left(K_{CC}+1\right)p_N M\left[\left(1+SNIR_R\right)^{1/M}-1\right]R^2}{\lambda^2 G_{MSC}G_{MST}\, log_2\left(1+SNIR_R\right)}.
\end{aligned}
\tag{12}
$$

In these relationships, it is also necessary to take into account that the distance R between the satellite and the ST is determined not only by the orbit altitude H_S and elevation angle θ at which LEOS ML is directed to the earth's surface, but also by the earth's surface curvature - its sphericity with a radius R_E (Fig. 1):

$$
R = \sqrt{R_E^2\, sin^2\,\theta + H_S^2 + 2R_E H_S} - R_E\, sin\,\theta. \tag{13}
$$

D. Average Area Traffic Capacity and EMB Level.

Depending on the scenario of LEOS operation with a circular orbit of constant altitude H_S, the distance R between the LEOS transmitting antenna and the OP on the earth's surface falling into the ML "irradiation spot" (Fig. 1) can be taken either fixed or variable within certain limits.

Scenario 1. If LEOS uses a narrow conical beam of width $\Delta\varphi_{SC}$ with a constant tilt angle ε with respect to the tangent to the orbit or with a fixed elevation angle θ of the direction of arrival of the LEOS signal to the ground ST (Fig. 1), then the distance from the satellite - a source of the EMR to the OP in the irradiation spot on the earth's surface is practically constant: $R \approx$ const. Thus, in this scenario, the required LEOS total radiated power $P_{TRCS}(R)$ can be determined directly using (11).

Scenario 2. If LEOS and ST use narrow conical beams of width $\Delta\varphi_{SC}$ and $\Delta\varphi_{ST}$, respectively, with variable tilt angles ε with respect to the tangent to the orbit or with variable elevation angles θ of the direction of arrival of the LEOS signal to the ground ST in such a way that in the range of elevation angles $\theta \in [\theta_{\min}, 90°]$, $\theta_{\min} \geq 0°$, when MLs of satellite and ST antennas are directed at each other, then the interval of distance values between the LEOS and ST is equal to $R \in [H_S, R_m \leq R_{\max}]$ (Fig. 1). With an equally probable LEOS location at different points of the orbit, the distance (13) is also random with the probability distribution density (p.d.d.) $w(R)$, which has the following form [1]:

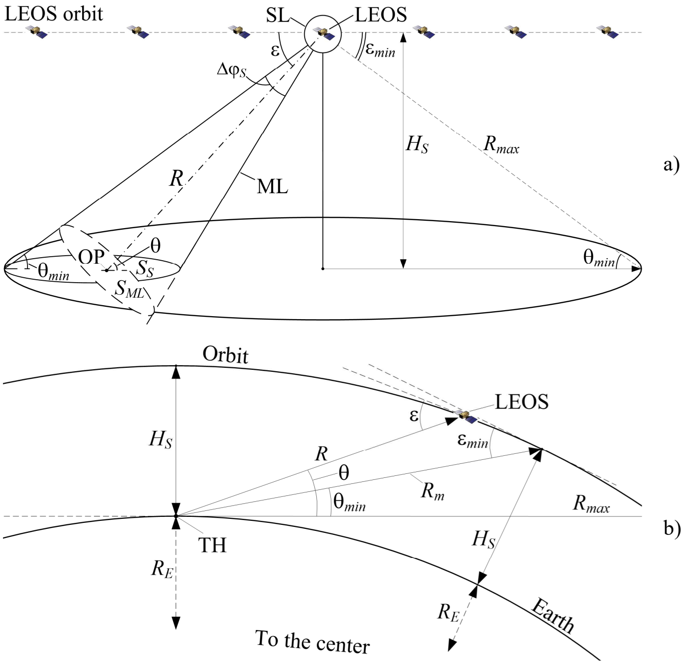

Fig. 1. Mutual arrangement of the LEOS and the ground observation point (OP): a) - formation of a main lobe (ML) "spot" on the earth's surface, b) - taking into account the sphericity of the earth's surface

$$\begin{gathered} w(R) = 2R\big/\left(R_m^2 - H_S^2\right), \\ H_S \leq R \leq R_m \leq R_{max}; \quad R_{max} = \sqrt{2R_E H_S + H_S^2}. \end{gathered} \tag{14}$$

When analysing this scenario, the following options should be taken into account:

1) Availability of P_{MLS} Adaptive Power Regulation

If P_{MLS} power control in SCS is used ($P_{MSC}(R) \approx P_{TRSC}(R)$), the constant value is the required power P_0 of the useful signal (3), which determines the specified capacity of the "LEOS–ST" radio channel. The random variables are the required LEOS total radiated power $P_{TRSC}(R)$ and the required level of radiated energy per bit of transmitted data $E_{bt}(R)$. The p.d.d. $w(E_{bt})$ and the mathematical expectation $\langle E_{bt}\rangle$ can be determined using the well-known method [1]:

$$\left.\begin{aligned} w(E_{bt}) &= \frac{1}{E_{bt\,max} - E_{bt\,min}} = \frac{1}{X\left(R_m^2 - H_S^2\right)}, \\ \langle E_{bt}\rangle &= \frac{E_{bt\,max} + E_{bt\,min}}{2} = \frac{X\left(R_m^2 + H_S^2\right)}{2}. \end{aligned}\right\} \tag{15}$$

$$\left.\begin{aligned} X &= \frac{16\pi^2 (K_{CC}+1) p_N \left(2^{m\upsilon_R} - 1\right)}{\lambda^2 G_{M\,SC} G_{M\,AT} m \upsilon_R} = \\ &= \frac{16\pi^2 (K_{CC}+1) p_N m\left[\left(1+SNIR_R\right)^{1/m} - 1\right]}{\lambda^2 G_{M\,SC} G_{M\,AT} \log_2\left(1+SNIR_R\right)}. \end{aligned}\right\} \tag{16}$$

The average area traffic capacity ATC_A, created on the earth's surface by EMRs of all N_{SC} LEOS belonging to the SCS, via downlink radio channels "LEOS-ST" with a capacity of each channel V_{CH} bit/s, is equal to:

$$ATC_A = V_{CH} N_{SC} \big/ \left(4\pi R_E^2\right). \tag{17}$$

III. Analysis Results and Discussion

The calculated $ATC_A(C_{CH})$ dependencies for different numbers N_S of LEOS are shown in Fig. 2a.

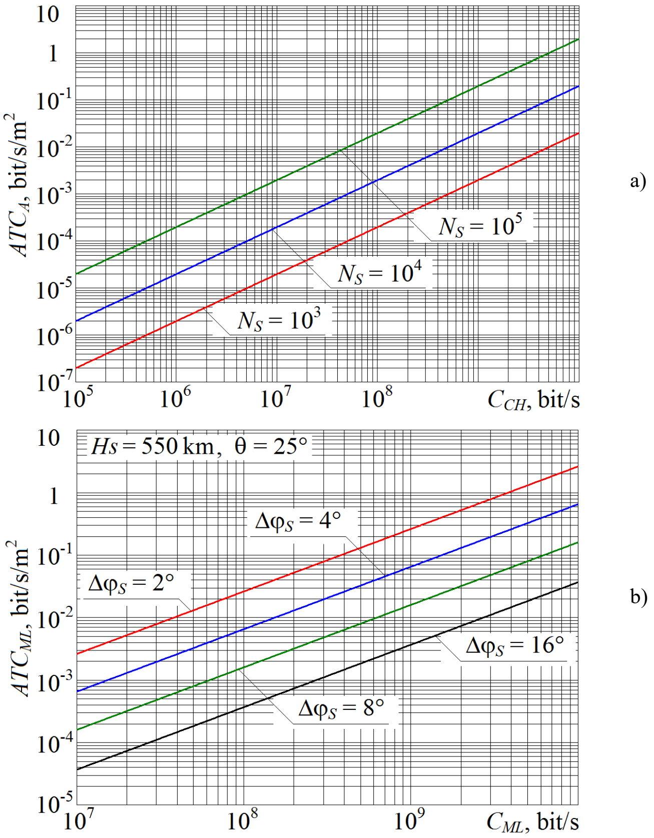

Fig. 2. Calculated dependencies of the average area traffic capacity on the data transfer rate in the downlink radio channel (C_{CH}) and in the LEOS main lobe (C_{ML}): a – $ATC_A(C_{CH})$ dependencies for different LEOS numbers in their constellation; b – $ATC_A(C_{ML})$ dependencies in the LEOS main lobe "spot" on the earth's surface for $\theta = 25°$, $H_S = 550$ km and different main lobe width $\Delta\varphi_S$.

The area traffic capacity ATC_{ML}, created by the EMR of a single LEOS in ML spot on the earth's surface, is equal to the ratio of the downlink radio channel data transmission rate $V_{ML} = V_{CH}$ bit/s and the area S_S of the ML spot on the earth's surface. Calculating S_S (see Fig. 1 and [1]), we obtain:

$$\left.\begin{aligned}&ATC_{ML} = V_{CH}/S_S \approx \\ &\approx \frac{V_{CH}\,2tg(\varepsilon+0.5\Delta\varphi_S)tg(\varepsilon-0.5\Delta\varphi_S)sin(\varepsilon)}{\pi H_S^2\left[tg(\varepsilon+0.5\Delta\varphi_S)-tg(\varepsilon-0.5\Delta\varphi_S)\right]\cdot tg(0.5\Delta\varphi_S)}.\end{aligned}\right\} \quad (18)$$

Calculated dependencies $ATC_{ML}(C_{ML})$ for different values of the ML width $\Delta\varphi_S$ are shown in Fig. 2b. These dependencies indicate that average area traffic capacity that can be created by SCS near the earth's surface is 6-8 orders of magnitude lower than the level declared [7] for 5G mobile communication systems, and 8-10 orders of magnitude lower than the level declared [8] for 6G systems.

If the average area traffic capacity ATC_A bit/s/m^2 is known, then in this scenario, when all energy radiated by LEOS in the ML reaches the earth's surface, the average EMB intensity Z_{ATC} created by these radiations at the earth's surface can be determined using (15), (17):

$$Z_{ATC} = \langle E_{bt} \rangle \cdot ATC_A . \quad (19)$$

Fig. 3a - 3d show the calculated dependences of the EMF level $Z_{ATC}(ATC_A)$ (19) for $\lambda = 2$ cm (15 GHz), $K_{CC} = 2$, $m = 2$, $\theta_{min} = 0°$ and the real ranges of change of G_{MSC}, G_{MAT}, υ_R, $SNIR_R$. Double digitization of scales is used: digitization in black font corresponds to the range of ATC_A values declared in [7, 8], for 4G/5G/6G systems, and digitization in color font corresponds to the range of ATC_A values corresponding to the data in Fig. 2.

The peculiarity of these dependencies is that the average ATC is considered constant over the entire earth's surface, regardless of the real uneven "focal" distribution of information service consumers across the territory. This can explain the fact that with hypothetical ATC values corresponding to 4G declarations (10^5 bit/s/m^2), the average intensity of the created EMB is relatively slightly lower than the maximum permissible level (MPL) of 10 μW/cm^2; at ATC = 10^7 bit/s/m^2, declared for 5G, the average EMB intensity is close to the MPL only at very high directivity of the satellite and ST antennas ($G_T = G_R = 40$ dB), and at $ATC = 10^9$ bit/s/m^2, declared for 6G, the calculated average intensity of the generated EMB is close to levels corresponding to the ICNIRP “thermal” recommendations, and even significantly exceeds these levels at $G_T = G_R < 40$ dB.

This means that the average ATC levels declared for 4G/5G/6G systems, as well as the calculated average EMB levels illustrated by the graphs in Fig. 3a - 3d, are peak levels, typical for small areas (hotspots) equipped with SCS terminals, onto which data flows from LEOS are “focused”, and where EMB is created by radiations from multiple access points (pico-BS) of hotspots.

The calculated Z_{ATC} levels in Fig. 3a - 3d, corresponding to the range of real average ATC_A values [10^{-4}, 10^2] bit/s/m^2 (color digitization of scales horizontally and vertically), are 2–3 orders of magnitude higher than levels [9] of natural EMB in the range of 10 – 20 GHz and are close to previously performed estimates [1] of the created average EMB intensity using data on the LEOS total radiated power P_{TRSC} and the number of LEOS in SCS, which can serve as confirmation of the adequacy of the model (19).

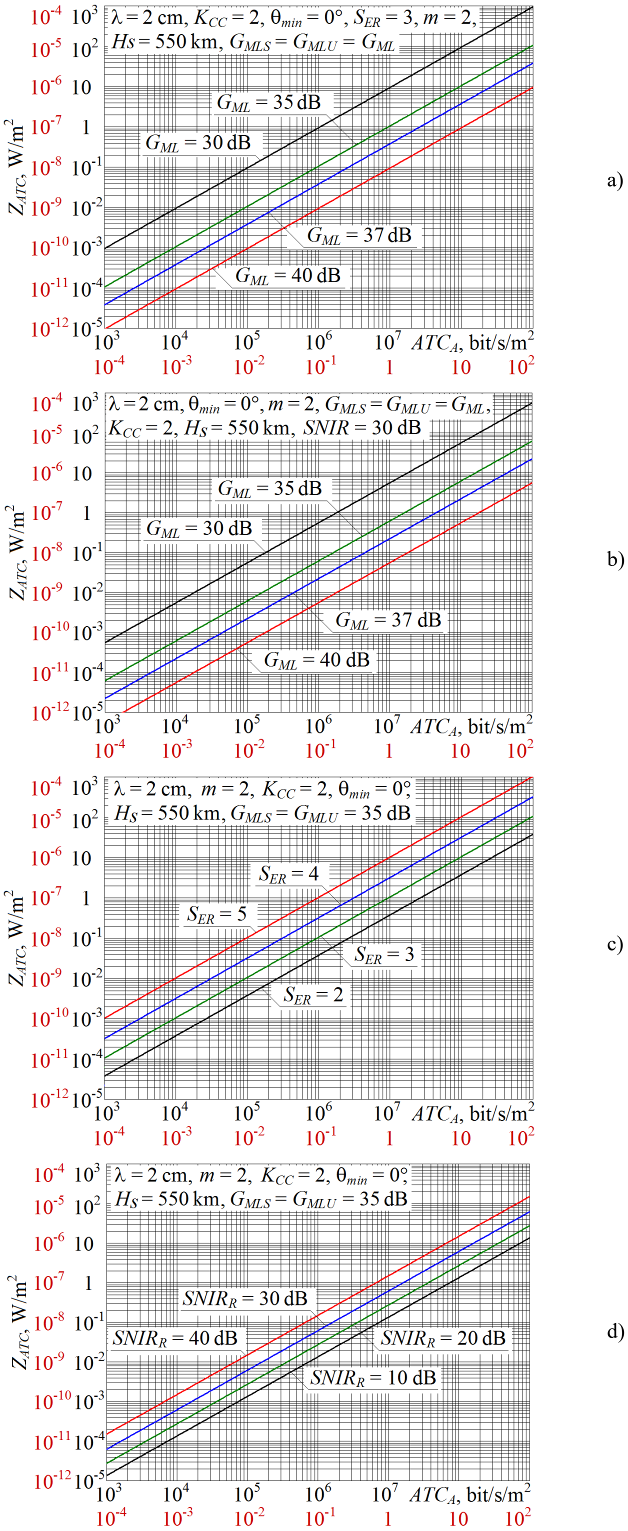

Fig. 3. Calculated $Z_{ATC}(ATC)$ dependencies for the previously adopted radio channel typical characteristics: a –for $S_{ER} = 3$; b –for $SNIR_R = 30$ дБ; c –for different radio channel spectral efficiency; d –for different $SNIR_R$ ratios in radio channel.

2) P_{MLS} *Power Control in SCS is Absent.*

If the P_{MSC} control in SCS is absent, P_{TRSC} is fixed and ensures constancy of the radiated energy per bit of transmitted data in the downlink radio channel: $E_{bt} = const$. The random variables are values of PFD created by LEOS radiation at the location of the earth-based serviced ST, the power of useful signal P_0 and *SNIR* at the ST receiver input, and the radio channel capacity V_P. The receiving energy E_{br} of 1 bit of data depends on the random variable R with p.d.d. (14). P.d.d. $w(E_{br})$ and mathematical expectation $<E_{br}>$can be determined using (10) according to the known technique [1]:

$$\left.\begin{aligned}
&w(E_{br}) = \frac{E_{br\,min}E_{br\,max}}{(E_{br\,max} - E_{rb\,min})E_{br}^2},\ E_{br\,min} \le E_{br} \le E_{br\,max};\\
&E_{br\,min} = \frac{E_{bt}G_T G_R \lambda^2}{16\pi^2 R_m^2},\quad E_{br\,max} = \frac{E_{bt}G_T G_R \lambda^2}{16\pi^2 H_S^2};\\
&\langle E_{br}\rangle = \frac{E_{br\,min}E_{br\,max}}{E_{br\,max} - E_{br\,min}} ln \frac{E_{br\,max}}{E_{br\,min}},
\end{aligned}\right\} \quad (20)$$

where R_m is determined by formula (13) at $\theta = \theta_{min}$.

Using (1)–(4), the values of $E_{br\,min}$, $E_{br\,max}$ can be related to the minimum and maximum values of ratios $SNIR_P$, $SNIR_R$ and to the corresponding values of spectral efficiency υ_P , υ_R:.

$$\left.\begin{aligned}
&E_{br\,min} = \frac{(K_{CC}+1)p_N m\left((1+SNIR_{R\,min})^{1/m}-1\right)}{log_2(1+SNIR_{R\,min})} =\\
&= \frac{(K_{CC}+1)p_N\left(2^{\upsilon_{P\,min}}-1\right)}{\upsilon_{P\,min}} = \frac{(K_{CC}+1)p_N\left(2^{m\upsilon_{R\,min}}-1\right)}{m\upsilon_{R\,min}},\\
&E_{br\ max} = \frac{(K_{CC}+1)p_N m\left((1+SNIR_{R\,max})^{1/m}-1\right)}{log_2(1+SNIR_{R\,max})} =\\
&= \frac{(K_{CC}+1)p_N\left(2^{\upsilon_{P\ max}}-1\right)}{\upsilon_{P\,max}} = \frac{(K_{CC}+1)p_N\left(2^{m\upsilon_{R\ max}}-1\right)}{m\upsilon_{R\,max}},
\end{aligned}\right\} (21)$$

where

$$\left.\begin{aligned}
&\upsilon_{P\,min} \approx log_2(1+SNIR_{P\,min}),\ \upsilon_{P\,max} \approx log_2(1+SNIR_{P\,max}),\\
&SNIR_{P\,max}/SNIR_{P\,min} = R_m^2/H_S^2.
\end{aligned}\right\} (22)$$

Using (20) and (4), we can estimate the EMB value at the earth's surface, created both in the ML spot of a separate LEOS and in the entire SCS, as well as changes in $SNIR_R$, υ_R and Z_{ATC} with a change in the distance between the ST and the LEOS due to its movement along the orbit. However, it is obvious that, due to the relatively small dynamic range of changes in the distance R between them, these estimates will differ relatively little from the estimates given in Fig. 3a – 3d.

The average power of the received signal $<P_0>$ is equal to the product of the average energy (20) of one bit of this signal $<E_{br}>$ by the rate V_P of data reception: $<P_0> = V_P<E_{br}>$. The average PFD value $<Z_{STA}>$, created by LEOS in ML spot, which ensures the data reception by the ST with an antenna of effective area S_{eST}, will be equal to $<Z_{STA}> = <P_0>/S_{eST}$. In this case, the power P_{rSC} radiated in ML of LEOS antenna can be determined through the area S_{ML} of the surface subtending the ML solid angle (Fig. 1a) by the product: $P_{rSC} = S_{ML} <Z_{STA}>$.

IV. CONCLUSION

The paper presents the main methodology propositions that allows to analyze characteristics of the EME near the earth's surface based on estimates of the average *ATC* created by LEOS constellations, and their available system characteristics. The initial data include the orbit altitude, the number of LEOS in the SCS, the LEOS antennas directivity patterns, and restrictions on the elevation angle at which ST servicing is allowed, as well as the features of ST servicing scenarios.

The calculated EMB levels corresponding to the range of *ATC* real values generated by LEOS constellations on the earth's surface are 1-3 orders of magnitude higher than the levels of natural EMB [9] in the frequency band of 10-20 GHz. This corresponds to the estimates in [1], which were obtained using data on the LEOS total radiated power and their number in the SCS, which can serve as a confirmation of the adequacy of the developed methodology for EMB estimating.

Reception/transmission of large data volumes via SCS radio channels for individual consumers instead of using the terrestrial infrastructure of 4G/5G mobile networks can provide a significant local reduction in the intensity of radio frequency EMB near the earth's surface to levels several orders of magnitude lower than the established MPL for the population. Therefore, the integration of low-orbit SCS and terrestrial 4G/5G/6G systems can become a promising way to ensure electromagnetic ecological compatibility and safety of these systems for the population.

Integration of SCS with terrestrial systems can be based on the creation of hot spots and local clusters equipped with one ST, which implements a "wired", fiber-optic or low-energy wireless user access for receiving/transmitting data of SCS and terrestrial 4G/5G/6G radio networks.

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