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Electromagnetic Compatibility of Low-Orbit Mega-Constellations and Terrestrial Radio Systems

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***Abstract* — A technique for analyzing the electromagnetic compatibility (EMC) of low-orbit mega-constellations (LOMC) with terrestrial radio systems is developed. The technique is based on estimating the power flux density (PFD) at the Earth's surface of radio-frequency electromagnetic radiation generated by satellites of mega-constellation. The initial data for the assessment of PFD are the system characteristics of mega-constellation: the height of orbital shells, the number of satellites in one shell, the capacity of space-to-Earth channels, the parameters of antennas of satellites, user earth stations (UES), and gateway earth stations (GES). The developed technique has been applied to analyze the EMC of a LOMC with radio relay communication links (RRL) that uses frequencies in the band 17.7–19.3 GHz on a secondary basis. It has been established that with an increase in the number of satellites and gateway earth stations in a LOMC, the probability of interference created by LOMCs to the functioning of RRL decreases due to the increasing of the elevation angle of satellites connecting with GES and the spatial selection of satellite radiation by RRL antennas. However, the increase in the number of deployed LOMC requires tightening the operating rules for each of them to ensure EMC with terrestrial radio systems.**

***Keywords* — electromagnetic compatibility, worst-case models, satellite communication systems, terrestrial radio systems, radio relay communication.**

I. INTRODUCTION

The development of broadband Internet access, Direct-to-Cell technologies, Internet of Things (IoT), Machine-to-Machine (M2M) and Business-to-Business (B2B) communications, automatic identification systems (AIS), and navigation satellite systems (GNSS) increases the demand for high-speed data transmission services. This determines the expansion of numerous low-orbit satellite constellations [1].

The existing satellite constellations of communication (SCC) (Globalstar second-generation, Orbcomm OG2, Iridium Next) are being developed [1]. The Starlink Gen1 constellation (consisting of 4408 low-orbit communication satellites (LOCS) in accordance with the Application [2]) and OneWeb (Gen1) (planned number of LOCS is 720 according to Application [3]) have been put into operation.

A number of SCC are in the design stage, the largest of which (consisting of more than 100 LOCS) are Astra (13 620 LOCS), Project Kuiper (3 263 LOCS), Guo Wang (12 992 LOCS), Stellar, Hughes, Orbit20, Hanwa Systems, Genesat, Efir/Sfera [1]. Applications have been submitted to expand and update the low-orbit mega-constellations (LOMC) Starlink V2 (29 988 satellites according to [4]) and OneWeb (47 844 satellites [5]). Thus, the total number of LOCSs may soon exceed 100 000, and the number of gateway earth stations (GES) may reach of about 1 000.

At present, a set of international and national regulations has been created [6]–[10] to ensure electromagnetic compatibility (EMC) of SCC, broadcasting, identification, navigation, and other satellite systems with each other as well as with terrestrial radio systems. For example, Article 21 of the Radio Regulations (RR) [6] contains restrictions on the power flux density (PFD) generated by the satellite service on downlinks. These restrictions should ensure protection of terrestrial radio services from interference in the frequency bands of 10.7–12.7 and 17.7–19.3 GHz. However, a rapid development of LOMC requires to clarify these documents on the basis of already available data about the operating constellations [2], [3] and taking into account possible trends in their development [1], [4], [5]. An example of such clarifications is the introduction of amendments to Article 21 of the RR (compare [6] and [7]), which eliminate the contradictions in the analysis of LOMCs (see [2]–[5]).

The solution of problems deal with the PFD created by emissions of LOCSs on the Earth's surface is important not only for specialists ensuring the functioning of LOMC, but also for specialists designing terrestrial radio systems, specialists in radio astronomy and in electromagnetic ecology. To solve these problems, the analysis should be carried out for a set of LOMCs, the satellites of which create a contribution to the PFD on the Earth's surface. Note that the fulfillment of the requirements of Articles 21 and 22 of RR [6] by each LOMC does not guarantee the absence of interference to ground- and terrestrial systems from all satellite constellations functioning simultaneously. Therefore, the development of a technique for express assessment of the PFD created on the Earth's surface by a set of satellite constellations is an actual task.

The purpose of this work is to develop a technique based on worst-case models that allow estimating the PFD on the Earth's surface for analysis of the EMC of LOMCs and terrestrial radio systems (TRS). The initial data for analysis are only available information about the system characteristics of satellite constellations.

II. ESTIMATION OF PFD CREATED ON THE EARTH'S SURFACE BY LOMC RADIATION

A. Dependence of PFD on the Earth's Surface on System Parameters of LOMC

Low-orbit mega-constellations, which provide broadband Internet access, serve user earth stations (UES) within the beams formed by the satellite antennas. Each beam, which corresponds to a frequency channel of a given bandwidth, has a narrow main lobe (ML) and irradiates a certain region of the Earth's surface (after it is called as beam spot). To reduce the level of intra-system interference, neighboring beam spots correspond to radio channels of different frequencies and polarizations. As a rule, right and left circular polarizations are used in LOMC downlink channels [2], [3].

To ensure high quality of communication services (high speed of information transfer with low probability of errors) provided by the LOMC, while fulfilling the requirements [6] for the PFD of electromagnetic (EM) radiation created by LOCS on the Earth's surface, the parameters of the equipment of the ground and space segments are being improved. Let us determine the relationship between the restrictions on the value of the PFD, the information transfer rate and the system parameters of the LOMC.

The power of the intended signal P_s received by the UES, determines the information transfer rate C_R in the downlink channel with a bandwidth of Δf by formula:

$$P_s = P_n\left(2^{C_R/\Delta f} - 1\right), \tag{1}$$

where P_n is the total noise and interference power, which depends on the receiver characteristics and radio reception conditions:

$$P_n = P_0 K_N (1 + K_C),\ P_0 = kT_0\Delta f,\ K_C = P_I/P_0, \tag{2}$$

where P_0 is the receiver noise power (in W); K_N is a noise figure (in times); K_C is the ratio of interference power P_I to the noise power P_0 (I/N, in times); $k = 1.38 \cdot 10^{-23}$ J/K is Boltzmann constant; T_0 is the receiver temperature (it is chosen equal to $T_0 = 290$ K for all receivers under consideration).

Power P_s is expressed by the PFD of the EM radiation Z_T, which incidents on the receiving antenna placed in the beam spot by formula [11]:

$$P_s = Z_T A_R F_R(\delta, \varphi)|\xi|^2(1 - |\Gamma_R|^2), \tag{3}$$

where $F_R(\delta, \varphi)$ is the normalized antenna pattern (AP) of the receiving antenna (by the power); δ is the angle relative to xOy plane in the system of reference (SR) associated with the receiving antenna (axis Ox of this SR is directed along the axis of the antenna radiation ML); φ is the angle in the plane xOy relative the Ox axis; ξ is the polarization coefficient; Γ_R is the reflection coefficient of current waves from the receiving antenna load; A_R is the effective area of the receiving antenna:

$$A_{R\,i} = \lambda_i^2 G_{R\,\max}/(4\pi\,\eta_R), \tag{4}$$

where λi is the wavelength corresponding to the carrier frequency of i-th beam, $\lambda i = c/f_i$; c is the speed of EM waves in free space; $G_{R\,\max}$ is the maximum antenna gain of the receiving antenna; η_R is the antenna efficiency.

For the worst-case estimation, it is supposed that $|\xi|^2 = 1$, $\eta_R = 1$ for receiving antenna of UES, $\Gamma_R = 0$ (the UES antenna is matched with the load in the working frequency band), and the ML of the UES antenna is directed on the LOCS servicing the beam spot: $F_R(\delta, \varphi) = 1$.

By substitution of (2) in (1), equaling the resulting expression to (3), and taking into account (4), we obtain the following formula for PFD Z_i, which is created by i-th beam of LOCS for the carrier frequency of f_i and the bandwidth of Δf_i, when the information transfer rate is C_R:

$$Z_i = \frac{4\pi B(C_R, \Delta f_i, K_N, K_C)\, f_i^2}{c^2 G_R(f_i)}, \tag{5}$$

where $B(C_R, \Delta f_i, K_{N1}, K_{C1})$ is multiplier (in W) that depends on the system parameters of LOMC:

$$B(C_R, \Delta f_1, K_N, K_C) = kT_0\left(2^{C_R/\Delta f_i} - 1\right)\Delta f_i K_N (1 + K_C). \tag{6}$$

Formulas (5), (6) show that for a given value of the PFD Z_i in the beam spot, the potential information transfer rate C_R in the beam is increased with an increase in the gain of the UES receiving antenna and decrease in the level of noise and interference. The bandwidth Δf_i, corresponding to the beam, is limited by the frequency range specified in [6] for connecting of LOCS with UES via downlink channels, by the distribution of frequency range by beams, and by the number of beams, which is determined by the number of simultaneously served subscribers and their distribution on the Earth's surface.

The normalized AP $F_T(\chi, \psi)$ (by power) of LOCS antenna characterizes the non-uniformity of the PSD distribution over the beam spot area. The PFD value created in the center of the beam spot is twice more than at the spot boundary determined by the –3 dB level. The PFD value in the observation point (OP) on the Earth's surface is obtained by multiplying (5) by $F_T(\chi, \psi)$, where the angles χ, ψ determine the direction on the OP relative to the direction of the ML axis of the LOCS transmitting antenna.

B. Estimation of PFD in Center of Spot for Beam Providing the Downlink Channel LOCS–UES

Let us compare the results obtained using (5) by substituting data that characterize the Starlink Gen1 system with the limits given in Article 21 [6] for the frequency band used for downlink channels of communication between the LOCS and the UES (10.7–12.7 GHz). Each beam corresponds to the channel with the bandwidth of $\Delta f = 240$ MHz [2]. Thus, each LOCS of Starlink Gen1 can simultaneously transmit information by 8 beams of the LOCS–UES downlink channels in one polarization. According to [2], [12], the maximum information transfer rate is $C_{R\,AT\,\max} = 850$ Mbit/s in the radio channel corresponding to one beam. Then, for the specified Δf and $C_{R\,AT\,\max}$, and for the following parameters of the UES receiver $K_N = 3$ (5 dB), $K_C = 0.25$ ($I/N = -6$ dB), the signal/(interference + noise) ratio is 10.64 and the output power of the UES's receiving antenna is $P_{sA} = 3.8 \cdot 10^{-11}$ W. Active phased array antennas [2], [12], which have dimensions of about 0.4×0.4 m and the effective area $A_{R\,\max} = 0.15$ m^2 (according to the estimation given in [12]) are used as UES's antennas in the Starlink Gen1. Then the PFD in the center of beam spot calculated according to (5), (6) is equal to $Z_{A\,\max} = 2.6 \cdot 10^{-10}$ W/m^2 (or $Z_{A/4k} = -144$ dB W/m^2/4kHz for the reference bandwidth of 4 kHz). This PFD value satisfies the requirements of Article 21 [6] for beams radiated by satellites with an elevation angle $\delta \geq 25^0$ for given OP.

To provide the same information transfer rate in the LOCS–UES downlink channels for all permissible beam positions, the LOCS of Starlink Gen1 automatically adjusts the equivalent isotropically radiated power (EIRP) and UES orients the ML of its antenna in the direction of servicing beam. The formula for the dependence of EIRP E_T on the distance R between LOCS and UES in the approximation of free space radio wave propagation (RWP) is:

$$E_T = 4\pi R^2 Z_{A\,\max}, \tag{7}$$

where $Z_{A\,\max}$ is defined by formula (5) and

$$R = \sqrt{2R_E(H_s + R_E)(1 - \cos(\alpha)) + H_S^2}, \tag{8}$$

$$\alpha = 0.5\pi - \delta - \arcsin\left(\frac{R_E \cos\delta}{R_E + H_S}\right), \tag{9}$$

where R_E is the Earth radius; H_s is the altitude of the LOCS at the circular orbit and δ is the elevation angle of the LOCS relative the UES, $\alpha(\delta)$ is the angle between the direction to the LOCS and to the UES from the center of Earth.

Similar estimates based on the worst-case approach were made for the OneWeb SCC, where beam EIRP control is not implemented. Assuming free space RWP, with the given orbit altitude $H_S = 1200$ km and PFD $Z_{A/4k} = -144$ dB W/m^2/4kHz, we obtain the value for the OneWeb satellite antenna EIRP: $E_{\max/4k} = -11$ dB W/4kHz.

The obtained values of the PFD and EIRP coincide with an accuracy of 3 dB with the corresponding values given by operators of LOMCs (see Applications [2] and [3]) for the communication channels LOCS–UES. This confirms the adequacy of the developed model based on the consideration of the system parameters of the LOMCs and the correctness of the estimation of these parameters.

C. Estimation of PFD in Center of Spot for Beam Providing the Downlink Channel LOCS–GES

Frequency band 17.7–19.3 GHz is used for the realization of communication channels between the LOCS and the GES (for example, in the LOMC Starlink Gen1, frequencies of 17.8–18.6 GHz and 18.8–19.3 GHz [2] are used for this aim). To analyze the satisfying the LOMC radiation to requirements of Article 21 [6] in this frequency band within the framework of the worst-case model, we assume that the information transfer rate in the LOCS–GES channel is equal to the maximum information transfer rate in one communication channel LOCS–UES multiplied by the number of that channels realized by the satellite (for each of polarizations):

$$C_{RG\,\max} = N_{R\,AT} \cdot C_{R\,AT\,\max}. \tag{10}$$

When the number of beams in one polarization is $N_{R\,AT} = 8$ (as in Starlink Gen1 and OneWeb), and maximum information transfer rate in one LOCS–UES beam is $C_{R\,AT\,\max} = 850$ Mbit/s, maximum information transfer rate in one LOCS–GES beam is $C_{R\,G\,\max} = 6.8$ Gbit/s. So, in the framework of worst-case model, the calculation by (1), (2) for $\Delta f_G = 1.3$ GHz, $K_N = 3$, $K_C = 0.25$ gives for the power at the receiving GES antenna output the value $P_{sG} = 7.1 \cdot 10^{-10}$ W. Taking into account that the effective area of GES antenna for Starlink Gen1 is $A_G = 1.4$ m^2 (according to estimation made in [12]), we can calculate using (5) the maximum value of PFD on the Earth surface in the spot of beam created by LOCS with the orbit altitude of 550 km for $\delta = 90^0$. The PFD under consideration is $Z_{G\,\max} = 5.1 \cdot 10^{-10}$ W/m^2 or for the reference bandwidth of 1 MHz: $Z_{G/1M} = -124.1$ dB (W/m^2/1MHz). This value coincides with the value given in [2] and satisfies the requirements of Article 21 [6] in the frequency band of 17.7 – 19.7 GHz for beams arriving in OP from satellites that have the elevation angle $\delta \geq 25^0$.

To calculate the limitations on the PFD value for $\delta < 25^0$, the formulas depending on the quantity X are given in [6], [7]. The value of X in [7] depends on the total number of satellites in constellation. The use of formulas given in [7] leads to the no-adequate results for PFD created by SCC containing of more than 840 LOCSs (see [2]). As an alternative approach, it was proposed in [5] to use the estimations of PFD in accordance with ITU-R F.1495 [13]. The refinement of PFD calculation technique given in [6] takes into account only LOCS, which are in the line of sight (LOS) from the OP under consideration.

In accordance with [6], the number of satellites in line of sight is defined as the maximum visible satellite's number calculated for different observation points and for different points in time. The number of OP and points in time is not specified and can be large. It is assumed that the modeling can be carried out by the use of specialized software, see [8]–[10].

D. Estimation of Maximum Number of LOCS in Line of Sight for Observation Point at Earth's Surface

The initial data for the estimation of maximum number of LOCS in line of sight for given observation point are the number of orbital shells S, the number of orbits in the shell M_s, and the number of satellites in the orbit N_{sm} (m is the number of the orbit, s is the number of the shell). The orbit altitude H_s and orbit inclination I_s are used too.

The line of sight region for the given OP at the Earth's surface in the case of LOMC with the circular orbits of the altitude of H_s is the cone with the apex in the Earth's center and the angle $\alpha_{LOS\,s}$ at the cone axis:

$$\alpha_{LOS\,s} = arc\cos\frac{R_E}{R_E + H_s}\ . \tag{11}$$

The analysis is carried out for the uniform distribution of LOCSs at the orbits and the uniform distribution of orbits in the shell as it is realized in the operating LOMCs Starlink Gen1 [2] and OneWeb [3] (and planned for realization in new generations of LOMCs [4], [5]). Consideration of low-orbit constellations ($H_s \ll R_E$) is carried out in the approximation when $\sin\alpha_{LOS} \approx \tan\alpha_{LOS} \approx \alpha_{LOS}$. To estimate the maximum number of LOCS in line of sight, the OP at the Earth's surface is selected in the region with the latitude $\Theta \leq I_s - \alpha_{LOS\,s}$ (for all of shells s). Than the number of orbits, which will be in the line of sight region is:

$$N_{s\,V} = \mathrm{ceil}(2\alpha_{LOS\,s} M_s/\pi), \tag{12}$$

where "ceil" is the function that returns the integer number nearest to the result of dividing.

$$N_{LOS\,max} = \sum_{s=1}^{S}\left[\frac{N_{sm}}{\pi}\sum_{k=0}^{N_{sV}/2}\left(\sqrt{{\alpha_{LOS\,s}}^2 - \left(\frac{\pi \cdot k}{M_s}\right)^2}\right)\right]. \tag{13}$$

If the shift angle for the satellites at the neighboring orbits is $\Delta\varphi = \pi/(2N_{sm})$, as it is realized in Starlink Gen1, then it is necessary to subtract the value $N_{sV}/2$ from (13).

III. EMC ANALYSIS OF LOW-ORBIT MEGA-CONSTELLATIONS AND TERRESTRIAL RADIO SYSTEMS

A. Worst-Case Model for Calculation of Power Received by Antenna of Terrestrial Radio System

Maximum gain of the receiving antenna of terrestrial radio system is G_{R2} and its normalized AP is $F_{R2}(\delta_2, \varphi_2)$, where angles δ_2, φ_2 determine the direction to the LOCS relative the ML axis of this antenna. Suppose that for antennas of terrestrial radio system $\Gamma_{R2} = 0$ (since they use the working frequencies of LOMC at the secondary basis) and use (5), (6), we can write (3) in the form:

$$P_{R2} = \frac{G_{R2}}{G_R} B(C_R, \Delta f_1, K_{N1}, K_{C1}) F_{R2}(\delta_2, \varphi_2) F_T(\chi, \psi) |\xi_{12}|^2, \quad (14)$$

where G_R is the antenna gain of ground segment of LOMC (UES or GES), ξ_{12} is the polarization coefficient taking into account the influence of LOCS radiation to receiving conditions of antennas of the terrestrial radio system.

In [6]–[9], the concept of equivalent power flux density (EPFD) was introduced to analyze the influence of the space segment on terrestrial systems. To calculate EPFD, the software described in [10] is used. In the general case, the EPFD created at Earth's surface in OP by all beams of LOMCs under consideration is changed during the time and for estimation of the worst-case scenario, which corresponds to maximum EPFD value, it is necessary to carry out statistical simulations [9]. Obtained result is compared with the limits that specified for the time percentage for which the EPFD created by radiation of all LOCSs in OP may exceed the value specified in Article 22 [6].

The analysis of the interference criterion for protecting terrestrial fixed services (FS) from time-varying aggregate interference created by other radiocommunication services sharing the 17.7–19.3 GHz frequency band uses the technique presented in [13]. The technique is based on the definition of the interference-to-noise ratio $I/N = K_{C2}$ ($K_{C2} = P_{R2}/P_{02}$, see (1) written for FS receivers) and analysis of I/N for cases of long-term and short-term excesses of the limiting values. Here, the interference power $P_{\Sigma R2}$ is the power radiated by the set of beams of all LOCSs belonging to the considered LOMC and received by the FS antenna, for example, the antenna of radio relay (RRL) station. So, it is necessary to calculate the sum of expressions (14) for the angles of arrival of EM radiations from different satellites. Then, based on (5), (6), interference-to-noise ratio takes the form:

$$K_{C2} = \frac{G_{R2}}{G_R k T_0 \Delta f_2} B(C_R, \Delta f_1, K_{N1}, K_{C1}) |\xi_{12}|^2 D(F_{R2}, F_T), \quad (15)$$

$$D(F_{R2}, F_T) = \sum_{i=1}^{N_{\delta\max}} F_{R2}(\delta_{2i}, \varphi_{2i}) F_{Ti}(\chi_{2i}, \psi_{2i}), \quad (16)$$

where Δf_2 is the bandwidth of working frequency band of terrestrial FS (RRL in the case under consideration); ξ_{12} is the polarization coefficient for taking into account the influence of radiation of LOCS to the receiving conditions of RRL antenna (it is chosen the same for all LOCS antennas and RRL antennas).

The number $N_{\delta\max}$ of LOCSs that irradiate the region of the terrestrial FS antenna placement is obtained by the use of the method described in Section II-D. This region is limited by the angle α_{lim} calculated by (9) through the minimum elevation angle $\delta_{\min}$, for which the servicing of ground segments of LOMC by downlink beams of LOCS is allowed.

B. Worst-Case Analysis of Influence of Downlink Channels LOCS–GES on the Receiving Antennas of Terrestrial FS

Within the worst-case model for the downlink channels LOCS–GES, it is assumed that for the normal operation of the LOMC, the GES establishes communication channels with all LOCS that have an elevation angle greater than the minimum angle specified for the LOMC (for example, not less than 5° for Starlink Gen1 [2]). The GES is a complex of antennas localized over a small area on the Earth's surface [2], [12]. When moving in orbit, the ML of the LOCS's antennas intended for communication with the GES are constantly directed towards the location of the GES: $F_{Ti}(\chi_{G\,i}, \psi_{G\,i}) = 1$. Within the worst-case model, it is supposed that the information transfer rate via the LOCS–GES channels is maximum (10). The distribution of orbits in the shell and the distribution of satellites in orbits are uniform: the distance between the LOCSs is the same in each orbit; the shift angles between the satellites in adjacent orbits of the shell are constant. To ensure the maximum value of the power received by the RRL antenna, it is also assumed that this antenna is located near the GES and the direction of its ML lies in the plane tangent to the Earth's surface and in the plane of one of the LOMC's orbit. In this plane azimuthal angle $\varphi_2 = 0$, and the angle of arrival of radiation from the LOCS to the RRL antenna is equal to the elevation angle δ of the LOCS (Fig. 1a). Fig. 1 shows the instantaneous position of the LOCS closest to the GES. This position ensures the maximum interference power from the one of the orbital shell of LOMC to the RRL station. Parameters of the orbital shell under consideration are as follows: $H_1 = 550$ km, $N_{1,1} = 1548$ [2].

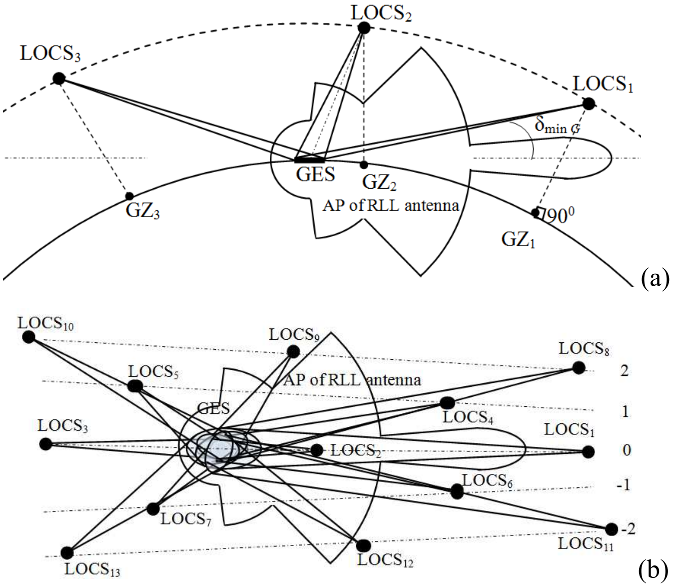

Fig. 1. Instantaneous position of LOCSs: (a) in the vertical plane; (b) in the projection onto the Earth's surface.

For LOMC Starlink Gen1 [2], the number of LOCS at one orbit of the shell under consideration is $N_1 = 22$ [2], [12]. The angle between LOCS moving on the same orbit is 16.3°. The considered orbit shell of Starlink Gen1 contains $M_s = 72$ orbits and the angle between the neighboring orbits is 2.5°. For minimum elevation angle $\delta_{\min G} = 5°$ allowed for channel LOCS–GES in LOMC Starlink Gen1, each GES can establish connections with LOCSs moving on 15 nearest orbits of the considered shell. The numbers of orbits are as follows: (-7,-6…-1,0,1…6,7). In Starlink Gen1 [2], positions of LOCSs moving at neighboring orbits differ by the shift angle $\Delta\varphi = 8.8°$. Therefore, in the worst case, GES can establish connection with 9 LOCSs on orbits with the numbers -2, 0, 2, with 4 LOCSs moving on orbits with numbers -1, 1, and with 10 LOCSs at the remaining orbits (by 1 LOCS at each remaining orbit), see Fig. 1.

Medium- and low-gain RRL antennas (by terminology of [14]) are considered here. A medium-gain antenna (type 1) is characterized by the ML width defined by level of –3 dB of $\theta_{3dB1} = 1°$ (the AP is considered as axially symmetric). A low-gain antennas (type 2) has $\theta_{3dB2} = 3°$. Then the ratios of the antenna diameters to the wavelength for the working band are equal to $D_1/\lambda = 70$, $D_2/\lambda = 23$ respectively, and the maximum values of gains are as follows: $G_{R2\max1} = 44.5$ dBi, $G_{R2\max2} = 35$ dBi [14]. The graphs of normalized APs of RRL antennas of types 1 and 2 are shown in Fig. 2.

All LOCS's beams have a circular polarization [2] and RRL antennas have a linear working polarization [14]. Then, based on the worst-case estimation presented in [15], the polarization coefficient is $|\xi_{12}|^2 = 0.5$ in (15). Quantity (6) is $B(C_R, \Delta f_1, K_{N1}, K_{C1}) = 4.3 \cdot 10^{-10}$W for $C_{RG} = 6.8$ Gbit/s and $\Delta f_{1G} = 1.3$ GHz (for each polarization, see Section II-C). Working bandwidth of RRL is $\Delta f_{RC} = 500$ MHz [13], [14]. Maximum gain of GES antennas for LOMC Starlink Gen1 is $G_{RG1} = 47.7$ dBi (by estimation [12]). To calculate the sum in (15), the values of normalized AP of RRL antennas for elevation angles that determine the positions of LOCSs relative the GES (and nearest RRL station) are needed. These angles can be estimated on the basis of LOMC Starlink Gen1 parameters: δ_{KA1}=5.0°, δ_{KA4}=20.3°, δ_{KA6}=17.2°, δ_{KA8} = 5.7°, δ_{KA9}=40.2°, δ_{KA12}=35.1°. For the remaining LOCSs, angles of deviations from the axis of AP are more than 48° and the normalized AP value for these beams is constant (see Fig. 2).

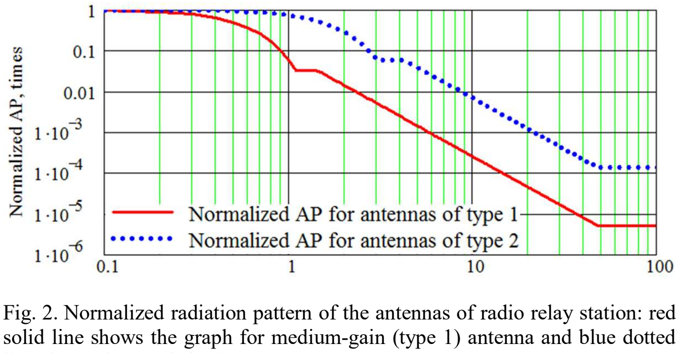

Fig. 2. Normalized radiation pattern of the antennas of radio relay station: red solid line shows the graph for medium-gain (type 1) antenna and blue dotted line shows the graph for low-gain (type 2) antenna.

Using normalized AP of RRL antennas shown in Fig. 2, the value of K_{C2} calculated by (15) is $K_{C2(1)} = 0.305$ (or –5.5 dB) for antennas of type 1 and $K_{C2(2)} = 0.916$ (or –0.38 dB) for antennas of type 2.

C. Evaluation of Long-Term Excesses of the Interference-to-Noise Ratio Limit

The values of EPFD obtained above in the framework of the worst-case model are instantaneous values, which correspond to positions of the LOCS's and GES's antennas given in Fig. 1. To compare the obtained results for *I/N* with the limits given in [13], it is necessary to estimate the time of excesses of these limits by *I/N* when LOCSs are moving at orbits. The dependence of the elevation angle $\delta(t)$ of LOCS on the time is defined by the formula:

$$\delta_{si}(\mathrm{t}) = \left|\arccos\left(\frac{(R_E+H_s)\sin(\omega t+\Delta\varphi_i)}{\sqrt{(2R_EH_s(1-\cos(\omega t+\Delta\varphi_i)))+H_s^2}}\right)\right|, \qquad (17)$$

where ω is the angular velocity of LOCS at the orbit (rad/s) depending on the orbit altitude: $\omega \sim (R_E + H_s)^{3/2}$; t is the time, point in time $t = 0$ corresponds to the following position of LOCS No. 1: $\delta_1(0) = 90°$.

Satellites moving in the shell under consideration are distributed uniformly, therefore the same spatial arrangement of LOCSs and maximum value of K_{C2} will repeated for the given OP with the period $T_{NKA} = 2\pi/(N_1\omega)$ (for Starlink Gen1 $T_{NKA} = 270$ s). It follows from (15) and parameters of the normalized AP of RRL antennas (Fig. 2), value of *I/N* do not excess –10 dB until $\delta_{i1}(t) \geq 6.4°$ for antennas of the type 1 and until $\delta_{i2}(t) \geq 13.1°$ for antennas of type 2. Using (17), we obtain that the time corresponding to changing of the elevation angle δ from 6.4° to 5.0° is 3.1 s. The changing of δ from 13.1° to 5.0° corresponds to the time interval of 18 s. In the arrangement of LOCS corresponding to the worst case (Fig. 1), the LOCS with No. 1, 4, 6, 8, 11 make the main contribution in power of interference received by RRL antenna. The following configuration, for which the value of *I/N* excess the value of –10 dB is determined by the emission of LOCS with No. 4, 6, 2, 9, 12. The others configurations of LOCSs moving on the orbits do not lead to exceeding the level –10 dB by *I/N*.

Performing similar calculations for the remaining orbital shells of the LOMC Starlink Gen1 and summing up the results obtained for each shell, we find that for RRL antennas of type 1, the time during which *I/N* excess the value of –10 dB is 9.3 s. It corresponds to 3.6% of the total time of irradiation of the RRL station placed near the GES. For RRL antennas of type 2, the time during which *I/N* excess the value of –10 dB is 50 s, i.e. 18.8% of the total time of irradiation. So, the parameters of EM radiation emitted by the LOMC Starlink Gen1 satisfy the requirements of [13] for the long-term excess time. Note that according to these requirements, the excess of the value of *I/N* = –10 dB can be realized for no more than 20% of the total time of irradiation. The calculation results obtained by the model coincide with the results given in [2] calculated using the software presented in [10].

D. Evaluation of Short-Term Excesses of the Interference-to-Noise Ratio Limit

When analyzing short-term excesses, the following situation should be considered: the ML of the beam realizing the channel LOCS–GES is directed to the GES at the angle of no less 5°, and the side lobe (SL) of this beam irradiates the antenna of RRL station in such a way that this radiation is received by the ML of the RRL antenna (Fig. 3).

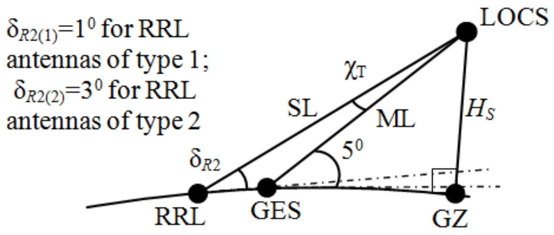

Fig. 3. Geometric model of the problem of short-term excesses of *I/N* values in comparison with limits specified in [13].

To realize this process, the considered RRL antenna should be located behind the GES antenna on the line connecting the GES and the GZ point corresponding to the LOCS that irradiates the considered area. For LOMC Starlink Gen1, containing LOCSs at the orbit with altitude of $H_s = 550$ km, the distance between the RRL antenna of type 1 and the GES should be in the range of 391–500 km, and for the RRL antenna of type 2 and the GES, the range of distances should be 187–500 km (the RRL antenna is located behind the GES).

Taking into account that the maximum PFD at the boundary of the beam spot (defined by the level of -3 dB) is $0.5Z_G = 2.5 \cdot 10^{-10}$ W/m^2, (see section II-C) then $I_1/N_1 = 12$ dB for RRL antennas of type 1 and $I_2/N_2 = 2$ dB for RRL antennas of type 2. Obtained results correspond to data given in [2].

The PFD created by the SL of LOCS antenna is changed with a rate determined by the change in AP $F_T(\chi_T,\psi_T)$. The change of this function is associated with both the satellite's orbital motion and the change in the ML direction, since the beam from the satellite to Earth is constantly directed on the GES:

$$\left|\frac{dF_T(\chi_T,\psi_T)}{dt}\right| = \left|\frac{dF_T(\chi_T,\psi_T)}{d\chi_T}\cdot\frac{d\chi_T}{dt}\right|, \tag{18}$$

and $d\psi/dt = 0$ in the plane under consideration where *I/N* reaches maximum values.

Using Fig. 3, we obtain that for Hs = 550 km the sighting angle $\chi_{T1} = 0.515°$ for antennas of type 1 and $\chi_{T2} = 0.327°$ for antennas of type 2. Assuming that the diameter of parabolic LOCS antennas used for connecting with the GES $D_{KA} \approx 20\lambda$ (according to the estimate of [12]) and their maximum gain is of about 31–35 dBi [2], [12], we determine the rate of decrease of $F_T(\chi_T, 0)$ with an increase in the angle χ_T using Fig. 2 for antennas of type 2 (blue dotted line): $dF(\chi)/d\chi = 0.128$ rad^{-1}. The averaged value $<d\chi/dt>$ in (18) for small angles χ is equal to 0.45 deg/s. Then the percentage of time of short-term excess of *I/N* for RRL antennas of type 1 is 0.06% and for type 2 is 0.037%. Consequently, the radiation of the LOCSs belonging LOMC Starlink Gen1 satisfies the requirements [13] for the short-term excesses.

IV. CONCLUSION

The following conclusions can be made based on obtained results. Firstly, with an increase in the number of satellites and GES in a LOMC, the probability of interference created by LOMC to the functioning of terrestrial FS decreases as result of the increasing of the elevation angle of satellites connecting with GES and UES, due to the spatial selection of terrestrial FS antennas. Secondly, the increase in the number of deployed LOMCs requires the development of new rules of their simultaneous operation to ensure EMC with terrestrial radio systems because emissions of various LOMCs are not coordinated.

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