Spectrum Coexistence of LEO and GSO Networks: An Interference-Based Design Criteria for LEO Inter-Satellite Links

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***Abstract*—As small satellites become more capable through miniaturized electronics and on-board processing, constellations of low-cost satellites lunched in Low- Earth Orbit (LEO) become feasible. The increase in the number of LEO satellites drives the need for frequency coexistence between the LEO constellation systems with the already existing geostationary (GSO) satellite networks. In this context, it is crucial to design the communication links paying special attention to interference analysis. This is particularly true when the LEO satellite constellation exploit inter-satellite communication links (ISL). In this paper, a radio frequency interference analysis based on simulation of the dynamic satellite constellation is presented and the design parameters of the inter-satellite links are analyzed. The results suggest that carefully choosing the design parameters of the inter-satellite links, spectrum coexistence of LEO and GSO networks may be possible.**

***Index Terms*—Satellite Antennas, Interference, Coexistence.**

I. Introduction

The maturity of many advanced technologies make possible the deployment of low Earth orbit (LEO) satellite constellations consisting of tens or even hundreds of LEO satellites [1]. Satellite constellations evidence important benefits such as resilience to individual satellite failure, payload redundancy, distributed storage and processing, incremental launching, and in-flight replacement. Beside that, compared to traditional geostationary satellite, the communication with a LEO satellite constellation has the advantages of shorter transmission delays, low-cost, and low-power ground terminals. However, the deployment of LEO constellations may bring a serious interference problem to GSO networks and therefore spectrum coexistence of these networks has to be carefully analyzed.

The electromagnetic spectrum is one of the most prominent natural resources that is increasingly demanded for communications. In order to optimize the use of frequency spectrum, frequency-band sharing policy between two or more coexistence services is often adopted. As the potential of LEO constellations specially rely on inter-satellite links communications, its design is a twofold challenging task, in a way due to critical technological issues to provide significantly increased data throughput, compared with the conventional ground-to-satellite/satellite-to-ground links, and in another way because is necessary to taking into account a potential harmful interference to other services [2], [3]. Moreover, the highly dynamic nature of LEO constellation leads to a challenging coexistence environment for future satellite networks.

In [4]–[7], coexistence scenarios of GSO and LEO networks are analyzed considering mainly in-line interference that arises whenever a LEO satellite passes through a line of sight path between an earth station and a GSO satellite. Most of those works analyze uplink and downlink scenarios where coverage areas of LEO and GSO satellites are overlapping. However, inter-satellite links may cause a serious interference problem not only by the overlap of coverage areas but also in other areas where only inter-satellite communications take place. In this paper, we analyze the impact of the interference generated by inter-satellite links of a LEO constellation over both GSO satellites and Earth-stations that are part of the GSO satellite network. As the relative position of the antenna beams change over time due to the constellation dynamics, the interference analysis between the GSO and LEO systems becomes more challenging and simulation of complex scenarios are used to derived design criteria for LEO inter-satellite links.

The paper is structured as follows. Section II explains orbital characteristics of satellites and the measurement of interest. The analyzed scenario is detailed in Section III. Section IV describes the simulation tool used for the interference evaluation and presents the simulation results for different designed LEO constellations. Finally, our conclusions are presented in Section V.

II. Orbital Model and Interference Analysis

The orbital model represents the motion of the low orbit satellites. The Simplified General Perturbations models, such as SGP4 and SDP4, provide orbital state vectors for satellite and space referenced to Earth Center Inertial (ECI)

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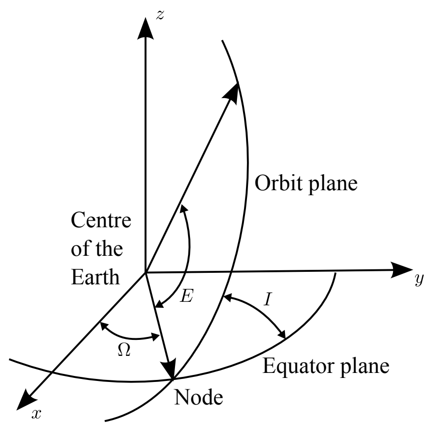

Fig. 1. Coordinate system.

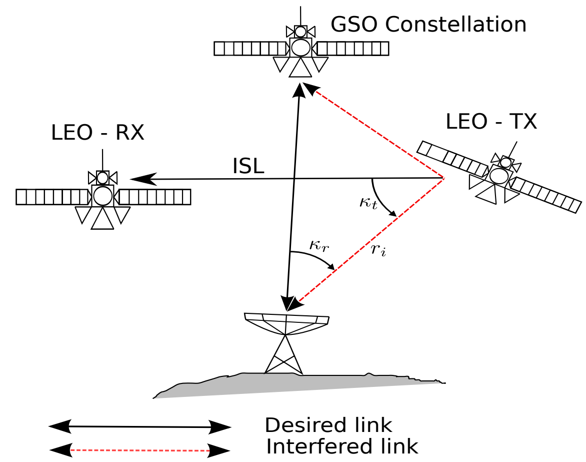

Fig. 2. Scenario under analysis.

coordinate system based on classic orbital elements. SGP4 was developed by Ken Cranford in 1970 [8] and includes analytical gravitational and atmospheric models for near-Earth (orbital period less than 225 minutes) orbiting elements. This model provided accurate results, without significantly increasing computer time requirements. The implementation of SGP4 takes Keplerian orbital parameters as input in objects called Two Line Element (TLE).

TLE format [9] is chosen since TLE orbital data can be import from public databases. Nevertheless, the input of the initial conditions for the SGP4 propagator can be set manually as well.

The satellite position is described by their Keplerian elements, such as E, I, and Ω, which denotes the *truth anomaly*, the *Orbit Inclination* and the *Right Ascension of the Ascending Node* (RAAN) of the orbit. The relationship of these parameters are shown in Fig. 1. The truth anomaly E is an angular function that depends on both the initial spatial satellite position (at time t_0) and its angular displacement speed ω (rad/sec). The truth anomaly at time t can be estimated by

$$E = E_0(t_0) + \omega t. \tag{1}$$

The total *orbital precession* of the Ω is expressed as

$$\Omega = \Omega(t_0) + \Omega_r t, \tag{2}$$

where $\Omega_0(t_o)$ (rad) represents the RAAN of the space station at time t_0 , and the space station orbital precession is given by

$$\Omega_r = -\frac{3}{2} J_2 \cos(I) R_e^2 \frac{\sqrt{r\mu}}{r^4}. \tag{3}$$

In the last equation, J_2 is the *second harmonic Earth potential constant* $(1082, 6 \times 10^{-6})$, R_e is the *radius of a perfectly spherical Earth*, r is *the radius of orbit* and μ is the *Earth attraction constant* $(3.9865 \times 10^{14}$ $m^3/sec^2)$. Finally, the spatial vehicle position is described by

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} r[\cos(\Omega)\cos(E) - \sin(\Omega)\cos(I)\sin(E)] \\ r[\sin(\Omega)\cos(E) + \cos(\Omega)\cos(I)\sin(E)] \\ r[\sin(I)\sin(E)] \end{bmatrix}. \tag{4}$$

To determine the interference-to-noise-ratio (I_0/N_0) on the affected receiver, the interference-power-spectral density is given by,

$$I_0 = \frac{P_t}{BW_t} G_t(\kappa_t) G_r(\kappa_r) \left(\frac{\lambda}{4\pi r_i}\right)^2 \quad \left[\frac{\text{W}}{\text{Hz}}\right], \tag{5}$$

where I_0 is the *power spectral density* at the input of the receiver. The available transmission power, applied over BW_t bandwidth (Hz), is denoted by P_t (W). The transmitter's and receiver's antenna gain, κ off-boresight angle, are denoted by $G_t(\kappa_t)$ and $G_r(\kappa_r)$ respectively. The distance between the receiver and the transmitter positions is denoted by r_i, and λ is the wavelength in meters.

The *noise power spectral density* N_0 at the receiver is given by,

$$N_0 = kT \quad \left[\frac{\text{W}}{\text{Hz}}\right], \tag{6}$$

where k is the Boltzmann constant (1.38×10^{-23} J/K) and T is the total operating *Noise Temperature* of the receiver system.

III. Scenario

The scenario under analysis is composed by two LEO small-satellites and one GSO satellite (Fig.2). The last one belongs to a Data Relay System (DRS) satellite constellation, and operates with an Earth Station (ES). The analysis process of the impact of the interference level at victim receiver, as states [10], involves the interference-to-noise ratio (I_0/N_0) computation at both the GSO and ES receivers. In order to evaluate the system performance in the presence of interferers, three radiation patterns are considered in this work, in compliance with the Appendix 8 of the Radiofrequency Regulation 2012 (RR) [11].

The GSO satellite is located at -32 degree of longitude and its antenna boresight pointing to the centre of the Earth. The ES is set to -64 degree latitude and -31 degree longitude with the antenna boresight direction pointing to the GSO.

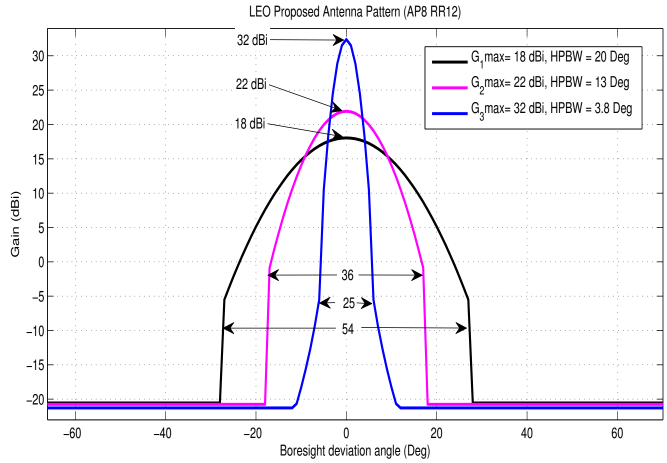

Fig. 3. Proposed LEO antenna radiation patterns.

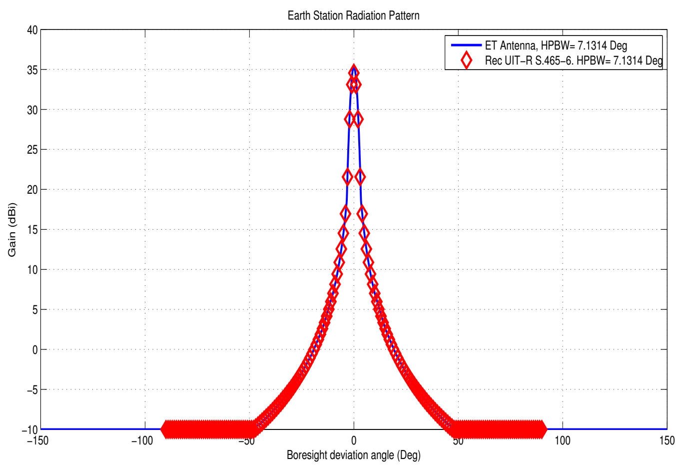

Fig. 4. Adopted ES antenna radiation pattern.

A. Antenna radiation patterns

The antenna radiation patterns considered in this work are based on the ITU-R recommendation. Fig.3 shows the proposed antenna radiation patterns for ISL LEO satellites in compliance with the Appendix 8 of the Radio Regulation 2012 for Non-GSO (Geo-Stationary-Orbit) space stations [12].

On the other hand, Fig.4 shows the adopted antenna radiation pattern diagram for the ES, which is described in the ITU-R recommendation *Interference Coordination and Evaluation in the frequency range from 2 to 31 GHz* [13]. The GSO antenna radiation pattern is in compliance with the ITU-R recommendation for use as a design objective in the fixed-satellite service employing geostationary satellites [14]. Table I summarizes antenna radiation characteristics proposed for the reference scenario.

For interference analysis, the LEO constellation orbit is set to a range of 1600, 5000, and 10000 km respect to Earth surface, with an orbital inclination of 90 degree. The relevant parameters for the Inter-Satellite link-budget are shown in the Table II, where for each scenario the EIRP (Equivalent Isotropically Radiated Power) is adjusted in order to keep the link-margin constant.

TABLE I
CONFIGURATION PARAMETERS OF GSO AND ES.

Parameter	GSO	ES
Max Antenna Gain (dBi)	+34.7	+35
Carrier Freq. (GHz)	2.24	2.24
Bandwidth (kHz)	4096	4096
Antenna radiation pattern	S.672[1]	S.465[2]
System Temp. (K)	600	300

1) Side-lobes were set at −24 dB [14].
2) [13].

TABLE II
ISL CONFIGURATION PARAMETERS OF ANALYZED SCENARIOS.

Parameter	Scenario 1	Scenario 2	Scenario 3
Phy. Temperature (K)	290	290	290
Range (km)	1000	1000	1000
Power Tx (W)	5	0.79	0.0079
Tx Loss (dB)	1.5	1.5	1.5
Free Space Loss (dB)	160	160	160
Rx Loss (dB)	1.5	1.5	1.5
Rx Noise figure (dB)	5	5	5
BER[3]	10^{-5}	10^{-5}	10^{-5}
Boresight Gain(dBi)	18	22	32
Link Margin (dB)	3.3	3.3	3.3
Antenna HPBW[1] (Deg)	20	12.8	4
Antenna FNBW[2] (Deg)	57	36	24
Side-lobes gain (dBi)	-20	-20	-20
Antenna radiation pattern[4]	App. 8	App. 8	App. 8

1) Half Power Beam-Width.
2) First Null Beam-Width.
3) Bit Error Rate.
4) Appendix 8. RR [11].

The radio-wave propagation in the space environment is considered similar to as free space loss. The effects of the cosmic radiation on the antenna temperature and possible fading behavior of the channel are neglected [15]. In base of this consideration, an ISL design involves the dimensioning of power transmitter taken into account the antennas radiation pattern and the channel model in order to satisfy the network communication requirements.

B. Receiver protection criterion

In the design of the uplink and downlink communication system of a GSO Network, the link margin is optimized in order to save weight and energy taking into account regulatory limitations of power flux density (PFD) on both over the Earth surface and the position of the GSO satellite. Communication links frequencies that operates up to 10 GHz, a typical link design margin is in the range of 3 to 6 dB [12]. Under that condition, the presence of a interference signal that generates an overall system noise power increase of 1 dB, is considered harmful for the link quality [16]. Assuming that the total operating noise temperature of a earth station is about 70 K, its noise power spectral density is

$$N_0 = 10\log(1.38 \times 10^{-23} \times 70) = -210.15 \text{ dB} \quad (7)$$

and the noise power spectral density of the system considering the presence of a interferer signal power is

$$N_0^{'} = -210 + 1 = -209.15 \text{ dB} \tag{8}$$

so, the interference-power-spectral density I_0 is given by

$$I_0 = 10 \log(10^{-209.15/10} - 10^{-210.15/10}) = -216 \text{ dB} \tag{9}$$

resulting a criterion for a maximum permitted interference-to-noise-ratio at the receiver of the earth station $I_0/N_0 = -216 + 210.15 \approx -6$ dB. Assuming that the total operating noise temperature of a GSO satellite is about 600 K and applying the same analysis, equal criterion for I_0/N_0 is obtained. However, considering that frequency bands will be shared between others space and terrestrial radio systems the maximum permitted interferece-to-noise-power-ratio adopted is $I_0/N_0 = -10$ dB [17].

C. Reference bandwidth

The reference bandwidth for protection criterion calculation depends on both the receiver type and the sensibility presented to a narrowband interference. In those receiver types that use phase loop-locked (PLL) technologies, to track the frequency carrier, the equivalent loop-noise bandwidth domain the behavior of the receiver when it's affected by a narrowband interference source [18]. Usually, the range of the bandwidth associated with this behavior is in the range of hundreds of Hz to few KHz, and 1 KHz is adopted as reference bandwidth [19].

D. Reference percentage time

The reference percentage time refers to the time during which space operation links can tolerate an interference level above the protection criterion. ITU establishes that the accumulated interference time should not exceed the 1% each day, and for critical stages, such as launch phases, critical spacecraft manoeuvres, should be temporary limited to 0.1% of the orbital time period [16].

IV. Simulation Results

A. Satellite network simulator

Interference analysis is carried out by a powerful simulation platform that enables evaluation of network satellite systems configuring not only logical channels but also realistic physical communication links. Developed at Digital Communication Lab of the National University of Cordoba in collaboration with the Space Agency of Argentina (CONAE), the simulation platform called *NetSim* is used for performance evaluation of different LEO satellites - constellations systems [20]. NetSim architecture is highly modular and extendable. Currently, NetSim is able to model and simulate physical phenomena such as signal propagation, power attenuation, bandwidth, noise effects, interference, antenna radiation pattern and depointing, Doppler shift, among others. Also, a wide variety of link layer protocol models are included such as CCSDS TM/TC, IEEE 802.11, Proximity-1, and others. Fig. 5 shows the simulator architecture.

B. Interference over other services

For all scenarios the total simulation time is set for a month with a sampling time of 1 second, where all interference events, $I_0/N_0 > -10dB$, were recorded. For the evaluation of interference level, it is assumed that the LEO satellite is transmitting continuously during the simulation. Fig.6 shows the percentage of time during which the interference level exceeds a given I_o/N_o value. Clearly, the results shows that it is unlikely to exceed the permitted downlink interference level threshold. It's worth to note that the location of the Earth Stations that operates with a GSO satellite are distributed between -60 and 60 degree latitude over the Earth, so the interference impact over the Earth station depends on its latitude location. However, in this works the Earth Station location is considered fixed. Fig.7 shows the results of the accumulated percentage time for the uplink case, i.e. the GSO operating as a receiver. In this case the threshold levels are exceeded in both time and level, however it is clear the positive impact of narrowing the antenna radiation pattern in scenario 3, where it becomes compatible with the threshold levels.

C. Interference over the Earth

Although the results presented are promising for system coexistence, at least for particular receiver on earth, a complete studio of potential interference involves the evaluation of power flux density levels over the Earth surface. Fig.8 and Fig.9 show the power flux density level over the Earth surface for different orbital height considering ideal antenna radiation pattern and helical antenna radiation pattern models. It is clear that the major contribution in the exceeding level of interference is due to the side-lobes of the antenna radiation pattern, showing that harmful interference on the Earth Station receiver is caused even in compliance with spectrum mask recommendation (Fig.10).

V. Conclusions

This work presents the impact of the interference in the GSO-DRS constellation and its Earth Station. To this end, interference evaluation of a LEO constellation is carried out for a complex scenario like the one that arises when the complete GEO-DRS constellation is taken into account. The presented study shows that an appropriate design of LEO constellation can guarantee the coexistence of LEO and

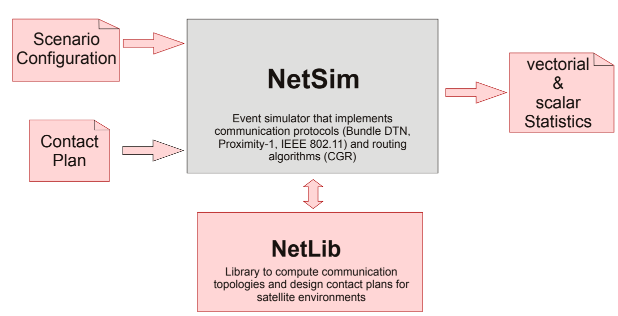

Fig. 5. Simulator Architecture.

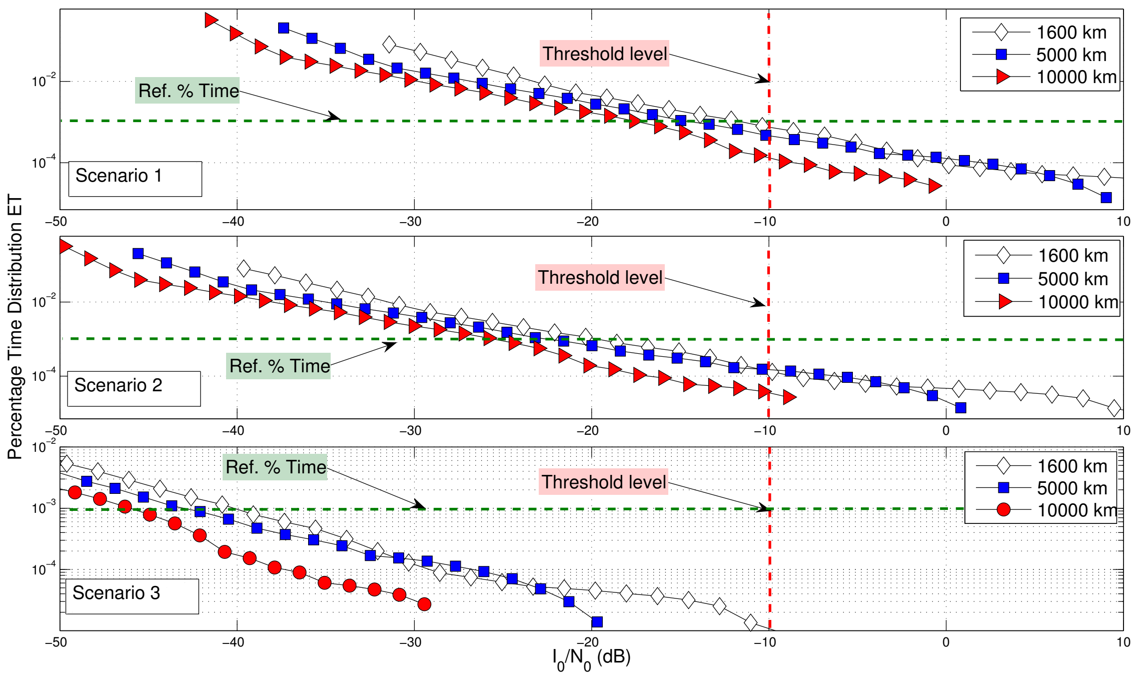

Fig. 6. Interference level over the Earth Station receiver.

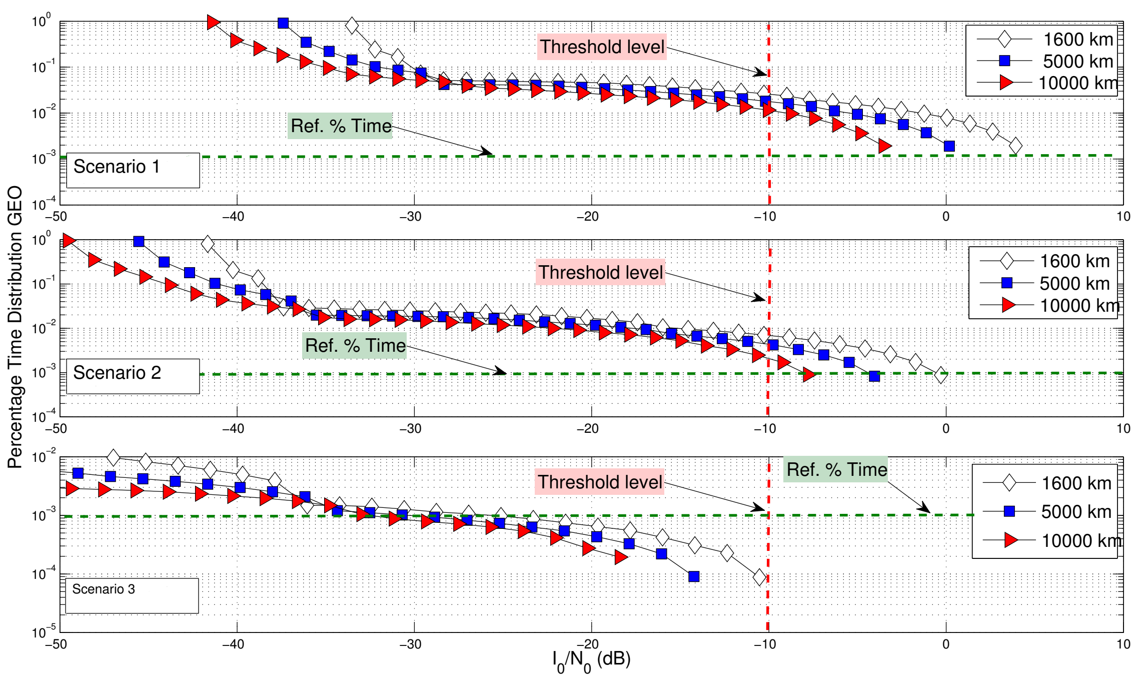

Fig. 7. Interference level over the GSO receiver.

GSO satellite networks. Envisioning massive satellite LEO constellations coexisting at different orbital heights with GSO satellite constellations, spectrum coordination between them becomes inevitable and appropriate simulation tools enable the analysis and design of more complex and challenging scenarios.

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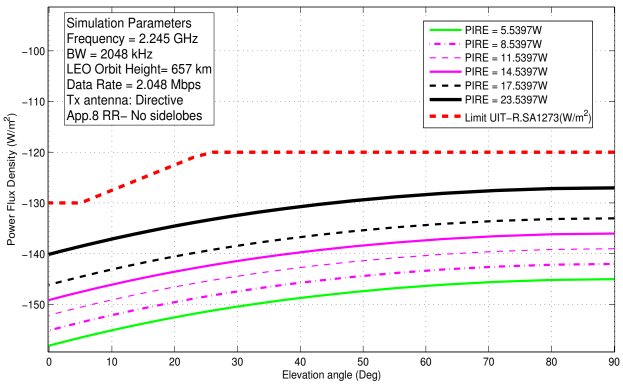

Fig. 8. Power flux density over the Earth (Omnidireccional pattern).

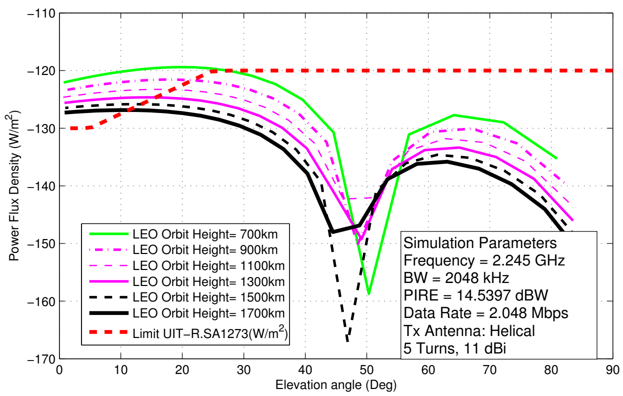

Fig. 9. Power flux density over the Earth (Helical pattern).

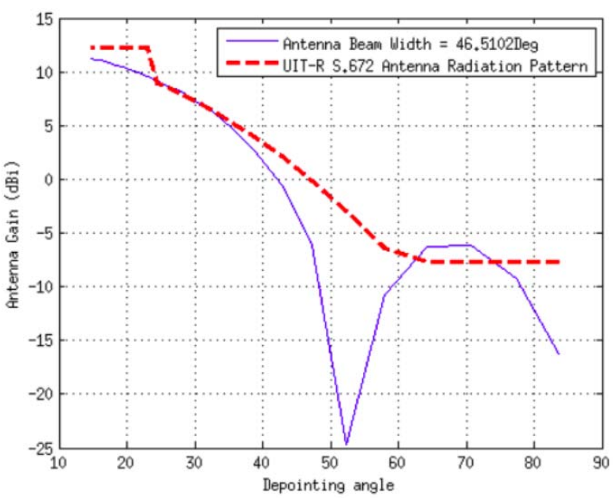

Fig. 10. Helical antenna radiation pattern.

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