Investigating the Interference Induced by NGSO Constellations on GSO System Ground Stations: a Simulation Approach

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***Abstract*—This contribution describes the development and application of a physically-based simulator to investigate the interference caused by NGSO satellite constellations onto GSO fixed-satellite services. The simulator calculates the yearly statistics of the Carrier to Interference Ratio (CI) of the gateway link of a GSO system ground station, considering all the variables at play, including the impact of precipitation. The analysis relies on the principle of protection of GSO systems by means of an exclusion zone, defined via an avoidance angle (α) and limiting the maximum number of NGSO satellites that can concurrently transmit in the area of the GSO ground station, *Max_co_freq*. Preliminary results, reported as a function of α and *Max_co_freq*, show the usefulness of the CI results to design future NGSO constellations while limiting their impact on GSO systems.**

***Index Terms*— Antennas, electromagnetics, propagation, interference, satellites.**

I. INTRODUCTION

The past few years have seen the development of massive low earth orbit satellite constellations aimed at the provision of broadband services. These *mega-constellations* represent a possible solution to the issue of increasing demand for broadband connectivity and for universal access to broadband services [1], thanks to the capability of relaying signals with quite short latency (~50 ms) and lower path loss when compared to Geosynchronous Orbit (GSO) satellites. These constellations also aim to achieve global coverage, bringing connectivity to rural and traditionally unserved areas. However, to provide service continuity, a large number of NGSO satellites needs to be deployed, since their visibility window is short (~10 minutes) and each of them has a limited coverage area. Moreover, the increasing number of NGSO satellites operating at low orbital altitude has increased the need to analyse the potential interference that those systems can cause on GSO fixed-satellite services whenever the two systems share the same operational band.

In this context, various techniques aimed at facilitating the coexistence and compatibility of different satellite-based communication systems have been conceived. Such techniques include the application of a minimum separation angle, commonly known as *avoidance angle*, formed by the line connecting the GSO satellite and the ground station, and the one between the same ground station and the NGSO satellite [2]; and a limitation to the number of satellites able to transmit simultaneously over the same geographical area and using the same frequency range, denoted as *Max_co_freq*.

This work presents the development and application of a simulator to investigate the interference induced by NGSO satellite constellations onto GSO-based fixed-satellite services. Specifically, the simulator allows evaluating the yearly statistics of the Carrier to Interference Ratio (CI) of a GSO system ground station (gateway link) considering all the variables at play and including the impact of atmospheric phenomena. Careful consideration of the atmospheric impairments experienced by all links is involved in the coexistence analysis: taking into account the correlation of the impairments given the orientation of each path is necessary to accurately evaluate the link carrier to noise plus interference ratio, C/(N+I), and other metrics such as total throughput and throughput degradation used in system compatibility analysis [3][4], particularly considering the proposed frequencies of operation (Ka, Q/V). To this aim, the simulator takes advantage of ST-MultiEXCELL [5], a model to generate synthetic rain maps correlated in time and space. In this way, the impact of rain on Earth-space links can be evaluated, which is the most detrimental tropospheric effect in the millimetre wave range.

The remainder of the contribution is organized as follows: Section II defines the scenario of interest reproduced by the simulator, introducing the specific implementation used for its development and design. Section III expands on the employed methodology to assess the level of interference of the system, describing all the parameters involved. Finally, Section IV presents the results obtained through a full-year simulation of the implemented scenario, showing different techniques to analyse the output data.

II. DEFINITION OF THE SCENARIO

This section describes the scenario under investigation, which includes the interaction between a GSO satellite and the associated ground station (gateway link) and satellites part of an NGSO satellite constellation.

A. Interfering NGSO Constellation

For the abovementioned scenario, the considered NGSO satellites belong to a LEO constellation operating in the Q/V bands to provide high-throughput connectivity. This constellation comprises a total of 7,518 satellites orbiting around the Earth distributed among three different orbital planes, as summarized in Table I [6].

TABLE I. MAIN FEATURES OF THE Q/V-BAND LEO CONSTELLATION IN THIS ANALYSIS [6]

Parameter	**Deployment**		
Altitude	345.6 km	340.8 km	335.9 km
Satellites per altitude	2547	2478	2493
Inclination	53°	48°	42°

The downlink channels operate at a frequency ranging from 37.5 GHz to 42.5 GHz. For coexistence analysis between the GSO and the NGSO systems, 40 GHz was chosen as the central reference frequency, and the worst-case scenario of maximum gain from the interfering system has been assumed.

B. *Inter-System Coexistence Techniques*

As mentioned above, various techniques to improve the probability of inter-system compatibility have been proposed to ensure that NGSO and GSO systems can share spectrum resources, while limiting inter-system interference [2]. As illustrated in Fig. 1, one of the key techniques is to consider the angle formed between the lines connecting the NGSO and GSO satellites to the same ground station, typically referred to as *separation angle* φ: if such an angle falls below a predetermined threshold angle, known as *avoidance angle* α, the NGSO satellite is forbidden to transmit. The NGSO satellite operation is thus limited by a fixed minimum angular separation from the line-of-sight of the GSO satellite and the ground station. This technique is known as GSO avoidance and is employed to avoid excessive main-beam to main-beam coupling between the NGSO and GSO signals directed to the victim ground station.

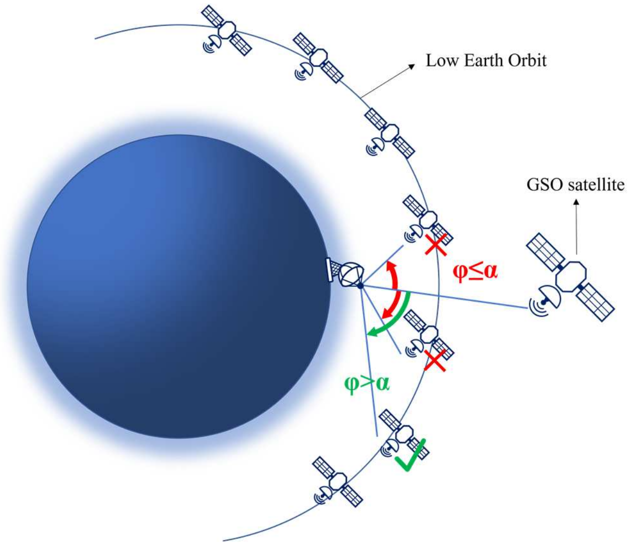

Fig. 1: Avoidance angle coordination mechanism.

The second main interference mitigation technique implemented in the simulator, following current regulatory practice [7], consists in a parameter which defines a limit to the maximum number of co-frequency NGSO satellites operating in the same area of service which includes the victim GSO earth station. We will refer to this parameter as *Max_co_freq*.

C. *Identification of Potential Interfering Satellites*

The simulator receives as input the orbital data of the NGSO constellation, of the wanted GSO satellite and the coordinates of the ground station. It then proceeds to identify the NGSO satellites in the constellation that are potential source of interference for the ground station based on geometrical visibility. Initially, the orbital data containing the geodetic information for both ground and space terminals are converted to Earth-Centered Earth-Fixed (ECEF) coordinates considering the standard WGS84. In this way it is possible to consider the positions of the terminals as vectors in the Euclidean space and conveniently resort to basic Euclidean geometry formulas.

Adopting this approach, the simulator evaluates the link elevation angles corresponding to each of the NGSO satellites in the constellation and it filters out all those characterized by an elevation angle lower than 5° (a practical limit to regular operations) with respect to the local horizon of the Earth station. Among the remaining satellites visible from the ground station, only the ones interfering with the GSO communications are of interest for the investigated scenario. Therefore, the simulator, which incorporates the compatibility techniques discussed above, needs to determine which NGSO satellites are eligible for communications and therefore could be potential sources of interference. To accomplish this objective, for each pair of GSO-NGSO satellites, the separation angle is calculated and compared to the avoidance angle α. NGSO satellites characterized by a separation angle smaller than α are ruled out, as they are not allowed to transmit. Among the set of potentially interfering satellites, only a number equal to the system parameter *Max_co_freq* are actually allowed to transmit. The criterion to select the *Max_co_freq* satellites among the set of eligible satellites (known as tracking or satellite selection strategy) is not unique and can vary from one system implementation to another. At present, the simulator selects a number of satellites among those that can be most problematic, i.e. those characterized by minimum separation angle above the α threshold. This process of satellite selection is executed for the whole duration of the simulation once every simulation step, which, in the investigated scenarios, was set to intervals of 30 seconds.

III. ASSESSMENT OF THE INTEFERENCE LEVEL

This section describes how the simulator calculates the link power budget, be it the one associated to the reference GSO satellite or to the interfering NGSO satellites.

A. Meteorological Environment

To realistically reproduce the meteorological environment affecting the considered Earth-space links, the simulator takes advantage of the rain maps generated by ST-MultiEXCELL. The maps define the rain rate distribution across a 200 km × 200 km area, with spatial resolution of 1 km × 1 km. All the maps are correlated in time (30-second temporal resolution), which allows simulating realistically the rain field space-time evolution. Each map consists of an aggregation of rain cells, whose ensemble reflects the local rainfall statistics. Fig. 2 shows a sample rain map impairing the reference Earth-space link: each pixel is shaded differently according to the corresponding rain rate value to visualize the rain field crossing the map. The red line represents the ground projection of the link portion affected by rain, whose length is L_G, while Ψ is the link azimuthal angle.

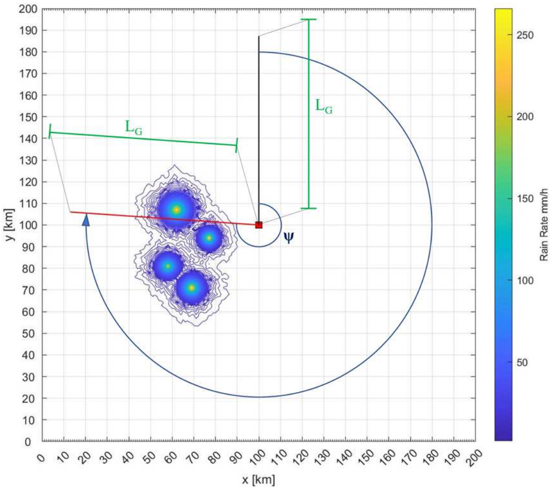

Fig. 2. Rain map affecting the Earth-space link.

While atmospheric impairments are not limited to rain, the simulator does not currently take into account the impact of gases and clouds, as at 40 GHz rain attenuation definitely plays the most important role.

Once the link geometry between the ground station and the satellite is established, the rain attenuation is calculated as:

$$A = a \int_L R(l)^b dl \tag{1}$$

where a and b are rain-to-specific attenuation conversion coefficients [8] that can be determined according to Rec. ITU-R P.838-3 [9], and L is the portion of the slant path affected by rain, in turn dependent on the local rain height: its value is extracted from Rec. ITU-R P.839-4 [10].

B. GSO Link Power Budget

The GSO wanted signal downlink RF power budget, is defined (in dBW) as follows:

$$P_{RX,\,GSO} = EIRP_{GSO} + G_{RX} - fsl - Att_{rain} \tag{2}$$

where the $EIRP_{GSO}$ is the Effective Isotropic Radiated Power of the satellite (dBW), G_{RX} is the ground station antenna gain (dB), fsl is the free space loss component (dB) and Att_{rain} is the rain attenuation affecting the link (dB).

The selected reference GSO satellite is characterized by:

- Latitude, Longitude, Altitude: 0°, 39°, 35786 km
- Carrier frequency: 40 GHz
- EIRP density = 36 dBW/MHz
- Bandwidth = 1 MHz

where the last two parameters were selected according to ITU-R Resolution 770 [4].

C. NGSO Link Power Budget

The NGSO downlink power budget is calculated (in dBW) as follows:

$$P_{RX,\,NGSO} = PFD_{NGSO} + A_{eff} - Att_{rain} \tag{3}$$

where the PFD_{NGSO} is the Power Flux Density emitted by the satellite at the ground and is measured in dB(W/m^2), A_{eff} is the effective area of the ground station antenna in dB(m^2). For the purpose of this study, we considered that the NGSO system is able to produce a PFD_{NGSO}=–105.72 dBW/m^2/MHz in clear sky, and able to maintain that value as the satellite moves by means of power control [6].

The total interfering power, resulting from the aggregation of the *Max_co_freq* satellites, is calculated in Watts as the sum of the single values of received power, since they can be considered as independent signals:

$$P_I^W = \sum_i^{Max\ co\ freq} 10^{\frac{P_{RX,NGSO,i}}{10}} \tag{4}$$

IV. RESULTS

This section illustrates the results for a full-year simulation for the specific case involving a ground station located at Spino d'Adda, Italy, communicating to a GSO satellite with a 30° elevation angle.

A. Time Series Analysis

The time series analysis allows appreciating the temporal evolution of the system. As an example, Fig. 3 and Fig. 4 illustrate the temporal trends of $P_{RX,GSO}$ (top panels) and of Att_{rain} (bottom panels) for the GSO and NGSO paths, respectively, the latter one obtained by considering for each time step a random satellite among the *Max_co_freq* ones that are causing interference. While the trend for the GSO results appears more stable, for the case of NGSO links, it is possible to observe significant oscillations: this is due to the fact that a different satellite (with its corresponding elevation angle) is considered for each time step.

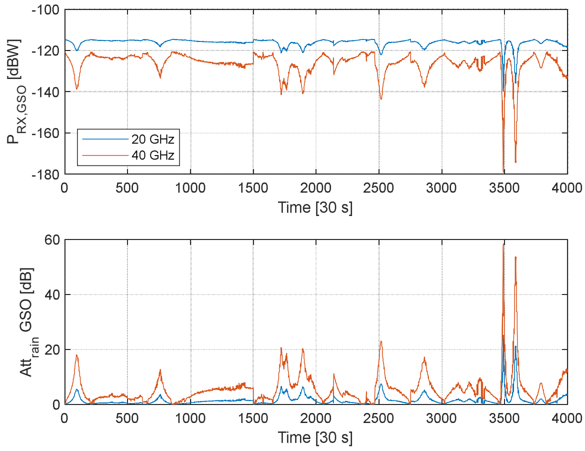

Fig. 3. Time series comparing the temporal trends of $P_{RX,GSO}$ and the corresponding Att_{rain} affecting the link, for operational frequencies of 40 GHz (red lines) and 20 GHz (blue lines).

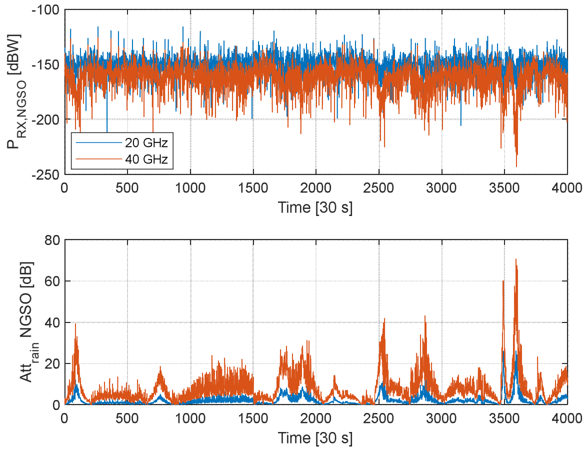

Fig. 4. Time series comparing the temporal trends of $P_{RX,NGSO}$ from one of the *Max_co_freq* interfering satellites and the corresponding Att_{rain} affecting the link, for operational frequencies of 40 GHz (red lines) and 20 GHz (blue lines).

As expected, peaks of rain attenuation correspond to a steep decrease in the received power level. For each subplot, two curves are actually shown, one indicating data corresponding to 40 GHz (red lines), and to 20 GHz (blue lines). The comparison between the two curves points out how increasingly significant the rain attenuation becomes as the frequency increases, as well as how strong its impact is in the Q band.

B. Statistical Results

While the examples reported in Fig. 3 and Fig. 4 illustrate the results provided by the simulator, a much wider picture can be obtained by inspecting the Complementary Cumulative Distribution Functions (CCDFs).

Fig. 5 shows the comparison of the CCDF of Att_{rain} affecting the GSO path (red line) and the corresponding one for the NGSO paths (blue line), considering the full year of simulations. The statistics for Att_{rain} on the NGSO paths were extracted from data accounting for an interfering set of satellites with *Max_co_freq* equal to 10.

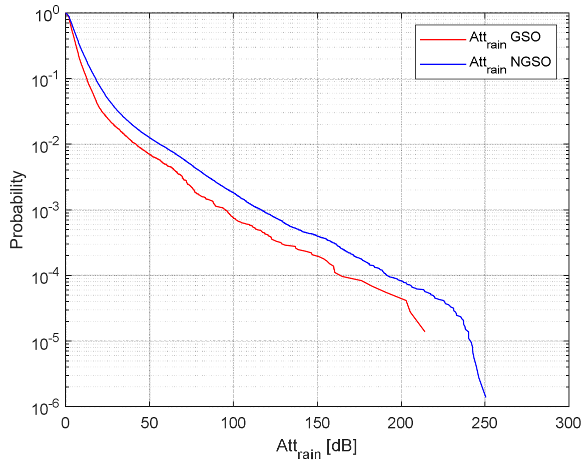

Fig. 5. CCDF of Att_{rain} of NGSO path for *Max_co_freq* = 10.

The interference level induced by the NGSO constellation on the GSO ground station can be quantified by resorting to the Carrier to Interference Ratio (CI), defined in dB as:

$$\mathrm{CI} = 10\log\left(\frac{P_C^W}{P_I^W}\right) = 10\log\left(\frac{10^{\frac{P_{RX,GSO}}{10}}}{P_I^W}\right) \qquad (5)$$

Fig. 6 and Fig. 7 illustrate the CCDF of the CI, for two different cases. In the former, α is fixed to 5° and the *Max_co_freq* parameter is modified, while the latter illustrates the opposite scenario, where α is the parameter being tuned. It is noteworthy to observe that, as expected, as *Max_co_freq* grows, the performance of the system shows a degradation, since the number of NGSO satellites contributing to the interference increases. On the other hand, increasing the value of α initially contributes to reducing the interference, since the coupling between the lines-of-sight of the two involved satellites and the ground station is smaller, though it appears that, beyond a certain value, increasing α does not provide additional benefits.

The CI is a powerful indicator to be used for the optimal tuning of the system, especially when considering the compatibility techniques mentioned in Section II. When the system requires a lower level of interference, it is indeed possible to reduce the *Max_co_freq* parameter or increase the threshold α. However ideally, in an NGSO constellation, it is beneficial to keep active as many satellites as possible, so whenever the CI allows a margin, the constraints on *Max_co_freq* and α should be relaxed. Therefore, by making use of the CI statistics, on top of evaluating the general performances of the system, it is also possible to tune the optimal values for compatibility mechanisms.

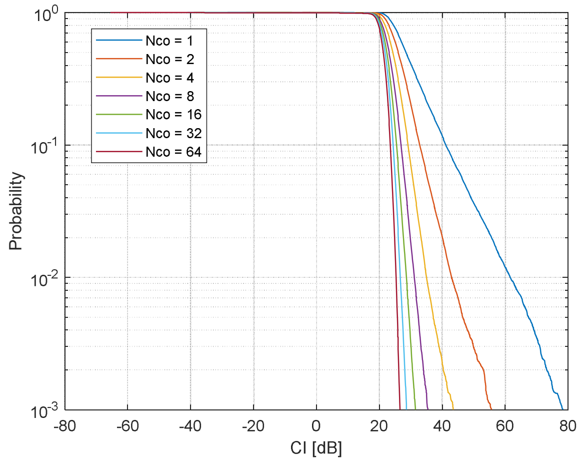

Fig. 6. CCDF of CI for α=5° and tunable *Max_co_freq*.

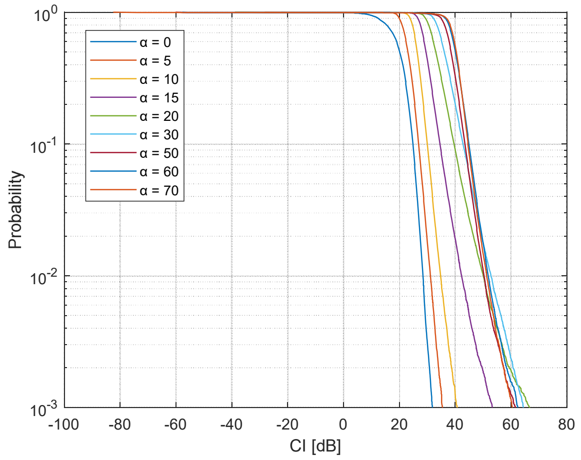

Fig. 7. CCDF of CI for *Max_co_freq* = 8 and tunable α.

V. CONCLUSIONS

The simulator presented in this paper allows analysing a spectrum coexistence and compatibility scenario involving a wanted GSO satellite link and an interfering constellation of NGSO satellites. The simulator first calculates the time series of the power budget for the wanted GSO and interfering NGSO satellites considering the evolution of the orbital positions for the latter. For an accurate computation of the interference budget, rain attenuation affecting each path is evaluated by taking advantage of the rain maps generated by the ST-MultiEXCELL model. In this manner, any potential correlation of the attenuation between the GSO and NGSO path is considered without resorting to additional assumptions. Power budget data are afterwards exploited to calculate yearly statistics of the Carrier to Interference Ratio (CI), considering the use of GSO avoidance angle (α) as compatibility technique, and the maximum number of NGSO satellites that can concurrently transmit in the proximity of the GSO ground station (*Max_co_freq*). Preliminary results, reported as a function of α and *Max_co_freq*, show the usefulness of the CI results to design future NGSO constellations while limiting their impact on legacy GSO systems.

Future work includes: a full reproduction of the meteorological environment, also accounting for the contribution of gases and clouds as tropospheric impairments; new simulations with different system parameters (e.g. GSO link elevation angle) to observe the most critical changes in system performances; analysis of throughput degradation and validation of current methodologies for inter-system coordination which rely on the existing propagation methods contained in ITU-R recommendations; a modelling activity for the simulated variables, to study their statistical distribution and possible mutual relationships (e.g. concurrent rain attenuation along GSO and NGSO paths). The aim of the modelling activity is to obtain a flexible tool for interference analysis that does not need time consuming simulations.

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