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Executive Summary of the Thesis

Model to investigate the interference induced by NGSO constellations on GSO system ground stations

Laurea Magistrale in Telecommunication Engineering - Ingegneria delle telecomunicazioni

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1. Introduction

In recent years, private companies and satellite operators are picking an interest in low altitude satellite constellations as a wireless alternative to terrestrial networks. Indeed, the evermore increasing data traffic is posing a problem for traditional terrestrial networks, which are limited in bandwidth and therefore experience also a limited backhaul capacity. *Non-Geostationary* (NGSO) satellites, specifically constellations at *Low Earth Orbit* (LEO), are seen as a solution for this issue, thanks to the capability of relaying signals with very short delays of ∼10 ms and low path loss. However, in order to provide continuity of service between the NGSO satellites and a ground station, a set, or constellation, of satellites needs to be implemented, since they sweep around the sky and have a limited coverage area. The increasing population of NGSO satellites at low orbital altitude is raising awareness over the interference these systems can cause on *Geosynchronous* (GSO) fixed-satellite services whenever the two systems share, even partially, the same frequency band of operation. This work presents a model to investigate the emissions produced by the aggregation of NGSO satellites operating at the same frequency bands of a GSO satellite in the fixed-satellite service. To thoroughly analyse a scenario of this kind, it is also crucial to take into account the attenuation caused by the atmosphere on the signals, since for the particular frequencies considered, well beyond 10 GHz, the atmospheric impairment becomes significant and cannot be neglected. Among the effects due to the atmosphere, the rain attenuation is the most detrimental one and, thus, it is the one mainly taken into account. In order to develop the model to investigate the described scenario, this work presents the implementation of a simulator to evaluate the rain attenuation affecting the link between the ground station and the satellite, by making use of rain maps produced by the rain-field generator *ST-MultiEXCELL*. The simulator then calculates the rain attenuation for every GSO and NGSO satellites of the scenario and investigates the yearly evolution of the system, collecting the simulated data. Finally, once all the data are stored, it is possible to analyse the performance of the system by calculating the power budget. The powers received from both the GSO system and the

NGSO one are compared to evaluate the interference. Moreover, it is also possible to study the long-term statistics of the parameters describing the system, such as the rain attenuation affecting the path between ground station and GSO satellite, A_{GSO}, as well as the one impairing the NGSO links, A_{NGSO}.

2. Implementation of the Simulator

This section addresses the method followed to build the simulator capable of investigating the impact of NGSO constellations on active communications between a ground station and a GSO satellite. The ultimate aim of the simulator is to calculate the power budget for the links connecting the ground station to each satellite, be it GSO or interfering. To achieve this goal, it is necessary to evaluate the rain attenuation affecting each path, since the considered system can operate in the *Ka*, *V*, *Q* frequency bands .

2.1. Rain attenuation simulator

The first step of the simulator, therefore, requires to evaluate the impact of the rain attenuation on the link between the ground station and a single satellite. The information needed for this operation are the geodetic coordinates of both the ground station and the satellite. Moreover, another input of the simulator is a rain map describing a 200 km × 200 km geographic area, obtained from the rain field generator *ST-MultiEXCELL* [1]. To each 1 km × 1 km pixel of the rain map is associated a value of rain rate in mm/h. The specific attenuation introduced by each pixel can be calculated with the following formula:

$$\alpha\left[\frac{dB}{km}\right] \cong a\,R^b \qquad (1)$$

where the constants a and b are selected according to ITU-R Recommendation P.838-3 [2]. The total attenuation is calculated by integrating the specific attenuation values over the length of the path affected by rain. Thence, it is necessary to identify the pixels of the rain map crossed by the projection on the ground of the satellite link delimited by the rain height, h_R. Once the rain height, also accounting for the melting layer, is evaluated as indicated in ITU-R Recommendation P.839-4 [3], the projection on the ground of the link can be calculated as:

$$L_G = \frac{h_R}{tan(\theta)} \qquad (2)$$

where θ is the elevation angle of the ground station link. Exploiting the information on the azimuth ψ of the link, it is possible to define the projected path on the map by rotating clockwise a segment directed to the North and of length equal to L_G by an angle equal to ψ, as depicted in *Figure 1*.

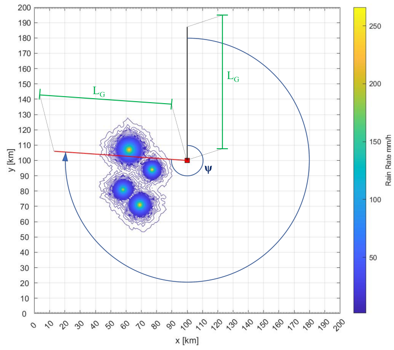

Figure 1: Rain field and projected path.

An auxiliary matrix with the same dimensions of the rain map is defined, in which are stored the portions of length of the projected link, $\Delta\,x$, crossing each 1 km × 1 km pixel, as shown in *Figure 2*. All the other values of this matrix are put to 0.

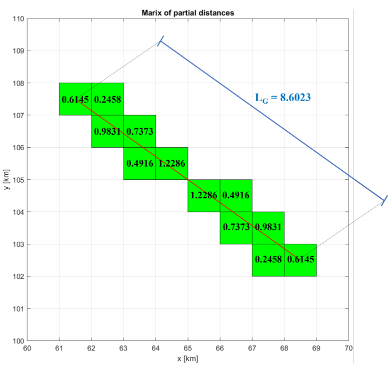

Figure 2: Distance matrix.

By exploiting the element by element multiplication between the latter matrix and the one containing the values of specific attenuation characterizing each pixel, what is obtained is a matrix containing $\alpha(x)\,\Delta\,x$ in the cells crossed by the link and 0 in all the others. Since this is a discrete case, the integration over the length path to calculate the total attenuation can be interpreted as a discrete sum:

$$\begin{aligned} A[dB] &= \int_{L_S} \alpha(l)\, dl \\ &= \int_{L_G} \alpha(x)\, \frac{dx}{cos(\theta)} \\ &= \frac{1}{cos(\theta)} \sum_{i=1}^{N} \alpha_i(x)\, \Delta x_i \end{aligned} \quad (3)$$

where L_S is the lenght of the slant path from the ground station to the rain height along the direction of the satellite link and N is the total number of pixels crossed by the ground projection of the link. Therefore, to evaluate the total rain attenuation, it is enough to calculate the sum of all the values of the matrix containing as elements the values $\alpha(x)\,\Delta\,x$ and dividing the result by $cos(\theta)$.

2.2. Extension for satellite constellations

The previous section described the method implemented by the simulator to calculate the rain attenuation affecting the path between a ground station and a generic satellite. This section, addresses how satellites are selected from an input constellation. In particular, the main goal is, given a GSO satellite, to consider the NGSO satellites in the constellation that are interfering with the communications. The scenario is depicted in *Figure 3*

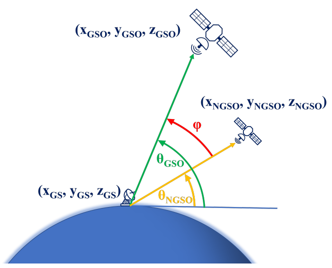

Figure 3: GSO satellite system scenario with NGSO satellite potentially interfering.

As a first step, the geodetic coordinates of the spacecrafts and the ground station are converted to the *Earth Centered, Earth Fixed* (ECEF) coordinate system, considering the reference ellipsoid *WGS84* for the conversion. In this way it is possible to consider the positions of the objects as vectors in the Euclidean space and conveniently resort to basic Euclidean geometry formulas. For example, it is possible to calculate the angle between two links, by simply inverting the dot product between the two corresponding vectors:

$$\begin{aligned} \mathbf{a} \cdot \mathbf{b} &= ||a||\,||b||\, cos(\Theta) \\ cos(\Theta) &= \frac{\mathbf{a} \cdot \mathbf{b}}{||a||\,||b|} \\ \Theta &= \cos^{-1}\left(\frac{\mathbf{a} \cdot \mathbf{b}}{||a||\,||b|}\right) \end{aligned} \quad (4)$$

At this point, 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°. Among the remaining satellites visible from the ground station, only the ones interfering with the GSO communications are of interest for the investigated scenario. As an interference-mitigation technique, NGSO satellites should refrain from transmitting whenever the separation (or avoidance) angle, indicated as ϕ in *Figure 3*, is below a prior-defined threshold α. However, all the NGSO satellites characterized by an avoidance angle greater than α keep their transmissions active, inevitably interfering with the GSO system and therefore must be taken into account for the analysis. Thus, the interfering satellites are selected as the ones having a ground station link elevation angle greater than 5° and with avoidance angle greater than α. Moreover, among this set of interfering satellites, the number of those allowed to actually transmit is defined by the system parameter *Nco*.
The procedure already described to evaluate the rain attenuation is thus repeated for each one of the links between the ground station and the newly selected interfering satellites.

2.3. Power Budget Simulator

By exploiting the parameters defining the satellite systems, such as the EIRP of the GSO satellite, the Power Flux Density of the NGSO satellites and the receive antenna gain, it is possible to finally calculate the power budget of the space-to-Earth downlink for each satellite.
To evaluate the received power, the total attenuation must also be taken into account, which can be mainly identified with the rain attenuation. The power budget equations respectively for the GSO satellite and the NGSO satellite are expressed as:

$$P_{rx,GSO}[dBW] = EIRP_{GSO}[dBW] + G_{rx}[dBi] + \\ - fsl_{GSO}[dB] - Att_{rain,GSO}[dB] \quad (5)$$

$$P_{rx,NGSO}[dBW] = PFD_{NGSO}\left[dB\left(\frac{W}{m^2}\right)\right] + \\ + A_{eff,GS}[dB(m^2)] - Att_{rain,GSO}[dB] \quad (6)$$

In particular, the power budget is calculated for each one of the interfering NGSO satellites and the total interfering received power is evaluated as the sum in Watt of all contributions received by the ground station:

$$P_{interfering}[W] = \sum_{i}^{Nco} 10^{\frac{P_{rx,NGSO,i}[dBW]}{10}} \quad (7)$$

3. Modelling activity

The simulator described in *Section 2* considers only a fixed instant in time. The same procedure can be reiterated for data describing not only the system parameters, but also their evolution in time. Specifically, in this Section, the obtained results are presented for the yearly evolution of the GSO satellite system while the NGSO constellation is interfering. The parameters simulated for the full year are in fact stored, so that their long-term statistics can be analysed and modelled.

3.1. Description of the scenario

The implemented scenario considers a ground station situated in Spino d'Adda, near Milano, Italy, identified by the coordinates:

- *latitude* : 45.4°
- *longitude* : 9.5°
- *altitude* : 0.084 km

The ground station receive antenna's main parameters of interest are:

- *Receive gain @40GHz* : 59.6 dBi
- *Radiation pattern* : ITU-R S580
- *Bandwidth* : 1 MHz

The GSO satellite is selected so that the ground station link elevation angle is as close as possible to 30°. Specifically, the coordinates that identify its position are:

- *latitude* : 39°
- *longitude* : 0°
- *altitude* : 35,786 km

The remaining key parameters to be considered for the GSO spacecraft are selected as indicated in Resolution 770 of ITU-R [4]. More in details, referring to the space-to-Earth downlink, the parameters corresponding to the GSO satellite transmitting the signal are:

- *EIRP density (Gateway)* : 36 $\frac{dBW}{MHz}$
- *Bandwidth* : 1 MHz

The NGSO constellation is the sub-constellation implemented by SpaceX and operating in the V band [5]. The satellites are almost uniformly distributed among the altitudes 335.9 km, 340.8 km and 345.6 km. The PFD characterizing each NGSO satellite is: PFD = -105.72 dB$\left(\frac{W}{m^2\, 1MHz}\right)$. The orbital data containing the information on the positions of each of the 7,518 satellites in the *Very-LEO* constellation, for a period of 5 days and a time resolution of 10 seconds, were provided by *SES S.A.*.
Finally, the signals transmitted by both systems are characterized by a frequency of 40 GHz and share a circular polarization along the same direction of rotation.

3.2. Rain attenuation results

The yearly evolution of the system is simulated and the obtained data are stored. In this way it is possible to study the long-term statistics of each of the parameters of interest. As an example, *Figure 4* shows the CCDF of the simulated data related to A_{GSO}. This graph is compared with a CCDF distributed as a log-normal, whose parameters are selected by operating a maximum likelihood estimation to best fit the data. The trend of the empirical CCDF of the simulated data is very well approximated by the log-normal, ultimately proving a result already known in literature, claiming that the long-term statistics for rain attenuation in mid-latitudes sites are well approximated by a log-normal distribution. This result confirms that the simulator is functioning correctly.

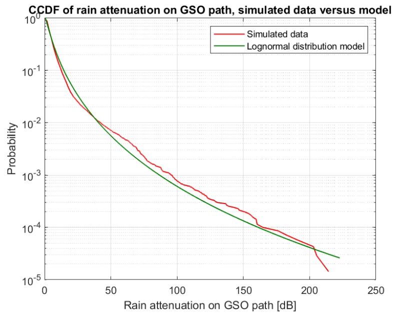

Figure 4: CCDF of A_{GSO}.

The same procedure can be applied to the data related to A_{NGSO}, attempting to find a family distribution that fits the data. This time, as can be seen from *Figure 5*, the log-normal distribution did not prove to be the best fitting, indeed the *Burr* distribution approximate better the trend characterizing the CCDF of the data. The data collected for A_{NGSO} in fact, correspond to satellite links defined by different values of elevation angle and azimuth, unlike the GSO satellite one, which is stable in time. It is plausible to assume, therefore, that A_{NGSO} depends on different system parameters and it is worth to investigate the relationships among them.

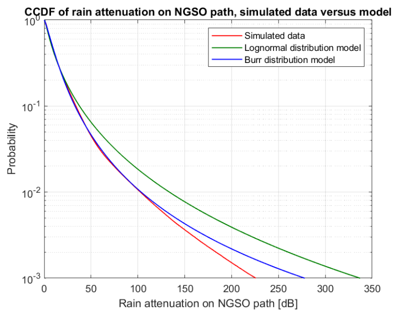

Figure 5: CCDF of A_{NGSO}.

3.3. Dependence on the avoidance angle

Figure 6 illustrates an intensity plot relating A_{NGSO} and the avoidance angle, ϕ, already defined in 2.2. An intensity plot can be interpreted as the 2D projected view of a 3D histogram, in which every vertical column of the 2D projected plane is normalized by its maximum value. In this way, these plots manage to reflect for each column how the data is distributed along the vertical direction. Since in *Figure 6*, for different values of avoidance angle, it appears that the data corresponding to A_{NGSO} distributes differently along the vertical direction, the two parameters does not seem to be independent and their relationship can be taken into account for a more coherent modelling of A_{NGSO}.

On the other hand, *Figure 7* shows a much more significant correlation between the way A_{NGSO} distributes along the vertical direction and the values of A_{GSO}. This correlation confirms the dependence of A_{NGSO} from A_{GSO}, as it would be expected from the spatial correlation characterizing the rain fields. Therefore, A_{GSO} must also be taken into consideration when attempting to model A_{NGSO}.

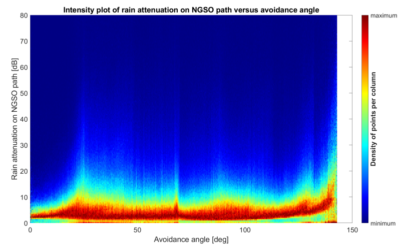

Figure 6: Intensity plot: A_{NGSO} versus ϕ.

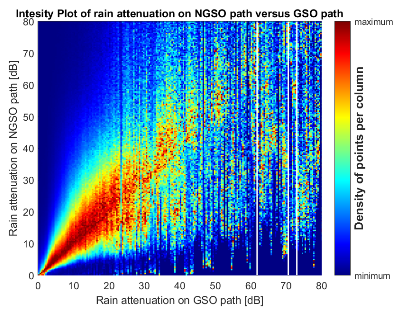

Figure 7: Intensity plot: A_{NGSO} versus ϕ.

3.4. Model development

Since a dependence of A_{NGSO} on A_{GSO} and ϕ is implied, it is interesting to study the behaviour of the conditional PDF $f(A_{NGSO}|A_{GSO}, \phi)$ in order to model A_{NGSO}. Indeed, by taking advantage of information on A_{GSO} and ϕ, it would be possible to model A_{NGSO} in a more accurate way, accounting for the spatial correlation of rain fields as well as for the geometry of the NGSO constellation with respect to the considered GSO satellite.

The above mentioned conditional PDF can be developed as follows:

$$P(A_{NGSO}|A_{GSO},\phi) = \\ = \frac{P(A_{GSO},\phi|A_{NGSO})P(A_{NGSO})}{P(A_{GSO},\phi)} = \\ \vdots \\ = \frac{P(A_{NGSO}|A_{GSO})P(A_{NGSO}|\phi)}{P(A_{NGSO})} \tag{8}$$

This relation is true only if $P(A_{GSO}/\phi, A_{NGSO}) = P(A_{GSO}/A_{NGSO})P(\phi/A_{NGSO})$, resulting in the conditional independence between A_{GSO} and ϕ given A_{NGSO}. This conditional independence can actually be empirically tested by taking advantage of the collected data and visualizing their relationship through intensity plots.

To model A_{NGSO}, a more general case is needed, therefore instead of single probabilities hereafter the procedure will take into account directly the corresponding Probability Density Functions. Specifically, the conditional Probability Density Functions needed for the model, $f(A_{NGSO}|A_{GSO})$ and $f(A_{NGSO}|\phi)$, are empirically evaluated by taking advantage of the set of stored data. The data is in fact organized in two sets of tuples: for the first conditional PDF pairs of corresponding $[A_{GSO}, A_{NGSO}]$; for the second conditional PDF pairs of corresponding $[A_{NGSO}, \phi]$. The tuples are further divided for classes of the conditioning parameter of interest (A_{GSO} in the first case and ϕ in the second), in such a way that every class contains a uniform number of tuples. Subsequently, the best distribution of A_{NGSO} is evaluated and stored for each class. This distribution actually reflects the trend of the searched conditional PDF, since it describes the distribution of A_{NGSO} in the corresponding conditioning class. Once all the PDF are stored, by knowing the values of A_{GSO} and ϕ, it is possible to refer to the right conditioning class and load the corresponding conditional PDF. Finally, $f(A_{NGSO}|A_{GSO},\phi)$ is evaluated as indicated in (*8*). The newly obtained PDF can generate samples of A_{NGSO} by resorting to the Inverse Transform Sampling method.

4. Final results

In this section, the final results achieved with the models described in *Section 3* are presented, with particular focus on the statistical model to generate A_{NGSO}.

4.1. Rain attenuation on NGSO path

Figure 8 compares the CCDF of the simulated and modelled data for the case of A_{NGSO}. The results are particularly appreciable since the CCDF is very well approximated for values of exceedance probability below 0.001, proving that the statistical model based on the conditioning on both A_{GSO} and ϕ successfully reproduces the statistics of the parameter.

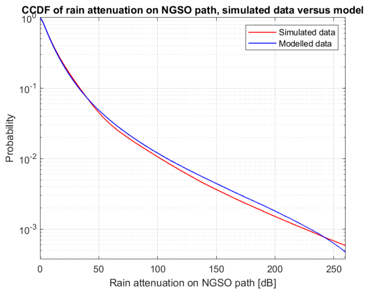

Figure 8: CCDF of A_{NGSO}.

4.2. Power Budget

Figures 9 and *10* respectively show the comparison of the simulated versus modelled CCDF for the power received from the GSO satellite and from the NGSO spacecrafts. Even in this case, the trends are very well approximated by the model, once again proving its efficiency.

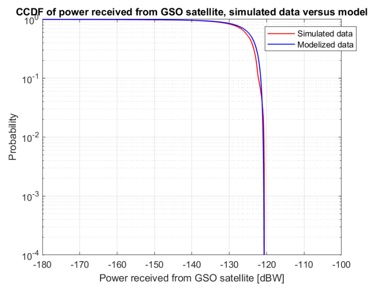

Figure 9: Power received from GSO satellite.

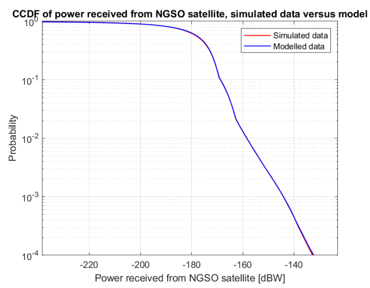

Figure 10: Power received from NGSO satellites.

4.3. C/I

For the purpose of further analysing the impact of the emissions produced by the aggregation of the NGSO satellite on the GSO system, another key parameter can be evaluated: the C/I ratio. This parameter is defined as the ratio of the wanted received power, in this case the GSO satellite's, over the interfering one, i.e. the emissions coming from the NGSO spacecrafts. The NGSO satellites contribute singularly in generating interference, depending on how strong their signal is, how many satellites are transmitting and how close they are to the line of sight between ground station and GSO satellite. Since they are independent signals, their total interfering power can be calculated as the sum in Watt of every single interfering received power. Once this value is obtained, the C/I ratio can be calculated as the ratio between the received power from the GSO satellite and the total interfering power coming from the NGSO satellites. Subsequently, it is reconverted back to dB:

$$C/I = 10\,log_{10}\left(\frac{P_{rx,GSO}[W]}{\sum_{i=1}^{Nco} P_{rx,NGSO,i}[W]}\right) \quad (9)$$

Figure 11 shows the trend of the CCDF of the C/I ratio calculated for the simulated data of the considered scenario. The figure evaluates the C/I ratio for different values of Nco, for a range from 2^0 to 2^6 and an avoidance angle threshold α fixed to 2°. As expected, the more NGSO satellites are interfering the more significant is the interference and thus the C/I will decrease.

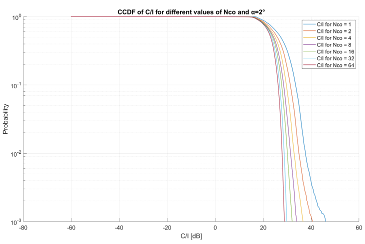

Figure 11: CCDF of C/I ratio.

5. Conclusions

This work presents a model to investigate the effects of a NGSO constellation on the communications between a ground station and a GSO satellite. The model includes a first phase in which it simulates the yearly evolution of the considered system, accounting for the spatial and time correlation of rain fields thanks to the rain maps generated by *ST-MultiEXCELL*, as well as the orbital data of the NGSO satellites sweeping around the sky. Another important feature provided by the model is the capability of calculating the power budget for each of the considered links, allowing further analysis to evaluate how significant the interference caused by the NGSO constellation is. To this aim, it is possible to plot the C/I ratio in order to visualize the performance of the system. The plot changes by tuning a few system parameters, such as the number of actively interfering NGSO satellites or the avoidance angle threshold below which a NGSO satellite must refrain from transmitting. Finally, the model makes use of the large set of stored data to analyse the long-term statistics of the system parameters, as well as the relationships between them, allowing to model the statistical distributions to accordingly generate new samples of said parameters. Indeed, one of the key results of this model is that it is able to statistically generate values of the atmospheric impairment, representing a more convenient alternative to running long simulations.

References

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