Multi-Criteria Ground Segment Dimensioning for Non-Geostationary Satellite Constellations

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***Abstract*—Non-Geostationary Orbit (NGSO) satellite constellations are becoming increasingly popular as an alternative to terrestrial networks to deliver ubiquitous broadband services. With satellites travelling at high speeds in low altitudes, a more complex ground segment composed of multiple ground stations is required. Determining the appropriate number and geographical location of such ground stations is a challenging problem. In this paper, we propose a ground segment dimensioning technique that takes into account multiple factors such as rain attenuation, elevation angle, visibility, and geographical constraints as well as user traffic demands. In particular, we propose a methodology to merge all constraints into a single map-grid, which is later used to determine both the number and the location of the ground stations. We present a detailed analysis for a particular constellation combining multiple criteria whose results can serve as benchmarks for future optimization algorithms.**

***Index Terms*—Ground Segment, Gateway Dimensioning, NGSO, Weather model**

I. Introduction

Recent advances in technology and private investment and ventures have rekindled interest in satellite communications (SatComs), as is the case of the mega-constellations formed by Non-Geostationary Orbit (NGSO) satellites for broadband communication services [1]. The ambitious goal of providing global internet coverage via low-orbiting and fast-moving satellites entails some technical challenges at the ground segment side of the system.

The wave of new NGSO systems promises to be a market revolution in remote connectivity but brings quite some technical challenges that have to be addressed before making them fully operational. Among those, in this paper we focus on the ground segment and, in particular, on the ground stations in charge of distributing payload data, telemetry and enabling the overall management of the satellites.

Ensuring ground connectivity to the different mega-constellation elements entails the need of multiple ground stations distributed over the system coverage area. Overdimensioning the ground segment may be seen as a conservative approach but generally becomes economically impractical. A study shown in [2] examines the optimal selection of Gateway Stations (GS) in satellite networks to reduce the overall installation cost while ensuring an acceptable level of outage probability based on the assumption that weather conditions at each site are independent. However, not only the effect of rain influences NGSO systems, other factors influence channel modeling compared to its geostationary (GEO) counterpart, such as the Doppler effect, which would complicate the control and visibility of Low Earth Orbit (LEO) satellites due to movement. Several channel models are presented in [3] that reflect the variability and lack of consensus in a channel model that allows us to design a unique or standard ground segment.

Several large constellations of NGSO satellites have been proposed by different companies, mainly with feeder links in Ka-band; however, the need for wider bandwidths and the increasing demand for capacity promote the development of systems with feeder links operating in Q/V-W bands. New architectures for ground segment are proposed in [4] for these feeder links based on Q/V bands, which reduce the number of GS required to support higher bandwidth and capacity. Instead, these frequencies are impaired by higher atmospheric attenuation, such as rain, which in turn causes outages in the services. For this reason, choosing the correct position of the GS is of vital importance to avoid areas where there is a high level of rain precipitation, among other mitigating factors for the power feeder link. To overcome service interruptions, the main strategy that has been used so far is site diversity, consisting of redundant GS with backup stations while switching the service in the event of an interruption. An overview of the site diversity concept and different strategies are described in [5] in two representative climatic groups; a temperate region and in a tropical climatic region. A site diversity optimization method for the EHF band is proposed in [6] for high-throughput satellite (HTS) systems, not being validated for NGSO. The strategy allows selecting the best diversity configuration with the number of groups and GS per group, geographical position of all available GS given the longitude of the HTS satellite, system availability, and characteristics of ground terminals. To decide the position of a GS with diversity using the rain attenuation criterion, rain prediction methods such as the one proposed in [7] have been considered in the past.

On the other hand, the gateway placement further affects the service coverage and access performance of the network to service demands [8], [9]. To avoid loss of service, one can also balance the traffic between the GS, considering a service data demand distribution. The authors in [8] propose a GS placement method for NGSO networks, which identifies the best GS locations that can balance traffic loads based on constraints such as link interference, satellite bandwidth, and the number of satellite antennas. Instead, atmospheric attenuation is not considered. The GS placement for remote access is considered in [9], using a distributed resource allocation mechanism based on the alternating direction method of multipliers algorithm where traffic distribution is also considered within the coverage area. Another parameter for the service considered in diversity is the delay. In [10], strategies are proposed to determine the positions of redundant GS considering this parameter.

The inconvenience of site diversity techniques and strategies would increase the development cost of the NGSO ground segment, which, as mentioned, is aggravated for current and upcoming mega-constellations, regardless of the criteria used to create the redundancy GS network (rain, traffic, access, delay). The interest is to reduce the possible number of GS that compose the ground segment. The works [4], and [8] already consider minimizing the number of GS but exclusively under a single criterion, the first for atmospheric phenomena, while the second for traffic distribution. Therefore, it is not an optimal solution to provide guarantees on the total availability of the service. Also, the character of the time-varying topology of the NGSO satellites has not been considered for satellite visibility.

Considering the drawbacks identified in the literature, in this paper, we propose a novel methodology to combine different criteria to determine the number and GS placement for any input NGSO constellation. In particular, our approach considers weather prediction models, expected traffic demand, satellite visibility period, and altitude data.

The rest of this paper is organized as follows: Section II describes the layered system model. Section III proposes a procedure to decide the gateway station placements based on multi-criteria. The results and challenges are presented in Section IV. Finally, the conclusions are summarized in Section V.

II. System Model

The objective of the system is to decide which are the best geographical positions to locate the GS, considering multiple criteria simultaneously. To do this, we have defined a system model based on layers, where each layer is called a grid and represents a choice criterion as shown in Fig. 1. The fundamental grid is defined by latitude and longitude, from which it will determine the dimension of the rest of the grids. The rest of the grids are defined by the requirements:

1) Rain attenuation
2) Traffic demand
3) Visibility
4) Terrain.

A. Weather Model grid based on ITU-R

The Weather Model is a statistical representation of the impact of atmospheric conditions on SatComs systems. Rain is one of the most significant factors that affect satellite communication and is quantified in terms of attenuation, which is the reduction in the strength of a satellite signal caused by the presence of rain.

Rain attenuation is calculated based on the International Telecommunication Union's Radio communication sector (ITU-R) Recommendation P.618-12 [11]. The ITU-R model

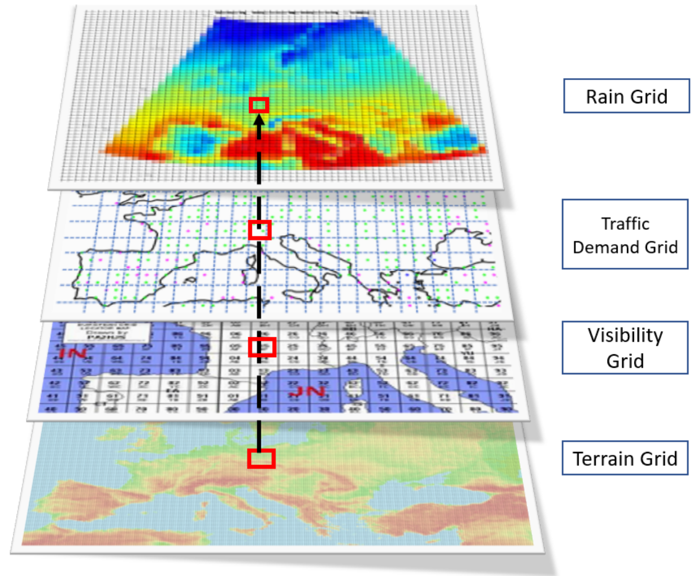

Fig. 1. Grid-based Architecture for System Model.

uses satellite frequency, rain rate, and geographic location to estimate the rain attenuation in decibels (dB) at a specific point in time. The calculation involves considering the effects of absorption, reflection, and scattering caused by the presence of raindrops in the atmosphere.

The Weather Model and the ITU-R's calculation of rain attenuation are crucial for ensuring the reliability and quality of SatComs systems. The model provides essential information for satellite system designers, operators, and users to mitigate the impact of atmospheric conditions, such as rain, on satellite communication links.

Based on the ITU model, a grid is defined with a matrix where each position of the matrix represents a geographical position, and the value represents the rain attenuation in dB. This can be represented in Fig. 2, which shows the rain attenuation for a frequency of 30 GHz, an availability of 99%, and an elevation of 10 degrees.

B. Traffic Demand grid

In order to generate the traffic demand grids, we use a traffic model based on population density. The traffic demand model described by the equation $d_r = C_u \cdot D \cdot F \cdot T$ is a comprehensive approach to estimating data demand for satellite communications systems. The model takes into account four key variables that influence data demand: the throughput per user (C_u), the population density (D), the penetration rate (F), and the concurrence rate (T).

Throughput per user (C_u) refers to the amount of data that a single user can receive or transmit in a given period of time. It is usually measured in bits per second (bps) per user. Population density (D) refers to the number of people living in a given area and is typically measured in inhabitants per square kilometer (inhabitants/km^2). Penetration rate (F) refers to the proportion of the population using SatComs services and

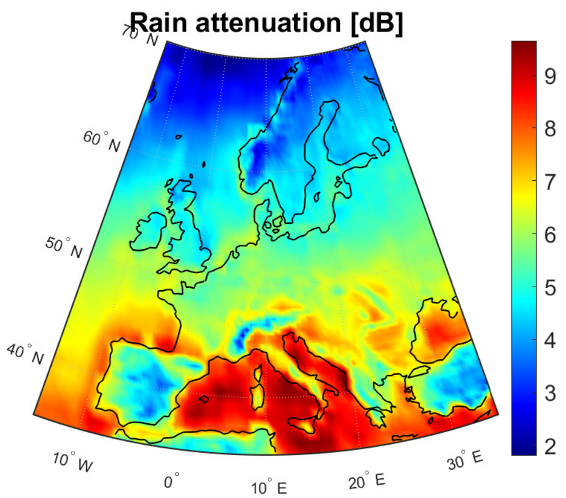

Fig. 2. Rain attenuation grid for Europe using a frequency of 30 GHz, an availability of 99%, and an elevation of 10 degrees.

is usually measured in users per inhabitant. The concurrence rate (T) refers to the proportion of users simultaneously using SatComs services. It is used to take into account the varying levels of usage that occur throughout the day.

The product of these four variables gives us the throughput density per square kilometer (d_r), which represents the total amount of data that is being transmitted or received in a given area. By using this model, we can estimate the data demand for different regions of the world and inform the deployment of satellites in a LEO mega-constellation, ensuring that the system is able to meet the needs of users in different regions.

Fig. 3 shows a grid representation of traffic demand for different traffic demand requirements, very low, low, medium, high, or very high demand, as a function of population density.

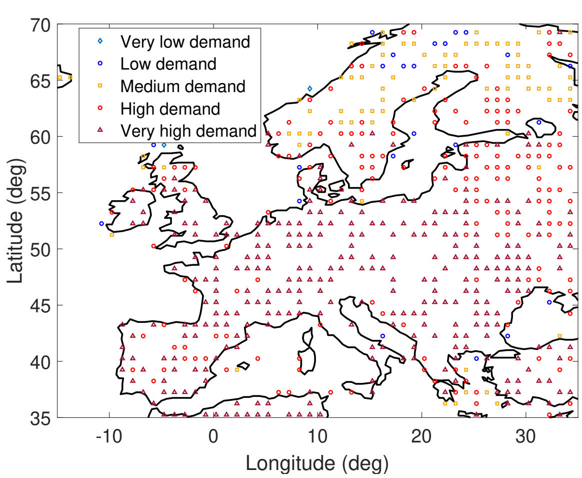

Fig. 3. Traffic demand grid for Europe.

C. Visibility grids

For visibility, we calculate two sub-grids: one for the average number of satellites that can be seen from the GS location and another for the time visibility of a satellite from the GS location. For this, we consider the NGSO constellations at 800 km as shown in Fig. 4, and 1200 km altitudes. The parameters used for these constellations are listed in TABLE I. Hence, using these constellations and the GS locations,

- Average number of satellites visibility ($\bar{\mathcal{S}}$): Suppose that at time t the number of satellites visible to a GS at latitude i and longitude j is denoted by $\mathcal{S}_{i,j}(t)$. Then, the average number of satellites visible to this gateway location over the satellite orbital period $\mathcal{T}$ is determined as

$$\bar{\mathcal{S}}_{i,j} = \frac{\int_{t=0}^{T} \mathcal{S}_{i,j}(t)dt}{\mathcal{T}}. \quad (1)$$

We simplify (1) by discretizing the time of the orbital period into N instants as follows

$$\bar{\mathcal{S}}_{i,j} = \frac{\sum_{n=1}^{N} \mathcal{S}_{i,j}[n]}{N}. \quad (2)$$

Thus, using (2), we calculate the visibility-grid with the number of satellites at 800 km and 1200 km altitudes.

- Maximum Time visibility of a satellite: This time visibility is based on the maximum time window obtained from satellites over the satellite's orbital period. This way, a gateway can communicate with satellites for the required time, while the inter-satellite link can be optimized for maximum communication between satellites.
Let the time visibility window of a satellite l for a gateway at latitude i and longitude j over the orbital period $\mathcal{T}$ be defined as $\mathcal{T}_{i,j}^{l}$. Then, the maximum time window that a gateway can be seen from one of the satellites is given by

$$\mathcal{T}_{i,j}^{max} = \max_{l} \left\{ \mathcal{T}_{i,j}^{l} \right\}. \quad (3)$$

TABLE I
NGSO CONSTELLATION PARAMETERS

	LEO 1200 km	LEO 800 km
Orbital Inclination	90 deg	90 deg
Number of Satellites	190	338
Phasing	9	6
Planes	10	13
Orbital period	1.8237 hr	1.6812 hr
Elevation angle	35 deg	35 deg

D. Terrain grid

The terrain grid indicates the sea-level altitude for each pair of coordinates. In this way, we create a binary grid in which we take into account whether or not there is terrain to place the GS only on landscape, not on any maritime coordinate.

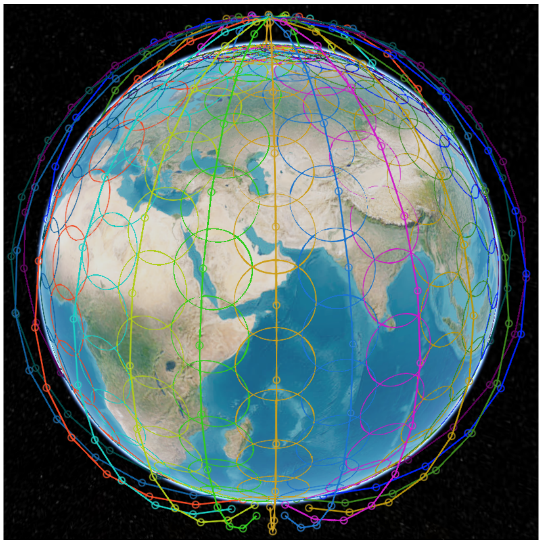

Fig. 4. NGSO constellation at 800km.

III. Multi-Criteria Ground Segment Dimensioning

To decide the best positions that meet all the criteria, we follow the steps as a sequential selection procedure as shown in Fig. 5, and summarized as follows

- **Step 1:** We define each grid following the description of the system model. The main grid will be for latitude and longitude, giving us the total number of candidate positions.
- **Step 2:** We define the thresholds for each grid, which will serve as a condition for selecting the position.
- **Step 3:** Select a pair of coordinates (Ω =longitude, latitude). For each Ω, perform steps 4-7.
- **Step 4:** Select Ω if it fulfills being an altitude above sea level. Only select positions on the ground.
- **Step 5:** Select Ω if the visibility is between 15 and 20 satellites.
- **Step 6:** Select Ω if there is traffic demand from any of the five profiles.
- **Step 7:** Select Ω if rain attenuation is below threshold (two cases: 50% and 25%).

In the event that all steps 4-7 meet the conditions of the established thresholds, we increase the number of GS (R_p) and move on to the following steps. If any checks are unsatisfied, we choose another Ω and repeat all the statements until the entire latitude and longitude grid is covered.

- **Step 8:** Select the area with more GS density and calculate the geographic mean to select the candidate GS position.

IV. Results and Challenges

Two scenarios are considered for dimensioning the NGSO ground segment based on multiple criteria: LEO satellites orbiting in 800 km and 1200 km. These cases are compared for elevation angles of 10 and 30 degrees from the GS. The frequency bands considered are traditional Ku,Ka-bands (19.7 GHz and 30 GHz) and Q/V emerging bands (40.5 and 47.2 GHz). To exemplify the placement of GS only Europe is shown here, where the latitude and longitude range used are [-15;35] deg and [35;70] deg, respectively. The grid size is 351x501, resulting in 175,851 candidate positions. The ratio of the total number of GS (R_p) is calculated in three phases. First, we get R_p for each individual criterion. Considering rain attenuation, we define a maximum attenuation for each (frequency, availability,elevation)-triplet, then we select 50% and 25% with respect to the maximum as threshold. Table II shows R_p for both cases. Using only these criteria, between 55% and 75% fill these criteria, which are so many options. For individual visibility- and traffic demand grids, Table III shows how many candidates meet with the visibility between 20 and 25 satellites and the number of candidates with traffic demand. These numbers are too high to assume the cost of deploying the ground segment. Second, we combine the conditions of the grids in pairs. We evaluate the pair rain-visibility,

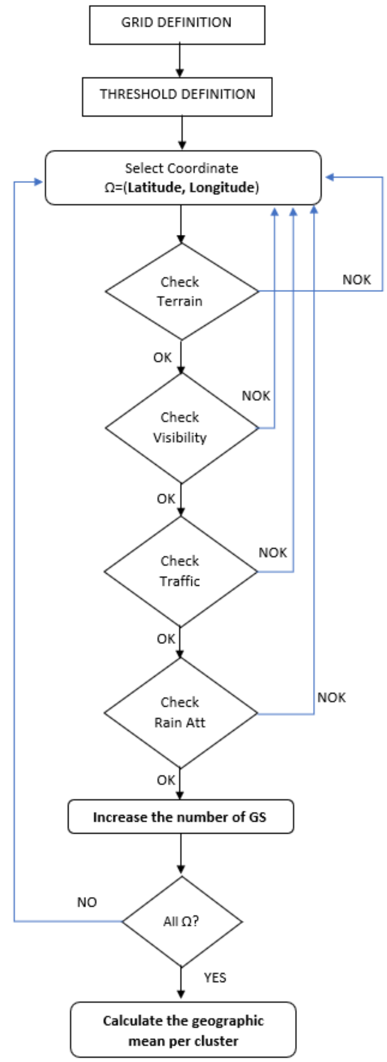

Fig. 5. Procedure for placement selection

TABLE II
NUMBER OF GS FOR INDEPENDENT RAIN ATTENUATION GRIDS.

Frequency	**Availability**	**Elevation** degrees	**Max** [dB]	**Number GS <50% RainAtt Ratio**	**Number GS < 25% RainAtt Ratio**
19.7 GHz	99.9%	10	24.3647	79.90	10.16
19.7 GHz	99.9%	30	8.9163	36.86	2.38
19.7 GHz	99.9%	90	7.582	58.15	10.93
19.7 GHz	99.5%	10	10.0138	79.97	11.83
19.7 GHz	99.5%	30	3.5941	42.17	3.86
19.7 GHz	99.5%	90	3.0239	62.58	13.89
30 GHz	99.9%	10	47.9926	78.81	9.21
30 GHz	99.9%	30	18.4488	36.17	2.29
30 GHz	99.9%	90	17.396	58.45	11.43
30 GHz	99.5%	10	20.6221	78.75	10.95
30 GHz	99.5%	30	7.8	40.85	3.77
30 GHz	99.5%	90	7.3266	62.91	14.14
40.5 GHz	99.9%	10	71.1757	77.35	8.33
40.5 GHz	99.9%	30	28.0056	35.11	2.11
40.5 GHz	99.9%	90	27.4988	57.34	11.11
40.5 GHz	99.5%	10	31.3851	77.27	9.92
40.5 GHz	99.5%	30	12.1694	39.16	3.57
40.5 GHz	99.5%	90	11.9349	61.91	13.80
47.2 GHz	99.9%	10	84.201	76.51	8.09
47.2 GHz	99.9%	30	33.3733	34.43	2.03
47.2 GHz	99.9%	90	32.943	56.68	10.96
47.2 GHz	99.5%	10	37.5403	76.42	9.57
47.2 GHz	99.5%	30	14.6697	38.55	3.54
47.2 GHz	99.5%	90	14.4682	60.88	13.71

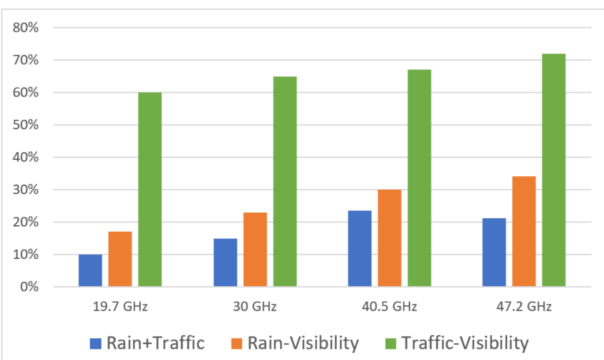

Fig. 6. Rate of positioning for combined grids.

rain-traffic and visibility-traffic grids in Fig. 6. The evaluation of two simultaneous criteria reduces the number of possible candidates. We can note that the most restrictive criterion is rain. Third, overlay all grids following the procedure described before. R_p is reduced to six areas with a high density of positions. For each area, the geographic midpoint is selected as the position for GS, as shown in Fig. 7.

TABLE III
NUMBER OF GS FOR INDEPENDENT TRAFFIC AND VISIBILITY GRIDS.

	800 Km		**1200 Km**	
Elevation Angle (degrees)	**10**	**30**	**10**	**30**
Number of GS for maximum Visibility	10%	25%	15%	26.30%
Number of GS for maximum traffic demand	1152			

Our methodology, which aims to find the most optimal positions to locate gateways based on rain attenuation, traffic demand, and visibility time, would face some important challenges for future work. Some of these challenges include:

- Elevation Variable: The elevation of the gateway location can significantly impact the signal propagation and link budget and influence the rain attenuation. Therefore, the methodology should consider the elevation variable to determine the most optimal positions for the gateways.
- Attenuation Threshold: The methodology should determine the appropriate attenuation threshold the system can tolerate without significantly degrading the service quality. This threshold can vary depending on the frequency band and system design.
- Geo-policy: The methodology should consider the geo-policy regulations of the countries or regions where the mega-constellation is deployed. The placement of GS should comply with spectrum allocation, environmental protection, and other regulatory requirements.
- Distance between GS and the network core: The distance between the gateway and the 5G or 6G network core can affect the system's performance, especially the end-to-end latency and the network throughput. The methodology should consider the distance and network architecture to optimize the gateway placement for better integration with the network.
- Complex Optimization: Finding the optimal positions for gateways requires a complex optimization process that considers multiple factors, such as traffic demand, visibility time, rain attenuation, and other technical and operational constraints. The methodology should use advanced algorithms and modeling techniques to generate accurate and efficient solutions.

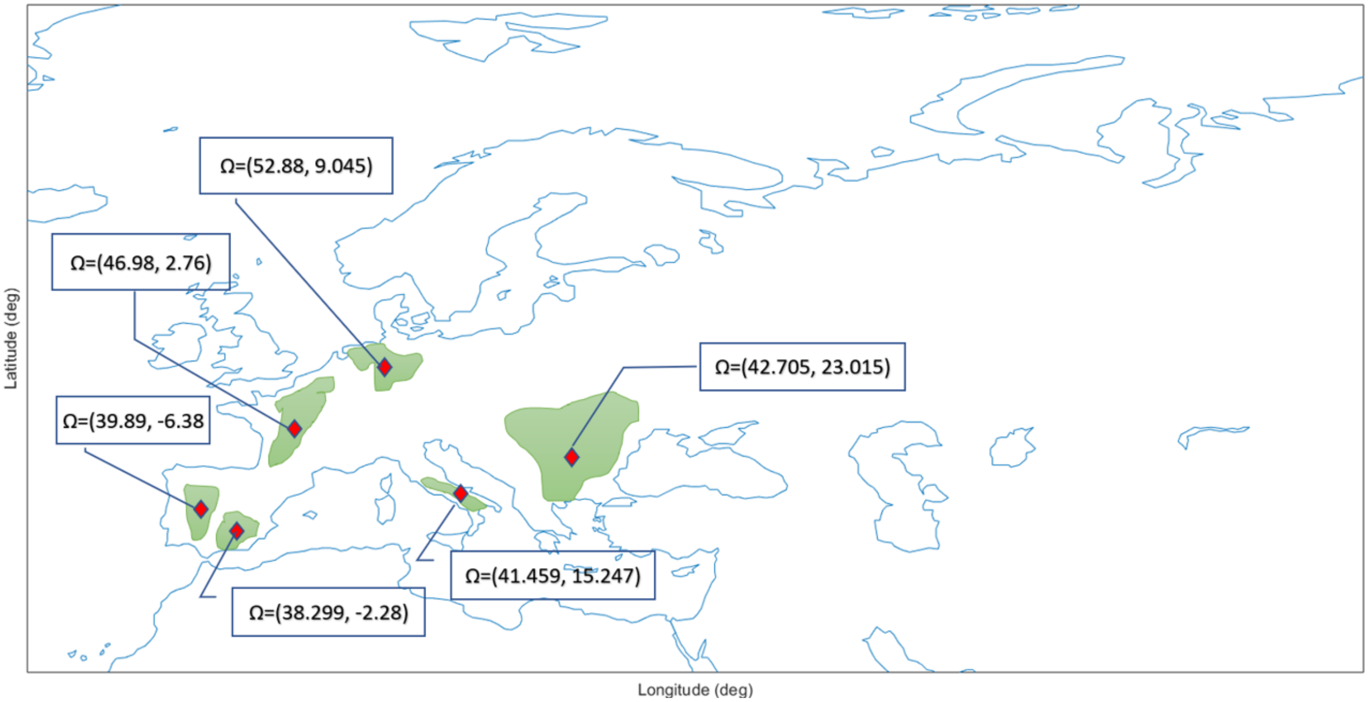

Fig. 7. Ground stations positioning for Europe.

- Integration with existing infrastructure: The methodology should also consider the existing infrastructure, such as ground stations and backhaul links, and ensure the integration of the mega-constellation with the existing infrastructure for seamless service delivery.

V. Conclusions

In this work, we address the need to size the ground segment for the NGSO constellation, especially the placement of the gateway stations based on multiple criteria. We analyze the number of GWs that are necessary to offer coverage worldwide. The requirements and various criteria are combined to reduce the number of GS needed to decrease deployment costs. We analyze the results for a particular constellation in 800 km and 1200km, considering different elevation angles, rain attenuation, visibility, and traffic demand which serve as benchmarks for future optimization algorithms. In addition, challenges are analyzed to optimize the minimization of the number of gateway stations needed.

Acknowledgements

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