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Ground Segment Design For Q/V Band NGSO Satellite Systems via ℓ_0-norm Minimization

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***Abstract*—This work presents a robust approach to derive a quasi-optimal ground segment design in Q/V band for providing connectivity to non-geostationary satellites, considering a "N+P" diversity scheme to cope with rain fading. An optimization problem is formulated with the objective of guaranteeing to each satellite a minimum uplink sum-rate while minimizing the total number of GWs via a ℓ_0-norm representation. A two-stage algorithm is proposed to tackle the non-convexity of the above and achieve GW diversity. Numerical results demonstrated that the proposal outperforms algorithms in the literature by reducing the required total number of GWs by 47%-67%.**

***Index Terms*—NGSO, Q/V band, Optimization.**

I. Introduction

Non-Geostationary Orbit (NGSO) satellite constellations have become increasingly popular due to their potential to provide global broadband services [1], allowing for reduced latency and enhanced coverage with respect to the geostationary ones. This advancement is driven by the growing demand for high-speed internet and reliable communication services worldwide [2]. The design of the ground segment infrastructure is crucial for NGSO constellations, as the gateways (GWs) sites, equipped with large antenna systems, ensure efficient control and data transmission. Due to the ongoing scarcity of spectrum in the Ka-band, it is envisioned that these GW links will exploit the Q/V band, which however is known for its susceptibility to weather-related disruptions, i.e., rain fading. To guarantee operational effectiveness and achieve a level of diversity, the incorporation of multiple GWs is essential.

Many contributions in the literature, such as [3]–[5], propose different switching strategies to adopt in case of outage events, which however is out of scope for this work. To the best of authors' knowledge, [6] is the only contribution that proposes a GW placement approach in Q/V band, while taking into account the rain fading following the International Telecommunication Union (ITU) recommendations [7]. However, heuristic techniques, e.g., genetic algorithm (GA) based algorithms, do not necessarily guarantee convergence to a optimal solution and are computationally expensive. This work presents a more robust approach to achieve a quasi-optimal ground segment design considering a "N+P" diversity scheme [3] to cope with rain fading. In this regard, the major contributions of this paper work can be summarized as follows.

- A mathematical model is developed to represent a satellite constellation requiring connectivity via GWs distributed globally. Potential locations are initially modeled using a grid, while the target design is represented by a binary matrix that selects the desired GWs. Communication aspects, such as rain fading, are considered based on ITU specifications.
- An Integer Non-Linear Programming (INLP) problem is formulated to minimize the total number of GWs required to guarantee a minimum sum-rate for each satellite under clear-sky conditions, using the ℓ_0-norm representation.
- An optimization algorithm is proposed to solve a convex approximation of the problem, combining a logarithmic representation of the ℓ_0-norm and the Successive Convex Approximation (SCA) technique.
- GW diversity is introduced by considering the probability that a maximum number of GWs will simultaneously experience fading. This allows for determining the additional sites required for each link to ensure a minimum sum-rate is achieved, given a target probability. The above optimization algorithm is then applied to derive another solution, that combined with the clear-sky one leads to the final ground segment design.

The conducted simulation campaign demonstrated that the number of GWs (with diversity) grows as the minimum sum-rate required with a concave trend after 30.3 bit/s/Hz. When compared with a GA baseline, the proposed algorithm demonstrated 47%-67% reduction of the GWs required.

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II. System Model

In the reference scenario, the minimum number of GWs is selected from a set of K candidates to provide connectivity, acting as feeder links, to N NGSO satellites. Every GW site is equipped with multiple antennas characterized by a gain G_{G}, each one serving at most one satellite. Similarly, each satellite communicates through a single antenna, all having a gain G_{s}. The considered 24 hour observation time span is split into T time slots, namely orbital configuration, of equal duration τ.

Therefore, the positions of the satellites over time in terms of latitude, longitude, and altitude are denoted by $\mathbf{q}^{\text{s}}_{t,n} \in$

$\mathbb{R}^3, \forall t = 1, \ldots, T, n = 1, \ldots, N$. The candidate GWs' positions are modeled as points of a grid over the Earth's surface, which accounts already for the planet curvature and excludes the oceans and the Antarctica region. The granularity of the grid can be controlled, for instance, by the number of points per degree of latitude and longitude. This in turns determine also the number of possible GWs locations, denoted as $\mathbf{q}_k^{\text{G}} \in \mathbb{R}^3, \forall k = 1, \ldots, K$. Moreover, the design of the ground segment is achieved through the optimization of a 3D binary matrix $\mathbf{X} \in \{0,1\}^{T \times N \times K}$, which accounts for all the available degree of freedom, namely time, satellites, and GWs. Each entry is uniquely identified by $x_{t,n,k}$ that describes if a link between GW k and satellite n at time t is active ($x_{t,n,k} = 1$) or not ($x_{t,n,k} = 0$). Hence, the vector containing the total number of accesses for each GW can be expressed as $\mathbf{x} = \mathbf{1}_N^{\mathsf{T}} \mathbf{1}_T^{\mathsf{T}} \mathbf{X} \in \mathbb{R}_+^K$, which corresponds to the sum of the first two dimensions of $\mathbf{X}$, i.e., timeslots and satellites. Finally, $d_{t,n,k}$ is the distance between each satellite and GW, i.e. the slant range.

A. Communication Modeling

The whole communication system is assumed to employ Fractional Frequency Reuse (FFR) and beam directivity to minimize the interference among multiple signals coming from the GWs. Without loss of generality, the LoS channel coefficient $h_{t,n,k}$ between a GW k and a satellite n in timeslot t is $h_{t,n,k} = \sqrt{G}\lambda(4\pi d_{t,n})^{-1}$, where $G = G_{\text{G}} G_{\text{S}}$ denotes the combined gain of the GW and satellite antennas, with λ being the wavelength of the carrier frequency. The maximum achievable sum-rate (in bit/s/Hz) measured at the a certain satellite n in timeslot t under clear sky conditions is

$$r_{t,n} = \sum_{k=1}^{K} \log_2 \left(1 + \gamma \frac{G\lambda^2}{16\pi^2 d_{t,n,k}^2} x_{t,n,k} \right) \tag{1}$$

with γ being the average Signal-to-Noise Ratio (SNR) of a GW-satellite link.

B. Rain Fading Modeling

In the Q/V band, the main source of impairment is represented by the rain fading which, especially at high frequencies, can cause a drop of the SNR in the order of tens of dBs. As a matter of fact, the other source of attenuation due to atmospheric gas, clouds, and scintillations are negligible and are assumed to be compensated employing a power control scheme [3] or by keeping a fixed link margin of a few dBs.

Different methodologies can be employed to obtain the probability $p_{t,n,k}$ that the rain attenuation $A_{t,n,k}$, usually modeled as a positive random variable in dB, along a specific link exceeds a certain threshold $\Delta_{t,n,k} \geq 0$:

$$p_{t,n,k} = \mathbb{P}\left(A_{t,n,k} \geq \Gamma_{t,n,k} - \Gamma_0 \triangleq \Delta_{t,n,k} \right) = F(\Delta_{t,n,k}), \tag{2}$$

where $\Gamma_{t,n,k} = 10 \log_{10} \left(\gamma \frac{G\lambda^2}{16\pi^2 d_{t,n,k}^2} \right)$ and $\Gamma_0 = 10\log_{10}(\gamma_0)$ are the SNR and the target margin (both in dB), while $F(\cdot)$ is the complementary cumulative distribution function. The first consists in approximating the attenuation with a log-normal random variable, as specified in ITU-R Recommendation P.1853-2 [8], which demonstrated good results but could be imprecise in some circumstances. Two more conservative approaches envision to directly leverage: the annual rainfall probability $\overline{p}_k$ obtained according to ITU-R Recommendation P.837-7 [9] and the probability of rain attenuation on a slant path computed following the ITU-R P.618-14 [7, Sec. 2.2.1.2]. The latter, however, forces $\Delta_{t,n,k} = 0$. Nonetheless, the same specifications provide in [7, Sec. 2.2.1.1] another methodology with a formulation that can be analytically inverted.

Therefore, inspired by [6], in this work a hybrid approach is adopted to compute $p_{t,n,k}$: for probabilities smaller than $5 \cdot 10^{-2}$, [7, Sec. 2.2.1.1] is chosen, while the rain attenuation transition from $5 \cdot 10^{-2}$ to $\overline{p}_k$ is assumed to be linear:

$$\Delta_{t,n,k} = \frac{p_{t,n,k} - \overline{p}_k}{5 \cdot 10^{-2} - \overline{p}_k} F^{-1}(5 \cdot 10^{-2}), \tag{3}$$

where the rain attenuation $F^{-1}(5 \cdot 10^{-2})$ is again computed through [7, Sec. 2.2.1.1]. Moreover, it is assumed that the rain attenuation threshold is $\Delta_{t,n,k} = 0$ [6] for fractions of time larger than the yearly rainfall probability $\overline{p}_k$ [9]. Lastly, for the sake of tractability, it is assumed that the GW sites described through the grid are far enough, i.e., few thousands kilometers, to consider the rain fading among different sites spatially uncorrelated [3], [6].

III. Problem Formulation

The ground segment design accounting for the rain fading is a challenging goal, and hence it is decomposed in two stages. First, it is formulated an optimization problem aiming at minimizing the number of GWs required during the analyzed timeframe T through the optimization of $\mathbf{X}$ in clear sky conditions. Then, the derived solution is augmented to provide redundancy to the entire system. Only the GWs satisfying a minimum elevation angle with respect to a satellite are considered, which in turn decreases the complexity of the system. This aspect is modeled via a set V containing all the $\{t,n,k\}$ index triplets which do not match the above requirement. As a consequence, there could be $\{t,n\}$ for which no GWs are available, e.g, over the ocean, which can be mathematically formulated as $\sum_{k=1}^{K} x_{t,n,k} = 0$. The set containing all the $\{t,n\}$ for which the previous sum is strictly greater than zero is defined as V'.

Therefore, the optimization problem can be formulated as:

$$\min_{\mathbf{X}} \|\mathbf{x}\|_0 \quad \text{s.t.} \tag{4}$$

$$\mathbf{X} \in \{0,1\}^{T \times N \times K}, \tag{4a}$$

$$x_{t,n,k} = 0, \quad \forall \{t,n,k\} \in V, \tag{4b}$$

$$r_{t,n} \geq \overline{r}, \quad \forall \{t,n\} \in V', \tag{4c}$$

where the minimization of the ℓ_0-norm accounts for the maximization of the vector entries, which in turn leads to the minimization of the selected GWs. Further, (4a) forces the binary nature on the design matrix. (4b) states that, when the minimum elevation angle requirement is not satisfied, the selection variable is set to 0. Finally, (4c) guarantees that, when

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at least one GW is visible from a satellite, a minimum data rate $\overline{r}$ must be guaranteed.

As a matter of fact, (4) is a INLP problem and hence difficult to solve. Indeed, the above formulation is intractable, since the the objective function and constraint (4a) are non-convex.

IV. Proposed Solution

The original problem need to be mathematically manipulated in order to derive a tractable convex approximation and hence a quasi-optimal solution.

A. ℓ_0-norm Approximation

The ℓ_0-norm minimization, also known as sparse recovery problem, is a well-known NP-Hard problem in the scientific community that has been applied in manifold applications. In the literature, the solution adopted to cope with this issue are (i) greedy algorithms, such as Orthogonal Matching Pursuit (OMP) or (ii) solving an alternative mathematical representation. The first approach is not always viable since it is designed for linear systems and in order to be employed it must satisfy some conditions. The second approach instead is more practical and provides the benefit to deal with a manipulable expression. Inspired by [10], the objective function in (4) is reformulated leveraging an equivalent representation through the sum of logarithmic functions. For the benefit of the reader, a simpler proof is provided hereby.

Lemma 1. *The minimization of the ℓ_0-norm of vector $\mathbf{x}$ can be equivalently achieved as the minimization of*

$$\log\left(\mathbf{1}_K^{\mathsf{T}}\left(\mathbf{1}_K+\mathbf{x}\right)\right)=\sum_{k=1}^{K}\log\left(1+X_k\right), \tag{5}$$

with $\mathbf{x}=[X_0,\dots,X_K]$ and $X_k=\sum_{t=1}^{T}\sum_{n=1}^{N}x_{t,n,k}$ being the number of accesses for each GW k.

Proof. Let $\{\mathbf{x}_m\}$ with $m=1,\dots,M$ be the set of the vectors containing the total number of accesses for each GW, corresponding to the M suitable ground segment designs $\{\mathbf{X}_m\}$ satisfying the constraints of Problem 4. Without loss of generality, let this set contain two solutions: one with a single GW k and the other with two k' and k'', respectively. Hence, the total number of accesses, which is a integer quantity, in the two configurations obeys the following

$$X_k \le X_{k'}+X_{k''}, \tag{6}$$

$$1+X_k \le 1+X_{k'}+X_{k''} < (1+X_{k'})(1+X_{k''}), \tag{7}$$

$$\log(1+X_k) < \log(1+X_{k'})+\log(1+X_{k''}), \tag{8}$$

which is exactly the definition of the new objective function (5). As can be seen, the logarithm sum splits its codomain in separate regions depending on the number of GWs. This holds true even if the number of accesses in the two designs is the same, i.e., the strong inequality sign in (6) is not affected when (8) holds with equality. All the above can be easily extended to configurations with different K noting that $X_{k'}$ and $X_{k''}$ can be written as sums of smaller terms. ■

Unfortunately, the derived objective, even though tractable, is still non-convex with respect to $\mathbf{X}$. To tackle this issue, the SCA technique is employed, and hence the solution is iteratively derived through the first-order Taylor expansion of the objective function. For each local point $\overline{X}_k=\sum_{t,n}\overline{x}_{t,n,k}$, the convex approximation is $\mathcal{F}=\sum_{k=1}^{K}X_k/(1+\overline{X}_k)$.

B. GW Design Binary Matrix

Furthermore, to cope with the non-convexity of constraint (4a), it is necessary to relax it as

$$0\le x_{t,n,k}\le 1, \quad \forall\{t,n,k\}\notin V, \tag{9}$$

which, however, does not necessary lead to an integer solution. Indeed, inequality (8) in Lemma 1 does not hold anymore if the above is adopted, since manifold optimal fractional solutions exist. The following Lemma provides a solution to circumvent this issue.

Lemma 2. *To enforce a binary site selection, it is sufficient to impose a integer number $g_{t,n}\in\mathbb{N}_{\setminus 0}$ of minimum GWs selected for each orbital configuration by every satellite, which can be modeled as follows:*

$$\sum_{k=1}^{K}x_{t,n,k}\ge g_{t,n}, \quad \forall\{t,n\}\in V'. \tag{10}$$

Proof. Applying (10) to proof of Lemma 1, it can be seen that even if (9) is considered, (6) holds with equality, i.e., $X_k=\sum_{t,n}g_{t,n}$, as well as the proof of Lemma 1, which can be therefore employed again in the solution of the problem. ■

Note that, however, the above solution guarantees only $g_{t,n}$ integer GW selection, which can be insufficient or, on the contrary, excessive number. The choice of $g_{t,n}$ strictly depends on the parameters of the scenario, such as the satellites' orbits, visible GWs, and minimum sum-rate required, i.e., $\overline{r}$.

Without any knowledge of the system, $g_{t,n}=1$ which can be increased until no further improvement is detected.

C. Problem Convexification

To capitalize on the results of Lemma 2, an iterative approach is put in place. Starting with a minimum number of GWs $g_{t,n}=1,\ \forall\{t,n\}\in V'$, the final formulation of the problem reads

$$\min_{\mathbf{X}} \mathcal{F} \quad \text{s.t.} \tag{11}$$
$$(4b),(4c),(9),(10).$$

which can be now iteratively solved with standard software as CVX, until convergence is achieved. After the optimization process, $\mathbf{X}$ undergoes a rectification procedure, where only the values greater than a certain threshold, e.g., .99, are set to unity, thus selecting the first candidate ground segment design. In case of $\{t,n\}$ for which the sum-rate requirement in (4c) is not satisfied (due to the rectification), it is sufficient to increment the corresponding $g_{t,n}$ and repeat the optimization process until (4c) is completely satisfied. The algorithm is summarized in Algorithm 1. Theoretically, SCA is not guaranteed to converge, since $\mathcal{F}$ is an upper-bound of (5). Nonetheless, when the approximation is tight enough, it leads to a quasi-optimal solution, as will be numerically verified.

Algorithm 1: Clear-Sky Ground Segment Design

Initialize $g_{t,n} = 0, \forall t, n$;
do
  Increase by one every $g_{t,n}$ corresponding to the sum-rates not satisfied;
  Randomly initialize $\mathbf{X}$ and, accordingly, $\overline{X}_k$;
  repeat
    Solve problem (13) to obtain $\mathbf{X}$;
    Update $\overline{X}_k, \forall k$ given the optimal $\mathbf{X}$;
  until *convergence is achieved*;
  Rectify the derived solution by setting to unity only the entries of $\mathbf{X}$ which are greater than 0.99;
  Compute the sum-rates according to the rectified solution;
while (4c) *is not satisfied*;

V. Rain Fading and GW Diversity

The impact of rain fading on SNR degradation has been characterized in Section II-B through the probability that the attenuation is greater than a certain threshold. The objective is to augment the quasi-optimal clear-sky solution, derived in the previous Section, with a certain number of other GWs in order to guarantee a target outage probability. Let $S_{t,n}$ be the sets of the indexes of the previously selected ones.

In order to provide diversity, it is necessary to first obtain the number of new GWs. With this aim, the probability that at most $J \leq S_{t,n}$ GWs previously selected through $\mathbf{X}$ are in fading for each $\{t,n\}$ is

$$p^{\text{out}}_{t,n,J} = \prod_{k \in S_{t,n}} (1 - p_{t,n,J}) + \sum_{j=1}^{J} \prod_{j' \in E_j} p_{t,n,j'} \prod_{j'' \notin E_j} (1 - p_{t,n,j''}), \tag{12}$$

where the first term is the probability that none of the selected sites are faded, while the second term accounts for the probability that J GWs are faded. The sets E_j contain all the possible combinations without repetitions of the GW indexes of the clear sky solution. This process is carried out for all satellites and orbital configurations by increasing J and comparing the results with a certain desired threshold p_0. It is worth specifying that $J = 0$ is a possible case, i.e., no additional GWs are required. Otherwise, the worst-case scenario occurs when the GWs that contribute the most to the sum-rate are faded. In this case, those GWs cannot be selected by the satellite during that specific timeslot. Therefore, these index triplets together with the ones in V are contained in a new set V'', while the remaining ones, i.e., GWs with lower rate, in V'''. Hence, a new GW configuration can be obtained solving the following modified version of Problem (11):

$$\min_{\mathbf{X}} \mathcal{F} \quad \text{s.t.} \tag{13}$$

$$x_{t,n,k} = 0, \quad \forall \{t,n,k\} \in V'', \tag{13a}$$

$$x_{t,n,k} = 1, \quad \forall \{t,n,k\} \in V''', \tag{13b}$$

$$(4c), (9), (10).$$

following the same procedures discussed in Section IV-C. Clearly, $g_{t,n}$ can be initially initialized as the value assumed at the end of the clear sky stage and then incremented if necessary. Finally, the redundant configuration can be obtained performing an OR between the two solutions. Clearly, the derived ground segment design is not exempt from fading, whose probability can be computed according to (12) with the updated GW selection.

VI. Overall Algorithm Complexity

The overall algorithm complexity is the summation of different contributions. The complexity associated with the clear-sky solution is $\mathcal{O}\big(I(|V'|)^{3.5}\big) \leq \mathcal{O}\big(I(TNK)^{3.5}\big)$, with I being the number of iterations required by the SCA and iterative approach to satisfy (4c), while $|V'|$ is the cardinality of the set. Typically the latter is only the 10% of the total possible GWs, as will be shown in the next Section. Further, the complexity associated with the probability calculations in (12) corresponds about to the number of total combinations $TN \sum_j \binom{J}{j}$. Nonetheless, J is always remarkably small due to practical limitations in terms of number of simultaneous link that a satellite can maintain. Therefore, considering that the problem must be re-solved to provide diversity, the total time complexity of the algorithm is $\mathcal{O}\big(2I(|V'|)^{3.5} + TN \sum_j \binom{J}{j}\big) \simeq \mathcal{O}\big(TN(2I(TN)^{2.5} + \sum_j \binom{J}{j})\big)$. Please note that Algorithm 1 is an off-line strategy executed only during the ground segment design phase.

VII. Numerical Results and Discussion

In this section, the obtained simulation results are analyzed. Specifically, the tests are conducted on a Intel Core i7-13800H with 32 GB of RAM. The grid from which the GWs are selected is 30x30 points which corresponds to 5° per latitude point and 12° per longitude point. Accounting for Earth's curvature, and excluding the oceans and Antarctica, the total number of satellites is $K = 319$. After filtering for a minimum elevation angle of 10°, the actual number drops to 24 possible visible GWs at the same time, which confirms the complexity analysis in Section VI. The number of timeslots is set to $T = 201$ and hence a duration $\tau \simeq 7$ min, with $N = 3$ satellites on different orbits, characterized by inclination 73°, phasing 2, and 550 km altitude. Their complete trajectories, depicted as solid lines in Fig. 1, show a thorough coverage which can also be seen as a virtual constellation of $TN = 603$ satellites fixed in time. Furthermore, $\Gamma_0 = 0$ dB, $p_0 = 0.995$, the carrier frequency is set to 50 GHz, thus $\lambda = 6$ mm; $\gamma = 131$ dB at 100 W with 1 GHz bandwidth for each link and total noise system temperature of 596.91 K [6]. All antennas considered are assumed to be parabolic, hence the total gain $G = \eta_{\text{G}} \eta_{\text{S}} (\pi/\lambda)^4 D_{\text{G}}^2 D_{\text{S}}^2$, where $D_{\text{S}} = 0.5$ m and $D_{\text{G}} = 2.4$ m are the diameters of the satellite and GW antennas and $\eta_{\text{S}} = \eta_{\text{G}} = 0.65$ their efficiency. To analyze the quality of the solutions obtained, Fig. 1 illustrates the maps for $\overline{r} = 10$ bit/s/Hz obtained with the proposed algorithm and a Genetic Algorithm (GA)-based approach, employed to solve the original Problem (4). The choice of this algorithm as baseline is motivated by the adoption of GA-based approaches in other works [6]. The main GA parameters are the population size, the elite count, and the generation number, each one set to 400, 150, and 350, respectively. The GA selects the solution

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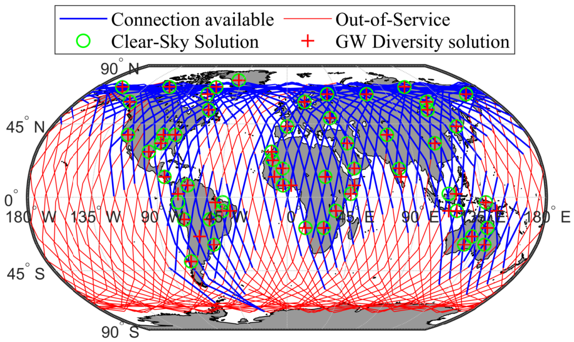
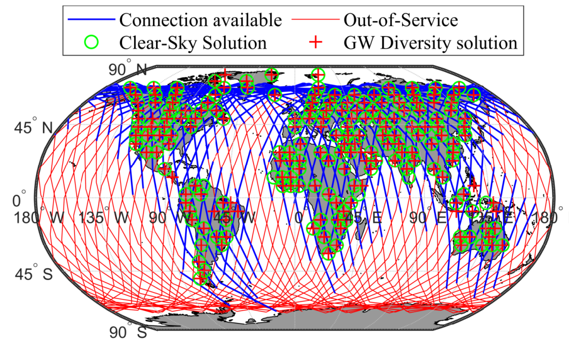
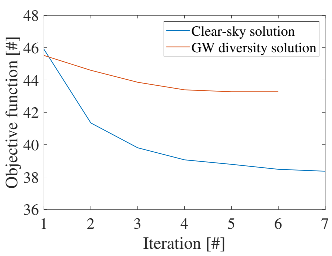


(a) Proposed algorithm.

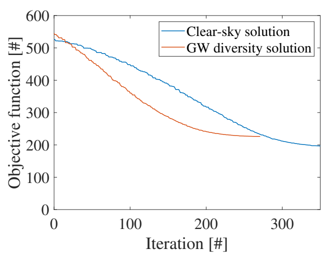


(b) GA baseline.

Fig. 1: Comparison between two configurations for $\overline{r} = 10$ bit/s/Hz and $g_{t,n} = 1 \forall t, n$.



(a) Proposed algorithm.



(b) GA baseline.

Fig. 2: Convergence curves in the two stages.

$g_{t,n}$	Up to $\overline{r}$ bit/s/Hz	This work		GA	
		Tot. # of GW	Reuse	Tot. # of GW	Reuse
1	15.1	63	77.8%	193	87%
2	30.3	107	74.77%	246	90.2%
3	45.7	126	80.1%	263	96.2%
4	61.2	151	85.4%	284	97.2%

TABLE I: Performance comparison.

with the lowest number of GWs from the population. Clearly, the quasi-optimal ground segment design derived from the proposal outperforms the GA, while still allowing for global coverage (blue lines), except for Antarctica and the oceans (red lines) as desired. Indeed, the total number of sites required is significantly lower, 62 vs 200. The reuse factor, defined as the number of common sites between the solutions of the two stages over the total number of unique sites, is remarkable in both cases as $\sim$77.4% and 85.5%, respectively. Nonetheless, as shown in Fig. 2, the convergence speed of the proposal is superior to the baseline: only 12 iterations for the two stages with a precision of 10^{-3} against $\sim$600 of the GA.

Another important insight regards the fact that the maximum sum-rate achieved is actually greater than $\overline{r}$, even if $g_{t,n} = 1 \forall t, n$. This means that a certain ground design in a certain time instant can satisfy whatever minimum sum-rate $\overline{r}$ up to the maximum total capacity. This aspect is evident in Table I, where the solutions of the two algorithms are compared with the minimum number of sites selected per link and the corresponding maximum $\overline{r}$. The number of GW significantly increases after $g_{t,n} = 1$ but keeps a concave trend afterwards. Still, the proposed algorithm outperforms the GA in every configuration, with 47%-67% less GWs. The GA higher reuse factor is trivially due to the higher number of sites. Finally, the execution time in all the analyzed configurations is around 30 minutes for Algorithm 1 and about 36 hours for the baseline, which further corroborates the effectiveness of this work.

VIII. Conclusions

In this work, a novel iterative algorithm to derive the quasi-optimal ground segment design subject to sum-rate constraints and robust against the rain fading has been proposed. The comparison with a GA baseline proved the effectiveness of the proposal. Future works will investigate the inter-satellite links with limited capacity and antennas for each GW, with a focus on enhancing the scalability of the algorithm.

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