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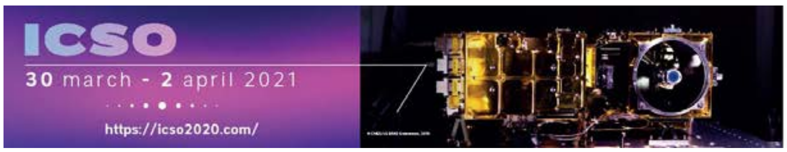

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Low-Complexity Optimization Algorithm for Ground Network Design in Optical Satellite Networks

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ABSTRACT

Free space optics (FSO) is considered a promising technology for satellite communications due to its various advantages over radio-frequency (RF) systems, such as higher throughput, lower energy consumption and smaller mass. Nevertheless, optical satellite communication systems are heavily affected by atmospheric impairments, mainly by clouds. In order to cope with cloud coverage, site diversity technique is employed at the expense of installing extra optical ground stations (OGSs). As a consequence, the interest in ground network optimization is rapidly increasing with the aim to guarantee a given service availability. In this paper, a low-complexity optimization algorithm for ground network design in optical geostationary (GEO) satellite systems is presented, taking into account the spatial correlation between sites. Specifically, the objective is to choose a group of candidate OGSs that minimizes the overall cost of the ground network and meets certain availability requirements for every time period (thus incorporating the temporal variability of cloud coverage). Moreover, an extension of the methodology to optical medium-Earth-orbit (MEO) satellite systems is provided. Lastly, the performance of the proposed algorithm is evaluated via numerical experiments.

Keywords: Optical satellite communications, site diversity, cloud-free line-of-sight (CFLOS) probability, system availability, ground station selection, optimization.

1. INTRODUCTION

Recently, there has been a lot of interest in the utilization of free space optics (FSO) in satellite communication networks. In particular, FSO technology is able to provide larger bandwidth, higher data-rates as well as increased security [1]. Several atmospheric phenomena affect the propagation of optical signals, but the cloud coverage is the major fading mechanism that results in link outage. As a result, the optical link can be modeled as an on/off channel depending on whether or not there is a cloud blockage [2].

Site diversity is an effective technique which can be employed to mitigate the cloud coverage, combining the optical signals transmitted by geographically distributed OGSs towards the same satellite [1]-[4]. In spite of the fact that the OGSs are preferably selected to have large separation distances (thus very low spatial correlation), this is not always the case in practice, so their spatial correlation should be taken into account when estimating the system availability. To this end, the cloud-free line-of-sight (CFLOS) probability, for either a single or multiple links, has been studied extensively in the literature [2]-[3], [5]-[8].

Furthermore, the optimum selection of OGSs has become an interesting research topic nowadays. For example, GEO satellite systems have been examined in [7]-[12], MEO satellite networks have been analyzed in [13]-[15], and low-Earth-orbit (LEO) satellite systems have been studied in [16]. All these approaches provide useful tools and optimization algorithms in order to design the ground segment of optical satellite networks.

The main contribution of this paper is the presentation of a unified methodology for the optimum selection of OGSs in optical GEO/MEO satellite networks in order to minimize the overall cost of the ground network and satisfy given availability requirements per time period. To the best of our knowledge, this is the first work that studies the minimization of the total cost of OGSs (not merely their number) and, at the same time, takes into consideration not only the temporal variability of clouds, but also the spatial correlation of OGSs.

The rest of the paper is organized as follows. In Section 2, the optimization problem is formulated, while a low-complexity optimization algorithm is presented in Section 3. In addition, an extension of the proposed methodology to optical MEO satellite systems is described in Section 4 and simulation experiments are provided in Section 5. Lastly, some conclusions and directions for future work are given in Section 6.

2. PROBLEM STATEMENT

To begin with, we consider an optical GEO satellite network with $\mathcal{K} = \{1, 2, \ldots, K\}$ being the set of candidate OGSs and $\mathcal{T} = \{1, 2, \ldots, T\}$ being the set of time periods (e.g., months). Subsequently, we attempt to find a subset $\mathcal{I}$ of $\mathcal{K}$ that minimizes the overall cost of the ground network, $C(\mathcal{I})$, under availability constraints for each time period. As a result, we can formulate the following optimization problem:

$$\begin{aligned} \underset{\mathcal{I}}{\text{minimize}} \quad & C(\mathcal{I}) = \sum_{i\in\mathcal{I}} c_i \\ \text{subject to} \quad & A_\tau(\mathcal{I}) \geq A_\tau^{\text{th}}, \quad \forall \tau \in \mathcal{T} \\ & \mathcal{I} \subseteq \mathcal{K} \end{aligned} \tag{1}$$

where $c_i > 0$ is the cost of OGS i, $A_\tau(\mathcal{I})$ is the system availability (or, the joint CFLOS probability) in time period τ achieved by the set $\mathcal{I}$ of OGSs, and A_τ^{th} is the system availability threshold for time period τ. More precisely, the system availability $A_\tau(\mathcal{I})$, i.e., the probability of having at least one OGSs in $\mathcal{I}$ available in time period τ, is expressed as follows:

$$A_\tau(\mathcal{I}) = \mathbb{P}\left(\bigcup_{i\in\mathcal{I}}\left\{X_i < x_{i,\tau}^{\text{th}}\right\}\right) = 1 - \mathbb{P}\left(\bigcap_{i\in\mathcal{I}}\left\{X_i \geq x_{i,\tau}^{\text{th}}\right\}\right) = 1 - \int_{\mathcal{D}_{\mathcal{I},\tau}} \varphi_{\mathbf{X}_\mathcal{I}}(\boldsymbol{x}_\mathcal{I}) d\boldsymbol{x}_\mathcal{I} \tag{2}$$

$$\varphi_{\mathbf{X}_\mathcal{I}}(\boldsymbol{x}_\mathcal{I}) = \frac{\exp\left(-0.5\boldsymbol{x}_\mathcal{I}^\top \mathbf{R}_\mathcal{I}^{-1} \boldsymbol{x}_\mathcal{I}\right)}{\sqrt{(2\pi)^{|\mathcal{I}|}\det\left(\mathbf{R}_\mathcal{I}\right)}} \tag{3}$$

where $\mathbf{X}_\mathcal{I} = [X_i]_{i\in\mathcal{I}}^\top$ is a random vector of zero-mean unit-variance normally distributed random variables and $x_{i,\tau}^{\text{th}} = Q^{-1}(1 - P_{i,\tau})$ with $P_{i,\tau}$ being the individual CFLOS probability of OGS i in time period τ; this probability depends on the altitude and the elevation angle of the OGS and can be estimated by following the methodology presented in [5] using the integrated-liquid-water-content (ILWC) statistics [2]. Also, $\mathcal{D}_{\mathcal{I},\tau} = \left\{\boldsymbol{x}_\mathcal{I} = [x_i]_{i\in\mathcal{I}}^\top \in \mathbb{R}^{|\mathcal{I}|} \mid x_i \geq x_{i,\tau}^{\text{th}}, \forall i \in \mathcal{I}\right\}$ is the domain of integration, $\varphi(\cdot)$ is the probability density function (PDF) of the multivariate normal distribution, $d\boldsymbol{x}_\mathcal{I} = \prod_{i\in\mathcal{I}} dx_i$ and $\mathbf{R}_\mathcal{I} = [\rho_{i,j}]_{i,j\in\mathcal{I}}$ is the correlation matrix (symmetric and positive-definite) that captures the spatial correlation of OGSs and whose entries are given by [17]:

$$\rho_{i,j} = 0.35\exp\left(-\frac{d_{i,j}}{7.8}\right) + 0.65\exp\left(-\frac{d_{i,j}}{225.3}\right) \tag{4}$$

where $d_{i,j}$ is the distance between OGSs i and j, which is expressed in km; observe that $d_{i,i}=0 \Rightarrow \rho_{i,i}=1$. Last but not least, the multivariate normal integral in (2) can be calculated using readily available functions from scientific programming software, such as Matlab, based on quasi-Monte Carlo methods [18].

3. OPTIMIZATION ALGORITHM

A naive procedure to globally solve problem (1) is the exhaustive-enumeration algorithm which checks all the 2^K subsets of $\mathcal{K}$. Nevertheless, such an algorithm has exponential complexity in the number of candidate OGSs. To this end, we develop an efficient optimization algorithm that is able to find a near-optimal solution with much lower complexity. In the following analysis, $\mathcal{S}$ denotes the set of OGSs selected so far by the algorithm; at the beginning of the algorithm $\mathcal{S}$ is empty.

Firstly, we define a penalty function which accounts for the total violation of the availability constraints when OGS i is added to $\mathcal{S}$:

$$\vartheta_{\mathcal{S}}(i) = \sum_{\tau\in\mathcal{T}} \max\left(A_\tau^{\text{th}} - A_\tau(\mathcal{S}\cup\{i\}), 0\right), \quad \forall i \in \mathcal{K}\setminus\mathcal{S} \tag{5}$$

In addition, we define another function as the product of the cost c_i and the penalty function $\vartheta_{\mathcal{S}}(i)$:

$$\sigma_{\mathcal{S}}(i) = c_i \cdot \vartheta_{\mathcal{S}}(i), \quad \forall i \in \mathcal{K}\setminus\mathcal{S} \tag{6}$$

In essence, the last function encapsulates the increase in cost together with the overall constraint-violation yielded by selecting OGS i. The pseudocode of the proposed algorithm is given in Table 1. In every iteration, the OGS with the minimum $\sigma_{\mathcal{S}}(i)$ is chosen from the remaining OGSs and then added to $\mathcal{S}$. This process is repeated until satisfying all the availability constraints, since $\sigma_{\mathcal{S}}(i)=0 \Leftrightarrow \vartheta_{\mathcal{S}}(i)=0 \Leftrightarrow A_\tau(\mathcal{S}\cup\{i\}) \geq A_\tau^{\text{th}}, \forall\tau\in\mathcal{T}$.

Last but not least, the maximum number of subsets checked by the algorithm is $\sum_{m=0}^{K-1}(K-m) = \sum_{m=1}^{K} m = \frac{K(K+1)}{2} = = O(K^2) \ll 2^K$, which is polynomial (quadratic) in the number of candidate OGSs.

4. EXTENSION TO OPTICAL MEO SATELLITE SYSTEMS

Afterwards, an extension of the proposed approach to optical satellite networks with a single MEO satellite is presented. First of all, we introduce another set $\mathcal{B}=\{1,2,\ldots,B\}$ which represents the MEO-satellite orbital positions, i.e., we perform a discretization of the orbit of the MEO satellite. Secondly, we should make the following modifications:

- The new availability constraints, per time period and orbital position, are: $A_{\tau,b}(\mathcal{I}) \geq A_{\tau,b}^{\text{th}}, \quad \forall\tau\in\mathcal{T}, \forall b\in\mathcal{B}$.
- The quantities $A_\tau(\mathcal{I})$, A_τ^{th}, $x_{i,\tau}^{\text{th}}$, $P_{i,\tau}$ and $\mathcal{D}_{\mathcal{I},\tau}$ are replaced by $A_{\tau,b}(\mathcal{I})$, $A_{\tau,b}^{\text{th}}$, $x_{i,\tau,b}^{\text{th}}$, $P_{i,\tau,b}$ and $\mathcal{D}_{\mathcal{I},\tau,b}$, respectively. In other words, we replace every subscript τ with τ,b.

- The penalty function becomes $\vartheta_{\mathcal{S}}(i)=\sum_{\tau\in\mathcal{T}}\sum_{b\in\mathcal{B}}\max\left(A^{\text{th}}_{\tau,b}-A_{\tau,b}(\mathcal{S}\cup\{i\}),0\right),\quad \forall i\in\mathcal{K}\setminus\mathcal{S}$.

Now, the algorithm presented in Table 1 can be used exactly as it is. Finally, with regard to optical satellite networks with multiple MEO satellites (i.e., full MEO constellation), the desired system availability can be achieved if every selected OGS is equipped with adequate number of terminals [15].

Table 1. Optimization Algorithm for OGS selection in optical satellite networks.

1: $\mathcal{S}:=\varnothing$
2: **repeat**
3: $i^{*}:=\arg\min\left\{\sigma_{\mathcal{S}}(i)\mid i\in\mathcal{K}\setminus\mathcal{S}\right\}$
4: $\sigma^{*}:=\sigma_{\mathcal{S}}(i^{*})$
5: $\mathcal{S}:=\mathcal{S}\cup\{i^{*}\}$
6: **until** $\sigma^{*}=0$
7: **return** $\mathcal{S}$

5. SIMULATION EXPERIMENTS

In this section, the performance of the proposed algorithm is investigated via numerical simulations, assuming an optical GEO satellite system with $K=15$ candidate OGSs (shown in Table 2), $T=12$ time periods (the months of a year), and $A^{\text{th}}_{\tau}=A^{\text{th}}$, $\forall\tau\in\mathcal{T}$ (in what follows, A^{th} is referred to as the system availability threshold). In addition, all results have been averaged over 100 independent and identically distributed (i.i.d.) scenarios, where the OGS costs $c_i\sim\text{uniform}\{4,5,6,7,8\}$. Moreover, the relative error is used as a performance indicator, which is defined by:

$$\varepsilon_{\text{rel}}=\frac{C(\mathcal{S})-C^{*}}{C^{*}} \tag{7}$$

where $C(\mathcal{S})$ is the overall cost achieved by the proposed algorithm and C^{*} is the optimum cost obtained from the exhaustive-enumeration algorithm. Obviously, $C(\mathcal{S})\geq C^{*}$.

The average values of $C(\mathcal{S})$, C^{*} and ε_{rel} versus the system availability threshold are shown in Table 3. In particular, the optimum cost C^{*} increases with A^{th} ; this is expected, since greater availability requirement results in higher cost for the ground network development. Last but not least, the achieved relative error ranges from 6.8 to 17.6%.

Table 2. Candidate OGS locations.

No.	Site	Latitude [º N]	Longitude [º E]	Altitude [km]	Elevation Angle [º]
1	Malargue	-35.48	-69.59	1.4	48.1
2	Vernon	34.21	-99.4	0.4	43.6
3	Manassas	38.78	-77.57	0.12	45.1
4	Steele Valley	33.76	-117.3	0.6	32
5	Washington	39.9	-77.04	0.2	43.9
6	Oklahoma	35.44	-97.53	0.45	43.4
7	Santiago	-33.43	-70.64	0.3	50.5
8	South Mountain (CA)	34.33	-118.99	0.4	30.4
9	Las Vegas	36.12	-115.2	0.65	32
10	Buenos Aires	-34.6	-58.41	0.3	45.2
11	Lima	-11.94	-76.72	0.8	76
12	Sao Paulo	-23.55	-46.65	0.7	46.3
13	Dallas	32.74	-96.9	0.16	46.3
14	Lurin	-12.28	-76.85	0.1	75.6
15	Maryland	39.38	-77.08	0.22	44.4

Table 3. Performance evaluation of the proposed algorithm.

A^{th} (%)	$C(\mathcal{S})$	C^*	ε_{rel} (%)
98.1	22.52	19.17	17.6
98.4	22.55	19.68	14.7
98.7	22.39	20.18	11.0
99.0	26.63	22.94	16.2
99.3	27.58	24.47	12.8
99.6	32.18	28.62	12.5
99.9	40.54	37.92	6.8

6. CONCLUSION & FUTURE WORK

In summary, the optimum selection of OGSs in optical GEO/MEO satellite networks has been studied, in order to minimize the overall cost of the ground network and satisfy given availability requirements for each time period. The proposed approach captures the spatial correlation between the OGSs as well as the temporal variability of clouds. An efficient optimization algorithm has also been developed to find near-optimal solutions with affordable complexity. Finally, according to the simulation experiments, the proposed algorithm achieves an average relative error in the order of 10-15%. Although this algorithm has much lower complexity than the exhaustive enumeration of all subsets/combinations, it is a short-sighted heuristic algorithm that performs a greedy selection of the next OGS in each iteration. Therefore, it would be particularly useful to design more sophisticated optimization algorithms with better performance.

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