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

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INTRODUCTION

- 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). 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.

PROBLEM STATEMENT

- 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).
- Optimization problem formulation:

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

c_i → OGS costs

A_τ^{th} → System availability threshold for each time period

- System availability: $A_\tau(\mathcal{I}) = 1 - \int_{\mathcal{D}_{\mathcal{I},\tau}} \varphi_{\mathbf{X}_\mathcal{I}}(\boldsymbol{x}_\mathcal{I})\, d\boldsymbol{x}_\mathcal{I}$ → Multivariate normal integral
- Domain of integration: $\mathcal{D}_{\mathcal{I},\tau} = \left\{\boldsymbol{x}_\mathcal{I} = [x_i]_{i\in\mathcal{I}}^{\top} \in \mathbb{R}^{|\mathcal{I}|} \mid x_i \geq x_{i,\tau}^{\text{th}}, \forall i \in \mathcal{I}\right\}$

  where $x_{i,\tau}^{\text{th}} = Q^{-1}(1 - P_{i,\tau})$ → $P_{i,\tau}$: CFLOS probability of the OGS in each time period
- Correlation coefficients:

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

$d_{i,j}$ → Distance between the OGSs, in km

OPTIMIZATION ALGORITHM

- $\mathcal{S}$ denotes the set of OGSs selected so far by the algorithm; at the beginning of the algorithm it is empty.
- Penalty function which accounts for the total violation of the availability constraints when an OGS is added to $\mathcal{S}$:

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

- Another function as the product of the cost and the penalty function:

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

- 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.

$\mathcal{S} := \varnothing$

repeat

$\quad i^* := \arg\min\{\sigma_{\mathcal{S}}(i) \mid i \in \mathcal{K}\setminus\mathcal{S}\}$

$\quad \sigma^* := \sigma_{\mathcal{S}}(i^*)$

$\quad \mathcal{S} := \mathcal{S}\cup\{i^*\}$

until $\sigma^* = 0$

return $\mathcal{S}$

EXTENSION TO OPTICAL MEO SATELLITE SYSTEMS

- Optical satellite networks with a single MEO satellite
- $\mathcal{B} = \{1,2,\ldots,B\}$: the set of the MEO-satellite orbital positions
- Availability constraints, per time period and orbital position:

  $A_{\tau,b}(\mathcal{I}) \geq A_{\tau,b}^{\text{th}}, \quad \forall \tau \in \mathcal{T}, \forall b \in \mathcal{B}$
- Replace every subscript τ with τ, b.
- The penalty function becomes:

  $\vartheta_{\mathcal{S}}(i) = \sum_{\tau\in\mathcal{T}} \sum_{b\in\mathcal{B}} \max\left(A_{\tau,b}^{\text{th}} - A_{\tau,b}(\mathcal{S}\cup\{i\}), 0\right), \quad \forall i \in \mathcal{K}\setminus\mathcal{S}$
- Now, the proposed algorithm can be used exactly as it is.
- Full MEO constellation: every selected OGS should be equipped with adequate number of terminals [1].

SIMULATION EXPERIMENTS

- Optical GEO satellite system: $K = 15$, $T = 12$, $A_\tau^{\text{th}} = A^{\text{th}}, \forall \tau \in \mathcal{T}$
- 100 i.i.d. scenarios with $c_i \sim \text{uniform}\{4,5,6,7,8\}$.
- The relative error is used as a performance indicator: $\varepsilon_{\text{rel}} = \frac{C(\mathcal{S}) - C^*}{C^*}$
- The achieved relative error ranges from 6.8 to 17.6%.

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

CONCLUSION & FUTURE WORK

- Optimum selection of OGSs in optical GEO/MEO satellite networks: minimization of the overall cost of the ground network, satisfying 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.
- 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, 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.

REFERENCES

[1] N. K. Lyras, C. N. Efrem, C. I. Kourogiorgas, A. D. Panagopoulos and P.-D. Arapoglou, "Optimizing the Ground Network of Optical MEO Satellite Communication Systems," *IEEE Systems Journal*, vol. 14, no. 3, pp. 3968-3976, Sept. 2020.