

Feeder Link Constraints-Aware Inter-Satellite Routing for LEO Satellite Networks

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Abstract—In this paper, we address the routing problem in Low Earth Orbit (LEO) satellite networks under stringent feeder link (FL) constraints. LEO networks rely on satellites interconnected via inter-satellite links (ISLs) and connected to the ground through feeder links to a limited number of fixed-position ground gateways (GWs). While the large number of satellites provides spatial diversity for user access, the gateway infrastructure remains sparse due to economic and geographical limitations. As a result, FLs often become a bottleneck in the end-to-end (E2E) routing process, where traffic from user terminals (UEs) must traverse a satellite relay path before reaching a ground gateway. The dynamic nature of satellite positions, limited gateway visibility, and link congestion further complicate routing decisions. To address these challenges, we propose a routing strategy that explicitly accounts for FL availability during path construction. Unlike conventional methods that prioritize access or inter-satellite links first, our approach dynamically adapts routing decisions based on link feasibility, availability, and shared congestion.

Index Terms—LEO satellite, Satellite networks, Routing algorithm, Inter-satellite link, Feeder link

I. INTRODUCTION

Low-Earth Orbit (LEO) satellite networks have recently attracted significant attention as a viable means to enhance global connectivity, especially in areas where terrestrial infrastructure is unavailable or economically impractical [1]. Due to their low altitude, LEO satellites offer reduced latency and wide-area coverage compared to geostationary systems, making them a key component in emerging non-terrestrial networks (NTNs) [2]. In typical LEO architectures, user data is relayed to the terrestrial core network through a sequence of service links (SLs) from user equipment (UE) to satellites, inter-satellite links (ISLs) between satellites, and feeder links (FLs) from satellites to ground gateways (GWs) [3].

A fundamental structural constraint in this architecture is that SLs and FLs are limited to single-hop connections—each UE may connect to only one visible satellite, and each satellite may deliver traffic to only one visible GW [4]. In contrast, ISLs support multi-hop communication, allowing flexible routing between satellites. This asymmetry introduces potential bottlenecks at both the network ingress and egress, particularly at the FL stage where gateway visibility and capacity are often constrained by geometric limitations and sparse deployment [5].

Despite these constraints, much of the prior work on LEO network routing has centered on optimizing ISL paths, often treating FL assignment as an afterthought. This can result in infeasible or suboptimal end-to-end routes when feeder links are unavailable or congested. The problem is further exacerbated in realistic settings with limited gateway density and strict elevation angle thresholds.

To address this issue, we propose a Lagrangian relaxation-based routing algorithm that explicitly accounts for feeder link constraints during route construction. The proposed approach formulates the end-to-end routing problem as an optimization task and leverages dual decomposition techniques to decouple complex constraints while preserving global feasibility. Our algorithm dynamically incorporates both visibility and congestion information to identify feasible, high-throughput routes from UE to GW.

II. PROPOSED METHOD

We consider a LEO satellite network composed of a set of users $\mathcal{U}$, gateways $\mathcal{G}$, and satellites $\mathcal{S}$. Each user intends to deliver data to a gateway via a path consisting of one Service Link (SL), multiple Inter-Satellite Links (ISLs), and one Feeder Link (FL). Due to physical constraints, SLs and FLs are limited to one-hop connections, while ISLs allow multi-hop forwarding between satellites. Let $\mathcal{P}_k$ denote the selected path for the k -th user–gateway pair, and C_l be the capacity of link $l \in \mathcal{L}$. The binary variable $x_l^{(k)}$ indicates whether link l is used in $\mathcal{P}_k$, and r_k is the allocated end-to-end throughput for pair k . Our objective is to maximize the sum of all r_k while ensuring no link exceeds its capacity:

$$\max_{\{x_k\}} \sum_k r_k \quad (1)$$

$$\text{s.t.} \quad \sum_{k: l \in \mathcal{P}_k} r_k \cdot x_k \leq C_l, \quad \forall l \in \mathcal{L} \quad (2)$$

$$x_k \in \{0, 1\}, \quad r_k \geq 0, \quad \forall k \quad (3)$$

This forms a combinatorial resource allocation problem with integer constraints, which is NP-hard. To handle the capac-

ity constraints effectively, we adopt a Lagrangian relaxation approach. The Lagrangian function is defined as:

$$\mathcal{L}(x, r, \lambda) = \sum_k r_k - \sum_{l \in \mathcal{L}} \lambda_l \left(\sum_{k: l \in \mathcal{P}_k} r_k \cdot x_k - C_l \right) \quad (4)$$

where $\lambda_l \geq 0$ are dual variables associated with each link. The dual function becomes:

$$\mathcal{D}(\lambda) = \max_{\{x_k, r_k\}} \sum_k r_k \left(1 - \sum_{l \in \mathcal{P}_k} \lambda_l \right) + \sum_l \lambda_l C_l \quad (5)$$

The dual problem is solved via the subgradient method, updating λ_l at each iteration t as:

$$\lambda_l^{(t+1)} = \left[\lambda_l^{(t)} + \alpha_t \left(\sum_{k: l \in \mathcal{P}_k} r_k - C_l \right) \right]^+, \quad (6)$$

where α_t is the step size. At each iteration, once the shortest path $\mathcal{P}_k$ is selected for each user based on the current link weights λ_l , the throughput r_k is allocated conservatively to avoid violating any capacity constraint, typically by taking the minimum residual capacity along the path. As the algorithm progresses, links experiencing higher traffic become associated with larger λ_l values, discouraging further load allocation through those paths in future iterations. This dynamic adjustment effectively balances the network load, leading to more evenly distributed traffic across the topology.

III. PERFORMANCE EVALUATION

We evaluate the performance of the proposed routing method through simulations, comparing it against two heuristic baselines: the S-Greedy and F-Greedy schemes. In the S-Greedy approach, service links (SLs) are greedily assigned first, followed by inter-satellite links (ISLs) and finally feeder links (FLs). In contrast, F-Greedy prioritizes feeder links first, then assigns ISLs and SLs in order. Our proposed scheme employs a Lagrangian relaxation-based optimization method that jointly considers SL, ISL, and FL assignments under capacity and visibility constraints. The number following each scheme (100 or 75) denotes the number of satellites in the simulation.

The simulation environment assumes a LEO satellite constellation at an altitude of 550 km. Each satellite can connect to at most one ground gateway (GW) via a single-hop feeder link, and only if a gateway is within the satellite's visibility region. The network includes 10 gateways in total, with a minimum elevation angle requirement of 20 degrees for all ground-satellite links. The maximum allowable distance for ISLs is set to 4000 km.

Figure 1 presents the end-to-end throughput performance as a function of the number of UEs. Across all schemes, increasing the number of users leads to degraded throughput due to elevated traffic congestion and limited link capacity per satellite. Despite this trend, the proposed method consistently outperforms both heuristic baselines, demonstrating its ability to make globally informed routing decisions that better balance

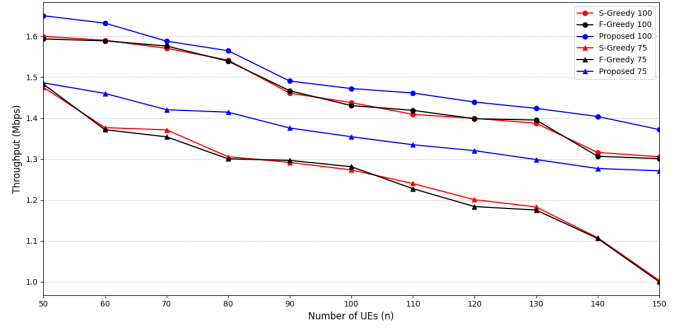


Fig. 1. Throughput according to the number of UEs

link utilization. The performance advantage becomes more pronounced in the more congested scenario with 75 satellites, indicating that the proposed method is particularly effective in dense traffic conditions. This suggests that the Lagrangian-based approach offers a scalable and robust solution for routing in large-scale LEO satellite networks under realistic operational constraints.

IV. CONCLUSION

In this paper, we proposed a Lagrangian relaxation-based routing algorithm for LEO satellite networks that jointly considers service link, inter-satellite link, and feeder link constraints in a unified optimization framework. By integrating link capacity constraints into the routing decision process through dual variables, the algorithm dynamically adjusts path selection to avoid congestion and ensure end-to-end feasibility. The iterative path update and dual variable adjustment process enables the identification of capacity-aware routes without requiring exhaustive search. The proposed approach offers a scalable and principled method for handling routing in large-scale LEO constellations, particularly under limited feeder link availability and strict single-hop access constraints.

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