International Journal of Information System Modeling and Design
Volume 16 • Issue 1 • January-December 2025

A Multipath Routing Algorithm Based on Data Replication for Low Earth Orbit Satellite Networks

Xuechao Liu
DFH Satellite Co., Ltd., China

Zhijian Zhang
DFH Satellite Co., Ltd., China

Yikang Yang
https://orcid.org/0000-0001-9638-3963
Xi'an Jiaotong University, China

ABSTRACT

As the number of low earth orbit (LEO) satellites increases, traditional direct communication links struggle to meet the telemetry and telecommand demands of large-scale satellite constellations. Inter-satellite routing offers a promising solution to this challenge. To enhance the reliability and timeliness of satellite telemetry and telecommand in mega-constellations, we propose the Data Copies-Based Multipath Routing (DCMR) algorithm. By transmitting multiple data copies over different paths, DCMR ensures reliable data delivery even when some paths fail. Additionally, DCMR optimizes the distribution of data across multiple paths to maximize transmission capacity and minimize end-to-end delay. To evaluate the algorithm's performance, simulations are conducted using the Starlink constellation within the STK and MATLAB environments. The results demonstrate that DCMR significantly outperforms single-path routing and backup multipath routing, showcasing its potential for telemetry and telecommand applications in LEO satellite networks.

KEYWORDS

Low Earth Orbit Satellites, Mega-Constellations, Satellite Telemetry and Telecommand, Multipath Routing Algorithm, Load Balancing Routing Algorithm

INTRODUCTION

Advancements in satellite technologies have significantly reduced the cost of producing and deploying low Earth orbit (LEO) satellites (Adilov et al., 2022), driving the rapid emergence of LEO satellite networks (Levchenko et al., 2020). For instance, the Iridium NEXT constellation (Kozhaya et al., 2023), launched in 2017, includes 66 satellites for global voice communication. The OneWeb constellation (McLain & King, 2017), with 180 of its planned 720 satellites in orbit, aims to deliver broadband services with speeds up to 200 Mbps download and 50 Mbps upload. The Starlink constellation (McDowell, 2020), with nearly 4,000 satellites and plans for over 10,000, offers network access at 1 Gbps bandwidth.

As the scale of LEO satellite networks grows, their system structures and network topologies become more complex (Ji et al., 2021). While larger constellations offer higher network capacity,

DOI: 10.4018/IJISMD.373198

faster access, and better services, fully harnessing these benefits requires in-depth research into routing algorithms for satellite networks, particularly in LEO constellations. Beyond satellite communication, similar challenges arise in distributed information systems such as Internet of Things networks, autonomous vehicular communication, and disaster-resilient networking, where dynamic topology changes and real-time constraints must be addressed.

On one hand, the unbalanced distribution of population and traffic demand across regions, such as polar areas, oceans, deserts, and urban centers, creates significant variations in communication needs (Wu et al., 2018; Zhang et al., 2023). This imbalance leads to unequal satellite load distribution, causing congestion in certain satellite nodes or inter-satellite links, ultimately degrading the performance of LEO satellite networks.

On the other hand, LEO satellite networks, with their large numbers of satellites and complex structures, rely on ground control centers to manage satellites through telecommand services (Maral et al., 2020). These services are essential for tasks such as orbital adjustments, attitude control, mode switching, and fault diagnosis, all of which demand high reliability and real-time performance. Direct telecommand links between ground stations and target satellites are limited by geographic distribution and visibility constraints, allowing real-time execution only when the satellite and ground station are in line of sight (Baldi et al., 2017). Using geostationary Earth orbit satellites as relays can address visibility issues but often relies on single transmission paths, which lack backup routes and are vulnerable to disruptions (Matracia et al., 2022). A more reliable solution involves leveraging the networked nature of mega-constellations and using multipath strategies to reduce the impact of path failures. Therefore, developing robust satellite routing algorithms to ensure both high reliability and real-time performance is crucial for effective telecommand services in LEO satellite networks (Zhan et al., 2022).

Researchers have explored various routing algorithms to enhance telecommand services in LEO satellite networks. Traditional single-path algorithms (Del-Valle-Soto et al., 2014; Salameh et al., 2020) focus on optimizing link quality and energy efficiency. However, their reliance on a single path can lead to data loss if the path fails, challenging the reliability needed for telecommand services. To address this, multipath routing algorithms have been introduced. Zhao et al. (2021) developed a multi-constraint optimal routing algorithm using an enhanced ant colony method to optimize link selection, improving network reliability and load balancing. Similarly, Yang and Yao (2021) proposed an ant colony–based multipath algorithm that reduces link handoffs, enhances network security, and meets quality of service requirements. Other algorithms, such as the adaptive routing algorithm (Wang et al., 2019) and the software-defined routing algorithm (Zhu et al., 2017), focus on reducing delays and congestion while optimizing routing paths in LEO satellite networks. Yang et al. (2016) introduced energy-efficient algorithms to extend satellite battery life, and Jin et al. (2022) proposed a disruption-tolerant routing algorithm to adapt to frequent topology changes, reducing packet loss and delay. In contrast, multipath algorithms such as the sub-branch protocol (Challal et al., 2011) and the network coding-based method (Xu et al., 2018) improve reliability by selecting alternative paths, boosting throughput, and reducing delay in multilayered satellite networks. However, while multipath routing increases reliability, it can also introduce retransmission delays due to the long transmission distances between satellites, which may impact the real-time performance required for telecommand services (Cao et al., 2022). Moreover, many of these algorithms are designed with a networking perspective but lack a broader connection to information system design principles, such as adaptive resource allocation, load balancing, and performance optimization. Incorporating these principles could enhance the robustness and scalability of routing strategies, making them applicable to a wider range of dynamic communication environments.

To address the communication challenges in LEO satellite networks, this paper proposes the data copies–based multipath routing (DCMR) algorithm, which enhances reliability while minimizing end-to-end transmission delay. The routing model is inspired by previous research (Kumar et al., 2020, 2022, 2023a, 2023b, 2024a, 2024b). The main contributions of this paper include the following: