

Backup Routing Method for Optical Satellite Networks: Addressing Orbital-Motion-Induced Link Switches and Sudden Link Failures

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Optical satellite networks (OSNs) built on low-Earth-orbit constellations promise global, low-latency connectivity, yet their links are repeatedly disrupted by predictable orbital-motion-induced switches and sudden failures caused by weather or hardware. Conventional virtual-topology routing mitigates predictable link switches, and distributed backup schemes handle unexpected link failures, but neither copes when these events overlap. We present an adaptive routing method that handles both orbital-motion-induced link switches and sudden link failures. By integrating timing-based switch mechanisms with backup forwarding tables, this approach ensures that packet routing dynamically adapts to network conditions. Simulation studies on representative Low Earth Orbit (LEO) constellations demonstrate significant reductions in packet loss and latency variability. The proposed scheme provides a practical step toward reliable OSNs.

Key Words: Laser Optical Communication, Satellite Constellation, Non-terrestrial Network, Network Efficiency and Reliability, Numerical Simulation

Nomenclature

e	: edge
E	: set of edges
E_v^k	: set of edges in the k th snapshot where information is stored at node v
G	: graph topology of network
G_v^k	: graph topology of network in the k th snapshot where information is stored at node v
N_{orbit}	: number of orbit planes
$N_{\text{sat/orbit}}$	: number of satellites per orbit plane
t	: time, s
v	: node
V	: set of nodes
V_v^k	: set of nodes in the k th snapshot where information is stored at node v
$\varphi^{\text{latitude}}$	: latitude angle
θ	: bright-body exclusion angle; interior angle between the line of sight from the Laser Communication Terminal to the Sun/Moon and the line of sight from the same LCT to the communication target, deg

Subscripts

gs	: ground station
internet	: internet
sat	: satellite

1. Introduction

1.1. Background

In recent years, the demand for space-based communications with extensive coverage and low latency has grown significantly. This trend is driven by the increasing use of Earth observation satellites, the need for alternative communication methods during terrestrial disruptions, such as natural disasters, and the rising demand for reliable internet connectivity in maritime and aerial regions ¹⁾.

To meet this growing need, Optical Satellite Networks (OSNs) have gained attention as a promising solution. These non-terrestrial networks leverage optical communication technologies, which offer considerably higher data transmission rates compared to traditional radio frequency systems and are integrated with Low Earth Orbit (LEO) satellite constellations. LEO satellites are particularly well-suited for global communication due to their wide coverage and low latency ^{2,3)}.

While earlier LEO satellite constellation projects from the 1990s—such as Globalstar, Iridium, Odyssey, and Teledesic—encountered difficulties related to high costs and insufficient market demand, recent initiatives like Starlink, Kuiper, and Telesat are making significant advancements in developing new LEO constellations ^{4,5)}.

The characteristics of OSN can be defined as follows:

- The optical communication link switches due to the orbital movement of the satellite.
- The optical communication links between satellites and ground stations are interrupted by clouds.
- There is a higher probability of equipment failure and malfunction due to the harsh space environment compared to terrestrial networks.

Applying conventional routing methods in terrestrial networks directly to OSN would result in frequent link

switching and unexpected link failures, leading to data loss and increased latency. Therefore, there is an urgent need for communication routing methods tailored to the specific characteristics of OSN.

1.2. Related Works

There are two main categories of communication link disconnections in OSN. The first category includes periodic link switches caused by the satellite's orbital motion (corresponding to OSN characteristic A). The second category involves sudden link failures due to cloud interference or equipment failure/malfunction (corresponding to OSN characteristics B and C).

The former predictable periodic link switch has been previously considered in studies on routing in satellite constellations for RF (Radio Frequency) communication^{6,7)}. In these studies, virtual topology was assumed to handle the periodic link switch. In the virtual topology, the satellite operation period is divided into several time intervals, and the satellite network topology is assumed to remain constant within each interval⁸⁾. As the orbital motion of a satellite can be predicted, a forwarding table, which stores routes and determines where data packets should be forwarded, can be created in advance for each topology snapshot by dividing the network topology when the change is predicted.

In the case of the latter type of unpredictable and sudden link failure, the previous studies proposed distributed routing methods²⁾. In such an event, a special packet is generated and transmitted to broadcast the link failure information within the network. The link failure status is then shared among all satellites, and rerouting is performed by each satellite based on the received status. However, the interval between the dissemination of link failure information and the convergence of rerouting is not considered, resulting in the loss of communication data during this period.

In response to this issue, Chen et al. proposed a method that leverages the concept of "Fast Reroute," commonly employed in terrestrial networks to pre-calculate backup paths¹²⁾. By integrating centralized computing with distributed Segment Routing (SR), their approach successfully reduces computational costs and adapts the technique to space networks. However, their method does not address scenarios involving multiple link failures, highlighting an area for potential improvement. Additionally, previous studies have inadequately considered failures in feeder links, communication links between satellites and ground stations, which are crucial in practical network operations.

Chen et al.¹²⁾ mitigated this issue by adopting the Fast Reroute concept: backup paths are pre-computed, and centralized computation is combined with distributed Segment Routing (SR). While effective for single-link failures, this method does not address multiple simultaneous failures and largely ignores feeder (satellite-ground) links failures, which are critical in practice.

Our earlier work^{13,14)} also belongs to the Fast Reroute family, but differs in two key respects: (i) it remains effective under multiple simultaneous link failures, and (ii) it explicitly covers feeder-link disruptions as well as inter-satellite links. Satellites autonomously switch to appropriate backup forwarding tables when failures are detected. Nevertheless, the method did not fully consider cases where a failure coincides with an imminent periodic switch. If a link fails just before the scheduled switch, the topology changes mid-transmission, potentially invalidating the backup route and degrading performance.

1.3. Contributions

This paper proposes an adaptive routing method tailored to OSNs that handles both orbital-motion-induced link switches and sudden link failures. By integrating timing-based switch mechanisms with backup forwarding tables, this approach ensures that packet routing dynamically adapts to network conditions. For orbital motion-induced link switches, we update forwarding tables in advance, factoring in propagation delay to the destination. In cases of sudden link failure, we evaluate the need to implement backup tables immediately before the switch, allowing packets to reach their destination through the optimal route.

To evaluate the effectiveness of our proposed routing method, we model the structure and data flow of LEO optical communication satellite constellation network, enabling the accurate numerical simulation of network behavior. Simulation studies on representative Low Earth Orbit (LEO) constellations demonstrate significant reductions in packet loss and latency variability.

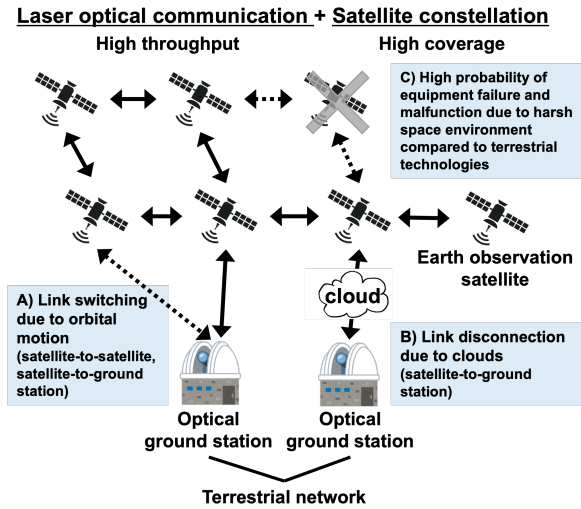
The rest of this paper is organized as follows. Section 2 details the OSN model. Section 3 describes the distributed routing algorithm. Section 4 provides the performance evaluation and numerical analysis by packet-level communication simulation. Finally, we conclude this paper in Section 5.

2. Modeling of OSNs

In this section, we describe the OSN network topology design and network model. The discussion largely follows the framework introduced in Section 2 of our earlier paper¹⁴⁾ therefore, we outline the baseline architecture and describe in depth the modifications and extensions unique to the present work.

2.1. OSNs Architecture

Figure 1 illustrates the conceptual diagram of the OSN assumed in this paper. Earth observation satellites or user terminals connect to ground-based networks via the OSN. Within the service satellite constellation, both inter-satellite communication and satellite-to-ground communication utilize optical communication technology.

Fig 1: Conceptual diagram of OSN ¹⁴⁾.

2.1.1. Satellite constellation

LEO constellations are classified by the right-ascension distribution of their orbital planes. A Walker star (π -constellation) spans 180° , whereas a Walker delta (2π -constellation) spreads evenly over 360° . The counter-rotating planes of a π -constellation create large relative velocities that hamper stable optical Inter-Satellite Links (ISLs). Consequently, this study adopts the 2π -constellation, composed of N_{orbit} circular planes with $N_{\text{sat/orbit}}$ satellites each.

2.1.2. Optical inter-satellite links (ISLs)

Every spacecraft carries five Laser Communication Terminals (LCTs): two for intra-plane ISLs, two for inter-plane ISLs, and one spare that may serve feeder or cross-segment connections. Owing to the narrow divergence of optical beams, each LCT integrates a Pointing-Acquisition-Tracking (PAT) opt-mechanics and gimbal that supplements the satellite's attitude control to maintain sub-microradian alignment.

2.1.3. Optical Feeder (satellite-ground) links

Downlinks employ the same optical technology but traverse the turbulent, cloud-laden atmosphere. Turbulence introduces wave-front distortion and pointing jitter, while clouds can fully extinguish the beam. We therefore model cloud-induced outages as unpredictable link failures.

2.1.4. On-board signal processing

Each satellite functions as an optical router. Incoming light is converted to the electrical domain, processed, and retransmitted optically—an Optical-Electrical-Optical (OEO) architecture that simplifies switching and supports protocol flexibility.

2.2. Network Topology design

Throughout this study the set of active communication links, collectively the network topology, is treated as a deterministic input. We specify separate design rules for ISLs and feeder links, then formalise the time-varying graph model used in the analysis.

2.2.1. ISL topology: Manhattan-Street Network (MSN)

Following Li et al. ¹⁵⁾, we adopt the Manhattan-Street Network (MSN) scheme as shown in Fig. 2:

- Intra-plane ISLs connect satellites in the same orbital plane in a fixed, linear chain; link length and orientation are constant.
- Inter-plane ISLs connect in-phase neighbours in adjacent planes. Because the satellites drift longitudinally, both length and direction of these cross-plane links evolve continuously.

This MSN arrangement balances connectivity with optical-payload count and keeps link dynamics sufficiently predictable for routing.

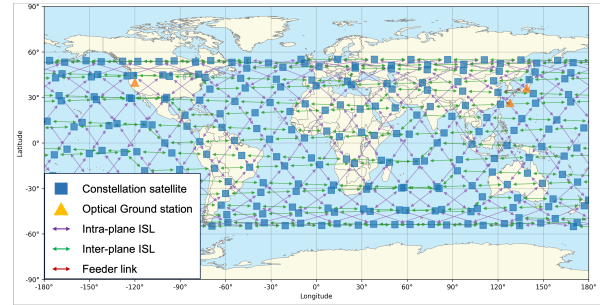


Fig 2: Manhattan-Street Network.

Constellations with inclined orbits experience orbital-plane crossings near the poles. At each crossing point the LCTs on neighbour satellites must switch their counterpart in the adjacent plane as shown in Fig. 3. During this hand-over the optical beam is lost, because the new link requires a new PAT sequence; the result is a transient interruption of the inter-plane ISL. To reproduce this deterministic outage behaviour without modelling PAT dynamics explicitly, we omit every inter-plane ISL whose midpoint latitude exceeds a threshold φ_{cut} (see Eq. 1). The resulting topology thus captures periodic polar-region link breaks while leaving all other temporal variations unchanged.

$$\begin{aligned} &\text{if } |\varphi_{\text{sat1}}^{\text{latitude}}| > \varphi_{\text{cut}} \wedge |\varphi_{\text{sat2}}^{\text{latitude}}| > \varphi_{\text{cut}} \\ &\text{then } e_{\text{sat1-sat2}} = 0 \end{aligned} \quad (1)$$

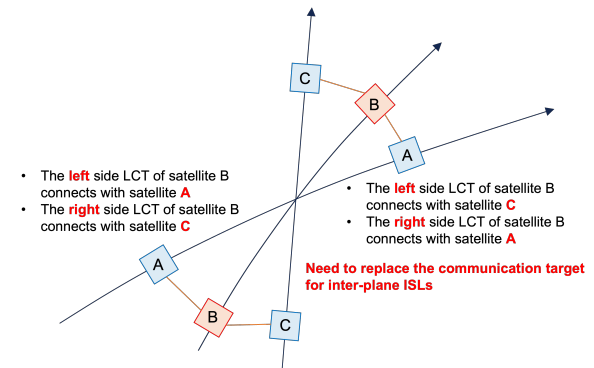


Fig 3: Communication link switch in orbital plane intersection

2.2.2. Feeder-link topology: maximum-visibility hand-over

Ground connectivity obeys the maximum visibility hand-over policy ¹⁶⁾:

- **Handover Triggering Condition:** A handover is triggered when the current satellite moves out of the ground station's visibility.
- **Next Satellite Selection:** The satellite to be handed over is selected based on its longest remaining visibility time. These rules pre-assign a deterministic hand-over sequence for every station without on-line optimisation.

2.2.3. Considering sun exclusion angle for LCTs

Bright celestial bodies produce a flood of unwanted photons that enter an optical receiver and overwhelm the desired signal. To mitigate this glare, much like shielding a camera lens from direct sunlight, the Optical Communications Terminal Standard (Version 4.0.0) ¹⁷⁾ prescribes a solar/lunar exclusion angle of 30 deg.

An LCT must not transmit or receive when satisfies Eq. 2.

$$\theta = \angle(\text{Bright Body, LCT, Communication Target}) \leq 30^\circ \quad (2)$$

Consider an inter-satellite link formed by LCT A and LCT B. Communication is inhibited whenever either terminal satisfies Eq. 3.

$$\theta_A \leq 30^\circ, \theta_B \leq 30^\circ \quad (3)$$

2.2.4. Time-varying network graph: virtual-topology

The full system is modelled as an undirected graph $G(t) = (V(t), E(t))$ comprising constellation satellites, optical ground stations (gateways), and an Internet node. To abstract the predictable link re-configurations caused by orbital motion we employ the virtual-topology concept of Sommeregger et al. ⁸⁾:

- Let $\{t_k\}_{k=1}^{\infty}$ denote the ordered time instants at which any link creation or teardown occurs.
- Over the interval $[t_{k-1}, t_k)$ the topology is frozen and represented by the snapshot graph $G_k = (V_k, E_k)$.
- Closed-form definitions of V_k and E_k are provided in Eq. 4.

$$\begin{aligned} \forall k \in \{1, 2, \dots\} \\ G^k &= (V^k, E^k) \\ V^k &= \{v_1^k, \dots, v_n^k\} \\ &= V_{\text{sat}}^k \cup V_{\text{gs}}^k \cup V_{\text{internet}}^k \\ E^k &\subseteq V^k \times V^k \end{aligned} \quad (4)$$

3. Distributed Backup Routing Method

This section describes the proposed distributed backup routing method, which raises network resilience by anticipating potential link failures and computing backup routes in advance, extending the strategy presented in Section 3 of our previous study ^{13,14)}. After a concise overview of that foundation, the discussion explains how each node constructs a time series virtual topology that captures satellite orbital dynamics and clarifies the procedure by which the backup forwarding table preserves connectivity when an unforeseen failure occurs immediately before a topology snapshot switch.

3.1. Overview of the distributed backup routing method

Figure 4 the architecture of the proposed distributed backup routing scheme for optical satellite networks. Each satellite node v is provisioned, before launch or during idle operational phases, with a series of virtual-topology snapshots $\{G_1, G_2, \dots, G_k\}$. Every snapshot encapsulates (i) the global graph structure and (ii) performance metrics such as propagation delay that correspond to the expected physical topology at discrete times $t_1, t_2, \dots, t_k$. On the basis of each snapshot, the node locally pre-computes one nominal forwarding table and a set of backup forwarding tables, where every backup excludes the set of candidate links.

During steady-state operation the current nominal table is consulted for each packet, guaranteeing hop-by-hop consistency across the constellation because all nodes share an identical snapshot. When an unexpected link failure is detected, the two adjacent satellites generate and flood Link-State Advertisement (LSA) packets. Upon receipt of the first LSA that identifies the failed link, every node executes the following lightweight sequence:

- A) Mark the failed edge in its local copy of the snapshot.
- B) Atomically switch the packet-forwarding process to the pre-computed backup table that was derived from the same snapshot under the “link-absent” condition.

This immediate switchover keeps data delivery uninterrupted while a full routing recalculation runs in the background. Once each node completes the recalculation on the updated topology, the freshly obtained new nominal table supersedes the interim backup table, restoring optimality until the next fault event.

Compared with conventional single-table distributed routing, the proposed method decouples failure recovery latency from the route-recomputation time: packet detouring starts after the LSA propagation delay (typically a few milliseconds) instead of waiting seconds for algorithmic convergence. The trade-off is a modest increase in off-line computation and on-board storage, but this is amortised over long mission durations and yields markedly higher resilience to transient laser-link outages.

3.2. Virtual topology construction

Given a time-ordered sequence of directed graphs $\mathcal{G} = \{(G_k, t_k)\}_{k=0}^{K-1}$ our goal is to derive a series of noise-robust virtual topologies that remain stable over a fixed aggregation interval t .

Let

$$\mathcal{B} = \{b_n = nt \mid n \in \mathbb{N}; t_0 \leq b_n \leq t_{K-1}\} \quad (5)$$

denote the set of interval boundaries. For every boundary $b_n \in \mathcal{B}$, we start from the most recent graph at or before the boundary, $G(b_n^-)$, and transform it through the following five deterministic operations:

- A) **Past-edge union:** Consider the past window $(b_n - t, b_n]$. All edges that appeared in any G_k inside this window are inserted into $G(b_n^-)$ if missing, endowed with their last observed attributes. This suppresses spurious link removals caused by sub- t outages.

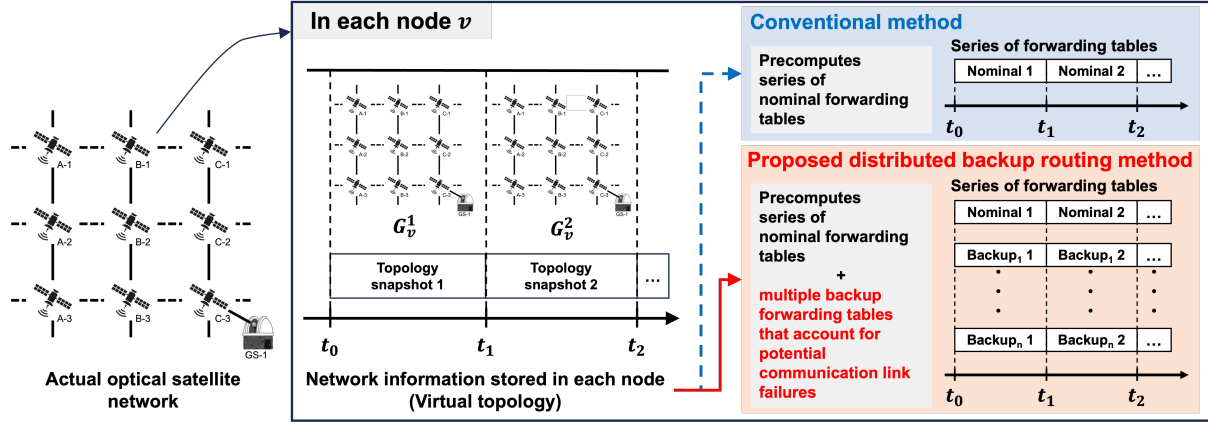


Fig 4: Overview of the proposed distributed backup routing method ¹⁴⁾

- B) Future-edge pruning: Over the future window $(b_n, b_n + t)$, compute the edge set common to every snapshot. Remove edges not in this stable-future intersection to prevent soon-to-vanish links from polluting the virtual topology.
- C) Mid-interval attribute refresh: All node and edge attributes are overwritten with those found in the snapshot nearest the midpoint $b_n + \frac{t}{2}$, pairing the structural state from Steps A-B with temporally centred parameters.
- D) Weight recomputation: Each edge (u, v) receives the weight $w_{uv} = d_{uv} + \max\{d_u, d_v\}$, where d_{uv} is link delay and d_u (resp. d_v) the node delay of each endpoint. Node weights equal their delays, capturing both propagation and processing latency.
- E) Snapshot deduplication: The resulting graph $G^*(b_n)$ is added to the output series only if it is not isomorphic to the previously stored virtual topology, guaranteeing a minimal yet lossless representation of topological evolution.

Applying this procedure to every $b_n \in \mathcal{B}$ yields an ordered set $\{(G^*(b_n), b_n)\}$ of t -second-granularity virtual topologies. The construction retains all edges persisting for at least one full interval, aligns link-state attributes to the interval midpoint, and eliminates redundant repeats, providing a compact and analytically convenient view of the dynamic network.

3.3. Decision on switching backup forwarding tables

3.3.1. Background and problem statement

In networks where a virtual topology is periodically switched at a scheduled time t_k , a link failure occurring shortly before the switch can lead to two conflicting requirements:

- Topology route mismatch: The backup route computed for the current snapshot may become invalid immediately after the switch, producing forwarding loops or black-holing.
- Performance degradation: If we wait until the switch is complete and then recompute routes, packets in flight between the failure time t_f and t_k suffer increased loss or delay.

Hence, when the failure time t_f is sufficiently close to t_k , it can be advantageous to activate the next-snapshot backup forwarding table BFT_{next} immediately, so that traffic continues on a route already consistent with the post-switch topology.

3.3.2. Guard-window concept Δt

To reconcile the opposing goals of (i) minimizing service disruption and (ii) preserving route optimality, we introduce a guard window Δt .

Decision rule

- If $t_f \leq t_k - \Delta t$: keep using the current backup table BFT_{curr} .
- If $t_f > t_k - \Delta t$: pre-activate BFT_{next} and continue to use it seamlessly after t_k .

This rule ensures that, during the critical interval immediately before the switch, packets are forwarded along routes that remain valid across the topology change.

3.3.3. Guidelines for setting Δt

We derive Δt as the maximum of three characteristic time scales:

- Recomputation time Δt_{recomp} : interval from failure notification to full deployment of an updated forwarding table.
- Switch overhead Δt_{switch} : control-plane delay intrinsic to executing the snapshot change itself.
- Half round-trip time $\frac{\text{RTT}}{2}$: buffer time that allows long-haul flows to migrate gracefully to the new path.

$$\Delta t = \max\left(\Delta t_{\text{recomp}}, \Delta t_{\text{switch}}, \frac{\text{RTT}}{2}\right) \quad (6)$$

4. Network performance simulation

In this section, we evaluate the performance of the proposed routing method through communication simulation. First, we describe the simulation environment. Next, we explain the simulation setup and analysis results for scenarios with orbital-motion-induced link switches and sudden link failures.

4.1. Simulation environment

The numerical simulations were conducted using a modularized simulator named COSMICA (Constellation

Table 1: Simulation setup parameters for geometric arrangement.

Parameters	Values
Constellation orbit	
Constellation type	2π -constellation (Walker delta)
Operating height	1000 km
Number of satellites	256
Number of orbits	16
Number of satellites per orbit	16
Inclination of orbits	55°
RAAN of first orbit	0°
Phase factor	1°
Gateways	
Locations	- Japan, Tokyo (36° N, 139° E) - Japan, Okinawa (26.5° N, 128° E) - USA, California (40° N, 120° W)
Minimum elevation angle	5°

Satellite siMulator for optIcal CommunicAtion), jointly developed by our research group. The configuration details of the simulator are provided in ^{18,19}. Using this simulator, we performed packet-level routing simulations.

4.2. Evaluation factor

We assesses the overall communication performance of the system using three metrics: packet delay, and cumulative received data. Packet delay is the elapsed time from when a data packet leaves the sender until it reaches the receiver. Cumulative received data denotes the total amount of information that arrives successfully at the destination for the traffic demand under consideration.

4.3. Simulation setup

As a use case, we consider communication from USA to Japan. Detailed simulation parameters are listed in Table 1 - 3. In this scenario, the timing of link switch driven by orbital motion is illustrated in Fig 3. ISL communications undergo frequent handovers, especially as the spacecraft traverse the polar regions and whenever the sun exclusive angle constraint is met. By contrast, satellite-to-ground communications experience far fewer handovers because the scenario assumes only a limited number of ground stations.

4.4. Simulation results

Figure 6 plots the end-to-end delay of every data packet, while Fig. 7 presents the cumulative volume of data that reaches the destination node. The shaded intervals in both figures correspond to network topologies in which the Japan-to-USA segment is temporarily disconnected; dur-

Table 2: Simulation setup parameters related to the performance of satellites and LCTs.

Parameters	Values
System's parameters	
Max ISL distance	5000 km
Max relative angular velocity	0.3°
Channel capacity of an ISL	10 Gbps
Channel capacity of a satellite-ground station link	10 Gbps
Processing delay at each node	10 ms
Delay between gateways to internet	10 ms
Link failure detection time	10 ms
Routing settings	
Shortest path algorithm	Dijkstra
Metric	Delay
Routing recalculation time	2 s

Table 3: Simulation setup parameters for scenario.

Parameters	Values
Traffic generator's parameters	
Packet size	1000 bytes
Average bandwidth	1 Gbps
Data generation model	Poisson distribution
Source node	Gateway California
Destination node	Internet Japan
Events	
Edge failure timing	30 min from start
Edge failure detection time by neighbor nodes	10 ms
Others	
Simulation start time	2026/1/1 00:00:00 (UTC)
Simulated duration	3600 s

ing these periods every intercontinental route is disabled and data flow is therefore suspended.

Outside the shaded intervals the observed delays remain tightly bounded between 0.1 s and 0.3 s. Two distinct delay behaviours can be distinguished:

- Gradual variations: In portions where the curve changes smoothly, the set of relay nodes on the path is unchanged. The delay varies only because the physical distances between nodes lengthen or shorten as the satellites move along their orbits, altering propagation time while leaving the logical route intact.
- Step-like increases: Sharp jumps occur when orbital motion induces a hand-over: a link on the path becomes

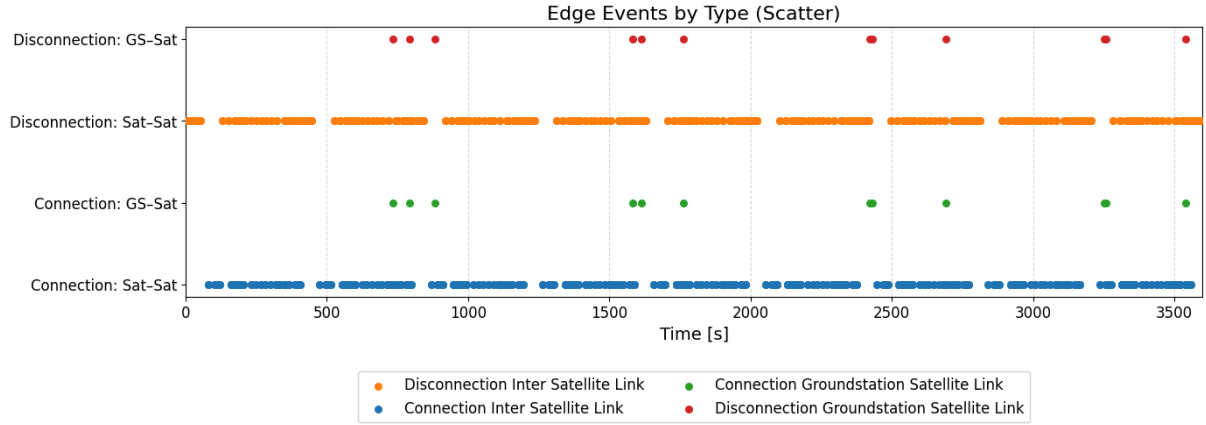


Fig 5: Edge switch timing by orbital motion.

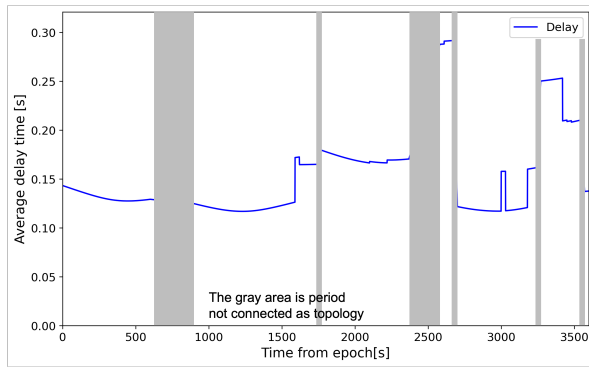


Fig 6: Packet delay for each data packet

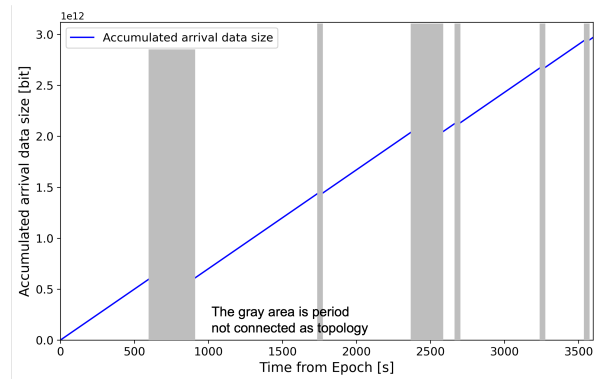


Fig 7: Accumulated arrival data size at the destination node

unavailable and the routing algorithm selects an alternative chain of relay nodes, typically with a different hop count. This discrete topological change manifests as an abrupt rise in delay.

An intentional single-link failure was injected 1800 s after the simulation start, severing the primary link on the current shortest path. No pronounced delay spike is visible, confirming that the backup-routing mechanism reroutes traffic fast enough to preserve performance.

The accumulated arrival data size curve in Fig. 7 rises linearly whenever the Japan-USA connection is available through the OSN (non-shaded intervals). The absence of noticeable slope changes or plateaus demonstrates that packet loss is negligible throughout those periods.

5. Conclusions

This study presents a distributed backup-routing scheme that keeps OSNs operational during scheduled orbital-motion-induced switches and unforeseen link failures. In the proactive layer, each satellite maintains a timeline of virtual-topology snapshots, each paired with a nominal forwarding table and compact backup tables that anticipate specific faults. In the reactive layer, a node immediately switches to the appropriate backup table when it receives a fault LSA, while a standard network-wide re-convergence proceeds in the background.

Packet-level simulations on a 256-satellite, 16-plane LEO constellation equipped with optical ISLs confirmed the concept, holding end-to-end delay to 0.1-0.3 s, preventing loss spikes, and keeping throughput almost linear across topology transitions.

Future research focuses on shrinking backup-table state, incorporating congestion awareness across LEO-HAPS-GEO layers, embedding power-attitude trade-offs from laser communication terminals into routing costs, and blending reserved and bursty traffic models to test robustness under more realistic demand patterns.

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