LEO CONSTELLATIONS · FREE-SPACE OPTICS

5G NTN & Space Global Backbone

LEO Orbital SRv6 Mesh — Distributed PCE, TSN, FSO Laser Mesh, Radiation Hardening

3–10ms	<50ms	0
LEO Latency	TI-LFA Recovery	Ground PCE SPOF

This white paper examines LEO satellite constellation SRv6 uSID routing mesh architecture: distributed hybrid PCE eliminating the ground-controller SPOF, TSN strict scheduling plus strict BFD for Doppler/link-bounce stability, SR-TE anti-polarization, multi-carrier ground station diversity, Free-Space Optics laser mesh routing, and radiation-hardened ASIC header verification.

1. LEO Orbital Mechanics and Routing Implications

LEO satellites at 550–1,200km altitude orbit every 90–100 minutes. Link metrics change on timescales of seconds — faster than IS-IS/OSPF convergence. SRv6 SR-TE with TLE-based pre-seeded path tables provides deterministic forwarding that adapts at planning timescales while maintaining sub-50ms TI-LFA recovery at runtime.

> ***"LEO propagation delay of 3–10ms rivals trans-Atlantic sub-sea cable — a credible backbone alternative."***

3–10ms	<50ms	90–100min	6–10
LEO Propagation Delay	TI-LFA Recovery	Orbital Period	Pre-Seeded Windows

2. Ground PCE SPOF — Problem and Solution

A centralized PCE at a ground station computing all orbital paths creates a single point of failure — unavailability halts path computation, forcing satellites onto default routes that ignore current orbital geometry.

On-Orbit Local PCE	Each satellite runs a lightweight PCE with localized N-hop view for near-zero-latency local decisions.
Ground PCE Policy Plane	Aggregates telemetry, computes global optimal paths, programs per-orbital-window policies via PCEP.
TLE-Based Pre-Seeding	Pre-computed path tables for 6–10 orbital windows (45–90 min ahead) — satellites operate autonomously on ground PCE loss.
PCEP Delegation (RFC 8231)	Stateful delegation to satellite local PCEs per neighborhood; authority reverts when connectivity restores.

IMPACT: **Distributed hybrid PCE eliminates the ground-controller SPOF entirely — no blackholing during ground station outage, uplink congestion, or interference.**

3. TSN Strict Scheduling + Strict BFD

LEO Optical Inter-Satellite Links experience Doppler-induced propagation delay variation of 1–3ms per orbital pass. Standard BFD millisecond timers misinterpret this as link failure, triggering oscillation and SRv6 path recomputation storms.

Mechanism	Setting / Behavior
Strict BFD Min-Tx/Rx	300–500ms (vs. standard 50ms) — margin above Doppler delay variation
BFD Multiplier	5–10 (vs. standard 3) — 1.5–5 second failure window
Carrier Delay Threshold	IS-IS hello/hold-time tuned per orbital window via NETCONF/YANG
BFD Dampening (RFC 5882)	Exponential backoff per false positive, resets after stabilization
TSN IEEE 802.1Qbv	Deterministic transmit windows per traffic class, pre-programmed per orbital window

4. SR-TE Anti-Polarization and Multi-Carrier GS Diversity

→ OISL Anti-Polarization: ECMP hash collisions concentrate traffic on a subset of bandwidth-constrained OISLs — SR-TE explicit paths distribute by real-time utilization, not hash.

→ Multi-Carrier GS Diversity: Independent carrier networks (A/B/C) with separate facilities, power, and PCE infrastructure for full route diversity.

→ TI-LFA Sub-50ms Failover: Automatic rerouting on GS link failure, enabling carrier-grade SLA guarantees.

5. Seamless Session Roaming Across NTN Boundaries

Transitioning a live subscriber session between a static terrestrial base station and a fast-moving satellite node is structurally difficult — the destination itself is in motion at orbital velocity.

Stateless Session Shifting	Sessions stay intact because ground and orbital nodes recognize identical SRv6 segment instructions.
Optically Aware Path Calc	Optimal ground-to-space path pre-calculated from real-time trajectory and atmospheric signal metrics.
End-to-End Slicing Continuity	Enterprise security/QoS preserved as a session moves from terrestrial 5G to orbital satellite.

6. Eliminating the Terrestrial WAN Boundary

→ Single Global Autonomous System: The entire international footprint runs over one unified space-based SRv6 fabric.

→ Direct Hyperscaler Interconnect: Traffic routes directly through the LEO mesh into cloud data centers, bypassing regional ISP chains.

→ Granular Multi-Continent Slicing: Secure isolated paths at the protocol layer, bypassing VPN tunnel overhead.

7. Free-Space Optics (FSO) Laser Mesh Routing

LEO constellations are transitioning inter-satellite links to FSO — terabit-class laser links that form a continuously shifting mesh as satellites cross orbital planes, overwhelming destination-based routing convergence.

Pre-Programmed Trajectories	Path options computed on the ground from predictable orbital tracks, embedded directly into the segment list.
Stateless Laser Forwarding	Satellites forward purely on the active segment instruction — no onboard route discovery or link-state flooding.
Dynamic Re-Pathing	Ground stations update the segment list in near-real-time around obstructions or alignment dropouts.

8. Ka-Band Bypass via Direct FSO Downlinks

→ Unregulated Terabit Bandwidth: Laser downlinks offer far greater capacity than congested, regulated Ka-band spectrum.

→ Unified Space-Ground Transport: Packets transition from laser mesh to terrestrial fiber on the same native SRv6 header — zero translation delay.

→ Dynamic GS Diversity: Flex-Algo steers downlink traffic toward clear-weather ground stations automatically.

9. Mitigating Laser Link Bouncing via TSN and Carrier Delay

Atmospheric turbulence and tracking micro-alignments cause laser links to disconnect and reconnect within microseconds — a distinct failure mode from Doppler delay variation, capable of saturating satellite processors with redundant convergence work if mishandled.

> **Why this matters:** Custom carrier delay timers hold protocol state steady through microsecond-scale dropouts, TSN jitter buffering absorbs realignment jitter at the line-card level, and TI-LFA dynamically replicates mission-critical packets over parallel laser paths — all absorbed below the routing control plane entirely.

10. Preventing IGP Meltdown on Satellite Backbones

Hundreds of moving LEO satellites generate thousands of link-state updates per hour. An unmodified IS-IS/OSPF domain across the full constellation risks CPU exhaustion, protocol timeouts, and cascading outage.

Constellation Partitioning	Flex-Algo planes restrict LSA flooding to localized orbital planes, containing regional failures.
Edge-Driven Path Control	TE computation shifted to thermally stable terrestrial ground stations, off satellite processors.
Stateless Packet Processing	Satellites move data on pre-coded segment instructions, keeping onboard CPU near zero.

11. Atmospheric Scintillation Hybrid Failover

→ Real-Time Telemetry Detection: SRv6 telemetry continuously monitors laser downlink signal quality for early degradation detection.

→ Automated Hybrid Re-Steering: Edge router instantly switches to backup Ka-band on detected degradation, with zero packet loss.

→ Unified Header Continuity: Both laser and Ka-band paths carry the same native SRv6 header — no protocol translation on failover.

12. Space-Ground FSO Gateway Integration

Data crossing from satellite laser meshes to terrestrial fiber must avoid queuing delay or protocol translation at the boundary. The gateway runs standards-compliant SRv6 uSID end-to-end — functionally just another forwarding node sitting at the physical-media boundary, with zero re-encapsulation anywhere in the path.

13. Radiation Hardening at the ASIC Layer

Hardware-Native FEC	Forward Error Correction implemented directly in the programmable ASIC forwarding path.
SRv6 Header Verification	End-to-end integrity checks on the segment list itself, applied at every forwarding hop.
Wire-Speed Detection	Radiation-induced bit flips detected and corrected at full line rate before propagation downstream.

14. Failure Mode and Mitigation Summary

Orbital Challenge	SRv6-Based Mitigation
Doppler link flap	Strict BFD timers + TSN scheduling
OISL hotspot formation	SR-TE explicit path anti-polarization
Ground-to-orbit handover	Uniform SRv6 SID across ground and space nodes
FSO mesh topology churn	Ground-computed stateless source routing
Ka-band weather degradation	FSO primary + automated hybrid failover
Laser link bouncing	Carrier delay dampening + TSN jitter buffering
IGP meltdown	Flex-Algo orbital plane partitioning
Cosmic ray bit flips	Hardware FEC + SRv6 header verification

White Paper Summary — SRv6 uSID Technology Conclusion

SRv6 uSID is the only routing architecture suited to LEO satellite constellation networking across both the RF and Free-Space Optics laser mesh eras: dynamic orbital topology, Doppler delay variation, ECMP polarization, ground PCE SPOF risk, and the physical-layer challenges laser links introduce.

The distributed hybrid PCE model, TSN strict scheduling, and SR-TE anti-polarization extend directly to FSO operation: stateless source routing computed on the ground and embedded in the packet header is identical whether the underlying link is RF or terabit laser.

With Flex-Algo constellation partitioning, hybrid laser-to-RF failover, unified header continuity across space-ground gateways, and radiation-hardened ASIC verification, SRv6 orbital mesh positions multi-carrier LEO constellations as a credible, resilient alternative to sub-sea cable for global Tier-1 backbone diversity.

Ready to Architect Your Orbital Mesh?

SRv6 TEK Innovations provides distributed PCE design, Flex-Algo constellation partitioning, and FSO laser mesh routing for your satellite backbone program.

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