Symmetry-Driven Asynchronous Forwarding with Fast Reroute for LEO Satellite Networks (SDAF)

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Advanced Networking Technology Lab

CONTENTS

1-Background: Influence of Micro-loops

What are micro-loops?

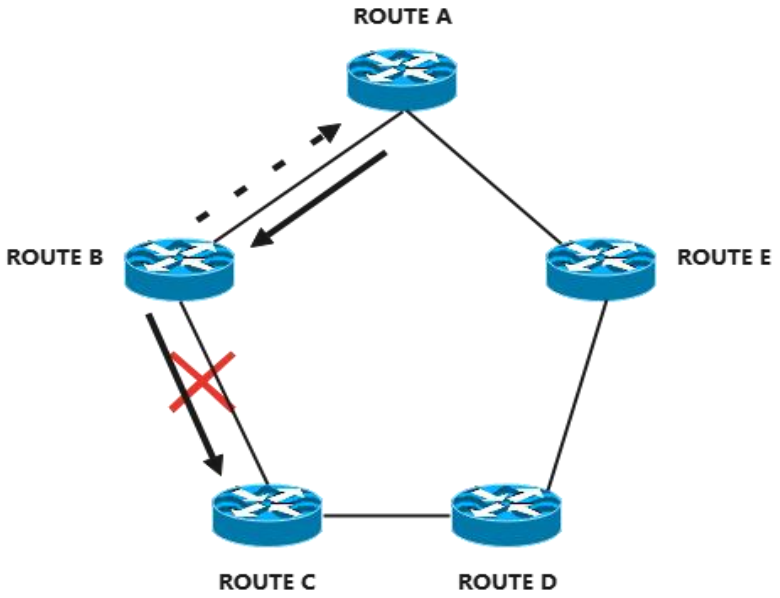
- The instantaneous loops generated during the IGP convergence process.

How are they triggered?

- Link failure triggers IGP convergence
- SPF/FIB updates are unsynchronized
- Forwarding Temporary inconsistency

Why do they matter?

- Packet loss & Congestion
- Reduced FRR effectiveness

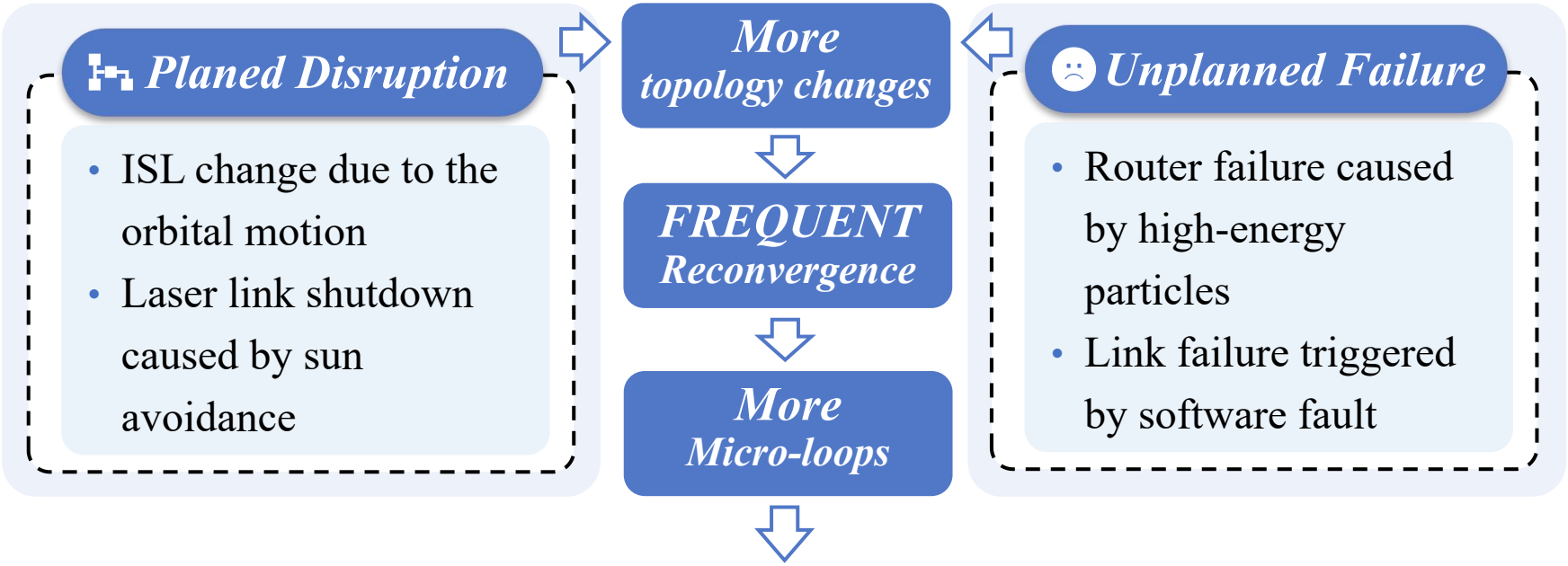


ROUTE	DESTINATION	NEXTHOP
A	C	B
B	C	A

RFC 5715: Micro-loops prevail in topology changes, causing congestion and repair starvation.

1-Challenge: Non-negligible Micro-loops in LSN

Micro-loops cause **non-negligibible damages** in *LEO Satellite Networks (LSN)* due to **more dynamic topology, longer propagation delay, limited onboard resources.**



Micro-loops have evolved from sporadic incidents into **routine events**, leading to performance degradation of the LSN

2-Existing Approaches & On-board Limitations

(1) Local Fast Reroute

IDEA: *Locally switch to precomputed backup paths after a failure.*

- ***Representative methods***
  - LFA, RLFA, Not-Via
- ***Typical Strength***
  - Fast local reaction
- ***Typical Limitation***
  - Coverage depends on topology
  - Extra complexity and overhead
  - Cannot fully avoid convergence-time loops

(2) Local Fast Reroute

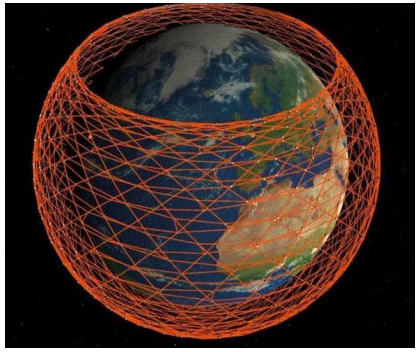
IDEA: *Reduce transient loops through safe update ordering or timing control*

- ***Representative methods***
  - Ordered FIB updates, SPF timing
- ***Typical Strength***
  - Better loop control
- ***Typical Limitation***
  - Slower convergence
  - Higher coordination cost
  - Less suitable for frequent topology changes

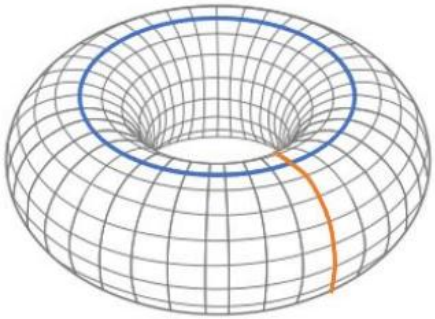
Current approaches are designed for terrestrial networks and fail to fully account for the space environment and constrained resources in LSN.

2-Motivation: Exploiting Symmetry of LSN Topology

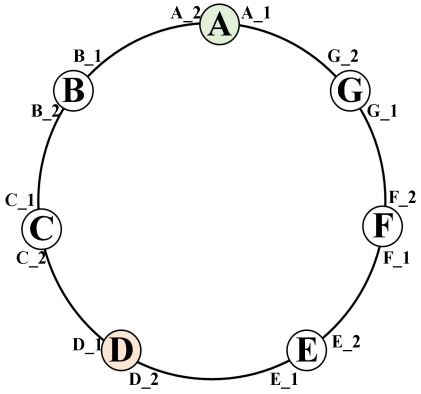
Walker Delta, Manhattan and **Twisted Manhattan** constellation can be abstracted as toroidal topology, with **rotational symmetry and reflection symmetry**.



- Walker-Delta Constellation



- Torus Topology constucted by ISL



- Ring Topology as basic unit

Regular "Grid+" ISL impose topological constraints on traffic forwarding, making rerouting and traffic protection switching a game grounded in symmetry.

3-SDAF Mechanism: Example on Ring Topology

Mechanism: Blockage → Reverse Forward; Same Port → Reverse Egress.

For the data packets sent from node A to node D:

State 1: Fault-free

Forwarding path: A → B → C → D

State 2: Link failure

Node C: arise

Detect C_2 fault → Redirect C_2 egress to C_1

Node B: process

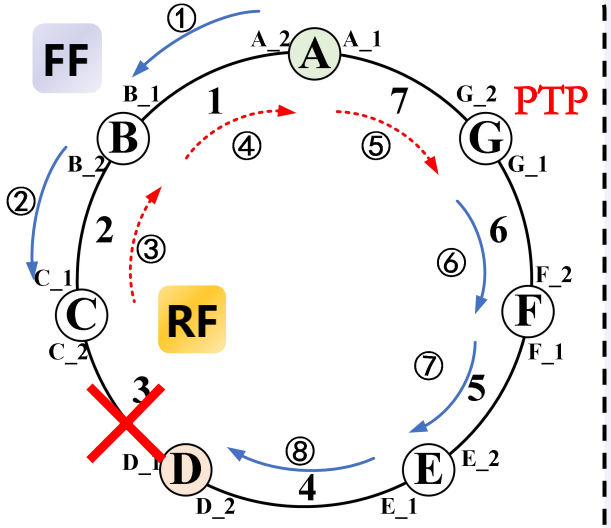
(1) Tag packets ingress via B_2

(2) If egress matches ingress, reverse-forward to B_1

Node G: end

(1) Tag packets ingress via G _2

(2) If egress port differs, forward as usual



- Forwarding path:

A → B → C → B → A → G → F → E → D

3-SDAF Procedures: 5 steps on local node

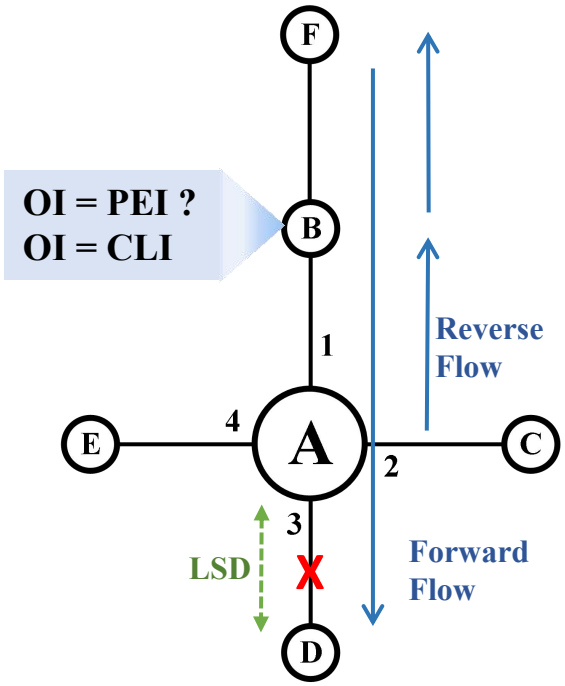
① Initialize
Configure ISMT
Install RF policy
Load LSD

② Detect
Interface down
Mark
unavailable

③ Trigger RF
Packet hits
failed PEI
Start reverse flow

④ Forward/Transition
Switch to an alternative interface
Reach the PTP
Return to FF

⑤ Recovery
Detect interface restoration
Resume normal forwarding



ISMT		
Interface 1	CLI	3
	LFI	2
		3

All operations are driven by Local State & configured symmetry rules on nodes

3-Ring to Torus: RF-CF vs RF-LF Policy

RF-CF		RF-LF
Priority: CFI → LFI	RF-CF VS. RF-LF	**Priority:** LFI → CFI
Best for: Intra-orbit failures		**Best for:** Inter-orbit failures
Detour rule: Counter-facing detour first		**Detour rule:** Lateral-facing detour first
Behavior: Try the counter-facing alternative before switching to a lateral option		**Behavior:** Try the lateral alternative before switching to a counter-facing option

Scalable to torus forwarding; lateral transfers in real constellations enhance reverse-flow PTP.

3-Comparison of SDAF with Existing FRR Mechanisms

- SDAF: A Stateless, Geometry-Driven FRR Mechanism for LEO Constellations

Dimension	SDAF	LFA/TI-LFA	MPLS-TP	SDN-FRR	Pre-computed FRR
Resource expenditure	Extremely low	high	Medium-high	medium	medium
Convergence speed	Microsecond level	Several milliseconds	Several milliseconds	Several milliseconds	Millisecond level
Complexity	Extremely low	low	high	high	medium

A Fresh Approach to Satellite Routing:
From Combating Dynamics to Leveraging Topology.

4-Simulation: Configuration

Simulation Configuration

- **Simulation Tool**
  - MATLAB Discrete-Event Simulation
- **Evaluation indicators**
  - Packet Loss Rate, Maximum Path Length (Hops)
  - Reverse Flow Utilization under Faults
- **Comparison Methods**
  - Normal Flow (NF), Loop-Free Alternative (LFA)
  - SDAF(RF-CF (Counter Flow) / RF-LF (Lateral Flow)
- **Topology** 16×16 Torus
- **Fault Probability**
  - Low (0.0001–0.01), Medium (0.001–0.1), and High (0.01–1)
- **Simulation Methods**
  - 1 packet/sec, random source-destination pairs
  - 1,000 independent simulations per configuration

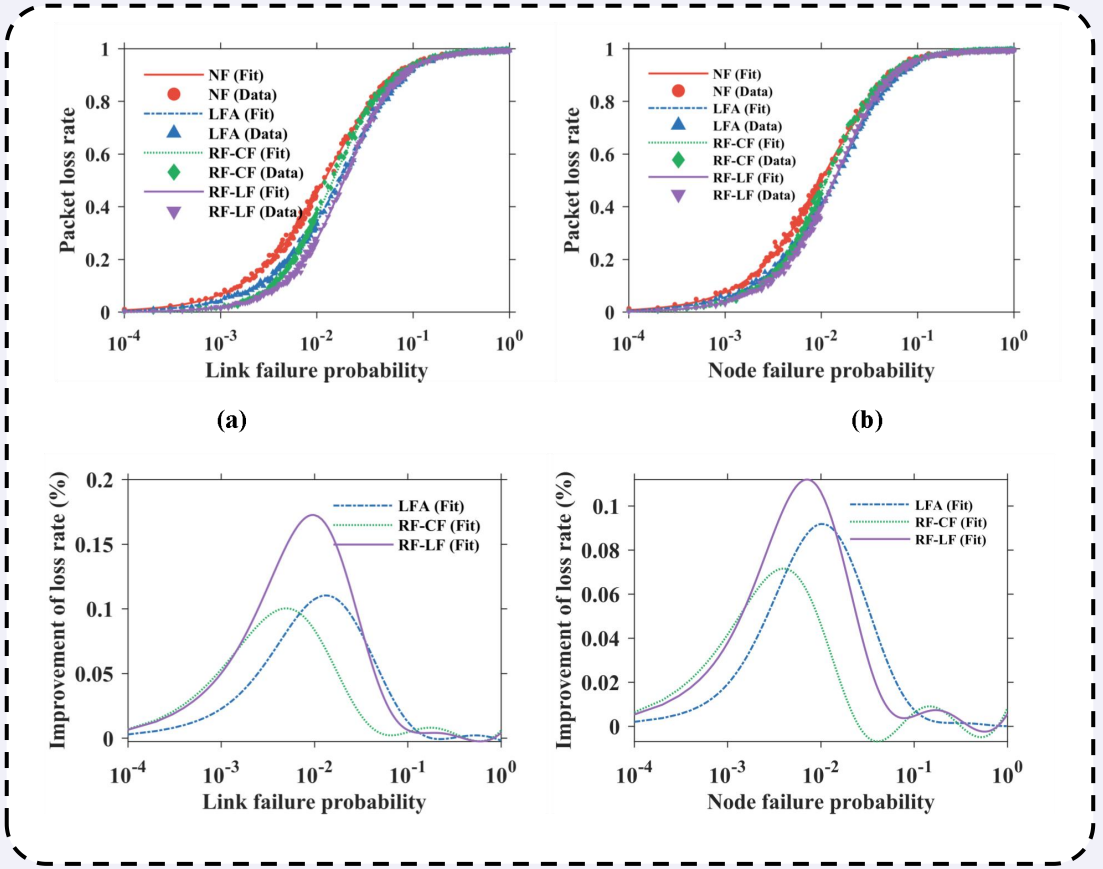
4-Simulation: Packet Loss Rate Comparison

Key Findings

- LFA, RF-CF, and RF-LF all effectively reduce packet loss
- **RF-LF demonstrates best performance**

Performance Improvement (vs. NF)

- Link fault conditions: **up to 17.5% reduction**
- Node fault conditions: **up to 11.2% reduction**

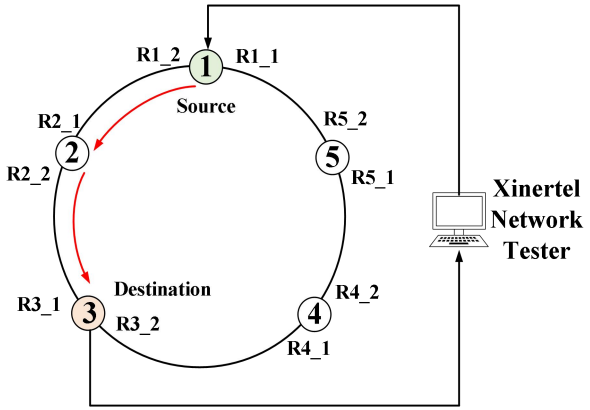


Packet Loss Rate Comparison

4-Experiments: Setup

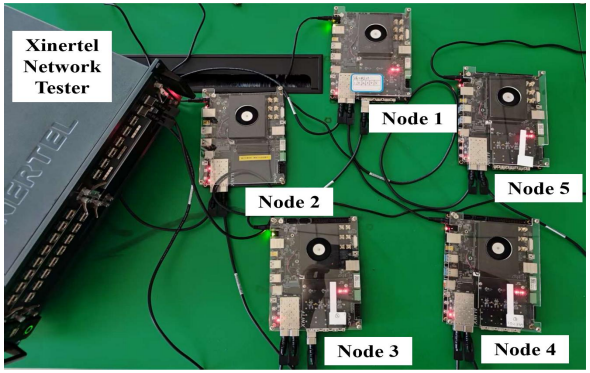
Experimental setup

- **Dynamic Routing Protocol:** Standard OSPFv3 (with/without SDAF)
- **Topology:** 5-router ring (end-to-end connected)
- **Fault Types:** No faults, Single-link failure



Performance Metrics

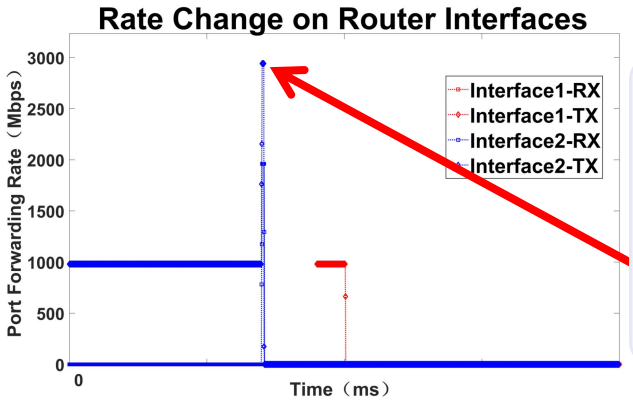
- Packet loss, Out-of-order delivery
- Latency, Jitter
- Routing black holes, Micro-loops



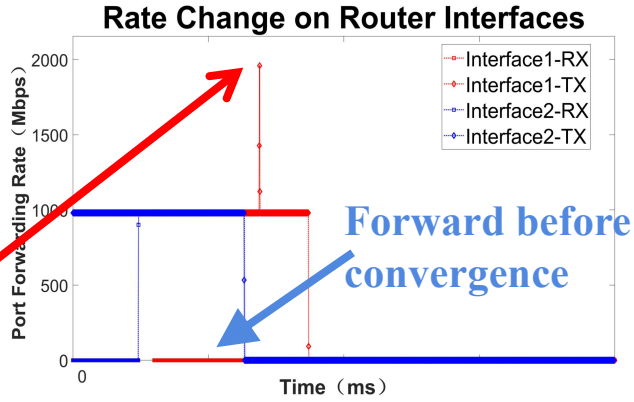
Procedure

1. **Enable OSPF dynamic routing**
2. **Start traffic generation (Xinertel Network Tester)**
3. **Inject link failures after Node 3 receives packets**
4. **Record end-to-end metrics**

4-Experiments: Results



Key Result:
Peak congestion reduced from 3,000 Mbps to 2,000 Mbps



Experiment 40, Node 1 | Experiment 47, Node 1

	Tester						Recorded metrics				Raw Data Table
								Microloop Packet Loss	TTL Packet Loss	Total Packet Loss	
								0	0	432359	35
								0	1293	500320	36
								1801	1961	407868	37
								804	1961	436191	38
								2702	1962	540993	39
								8893	1961	595320	40
								14456	1962	450577	41
								0	0	226	42
	5ms	1162	1961	36147.663	3157492.284	0.352	524.28	895	0	0	895	43

Performance Comparison (SDAF VS. No SDAF)

- Packet Loss: Significantly reduced (e.g., 310 vs. 432, 485)
- Microloop Packet Loss: Eliminated (0 vs. up to 14, 456)
- Black Hole Packet Loss: Reduced (e.g., 58 vs. 434, 159)
- Latency/Jitter: Comparable performance

SDAF reduces packet loss caused by micro-loop and black hole.

5-Summary & Next Steps

Core Contributions

- Control-plane-independent FRR for LEO satellites
- Leverages toroidal symmetry for sub-ms convergence
- Compatible with OSPFv3, IS-IS, MPLS (no modifications)

Applicability & Limitations

- Target: LEO constellations with toroidal/torus-like topology
- ⚠ Limitation: Requires connected impaired topology
- ⚠ Partitioned topology → Higher-layer recovery needed

We Seek RTGWG Feedback:

- • Is the problem statement relevant to RTGWG?
- • Is the symmetry-based reroute model technically sound?
- • What additional evidence would be needed for WG interest?

Thank You. Q & A?

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Backup Slide 1: Key Terminology

- **Flow & Distance**
  - • HD (Hop Distance): Hops on shortest path
  - • FF (Forward Flow): Decreasing HD, along minor arc
  - • RF (Reverse Flow): Increasing HD, along major arc
  - • Phase (P): + for FF, - for RF
- **Interfaces**
  - • PEI (Primary Egress Interface): Shortest-path egress
  - • CFI (Counter-facing Interface): Opposite to PEI
  - • LFI (Lateral-facing Interface): Orthogonal to PEI
- **Tables & Detection**
  - • ISMT (Interface Symmetry Mapping Table): Local, static
  - • LIST (Local Interface Status Table): Local, dynamic
  - • LSD (Link-State Detection): Local, low-latency
- **Transition**
  - • PTP (Phase Transition Point): Ingress interface ≠ PEI

Backup Slide 2: Security Considerations [Draft Section 8]

- **Potential Threats**
  - • LSD spoofing: False link-state information
  - • ISMT/LIST tampering: Incorrect forwarding decisions
  - • Policy inconsistency: Loop formation due to mismatch
- **Mitigation Mechanisms**
  - • LSD authentication: Leverage existing protocol auth (e.g., RFC 4552 for OSPFv3, RFC 5310 for IS-IS)
  - • Local table protection: ISMT/LIST stored in secure memory
  - • Policy consistency: Network-wide configuration validation
- **Security Scope**
  - • ISMT: Static preconfiguration, no external exposure
  - • LIST: Local runtime state, no external exposure
  - • LSD: Requires authenticated mechanism (future work)
- **Note: Full security analysis in future draft versions**