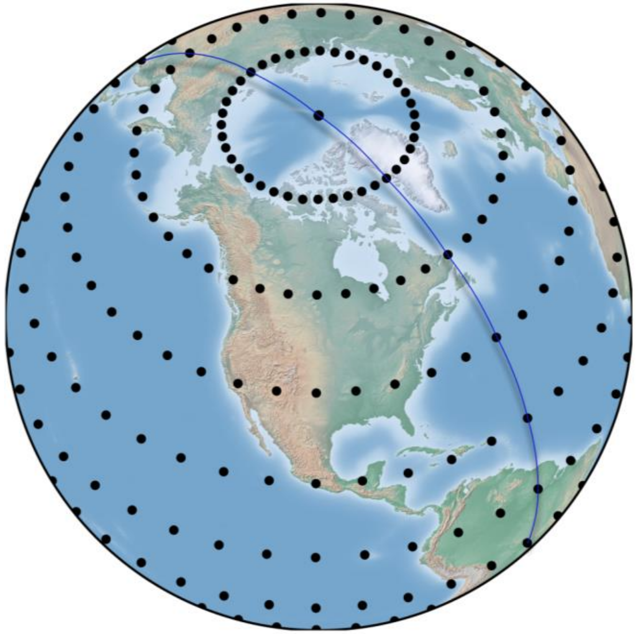
Routing in LEO Satellite Networks: How Many Link-State Updates Do We Need?

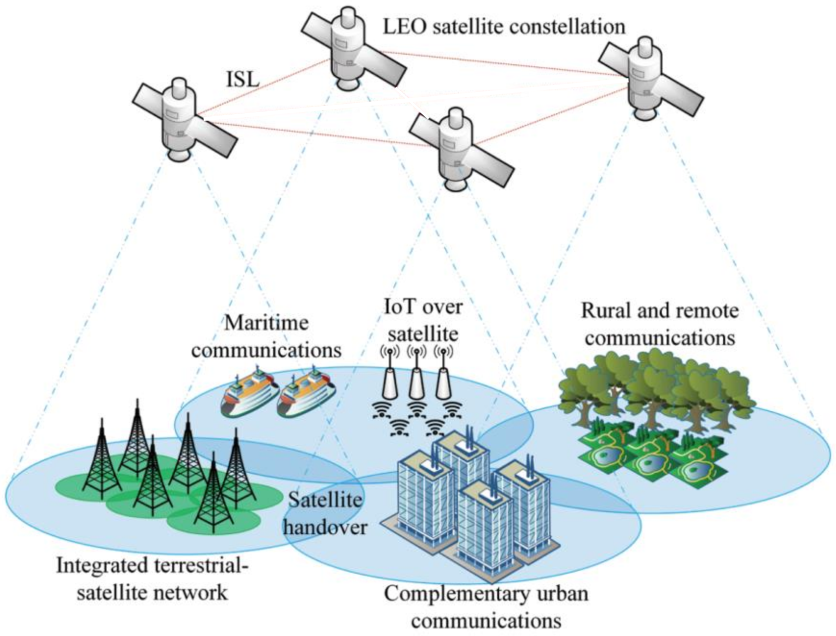
Qian Shan, Zhiyuan Wang, Shan Zhang, Qingkai Meng, and Hongbin Luo

Beihang University

IEEE Satellite 2023

Background & Motivation





- **Large-scale LEO satellite constellation is expected to provide ubiquitous Internet services**
- **Efficient routing & forwarding is necessary in LEO satellite networks**
- **Major challenge: topology instability**
  - Occasional ISL failure & recovery
  - Routing protocol should quickly detect & disseminate the topology changes

Background & Motivation

- **Previous link-state routing protocols for satellite networks are mainly based on OSPF[1-3]**
  - ***Globally*** disseminates ***coarse-grained*** link-states
  - Only focus on ISL connectivity
- **Neglect topology characteristics of LEO satellite networks**
  - Deterministic neighbor relationship
  - Predictable topology
- **Real-time connectivity of a far away ISL may not be crucial**

Question 1

Do we need global link-state dissemination in LEO constellations with deterministic neighbors?

Question 2

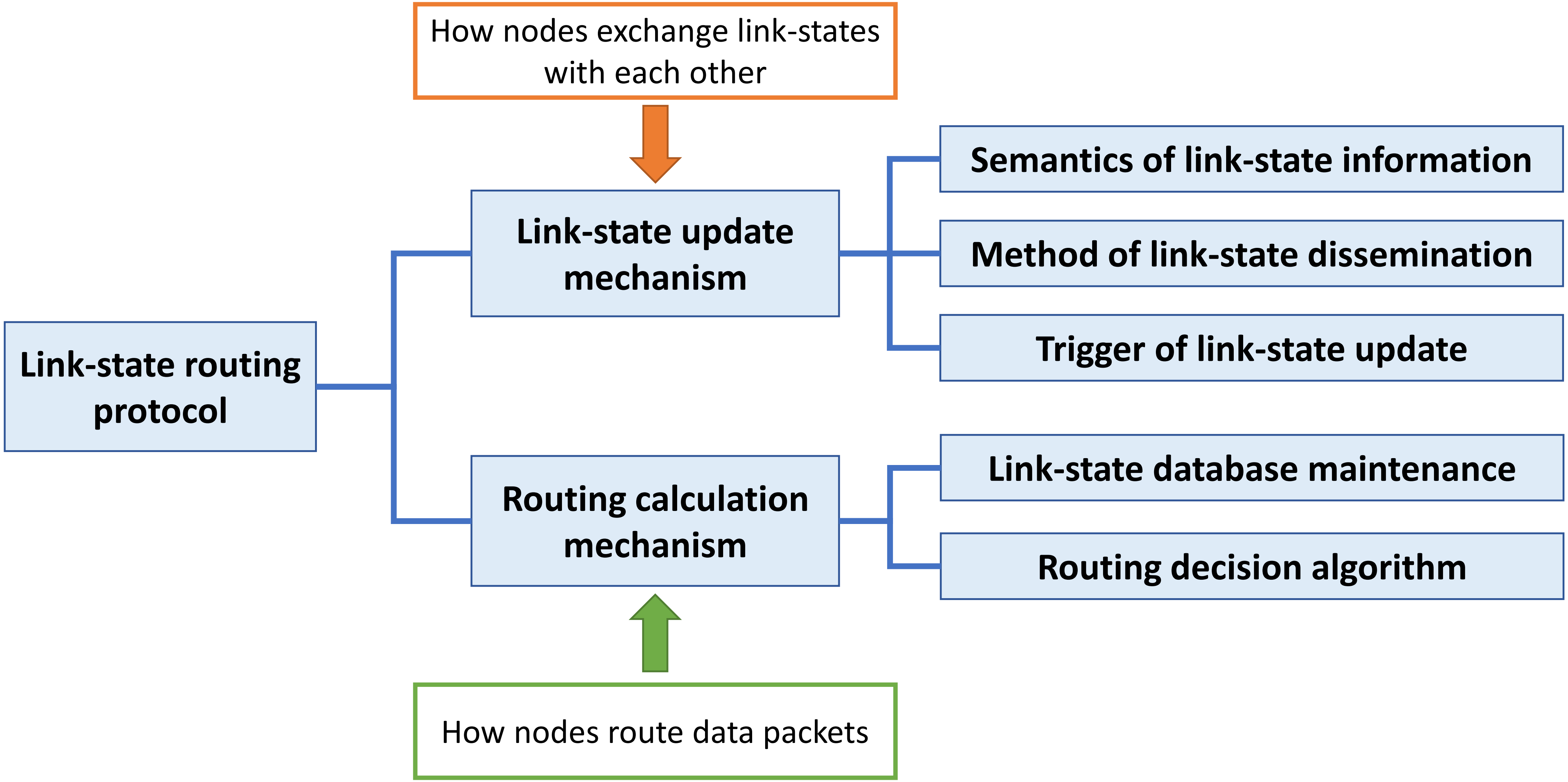
Which type of link-state update fits LEO constellations, global coarse-grained or localized fine-grained?

[1] Pan T, Huang T, Li X, et al. OPSPF: orbit prediction shortest path first routing for resilient LEO satellite networks. IEEE ICC, 2019.
[2] Ruan G, Pan T, Lu C, et al. Lightweight Route Flooding via Flooding Topology Pruning for LEO Satellite Networks. IEEE ICC, 2022
[3] Yan F, Lian P, Luo H, et al. Logic Path Identified Hierarchical (LPIH) Routing for LEO Satellite Network. IEEE Satellite, 2022

Overview of Our Work

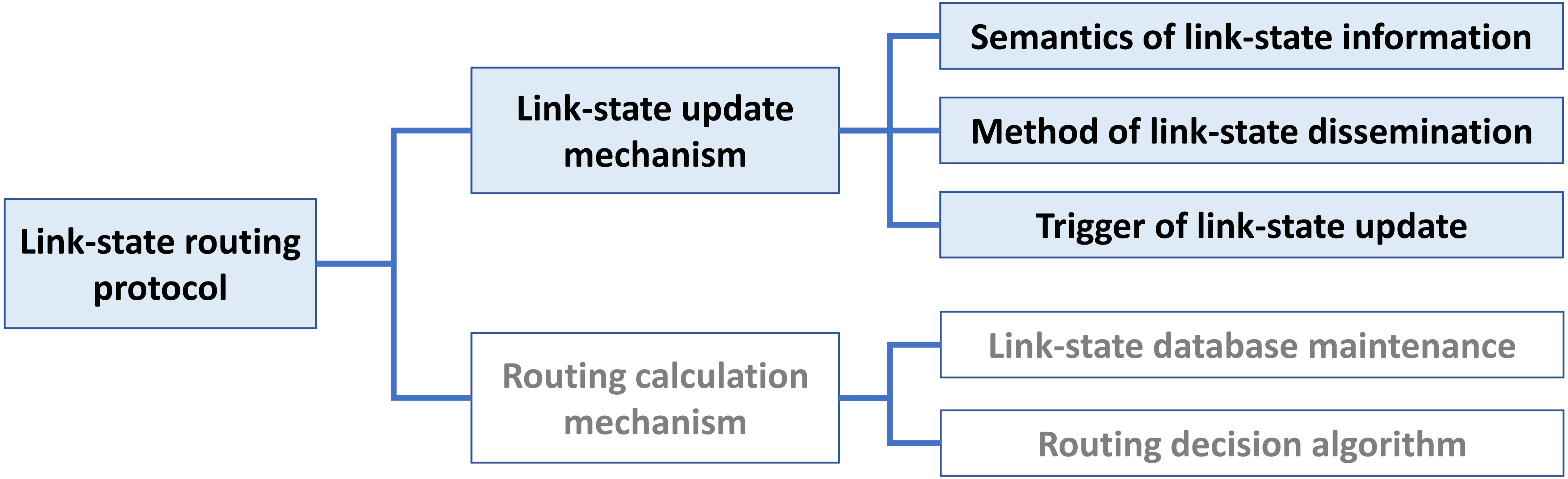
- A novel ***Localized Fine-grained (LoFi)*** **link-state protocol for LEO satellite networks**
- **Localized fine-grained link-state update**
- **Predictable-topology-based routing calculation**
- **Performance evaluation on packet-level experiments**

General Design Considerations of Link-State Routing Protocols



Link-State Update Mechanism in Our LoFi Protocol

- **Key ideas**
  - Reduce the range of link-state dissemination: localized
  - Enrich the link-state information with the link load: fine-grained
- **Satellites exhibit more valuable link-states at the cost of small communication overhead**



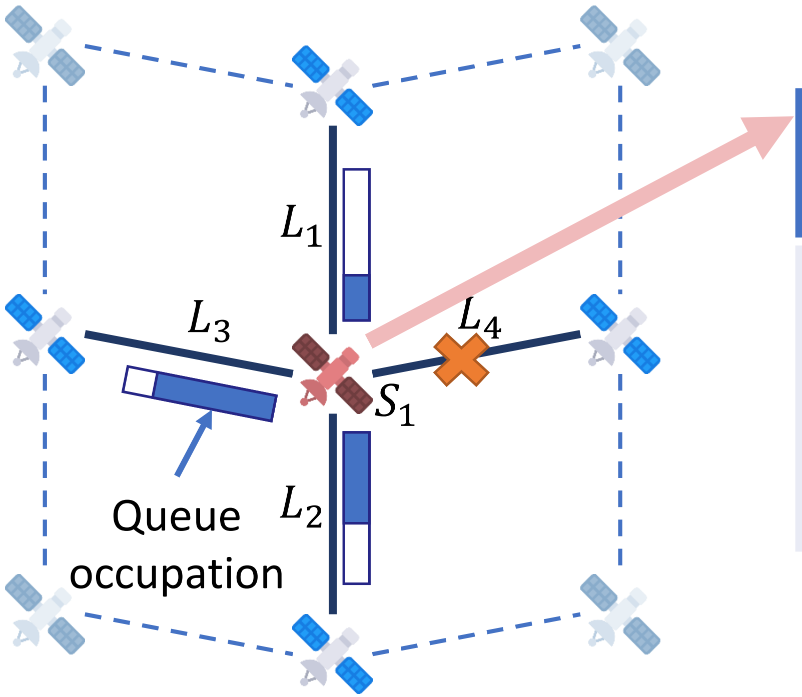
Semantics of Link-State Information in LoFi

Classic OSPF

- **Coarse-grained**
- Focus on **ISL connectivity**
- No load awareness

LoFi

- **Fine-grained**
- **ISL connectivity & ISL load**
- **Load aware:** occupation of forwarding queue



Generated link-state message

Advertising satellite	ISL	Link-state data	
		connectivity	load
S_1	L_1	true	0.3
	L_2	true	0.6
	L_3	true	0.8
	L_4	false	--

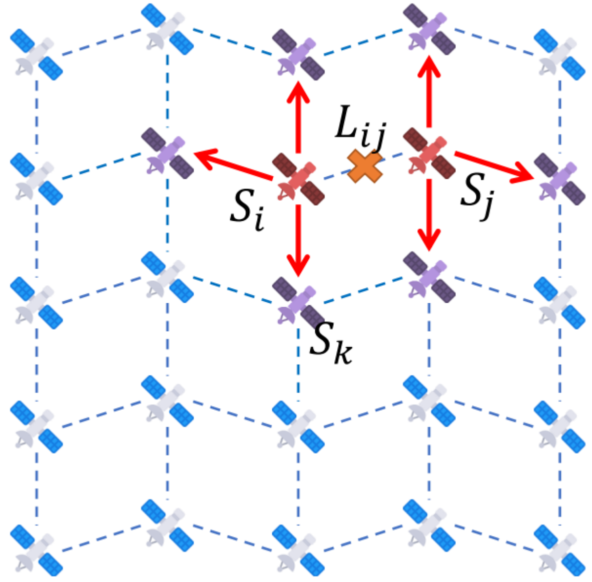
Method of Link-State Dissemination in LoFi

Classic OSPF

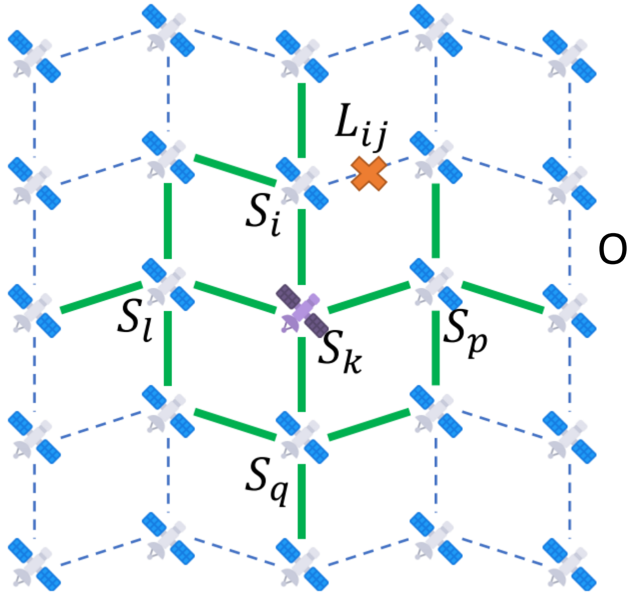
- **Global** link-state dissemination via flooding
- Globally consistent LSDBs
- Causes too much advertisement overhead

LoFi

- **Localized** link-state dissemination
- Parameterized by $\boldsymbol{n} \in \{\mathbf{0}, \mathbf{1}, \mathbf{2}, \dots\}$
- Link-states are disseminated within n hops
- Independent & **inconsistent LSDBs**
- **Reduces** advertisement overhead
- **Enables** ISL load incorporation



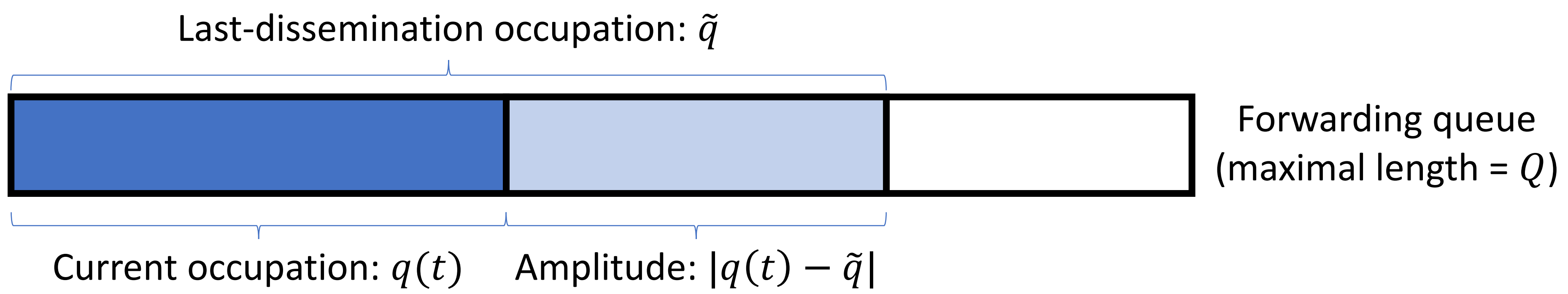
Range of dissemination when $n = 1$



Obtained links by S_k when $n = 1$

Trigger of Link-State Update in LoFi

- **Event-triggered link-state update mechanism**
- **Trigger1: ISL failure/recovery, the same as traditional link-state protocols**
- **Trigger2: ISL load change, enables load awareness in LoFi**
  - Parameterized by $\boldsymbol{\delta} \in [\mathbf{0}, \mathbf{1}]$
  - Disseminates ISL load change only if amplitude of queue occupation ratio exceeds δ



- **Trigger event:** $|q(t) - \tilde{q}| \geq Q \cdot \delta$

LoFi Parameters

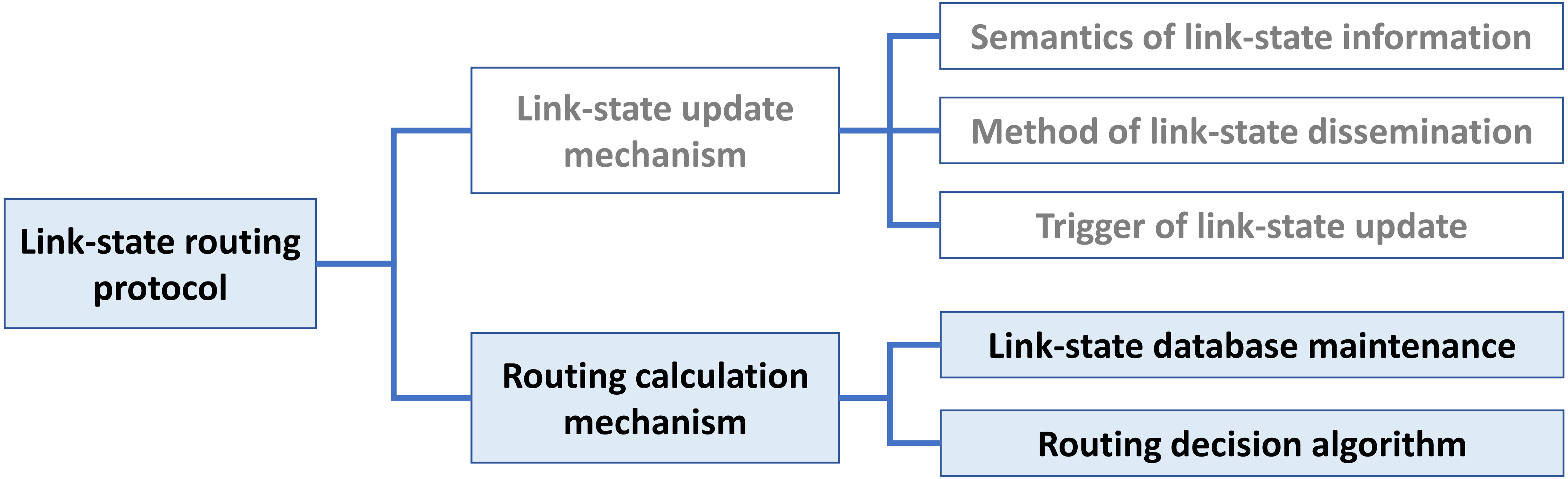
- $\boldsymbol{n} \in \{\mathbf{0}, \mathbf{1}, \mathbf{2}, \ldots\}$
  - Represents the **range** of link-state dissemination
  - A larger n means more link-states obtained, but larger advertisement overhead

- $\boldsymbol{\delta} \in [\mathbf{0}, \mathbf{1}]$
  - Represents the **sensitivity** of load awareness
  - A smaller δ means more sensitive to load changes, but larger advertisement overhead

- **LoFi(n, δ) framework generalizes a wide range of link-state protocols**
  - LoFi$(\infty, 1)$ is classic OSPF
  - **Trade-off** between different (n, δ) tuples is needed

Routing Calculation Mechanism in LoFi

- Link-states in LSDB come from local dissemination / predictable topology
- Each satellite builds the routing table using its LSDB



Routing Calculation Mechanism in LoFi

◆ **Link-state database maintenance**

- For ISLs within local dissemination range: **precisely obtained** through link-state updates
- For ISLs out of local dissemination range: **inferred** based on predictable topology

◆ **Routing decision algorithm**

- Each ISL is associated with a link-cost metric

$$Cost_{ISL} = d_{ISL}^{Propa} + d_{ISL}^{Queue}$$

Propagation delay

- **Within dissemination range**: precisely obtained
- **Out of dissemination range**: inferred based on predictable topology

Queuing delay

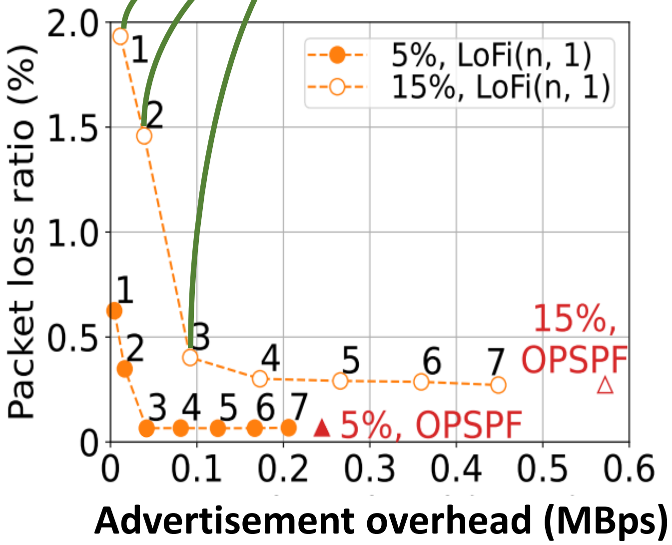
- **Within dissemination range**: precisely obtained
- **Out of dissemination range**: considered as zero

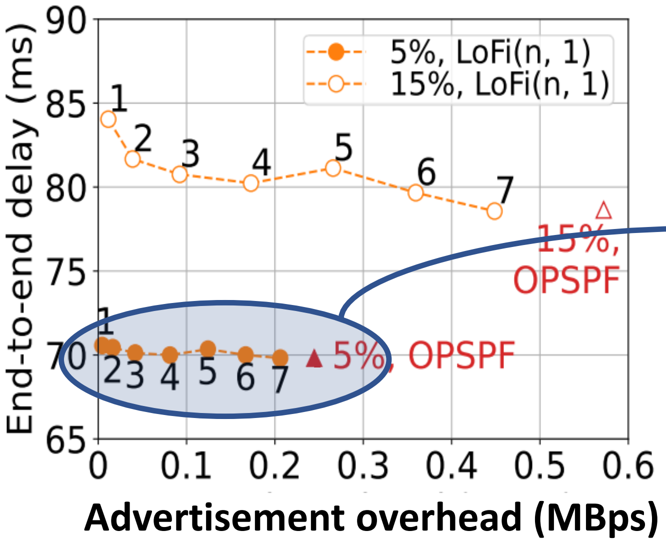
- Selects the path with the lowest cost when forwarding data packets

Performance Evaluation in OMNeT++

- **Experiment setup**
  - Iridium-like constellation
  - Performance metrics: Packet loss ratio, End-to-end delay, Advertisement overhead
- **Baseline: OPSPF[1], ELB[2]**

As n increases, the marginal performance gain is nearly zero when $n \geq 4$





Link failure rate = 5%

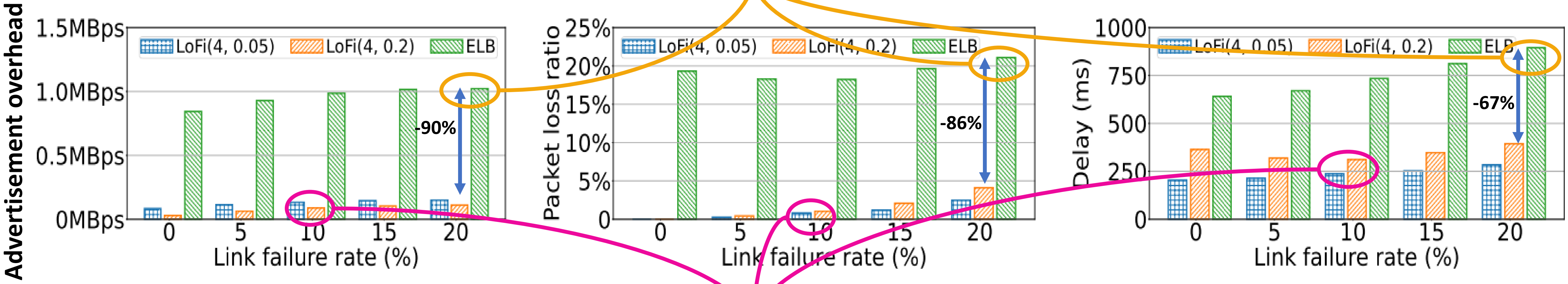
- LoFi(3, 1) almost achieves the same packet loss ratio & delay with OPSPF
- LoFi(3, 1) incurs **78% less** advertisement overhead than OPSPF

Localized link-state dissemination achieves comparable performance at a lower overhead

[1] Pan T, Huang T, Li X, et al. OPSPF: orbit prediction shortest path first routing for resilient LEO satellite networks. IEEE ICC, 2019.
[2] Taleb T, Mashimo D, Jamalipour A, et al. Sat04-3: Elb: An explicit load balancing routing protocol for multi-hop ngeo satellite constellations[C]//IEEE Globecom 2006. IEEE, 2006: 1-5.

Performance Evaluation in OMNeT++

LoFi(4, δ) significantly outperforms ELB in advertisement overhead, packet loss ratio & delay

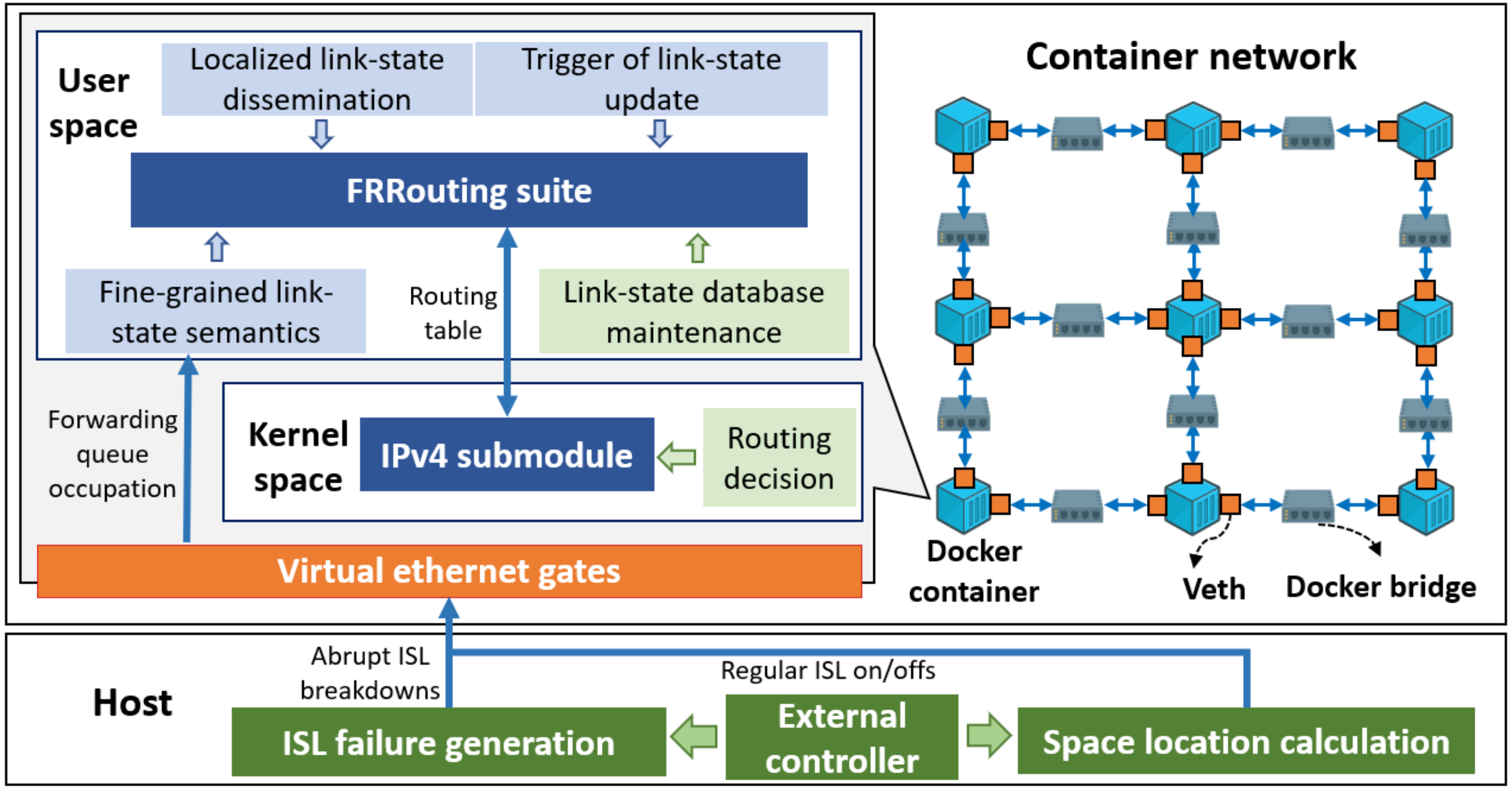


As δ decreases, LoFi sacrifices control overhead in exchange for a better packet delivery performance

Fine-grained link-state achieves load awareness at a low advertisement overhead

Container-based Emulator & Implementation on Linux Kernel

◆ Container-based emulator



◆Implementation of LoFi on the emulator

- ☐ Link-state update mechanism: implemented in user space
- ☐ Routing calculation mechanism: implemented in kernel & user space

Conclusion & Future Works

◆ Conclusion

- ☐ Proposed localized fine-grained (LoFi) link-state routing protocol for LEO satellite networks
- ☐ Performance evaluation on packet level experiments
- ☐ LoFi outperforms OPSPF & ELB

◆ Future works

- ☐ Deal with packet disorders
- ☐ Further evaluate the performance of LoFi based on the container-based emulator

Thanks

◆ An example of data forwarding