OpenSN: An Open Source Library for Emulating LEO Satellite Networks

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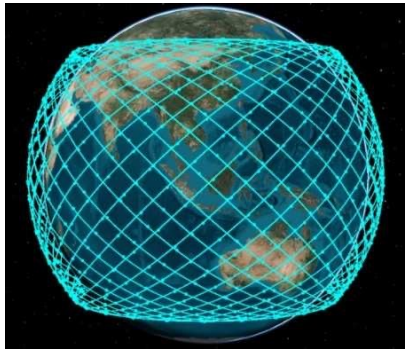
Background

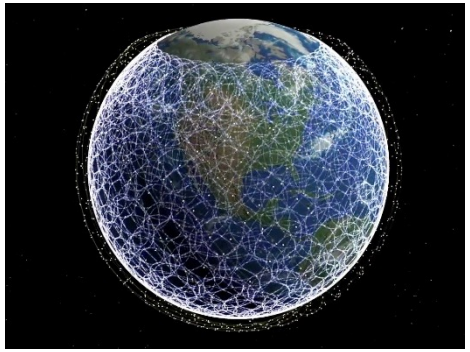
- **Rapid development of Low-Earth-Orbit (LEO) satellite constellations**

Iridium

OneWeb



Kuiper



Starlink

- **LEO satellite network is an indispensable part of future Internet**
  - **Low Latency: for real-time communications and military usage**
  - **Global Coverage: for remote area access and ocean shipping**
  - **High Capacity: for global IoT and industry and airplane network access**

Background

- **There have been many studies on LEO satellite networking**
  - ✓ IP-based routing architecture (e.g., [1],[2])
  - ✓ Content-centric routing (e.g., [3],[4])
  - ✓ Link-identified routing (e.g., [5])
  - ✓ Congestion control algorithms (e.g., [6])
- **How to evaluate these new architectures, protocols, and algorithms in a systematic and reproducible manner has been an open problem**

[1] Yan F, Luo, et al. A comparative study of IP-based and ICN-based link-state routing protocols in LEO satellite networks[J]. PPNA, 2023.

[2] Shan Q, Wang Z, et al. Routing in LEO Satellite Networks: How Many Link-State Updates Do We Need? IEEE Satellite Computing, 2023.

[3] Yan F, Wang Z, et al. Logic Path Identified Hierarchical Routing for Large-Scale LEO Satellite Networks[J]. IEEE TNSE, 2024.

[4] Liang T, Xia Z, et al. NDN in large LEO satellite constellations: a case of consumer mobility support[C] ACM ICN, 2021.

[5] Zhang H, Wang Z, et al. Optimizing Link-Identified Forwarding Framework in LEO Satellite Networks[C] IEEE WiOpt, 2023.

[6] Cao X, Zhang X. Satcp: Link-layer informed tcp adaptation for highly dynamic leo satellite networks[C] IEEE INFOCOM 2023.

Existing Simulator/Emulator for Satellite Networks

Simulator/Emulator		Fine Granularity	Routing	Efficiency	Open-source?
Discrete-event Simulator	STK	Orbit	/	/	❌
	StarPerf [1]	Flow-level	Route calculation	✅	✅
	OMNET-based [2]	Packet-level	Routing protocol	❌	❌
	NS3-based [3]			❌	❌
Virtual-network Emulator	LeoEM [4]	**Full-stack Realism**	**Route calculation**	✅	✅
	StarryNet [5]		**Routing software**	❌	**Partially**
	Our Work			✅	✅

Advantages in emulation efficiency, system scalability, and function extensibility

[1] Lai Z, Li H, Li J. Starperf: Characterizing network performance for emerging mega-constellations[C]. ICNP, 2020.

[2] Yan F, Luo, et al. A comparative study of IP-based and ICN-based link-state routing protocols in LEO satellite networks[J]. PPNA, 2023.

[3] Wang Z, Cui G, Li P, et al. Design and implementation of NS3-based simulation system of LEO satellite constellation for IoTs[C]. ICCC, 2018

[4] Cao X, Zhang X. Satcp: Link-layer informed tcp adaptation for highly dynamic leo satellite networks[C]. INFOCOM, 2023

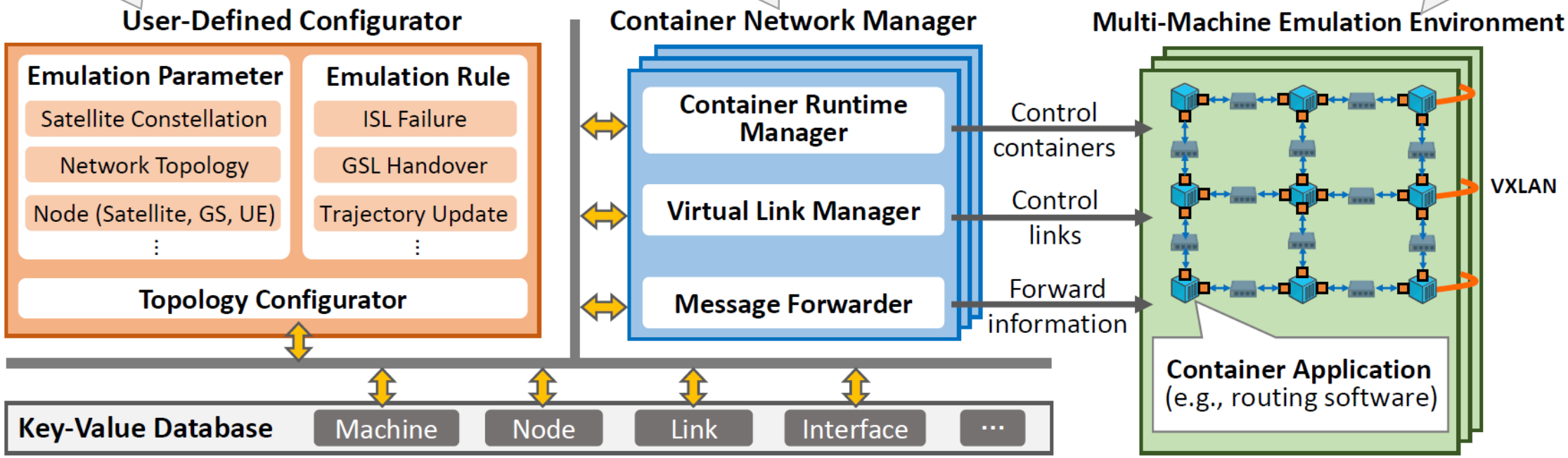
[5] Lai Z, Li H, Deng Y, et al. {StarryNet}: empowering researchers to evaluate futuristic integrated space and terrestrial networks[C]. NSDI, 2023.

OpenSN Framework

Allow user to specify emulation parameters, customize emulation rules

Virtual Environment Operator Deployed on each machine.

Represent the real network topology.
Consist of containers and virtual links



Record emulation configurations, deliver instructions from the User-defined Configurator to the Container Network Manager.

OpenSN Framework

- **OpenSN achieves better emulation efficiency, system scalability and function extensibility than existing SN emulators, i.e., StarryNet and LeoEM**

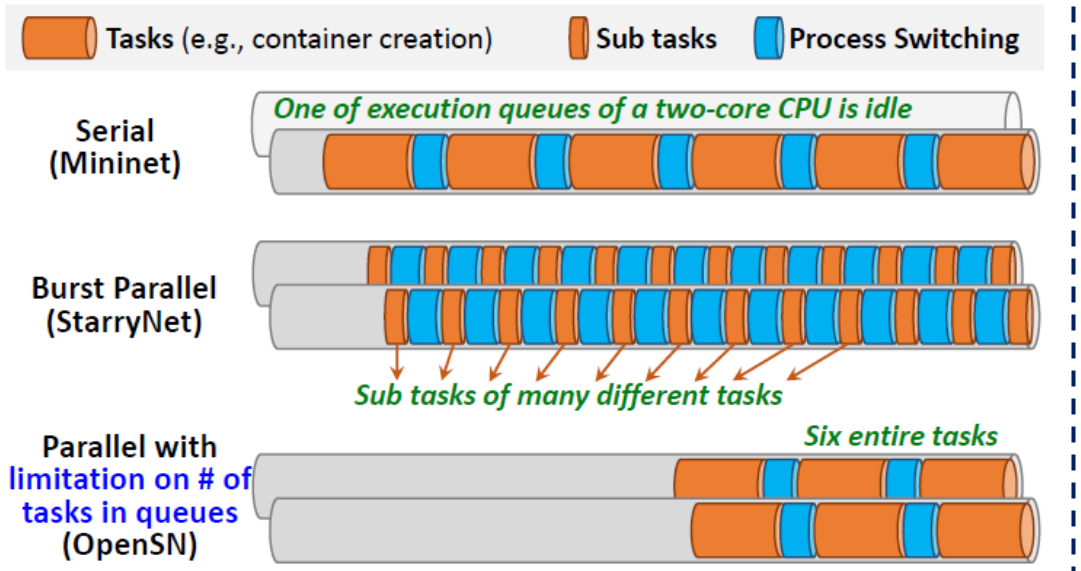
SN Emulator	Emulation Efficiency	System Scalability	Function Extensibility
LeoEM	**Efficient** for SN emulation thanks to the lightweight virtualization of Mininet	**Good vertical scalability** on single machine, **not horizontally scalable** to more machines	**Not able to emulate SN running distributed software** (e.g., routing) due to the lightweight virtualization
StarryNet	**Inefficient** due to direct interaction with Docker CLI in SN emulation	**Good horizontal scalability** to multiple machines, but is **not vertically scalable** due to direct interaction with Docker CLI	Allow for distributed software (e.g, routing), but **not flexible to modify images**, topology, etc
OpenSN	**Efficient** due to our improvement on the process of using Docker CLI in our managers	**Good vertical and horizontal scalability** due to improvement on the process of using Docker CLI in SN emulation	**Allow for distributed software** (e.g, routing), and **flexible to extend** (due to separation of user configuration from container network management)

Emulation Efficiency

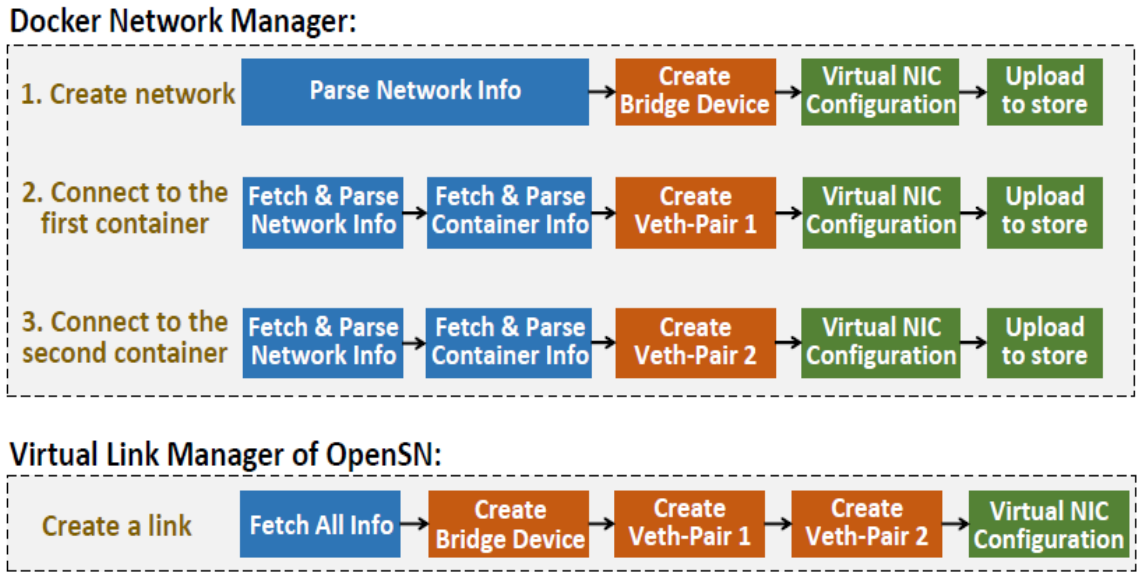
- **LEO satellite network emulator should be efficient**
  - **Creation:** thousands of satellite nodes and links
  - **Updates:** frequent GSL handover, link delay change, and other state changes

- **OpenSN achieves a better emulation efficiency via two aspects**

#1 Optimize Task Scheduling Rule

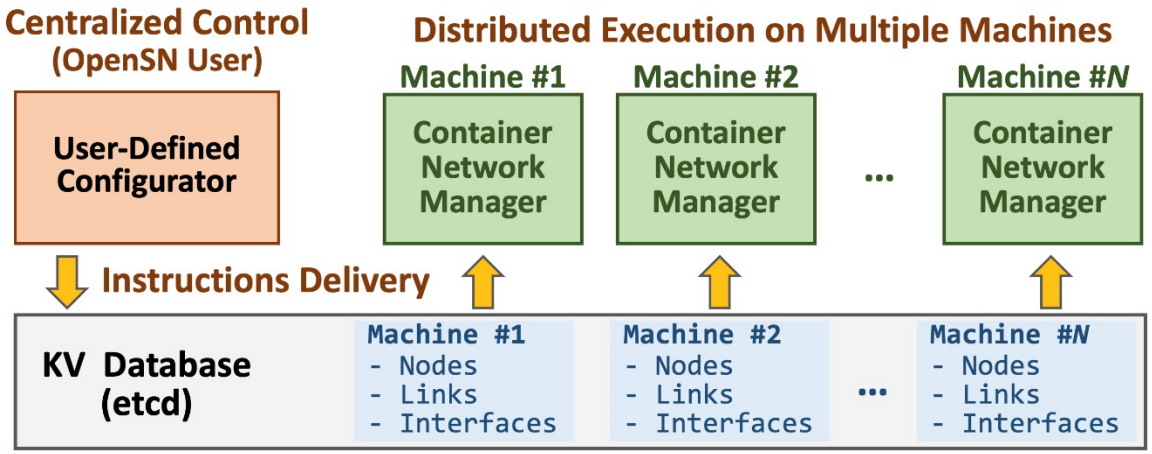


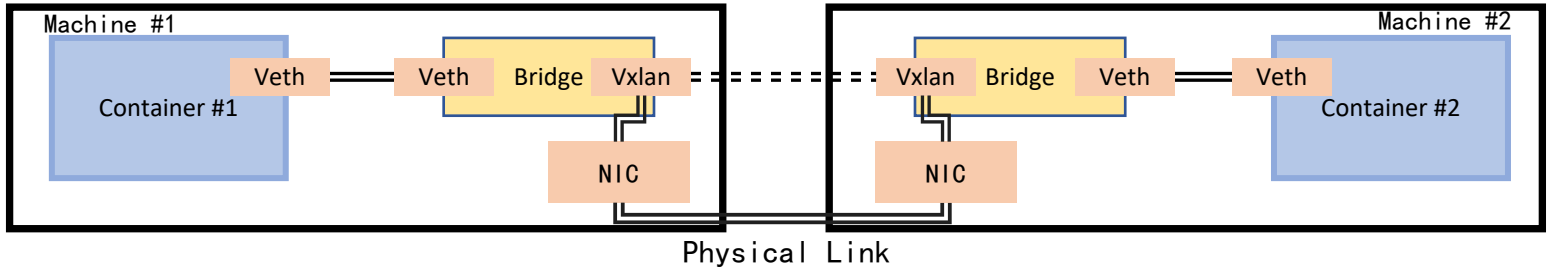
#2 Streamline Link Creation Procedure



System Scalability

- **LEO satellite network emulator should be system scalable**
  - **Huge amount:** A constellation container many satellites
  - **Distributed Software:** emulation need run software in each container
- **OpenSN achieves a better system scalability via multi-machine extension**
- **Control Plane**
  - Centralized Control
  - Distributed Execution
  - State-driven Instruction Delivery
- **Data Plane**
  - VXLAN Technology
  - Naturally point-to-point link

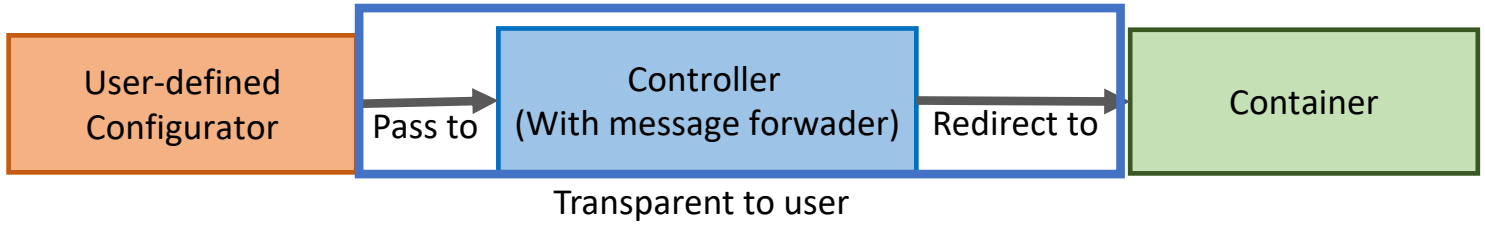




Function Extensibility

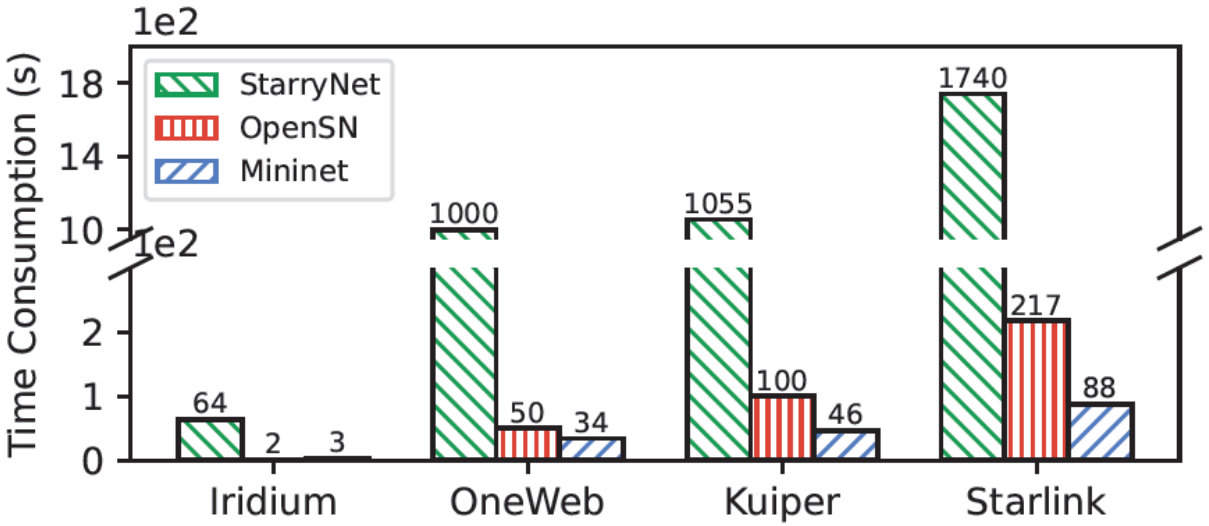
- **LEO satellite network emulator should be functionally extensible**
  - **Various Topology Patterns:** Integrated Satellite-Terrestrial Network, Multi-shell Satellite Network, ...
  - **Various Network Node Types:** Router Node, Switch Node, Terminal Node, Authorization Node, ...
  - **Various Rules for Topology Change:** GSL Handover Order, ISL Failure Type, Satellite Coverage Area, ...
- **OpenSN achieves a better function extensibility via split framework**
  - **Network Emulator = Simulation/Emulation Environment + Controller**
    - OpenSN = Overlay Network + Topology Configurator
      - Container Based Virtual Network
      - OpenSN daemon
      - OpenSN SDK
      - User-defined Configurator
    - OMNet++ Based Emulators = OMNet++ Engine + Simulation Control Code
      - Discrete Event Engine
      - OMNet++ Library
      - OMNet++ controller

OpenSN also support many user-defined container images by **decoupling the emulation controller and container images.**

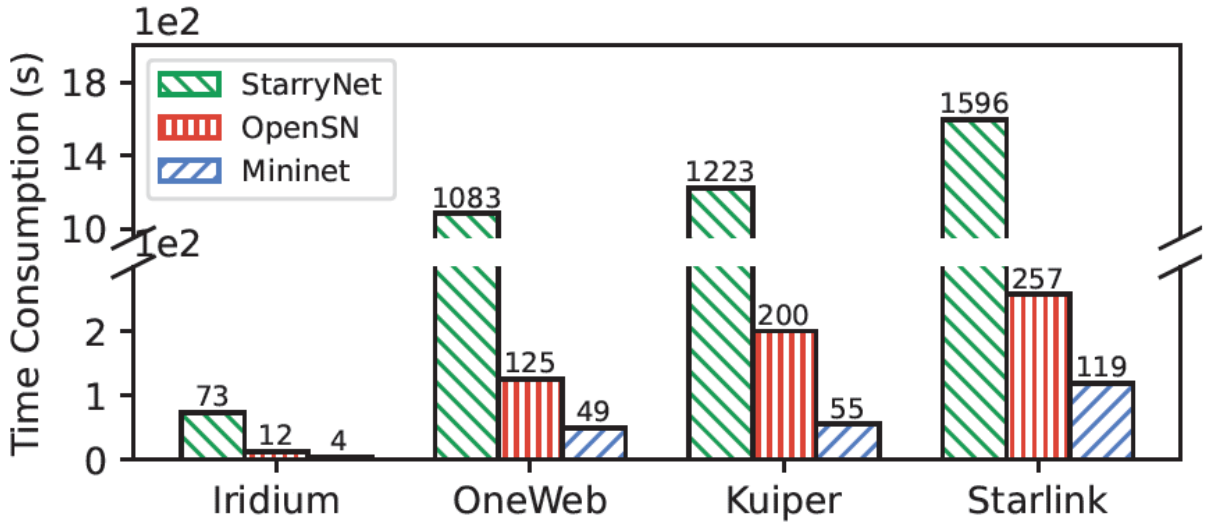


Performance Evaluation

SN Construction



SN Deconstruction

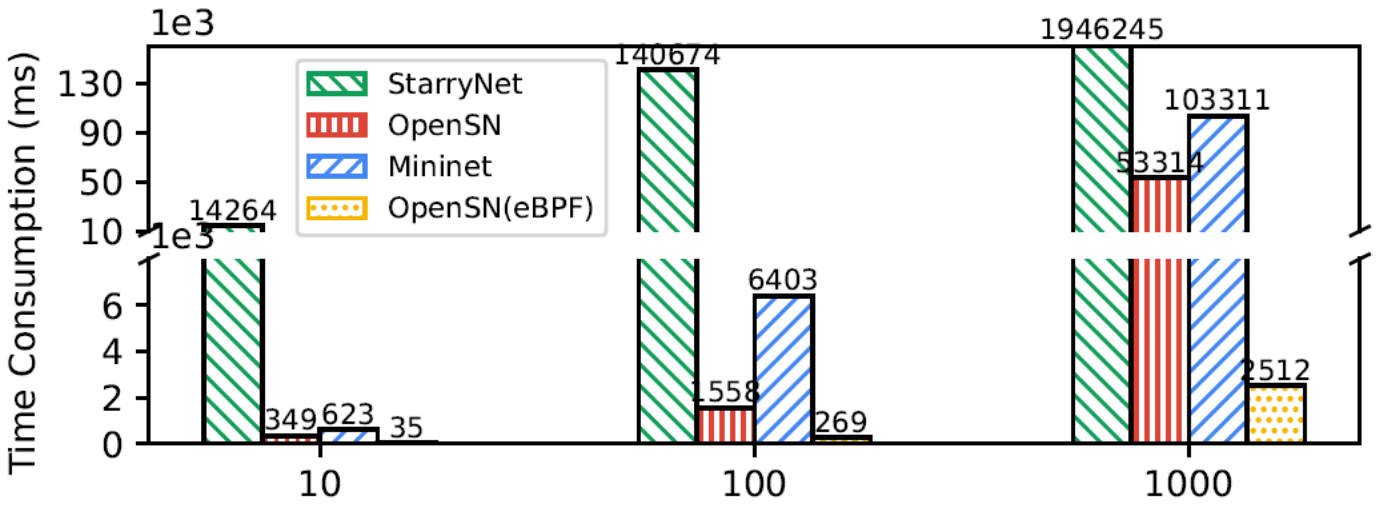


- **OpenSN is 15X faster than StarryNet in terms of SN construction/deconstruction**

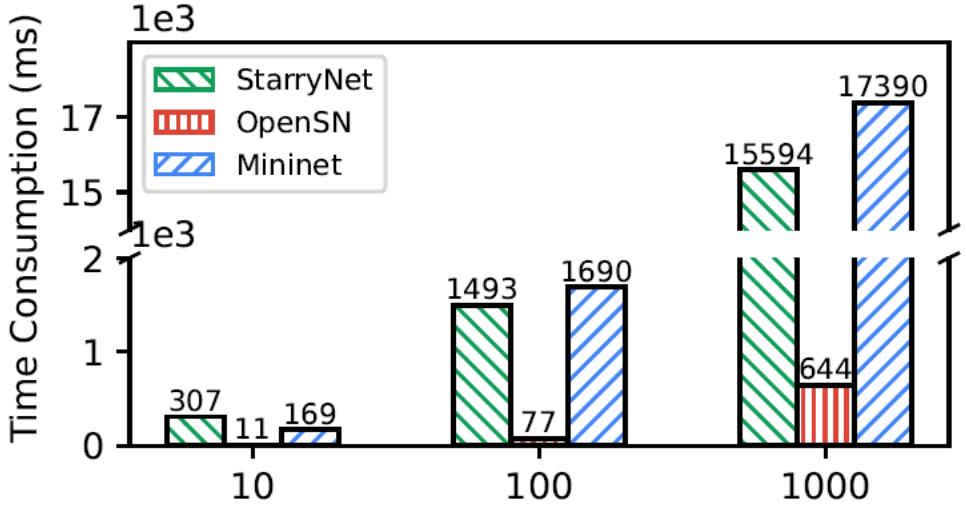
- **OpenSN is more powerful compared to LeoEM (relying on Mininet)**
  - **OpenSN:** run distributed routing software at each node
  - **LeoEM:** centralized routing calculation

Performance Evaluation

GSL Handover



ISL Latency Update

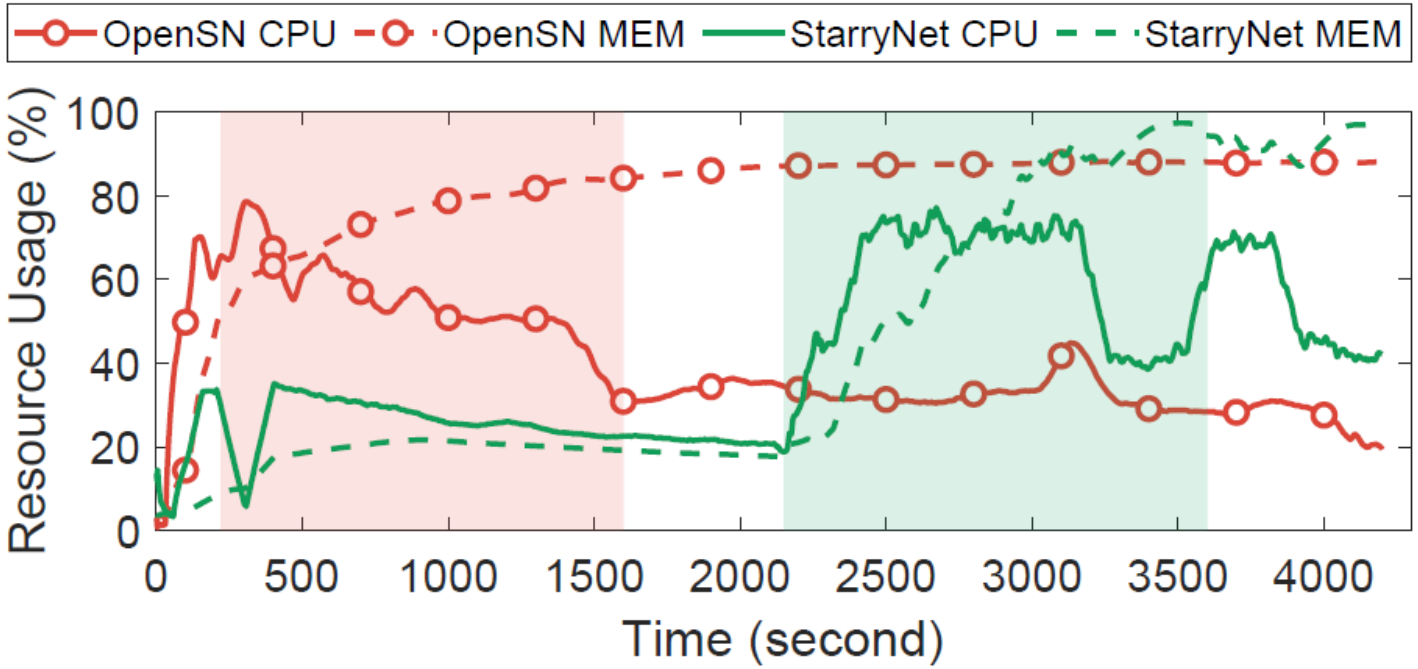


- **OpenSN is 30X faster than StarryNet in terms of GSL Handover**
- **OpenSN is 25X faster than StarryNet in terms of ISL Latency Update**

Performance Evaluation

Runtime Resource Usage

1. Network construction
2. Routing convergence (shaded)
3. Stable operation



- OpenSN maximizes the resource usage during the construction period.
- OpenSN consumes less resource in the stable operation period.

Conclusion

- **OpenSN:** an open-source library for emulating large-scale LEO satellite networks.

  Various studies on the LEO satellite network needs to be evaluated in a systematic and reproducible manner

- **Advantages of OpenSN**

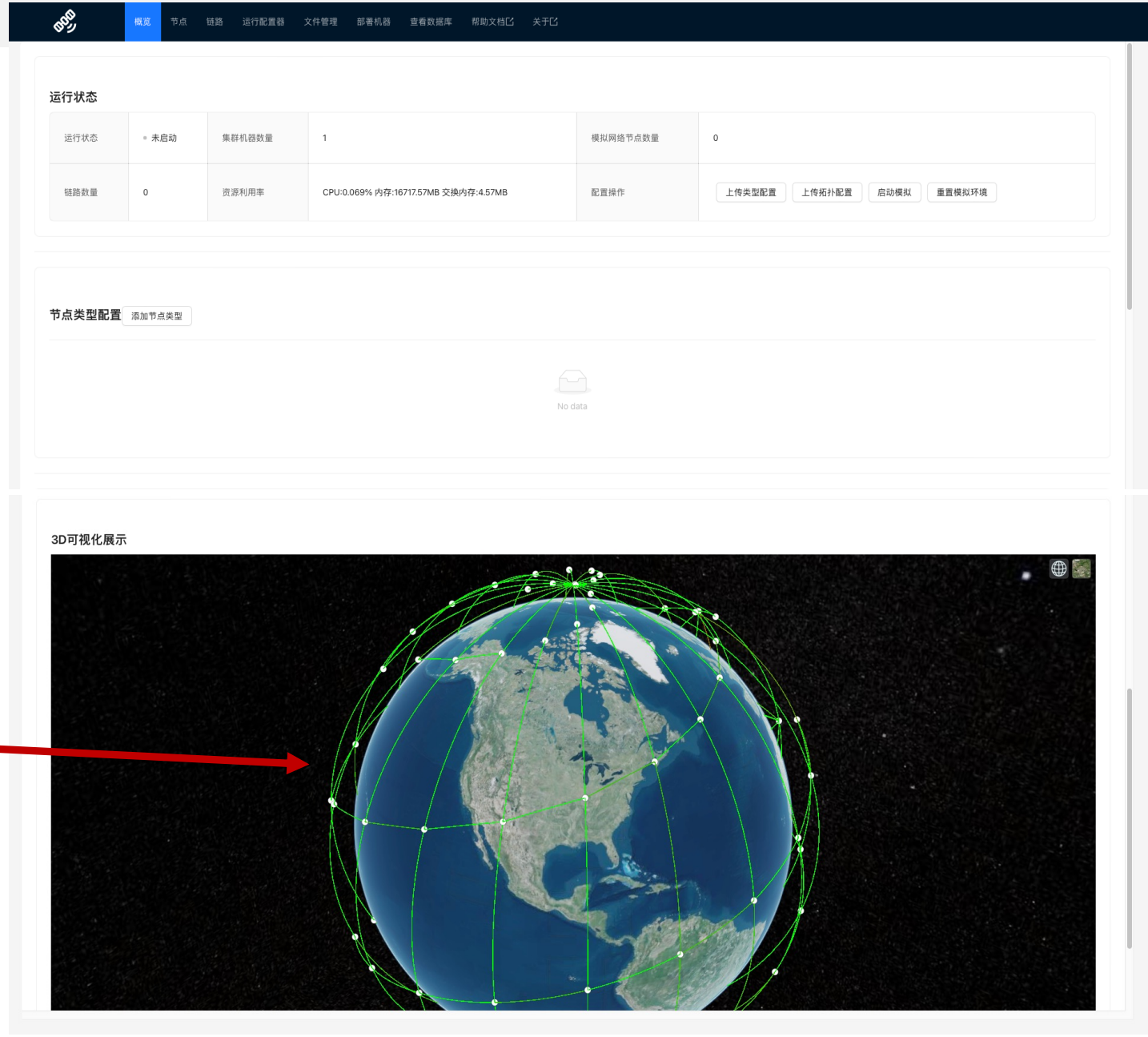
  - ✓ More functional
  - ✓ More efficiency
  - ✓ Better system scalability
  - ✓ Better function extensibility

Appendix

Appendix

- **OpenSN Web Console**
  - Emulation Overview
  - 3D Graphic Display
  - Configurator Editor
  - Database Viewer
  - Payload Metric

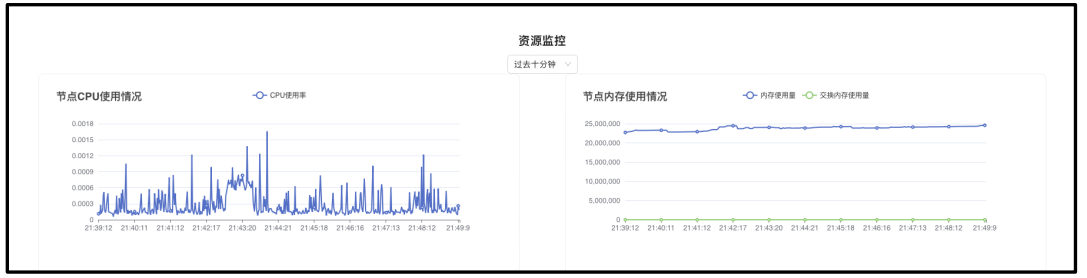
A unified control console for the multi-machine virtual environment.

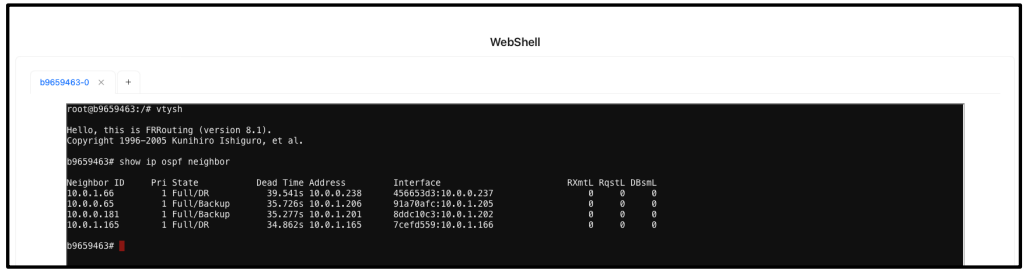


3D Graphic Display
Double Click entities can enter the detailed Page
(Will be introduced in next page)

Appendix

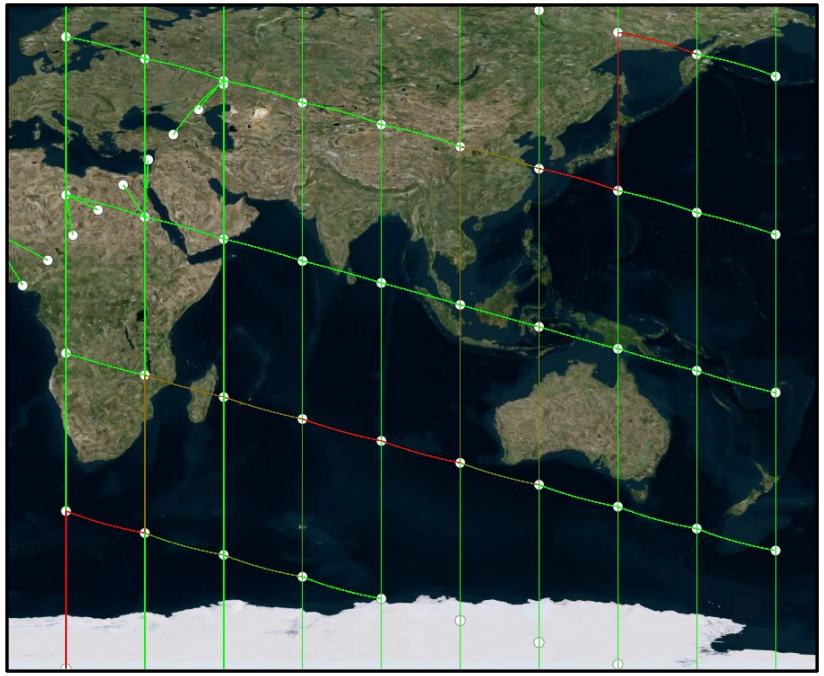
- **Node Detailed Page**
  - Node Configuration & Status
  - Connected Link and Neighbor Node
  - Web Shell Console
  - CPU & Mem Usage
- **Link Detail Page**
  - Endpoint Addresses
  - Throughput
  - Packet Capture Information



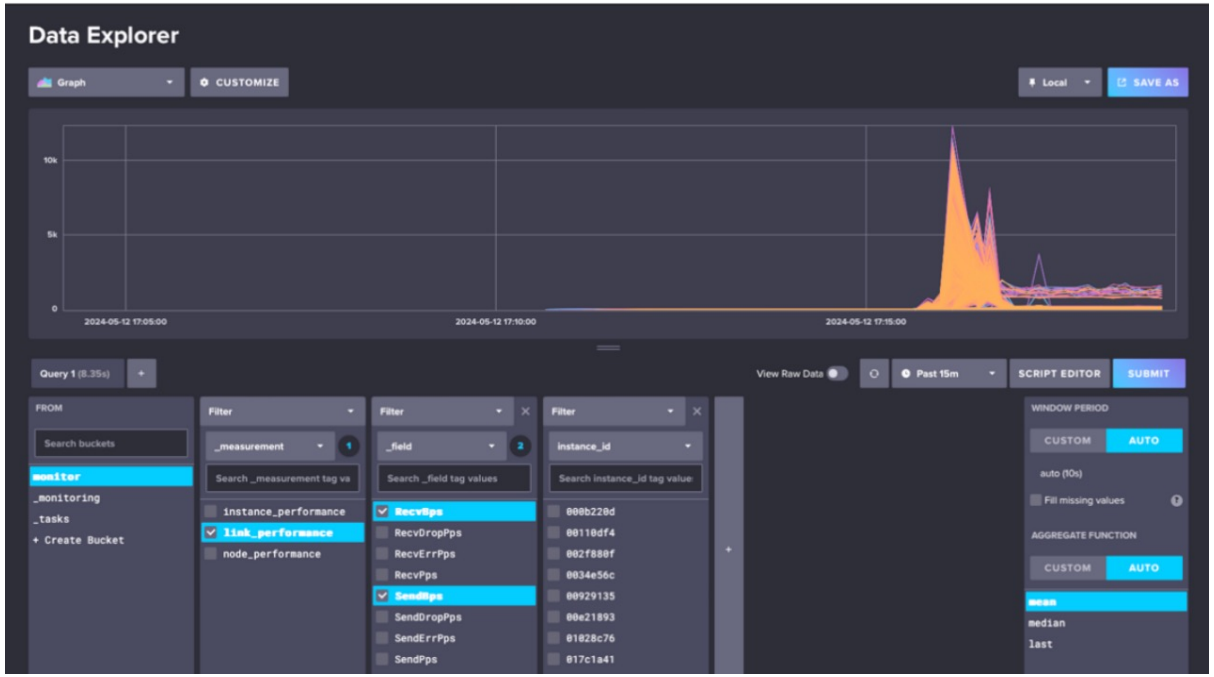


Appendix

- **Overview Payload Monitor**
  - Visual overall payload statistics.
  - More convenient to check the emulation status.



Throughput overview of links



Payload metric data static by InfluxDB

Thank You !

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Q&A

Background

The satellite Internet industry is developing rapidly, various technologies in the LEO satellite network have been published

Existing testbed cannot support the evaluation and verification tasks.

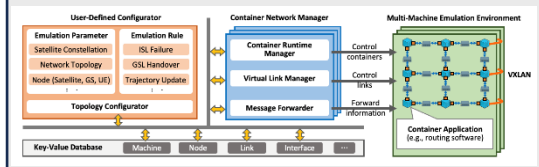
Simulator/Emulator		Fine Granularity	Routing	Efficiency	Open-source?
Discrete-event Simulator	STK	Orbit	/	/	✅
	StarPerf [1]	Flow-level	Route calculation	✅	✅
	OMNET-based [2]	Packet-level	Routing protocol	❌	❌
	NS3-based [3]			❌	❌
Virtual-network Emulator	LeoEM [4]	Full-stack Realism	Route calculation	✅	✅
	StarryNet [5]		Routing software	❌	Partially
	Our Work			✅	✅

So we present OpenSN to address such issues.

Framework

OpenSN Framework

- User-defined Configurator
- Key-Value Database
- Container Network Manager
- Multi-machine environment

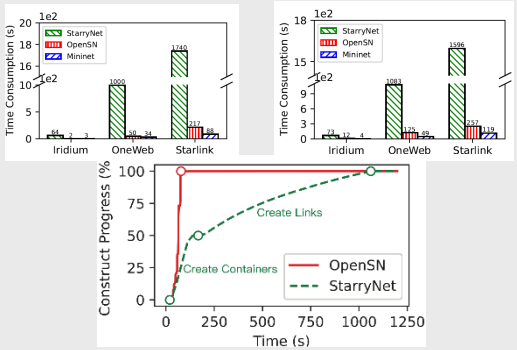


Advantages

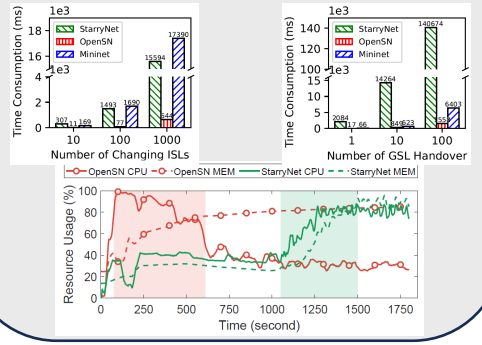
- Efficient Emulation
- System Scalability
- Function Extensibility

Performance Evaluation

Faster Network Construction and Deconstruction

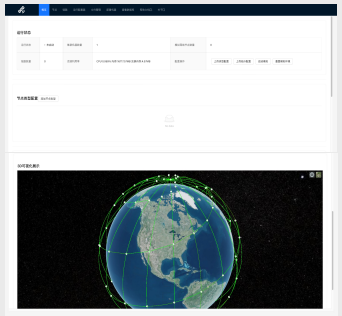


Faster Network operation and lower stable resource consumptions



Usage

OpenSN Web Console



Detailed Pages

Payload Overview