LEOTP: An Information-centric Transport Layer Protocol for LEO Satellite Networks

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Overview

LEO satellite networks is fast emerging. Unfortunately they bring challenges to end-to-end transmission control

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Segmented transmission control can solve these problems, but existing methods do not work

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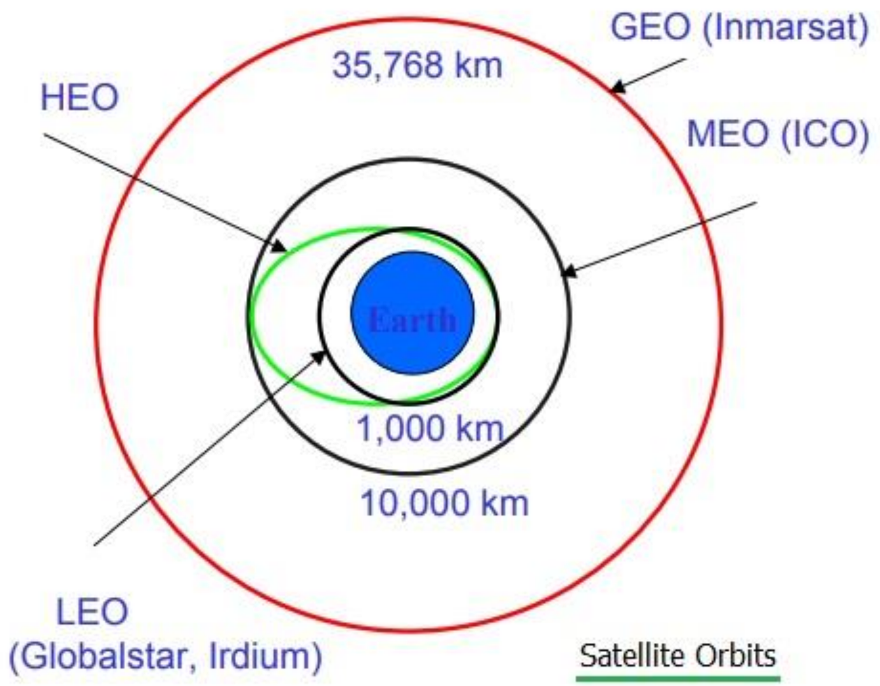
Our idea: borrow the idea of Information-Centric Networking (ICN)

Background

Benefits of LEO satellite networks

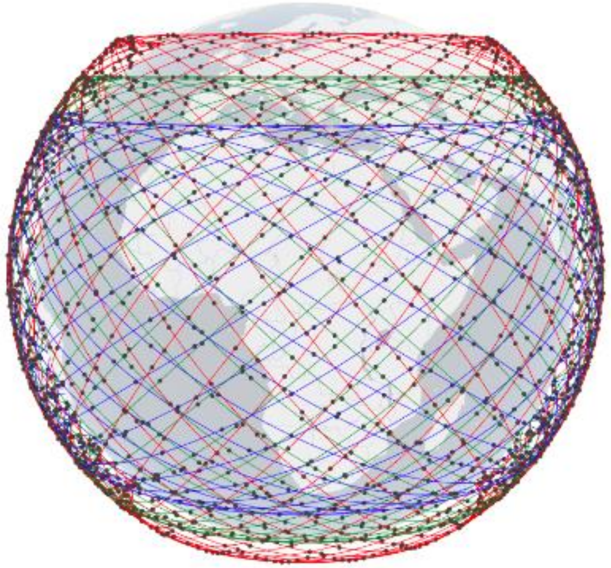
- High speed
- Low latency
- Wide coverage



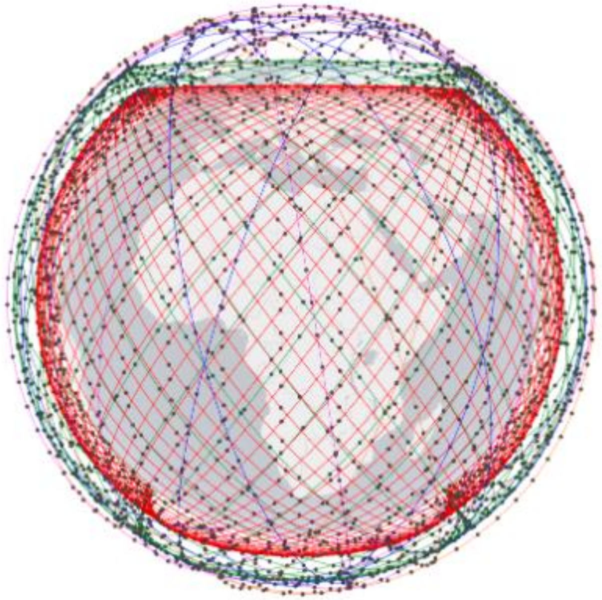
Background

LEO satellite networks are fast emerging

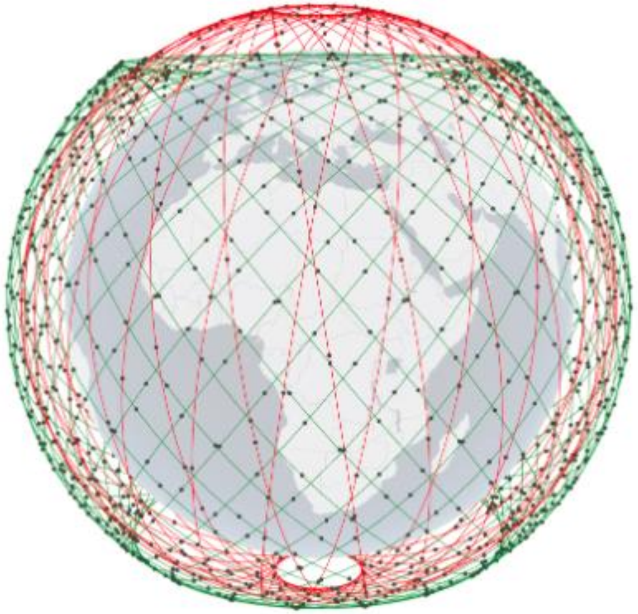
amazon | project kuiper



STARLINK



Telesat



[1] https://leosatsim.github.io/

Background

Challenges for transport layer in LEO satellite networks

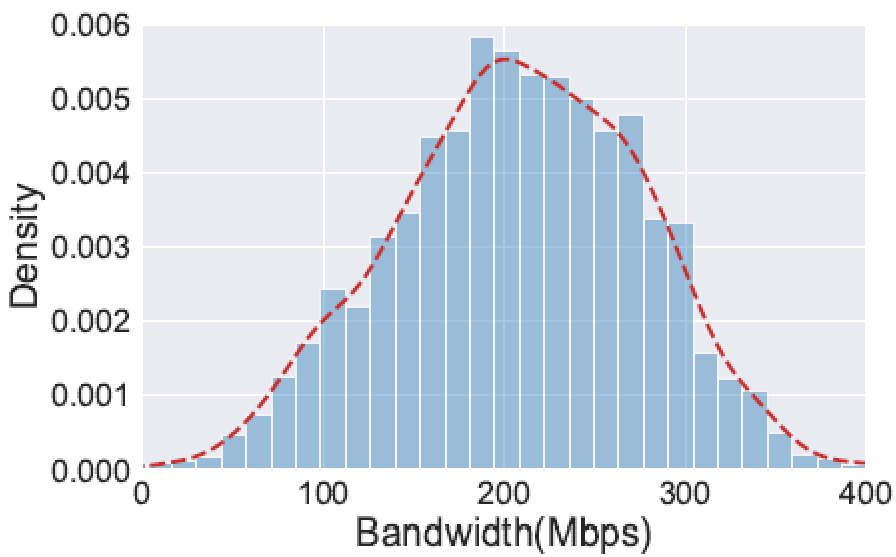
- **High packet loss:** *1.56% for downloads and 1.96% for uploads[2]*
  - Degrade throughput of loss-based congestion control
  - High tail delay due to retransmission

- **High queuing delay:** *95^{th} RTT is 175ms when propagation delay is only 20ms[2]*
  - Hard to support latency-sensitive services

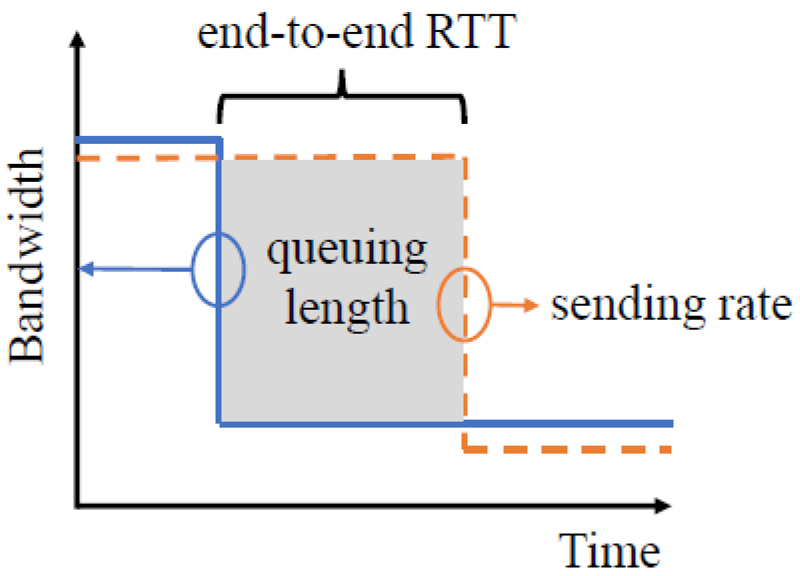
[1] Francois Michel, Martino Trevisan, Danilo Giordano, and Olivier Bonaventure. A first look at starlink performance. In Proceedings of the 22nd ACM Internet Measurement Conference, IMC ’22, page 130–136, New York, NY, USA, 2022. Association for Computing Machinery.

Background

Bandwidth variation with delayed feedback causes high queuing delay



(a) Bandwidth distribution in Starlink

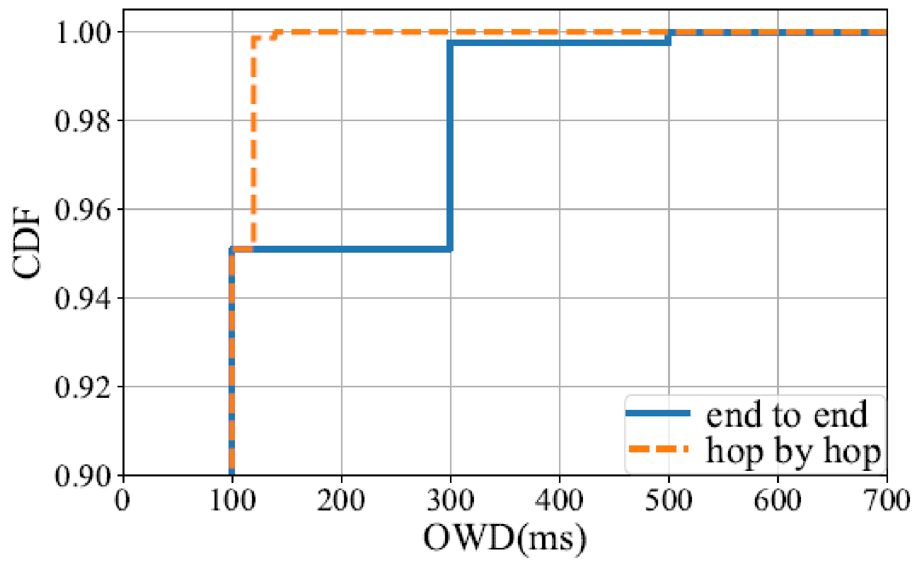


(b) Queuing due to bandwidth variations

Motivation

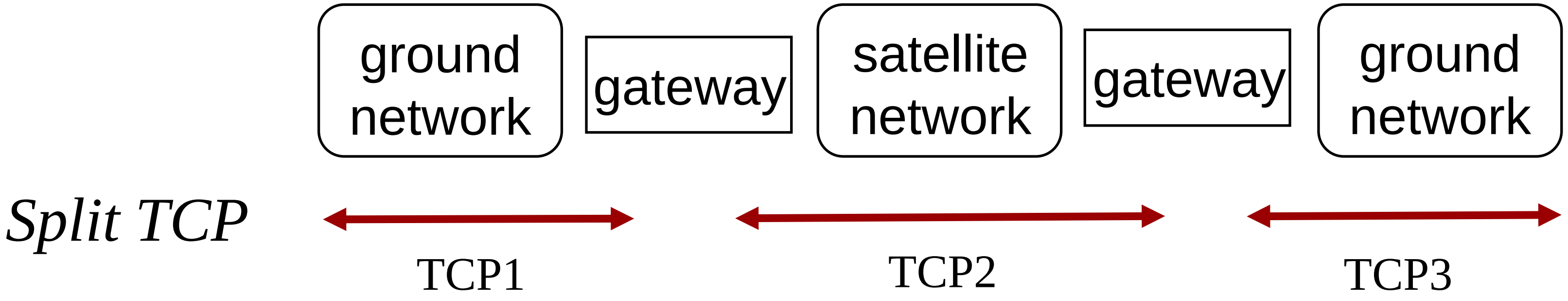
Potential improvement of segmented transport control

- In-network retransmission: lower cost for retransmission
- Hop-by-hop congestion control: faster reaction to bandwidth variation



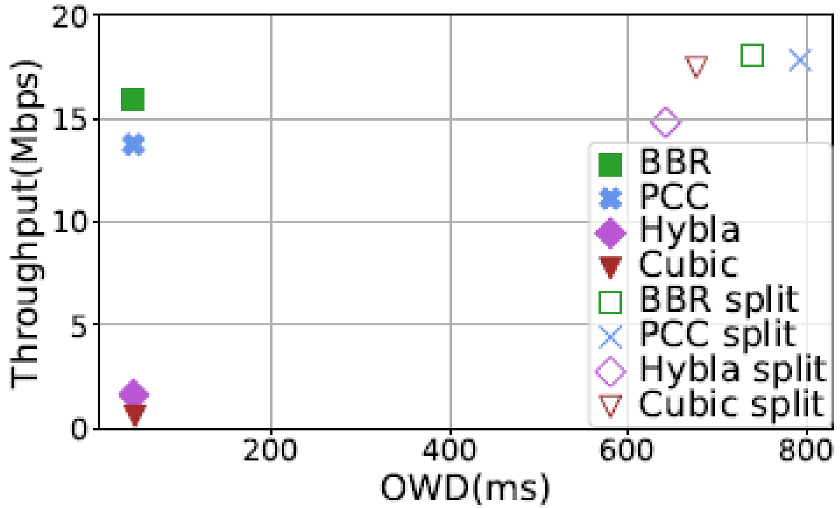
Motivation

Split TCP: a well-known solution



However, it does not work for LEO

- It can not keep connection in dynamic topology
- It can not guarantee end-to-end reliability
- Packet backlog at intermediate nodes

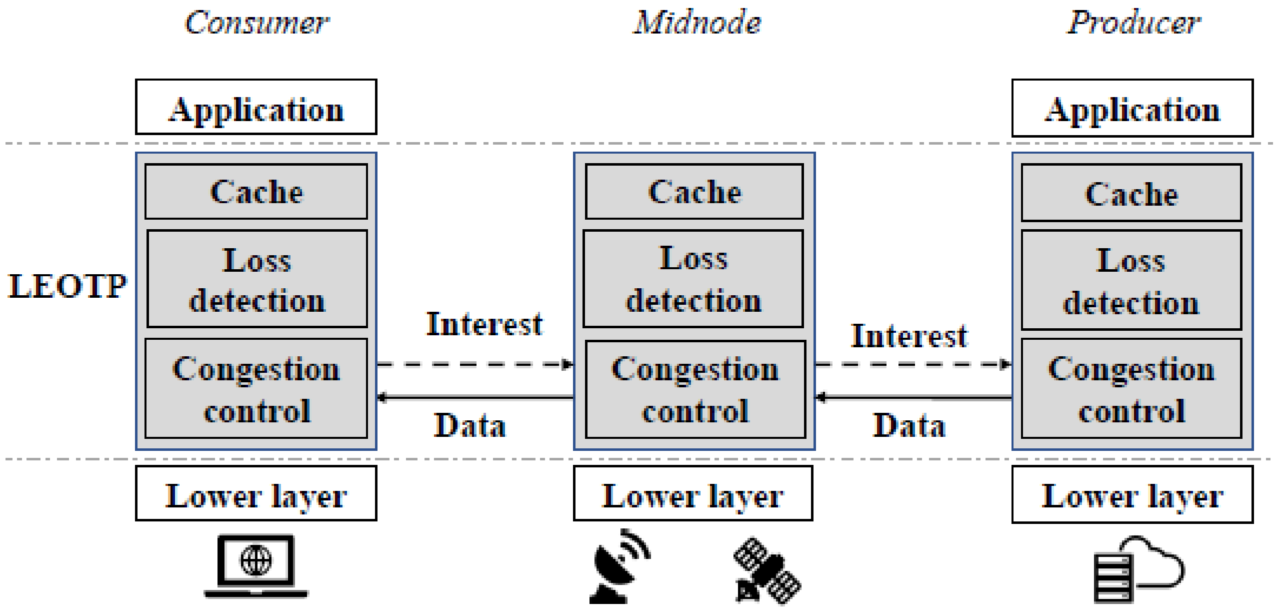


Design

System overview

- ➢ Request-response model
  - Location-independent naming
  - In-network caching
- ➢ Segmented transport control
  - Local loss detection
  - Congestion control

Data transmission is connectionless , thus support the mobility of intermediate nodes



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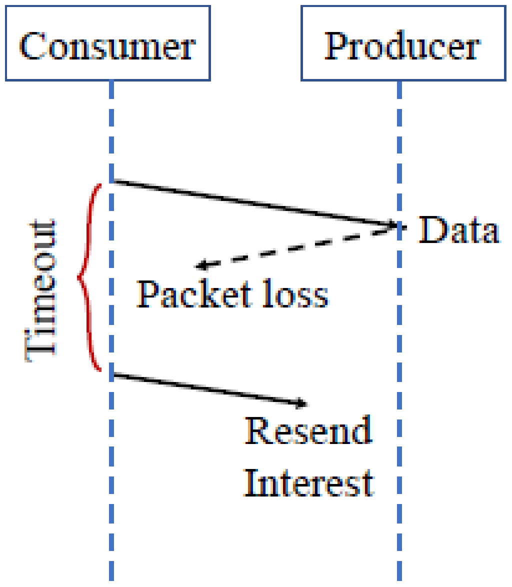
Hybrid transmission mechanism

- **Consumer-driven retransmission**
  - Based on timeout mechanism



(a) TR mechanism

guarantee end-to-end reliability

Design

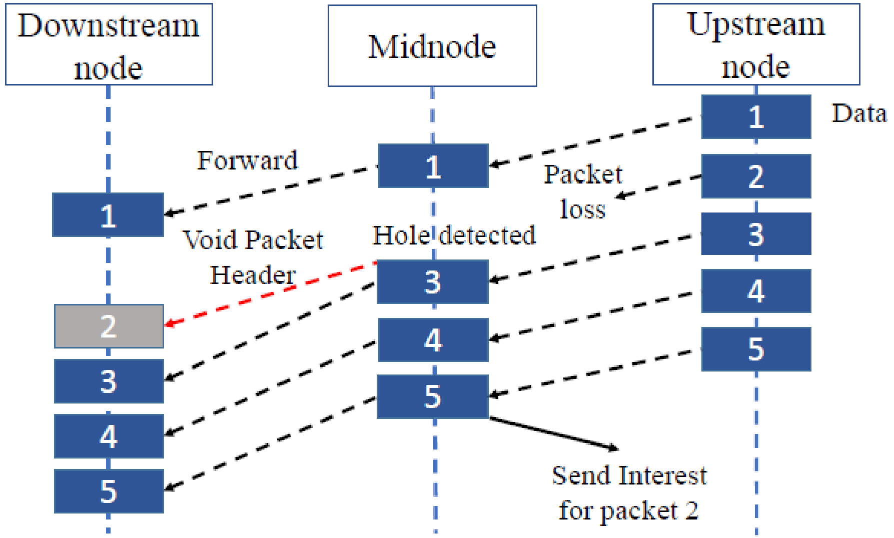
Hybrid transmission mechanism

- **In-network retransmission**

  recover most of the lost packets at a low cost of latency and bandwidth consumption

  - Based on sequence number holes
  - **Void Packet Header (VPH) mechanism**: VPH are sent downstream as notification when detecting packet loss

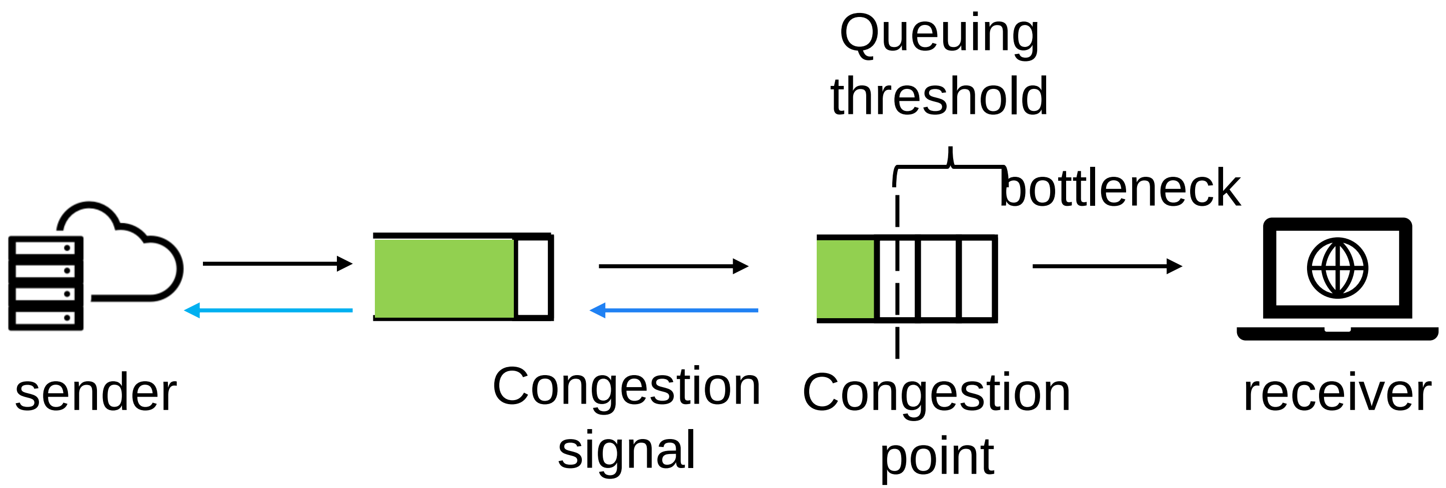
  avoid duplicated retransmission



(b) SHR mechanism

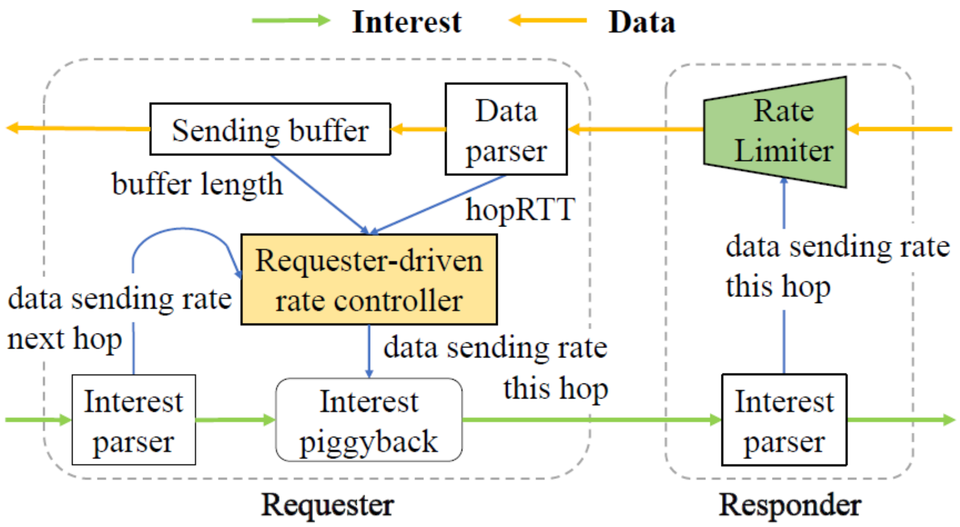
Design

Backpressure in hop-by-hop congestion control



Design

- Requester-driven



- RTT-based at individual hop

$$BDP = throughput * hopRTT_{min} \quad (6)$$

$$QueueLen = throughput * (hopRTT - hopRTT_{min}) \quad (7)$$

$$cwnd = \begin{cases} 2 * cwnd, & \text{if } state == SlowStart \\ cwnd + 1, & \text{else if } QueueLen \leq M \\ k * BDP, & \text{otherwise} \end{cases} \quad (8)$$

- Backpressure between hops

$$Rate_{bp} = Rate_{nextHop} + \frac{BL - BL_{tar}}{hopRTT} \quad (9)$$

$$Rate = min(\frac{cwnd}{hopRTT}, Rate_{bp}) \quad (10)$$

Evaluation

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- Experiment setup
  - Emulation platform Mininet
  - Dynamic route is provided by Hypatia[3]
  - Simulate bandwidth variation
- Baseline methods
  - Cubic
  - Hybla
  - BBR & PCC

[3] Simon Kassing, Debopam Bhattacherjee, Andre´ Baptista A´ guas, Jens Eirik Saethre, and Ankit Singla. Exploring the ”internet from space” with hypatia. In Proceedings of the ACM Internet Measurement Conference, IMC ’20, page 214–229, New York, NY, USA, 2020. Association for Computing Machinery.

Controlled experiments

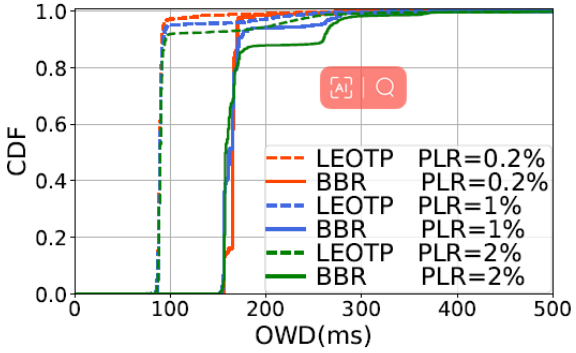


Fig. 10: The distribution of the retransmitted packets' OWD in lossy link.

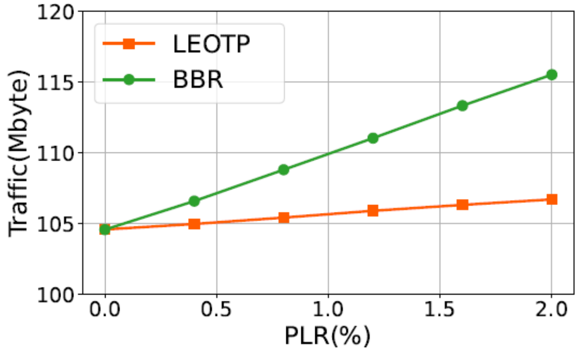


Fig. 11: The relation of loss rate and the traffic sent by sender for an 100MB file.

Low cost for retransmission

Results

Controlled experiments

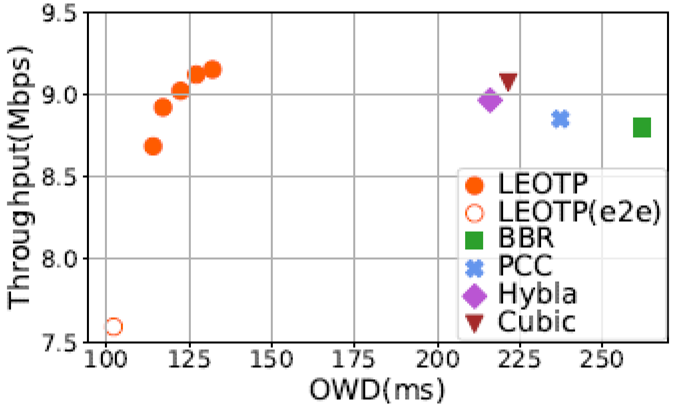


Fig. 14: Throughput-OWD trade-off under bandwidth fluctuations.

Low latency under bandwidth variations

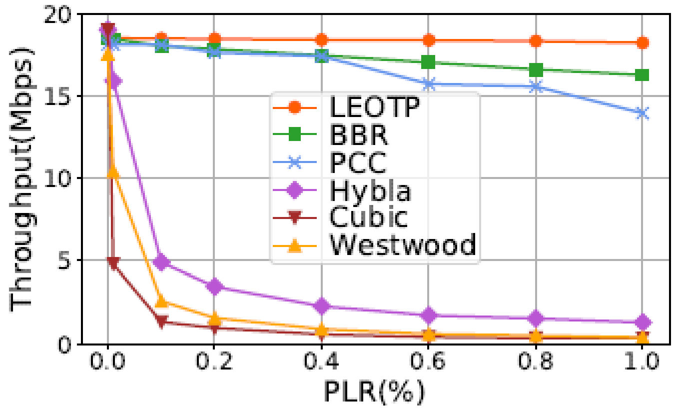
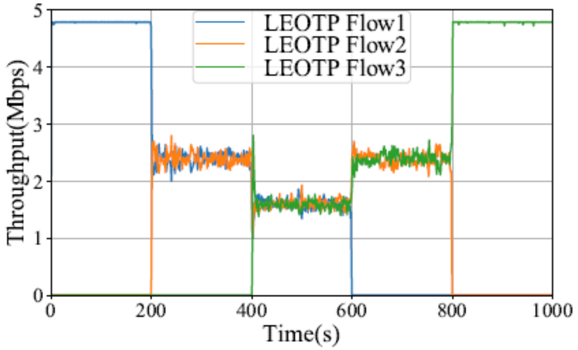


Fig. 12: The relation of loss rate and throughput.

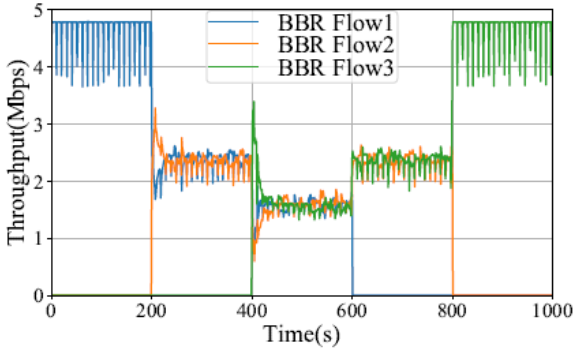
High throughput against high PLR

Results

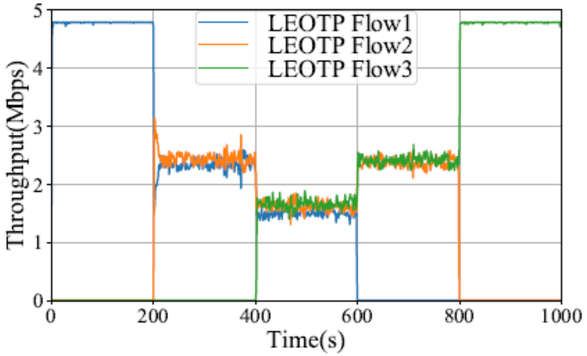
Controlled experiments



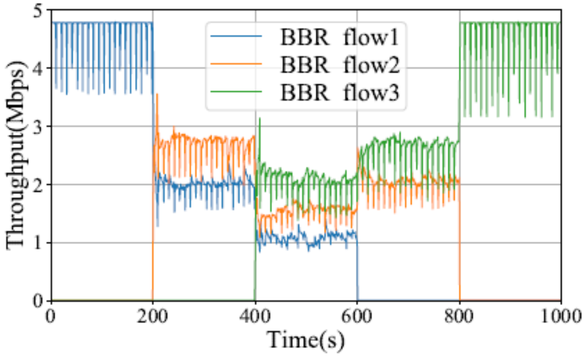
(a) LEOTP flows under same RTT



(b) BBR flows under same RTT



(c) LEOTP flows under different RTT

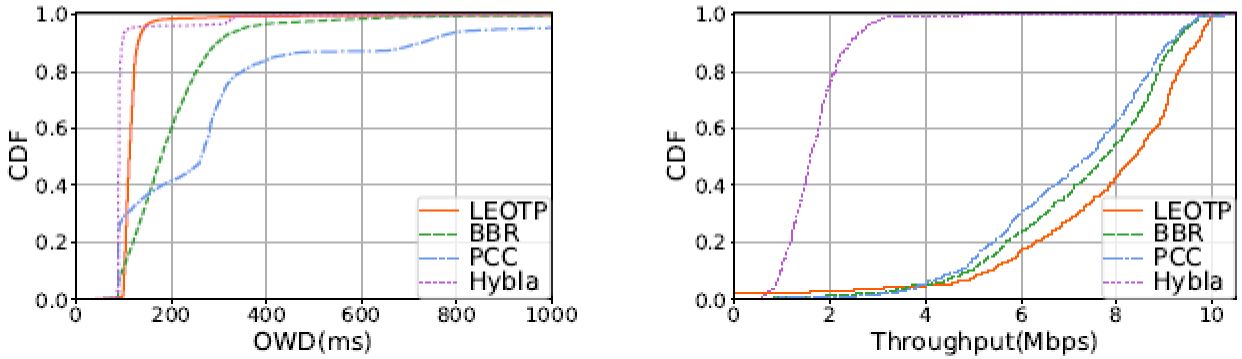


(d) BBR flows under different RTT

Optimized intra-protocol fairness

Results

Emulation experiments



(a) OWD

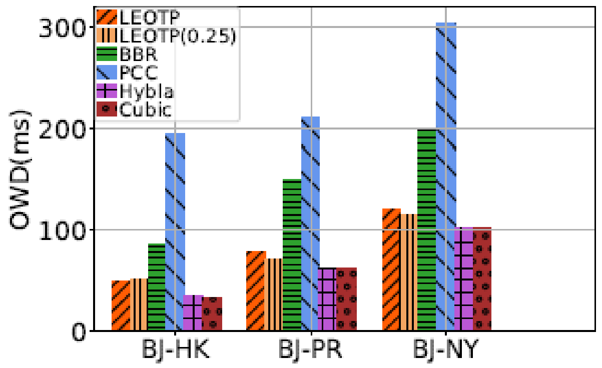
(b) throughput

Fig. 17: Cumulative distribution graph of OWD and throughput in Beijing-New York link with ISLs.

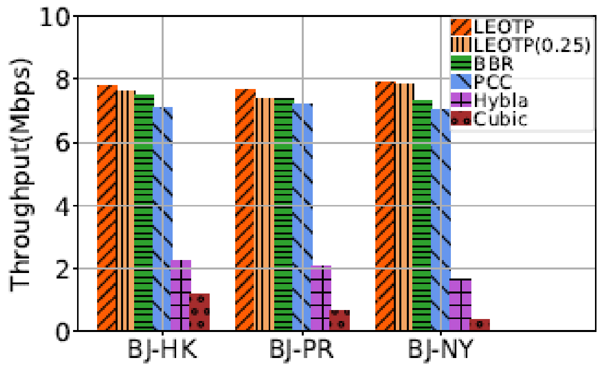
8%-12% higher throughput with 40%-60% delay reduction in transcontinental data transmission

Results

Emulation experiments



(a) OWD



(b) throughput

Fig. 18: Average OWD and throughput in different city pair links with ISLs.

- More significant improvement in long-distance communications
- Good performance with a small amount of LEO satellites

Results

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Emulation experiments

TABLE II: The result of the ablation experiment

	BJ-HK		BJ-PR		BJ-NY	
	Throughput (Mbps)	OWD (ms)	Throughput (Mbps)	OWD (ms)	Throughput (Mbps)	OWD (ms)
A	7.82	49.17	7.70	76.57	7.91	118.64
B	7.78	51.39	7.67	80.74	7.73	126.10
C	7.38	40.15	7.23	66.40	6.80	103.63
D	7.24	42.05	7.03	70.38	6.52	112.20

	In-network retransmission	Hop-by-hop congestion control
A	√	√
B	×	√
C	√	×
D	×	×

Both retransmission module and congestion control module contribute to the better performance of LEOTP

Conclusion

- End-to-end transport protocols have limitations in LEO satellite networks
- We present LEOTP, an information-centric, cache-assisted transport protocol
- The in-network retransmission use VPH as notifications, reducing redundant retransmissions while providing fast loss recovery
- The backpressure-based congestion control provides quick reactions in long-distance networks
- Results: reliability, high throughput, and low latency
- More resources: https://jl99888.github.io/LEOTP

Thanks

Netvideo Group https://www.icst.pku.edu.cn/NetVideo/

Email: jl99888@pku.edu.cn