Mind the Misleading Effects of LEO Mobility on End-to-End Congestion Control

Zeqi Lai, Zonglun Li, Qian Wu, Hewu Li, Qi Zhang

Presenter: Zeqi Lai

Tsinghua University

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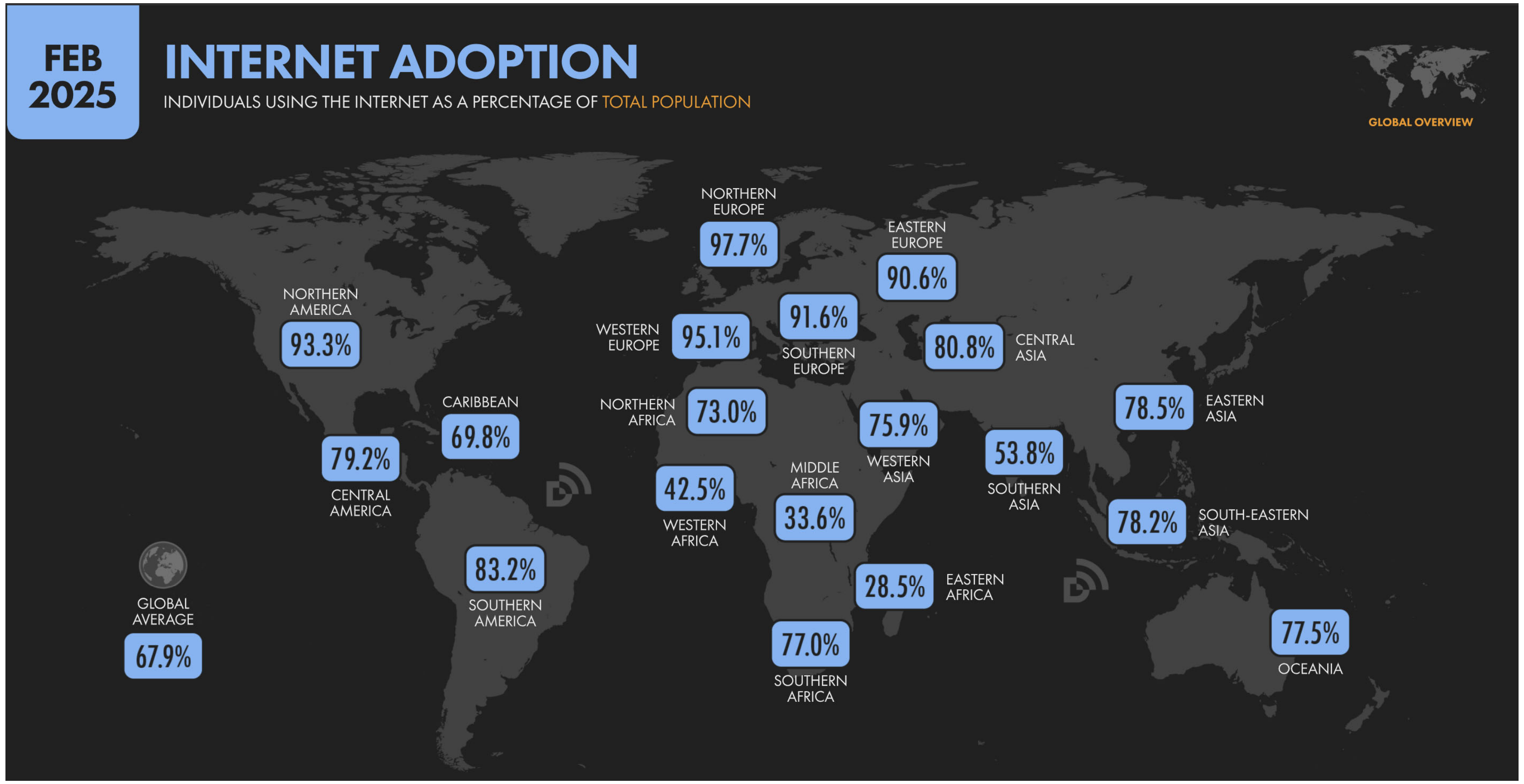
Outline

- **Background of Emerging LEO Satellite Networks**
- **Impacts of LEO Mobility on Internet Congestion Control**
- **Potential Mitigations**
- **Conclusion and Future Work**

Rapid Evolution of the Internet

Over the past decades, the Internet has undergone profound and transformative changes. However … …



Global Internet penetration: **67.9%**

Remote Area

Rural Education

Airplane

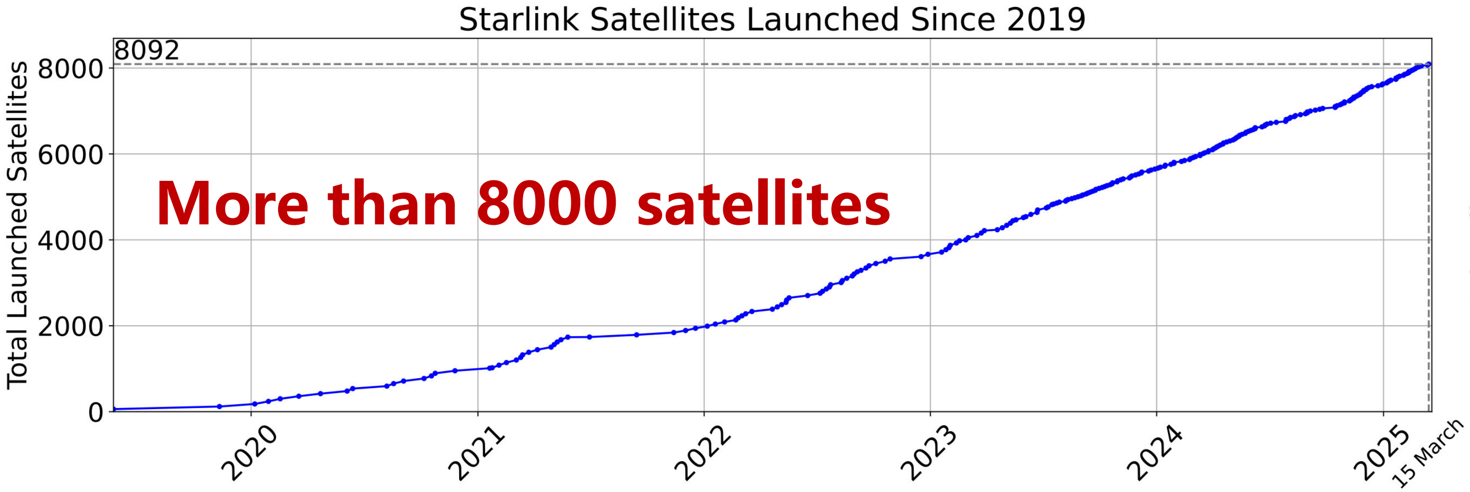
Maritime

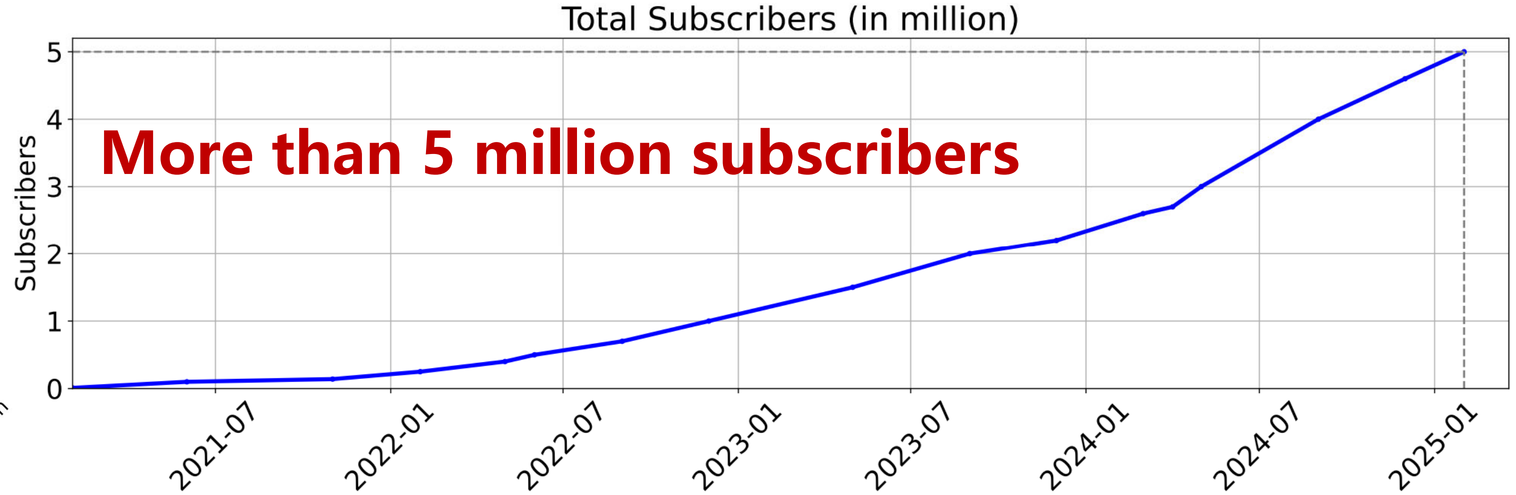
Without stable Internet services …

Source: https://datareportal.com/reports/digital-2025-global-overview-report

The Future of Internet Lies Up in the Sky

Connecting the Unconnected: broadband satellite constellations are extending the boundaries of Internet

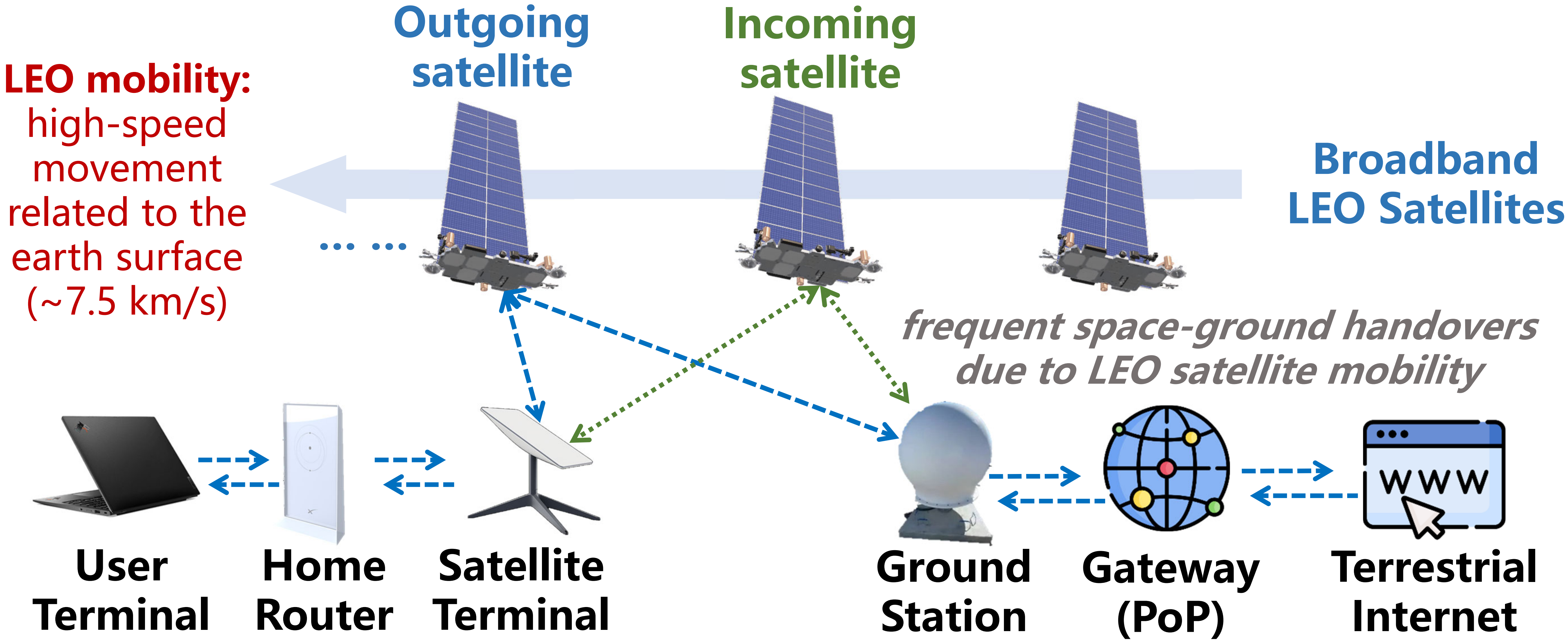




https://en.wikipedia.org/wiki/Starlink#Subscribers
https://en.wikipedia.org/wiki/List_of_Starlink_and_Starshield_launches#Totals

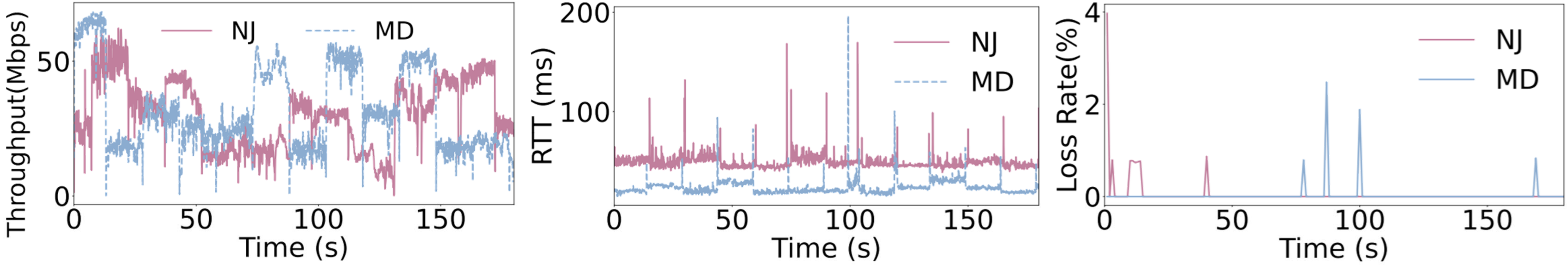
New Characteristics of LEO Networks

LEO Satellite Network (LSN): A global network with LEO satellites and distributed ground stations/terminals



New Challenges Involved by LEO Mobility

LEO mobility can cause **network instabilities** such as:
path changes, radio rescheduling, capacity fluctuations



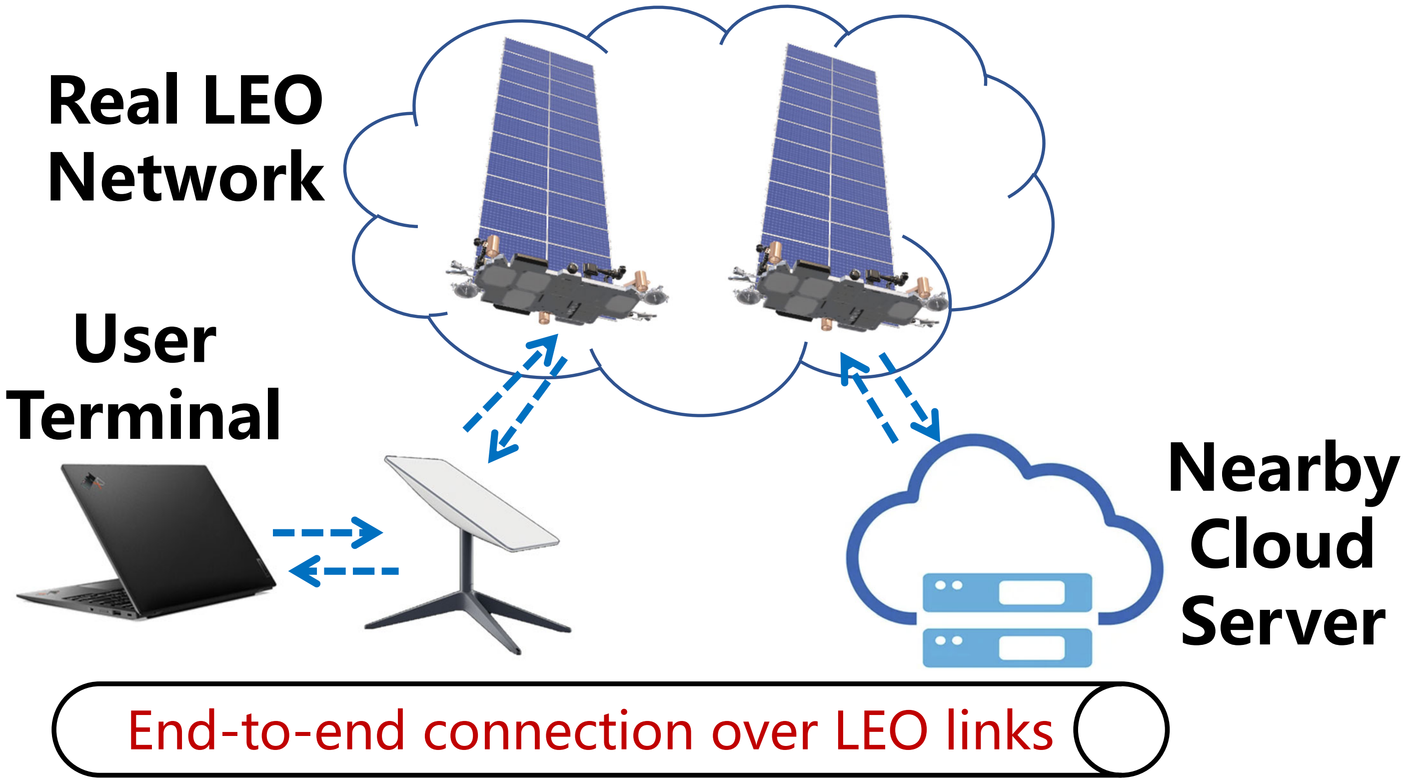
(a) Link capacity variation. (b) RTT variation. (c) Packet loss rate variation.

- Link capacity drastically fluctuates between 10Mbps and 65Mbps
- RTT drastically changes (20-200ms for MD)
- Flows experience unpredictable bursts of packet loss at low data rate

Results are measured from two terminals located in New Jersey (NJ) and Madrid (MD).

A Measurement Study in A Real LSN

Inspect the performance of existing **congestion control algorithms (CCAs)** based on a real LEO network



①Real-world measurement
(uncontrolled, unreproducible)

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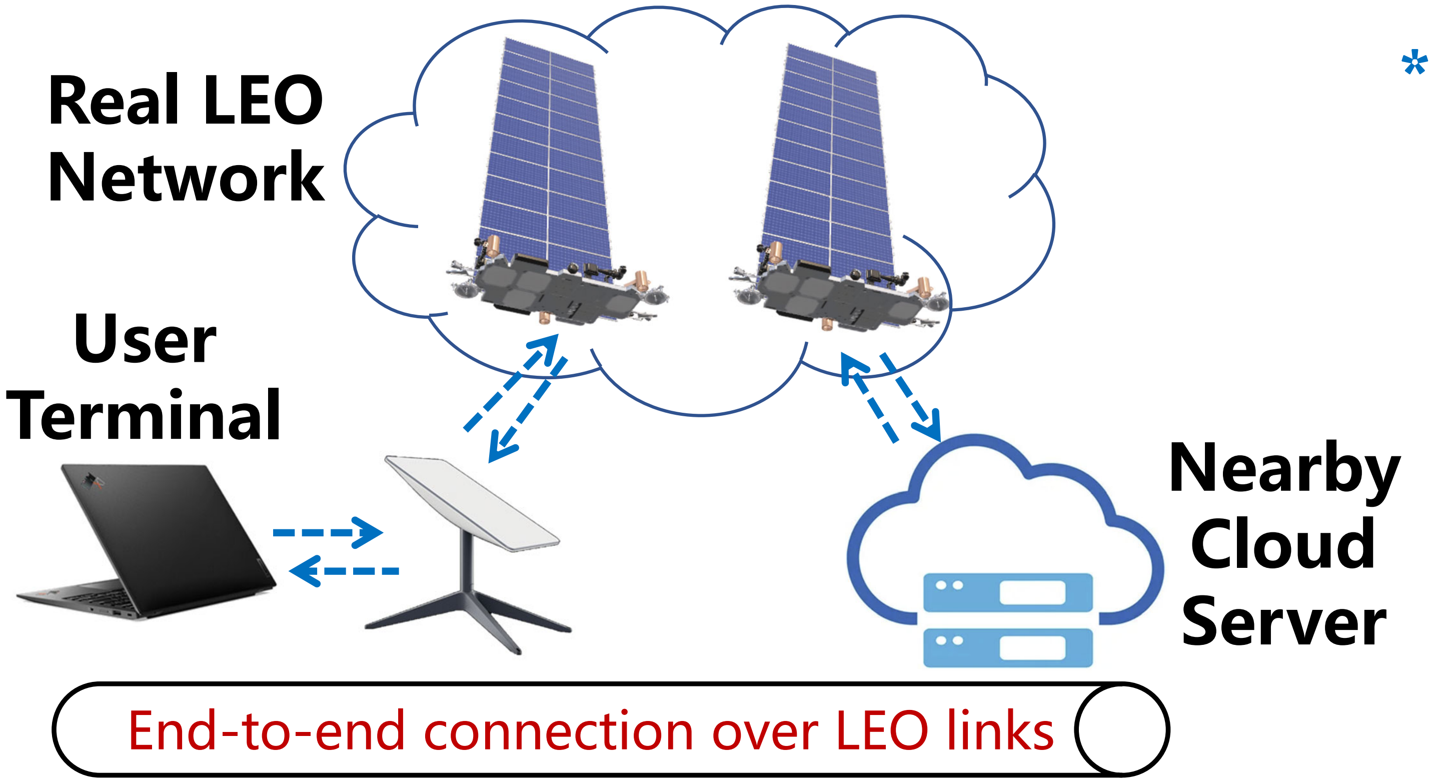

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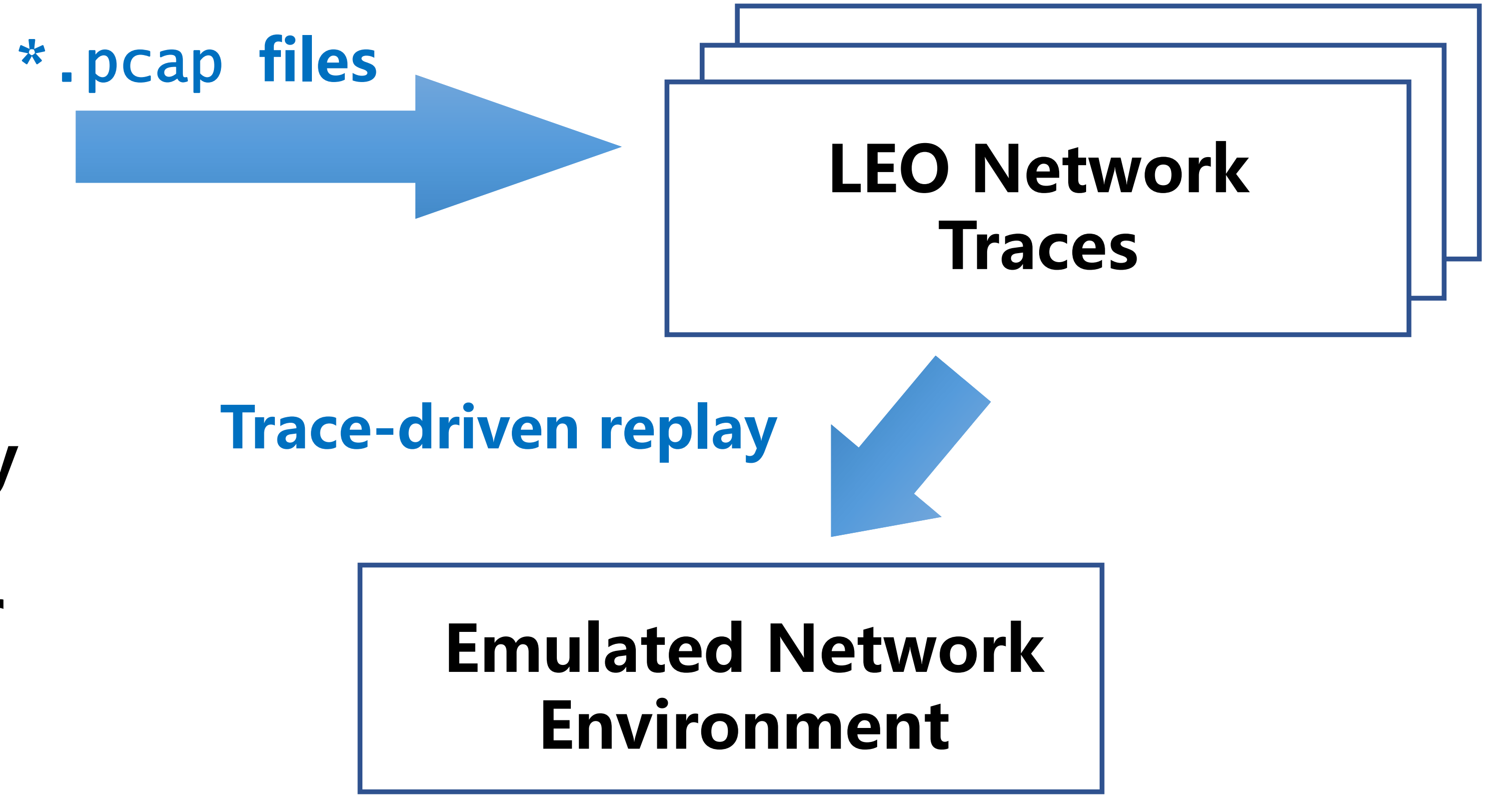
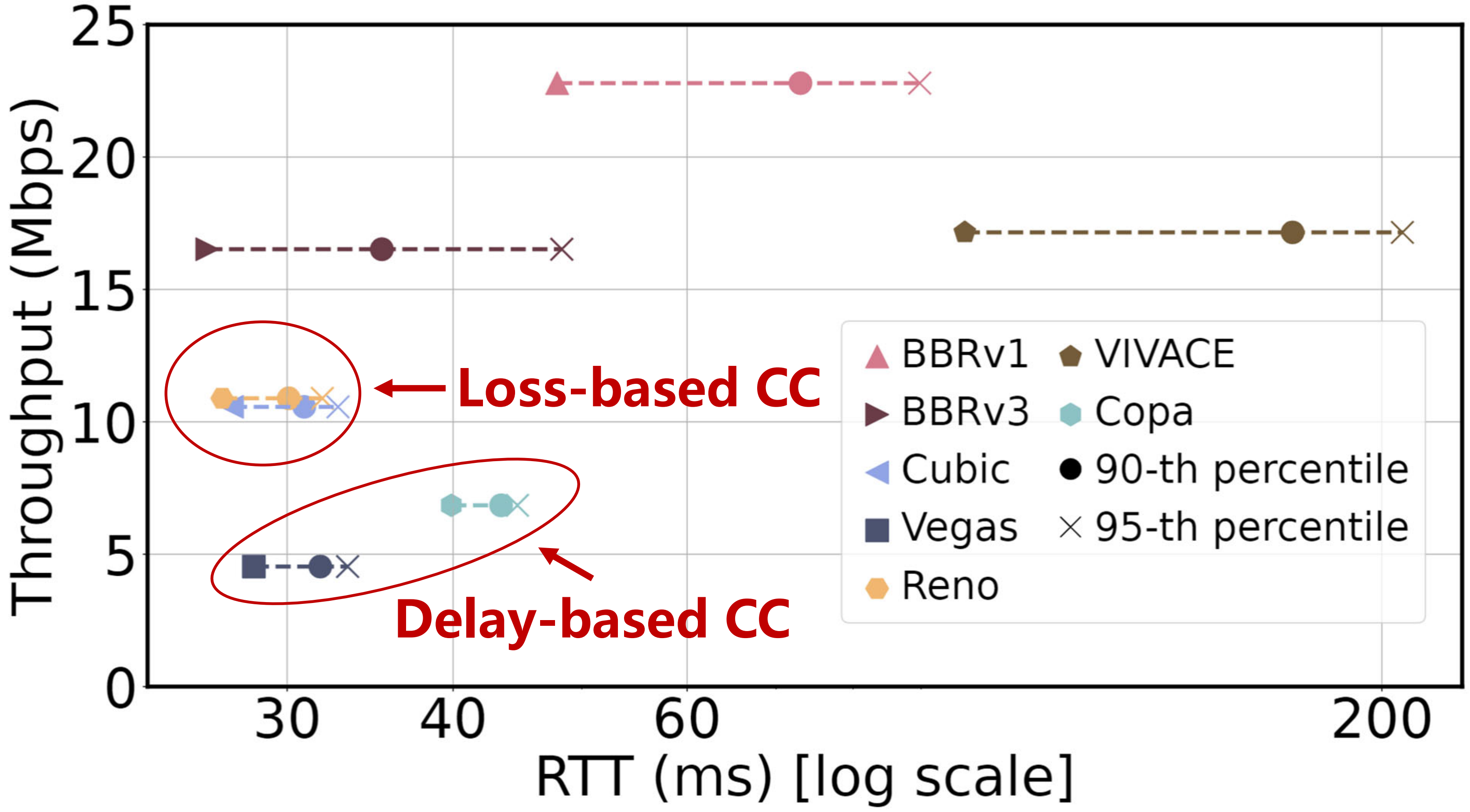


②Lab environment
(fully controlled, reproducible)

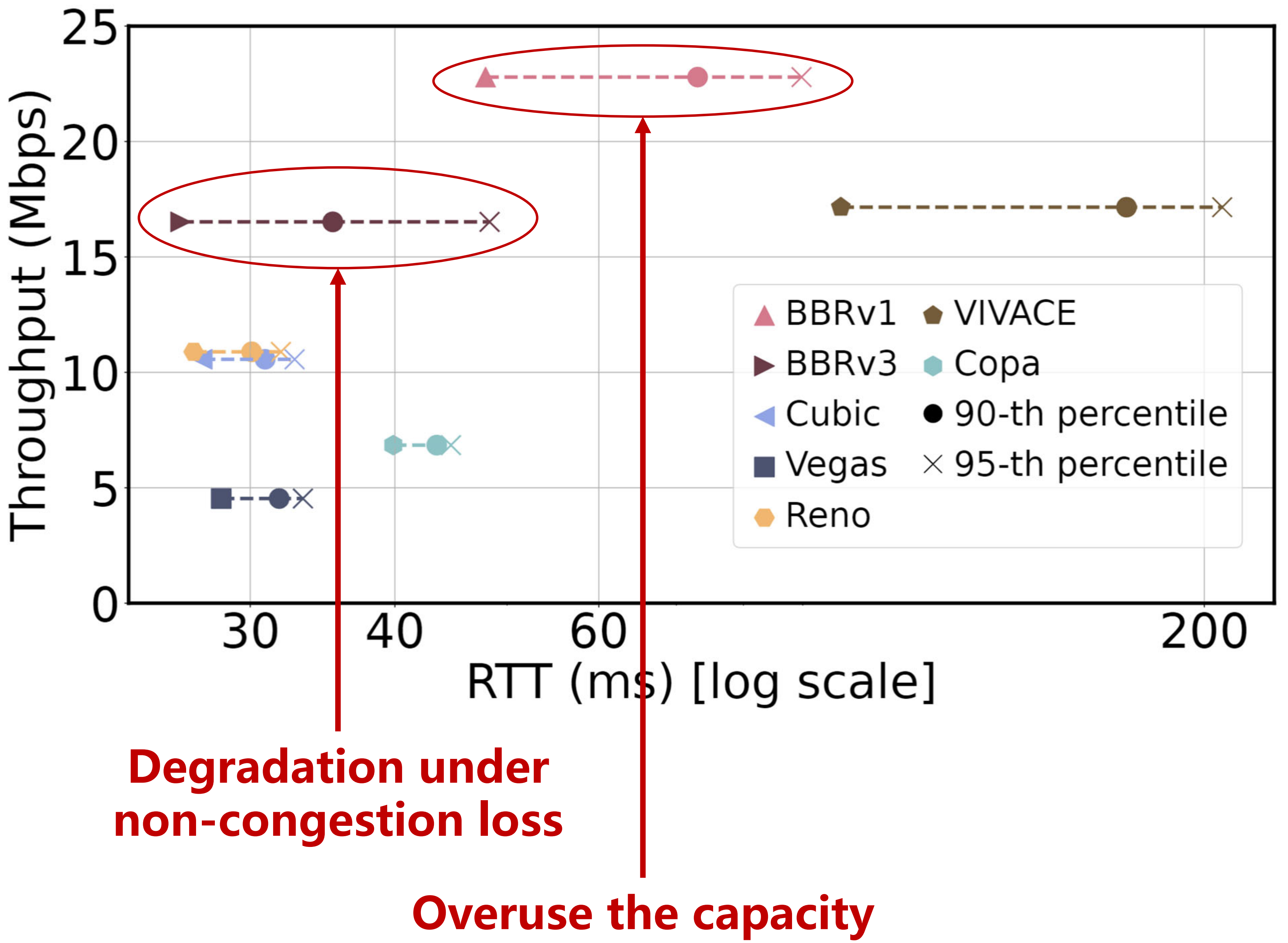
Performance Results: Real-World Statistics



- **Loss-based CC(Reno, Cubic)**
  - **Low throughput**
- **Delay-based CC(Vegas, Copa)**
  - **Low throughput**

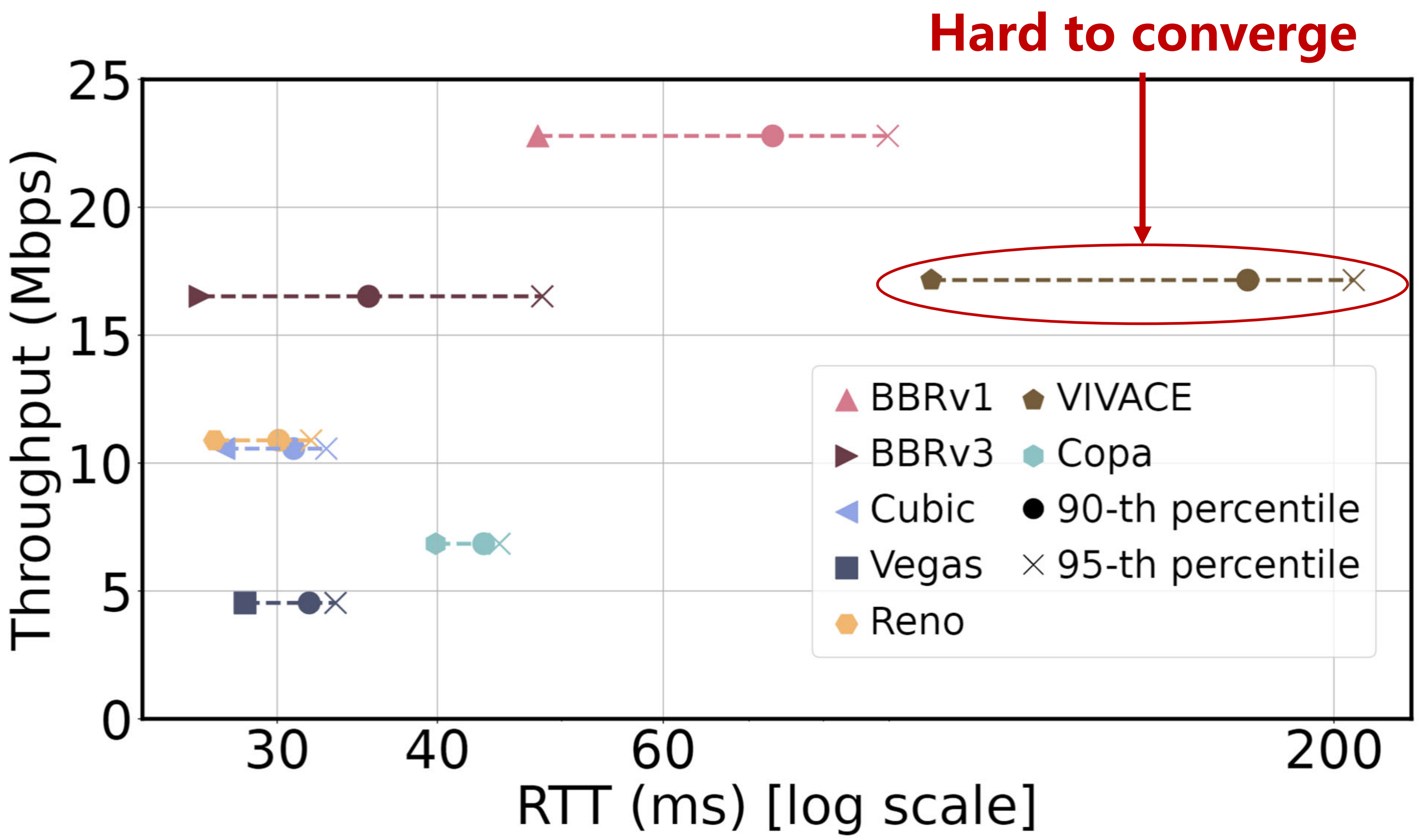
Because the real LEO conditions drastically change, we run each CCA for more than 30 tests, and each test lasts for more than 2 minutes to obtain the statistic results

Performance Results: Real-World Statistics



- Loss-based CC(Reno, Cubic)
  - Low throughput
- Delay-based CC(Vegas, Copa)
  - Low throughput
- **Model-based CC(BBR)**
  - **High delay and delay tail**
  - **or**
  - **Performance degradation**

Performance Results: Real-World Statistics



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  - Low throughput
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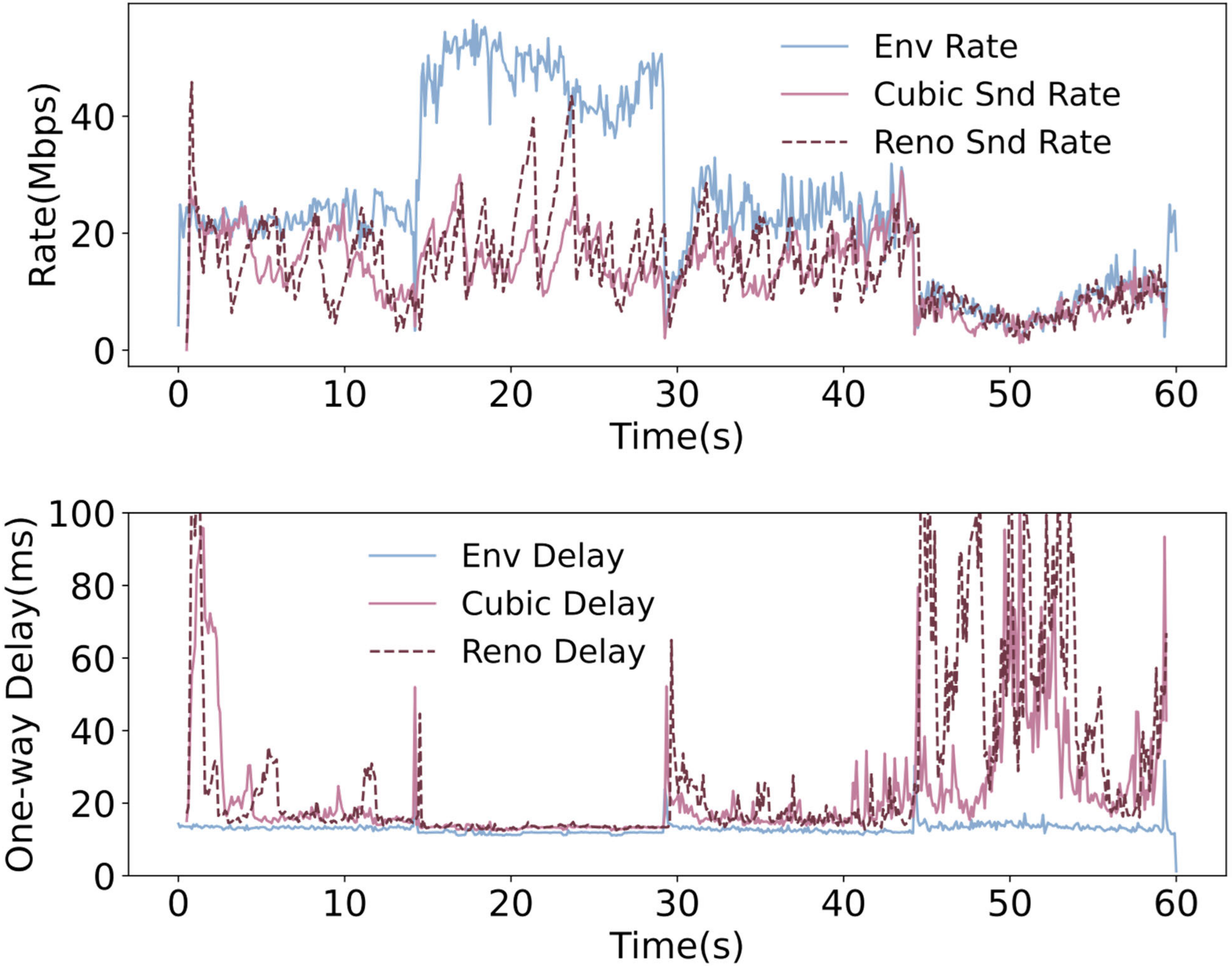
  - Low throughput
- Model-based CC(BBR)
  - High delay and delay tail
  - or
  - Performance degradation
- **Learning-based CC(VIVACE)**
  - **High RTT**

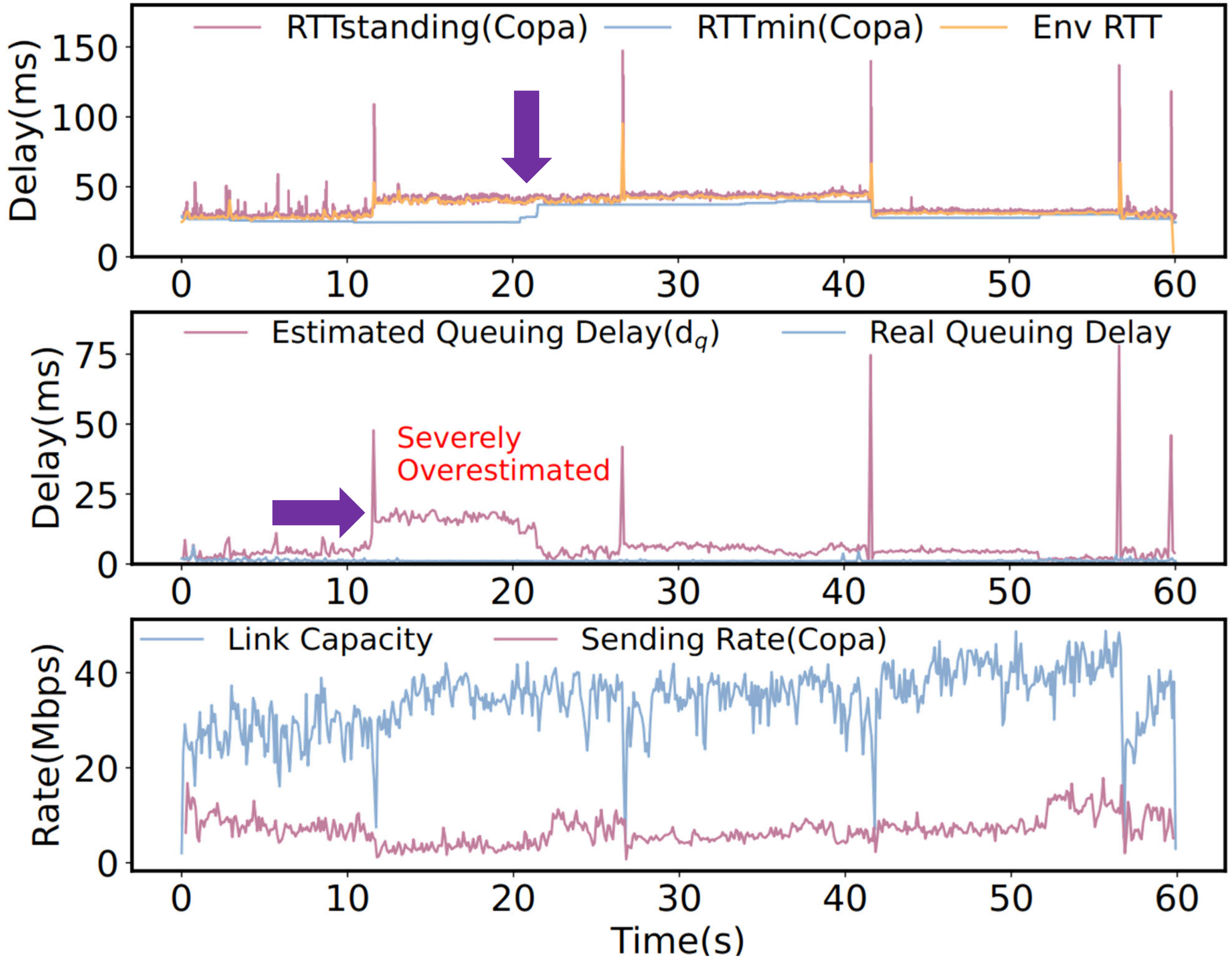
Reproducible Analysis: Loss-based CCAs



- Replay **LEO network traces** and conduct reproducible experiments in our lab environment

- **Cubic, Reno**
    - Overreacting to non-congestion packet loss

Reproducible Analysis: Delay-based CCAs

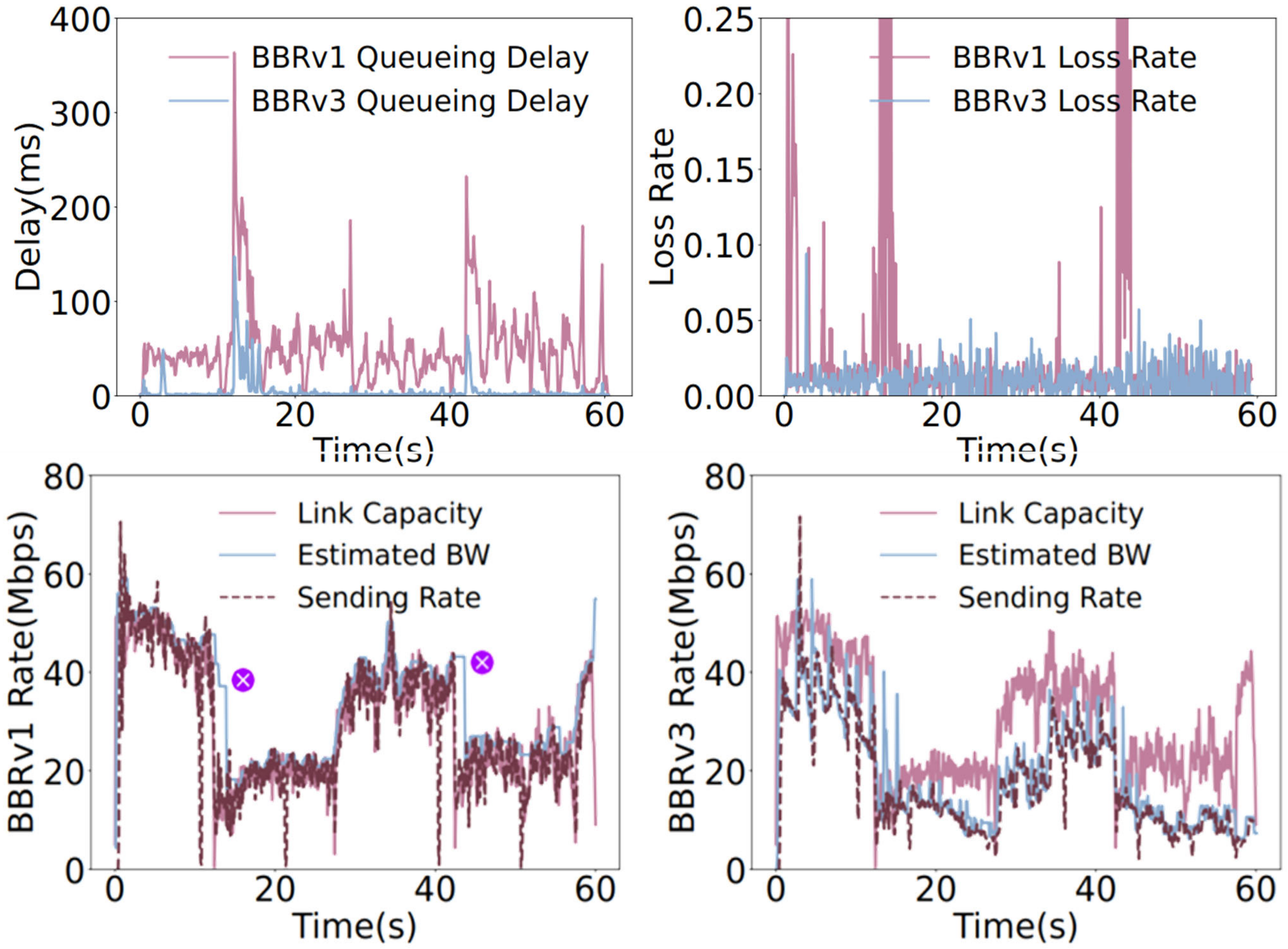


Core Idea: $$\lambda = \frac{1}{\delta \cdot d_q}$$

$$d_q = \text{RTTstanding} - \text{RTTmin}$$

- Drastic network variations may lead to the increase of inherent minimum RTT of the link
- **Long-maintained RTT_{min} fails to capture the increased minimum RTT**, overestimating the queueing delay

Reproducible Analysis: Model-based CCAs



Drastic network variations may lead to decrease in link capacity or increase in minimum RTT

BBRv1: Long-maintained BW_{max} and RTT_{min} still hold historical data from the previous link, leading to BW_{max} overestimation or RTT_{min} underestimation

BBRv3: Frequently suppress transmission rate due to loss

The Fundamental Changes and Mitigations

Massive non-congestion network variations break the fundamental models/assumptions of existing CCAs

↓

To mitigate this issue, one potential way is to **identify and filter out LEO-induced non-congestion variations**

↓

Is there an **effective indicator** to help endpoints distinguish non-congestion-related performance changes?

LEO Reconfiguration in LSNs

Constellations need to frequently reconfig its connections

Global Reconfiguration (12s/27s/42s/57s*)

PETITION OF STARLINK SERVICES, LLC FOR DESIGNATION AS AN ELIGIBLE TELECOMMUNICATIONS CARRIER

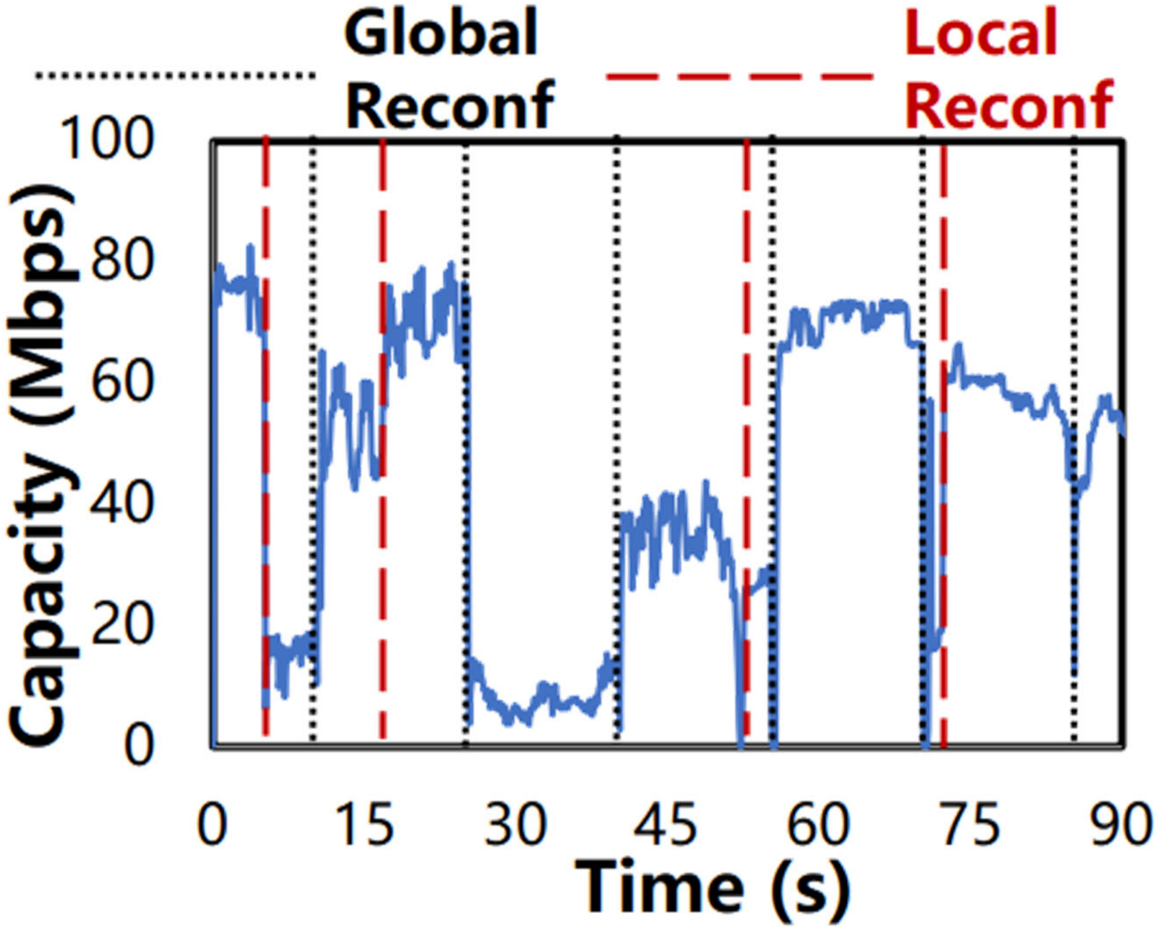
assigned to the user's service area. Because the Starlink satellites are constantly moving, the network plans these connections on 15 second intervals, continuously re-generating and publishing a schedule of connections to the satellite fleet and handing off connections between satellites.

Local Reconfiguration

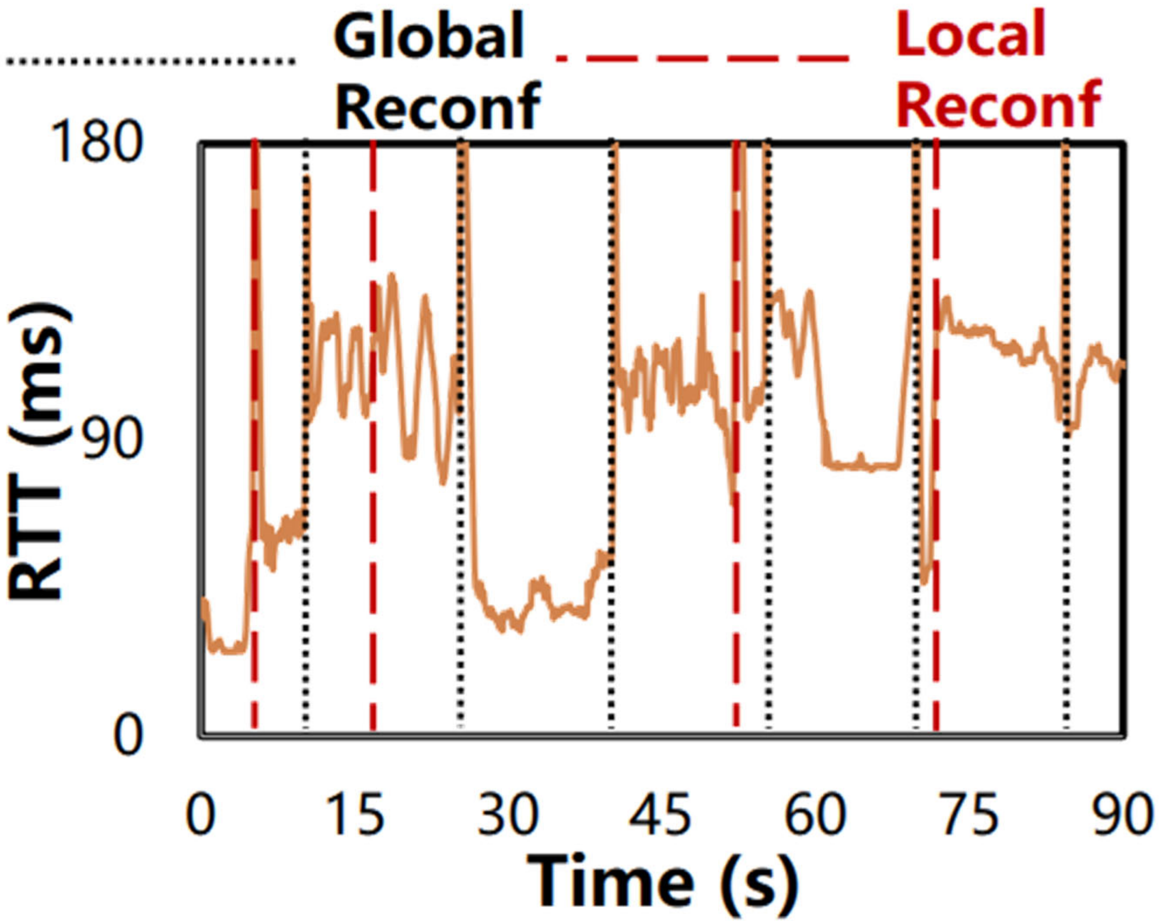
- Starlink terminal provides internal gRPC service
- extract obstruction maps from the dish
- compare the trajectory of connected satellite in two sequential obstruction maps

*source:https://www.telepolis.pl/images/2021/02/Starlink-Services-LLC-Application-for-ETC-Designation.pdf

Reconfiguration-Variation Relationship



(a) Link capacity.



(b) RTT.

Capacity/RTT can be fitted as a step function divided by a sequence of reconfigurations

Inside a step, Capacity/RTT changes are relatively mild and smooth

Reconfiguration-Variation Relationship

Use reconfiguration to optimize network estimation in LSN

- Existing CCAs leverage **time-window-based estimators** to probe network conditions
- maxBW / minRTT in BBR
- Queueing delay estimation in Copa

- **Key insight**
  - When a reconfiguration occurs, clear the historical data which is independent within the current reconfiguration interval

- **Modifications on Copa (Copa-m)**
  - Only use RTT samples after a recent reconfiguration for RTTmin and RTTstanding estimation

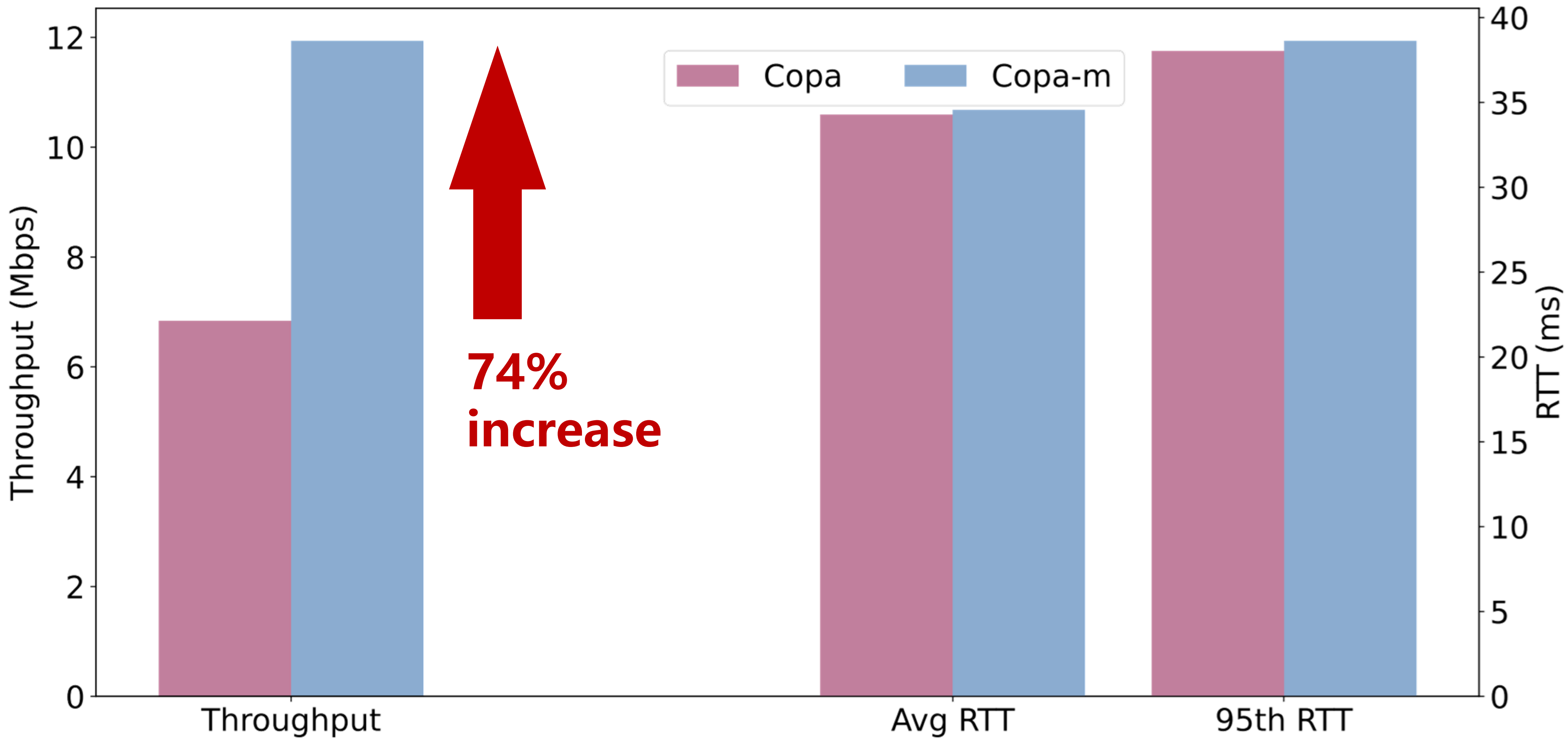
- **Modifications on BBR (BBR-m)**
  - Only use RTT samples after a recent reconfiguration for minRTT and maxBW estimation

Preliminary Results: Copa

$$d_q(T) = RTT_{standing}(T) - RTT_{min}(T)$$

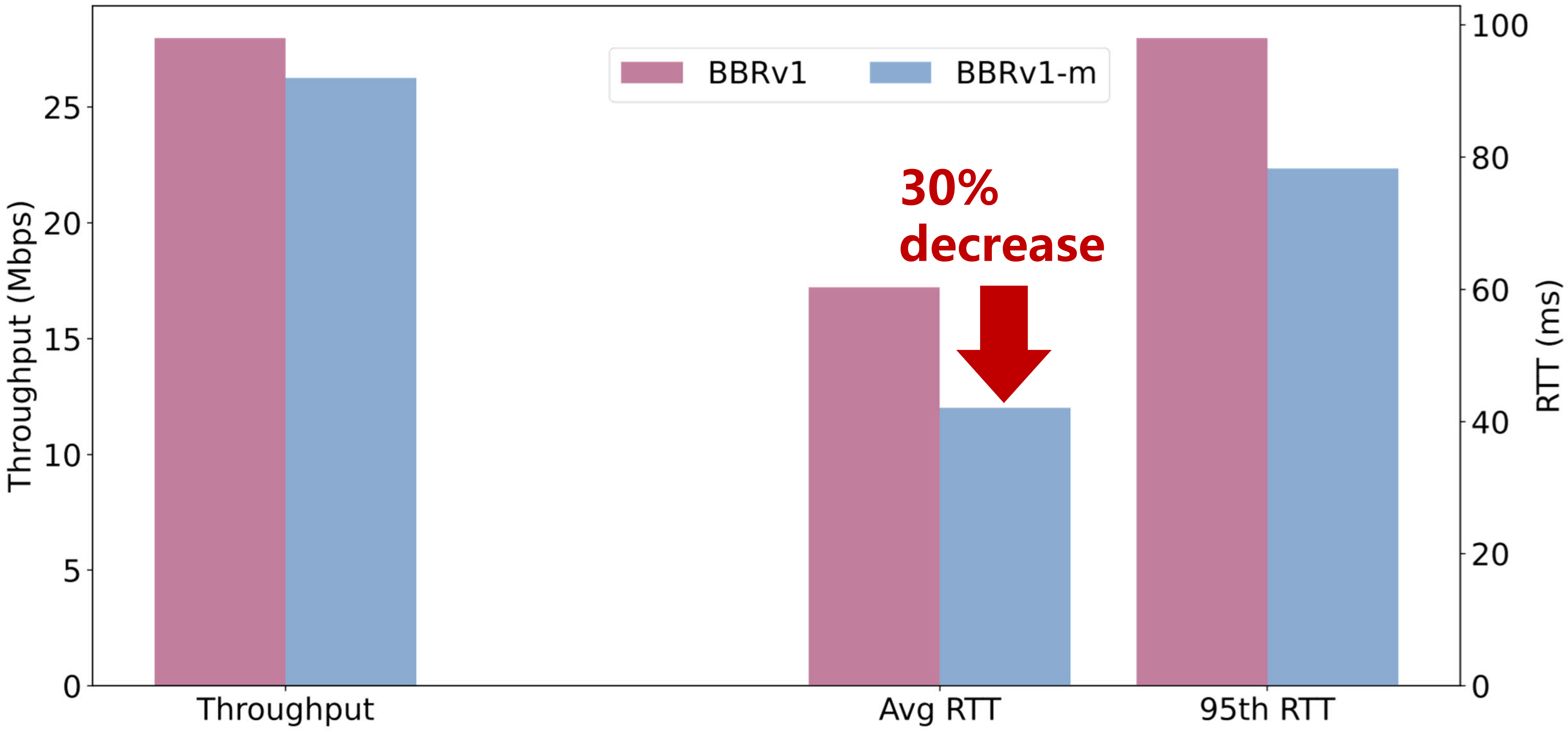
$$RTT_{standing} = min(RTT_t) \quad \forall t \in (max(t_{Rcf}^{last}, T - W_{short}), T)$$

$$RTT_{min} = min(RTT_t) \quad \forall t \in (max(t_{Rcf}^{last}, T - W_{long}), T)$$



Preliminary Results: BBR

$$bBW(T) = f(dRate_t) \quad \forall t \in (max(t_{Rcf}^{last}, T - W_{BW}), T)$$
$$pRTT(T) = min(RTT_t) \quad \forall t \in (max(t_{Rcf}^{last}, T - W_{RTT}), T)$$



Conclusion and Future Work

- **LEO satellite networks (LSNs)** are carrying an increasing amount of network traffic
- The unique **LEO mobility** causes **drastic end-to-end variations**, involving new challenges on Internet congestion control
- We performed a **performance study** on various CCAs in a real LSN, and we hope it provides insights for future CCA standards
- As our future work, we will explore improvements for CCAs in LSNs

Reference

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- [7] Measuring A Low-Earth-Orbit Satellite Network, in IEEE PIMRC 2023.

THANKS

Comments & Questions

zeqilai@tsinghua.edu.cn
lzl24@mails.tsinghua.edu.cn

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Zeqi Lai, Zonglun Li, Qian Wu, Hewu Li, Qi Zhang
Tsinghua University, China

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