

# LEO Satellite vs. Cellular Networks: Exploring the Potential for Synergistic Integration

Bin Hu<sup>†\*</sup>, Xumiao Zhang<sup>‡\*</sup>, Qixin Zhang<sup>§</sup>, Nitin Varyani<sup>§</sup>

Z. Morley Mao<sup>‡</sup>, Feng Qian<sup>†</sup>, Zhi-Li Zhang<sup>§</sup>

(\*equal contributions)

<sup>†</sup>University of Southern California

<sup>‡</sup>University of Michigan

<sup>§</sup>University of Minnesota

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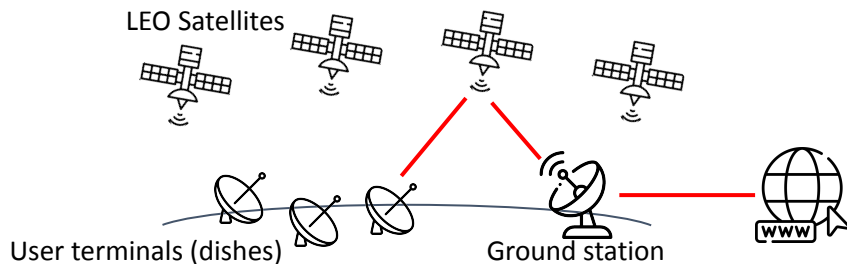


# Overview

- Background
- Methodology
- Performance
- Coverage
- Multipath

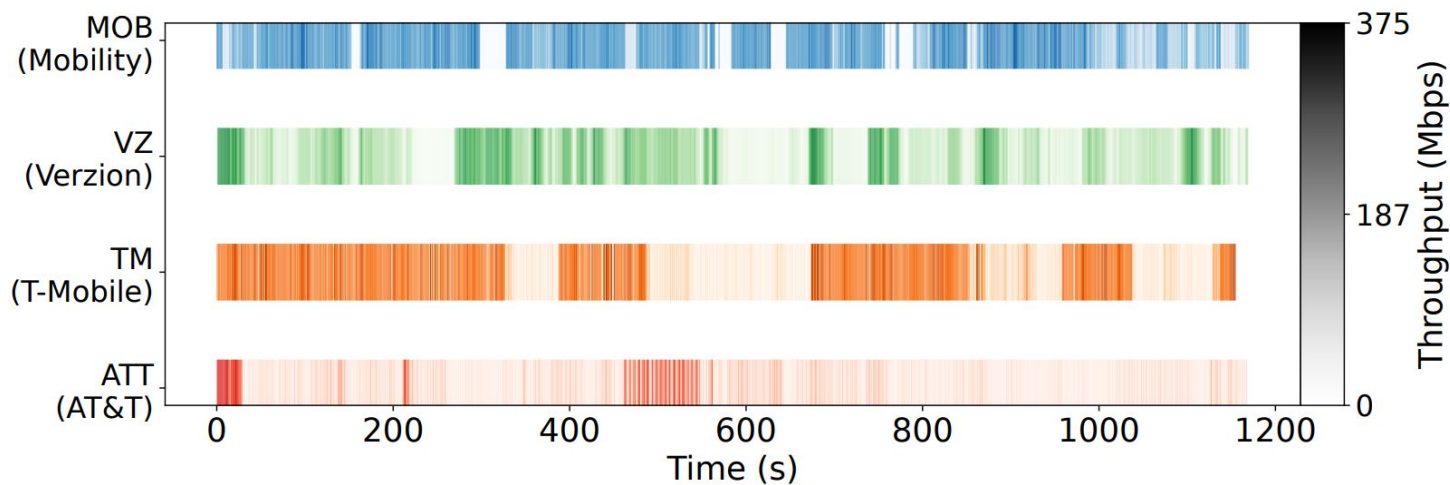
# Background

- Low Earth Orbit (LEO) satellite networks
  - e.g., Starlink, Kuiper, OneWeb, ...
- Both LEO and cellular networks face challenges
  - *Fail to consistently attain peak network performance*
- Open questions
  - *Performance of Starlink under mobility?*
  - *Starlink and cellular complement each other?*



# Background

- Satellite and cellular networks have distinct and complementary network performance distribution.
  - *(Darker colors indicate periods of higher throughput)*

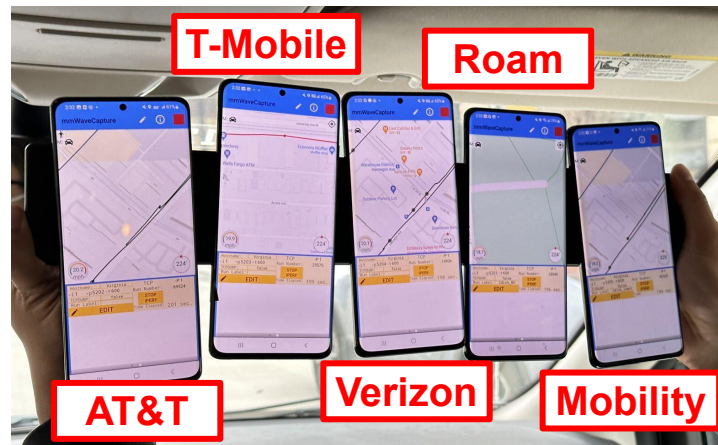


# Problems

- Understand the performance and coverage
  - *Compare Starlink and cellular networks*
- Explore the potential of enabling multipath
  - *Leverage their advantages across time and space*

# Measurement Methodology

- Hardware and services
  - *Satellite: Roam (RM), Mobility (MOB)*
  - *Cellular: AT&T (ATT), T-Mobile (TM), Verizon (VZ)*
  - *Smartphones: Samsung Galaxy S21 × 5*



# Measurement Methodology

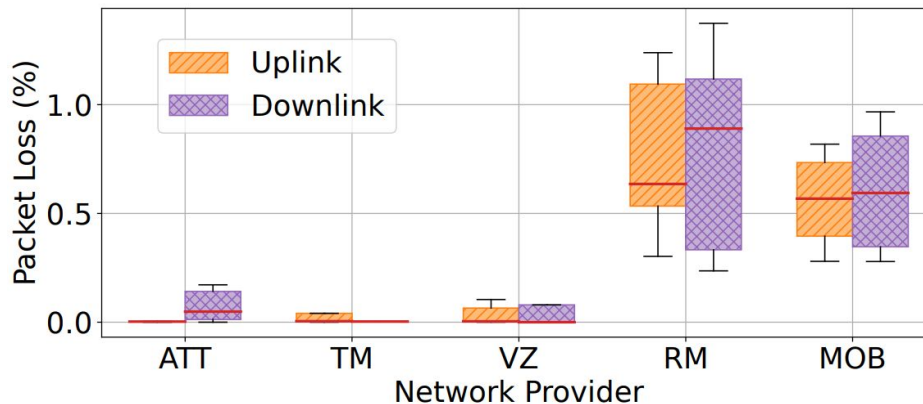
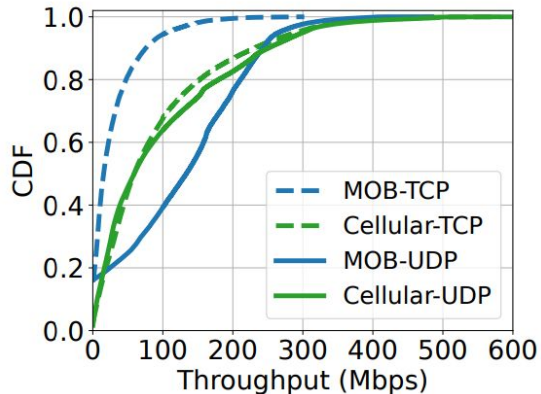
- Software measurement tools
  - *iPerf for TCP/UDP throughput test*
  - *UDP-Ping for latency*
  - *5G Tracker [1,2] for network type, speed, GPS location, signal strength, ...*
- Data collection: drive tests
  - *5 states in the US*
  - *1239 network tests*
  - *9083 minutes of traces*
  - *3800 km travel distance*

[1] Narayanan, Arvind, et al. "5G tracker: a crowdsourced platform to enable research using commercial 5G services." Proceedings of the SIGCOMM'20 Poster and Demo Sessions. 2020.

[2] Narayanan, Arvind, et al. "A variegated look at 5G in the wild: performance, power, and QoE implications." Proceedings of the 2021 ACM SIGCOMM 2021 Conference. 2021.

# Starlink-Cellular Performance Comparison

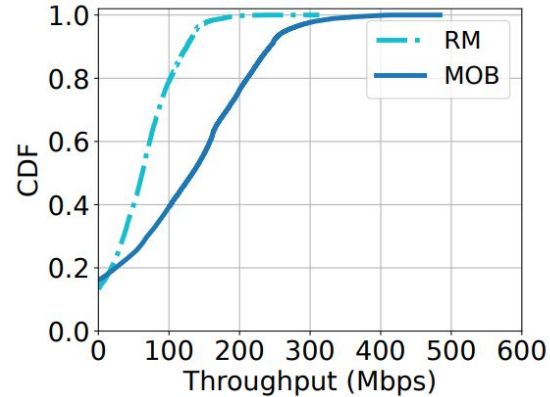
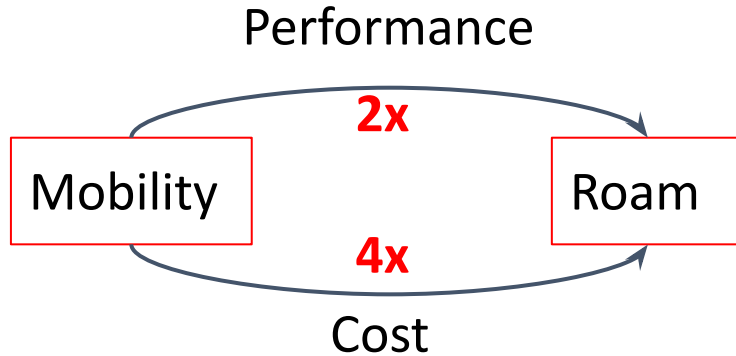
- **UDP outperforms TCP** in satellite networks due to **high packet loss**
  - *128 Mbps vs 29 Mbps*





# Starlink-Cellular Performance Comparison

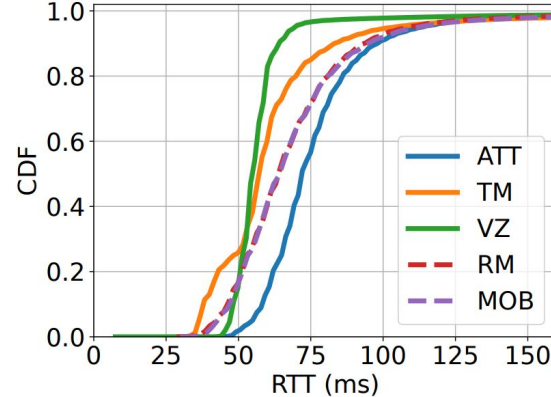
- “Roam” also works during in motion cases.
- “Mobility” exhibits superior performance than “Roam”



# Starlink-Cellular Performance Comparison

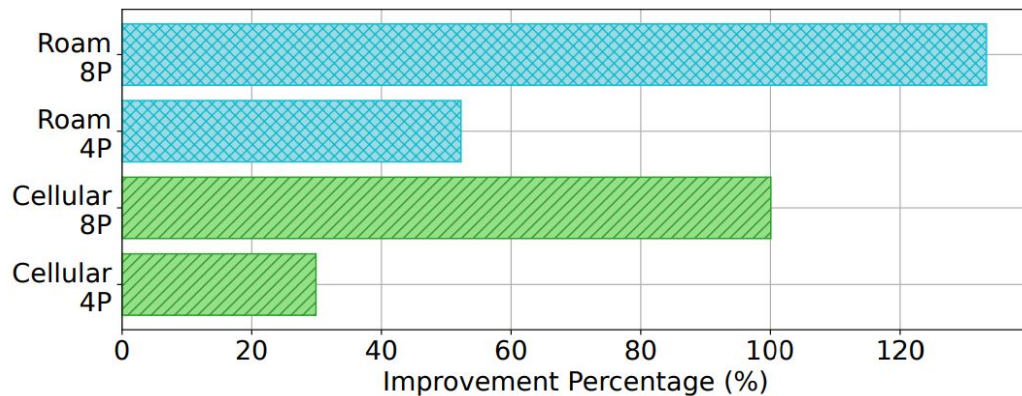
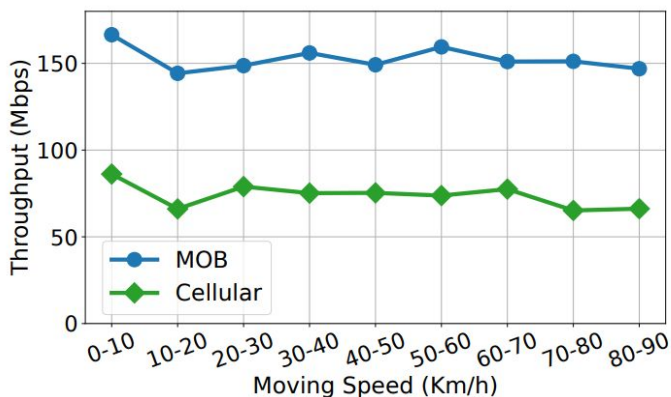
- Latency
  - *RTTs for all networks primarily fall within the range of 50 to 100ms*
  - *Starlink's latency is **not significantly worse** than that of cellular networks*
    - Only 1.8ms transmission latency one way, theoretically

$$\text{Latency} = \left( \frac{\text{Distance}}{\text{Speed of light}} \right) = \left( \frac{550 \text{ km}}{299792 \text{ km/s}} \right) = 1.835 \text{ ms}$$



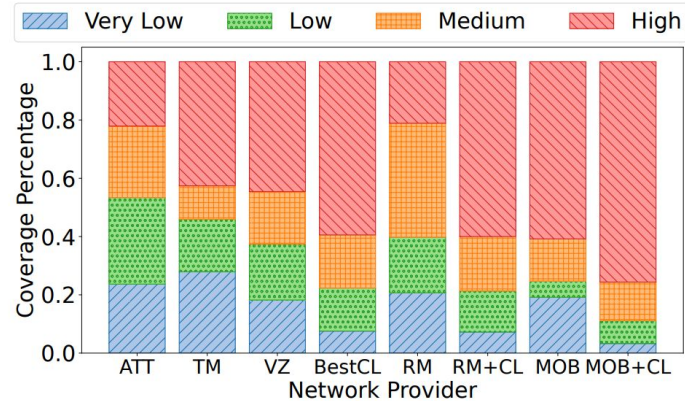
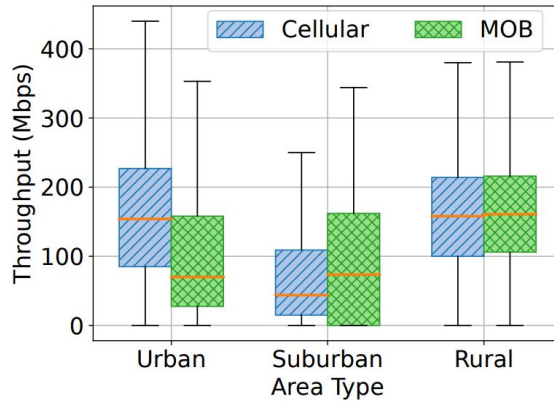
# Potential Factors Affecting Performance

- Moving speed
  - *Both satellite and cellular network throughputs have **minimal variation** in relation to driving speed*
- TCP parallelism
  - *Increase the number of TCP connections enhances throughput in both networks*



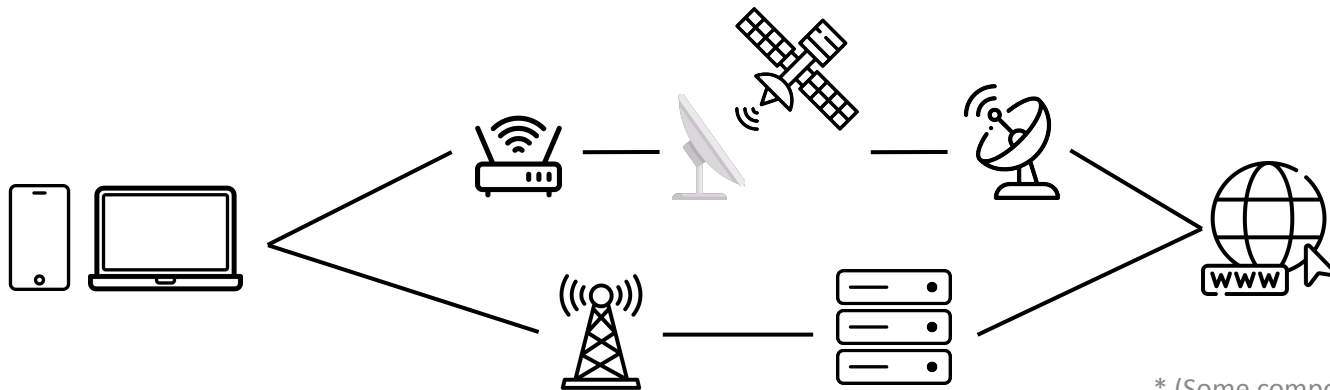
# Coverage Study

- **Starlink is better in rural areas** due to clear sky view.
- **Cellular is better in urban areas** due to density base station deployment.
- Starlink exhibits the **best overall performance**.
- **Combining** different networks improves the overall performance.



# Multipath Transport

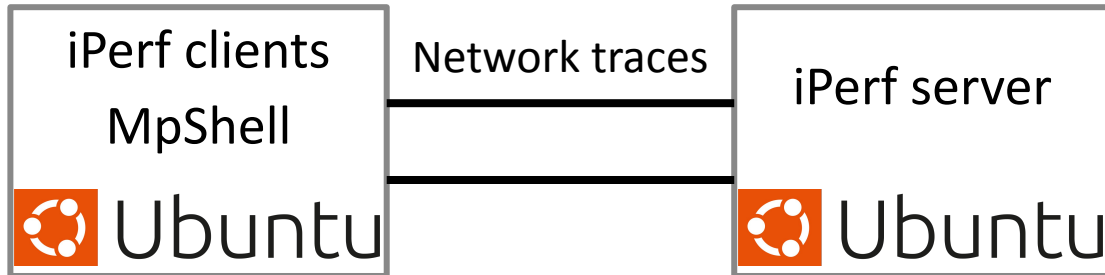
- Multipath (MPTCP, MPQUIC, ...) is popular and proved effective
  - *For different combinations of networks*
  - *For various network applications*
- Starlink + cellular MPTCP has been underexplored
  - *Take the first step to demonstrate the potential of enabling multipath*



\* (Some components like PoP omitted)

# Multipath Transport

- Experimental setup
  - *Ubuntu 22.04 VM hosts*
  - *MpShell (a variant of Mahi-mahi [1, 2]) for emulation*
  - *iPerf for throughput measurement*

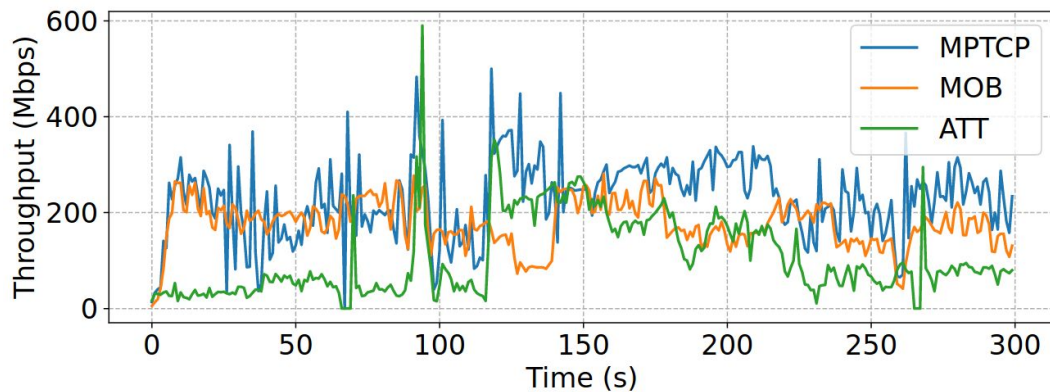
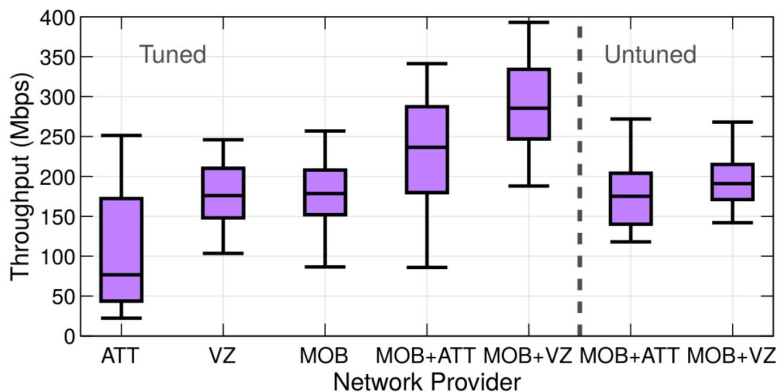


[1] Netravali, Ravi, et al. "Mahimahi: accurate Record-and-Replay for HTTP." 2015 USENIX Annual Technical Conference (USENIX ATC 15). 2015.

[2] Deng, Shuo, et al. "WiFi, LTE, or both? Measuring multi-homed wireless internet performance." Proceedings of the 2014 Conference on Internet Measurement Conference. 2014.

# Multipath Transport

- Using MPTCP between Starlink and cellular networks bring benefits
  - *Improve the bandwidth utilization by over 80%*
  - *Maintain decent performance when one service has severe degradation*
- Promising results but room for improvement
  - *Future work: MPTCP scheduler design tailored for LEO networks*



# Conclusion

- We conduct a large-scale data collection campaign
- We analyze the performance of satellite and cellular networks
- We explore the potential of multipath on satellite and cellular networks

Thank You!