Applied Networking Research Workshop

PhantomLink: Emulating Virtual End-to-End Links on Ground and in Orbit

ACM/IRTF Applied Networking Research Workshop (ANRW) 2025

Robin Ohs Gregory Stock **Juan A. Fraire** Holger Hermanns Andreas Schmidt

Saarland University, Saarbrücken, Germany

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Motivation

- **LEO Mega-Constellations**

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Data Transport

- Inter-satellite links (remote regions)
- Internet (TCP/IP) protocols

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Popular Example:

SPACEX STARLINK

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Image: DALL·E 3

Aviation, Maritime, and Underserved areas

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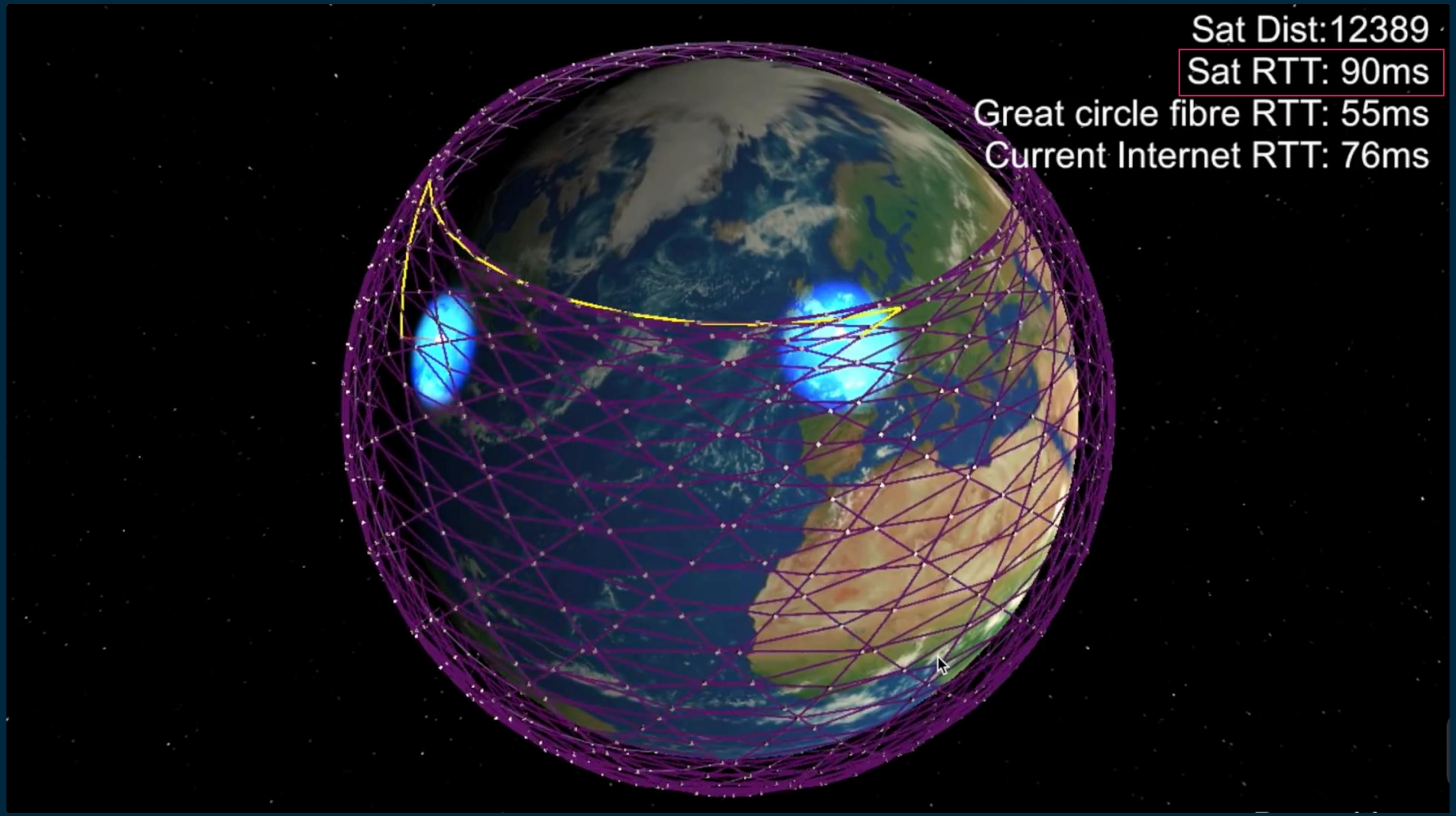
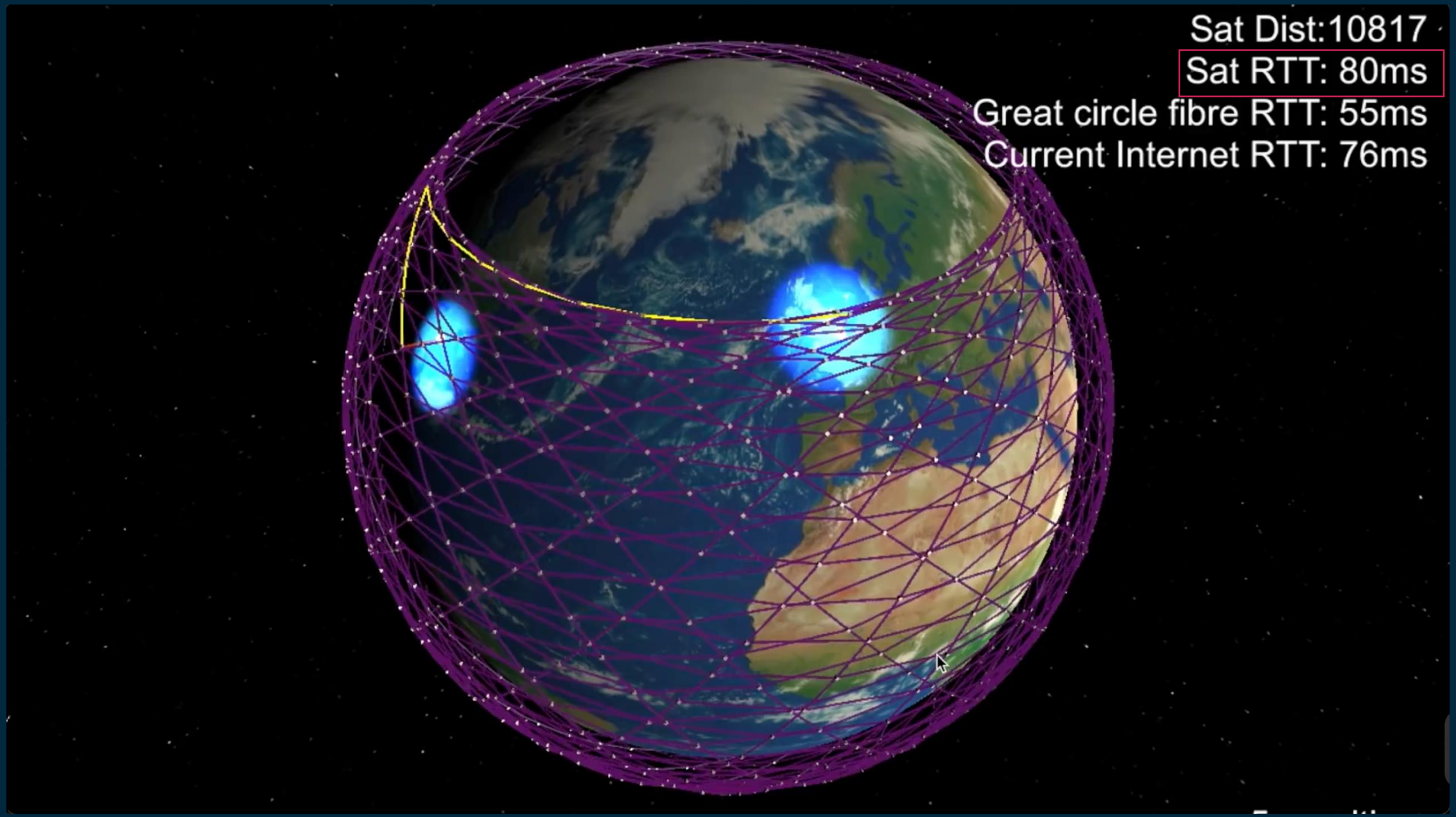
Network Properties

- Highly dynamic paths
- Predictable topology



Video: Mark Handley, https://youtu.be/QEIUdMiColU



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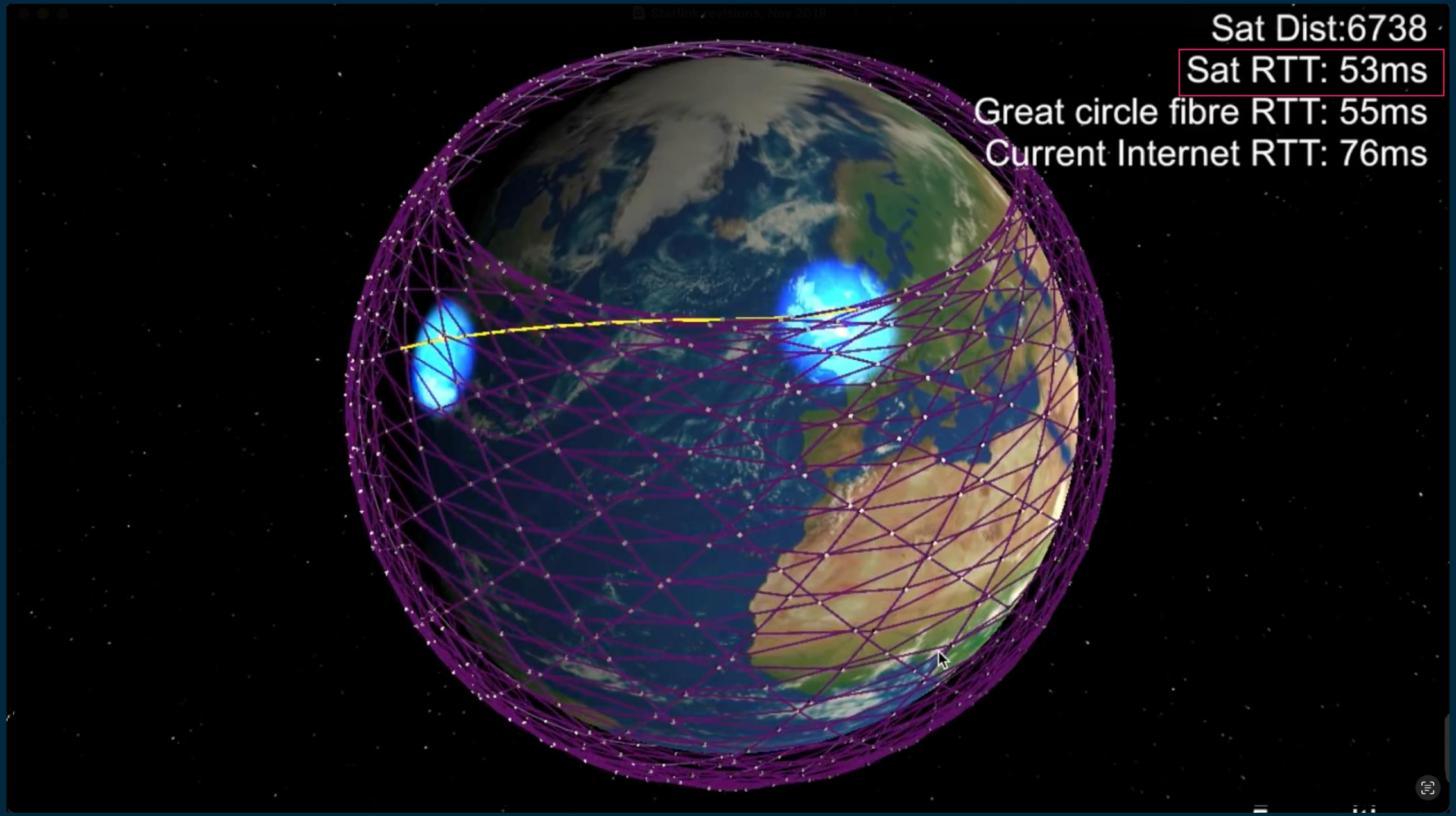

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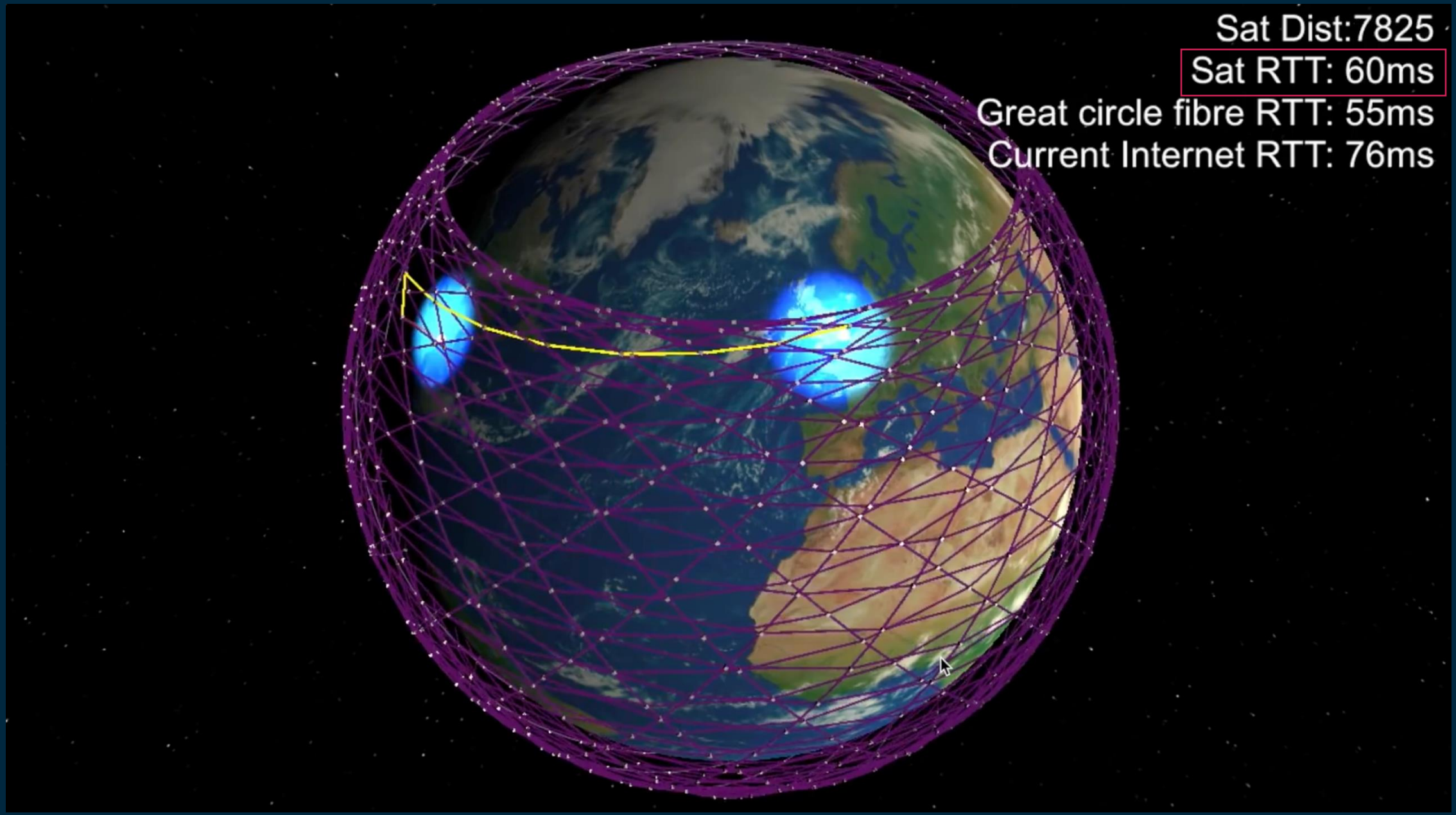

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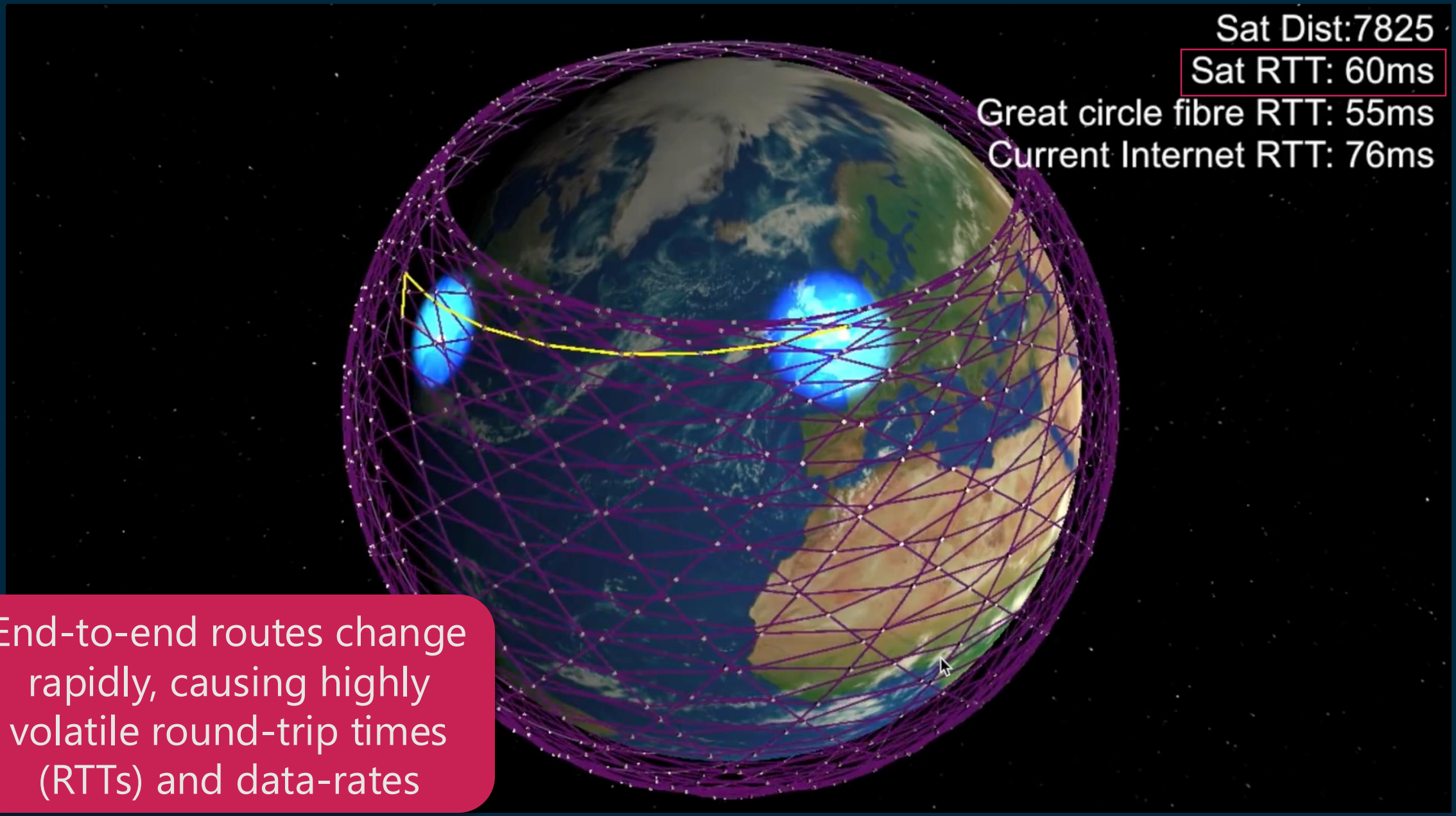

End-to-end routes change rapidly, causing highly volatile round-trip times (RTTs) and data-rates

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Dynamics

Orbital Dynamics
highly dynamic, but predictable & periodic

Application Performance
on top of, for example, TCP

Dynamics


Orbital Dynamics
highly dynamic, but predictable & periodic
constrain
Evolving Topology
nodes and edges
Application Performance
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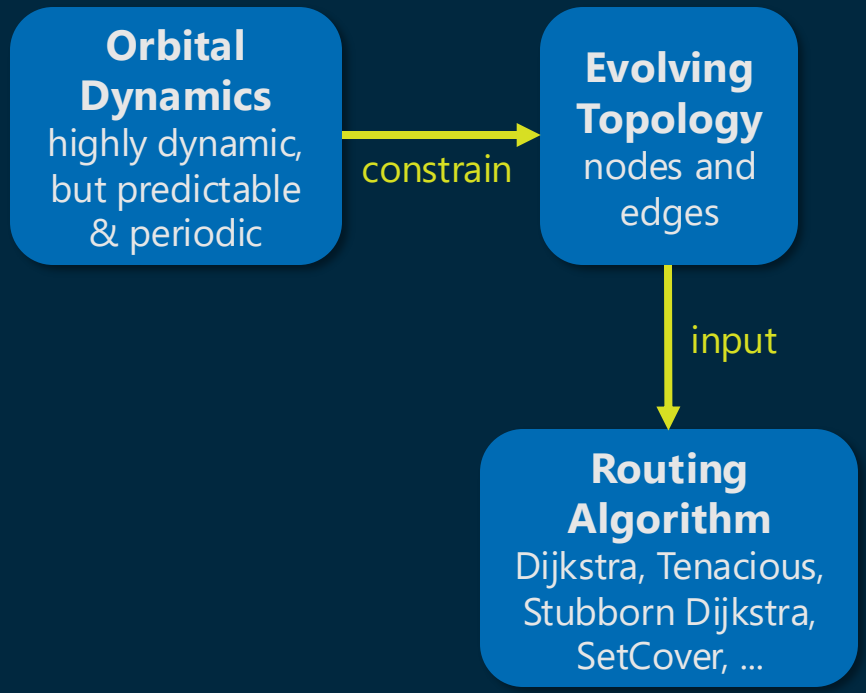

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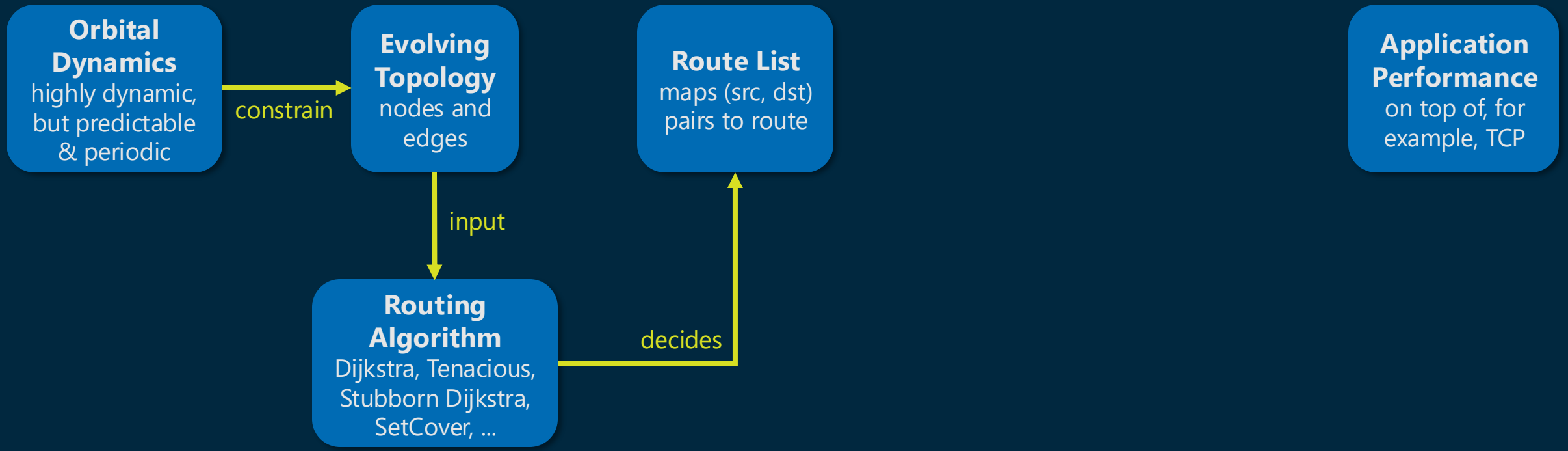
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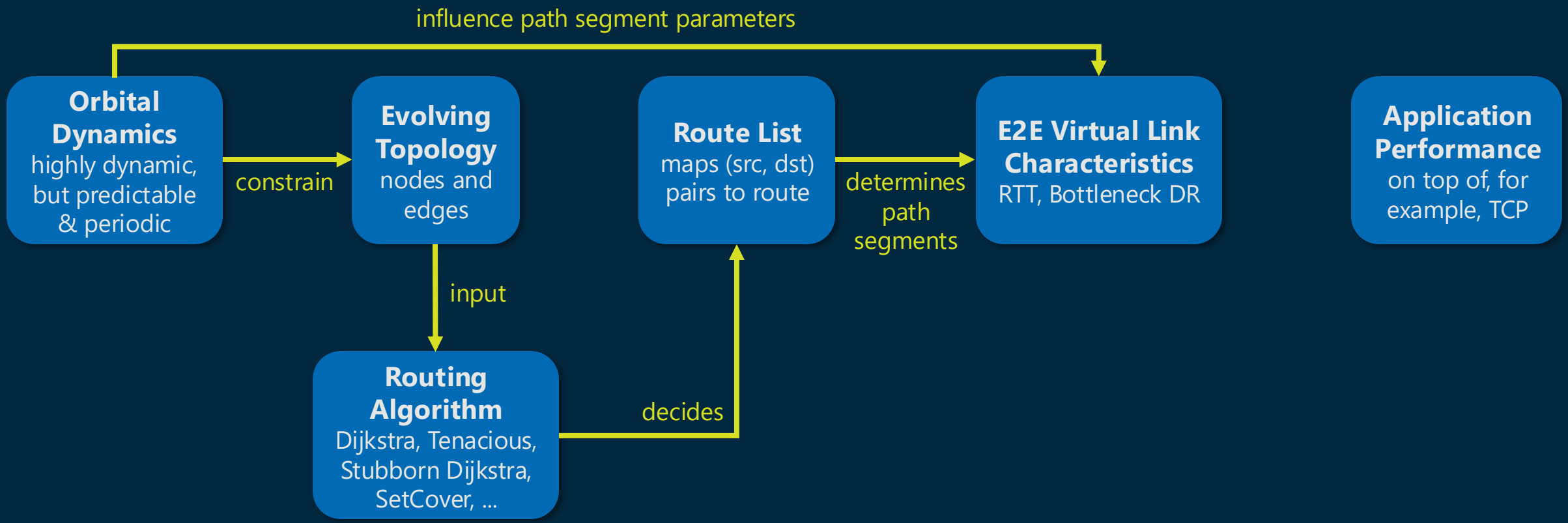
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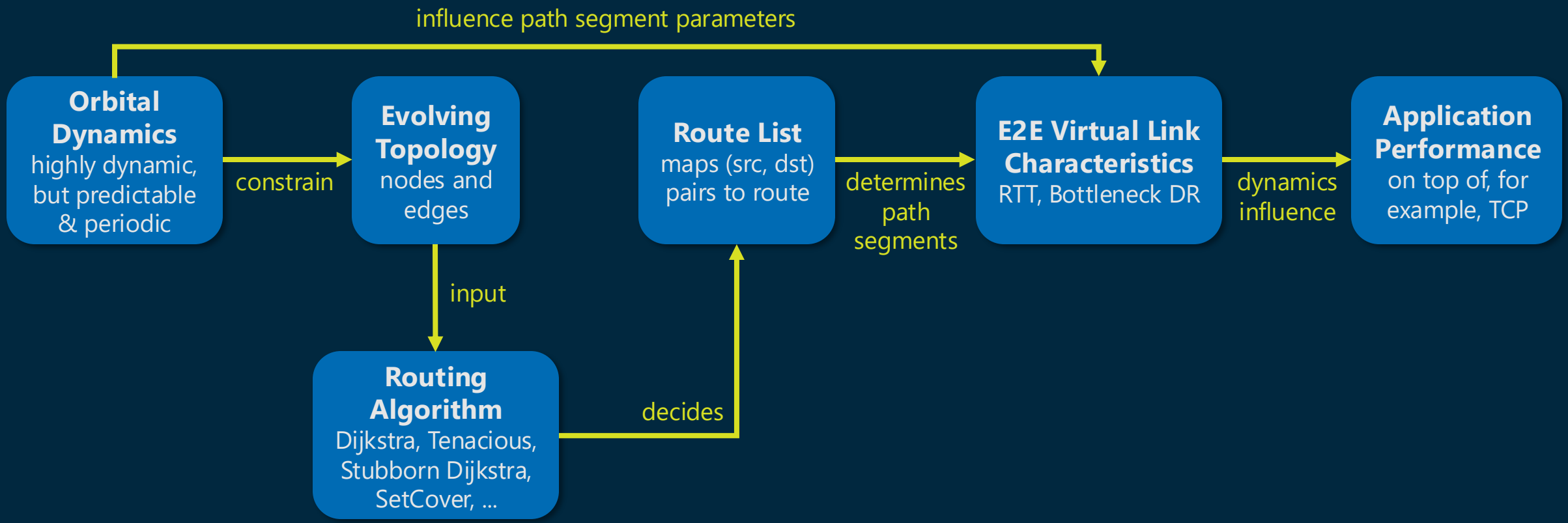
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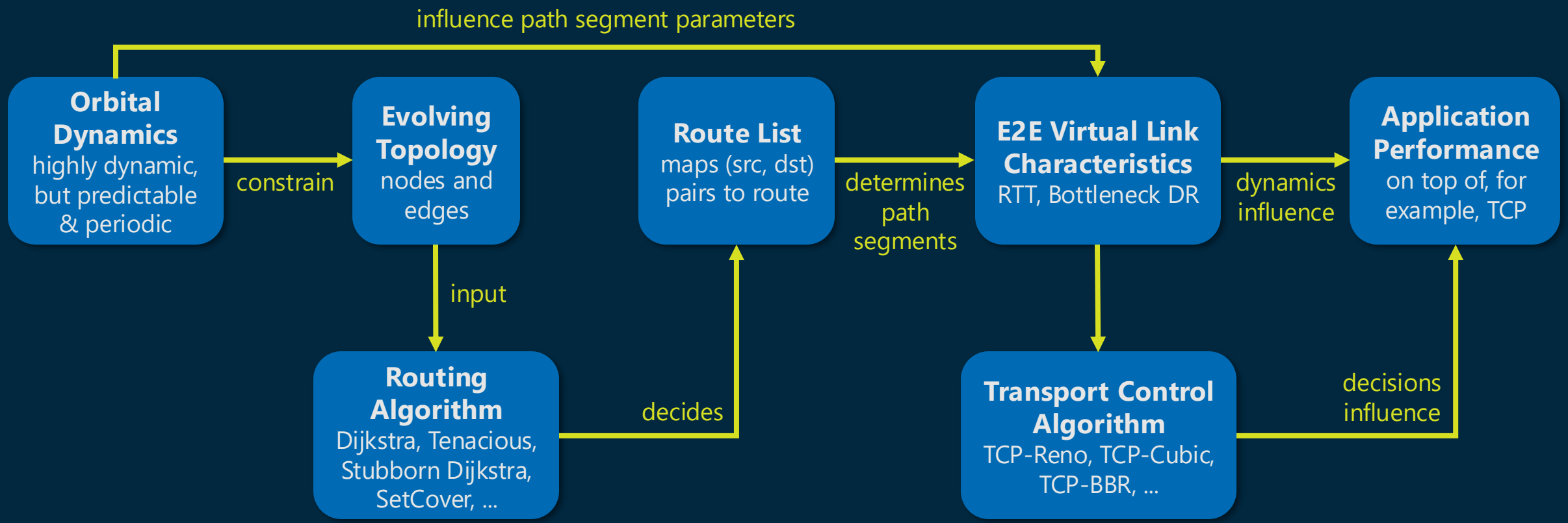
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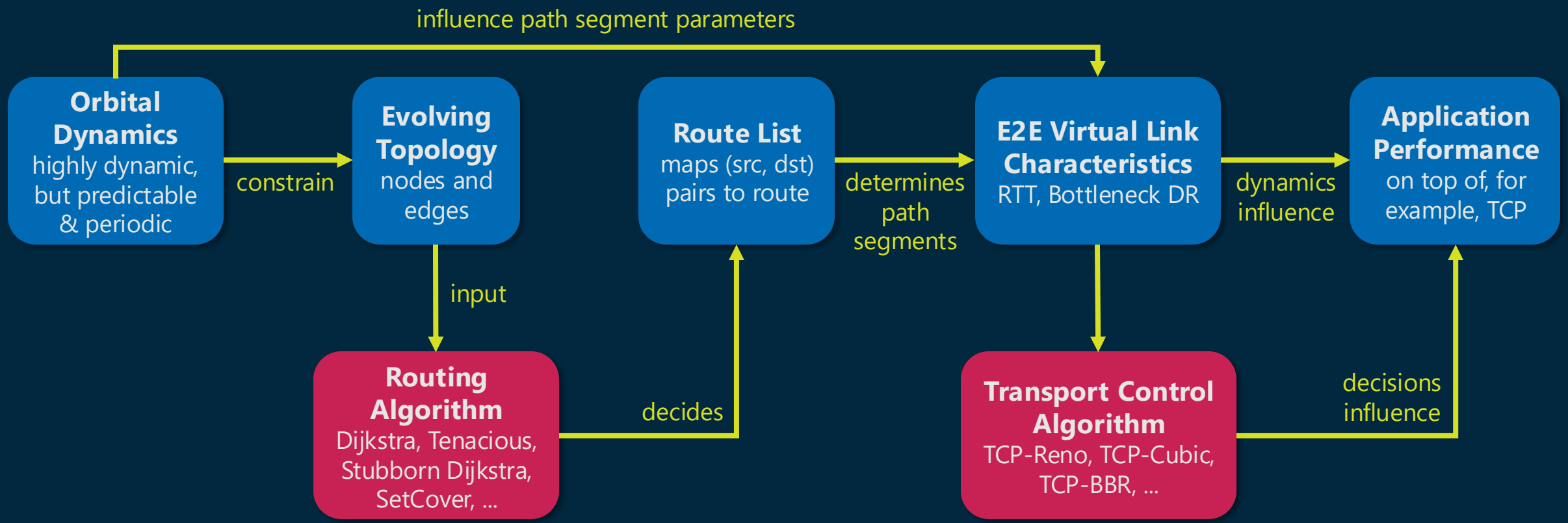
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Direct Control

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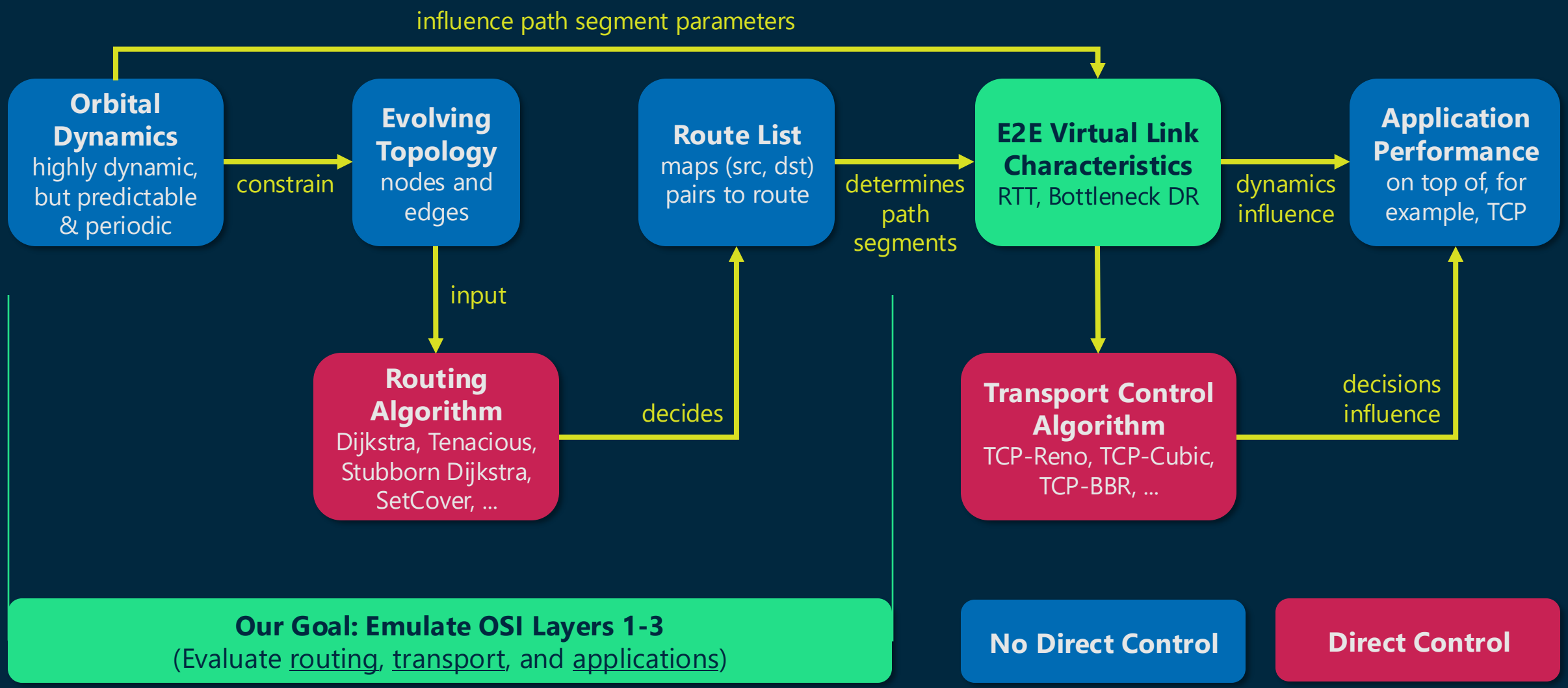
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Our Goal: Emulate OSI Layers 1-3
(Evaluate routing, transport, and applications)
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Direct Control

Challenge

Existing **network** tools are not designed for evolving, fine-grained orbital dynamics.

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OMNeT++ or ns-3

Do not support real congestion control implementations

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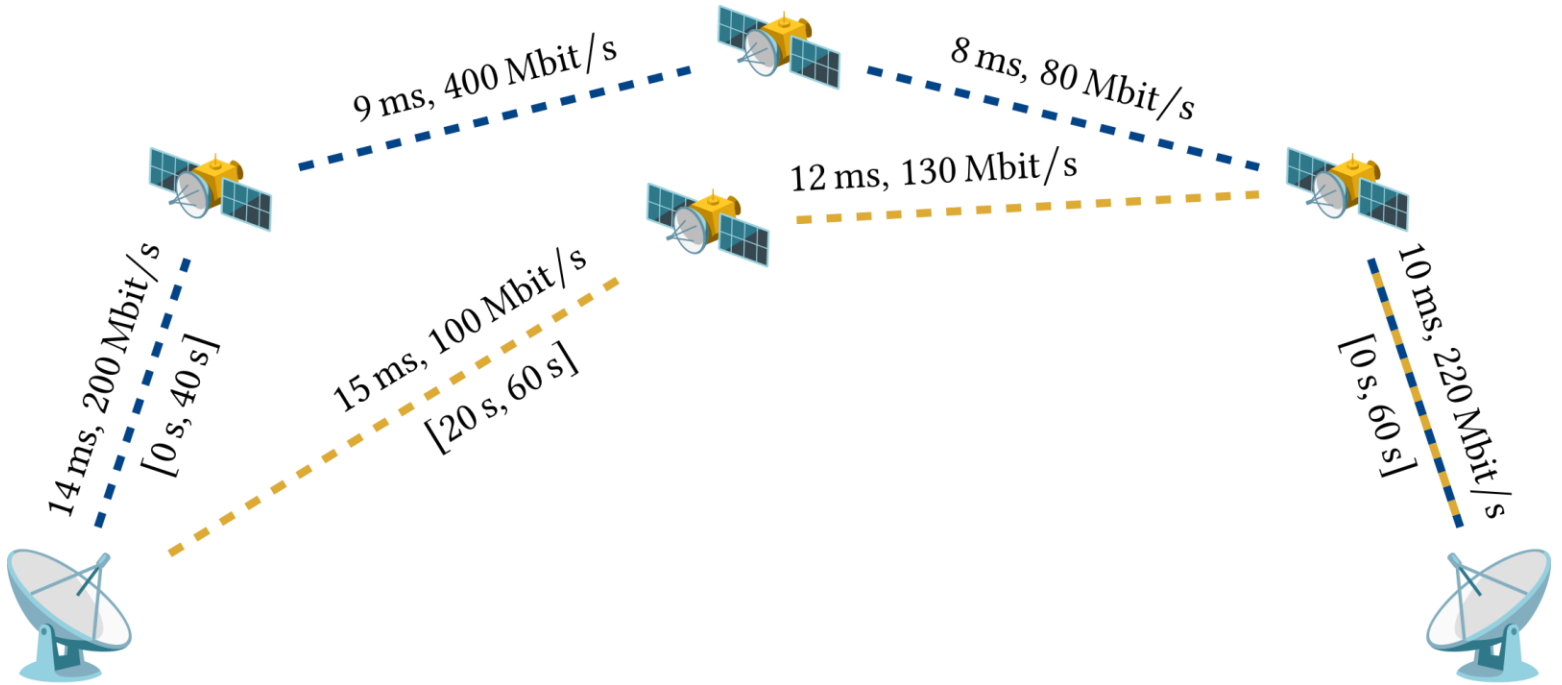
Utilities

Traffic Control (`tc`)

Do not support rapidly varying multi-path link conditions

Approach

Physical Path



Virtual E2E Links

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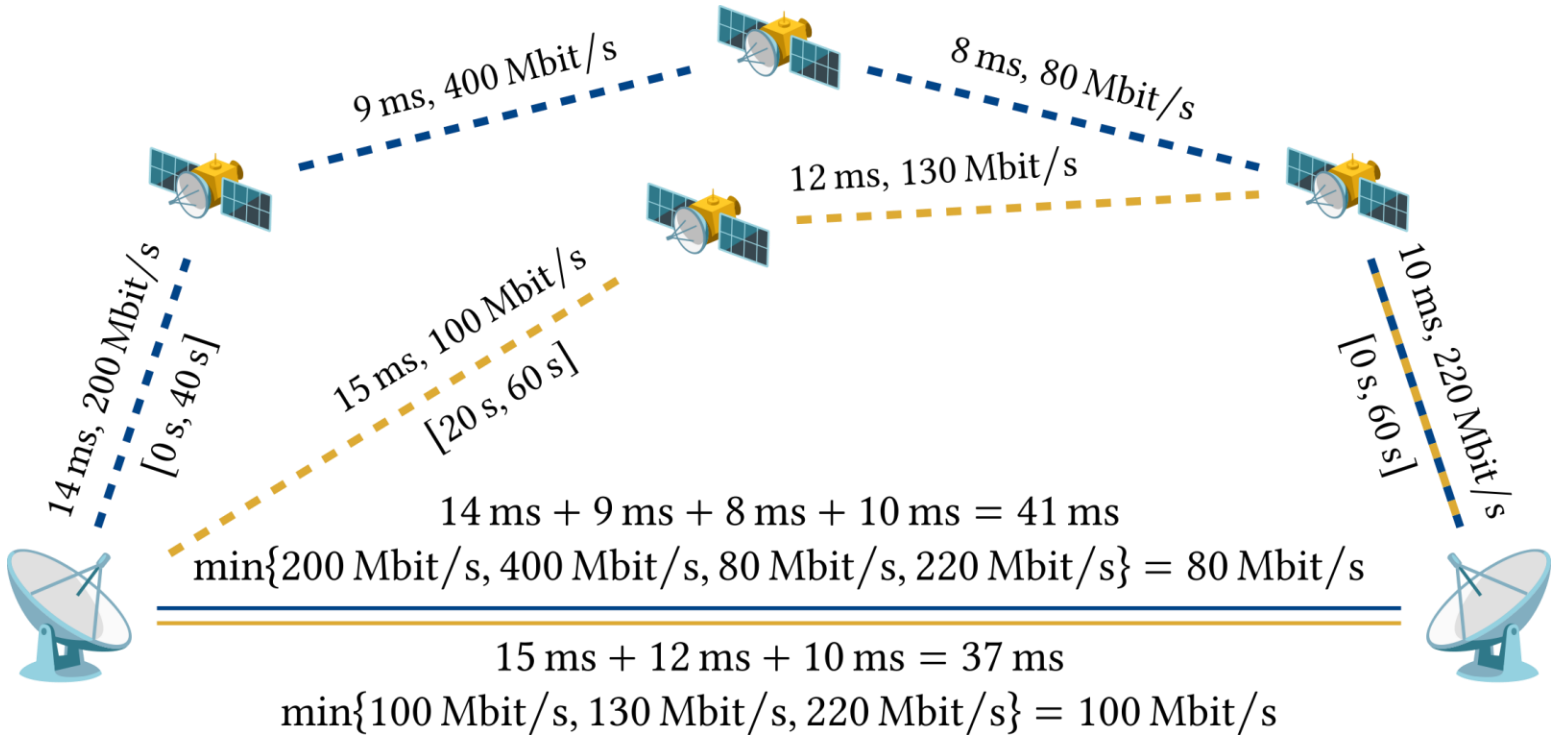
Physical Path



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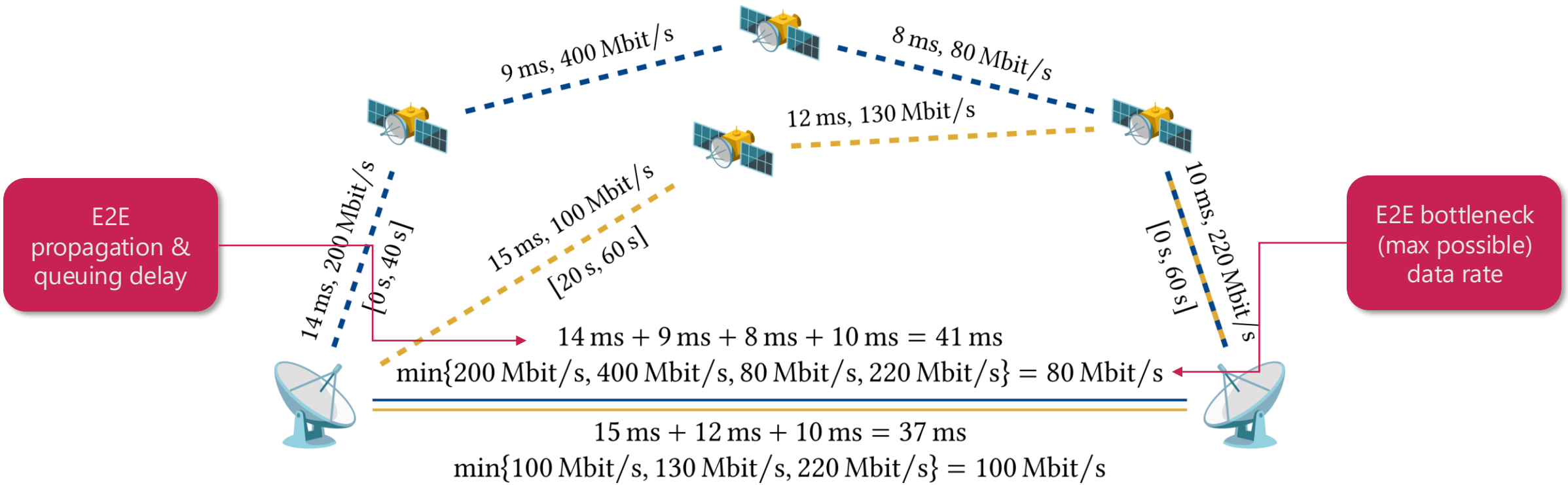

Virtual E2E Links

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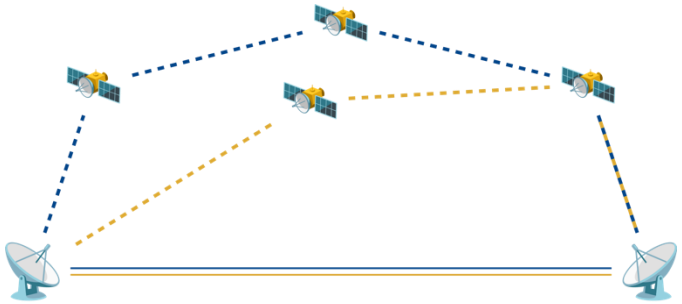

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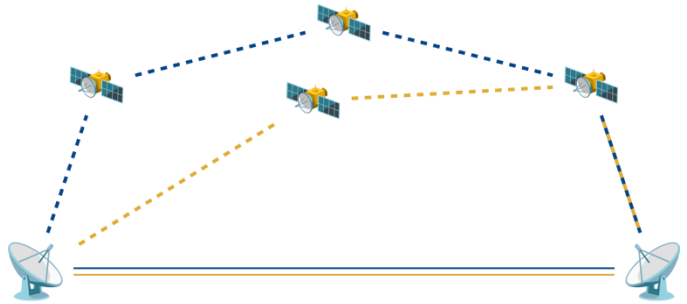
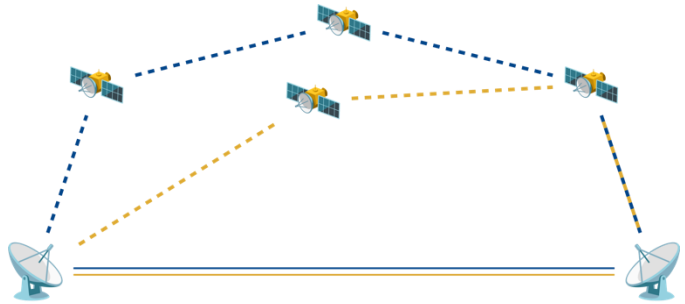
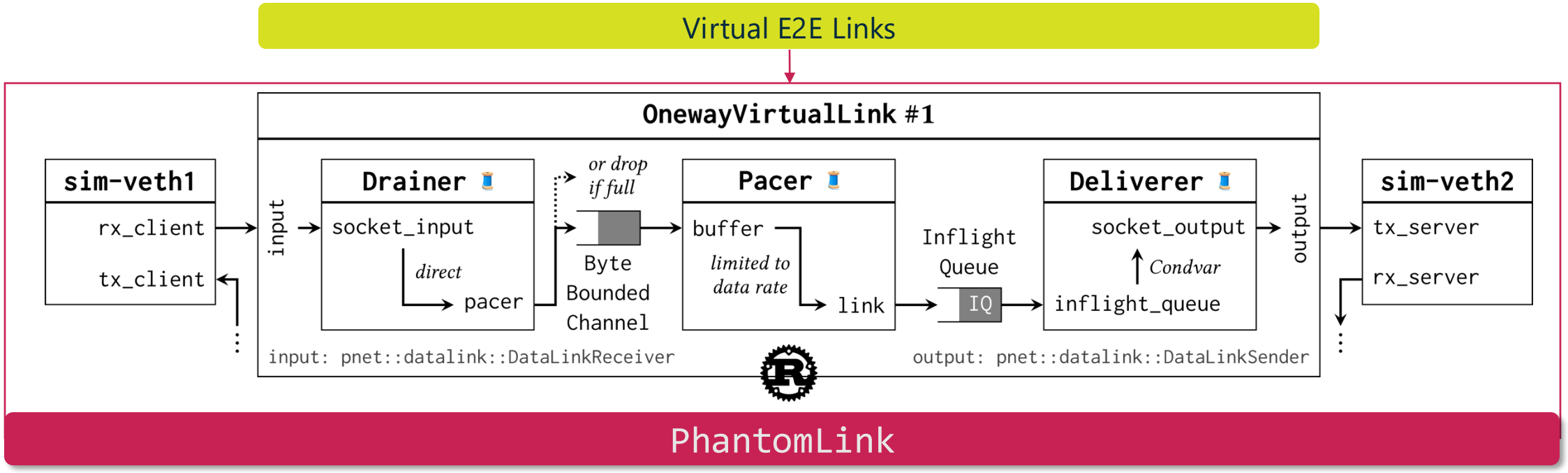


Virtual E2E Links

PhantomLink

Contribution





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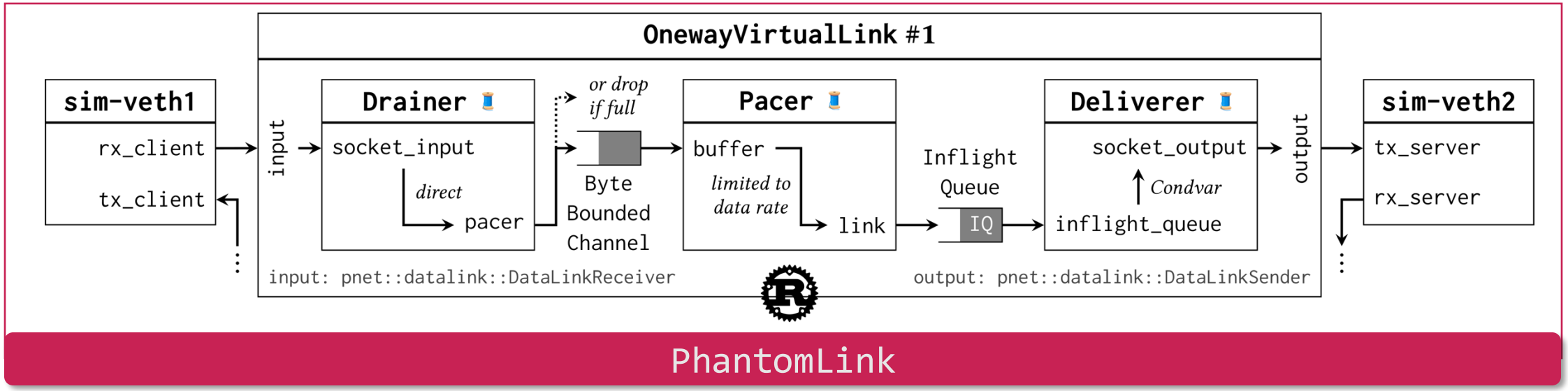

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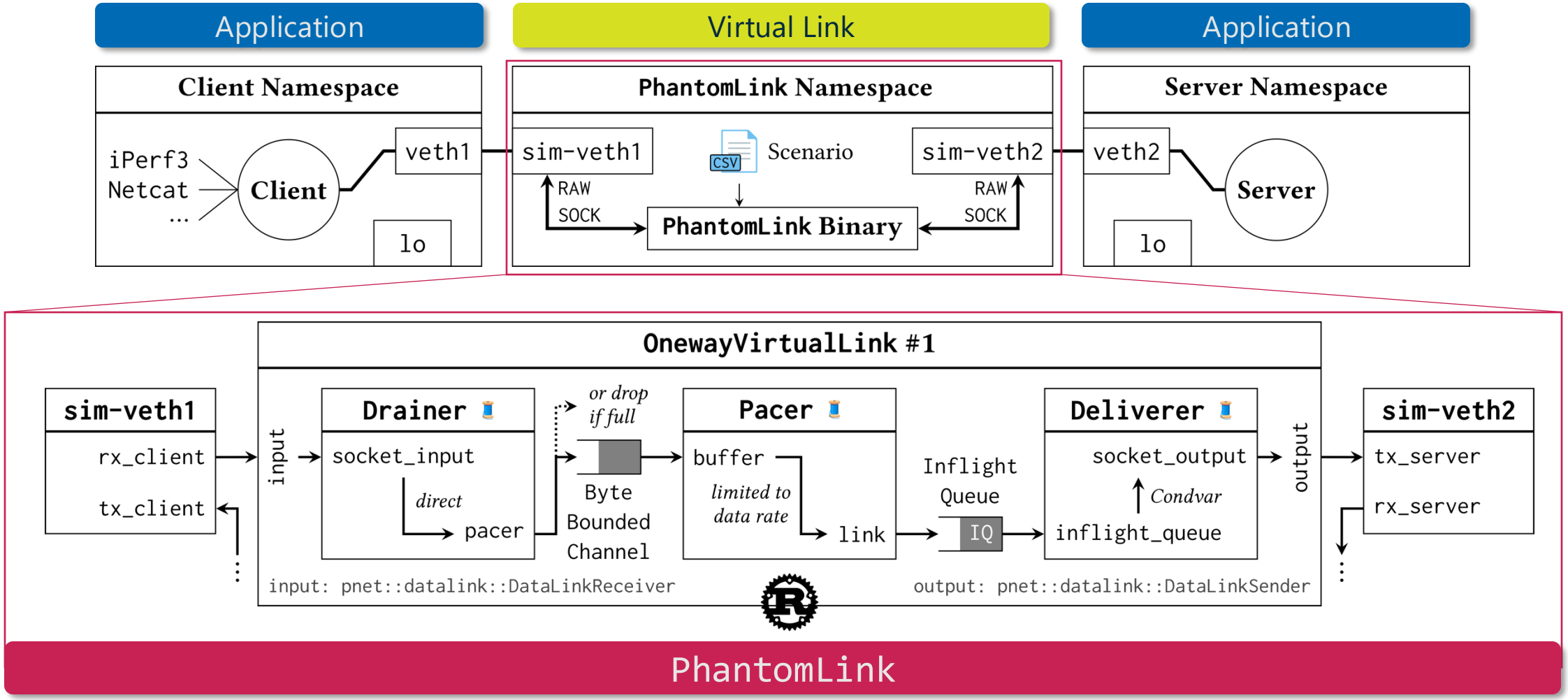
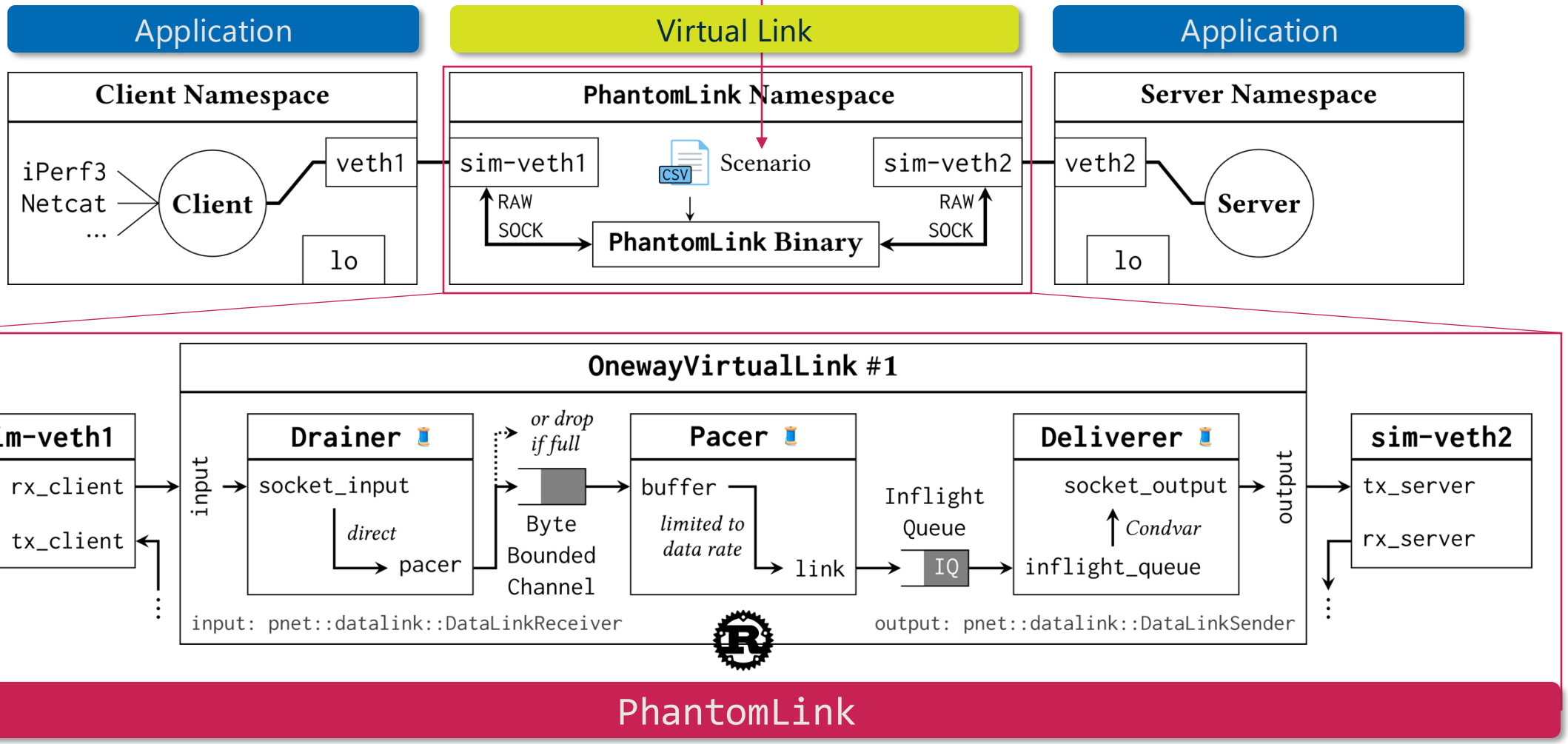


Contribution

Scenario dynamics obtained from realistic orbital propagators

Time[ms]	RouteID	Delay[ms]	Btldr[Mbps]
0	0	41.0	80.0
11 000	0	41.2	80.2
23 000	1	37.0	100.0
40 000	1	36.7	101.5
60 000	1	37.0	100.1



Evaluation

Congestion Control Algorithms Comparison using `iPerf3`

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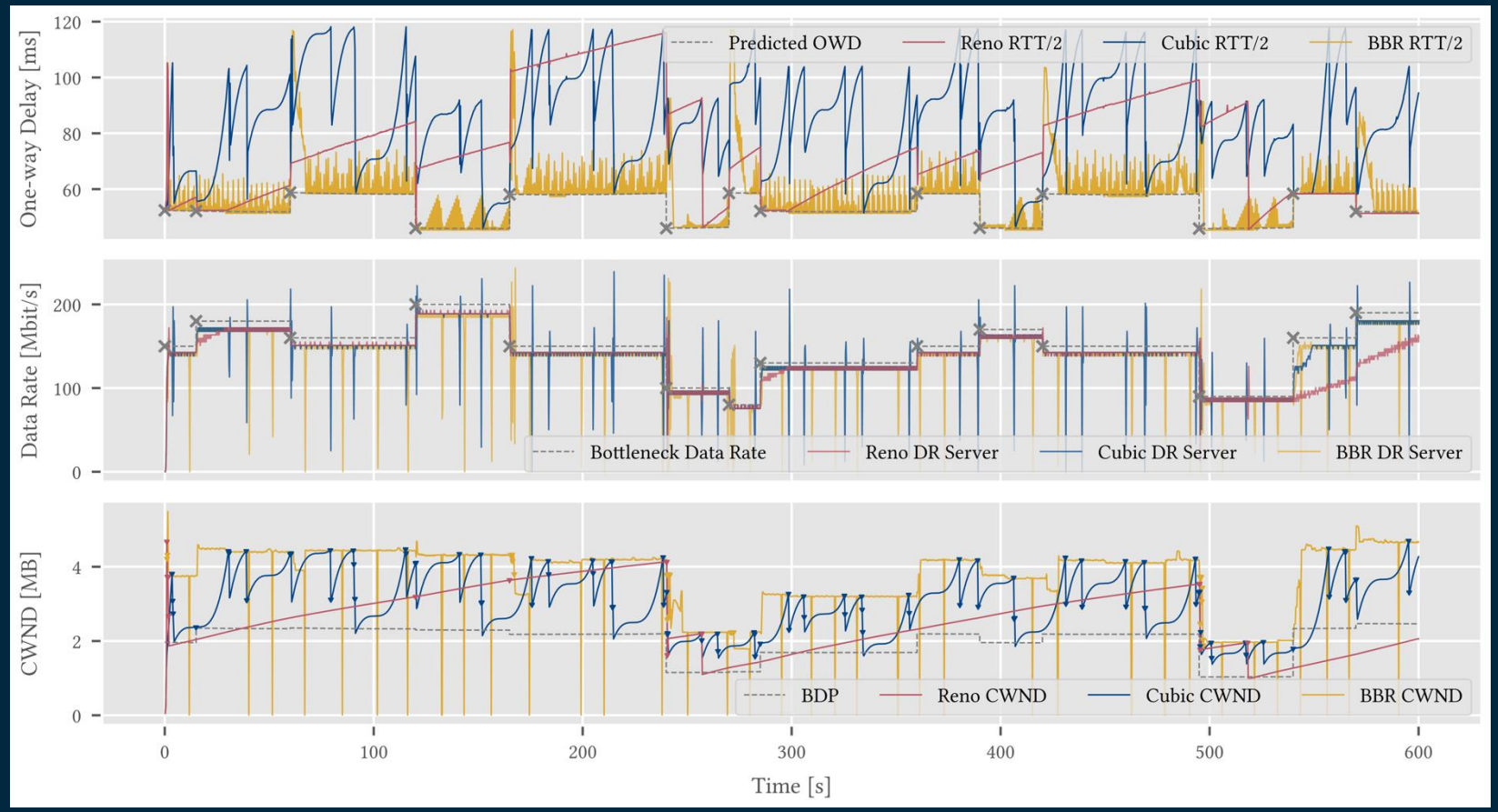

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Metric [Unit]	(New) Reno	Cubic	BBR
Received Data [GB]	10.240	10.474	10.271
95%-ile OWD [ms]	110.544	114.372	73.507
Retransmissions [1/min]	617.9	990.1	989.8

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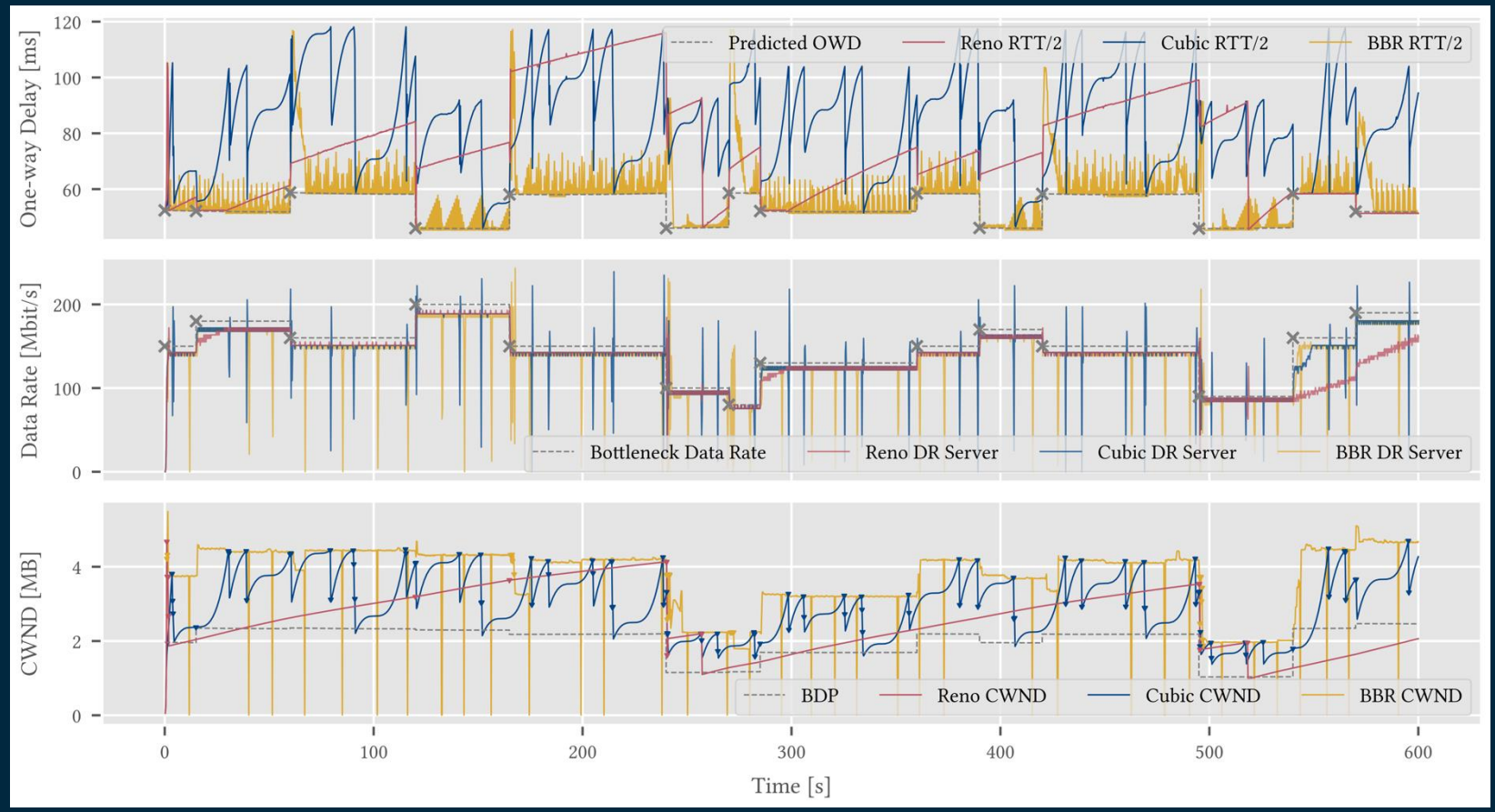

CCs behave as expected:
Reno: linear
Cubic: cubic
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Varying OWD and ReTx.

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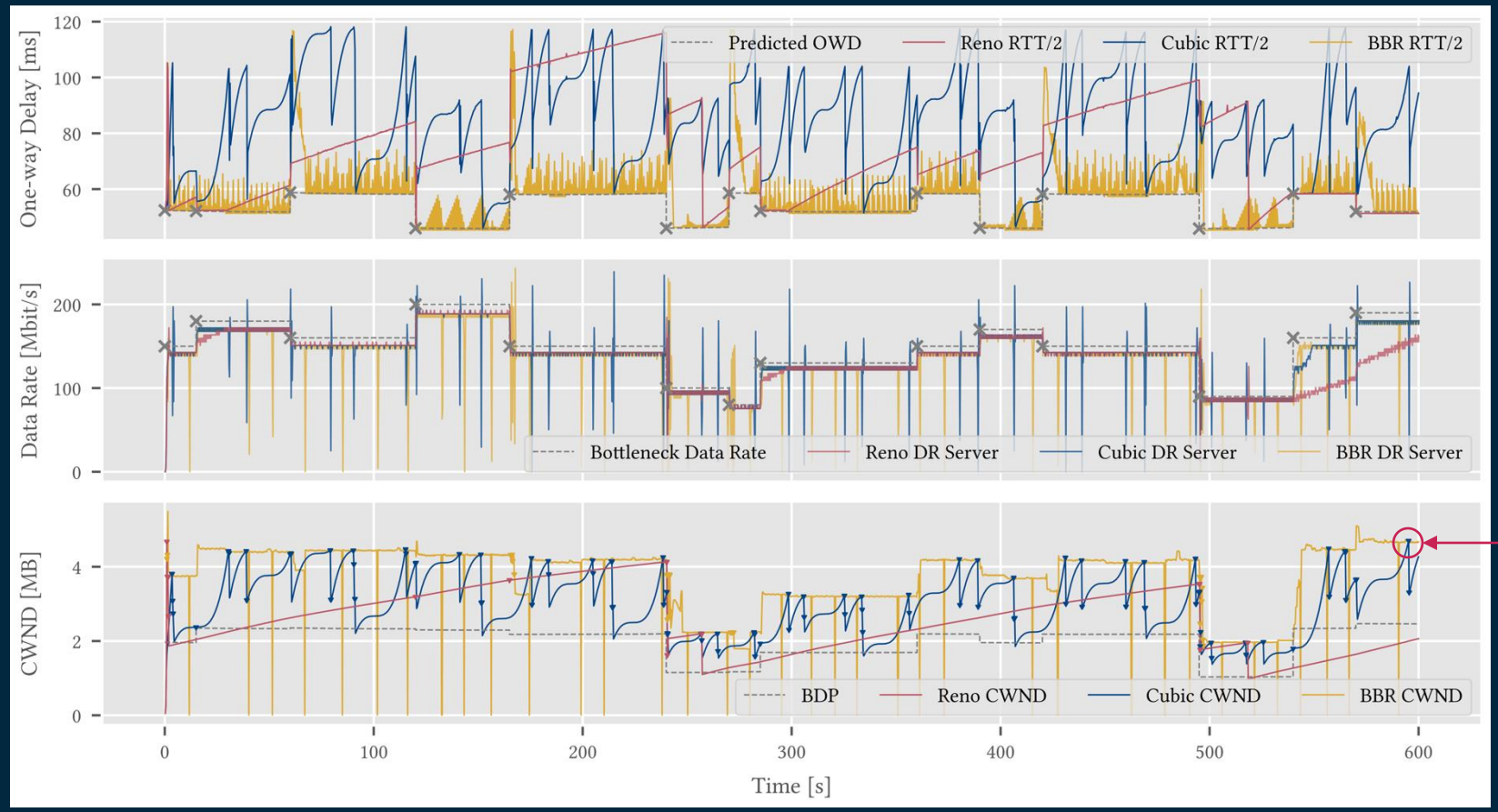

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ReTx due to:
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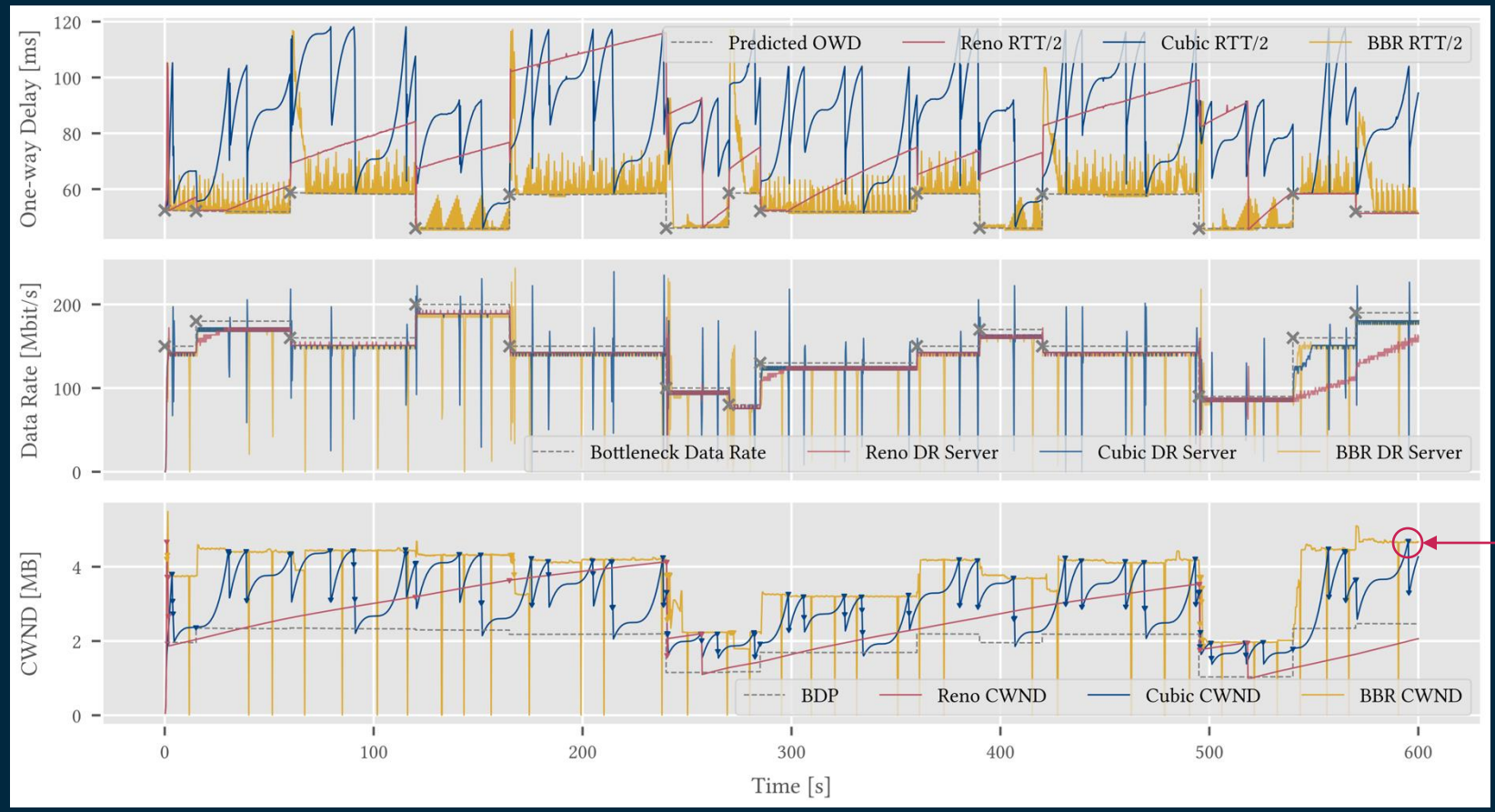
This evaluation is not possible with existing simulators using real TCP implementations



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Abstract

Low-Earth Orbit (LEO) networks are highly dynamic due to their closeness to Earth and fast movements. At the same time, these dynamics are also highly predictable as the LEO satellites have their fixed orbits. As this predictability is rarely found in terrestrial networks, existing network evaluation tools cannot be used in associated Internet research.

We propose PhantomLink, a tool to emulate an evolving virtual end-to-end (E2E) link in real time using the unmodified Linux networking stack. PhantomLink emulates general scenarios—which are inspired by, but not limited to, LEO networks. The tool represents a virtual network interface that can be used to send/receive packets as if they were using an actual multi-hop path. Finally, we showcase our tool in the context of current orbital Internet research.

CCS Concepts

• **Networks** → **Network dynamics**; *Network simulations*.

Keywords

Transport Layer Performance, LEO Routing, Emulation

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Robin Ohs, Gregory F. Stock, Juan A. Fraire, Holger Hermanns, and Andreas Schmidt. 2025. PhantomLink: Emulating Virtual End-to-End Links on Ground and in Orbit. In *Applied Networking Research Workshop (ANRW 25), July 22, 2025, Madrid, Spain.* ACM, New York, NY, USA, 8 pages. https://doi.org/10.1145/3744200.3744758

*Both authors contributed equally to the paper.

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1 Introduction

As of today, a significant share of Internet traffic is already running over Low-Earth Orbit (LEO) constellations—which will only increase over the next years, as it is for instance a solution for aviation and maritime connectivity [11, 31, 32]. While many properties and technologies are shared with the terrestrial part of the Internet, we see a major difference in the physical dynamics underlying the network transport.

Figure 1 provides a high-level abstract overview of end-to-end (E2E) Internet transport over LEO. The red hatched boxes in the lower row (and upcoming Red Terms) represent what researchers can influence during design. First, the decisions made in Constellation Design determine the Orbital Dynamics faced in operation. The Orbital Dynamics constrain the Logical Topology and have a direct effect on Virtual E2E Link Parameters (e.g. the physical distance determines the propagation delay, data rate, and hence, the bandwidth-delay product (BDP)). The Logical Topology serves as a basis for Routing algorithms, which determine the Routes that will be used over the lifetime of a connection. Each route has an impact on the Virtual E2E Link Parameters between sending and receiving transport layer. Part of the transport layer is Congestion Control, which determines the amount of data in flight and packet intervals. Eventually, all these factors contribute to the Application Performance.

Our tool PhantomLink[1] encapsulates the OSI layers 1–3 into the single opaque box: Virtual E2E Link Parameters. This tool is inspired by research on routing and congestion control [23, 34] and influences future Constellation Design. For instance, it could help to pick the most suitable transport protocol (e.g. TCP or QUIC) or congestion control algorithm (CCA) (e.g. Reno vs. Cubic) [5] and decide whether certain options are beneficial or not (e.g. TCP SACK [16]).

[1] *lat. phantom*, something having the form, but not the substance, of a real thing. PhantomLink looks and behaves mostly like a multi-hop path, but with a "substantially" lower cost.

Robin Ohs et al. *"PhantomLink: Emulating Virtual End-to-End Links on Ground and in Orbit"*. ACM/IRTF Applied Networking Research Workshop (ANRW). Madrid, 2025.

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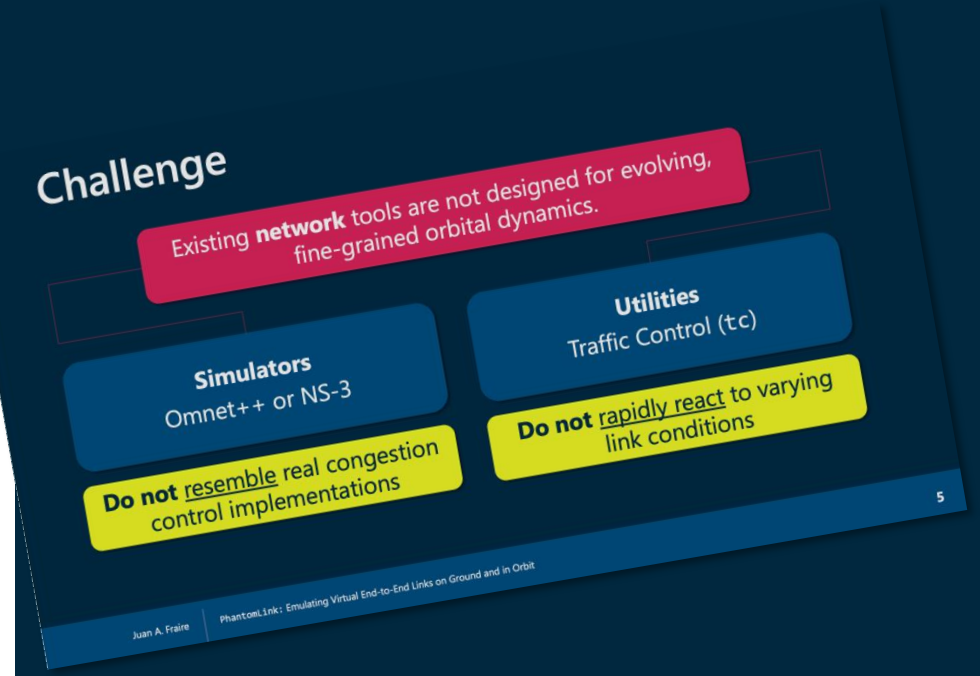

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Conclusion

PhantomLink: Emulating Virtual End-to-End Links on Ground and in Orbit

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Holger Hermanns Saarland University Saarbrücken, Germany

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Abstract

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CCS Concepts

• **Networks** → **Network dynamics**; *Network simulations*.

Keywords

Transport Layer Performance, LEO Routing, Emulation

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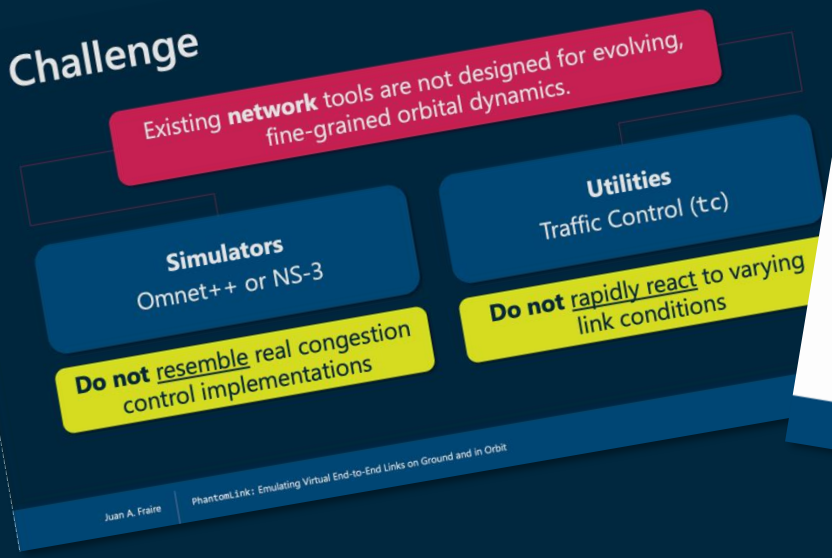

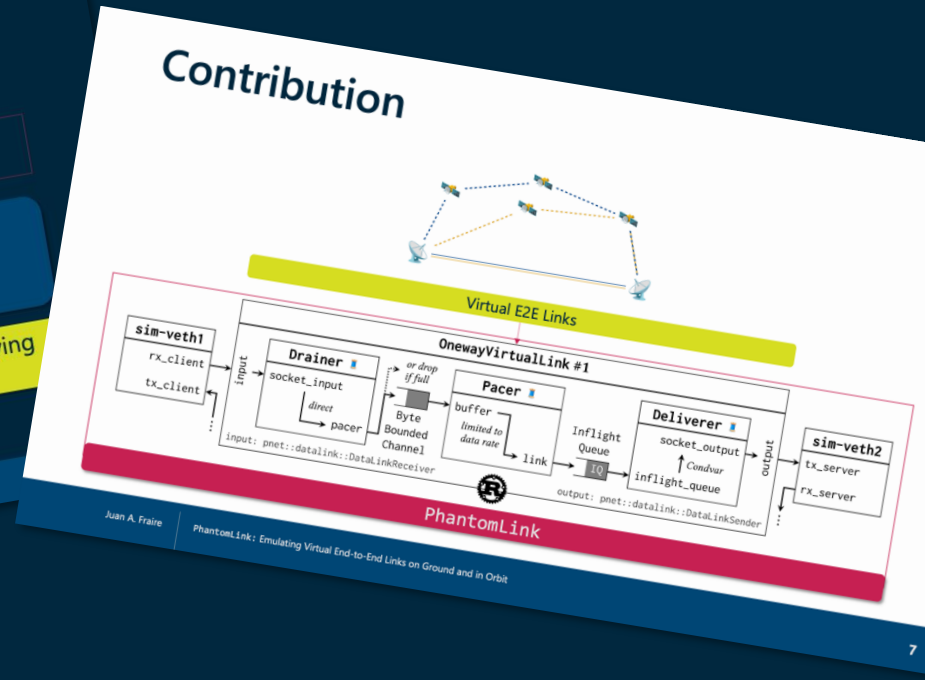

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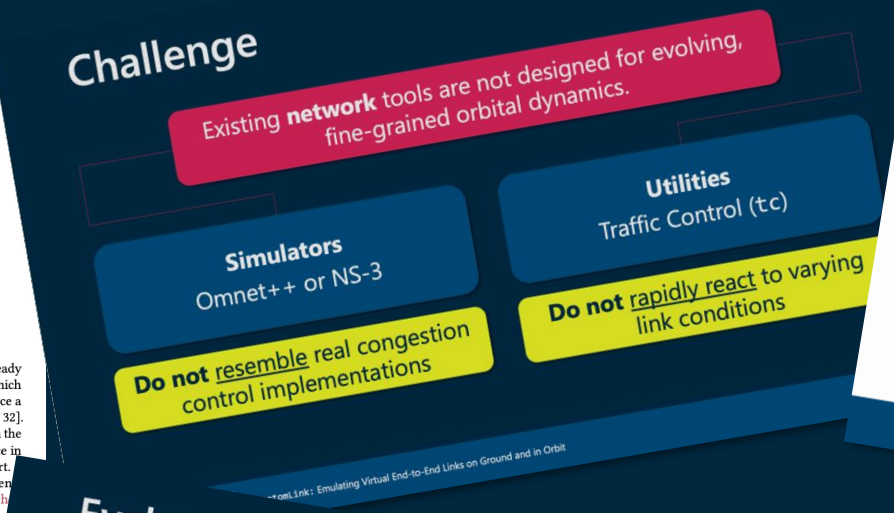

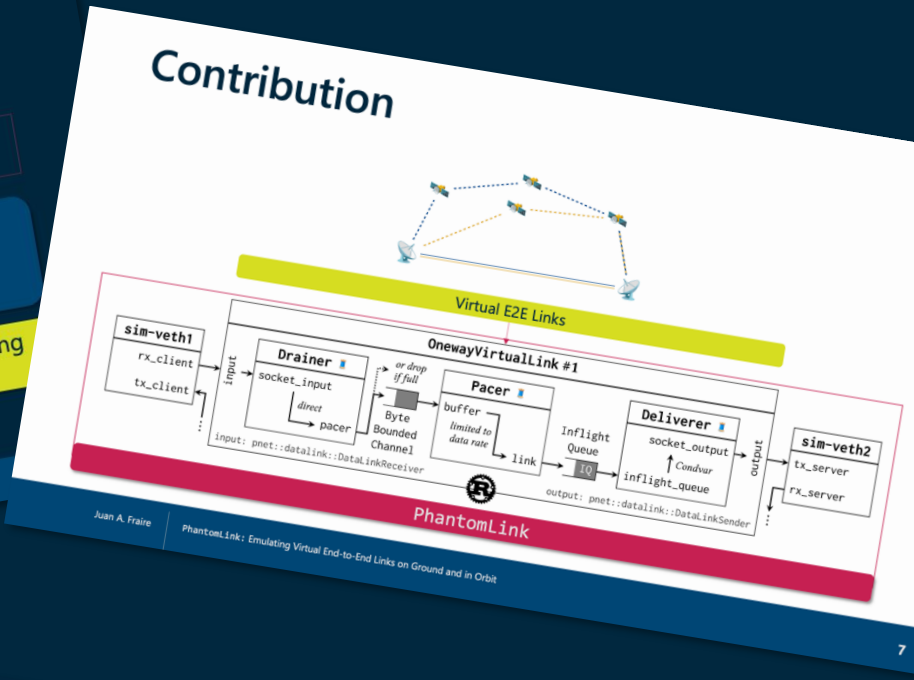

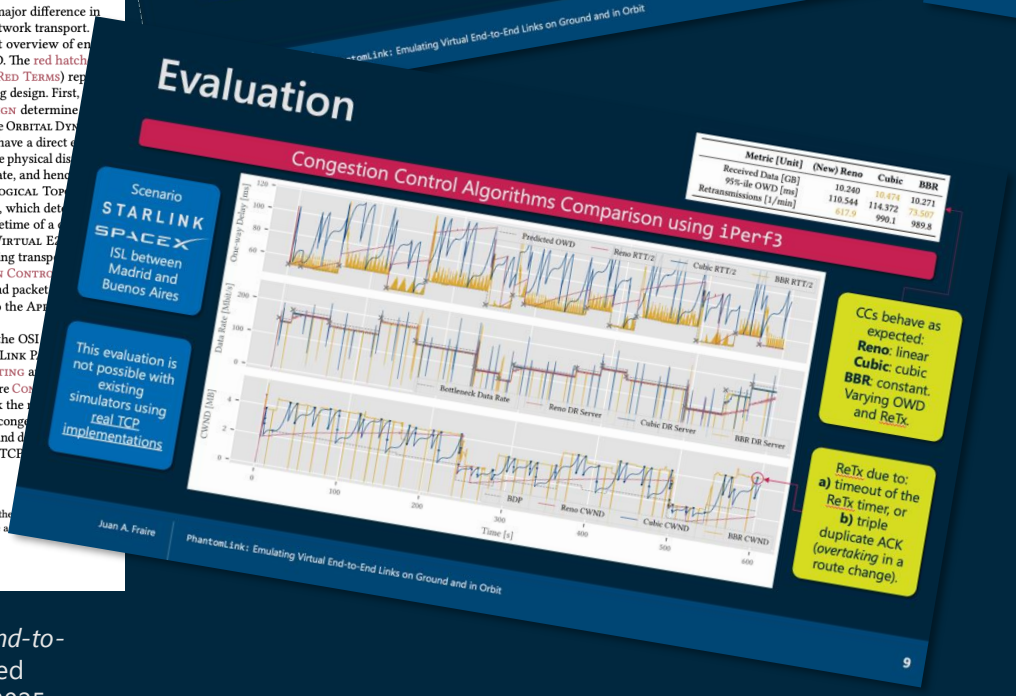

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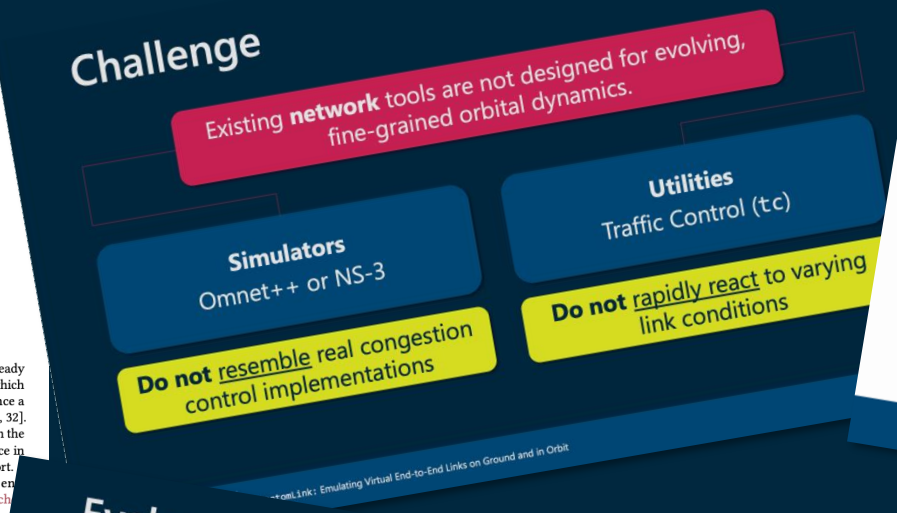

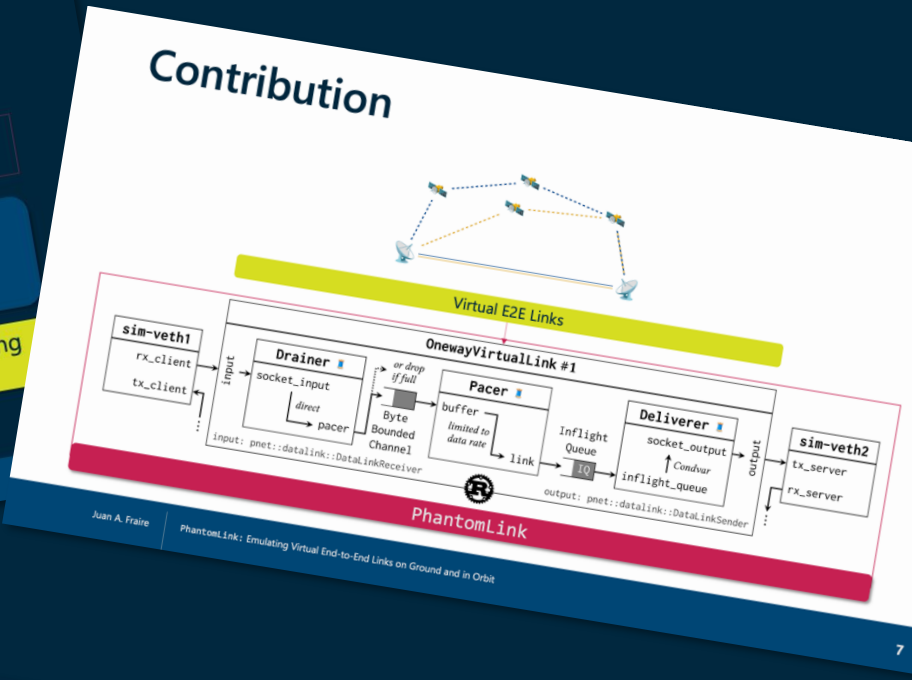

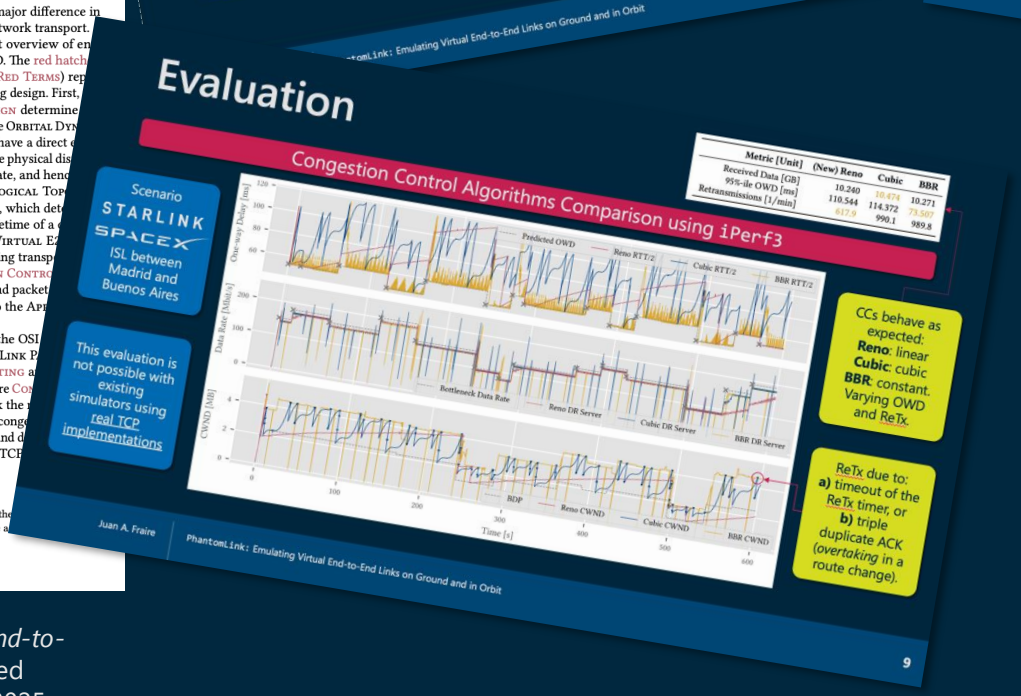

PhantomLink uniquely enables realistic evaluation of **routing**, **transport**, and **application** behavior over dynamic multi-hop near-Earth or deep-space links.

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