Computers in Orbit: Green & Efficient?

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Andreas Schmidt

joint work with

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MISSION

CPEC CENTER FOR PERSPICUOUS COMPUTING

There's No Atmosphere B

Dirty Bits in Low-Earth Orbit: The Carbon Footprint of Launching Computers

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Low-Earth Orbit (LEO) satellites are increasingly proposed for communication and in-orbit computing, achieving low-latency global services. However, their sustainability remains largely unexamined. This paper investigates the carbon footprint of computing in space, focusing on lifecycle emissions from launch over orbital operation to re-entry. We present ESpaS, a lightweight tool for estimating carbon intensities across CPU usage, memory, and networking in orbital vs. terrestrial settings. Three worked examples compare (i) launch technologies (state-of-the-art rocket vs. potential next generation) and (ii) operational emissions of data center workloads in orbit and on the ground. Results show that, even under optimistic assumptions, in-orbit systems incur significantly higher carbon costs—up to an order of magnitude more than terrestrial equivalents—primarily due to embodied emissions from launch and re-entry. Our findings advocate for carbon-aware design principles and regulatory oversight in developing sustainable digital infrastructure in orbit.

CCS Concepts: • **Hardware → Impact on the environment**; *Communication hardware, interfaces and storage.*

Additional Key Words and Phrases: sustainability, orbital data centers, in-orbit computing

et al. [30], the current trajectory of LEO development is consolidating power in the hands of a few dominant players. These vertically integrated actors—often controlling orbital infrastructure and end-user services—pose risks to openness, interoperability, and fair access. In response, some have advocated for decentralized models of satellite operation and ownership [33]; yet, such approaches may inadvertently accelerate the deployment of redundant or poorly coordinated constellations. A key concern is the escalating accumulation of space debris [12, 35], but mounting warnings also point to radio astronomy interference [1] and the environmental toll of satellite manufacturing [27] as critical sustainability threats. Without cohesive governance and shared architectural principles, LEO networks face a growing tension between scalability and sustainability.

While governance, orbital congestion, and electromagnetic interference are well-recognized challenges in the discourse on LEO constellations, a critical dimension remains conspicuously underexplored: the carbon footprint of orbital infrastructure. Recent evidence by Ogutu et al. [32] shows that LEO satellite broadband systems exhibit lifecycle emissions per subscriber of up to 14 times the

[HotCarbon2025]

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a) carbon-free

b) highly efficient

[various sources, just search for it]

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2️⃣ Data Centers
should move to space

[Bhattacherjee, HotNets'2020]

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🇪🇸 $I_{Energy,ES} = 123 \frac{gCO_2e}{kWh}$ Jul 6th '25

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t	Earth	Orbit
P_t in W/m^2	400	1367

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Where is the dirt?

Launch

$$C_{Lch,t}(n_{Reuse}) = \frac{TE_{Prod,t}}{n_{Reuse}} + TE_{Fuel,t}$$

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cleaner fuel, more payload/package, more reuse

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$$I_{Re-Entry,t} = \frac{m_{Payl} + m_{Pkg,t}}{m_{Payl}} \cdot I_{Re-Entry}$$

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$15.8\frac{kgCO_2e}{kg}$	– Starship – cleaner fuel, more payload/package, more reuse	$119.2\frac{kgCO_2e}{kg}$

1

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1

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Myth!

2. Clean DCs in Space?

Table 1. Idle (M) and Full Load ($O+M$) workload intensities for earthbound operation and different launch technologies.

Component Intensity Unit	**SCI**	**Earth**
CPU $\mu gCO_2e/s$	M $O+M$	18.0 282.8

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DRAM $\mu gCO_2e/(GB\,s)$	M $O + M$	3.0 3.2	4.0 4.9	3.8 4.5
SSD $\mu gCO_2e/(GB\,s)$	M $O + M$	0.040 0.047	0.056 0.090	0.052 0.080

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SSD	M	0.040	0.056	0.052
$\mu gCO_2e/(GB\,s)$	$O + M$	0.047	0.090	0.080
Transceiver	M	4.2	12.6	10.7
$\mu gCO_2e/pkt$	$O + M$	7.1	26.9	22.4

2

Clean Data Centers in Space?

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Myth!

🤔 Bust more?

🤔 Bust more?

check out our tool...

ESpaS

🤔 Bust more?

check out our tool...

EspaS

⚖️ MIT or Apache-2.0 🔊 \ɛs.pas\

gitlab.com/sustainable-computing-systems/espas

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Minimize $\frac{kgCO_2e}{GB}$.

or: maximum transferred data per carbon

How?

How?

A Stability-first Approach to Running TCP over Starlink

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*Saarland University – Computer Science, Saarland Informatics Campus, Saarbrücken, Germany
†CONICET – Universidad Nacional de Córdoba, Córdoba, Argentina
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***Abstract*—The end-to-end connectivity patterns between two points on Earth are highly volatile if mediated via a Low-Earth orbit (LEO) satellite constellation. This is rooted in the enormous speeds at which satellites in LEO must travel relative to the Earth's surface. While changes in end-to-end routes are rare events in stationary and terrestrial applications, they are a dominating factor for connection-oriented services running over LEO constellations and mega-constellations. This paper discusses how TCP-over-constellations is affected by the need for rerouting and how orbital route selection algorithms impact the end-to-end performance of communication. In contrast to the state of the art that primarily optimizes for instantaneous shortest routes (i.e. lowest delay), we propose several algorithms that have route stability and longevity in their focus. We show that this shift in focus comes with vastly improved end-to-end communication performance, and we discuss peculiar effects of the typical TCP-like implementations, taking inspiration from the Starlink constellation in our empirical investigations. The spectrum of algorithms proposed provides a basis for co-designing suitable orbital route selection algorithms and tailored transport control algorithms.**

***Index Terms*—Satellites, LEO Networks, Transport Layer**

of packets caused by overtaking, which can happen if the new route is shorter in delay. This can have a detrimental impact on communication reliability and efficiency [9], rooted in the fact that in every standard Transmission Control Protocol (TCP) implementation such a reordering is likely to lead to *duplicate acknowledgements (ACKs)*. But also changes to considerably slower routes can trigger adverse effects due to *timeouts* [10]. While the individual handling is partly up to the TCP variant, both effects tend to lead to a substantial reduction in the in-flight packet window size and hence a reduction in achievable data rate.

On the other hand, routing solutions tailored for satellite constellations can leverage the predictably periodic nature of orbital networks to address stability issues adeptly. This is in contrast to terrestrial mobile networks that also have dynamics, but which are less predictable as space constellations.

To the authors' knowledge, a route selection procedure that judiciously considers the instability inherent in routes within mega-constellations remains an open research topic [9]. In

[ICC 6GSatComNet'24]

Prediction-Aware Routing

[Stock et al., IEEE ICC 6GSatComNet 2024]

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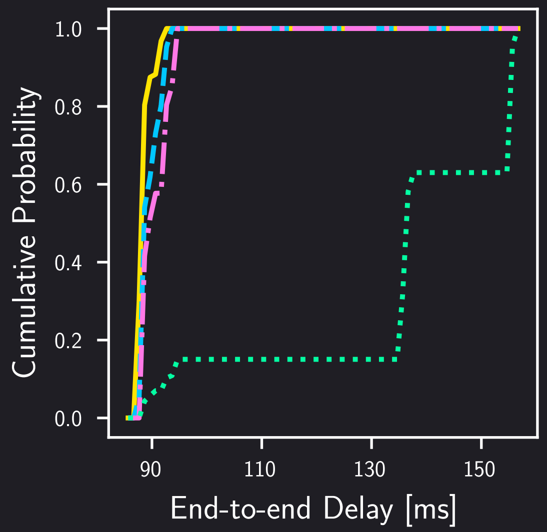

Σ Cumulative statistics

Bariloche to *Beijing* via Starlink

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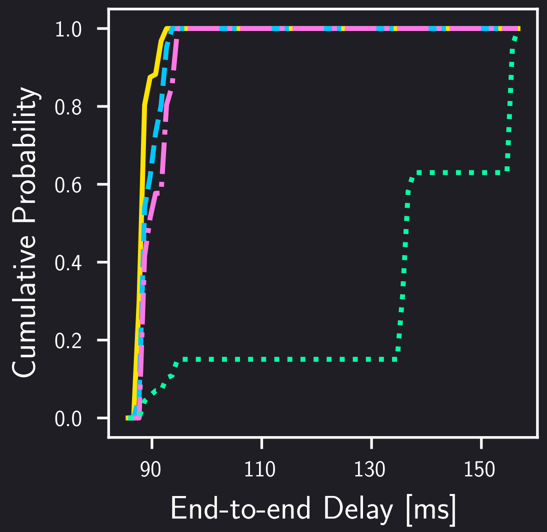

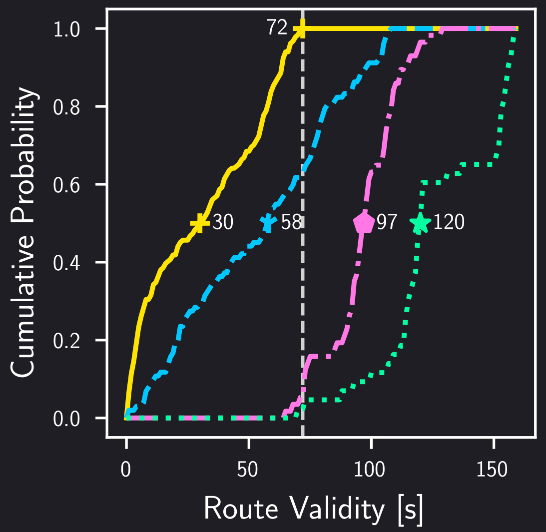

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- Routing changes can become more efficient.

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Questions

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Backup

X₁ Formalization

X_1 Formalization

Route r at Time t

- Bottleneck Datarate:

$$DR(r,t) = \min_{h \in hops(r)} DR(h,t)$$

- Round-Trip Time:

$$RTT(r,t) = \sum_{h \in hops(r)} RTT(h,t)$$

- Bandwidth-Delay Product:

$$BDP(r,t) = DR(r,t) \cdot RTT(r,t)$$

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$$\delta DR(b,a) = \frac{DR(a)}{DR(b)}$$

$$\delta BDP(b,a) = \frac{BDP(a)}{BDP(b)}$$

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Assumptions:
1) all flows in congestion avoidance
2) no flows join/leave

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(e.g. $\tau = 0.95$)

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Overtake/Timeout

Spurious Retransmission

QUIC (Overtake)

$\Delta RTT < -6 \cdot IPI$

TCP (Timeout)

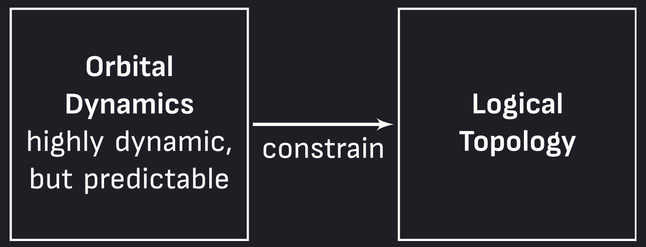
$\Delta RTT > 2 \cdot (RTO - IPI)$

Bird's Eye View

Orbital Dynamics
highly dynamic,
but predictable

OSI Layers: 1 – 3

Bird's Eye View



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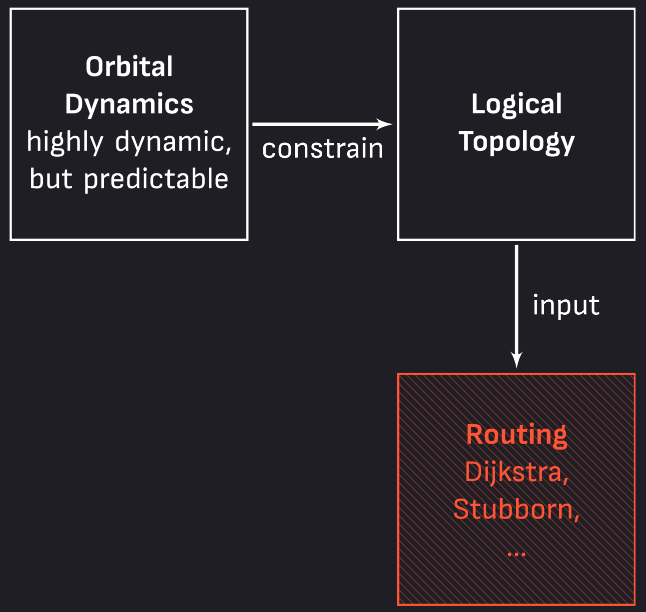

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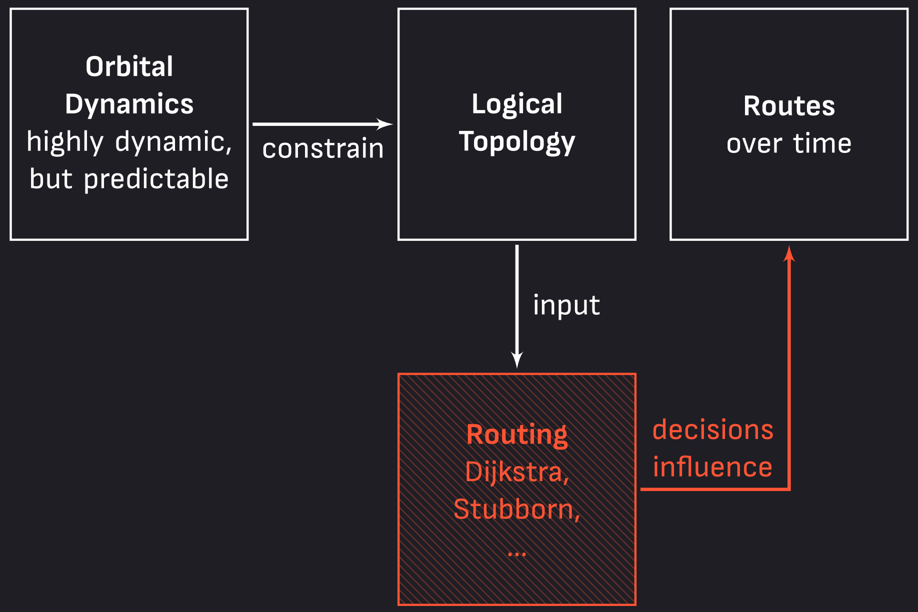

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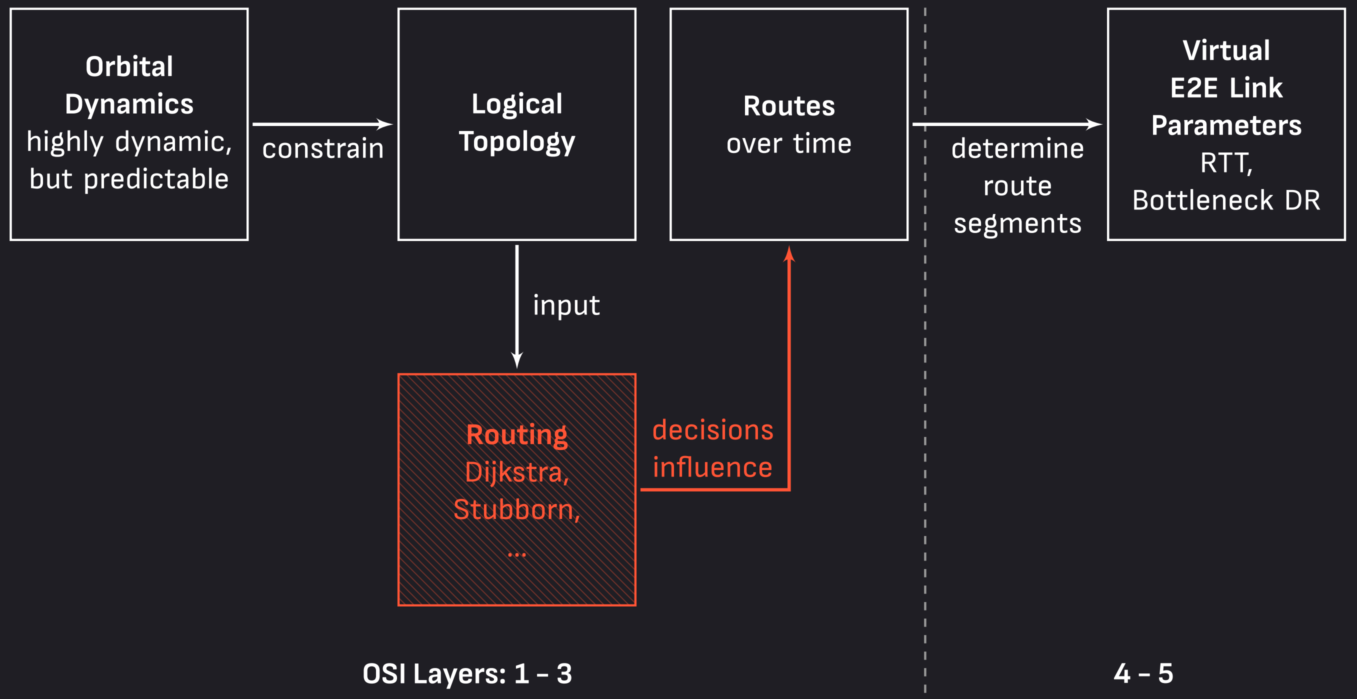

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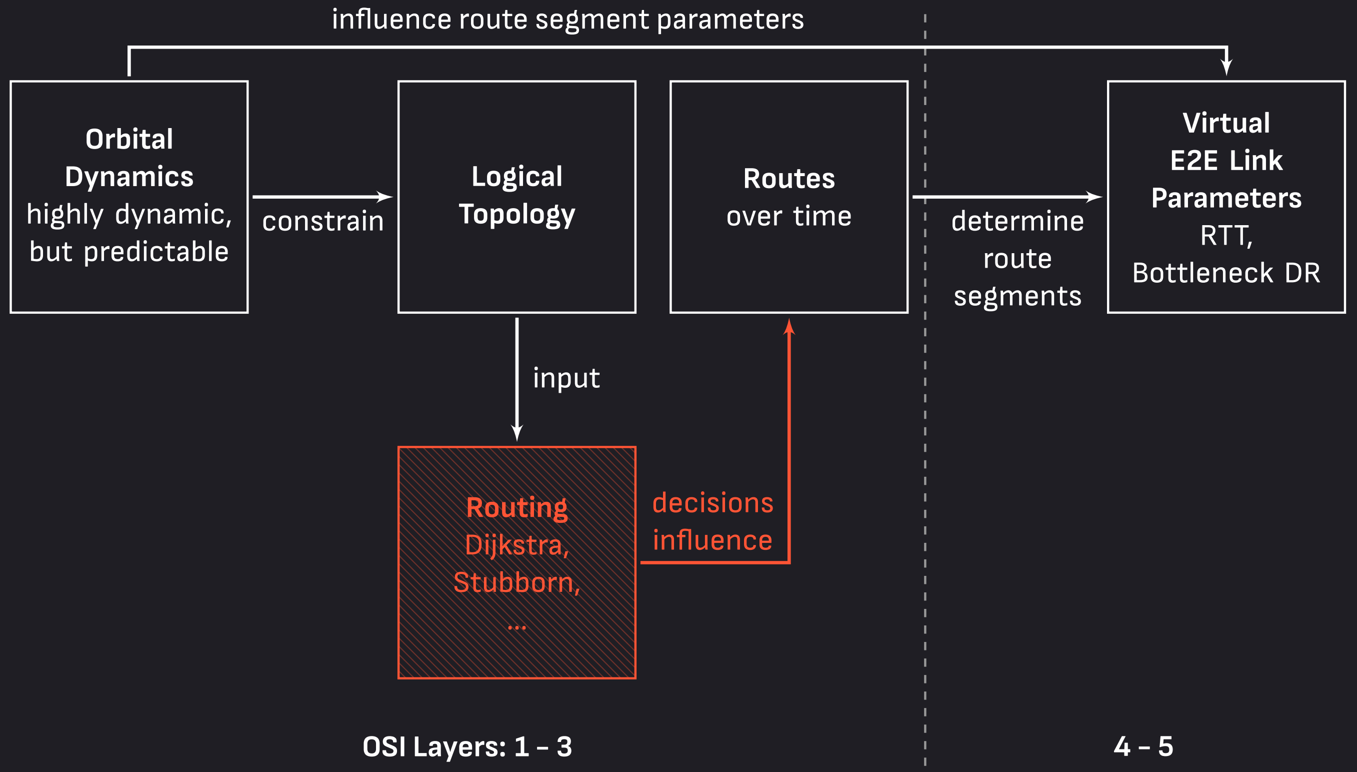

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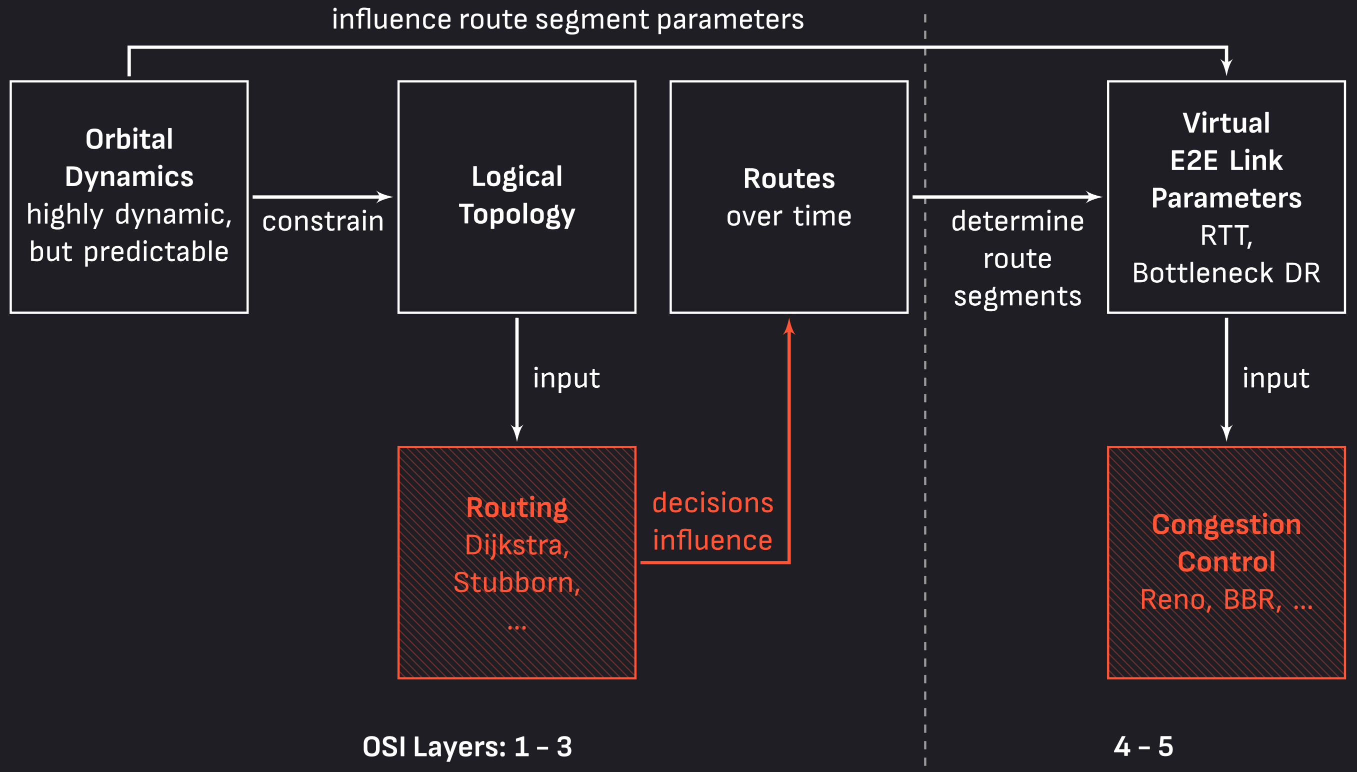

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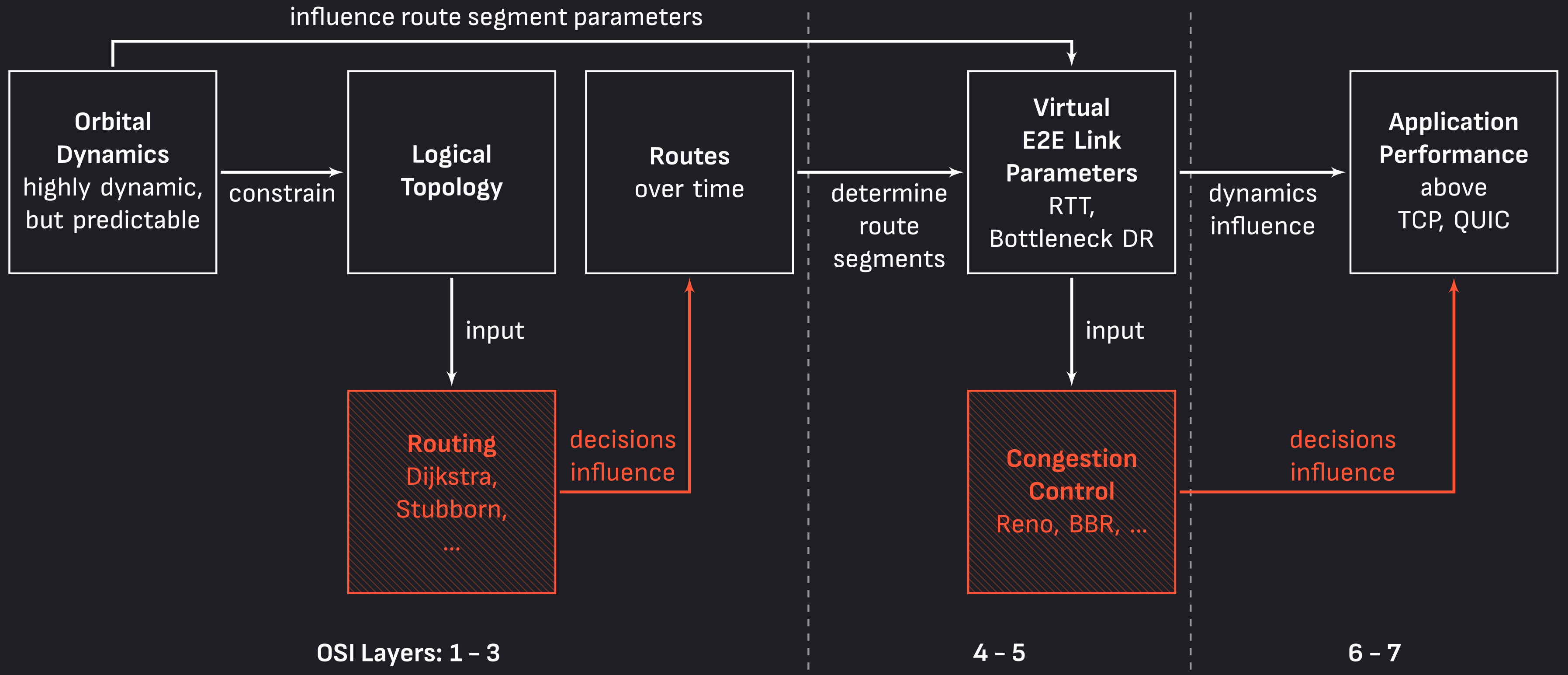

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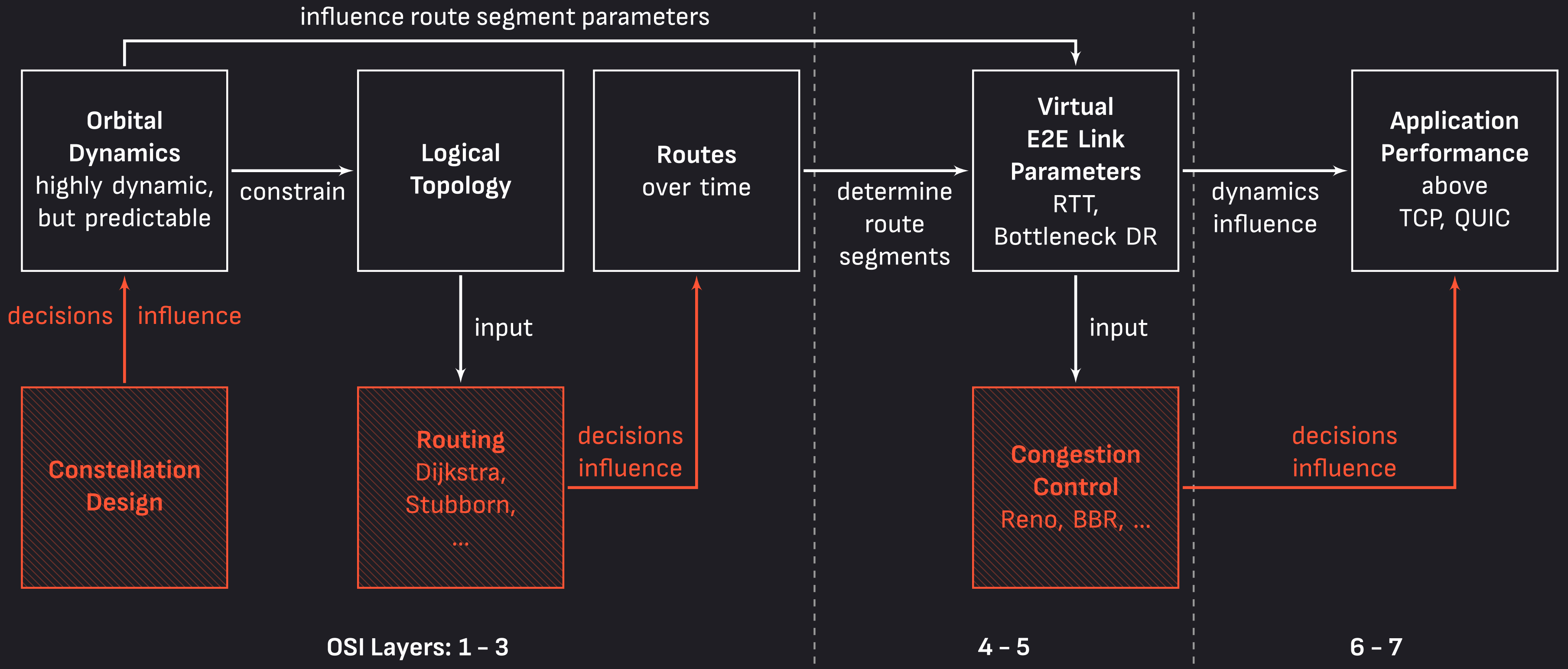

Ceci n'est pas une pipe

Our Research

ISLs ≈ GSLs

only link parameters, not type matters

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Our Research

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only link parameters, not type matters

StarLink*

Bent Pipe is enforced

upon reaching an Internet-GSL

* probably others as well