Delay and Buffer Bounds for QoS in Satellite Constellation Networks

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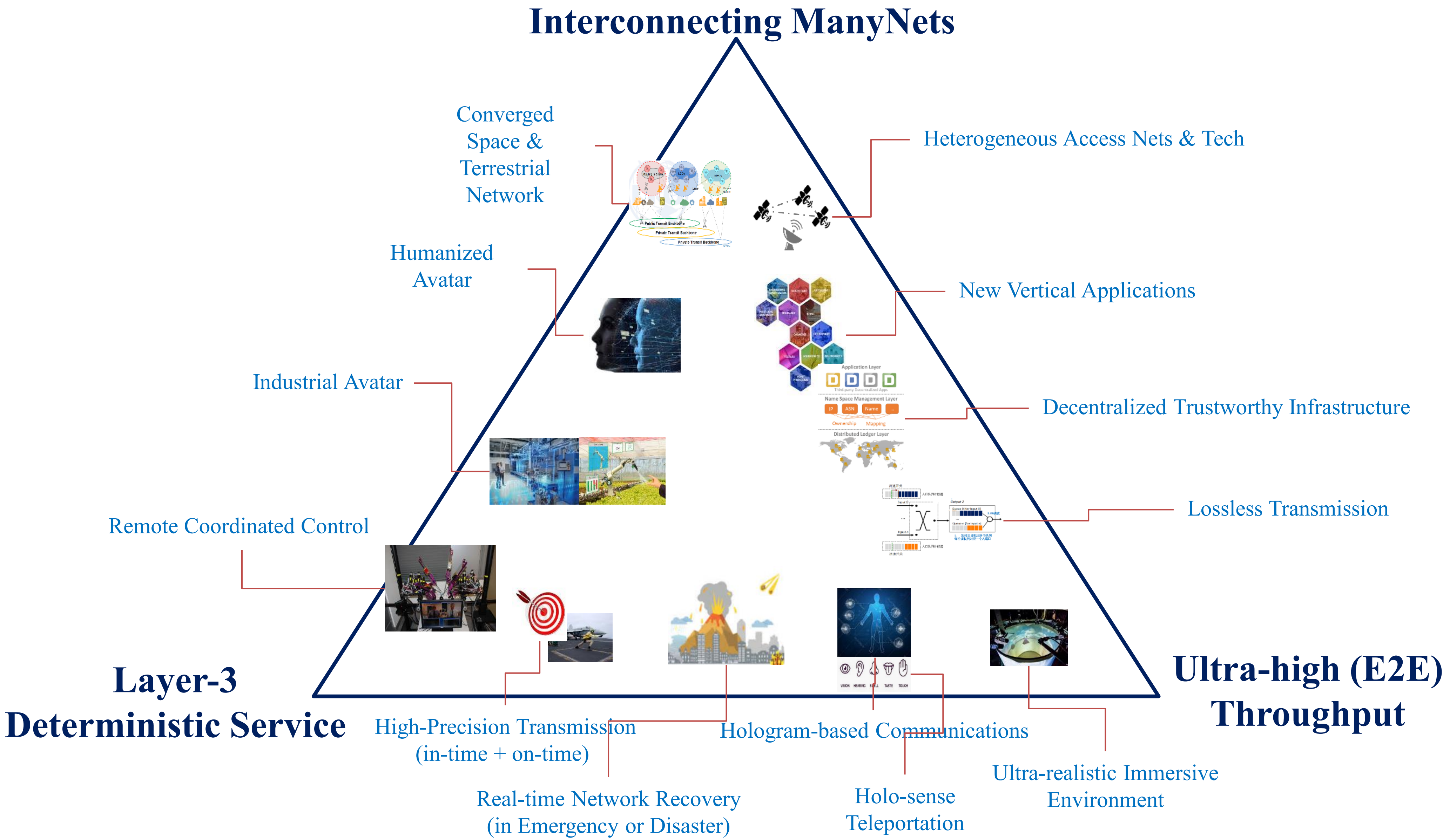
Requirements For Future Networks

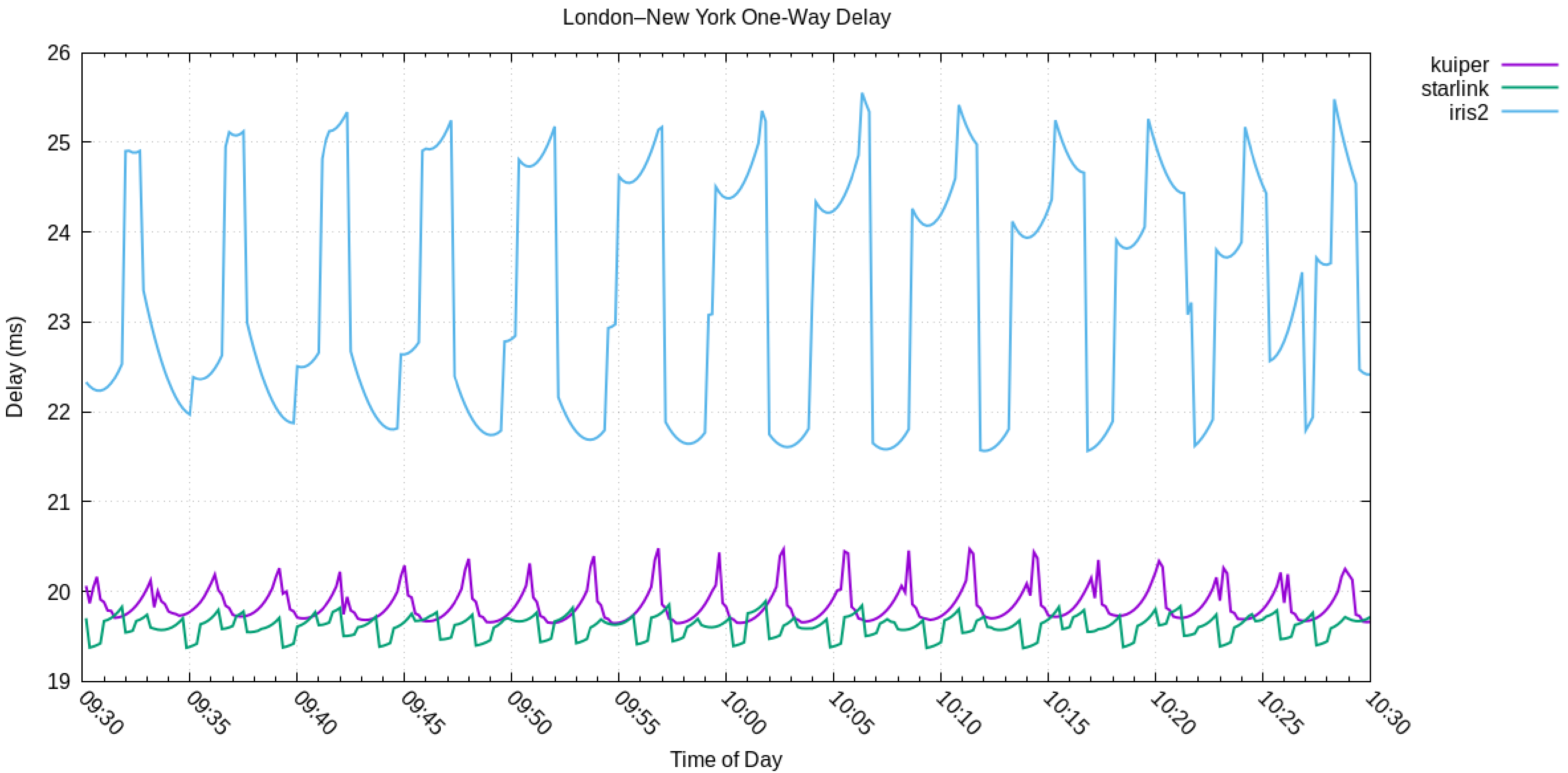


Example: Round-Trip Time for High Frequency Trading

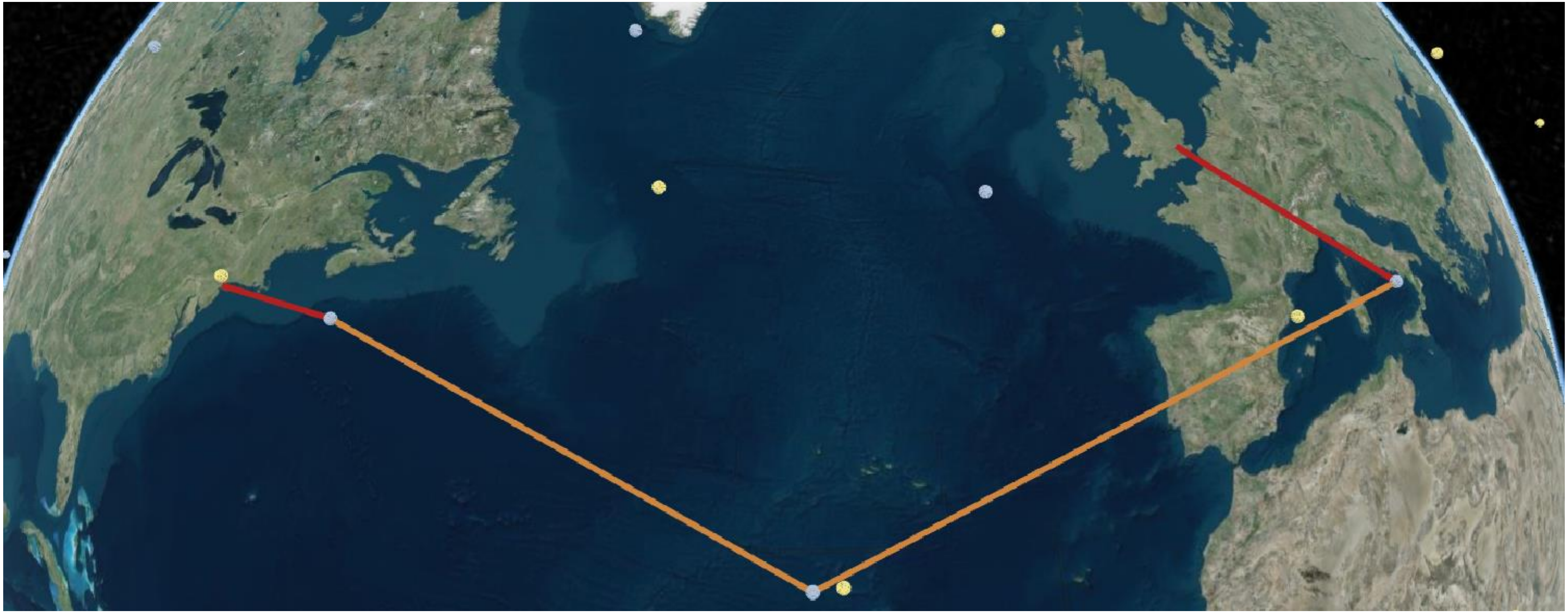
- Round-Trip Time with fiber :
  - **London and New York :**
    - Theoretically : *2 x 5 577 km x light speed * 0.66 = 55 ms*
    - Practical ping : *~75 ms*
  - **Sydney and New York**
    - Theoretically : *2 x 16 000 km x light speed * 0.66 = 161 ms*
    - Practical ping: *~200 ms*

https://news.satnews.com/2020/10/14/leo-speed-when-milliseconds-are-worth-millions-an-nsr-insight/

Delay Estimation With Modern Constellations

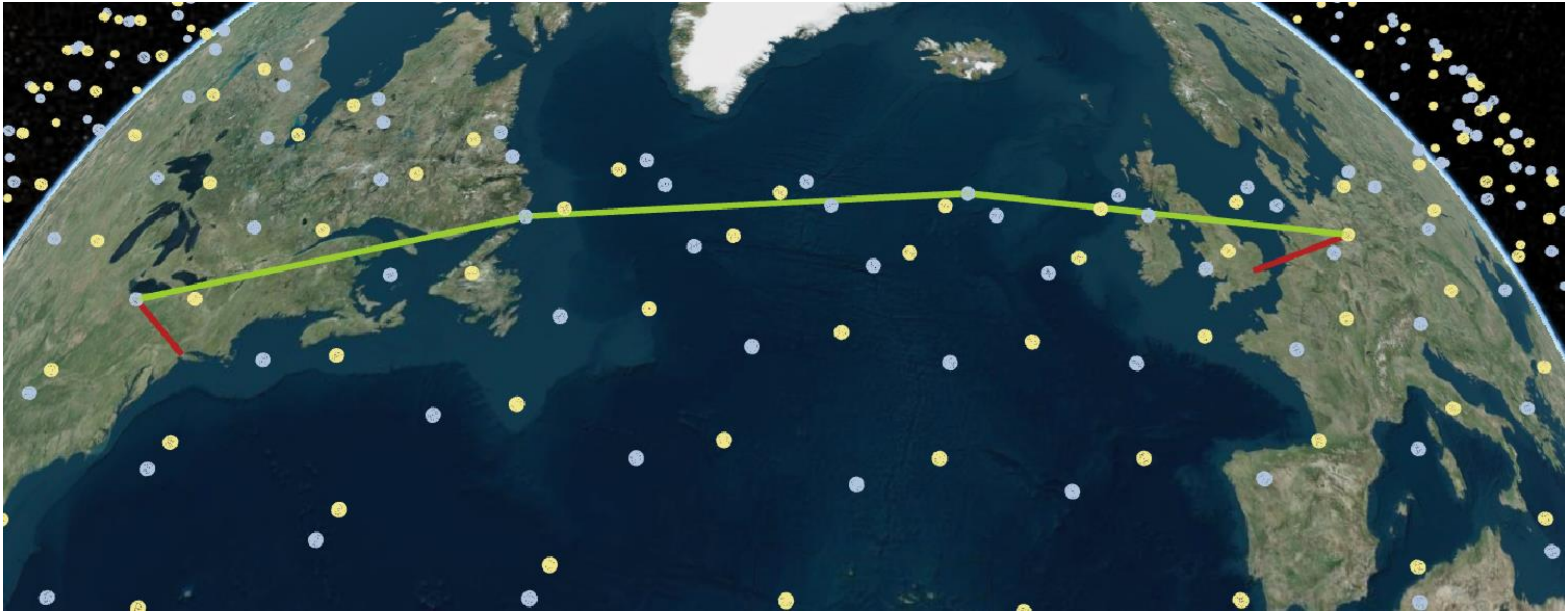


Iris² One Way Delay Test



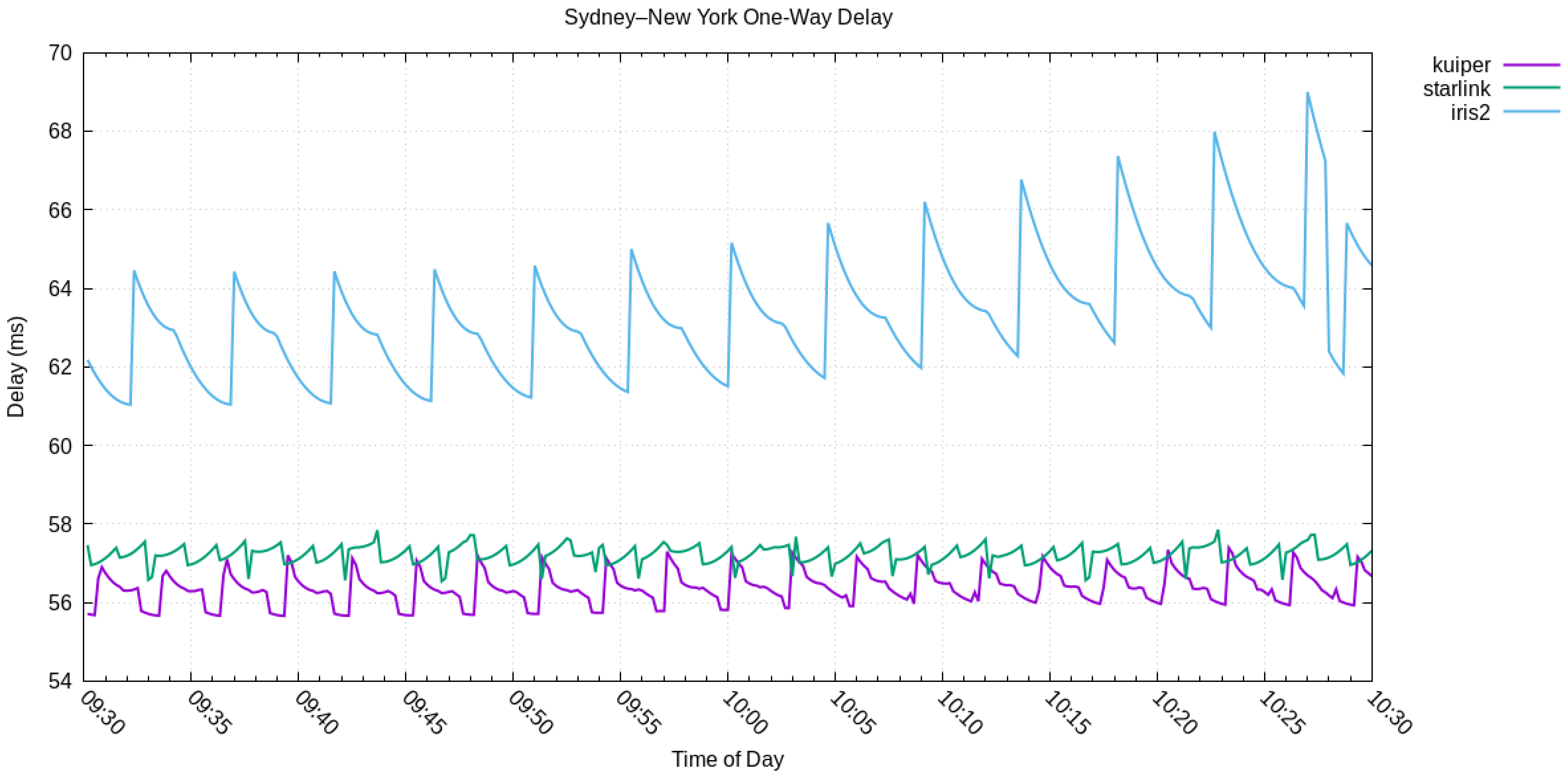
- Path length: 3 hops
- **Delay: 28ms**

Starlink One Way Delay Test

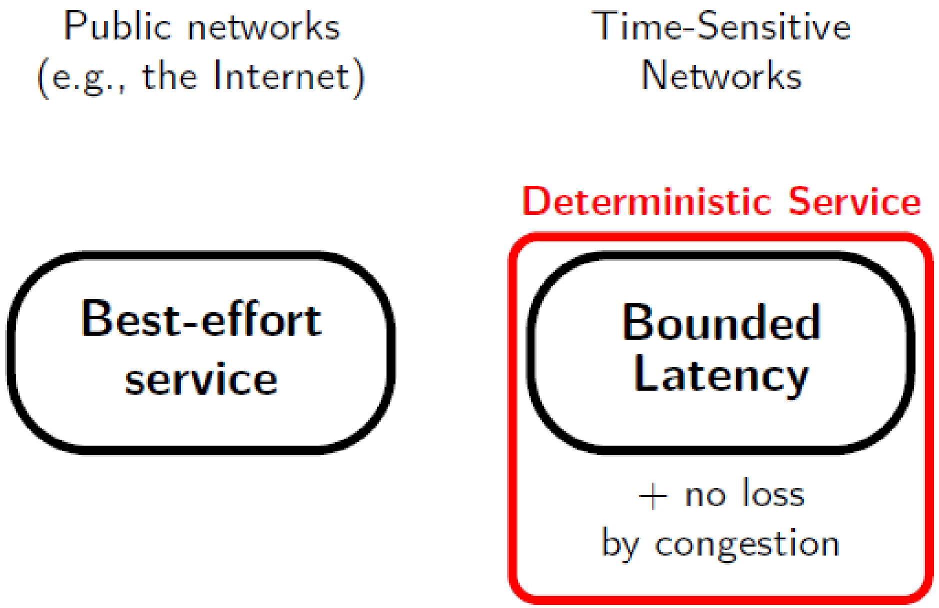


- Path length: 4 hops
- **Delay: 22ms**
- First hop is descending

Delay Estimation With Modern Constellations



Context and Motivation



IEEE *Time-Sensitive Networking* (TSN)
IETF *Deterministic Networking* (DetNet)

- Satellite Constellations will bridge the gap between both domains

$\Rightarrow$ Need deterministic guarantees on **end-to-end delays**
$\Rightarrow$ Need a method to compute guaranteed delays
$\Rightarrow$ **Network Calculus** is a potential solution commonly used for *Time-Sensitive Networks*

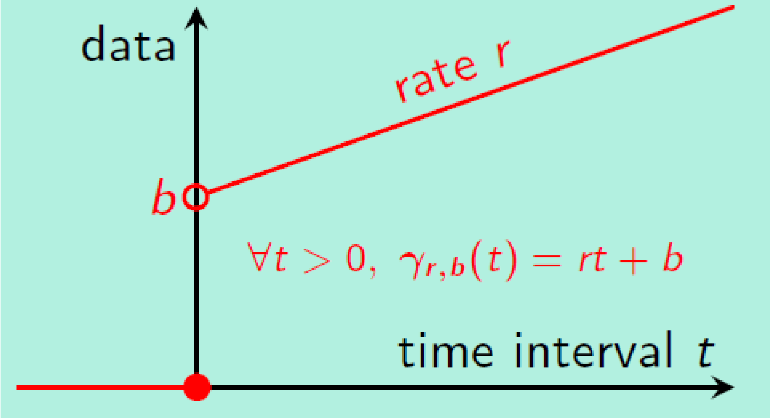
Network Calculus: Arrival and Service curves

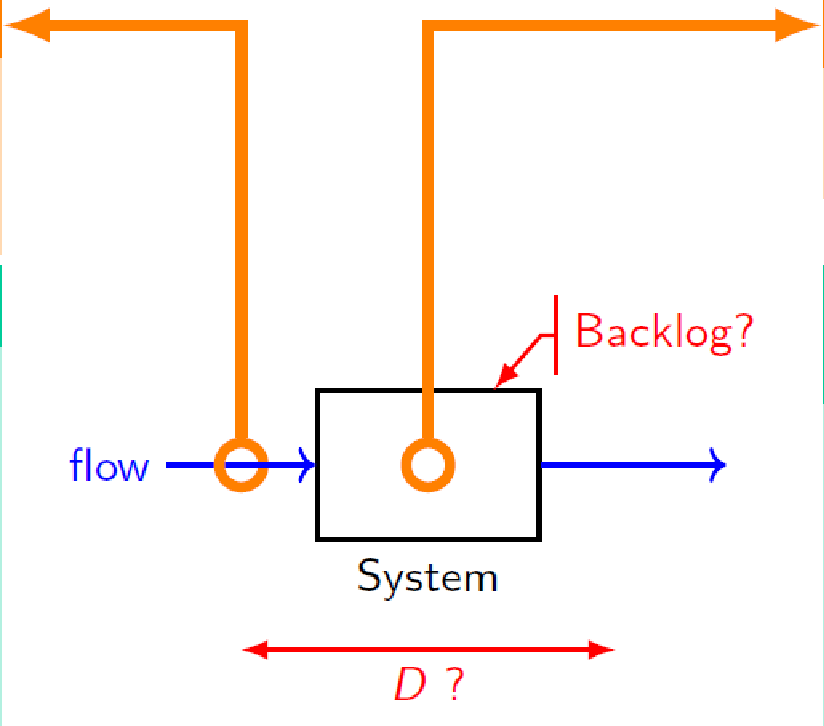
Network Calculus Relies on **Two Main Abstractions**

Arrival Curve α

upper-bounds the **maximum amount of traffic** of the flow over any interval

Leaky-Bucket $\gamma_{r,b}$



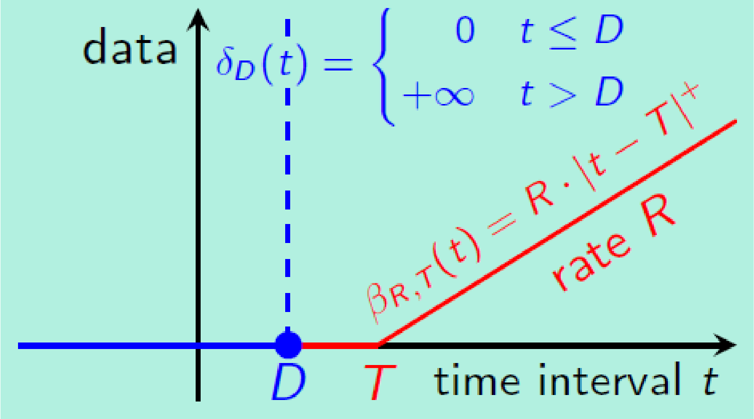


Guaranteed upper bounds?

Service Curve β

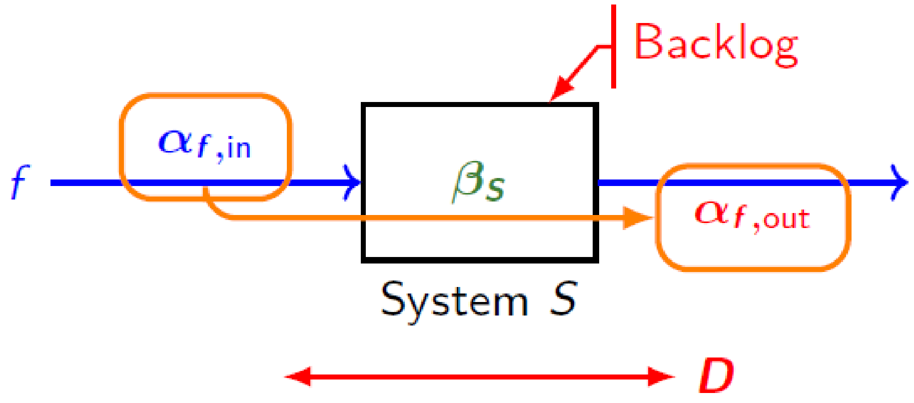
lower-bounds the **minimum amount of service** offered to the flow

Rate-Latency $\beta_{R,T}$
Bounded-Delay δ_D



$|\cdot|^+ = \max(0, \cdot)$

Network Calculus: Delay and Backlog Bounds

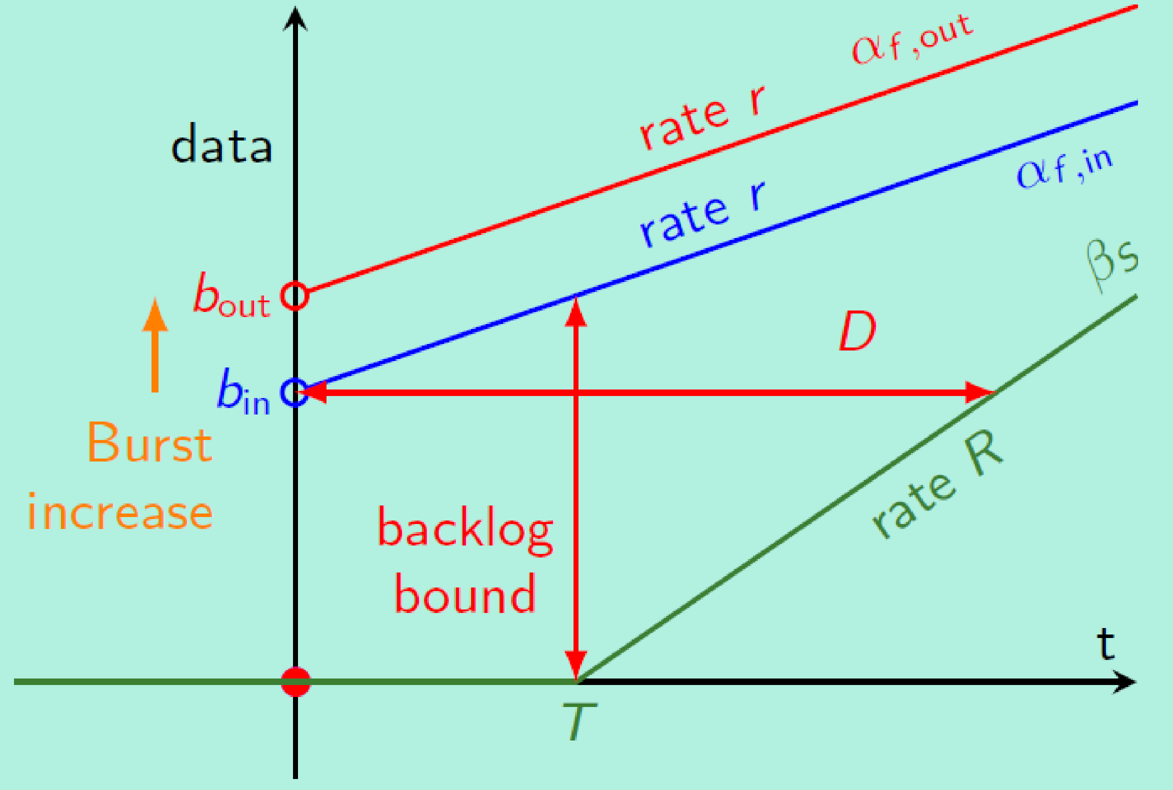


Network Calculus Main Result [Le Boudec, Thiran 2001]

Knowing $\alpha_{f,\text{in}}$ and β_S

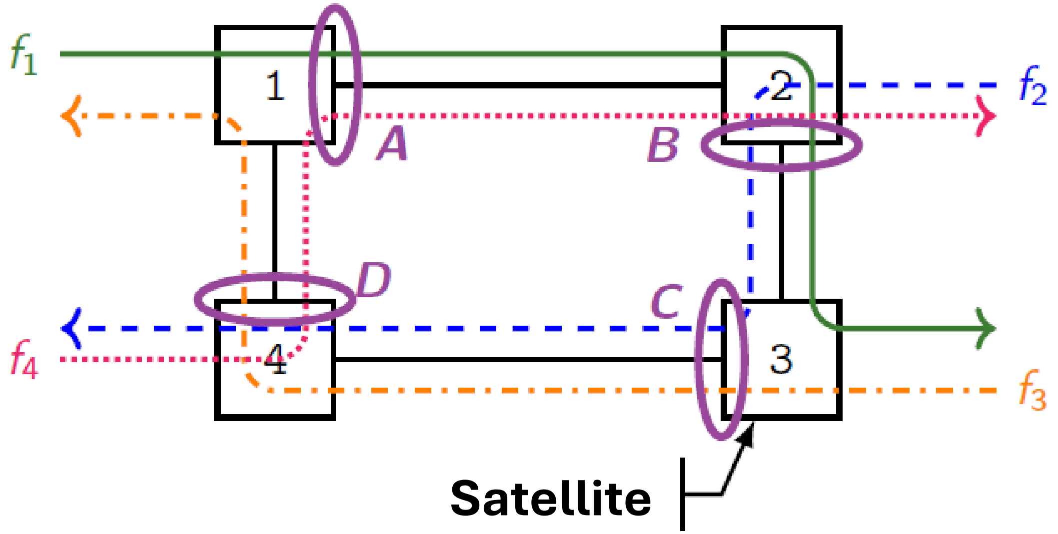
- Backlog upper-bound
- Delay upper-bound
- Output arrival curve $\alpha_{f,\text{out}} = \alpha_{f,\text{in}} \oslash \beta_S$

Leaky-bucket $\gamma_{r,b}$ and Rate-Latency $\beta_{R,T}$

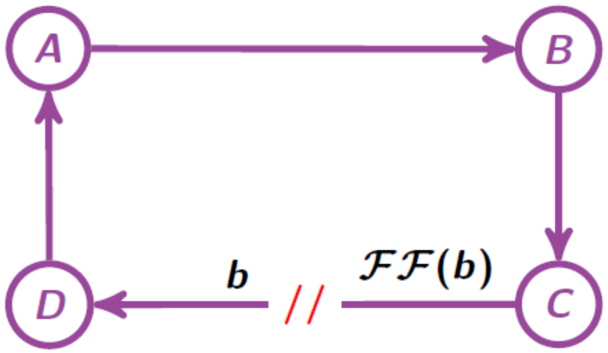


– [Le Boudec, Thiran 2001] Jean-Yves Le Boudec and Patrick Thiran [2001]. *Network Calculus: A Theory of Deterministic Queuing Systems for the Internet*. Berlin Heidelberg: Springer-Verlag. ISBN: 978-3-540-42184-9

Network Calculus Concepts: Cyclic Dependencies



Leaky-bucket-constrained flows, **cuts** and **fixed-point**.



Theorem (Validity of the fixed-point)

If the network is **initialy empty**, and if $\overline{b}$ is non negative and such that $\mathcal{FF}(\overline{b}) = \overline{b}$, then the network is stable and $\overline{b}$ is a valid bound for the bursts at the cuts.

➢ A possible consequence of the multi-path topology are **cyclic dependencies**

$\Rightarrow$ **Fixed Point Total Flow Analysis [Thomas et al. 2019]**

[Thomas et al. 2019] Ludovic Thomas, Jean-Yves Le Boudec, and Ahlem Mifdaoui [Dec. 2019]. "On Cyclic Dependencies and Regulators in Time-Sensitive Networks". In: *2019 IEEE Real-Time Systems Symposium (RTSS)*. DOI: 10.1109/RTSS46320.2019.00035

Use Case Description and Metrics

Assumptions:

- Constellation parameters: i=70° , P=12, Q=22
- Unicast communications
- Shortest path routing
- Mixed traffic with max utilization load of 40%

Scenarios:

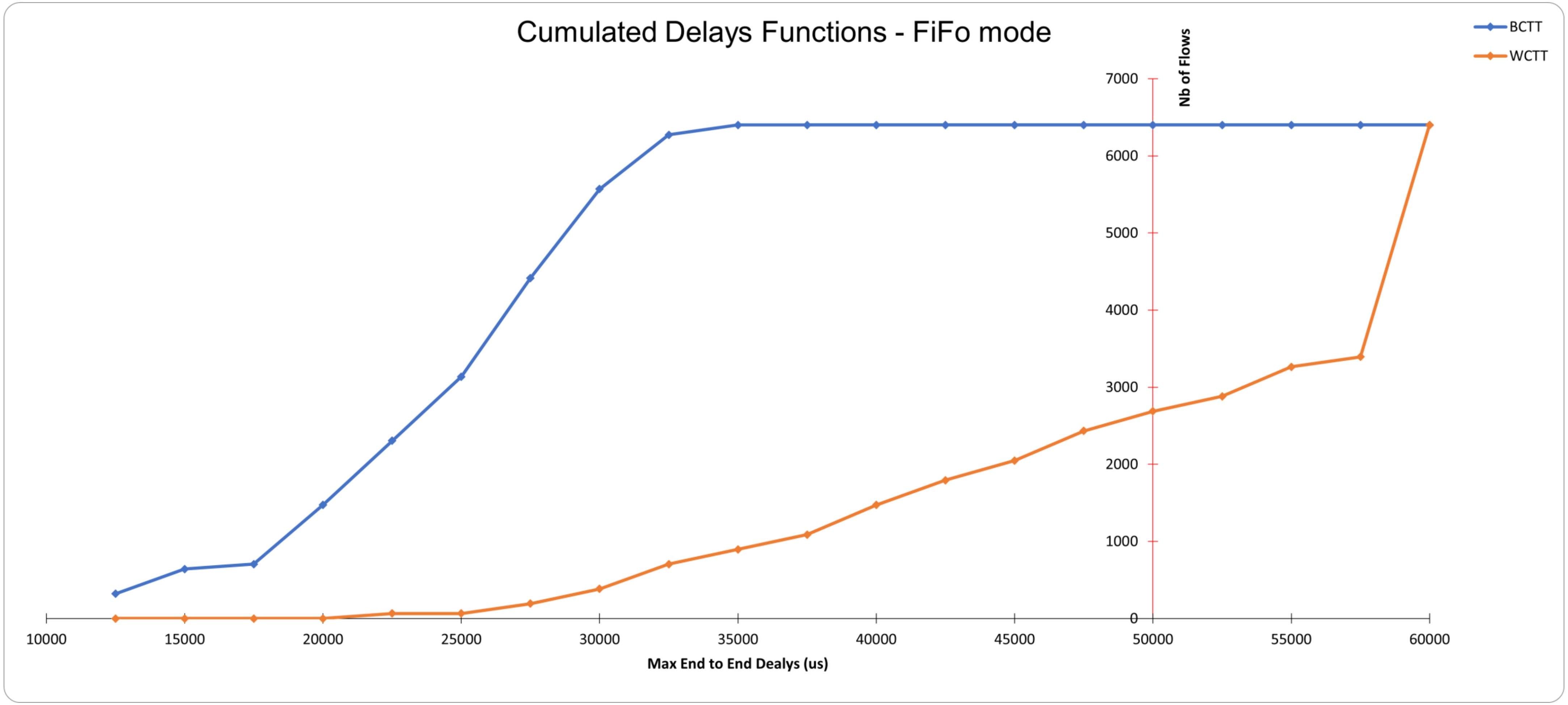
- **FIFO** and **FP (QoS)** policies within satellites
- Compute **min end-to-end delays** for critical flows (transmission + propagation)
- Compute **max end-to-end delays** for critical flows

Objectives:

- Measure the contention impact on guaranteed performance
- Measure Potential improvement with QoS mitigation

Class	Prio.	Description	Payload (bytes)	Freq. (Hz)	Time constraint
Critical	6	Small messages and critical,e.g., trading	32 to 96	1000 Hz	50 à 200 ms
Voice	5	big messages, e.g., voice	1500	50 Hz	500 ms
Video	3	Bursty and big messages, e.g., video	Bursty with many packets of 1500	50 Hz	2 s
Best Effort	0	File and monitoring messages	Thousands of packets of 1500	1 Hz	N.A.

Max/Min Delays under FIFO for Critical Data

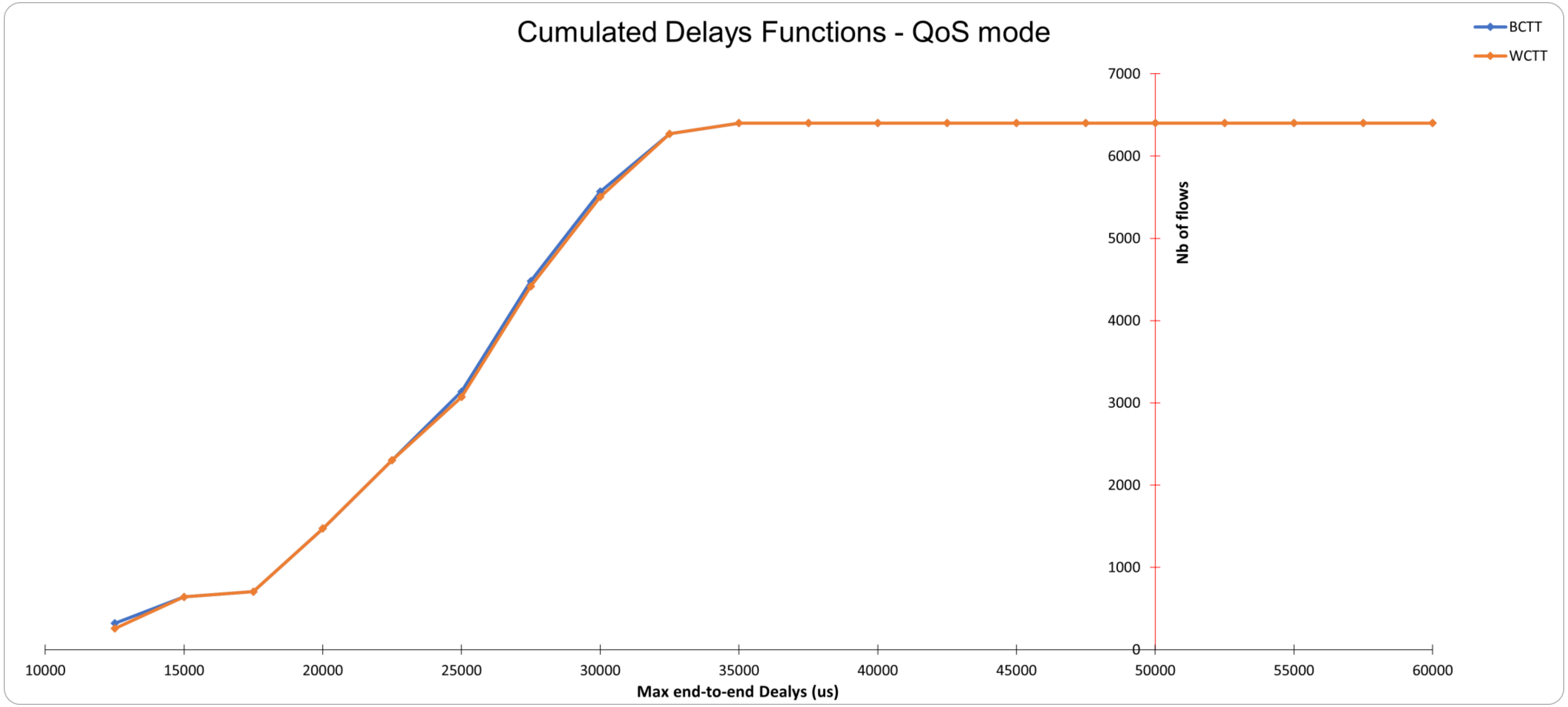


✓ **The impact of contention is high**

⇒ **where all critical flows have min delays <= 50ms**

⇒ **but only 42% have max delay <= 50ms**

Max/Min Delays under QoS for Critical Data



✓ **The performance is highly improved under QoS mitigation**

⇒ **The max delay increase is neglectable due to contention when critical flows have the highest priority**

⇒ **Max and Min delays are similar where all critical flows have end-to-end delays <= 50ms**

To go Further

- Need deeper analysis of QoS impact on performance guarantees

- Need to explore smarter routing algorithms to have further improvements of performance guarantees