



# Large-Scale Time-Sensitive Networks with End-to-end Deterministic Service Requirements

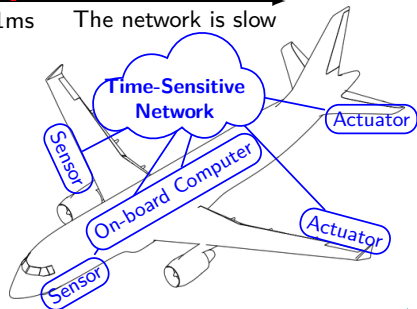
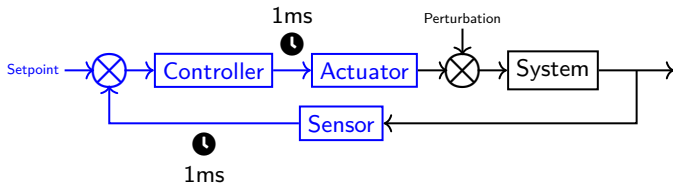
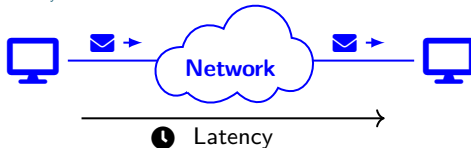
Presentation at RMESS, Toulouse

Ludovic Thomas

October 6th, 2026

## In this Presentation:

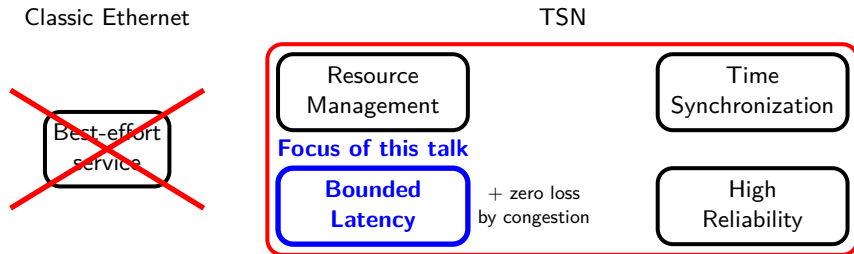
- 1 Layer-2 Time-Sensitive Networks
- 2 DetNet: L3 Deterministic Networking
- 3 FRONTIER or The Need For Large-Scale Time-Sensitive Networks
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- 5 Conclusion



Cyber-physical Systems (CPS)

## Time-Sensitive Networks

**IEEE time-sensitive networking (TSN):** the Ethernet for safety-critical applications (layer 2)

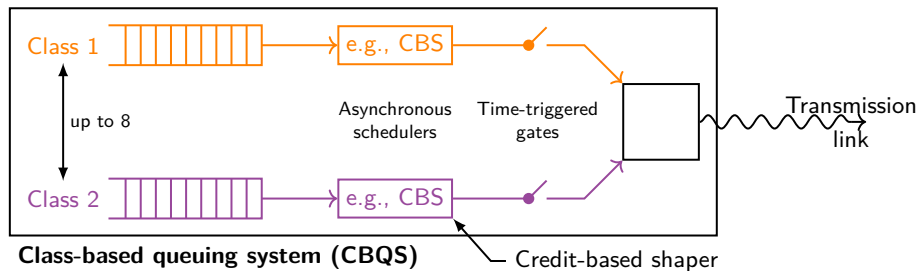


The four “key components” of TSN [farkasTSNBasicConcepts2018a]

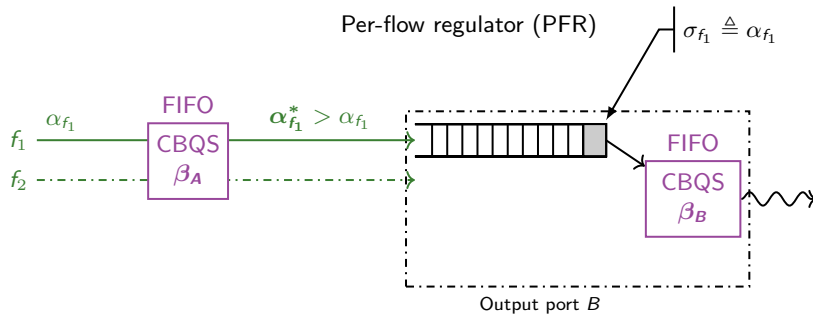
Similar ideas in **IETF deterministic networking (DetNet)** for IP and MPLS networks (layer 3) [RFC 8655]

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- [Farkas 2018] János Farkas [Nov. 11, 2018]. “TSN Basic Concepts”.
  - [RFC 8655] Norman Finn, Pascal Thubert, Balazs Varga, and János Farkas [Oct. 2019]. *Deterministic Networking Architecture*. Request for Comments RFC 8655. Internet Engineering Task Force. DOI: 10.17487/RFC8655

## Class-Based Queuing Mechanisms improve the Classic Ethernet Output Port

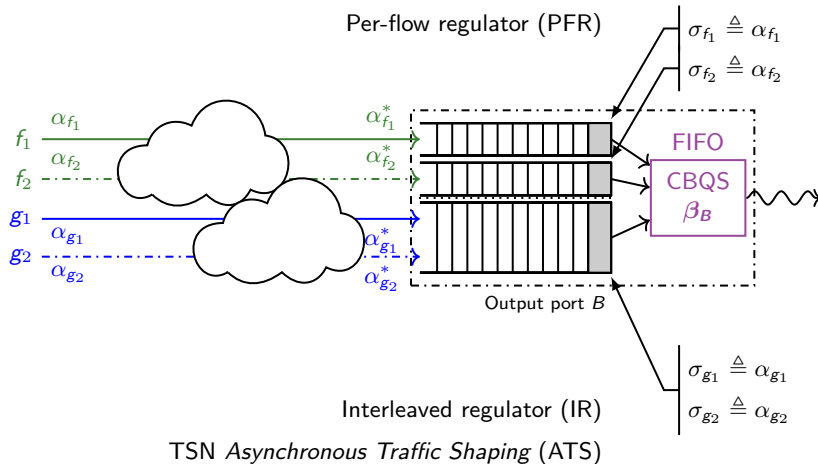


## Within One Class, **Traffic Regulators** Allow for a Per-Flow Control



CBQS: Class-based queuing system (FIFO for the class aggregate)

## Within One Class, **Traffic Regulators** Allow for a Per-Flow Control



CBQS: Class-based queuing system (FIFO for the class aggregate)

**Focus of  
this talk**

**Bounded  
Latency**

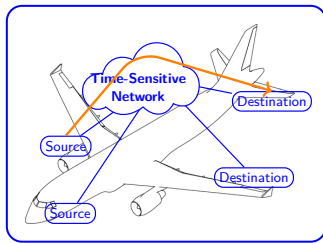
**Analysis ?**

**Class-based queuing mechanisms:**

- Asynchronous schedulers
- Time-triggered gates

**Traffic regulators:**

- Asynchronous Traffic Shaping (ATS)

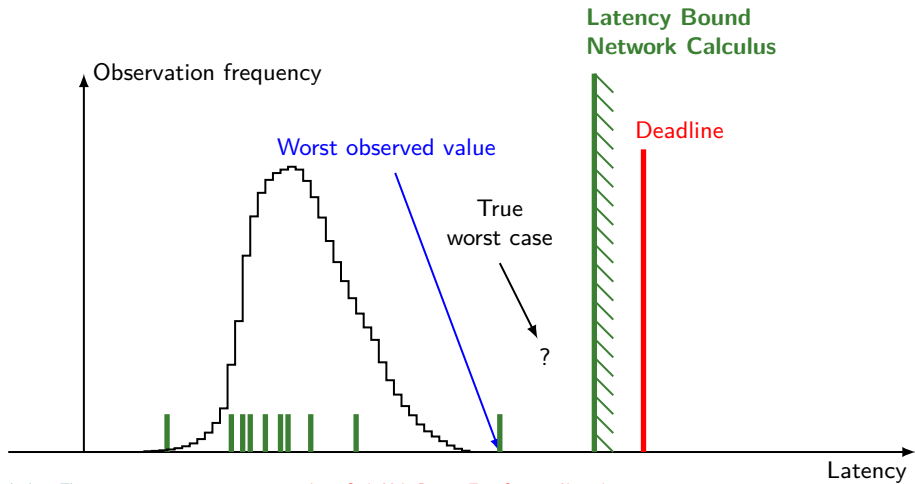


System owner  
(ex: Airbus)



Certification authority  
(ex: European Aviation Safety Agency)





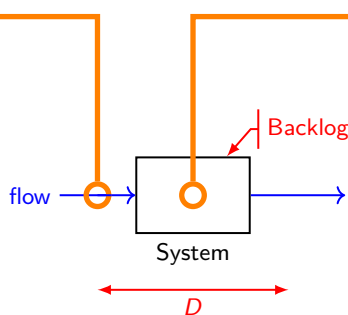
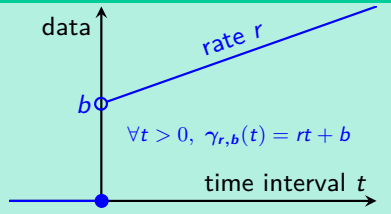
## Network Calculus Provides a **Model-Based** Analysis and **Verification**

Two examples of models:

### Arrival Curve $\alpha(t)$

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

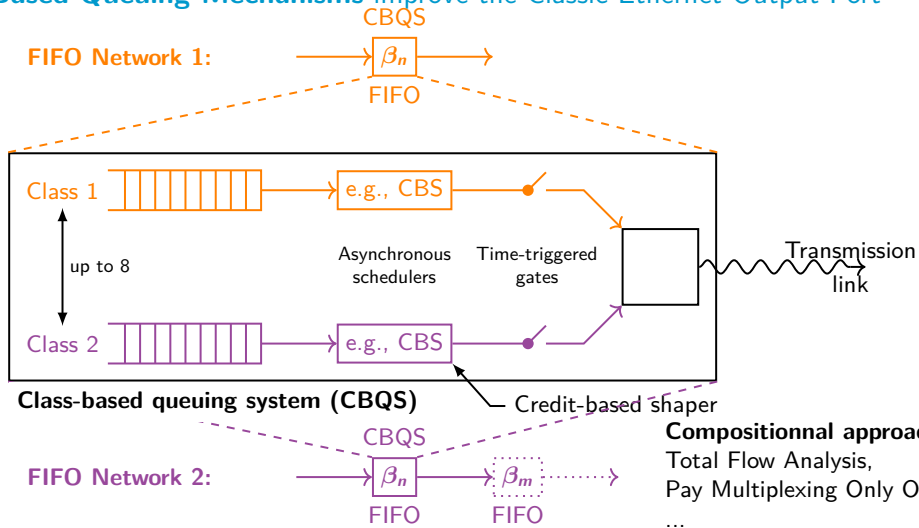
### Leaky-Bucket $\gamma_{r,b}$



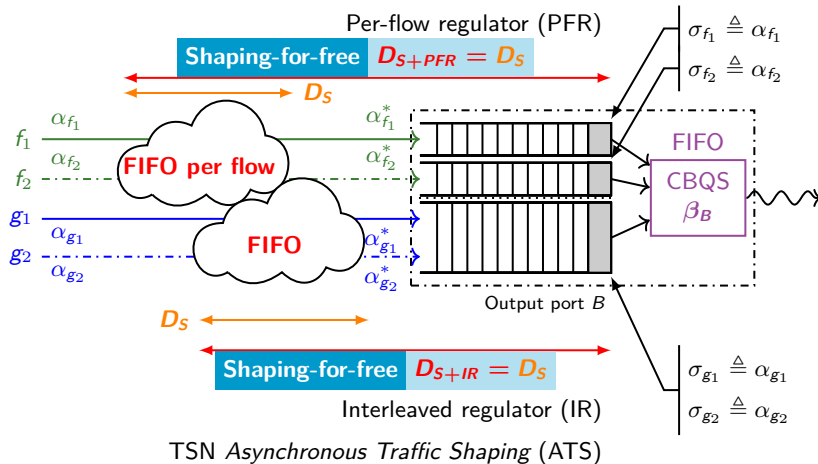
### Service Curve $\beta(t)$

captures the **minimum service** guaranteed to the flow by the system over any interval

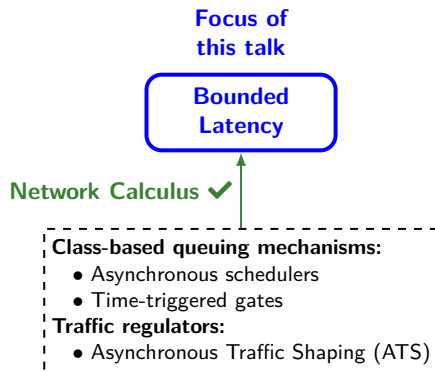
# Class-Based Queuing Mechanisms improve the Classic Ethernet Output Port



## Within One Class, Traffic Regulators Allow for a Per-Flow Control



CBQS: Class-based queuing system (FIFO for the class aggregate)



## Conclusion: Status of L2 Time-Sensitive Networks

- The A380, the A400M, and the A350 fly with AFDX networks, certified with Network Calculus.
- IEEE TSN is being deployed in Industry Automation, In-Vehicle Networks, etc.
- Network Calculus is versatile enough to also analyze other L2 time-sensitive networks: 5G, etc

Need a national experimental platform to test configurations & new or modified mechanisms ?

### Remaining Issues

- IEEE TSN is complex, industrials need easy-to-use configuration tools.
- Some TSN mechanisms need to be amended to fix issues identified by academia.
- Most industrials only need a fraction of IEEE TSN's capabilities.
- Need for interactions between technologies (TSN - 5G).

Join SCLICES-FR's *thematic group for expressing needs in time-sensitive networks* (GTEB-temps réel).



- 1 Layer-2 Time-Sensitive Networks
- 2 **DetNet: L3 Deterministic Networking**
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## DetNet: L3 Deterministic Networking

Use-cases are available in [RFC 8578].

### Excerpt from DetNet's charter

*The Working Group will initially focus on solutions for networks that are under a single administrative control or within a closed group of administrative control; these include not only campus-wide networks but also private WANs.*

Campus-wide networks are not very “large”, how about nationwide or continental networks?

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– [RFC 8578] [Ethan Grossman \[May 2019\]](#). *Deterministic Networking Use Cases*. [Request for Comments RFC 8578](#). Internet Engineering Task Force. DOI: [10.17487/RFC8578](#)

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## The Needs

### Why do we **not** need large-scale time sensitive networks?

Because physical phenomena have a maximum propagation speed (a plane has a maximum speed, we don't need to connect its take-off and landing airports with time-sensitive networks).

But there is at least one CPS where physical phenomena propagate at the speed of light: the **Electrical Grid**.

## The Continental Europe Synchronous Area (CESA)

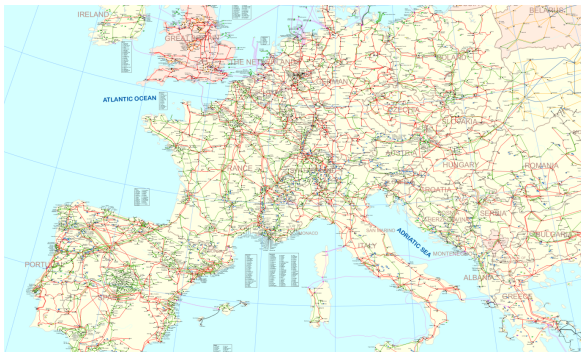


**Figure:** Continental Europe Synchronous Area. From ENTSOE.

The CESA is an AC grid with nominal frequency of **50 Hz**. The grid is stable (remains  $\sim 50\text{Hz}$ ) if at any point in time, the **power generated equals the power consumed**.

Overproduction  $\rightarrow$  frequency increases.  
Underproduction  $\rightarrow$  frequency decreases.

Frequency must remain within  $\pm 0.2\text{ Hz}$  of the nominal frequency, and electrical equipments start to disconnect if the frequency goes beyond  $\pm 1\text{ Hz}$ .

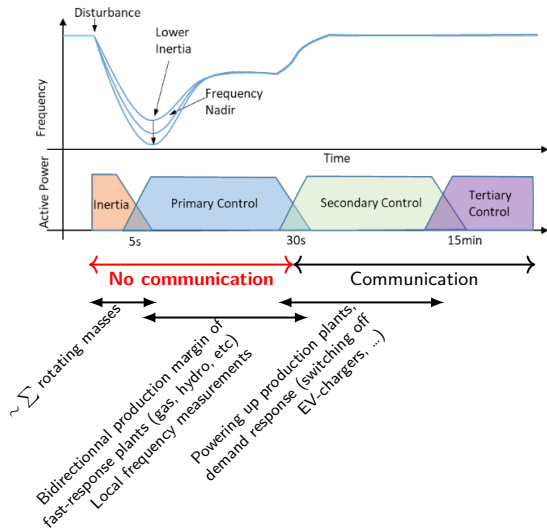
See <https://mainsfrequency.com/>.

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NB: Since March 16th, 2022, Ukraine is also connected to CESA.

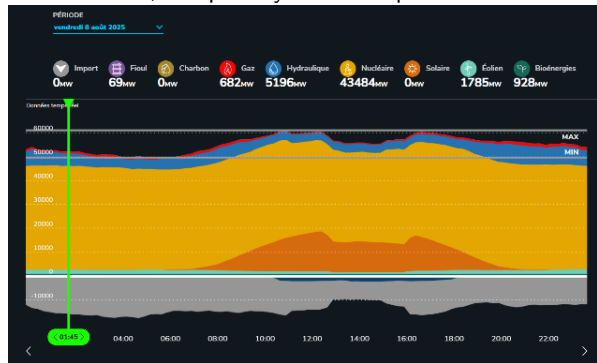
# Grid Stability 101

## Today's Stability Principles:



## Two Upcoming Issues:

- ⇒ Higher share of intermittent renewable energy sources
- less inertia, less primary-control capabilities.



Curtailment of renewable energy sources in summer.

⇒ Primary control does not consider powerline limits.

## Grid Stability in the Future

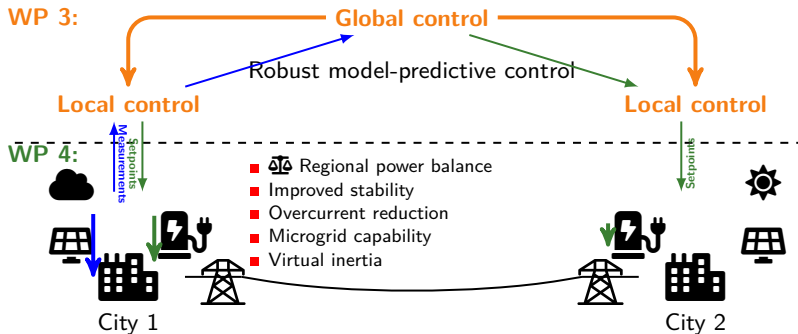
### ***Futurs Énergétiques 2050 - Principaux Résultats. [RTE 2022]***

- *"All scenarios towards carbon neutrality in 2050 require the deployment of demand-response flexibilities" (e.g., EV chargers)*
- Need for services of fast frequency response (e.g., based on demand response)
- *"The role of digital technologies will be increasingly important in the real-time management of a complex electrical system composed of more dispersed and weather-dependent generation resources"*

# FRONTIER (PEPR Future Networks)

**Future real-time networks  
towards the balance of large-scale  
cyber-physical systems and their optimization.**

LORIA  
ISAE-SUPAERO  
LIP6  
IRISA  
G2ELAB



## FRONTIER (PEPR Future Networks)

Recall from DetNet's Charter

### Excerpt from DetNet's charter

*The Working Group will initially focus on solutions for networks that are under a **single administrative control or within a closed group of administrative control**; these include not only campus-wide networks but also private WANs.*

How do we reach a continental scale with remotely-accessible devices (offshore windturbines, etc) within a single administrative control ?

# FRONTIER (PEPR Future Networks)

Future real-time networks  
towards the balance of large-scale  
cyber-physical systems and their optimization.

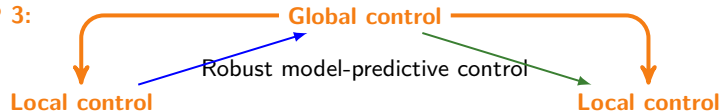
WP 1:



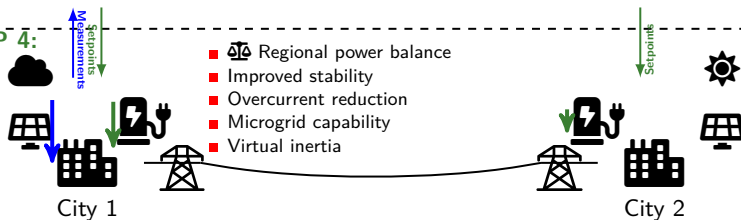
WP 2:



WP 3:



WP 4:



Specification,  
modeling

Performance  
analysis

Experimental  
validation

LORIA  
ISAE-SUPAERO  
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## DetNet's Strongest Limitation

### Excerpt from DetNet's charter

*The Working Group will initially focus on solutions for networks that are under a **single administrative control or within a closed group of administrative control**; these include not only campus-wide networks but also private WANs. **The DetNet WG will not spend energy on solutions for large groups of domains such as the Internet.***

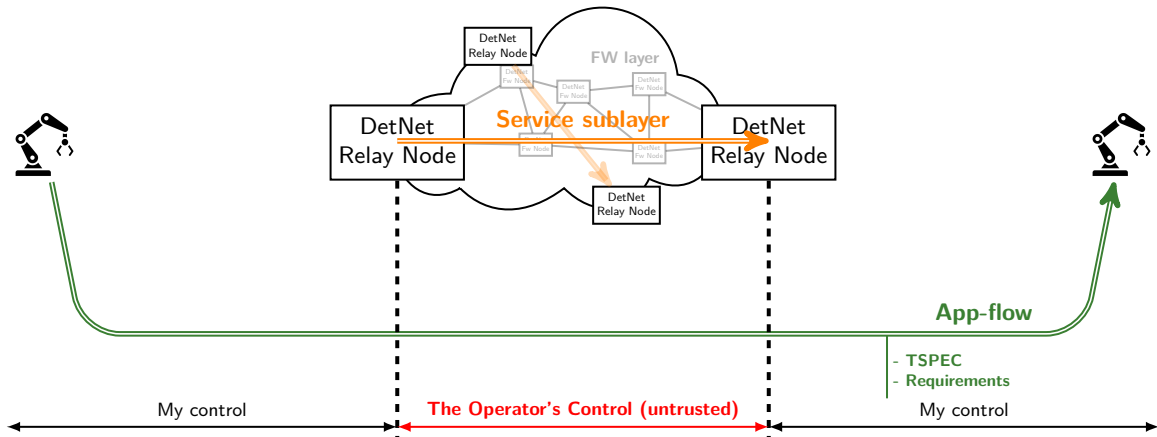
That's too bad....

### But we shall not forget why ATM, IntServ, etc. failed at being deployed at large scale

- Multiple administrative entities **do not trust each other** and **do not want to share their network's configuration**.
- The best-effort model of the Internet allows for interconnecting trustless networks.
- On the Internet, contractual agreements (SLAs) can be verified through monitoring stochastic quantities (means, 95% values etc.)  $\Rightarrow$  this is not sufficient for deterministic service agreements (DSA).

Can we find a solution for deterministic service agreements (DSA)?

# Trustless Deterministic Networking with **Customer Privacy** and **Confidential Configuration**



Network calculus can check the deterministic requirements but it requires the complete knowledge of the traffic and the network configuration. Only the operator has this knowledge. I (as a client) don't trust the operator.

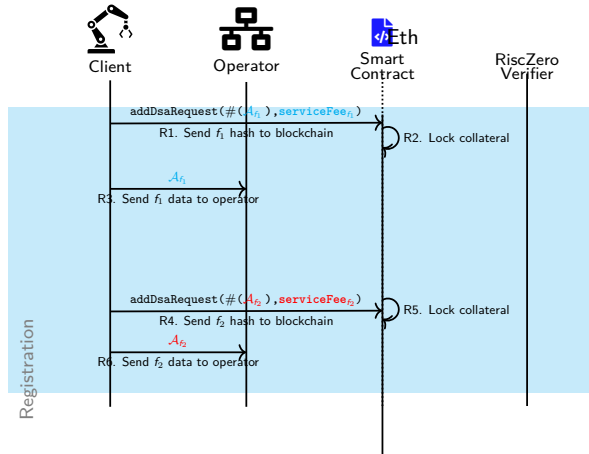
**Pieces of solution:** Zero-knowledge network-calculus proofs and smart contracts.

# DNaaS: Deterministic Network as a Service [Amet, Thomas, Song 2026]

Registration

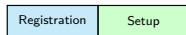
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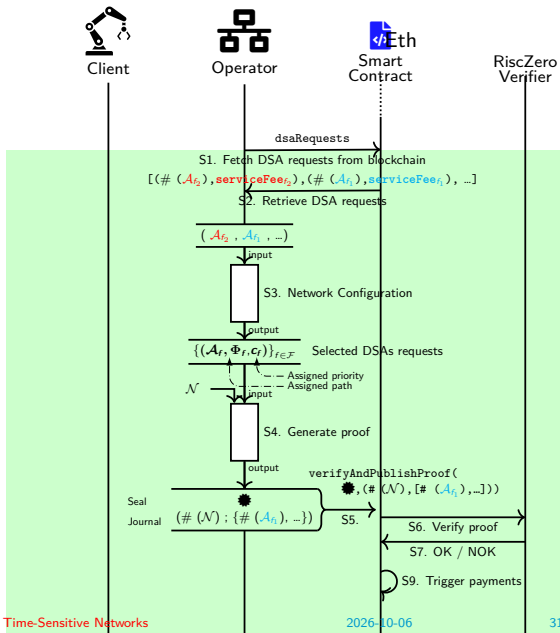
– [Amet, Thomas, Song 2026] [Matthieu Amet, Ludovic Thomas, and Ye-Qiong Song \[May 2026\]. “DNaaS: Towards Scalable and Trusted Time-Sensitive Networks”. In: IEEE INFOCOM 2026 - IEEE Conference on Computer Communications. DOI: 10.1109/INFOCOM59046.2026.11571313](#)

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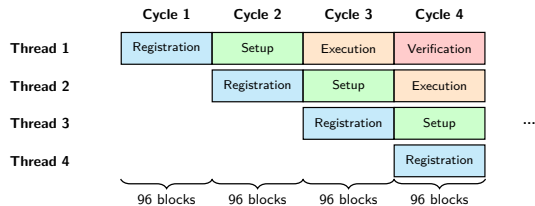


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# DNaaS: Deterministic Network as a Service



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## Conclusion

- There is a need for large-scale time-sensitive networks
- DetNet partially addresses this need
- DNaaS aims at going beyond the current charter of DetNet

## Bibliography I

- [Amet, Thomas, Song 2026] Amet, Matthieu, Ludovic Thomas, and Ye-Qiong Song (May 2026). “DNaaS: Towards Scalable and Trusted Time-Sensitive Networks”. In: *IEEE INFOCOM 2026 - IEEE Conference on Computer Communications*. IEEE INFOCOM 2026 - IEEE Conference on Computer Communications, pp. 1–10. DOI: 10.1109/INFOCOM59046.2026.11571313. URL: <https://ieeexplore.ieee.org/document/11571313> (visited on 07/09/2026).
- [Farkas 2018] Farkas, János (Nov. 11, 2018). “TSN Basic Concepts”. URL: <https://www.ieee802.org/1/files/public/docs2018/detnet-tsn-farkas-tsn-basic-concepts-1118-v01.pdf>.
- [Finn, et al. 2019] Finn, Norman et al. (Oct. 2019). *Deterministic Networking Architecture*. Request for Comments RFC 8655. Internet Engineering Task Force. 38 pp. DOI: 10.17487/RFC8655. URL: <https://datatracker.ietf.org/doc/rfc8655> (visited on 11/09/2022).
- [RTE 2022] RTE (Feb. 2022). *Futurs Énergétiques 2050 - Rapport Complet*. URL: [https://assets.rte-france.com/prod/2022-06/Futurs%20%C3%A9nerg%C3%A9tiques%202050%20\\_%20rapport%20complet.zip](https://assets.rte-france.com/prod/2022-06/Futurs%20%C3%A9nerg%C3%A9tiques%202050%20_%20rapport%20complet.zip) (visited on 12/10/2022).
- [RFC 8655] Finn, Norman et al. (Oct. 2019). *Deterministic Networking Architecture*. Request for Comments RFC 8655. Internet Engineering Task Force. 38 pp. DOI: 10.17487/RFC8655. URL: <https://datatracker.ietf.org/doc/rfc8655> (visited on 11/09/2022).

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