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

CNRS Interview

Ludovic Thomas

March, 24th, 2023

In this Presentation:

1 Career and Research Profile

2 A Significant Contribution

3 Research Project

Research Profile:

Performance Analysis...

...of **Communication Networks**

Research Profile:

Performance Analysis... ...of **Communication Networks**

5	Application	HTTP, ...
4	Transport	TCP, UDP
3	Network	IP
2	Link	Ethernet
1	Physical	

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Measurements

Discrete-Event Simulation (ns-3)

Analytical Approaches

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2018 *CNES, Toulouse, France*

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Modelization of **traffic regulators**.

Postdoc
2022-today *EPFL, Lausanne, Switzerland*

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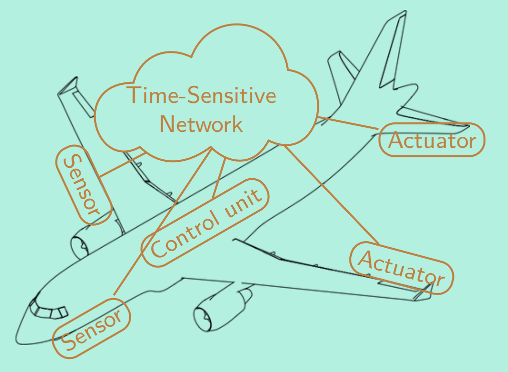
A Focus on **Time-Sensitive Networks**

Cyber-Physical Systems



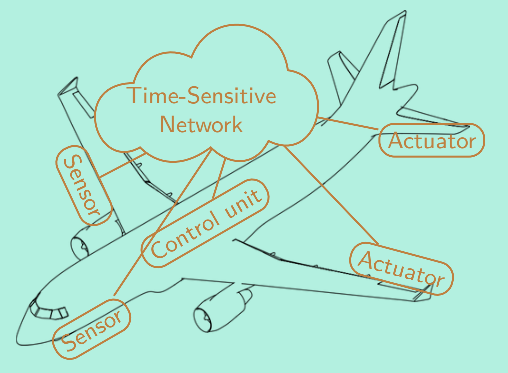
IEEE: Institute of Electrical and Electronics Engineers

A Focus on **Time-Sensitive Networks**

Classic Networks

Best-effort service

Cyber-Physical Systems



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Deterministic Service

Bounded Latency

+ no buffer overflow

+ targeted reliability

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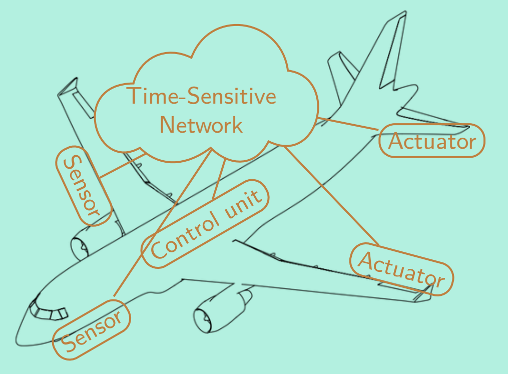

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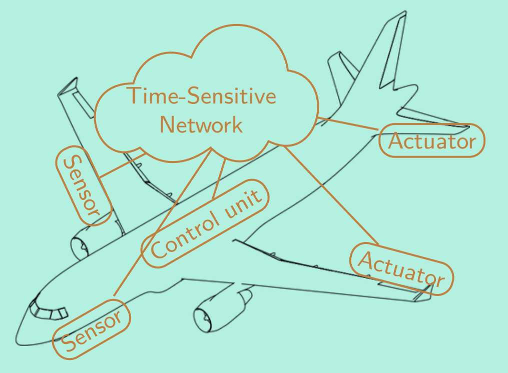
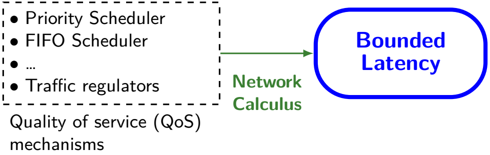


IEEE time-sensitive networking (TSN): Ethernet for safety-critical applications (layer 2)

IEEE: Institute of Electrical and Electronics Engineers

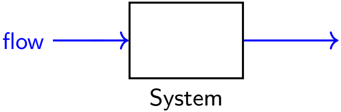
Quality-of-Service Mechanisms are Validated with **Network Calculus**



FIFO: First In, First Out

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

Two examples:



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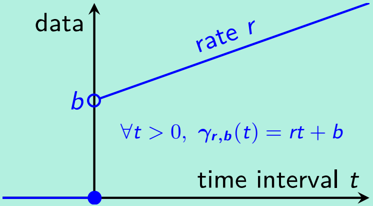
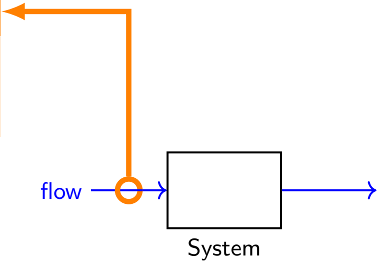
Arrival Curve $\alpha(t)$

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

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





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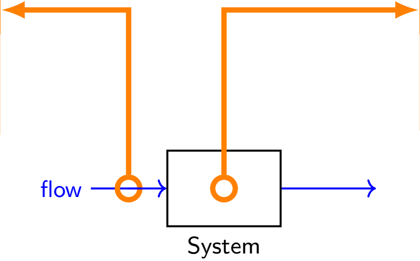

Service Curve $\beta(t)$

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

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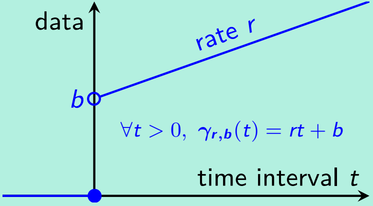

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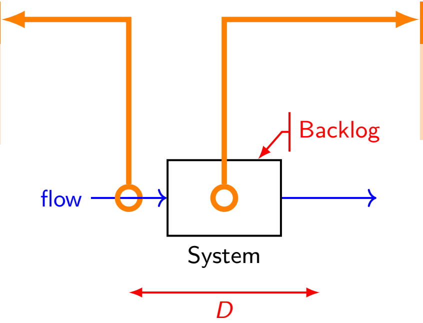

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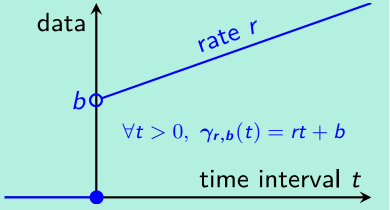
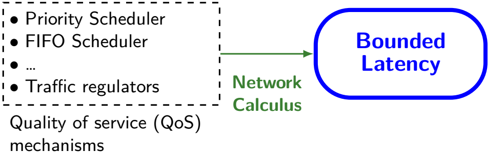


Good **Service-Curve Models** are not Known for All **QoS Mechanisms**



QoS: Quality-of-Service

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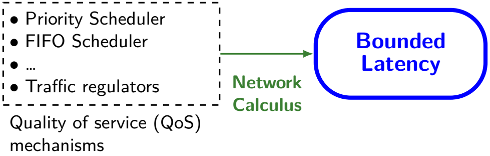

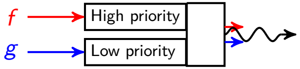

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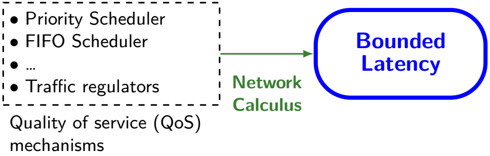

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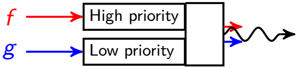
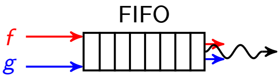
- Priority Scheduler
- FIFO Scheduler
- ...
- Traffic regulators

Quality of service (QoS) mechanisms

Network Calculus

Bounded Latency





Good service-curve model

β

Priority Scheduler

FIFO Scheduler

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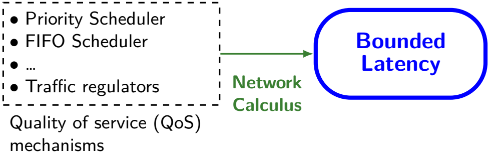

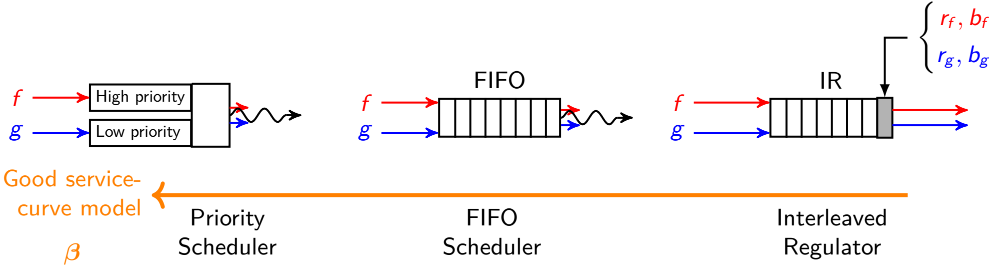

FIFO: First In, First Out | IR: Interleaved Regulator | QoS: Quality-of-Service

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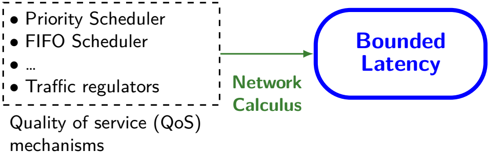

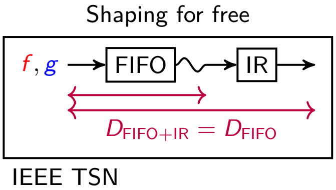

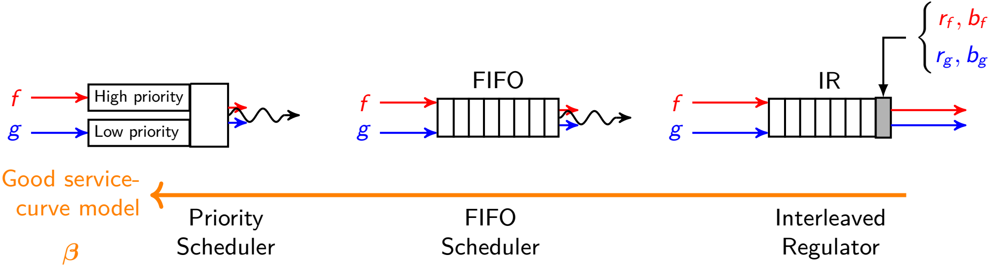

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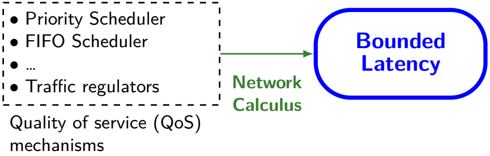

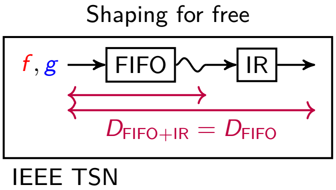

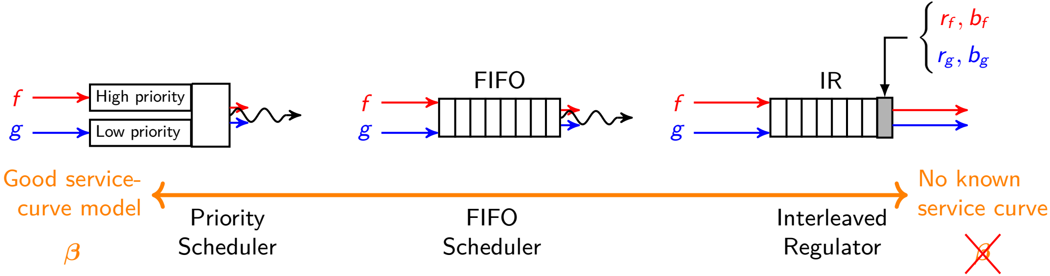

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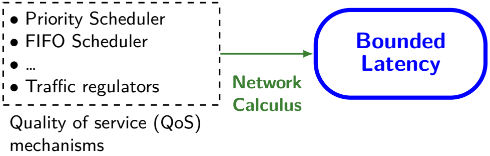

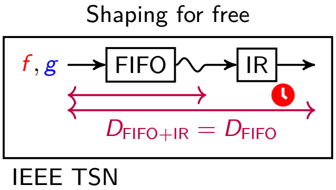

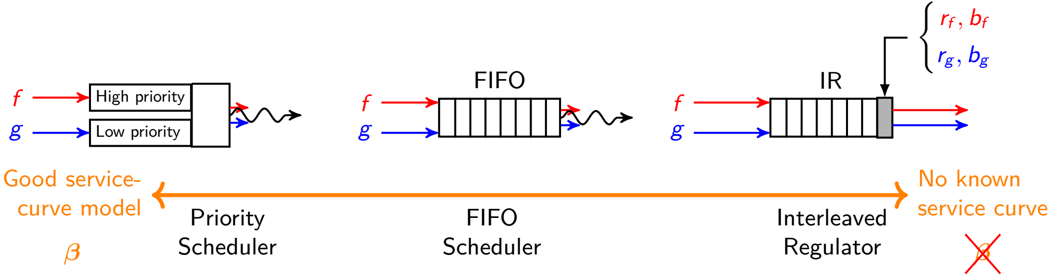

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Network Calculus Relies on **Time Intervals**

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Arrival Curve $\alpha(t)$

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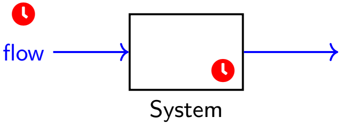

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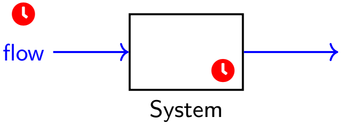

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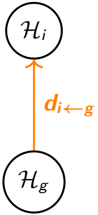
In [Thomas, Le Boudec 2020]:

- an extension of Network Calculus to networks with several clocks
- the theoretical grounds to understand the effects of clock non-idealities on latency bounds

– [Thomas, Le Boudec 2020] Ludovic Thomas and Jean-Yves Le Boudec [June 12, 2020]. "On Time Synchronization Issues in Time-Sensitive Networks with Regulators and Nonideal Clocks". In: *Proceedings of the ACM on Measurement and Analysis of Computing Systems* 4.2. DOI: 10.1145/3392145

We Provide a **Worst-Case Oriented** Model for **Non-Ideal Clocks**



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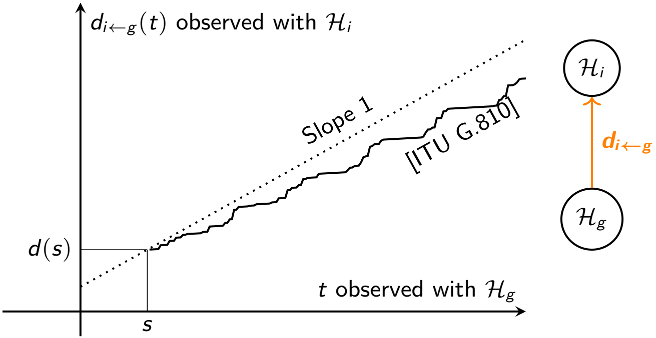

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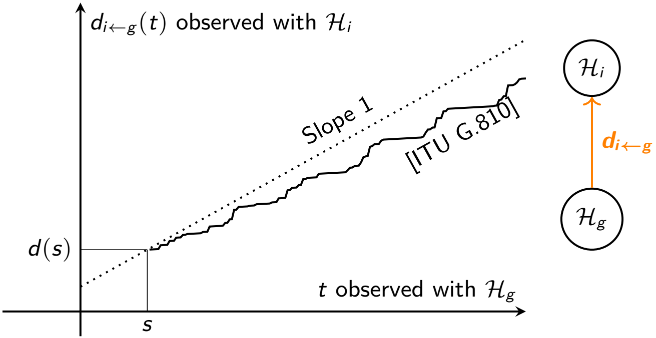

Non-synchronized model: $\forall s, t$

$$d_{i\leftarrow g}(t) - d_{i\leftarrow g}(s) \leq (t - s)\rho + \eta$$

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$\eta \sim$ 1ns (clock jitter) $\rho \sim 1 + 200$ ppm (clock stability)

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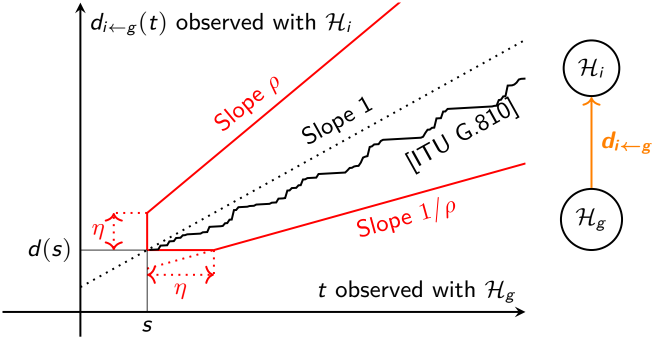

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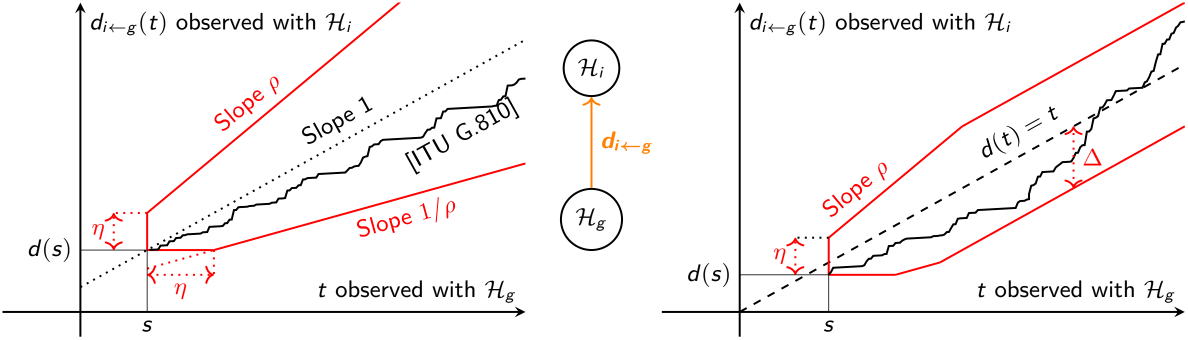

Non-synchronized model: $\forall \mathcal{H}_i, \mathcal{H}_g$, $\forall s, t$

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Synchronized model: $\forall \mathcal{H}_i, \mathcal{H}_g$,

$$+ : \quad \forall t, \quad |d_{i\leftarrow g}(t) - t| \leq \Delta$$

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$\eta \sim$ 1ns (clock jitter) $\rho \sim 1 + 200$ ppm (clock stability) $\Delta \sim 1\mu s$ (synchronisation precision)

A Toolbox of Results for **Changing the Observing Clocks**

$\boldsymbol{\eta} \sim$ 1ns (clock jitter) $\boldsymbol{\rho} \sim 1 + 200$ ppm (clock stability) $\boldsymbol{\Delta} \sim 1\mu$s (synchronisation precision)

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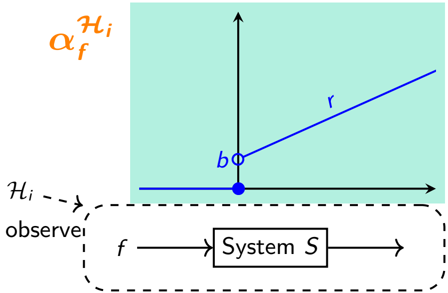

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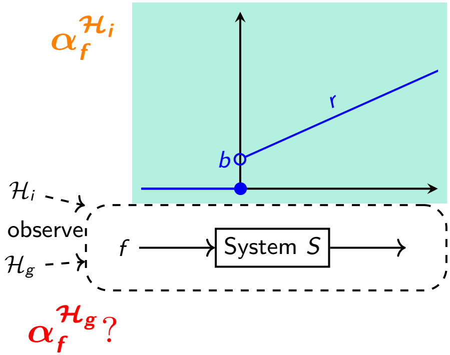

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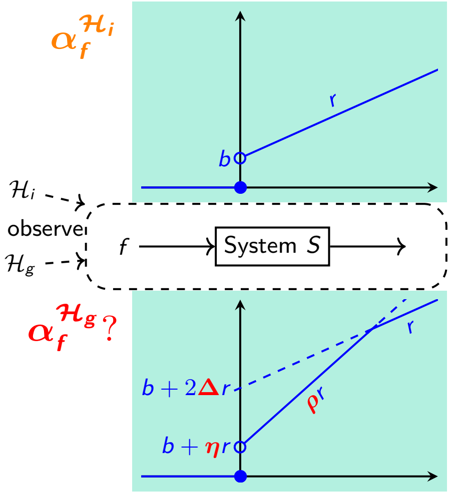

$+$ Service curves

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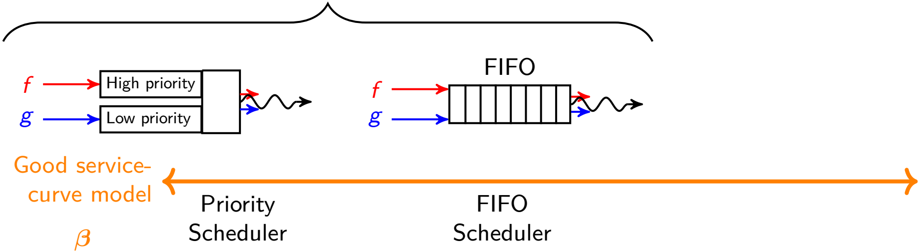
The Consequences of Clock Non-idealities on Latency Bounds depend on the Qos Mechanism



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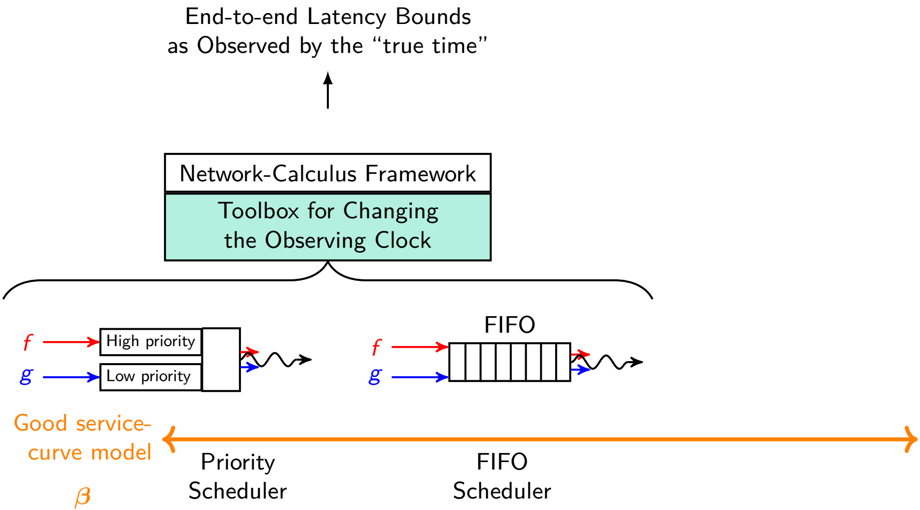

"true time": *temps atomique international* (TAI)

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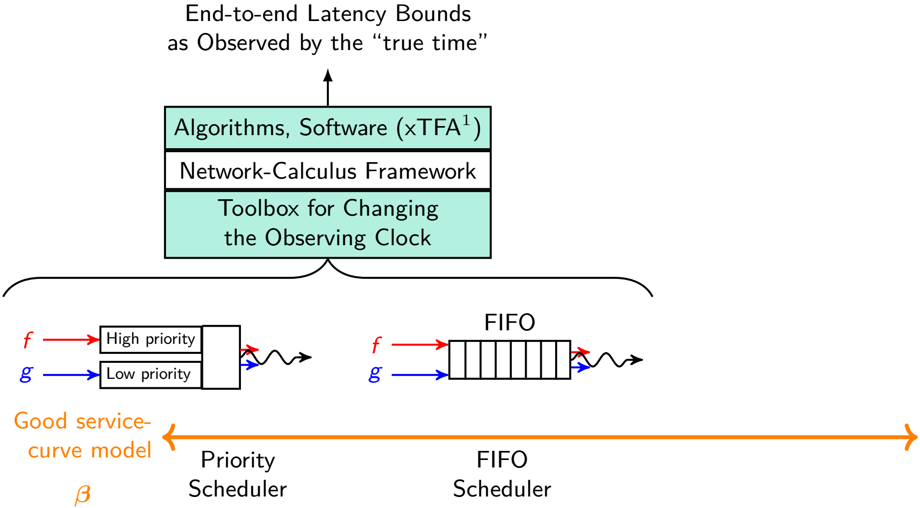

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[1] https://gitlab.epfl.ch/thomas/xtfa

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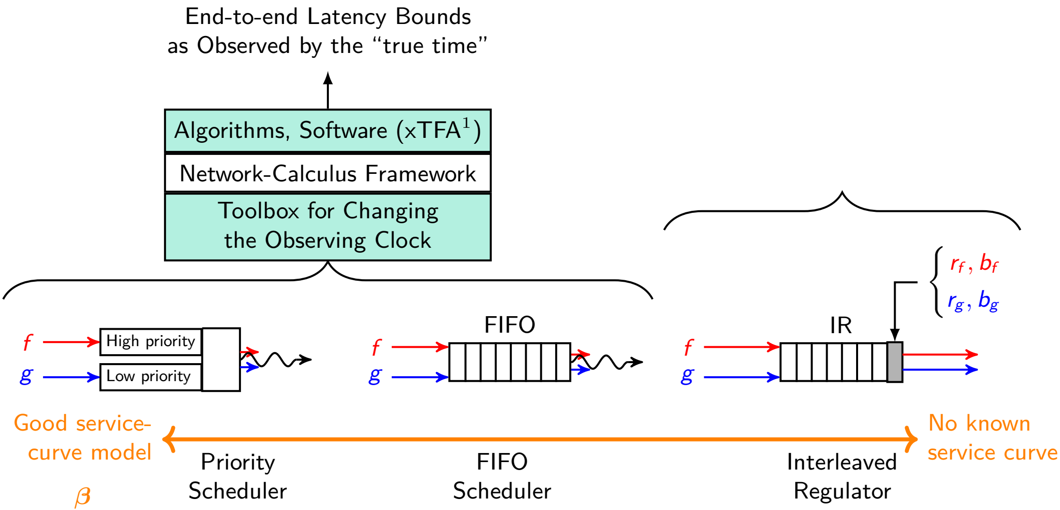

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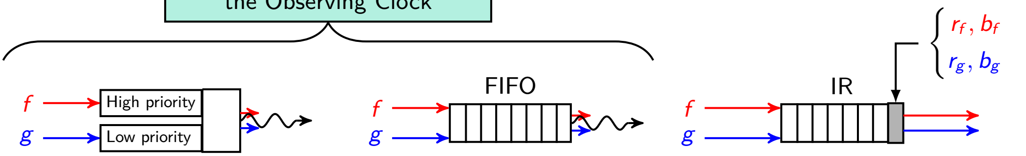
The Consequences of Clock Non-idealities on Latency Bounds depend on the Qos Mechanism

End-to-end Latency Bounds
as Observed by the "true time"

Algorithms, Software (xTFA[1])
Network-Calculus Framework
Toolbox for Changing the Observing Clock

$\#(\text{flows} \geq 3)$
$\Rightarrow D_{\mathrm{IR}} = +\infty$



Good service-curve model β ⟷ No known service curve

Priority Scheduler — FIFO Scheduler — Interleaved Regulator

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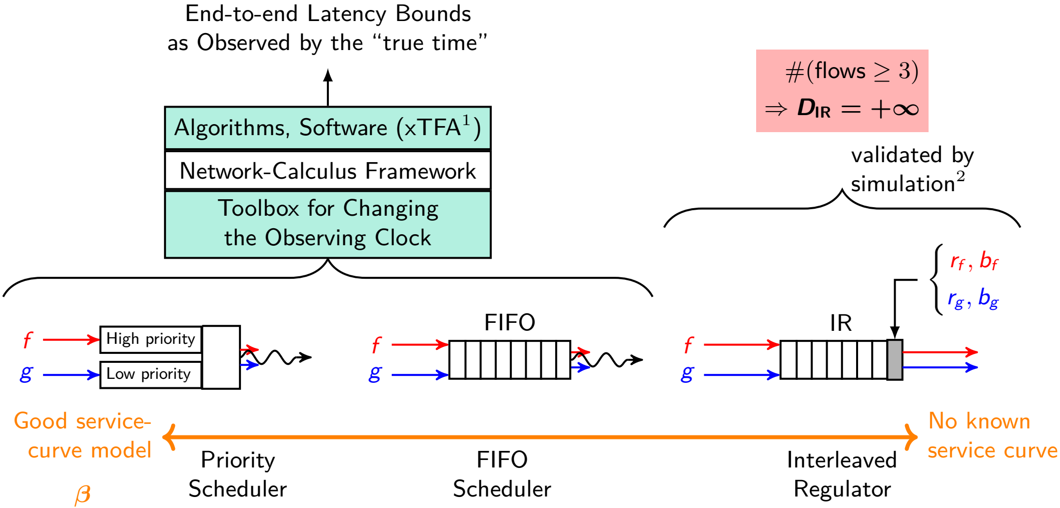

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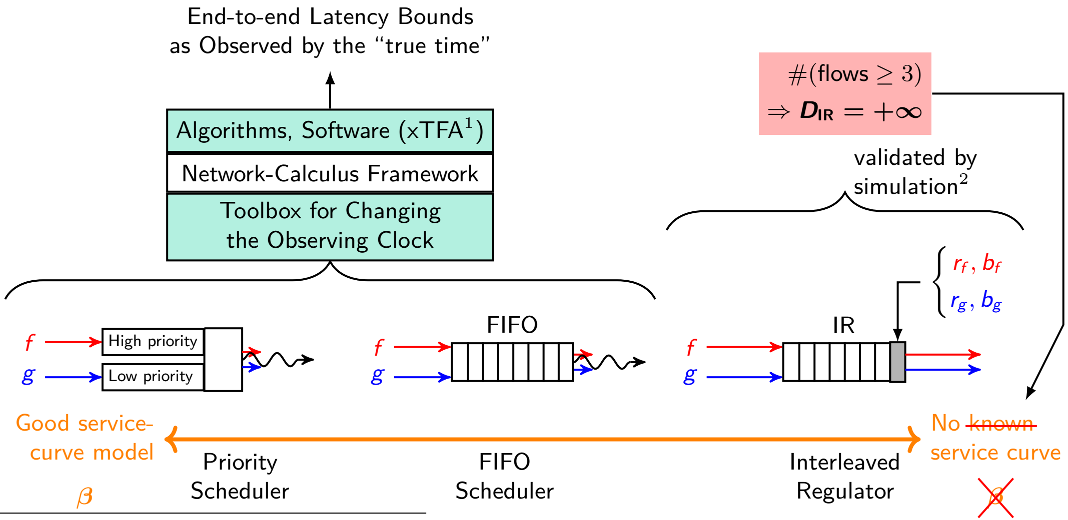

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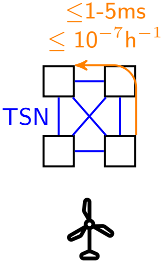
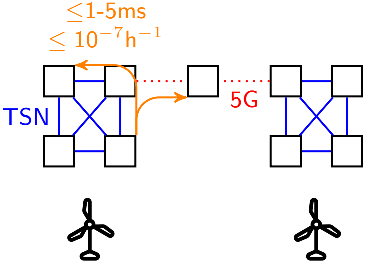
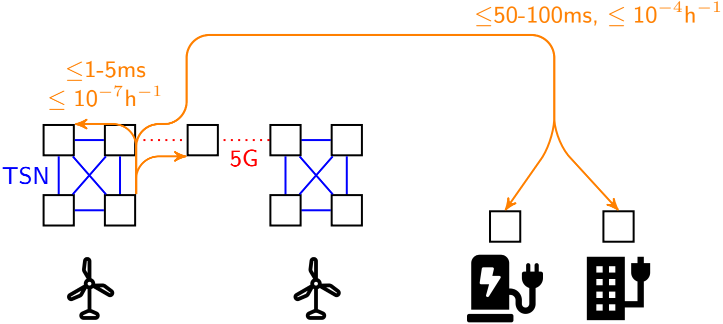
with End-to-end Deterministic Service Requirements



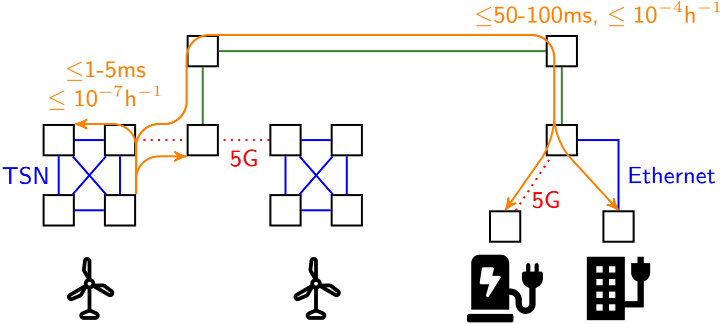
Large-Scale Multi-Domain Time-Sensitive Networks with End-to-end Deterministic Service Requirements



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

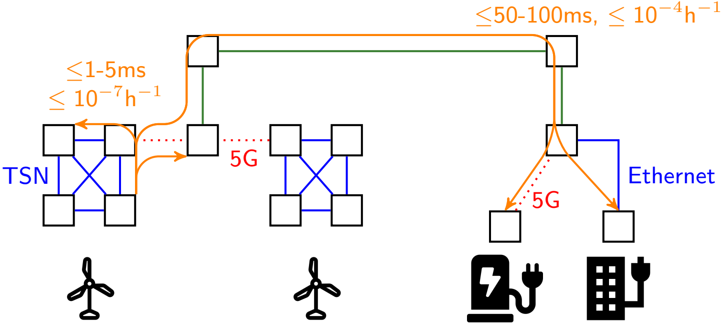


Large-Scale Multi-Domain Time-Sensitive Networks with End-to-end Deterministic Service Requirements



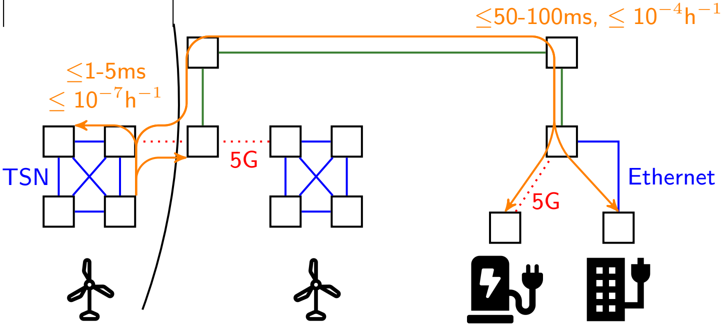
Large-Scale Multi-Domain Time-Sensitive Networks with End-to-end Deterministic Service Requirements

How to identify the flows?	Data Plane
How to configure the network?	Control Plane



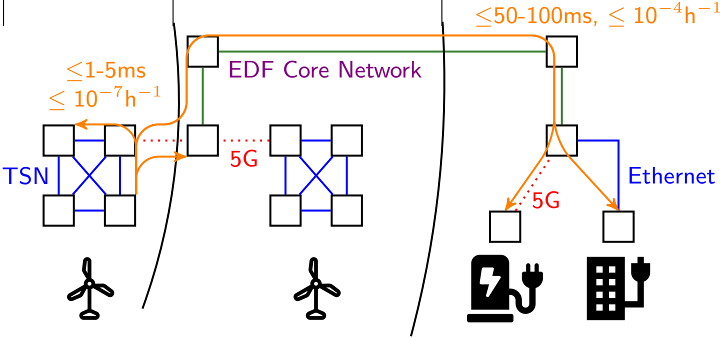
Large-Scale Multi-Domain Time-Sensitive Networks with End-to-end Deterministic Service Requirements

		Single subnet	
How to identify the flows?	Data Plane		
How to configure the network?	Control Plane		



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

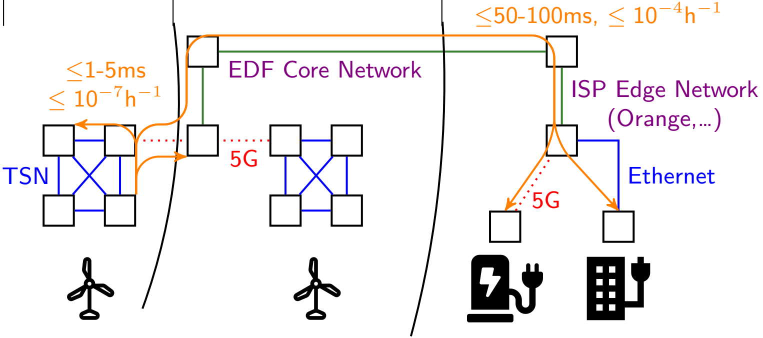
		Single subnet	Several subnets	
How to identify the flows?	Data Plane			
How to configure the network?	Control Plane			



EDF: Électricité de France

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

		Single subnet	Several subnets	Several domains
How to identify the flows?	Data Plane			
How to configure the network?	Control Plane			



EDF: Électricité de France | ISP: Internet Service Provider

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

		Single subnet	Several subnets	Several domains
How to identify the flows?	Data Plane			
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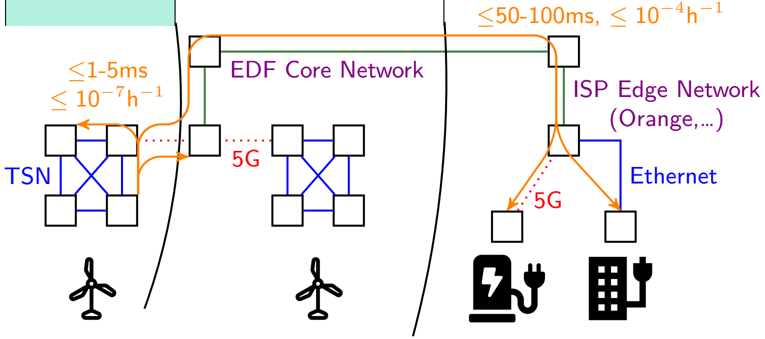

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Large-Scale Multi-Domain Time-Sensitive Networks with End-to-end Deterministic Service Requirements

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How to identify the flows?	Data Plane			
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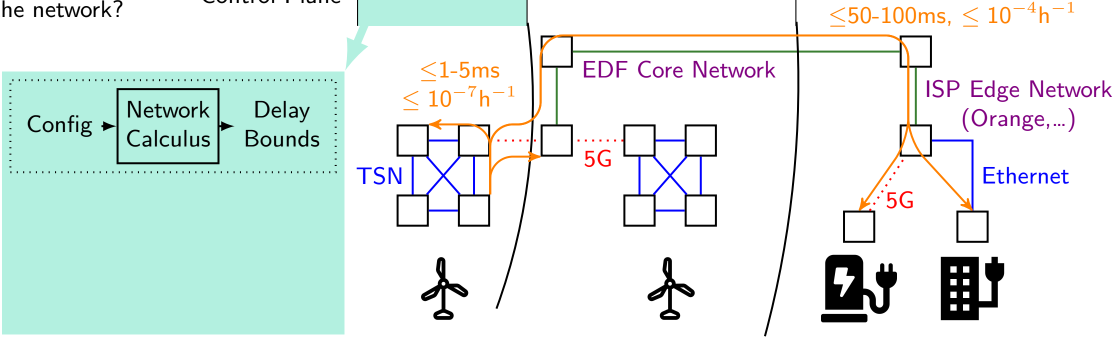

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Large-Scale Multi-Domain Time-Sensitive Networks
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		Single subnet	Several subnets	Several domains
How to identify the flows?	Data Plane			
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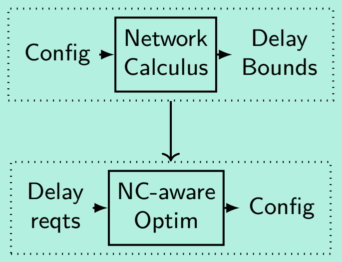
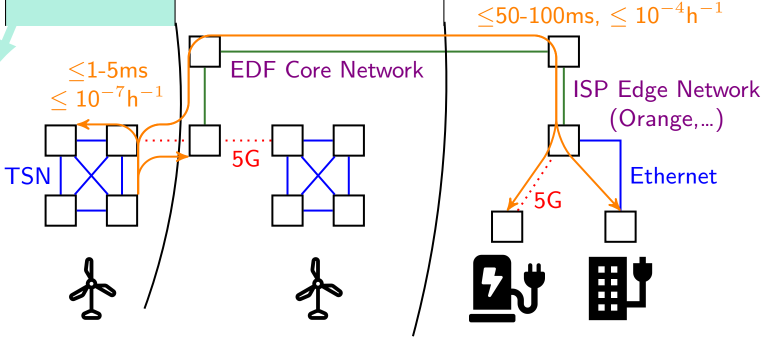
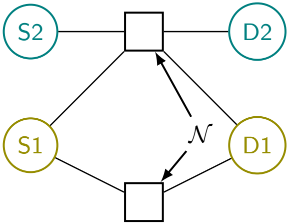


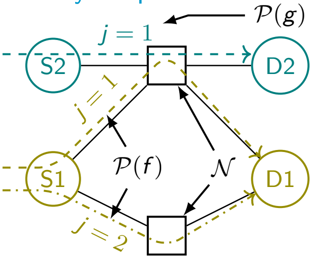


EDF: Électricité de France | ISP: Internet Service Provider

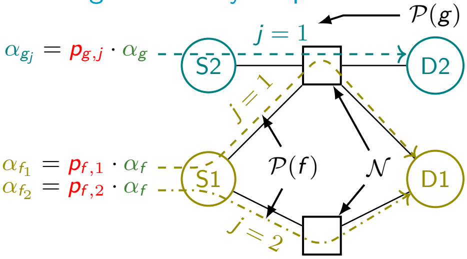
Routing with Delay Requirements



Routing with Delay Requirements



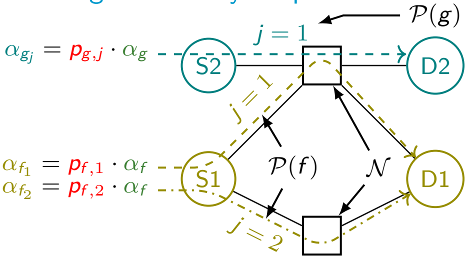
Routing with Delay Requirements



$$\text{s.t.} \quad \forall f \in \mathcal{F}, \qquad \sum_{j \in \mathcal{P}(f)} p_{f,j} = 1$$

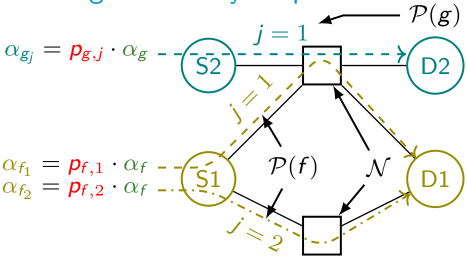
$$\forall f \in \mathcal{F}, \forall j \in \mathcal{P}(f), \quad p_{f,j} \in \{0, 1\}$$

Routing with Delay Requirements



$$
\begin{aligned}
\text{s.t.} \quad & \forall f \in \mathcal{F}, & \sum_{j \in \mathcal{P}(f)} p_{f,j} = 1 \\
& \forall f \in \mathcal{F}, \forall j \in \mathcal{P}(f), & p_{f,j} \in \{0,1\} \\
& \forall f \in \mathcal{F}, & D_f^{\mathrm{NC}}(\{p_{f',j'}\}, \{\alpha_{f'}\}, \{\beta_n\}_{n \in \mathcal{N}}) \leq \mathrm{deadline}_f
\end{aligned}
$$

Routing with Delay Requirements

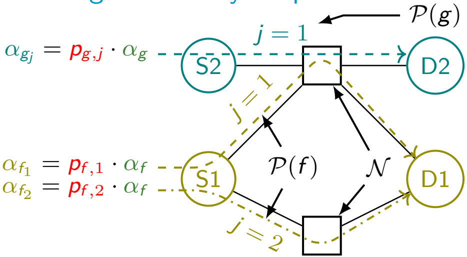


$$\min_{\boldsymbol{p}} \quad \max_{f \in \mathcal{F}} \Psi \left(\text{deadline}_f,\ D_f^{\text{NC}} \left(\{p_{f',j'}\}, \{\alpha_{f'}\}, \{\beta_n\}_{n \in \mathcal{N}} \right) \right)$$

$$\text{s.t.} \quad \forall f \in \mathcal{F}, \qquad \sum_{j \in \mathcal{P}(f)} p_{f,j} = 1$$

$$\forall f \in \mathcal{F}, \forall j \in \mathcal{P}(f), \qquad p_{f,j} \in \{0, 1\}$$

Routing with Delay Requirements



Non-Linear (NL)

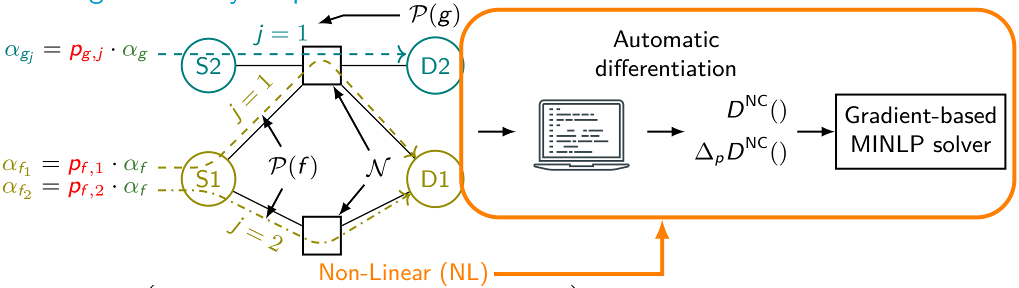
$$\min_{\boldsymbol{p}} \quad \max_{f \in \mathcal{F}} \Psi \left(\text{deadline}_f, D_f^{\text{NC}}(\{p_{f',j'}\}, \{\alpha_{f'}\}, \{\beta_n\}_{n \in \mathcal{N}}) \right)$$

$$\text{s.t.} \quad \forall f \in \mathcal{F}, \qquad \sum_{j \in \mathcal{P}(f)} p_{f,j} = 1$$

$$\forall f \in \mathcal{F}, \forall j \in \mathcal{P}(f), \qquad p_{f,j} \in \{0, 1\}$$ Mixed-Integer (MI)

Routing with Delay Requirements

[Geyer, Bondorf 2022]



$$\min_{\boldsymbol{p}} \quad \max_{f \in \mathcal{F}} \Psi \left(\mathrm{deadline}_f, \boxed{D_f^{\mathrm{NC}}}(\{p_{f',j'}\}, \{\alpha_{f'}\}, \{\beta_n\}_{n \in \mathcal{N}}) \right)$$

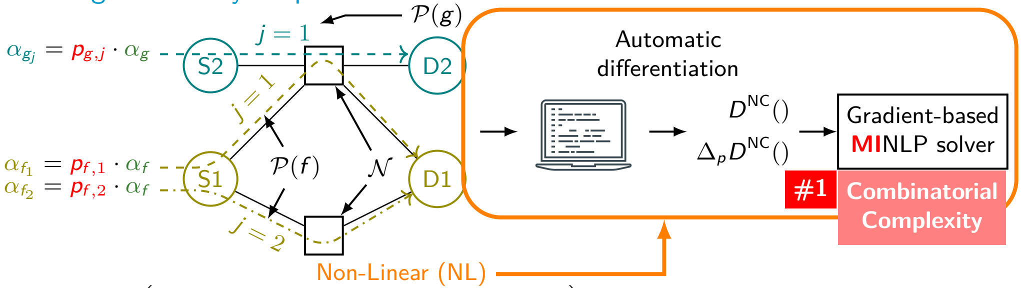
$$\text{s.t.} \quad \forall f \in \mathcal{F}, \qquad \sum_{j \in \mathcal{P}(f)} p_{f,j} = 1$$

$$\forall f \in \mathcal{F}, \forall j \in \mathcal{P}(f), \qquad \boxed{p_{f,j} \in \{0, 1\}}$$ Mixed-Integer (MI)

– [Geyer, Bondorf 2022] Fabien Geyer and Steffen Bondorf [May 2022]. “Network Synthesis under Delay Constraints: The Power of Network Calculus Differentiability”. In: *IEEE INFOCOM 2022 - IEEE Conference on Computer Communications*. DOI: 10.1109/INFOCOM48880.2022.9796777

Routing with Delay Requirements

[Geyer, Bondorf 2022]



$$\min_{\boldsymbol{p}} \quad \max_{f \in \mathcal{F}} \Psi \left(\text{deadline}_f, D_f^{\mathrm{NC}}(\{p_{f',j'}\}, \{\alpha_{f'}\}, \{\beta_n\}_{n \in \mathcal{N}}) \right)$$

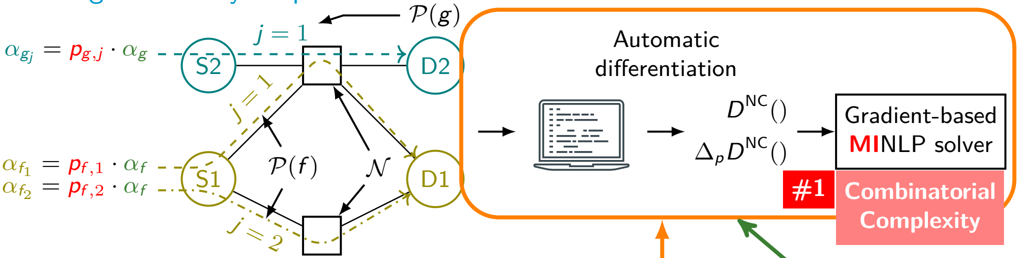
$$\text{s.t.} \quad \forall f \in \mathcal{F}, \qquad \sum_{j \in \mathcal{P}(f)} p_{f,j} = 1$$

$$\forall f \in \mathcal{F}, \forall j \in \mathcal{P}(f), \qquad p_{f,j} \in \{0,1\}$$ Mixed-Integer (MI)

$\ldots$

Routing with Delay Requirements

[Geyer, Bondorf 2022]



Non-Linear (NL)

Combine ?

$$\min_{p} \quad \max_{f\in\mathcal{F}} \Psi\left(\text{deadline}_f, D_f^{\mathrm{NC}}(\{p_{f',j'}\}, \{\alpha_{f'}\}, \{\beta_n\}_{n\in\mathcal{N}})\right)$$

$$\text{s.t.} \quad \forall f \in \mathcal{F}, \qquad \sum_{j\in\mathcal{P}(f)} p_{f,j} = 1$$

$$\forall f \in \mathcal{F}, \forall j \in \mathcal{P}(f), \qquad p_{f,j} \in \{0,1\}$$ Mixed-Integer (MI)

$$\cdots$$

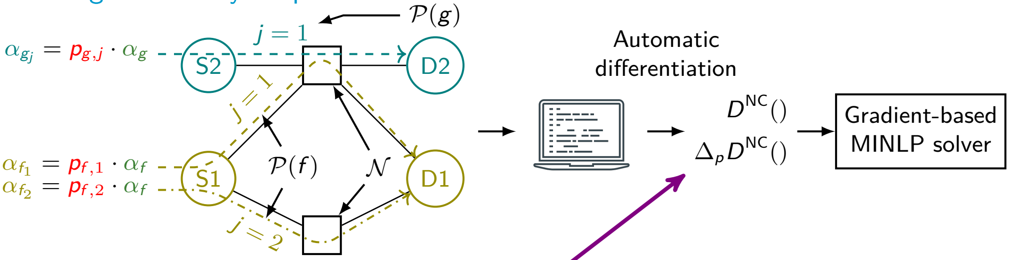
Heuristics for the Unsplittable Multi-Commodity Flow Problem (MILP)

[Lamothe, *et al.* 2021]

– [Lamothe, *et al.* 2021] François Lamothe, Emmanuel Rachelson, Alain Haït, Cedric Baudoin, and Jean-Baptiste Dupé [Dec. 1, 2021]. “Randomized Rounding Algorithms for Large Scale Unsplittable Flow Problems”. In: *Journal of Heuristics* 27.6. DOI: 10.1007/s10732-021-09478-w

Routing with Delay Requirements

[Geyer, Bondorf 2022]

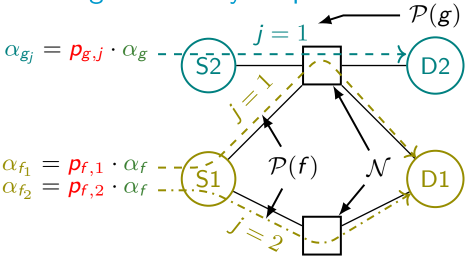


$$\min_{p} \quad \max_{f\in\mathcal{F}} \Psi\left(\text{deadline}_f,\, D_f^{\mathrm{NC}}(\{p_{f',j'}\}, \{\alpha_{f'}\}, \{\beta_n\}_{n\in\mathcal{N}})\right)$$

s.t. . . .

Routing with Delay Requirements

[Geyer, Bondorf 2022]



→ Automatic differentiation

→ $D^{\mathrm{NC}}()$ $\Delta_p D^{\mathrm{NC}}()$ → Gradient-based MINLP solver

$$\min_{p} \quad \max_{f\in\mathcal{F}} \Psi\left(\text{deadline}_f,\ D_f^{\mathrm{NC}}\left(\{p_{f',j'}\}, \{\alpha_{f'}\}, \boxed{\{\beta_n\}_{n\in\mathcal{N}}}\right)\right)$$

s.t. . . .

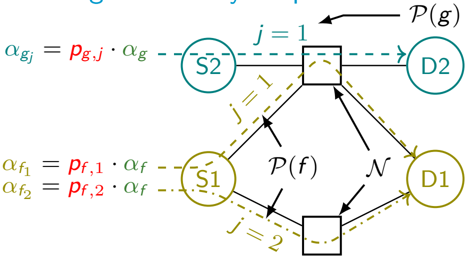
#2 **Vastly Pessimistic**

Arbitrary Scheduler

Good service-curve model ← Priority Scheduler, FIFO Scheduler, Interleaved Regulator → No known service curve

Routing with Delay Requirements

[Geyer, Bondorf 2022]



→

Automatic differentiation

→ $D^{NC}()$, $\Delta_p D^{NC}()$ → Gradient-based MINLP solver

$$\min_{p} \max_{f\in\mathcal{F}} \Psi\left(\text{deadline}_f,\, D_f^{NC}\left(\{p_{f',j'}\}, \{\alpha_{f'}\}, \{\beta_n\}_{n\in\mathcal{N}}\right)\right)$$

s.t. . . .

#2 **Vastly Pessimistic**

- The applicability to FIFO is unclear
- Limits of the service-curve model?

Arbitrary Scheduler

Good service-curve model ← Priority Scheduler — FIFO Scheduler — Interleaved Regulator → No known service curve

Conclusion: Research Project Overview

		Single subnet	Several subnets	Several domains
How to identify the flows?	Data Plane			
How to configure the network?	Control Plane	Routing and resource allocation under deterministic-service constraints.		

- IRIT (Équipe RMESS), Toulouse
- Loria (Département 3), Nancy

Conclusion: Research Project Overview

		Single subnet	Several subnets	Several domains
How to identify the flows?	Data Plane		Meta-data and transport	
How to configure the network?	Control Plane	Routing and resource allocation under deterministic-service constraints.		

- IRIT (Équipe RMESS), Toulouse
  - TSN/5G interconnection with application to Non-Terestrial Networks

- Loria (Département 3), Nancy
  - Wired/Wireless interconnection with application to Smart Grids

IETF DetNet: The *Deterministic Networking* working group of the *Internet Engineering Task Force*

Conclusion: Research Project Overview

		Single subnet	Several subnets	Several domains
How to identify the flows?	Data Plane		Meta-data and transport	
How to configure the network?	Control Plane	Routing and resource allocation under deterministic-service constraints.	Sofware-defined networks	

- IRIT (Équipe RMESS), Toulouse
  - TSN/5G interconnection with application to Non-Terestrial Networks
  - Transition analysis
- Loria (Département 3), Nancy
  - Wired/Wireless interconnection with application to Smart Grids
  - Software-defined networks

IETF DetNet: The *Deterministic Networking* working group of the *Internet Engineering Task Force*

Conclusion: Research Project Overview

		Single subnet	Several subnets	Several domains
How to identify the flows?	Data Plane		Meta-data and transport	Administrative borders
How to configure the network?	Control Plane	Routing and resource allocation under deterministic-service constraints.	Sofware-defined networks	Distributed routing and automatic contracts.

- IRIT (Équipe RMESS), Toulouse
  - TSN/5G interconnection with application to Non-Terestrial Networks
  - Transition analysis
- Loria (Département 3), Nancy
  - Wired/Wireless interconnection with application to Smart Grids
  - Software-defined networks

IETF DetNet: The *Deterministic Networking* working group of the *Internet Engineering Task Force*

Thank You for Your Attention

- **Publications:** 3 journals, 3 conferences with **high impact on modeling time-sensitive networks:** 1 ACM SIGMETRIS, 1 ACM/IEEE ToN, 1 IEEE RTSS.
- **Involved in the networking research community:** Founder of the network-calculus mailing list. Participation in standardization processes and conventions through email discussions. 7 presentations in workshops and conferences, attendance in more. GdR école d'été.
- **Co-supervision of student projects :** 1 semester project + 1 master project.
- **Open-source software development:** Network-calculus tool xTFA. Contribution to the ns-3 simulator.
- **Experience in working with industrials:** Project with Huawei, IRT project with Airbus, Thales, Continental. Personal contacts (internships, etc.) within aerospace companies and agencies.
- **Host institutions:** IRIT, Toulouse and Loria, Nancy

Bibliography I

[Geyer, Bondorf 2022] Geyer, Fabien and Steffen Bondorf (May 2022). "Network Synthesis under Delay Constraints: The Power of Network Calculus Differentiability". In: *IEEE INFOCOM 2022 - IEEE Conference on Computer Communications*. IEEE INFOCOM 2022 - IEEE Conference on Computer Communications, pp. 1539–1548. DOI: 10.1109/INFOCOM48880.2022.9796777.

[Lamothe, *et al.* 2021] Lamothe, François et al. (Dec. 1, 2021). "Randomized Rounding Algorithms for Large Scale Unsplittable Flow Problems". In: *Journal of Heuristics* 27.6, pp. 1081–1110. ISSN: 1572-9397. DOI: 10.1007/s10732-021-09478-w. URL: https://doi.org/10.1007/s10732-021-09478-w (visited on 03/10/2023).

[Thomas, Le Boudec 2020] Thomas, Ludovic and Jean-Yves Le Boudec (June 12, 2020). "On Time Synchronization Issues in Time-Sensitive Networks with Regulators and Nonideal Clocks". In: *Proceedings of the ACM on Measurement and Analysis of Computing Systems* 4.2, 27:1–27:41. DOI: 10.1145/3392145. URL: https://doi.org/10.1145/3392145 (visited on 11/06/2022).

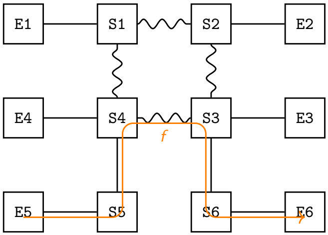
[Thomas, Le Boudec, Mifdaoui 2019] Thomas, Ludovic, Jean-Yves Le Boudec, and Ahlem Mifdaoui (Dec. 2019). "On Cyclic Dependencies and Regulators in Time-Sensitive Networks". In: *2019 IEEE Real-Time Systems Symposium (RTSS)*. 2019 IEEE Real-Time Systems Symposium (RTSS), pp. 299–311. DOI: 10.1109/RTSS46320.2019.00035.

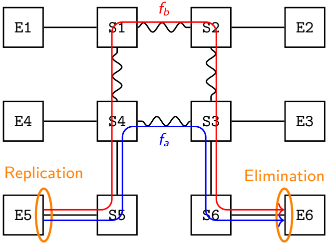
Bibliography II

[Thomas, Mifdaoui, Le Boudec 2022] Thomas, Ludovic, Ahlem Mifdaoui, and Jean-Yves Le Boudec (2022). "Worst-Case Delay Bounds in Time-Sensitive Networks With Packet Replication and Elimination". In: *IEEE/ACM Transactions on Networking*, pp. 1–15. ISSN: 1558-2566. DOI: 10.1109/TNET.2022.3180763.

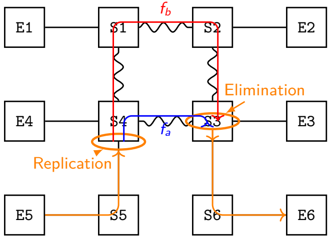
[ITU G.810] ITU (1996). "Definitions and Terminology for Synchronization Networks". In: *ITU G.810*. URL: https://www.itu.int/rec/T-REC-G.810-199608-I/en (visited on 10/14/2019).

We Provide a Model for **Redundancy Mechanisms** and their Effects on Latency Bounds





Cyclic dependencies
[Thomas, Le Boudec, Mifdaoui 2019]



Model for redundancy
[Thomas, Mifdaoui, Le Boudec 2022]

Theoretical grounds, methods, algorithms and data structures, code (xTFA).

– [Thomas, Le Boudec, Mifdaoui 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

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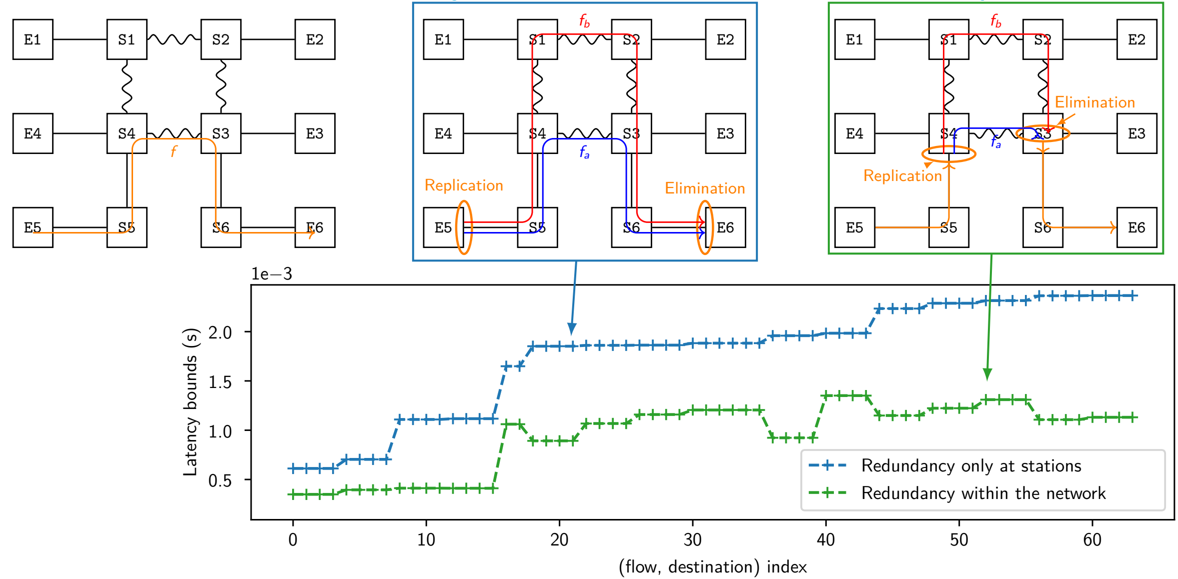
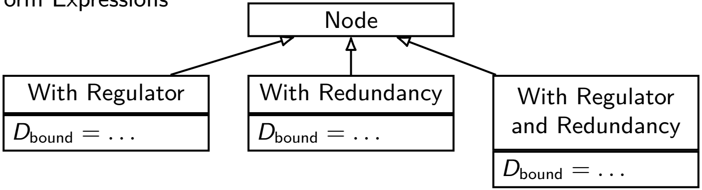
We Provide a Model for **Redundancy Mechanisms** and their Effects on Latency Bounds

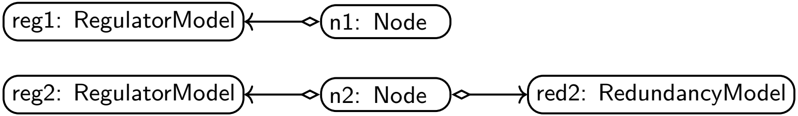


xTFA: An Open-Source **Analysis and Verification** Tool Based on Network Calculus

Before xTFA: Closed-Form Expressions



- xTFA: Experimental **Modular** Total-Flow Analysis



Computes worst-case performance bounds (end-to-end latency bounds, buffer occupation bounds) in time-sensitive networks with redundancy mechanisms, traffic regulators, non-ideal clocks and/or cyclic dependencies.
Uses standard input files. Repository: `https://gitlab.epfl.ch/thomas/xtfa` (GPLv3)

Contribution to the ns-3 Network Simulator: Local Clocks

Network Simulator 3, or ns-3 (`www.nsnam.org`):

- A Discrete Event Simulator for Networks and Protocols.
- It received the 2020 ACM SIGCOMM Networking Systems Award.
- But does not support local clocks (time is unique, perfect).

We provide a module for simulating local clocks that **does not require to change line** of already-existing code.

Barnes, Peter D. barnes26 at llnl.gov
Fri Nov 12 16:29:31 PST 2021

```
Hello Thomas and Guillermo,

I apologize for taking so long to take a look at this.  First let me say I'm impressed: you
have neatly identified the major difficulties and found workable solutions.
```

---

https://gitlab.com/nsnam/ns-3-dev/-/merge_requests/332
https://mailman.isi.edu/pipermail/ns-developers/2021-November/015584.html