

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

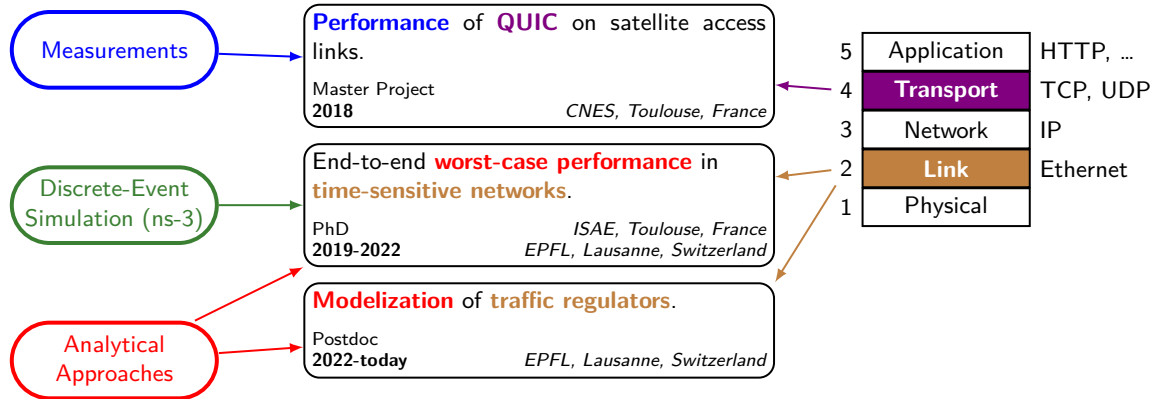
2 A Significant Contribution

3 Research Project

Research Profile:

Performance Analysis...

...of Communication Networks



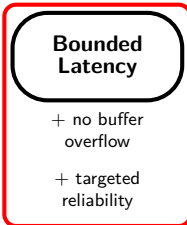
A Focus on Time-Sensitive Networks

Classic Networks

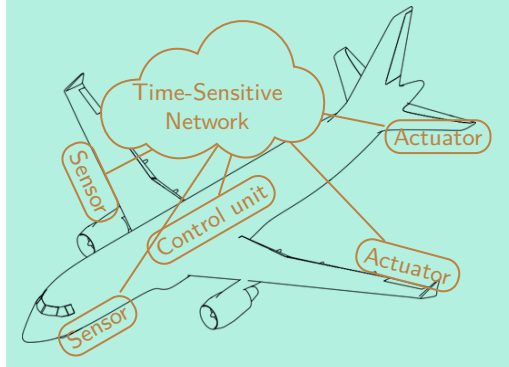


Time-Sensitive
Networks

Deterministic Service

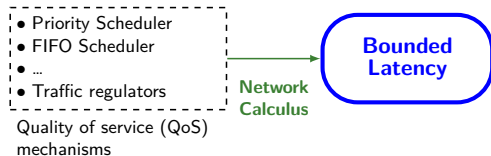


Cyber-Physical Systems



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

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



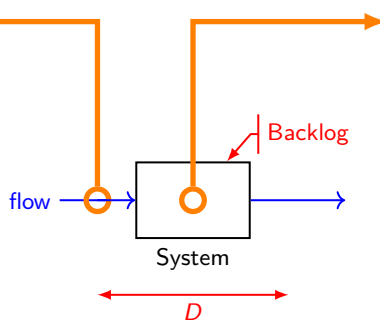
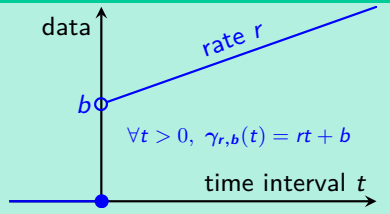
Network Calculus Provides a **Model-Based** Analysis and **Verification**

Two examples:

Arrival Curve $\alpha(t)$

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

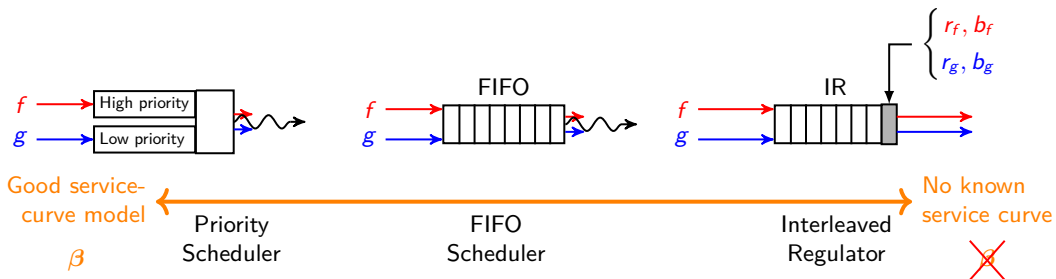
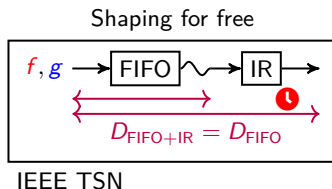
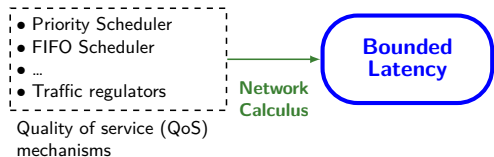
Leaky-Bucket $\gamma_{r,b}$



Service Curve $\beta(t)$

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

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



FIFO: First In, First Out

Ludovic Thomas

IR: Interleaved Regulator

Large-Scale Multi-Domain Time-Sensitive Networks

QoS: Quality-of-Service

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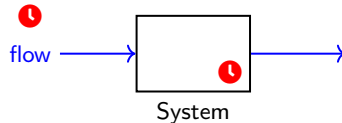
7 / 23

Network Calculus Relies on **Time Intervals**

Example:

Arrival Curve $\alpha(t)$

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



Service Curve $\beta(t)$

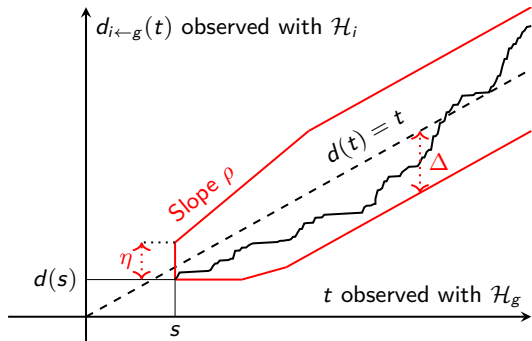
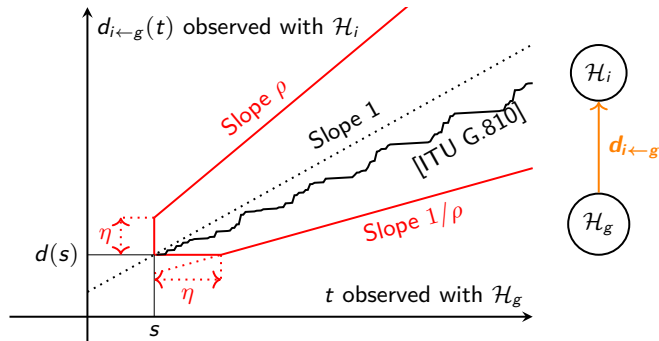
captures the minimum service guaranteed to the flow over any **interval**

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



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

$$\frac{1}{\rho}(t - s - \eta) \leq d_{i \leftarrow g}(t) - d_{i \leftarrow g}(s) \leq (t - s)\rho + \eta$$

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

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

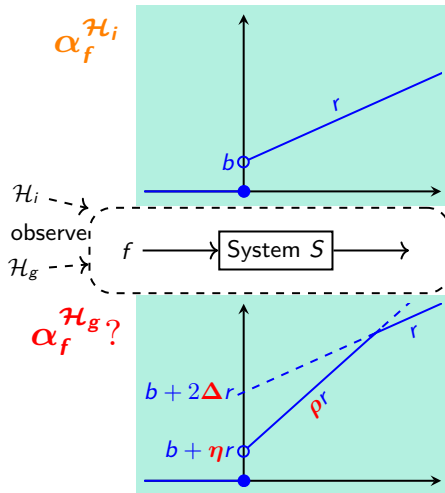
– [ITU G.810] ITU [1996]. “Definitions and Terminology for Synchronization Networks”. In: *ITU G.810*

$\eta \sim 1\text{ns}$ (clock jitter)

$\rho \sim 1 + 200\text{ppm}$ (clock stability)

$\Delta \sim 1\mu\text{s}$ (synchronisation precision)

A Toolbox of Results for Changing the Observing Clocks



+ Service curves

$\eta \sim 1\text{ns}$ (clock jitter)

Ludovic Thomas

$\rho \sim 1 + 200\text{ppm}$ (clock stability)

Large-Scale Multi-Domain Time-Sensitive Networks

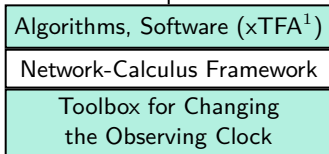
$\Delta \sim 1\mu\text{s}$ (synchronisation precision)

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10 / 23

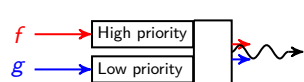
The Consequences of Clock Non-idealities on Latency Bounds depend on the Qos Mechanism

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



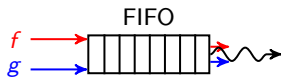
$\#(\text{flows} \geq 3)$
 $\Rightarrow D_{\text{IR}} = +\infty$

validated by
simulation²

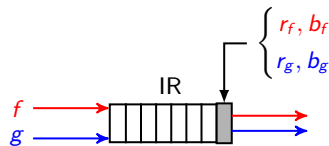


Good service-
curve model
 β

Priority
Scheduler



FIFO
Scheduler



Interleaved
Regulator

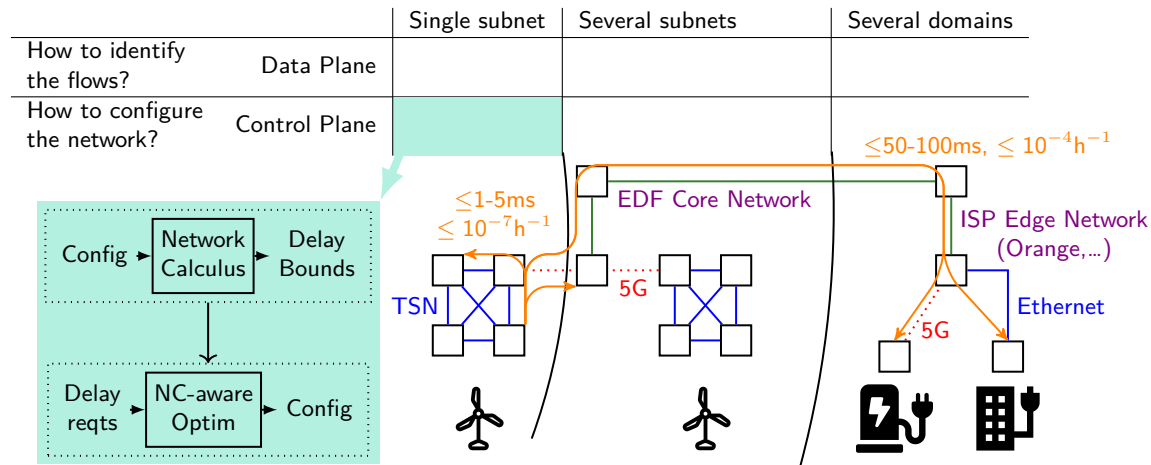
No ~~known~~
service curve
 \otimes

“true time”: *temps atomique international* (TAI)

¹<https://gitlab.epfl.ch/thomas/xtfa>

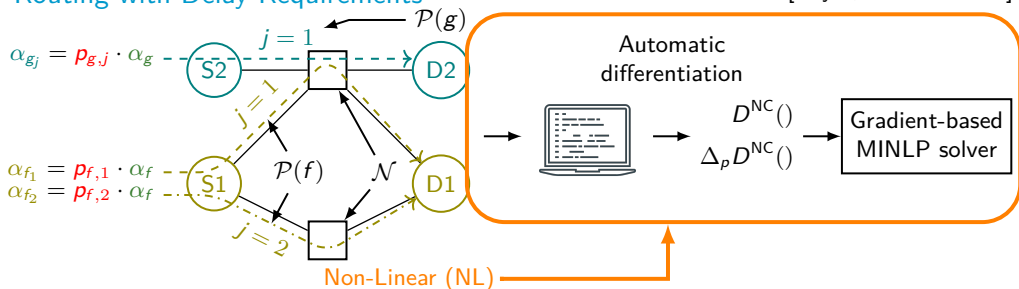
²https://gitlab.com/nsnam/ns-3-dev/-/merge_requests/332

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



Routing with Delay Requirements

[Geyer, Bondorf 2022]

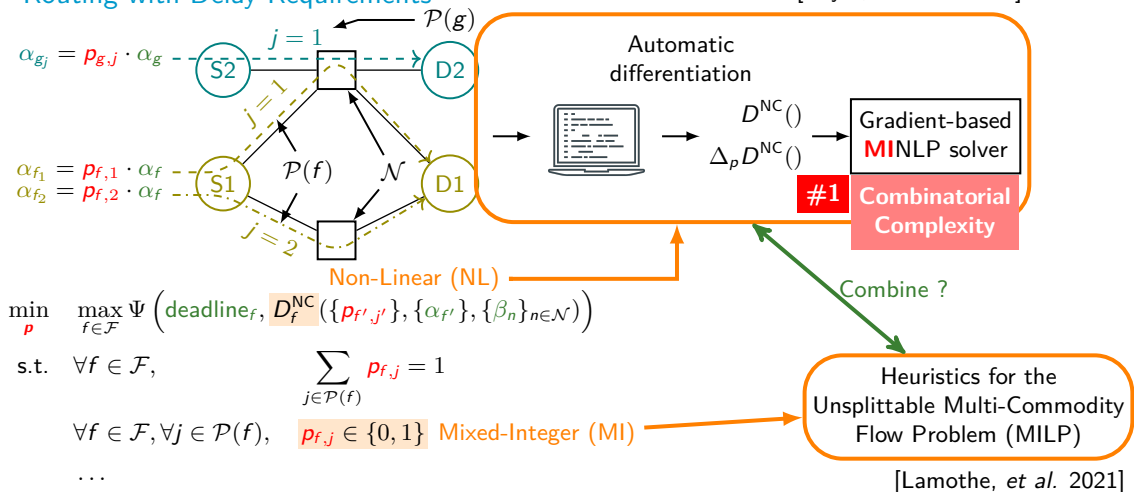


$$\begin{aligned}
 \min_{\mathbf{p}} \quad & \max_{f \in \mathcal{F}} \Psi \left(\text{deadline}_f, D_f^{\text{NC}}(\{p_{f',j'}\}, \{\alpha_{f'}\}, \{\beta_n\}_{n \in \mathcal{N}}) \right) \\
 \text{s.t.} \quad & \forall f \in \mathcal{F}, \quad \sum_{j \in \mathcal{P}(f)} p_{f,j} = 1 \\
 & \forall f \in \mathcal{F}, \forall j \in \mathcal{P}(f), \quad p_{f,j} \in \{0, 1\} \quad \text{Mixed-Integer (MI)}
 \end{aligned}$$

– [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

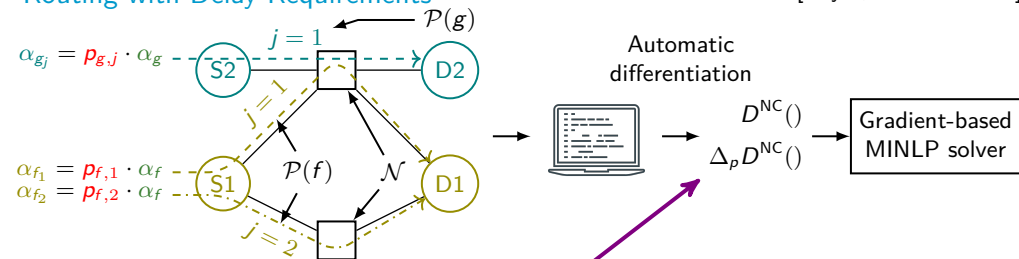
[Geyer, Bondorf 2022]



– [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](https://doi.org/10.1007/s10732-021-09478-w)

Routing with Delay Requirements

[Geyer, Bondorf 2022]



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

s.t. ...

#2

Vastly
Pessimistic

Arbitrary Scheduler

Priority
SchedulerFIFO
SchedulerGood service-
curve modelInterleaved
RegulatorNo known
service curve

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

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.	Software-defined networks	Distributed routing and automatic contracts.

■ IRIT (Équipe RMESS), Toulouse

- Modeling Time-Sensitive Networks with Trajectorial Approaches
- TSN/5G interconnection with application to Non-Terrestrial Networks
- Transition analysis

■ Loria (Département 3), Nancy

- Modeling Time-Sensitive Networks with Approaches similar to Trajectorial
- Wired/Wireless interconnection with application to Smart Grids
- Software-defined networks

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

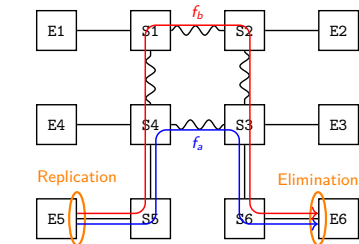
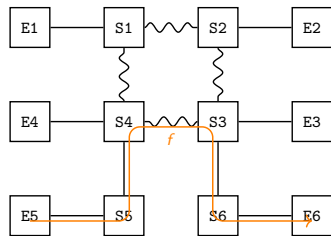
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- [Geyer, Bondorf 2022] Geyer, Fabien and Steffen Bondorf (May 2022). “Network Synthesis under Delay Constraints: The Power of Network Calculus Differentiability”. In: *IEEE INFOCOM 2022 - IEEE Conference on Computer Communications*. IEEE INFOCOM 2022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

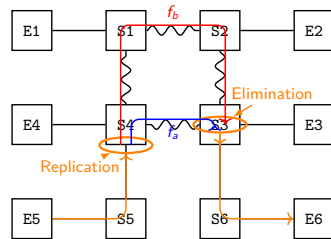
Bibliography II

- [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](https://doi.org/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]



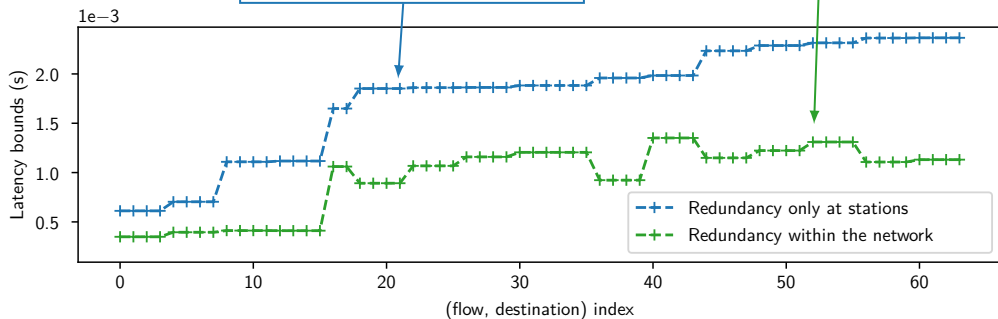
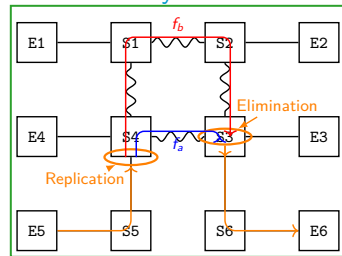
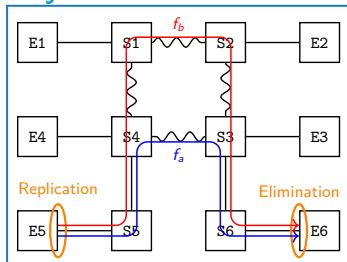
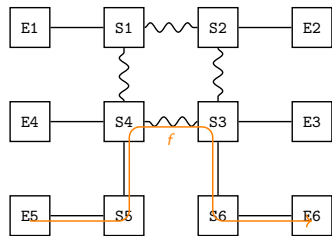
Model for redundancy
[Thomas, Mifdaoui, Le Boudec 2022]

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](#)

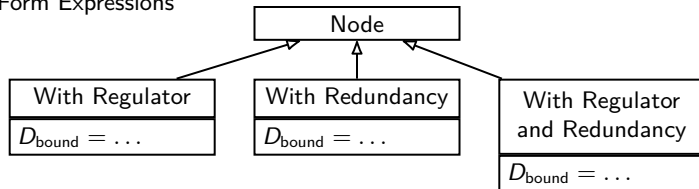
– [Thomas, Mifdaoui, Le Boudec 2022] [Ludovic Thomas, Ahlem Mifdaoui, and Jean-Yves Le Boudec \[2022\]. “Worst-Case Delay Bounds in Time-Sensitive Networks With Packet Replication and Elimination”. In: IEEE/ACM Transactions on Networking. DOI: 10.1109/TNET.2022.3180763](#)

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

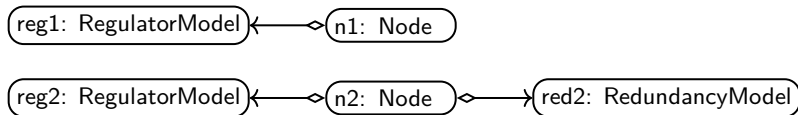


xTFA: An Open-Source **Analysis and Verification** Tool Based on Network Calculus

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](mailto:barnes26@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>