Analysis of the Side-Effects on Latency Bounds of Combinations of Scheduling, Redundancy and Synchronization Mechanisms in Time-Sensitive Networks

Ph.D defense

Ludovic Thomas

Supervised by Ahlem Mifdaoui and Jean-Yves Le Boudec

September 12th, 2022

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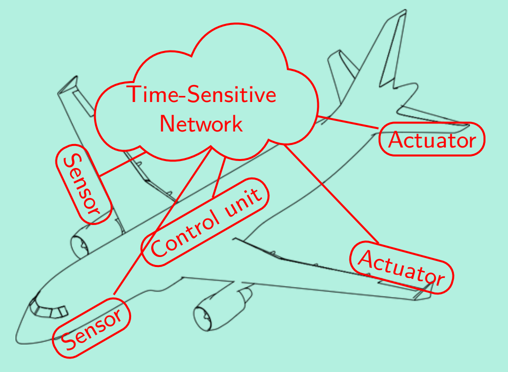
Cyber-Physical Systems



Safety-critical applications

Analysis of the Side-Effects on Latency Bounds of Combinations of Scheduling, Redundancy and Synchronization Mechanisms in Time-Sensitive Networks

Public networks
(e.g., the Internet)

Best-effort service

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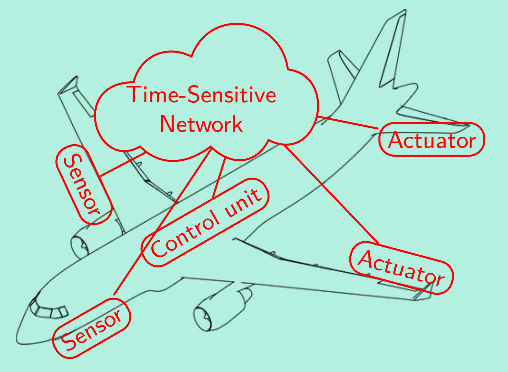

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Time-Sensitive Networks

Deterministic Service

Bounded Latency

+ no loss by congestion

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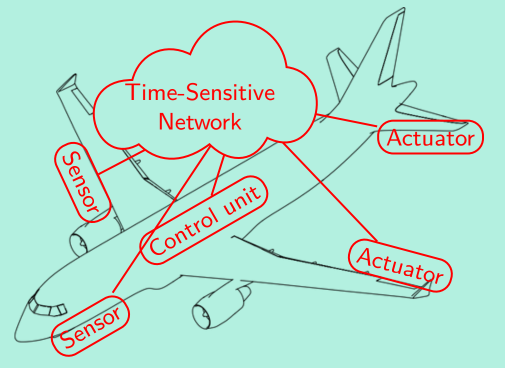

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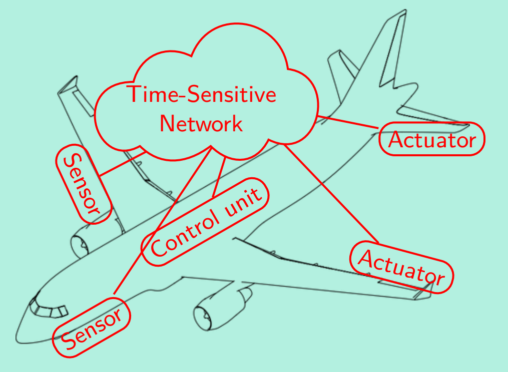
IEEE *Time-Sensitive Networking* (TSN)
IETF *Deterministic Networking* (DetNet)

Cyber-Physical Systems



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Bounded Latency

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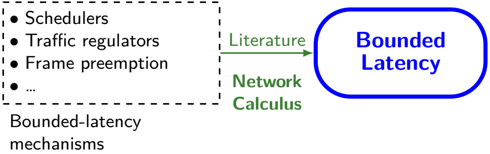

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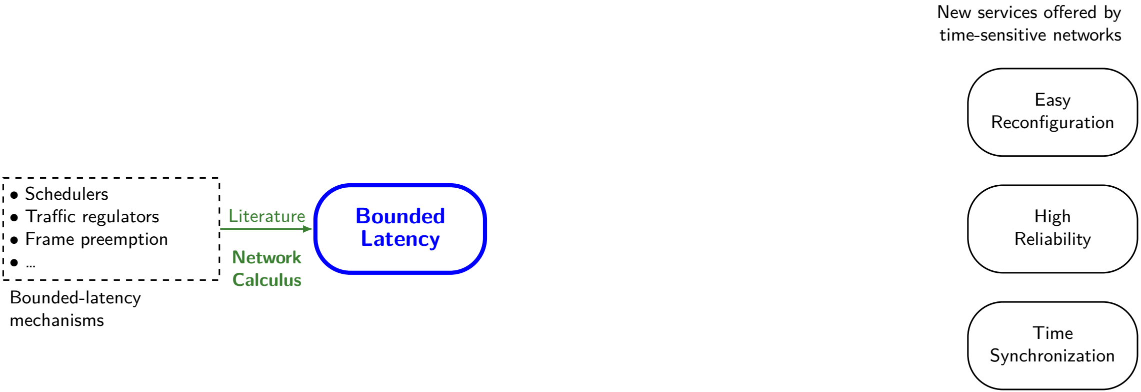

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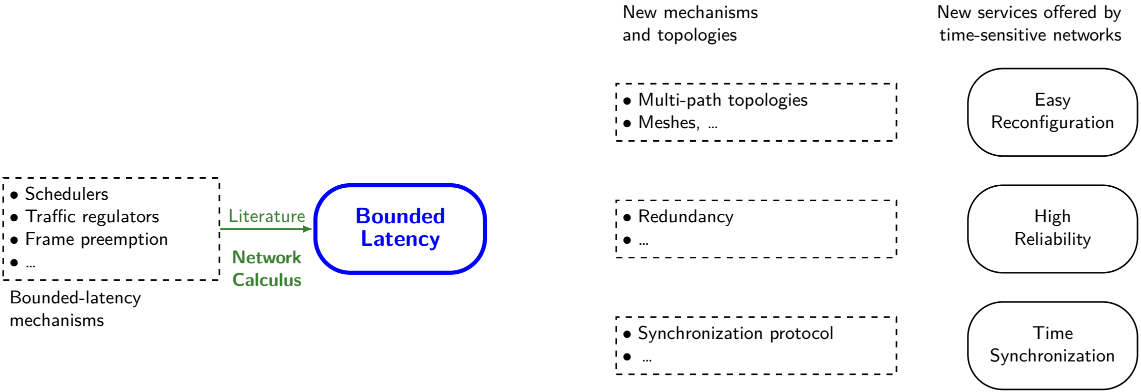

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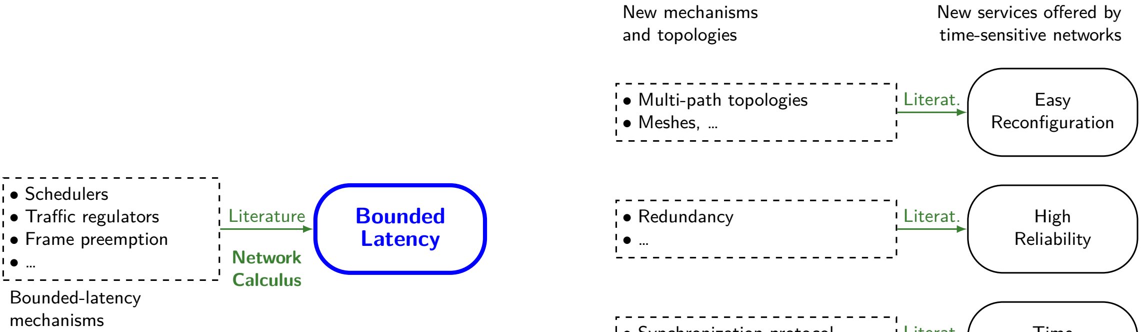

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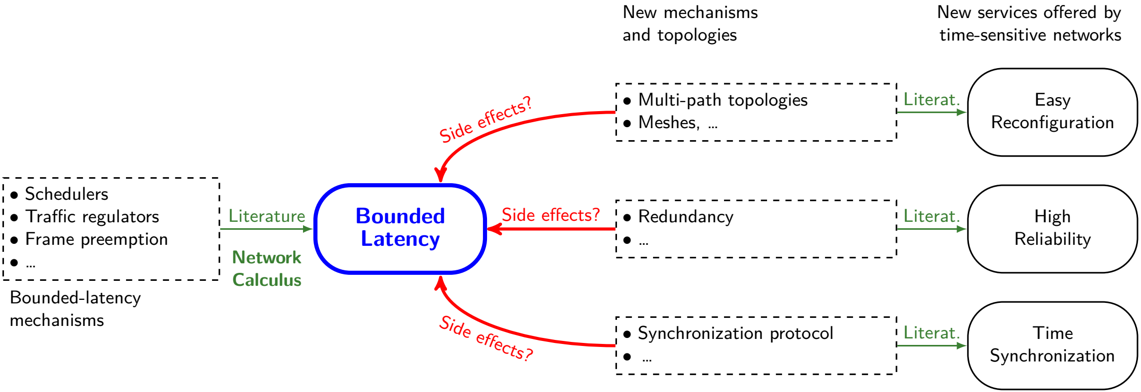

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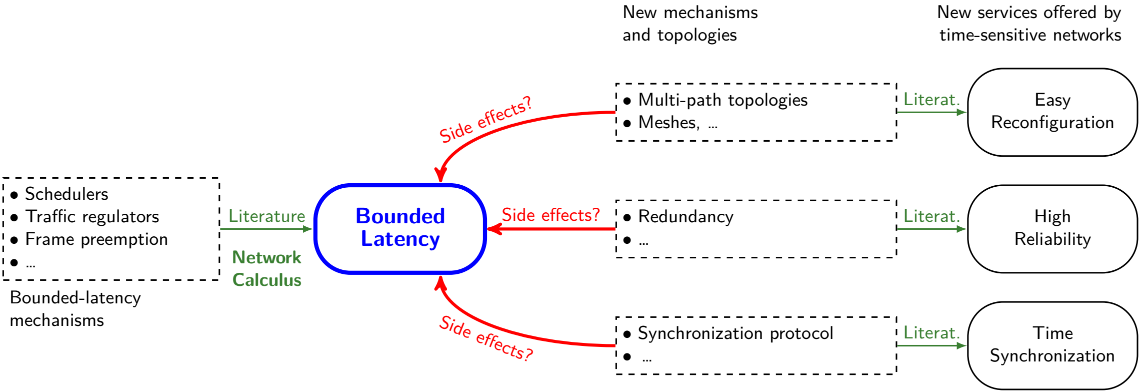
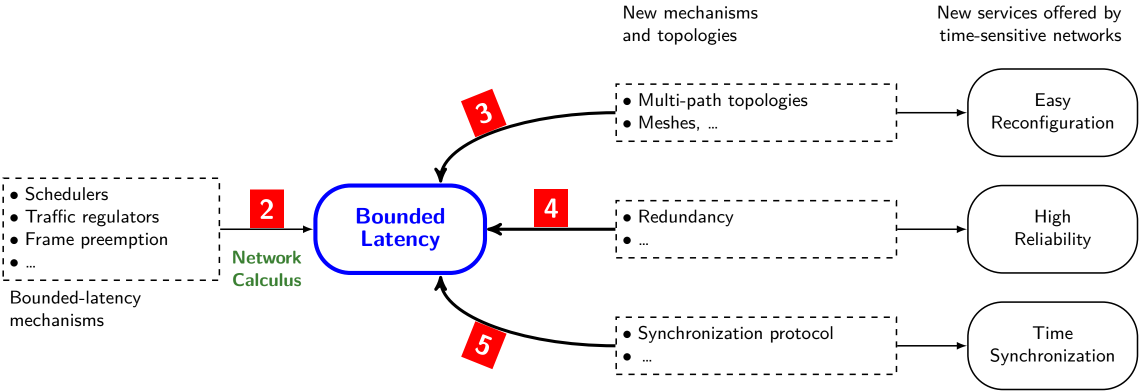
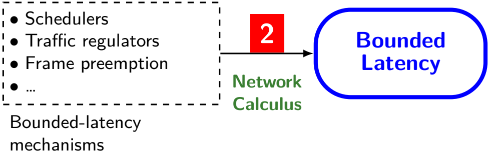


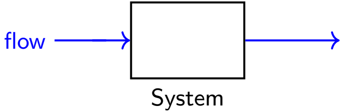
Outline of this Presentation



Network Calculus



Network Calculus Relies on **Two Main Abstractions**



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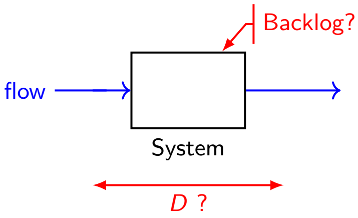

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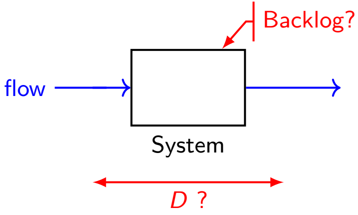


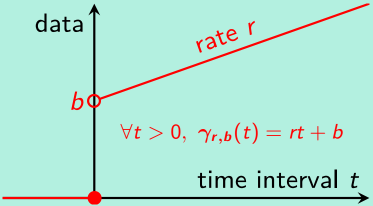
Guaranteed upper bounds?

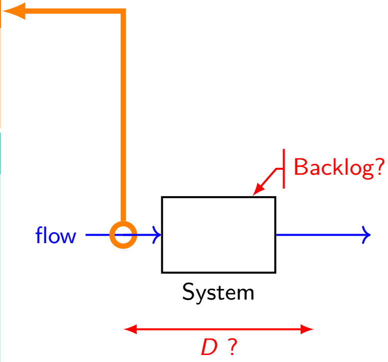
Network Calculus Relies on **Two Main Abstractions**

Arrival Curve α

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

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





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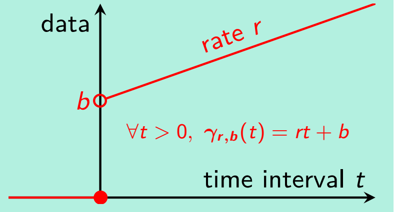

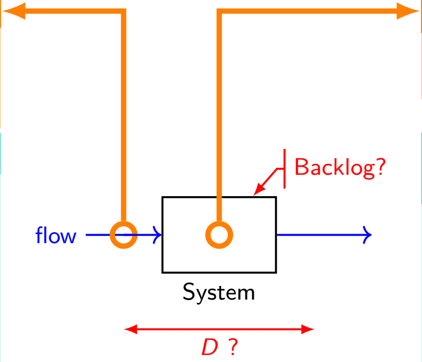

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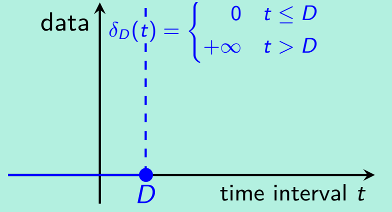
Service Curve β

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

Bounded-Delay δ_D



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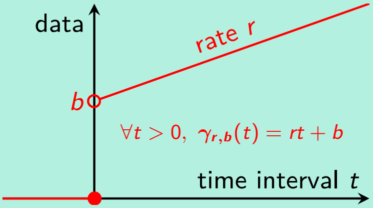

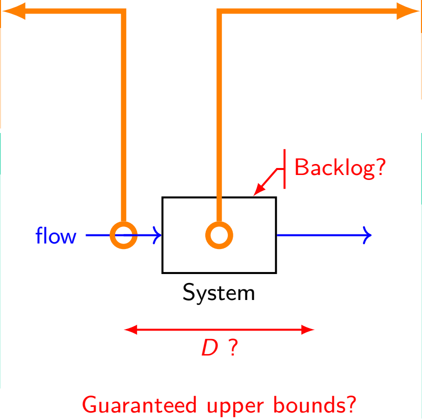

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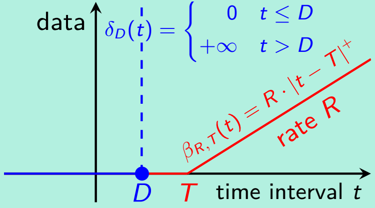
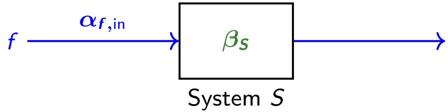
Rate-Latency $\beta_{R,T}$
Bounded-Delay δ_D

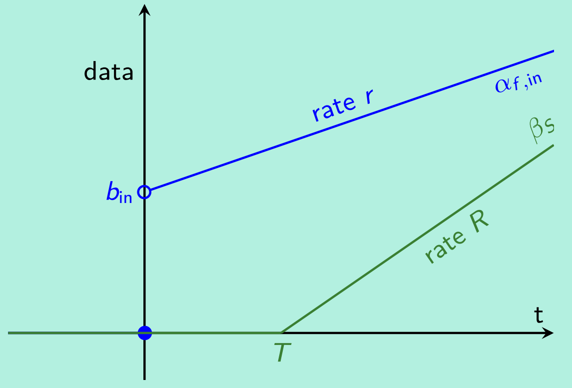


$|\cdot|^+ = \max(0, \cdot)$

Network Calculus Provides **Upper Bounds** For Worst-Case Delay, Backlog and Output Traffic



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



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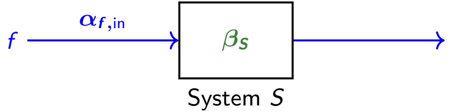

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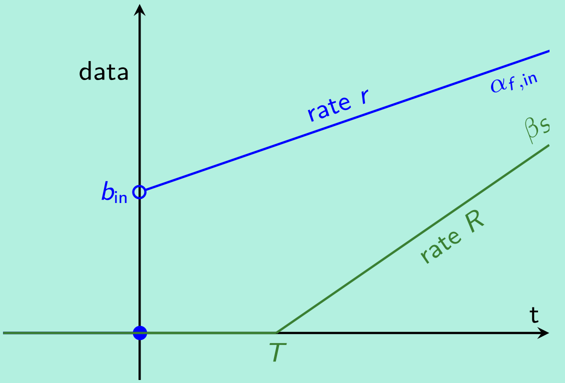

Network Calculus Main Result [Le Boudec, Thiran 2001]

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

– [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

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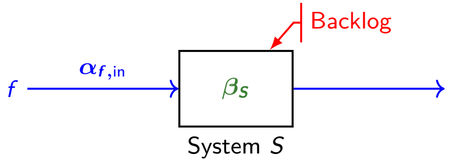

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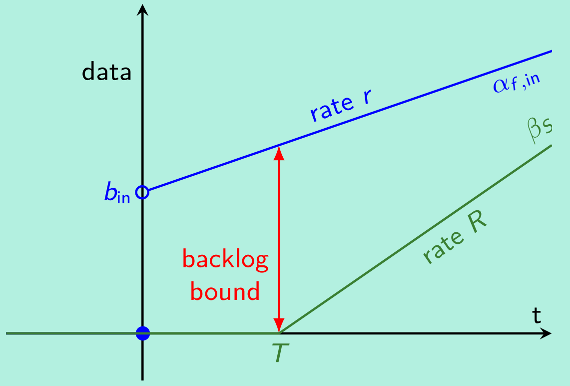

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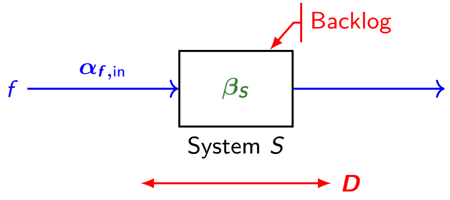

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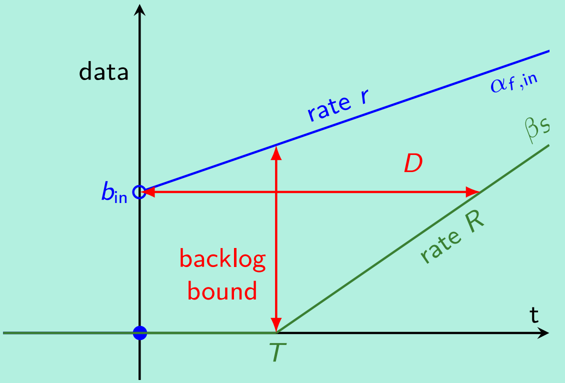

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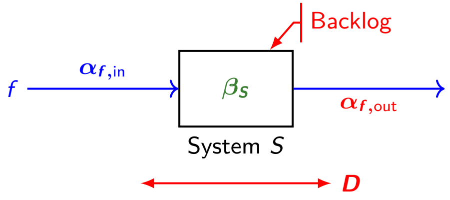

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- Delay upper-bound
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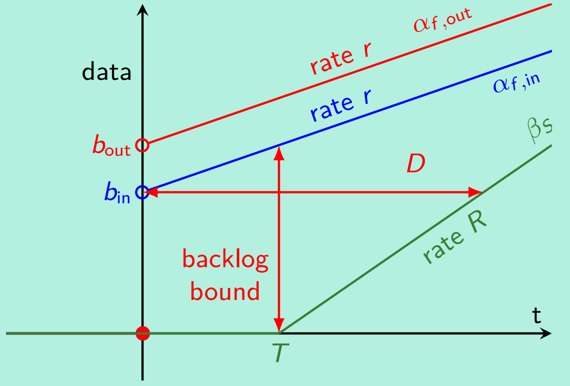

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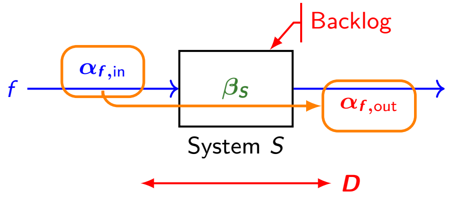

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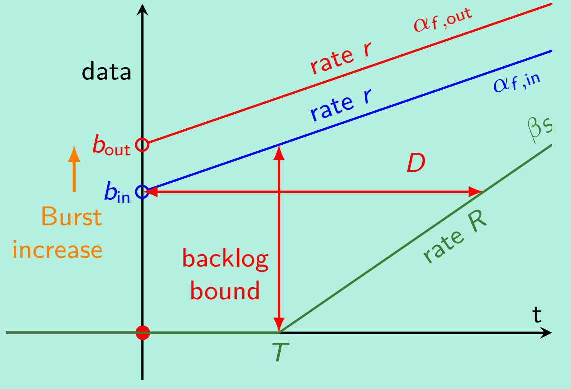

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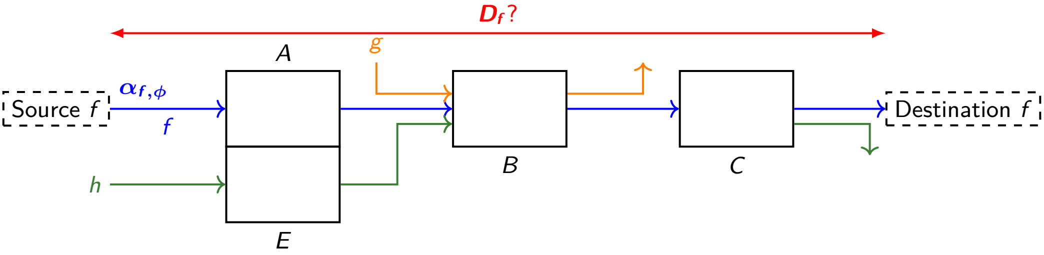
From a Multiclass Network to n FIFO Networks



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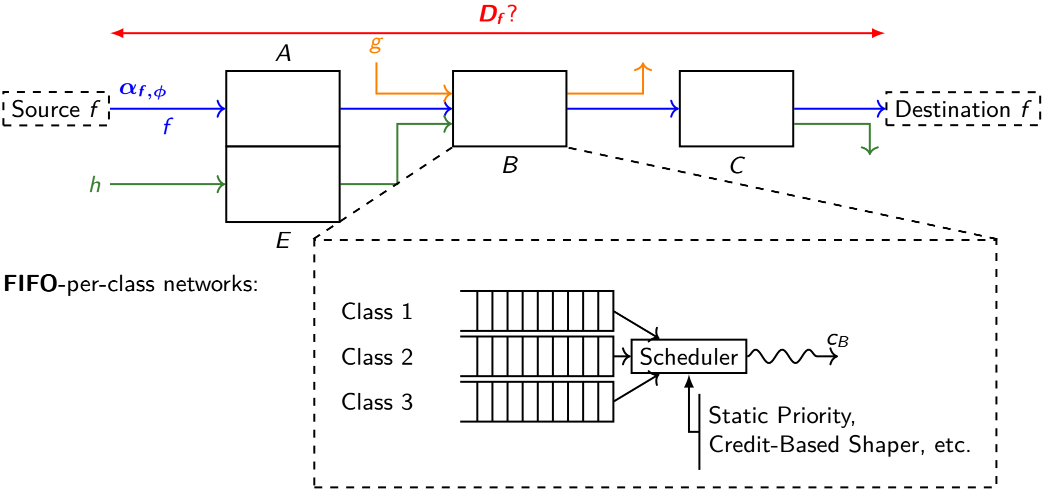

FIFO-per-class networks:

FIFO: First in, first out

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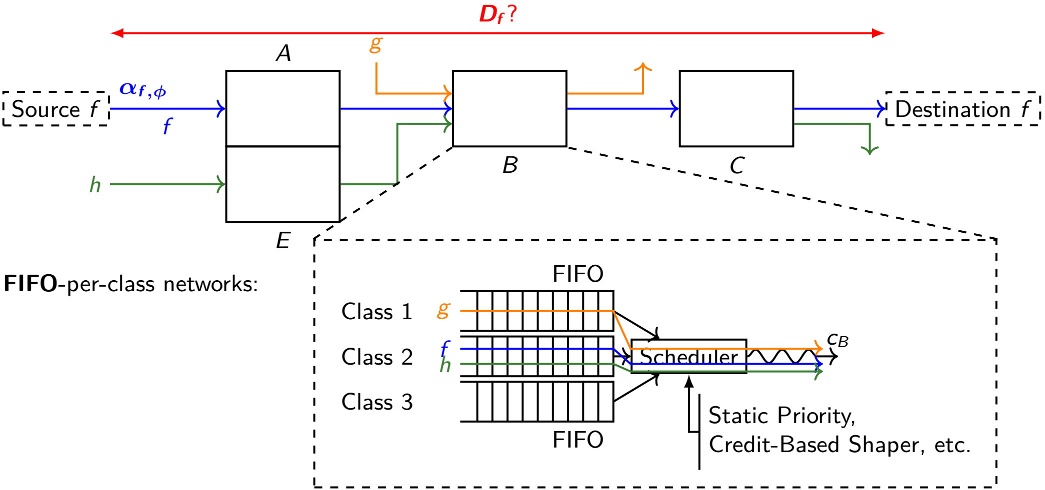

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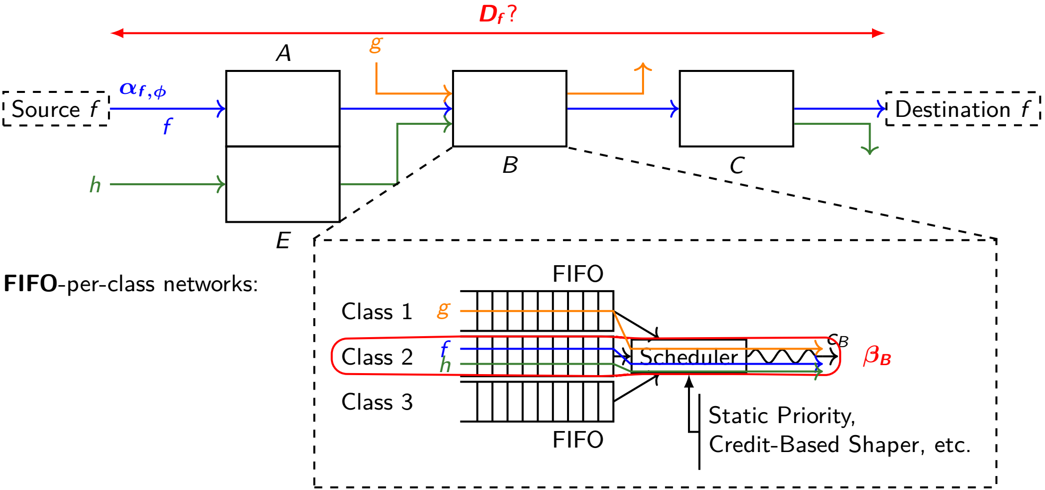

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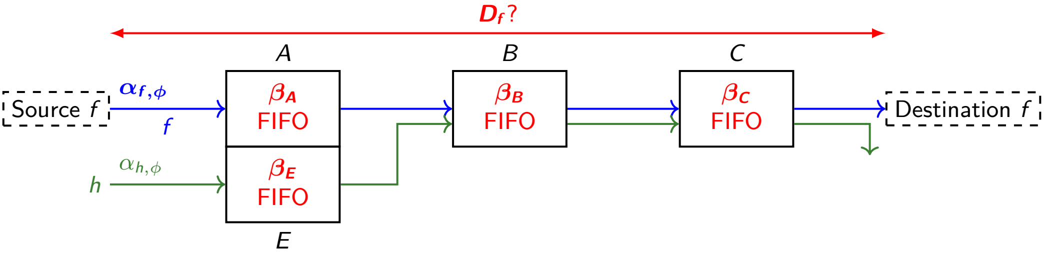
From a Multiclass Network to n FIFO Classes: We Focus on **One Class**



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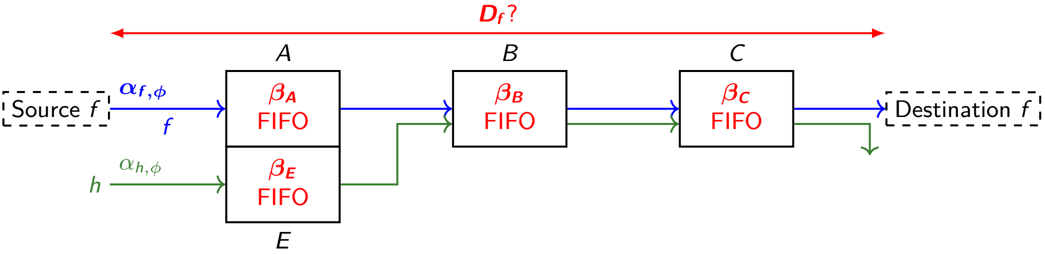
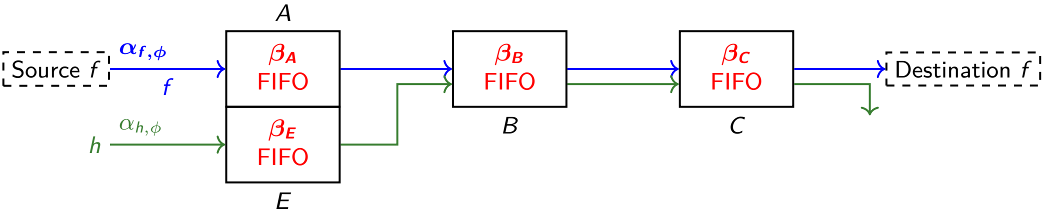


Compositionnal approaches: compute end-to-end latency bounds in **FIFO** networks (active research field).

Total Flow Analysis, a Compositionnal Approach for Obtaining End-To-End Latency Bounds



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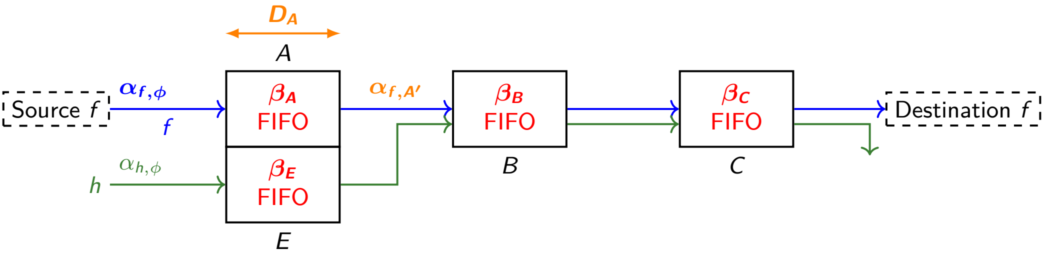

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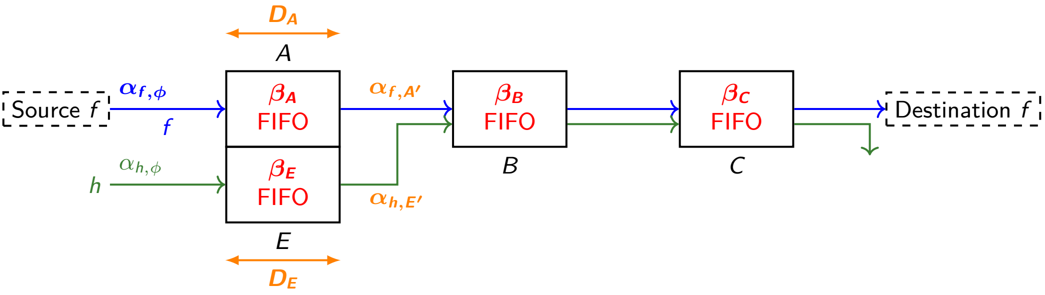

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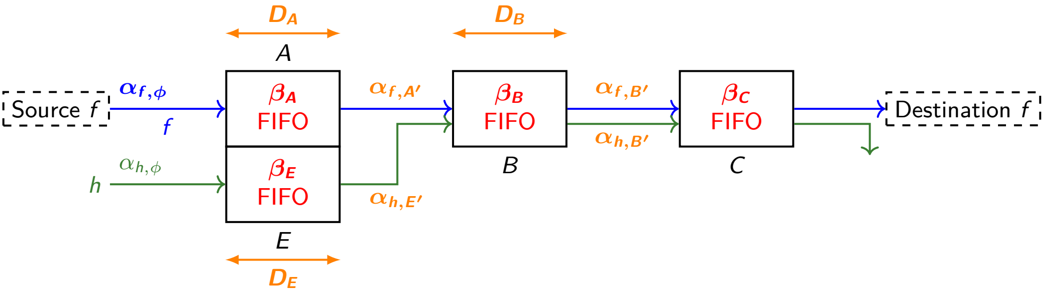

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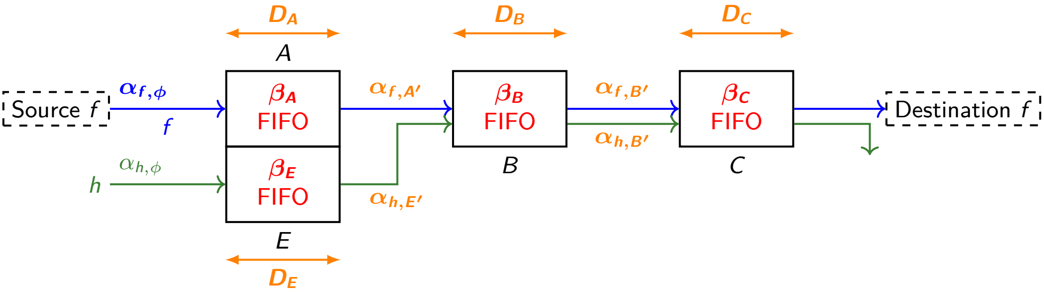

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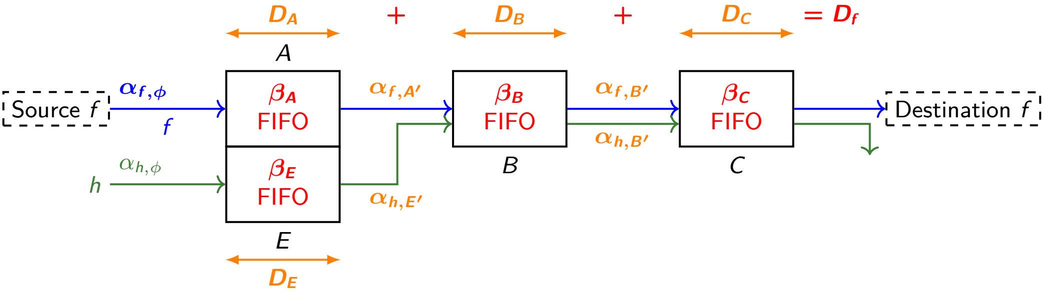

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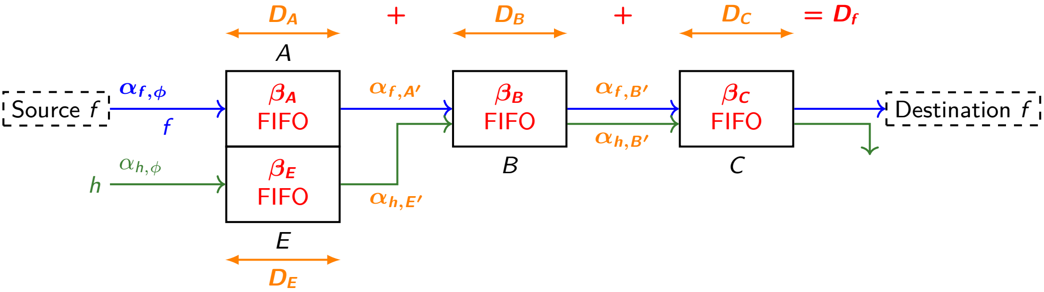

Properties of TFA (Total Flow Analysis)

- **Optimal** worst-case upper bounds are **not guaranteed**.

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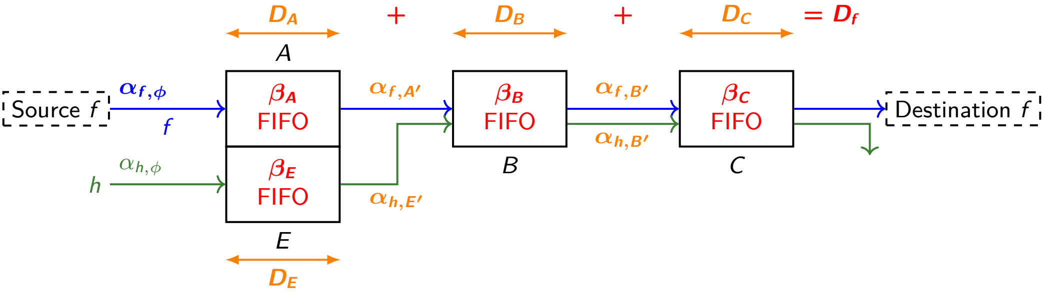


Properties of TFA (Total Flow Analysis)

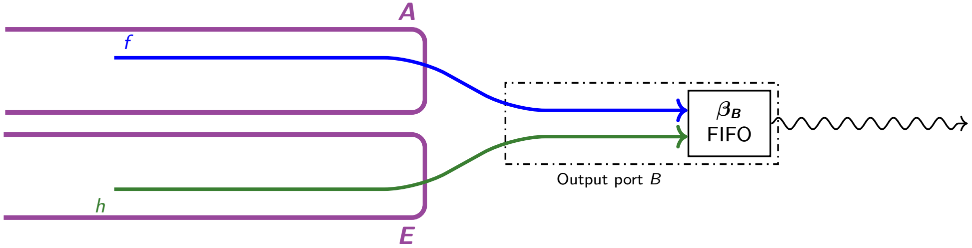
- **Optimal** worst-case upper bounds are **not guaranteed**.

but

- **scalable** (linear complexity with the network's size) and **flexible** (new models are easy to integrate)

Total Flow Analysis Proceeds in Three Steps for each Node

Zoom on B



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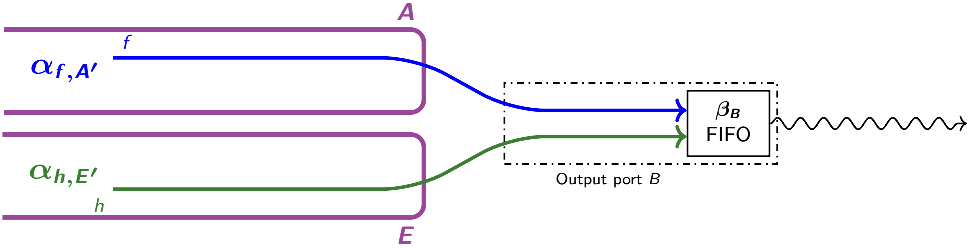

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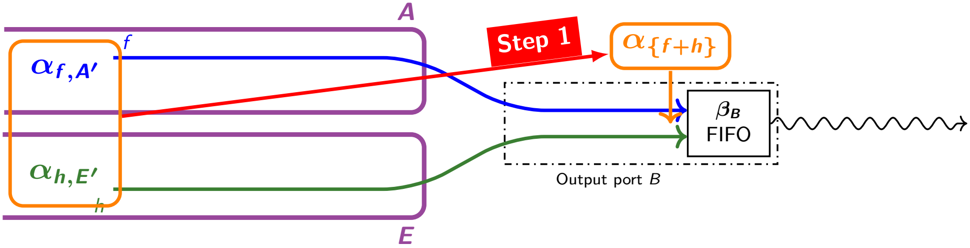

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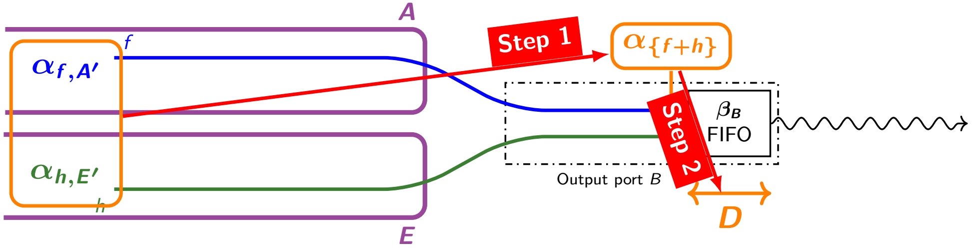

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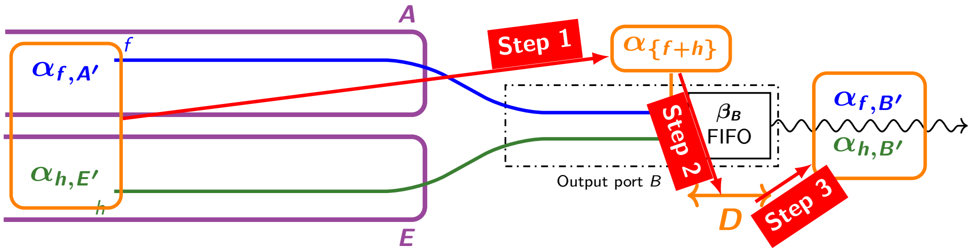

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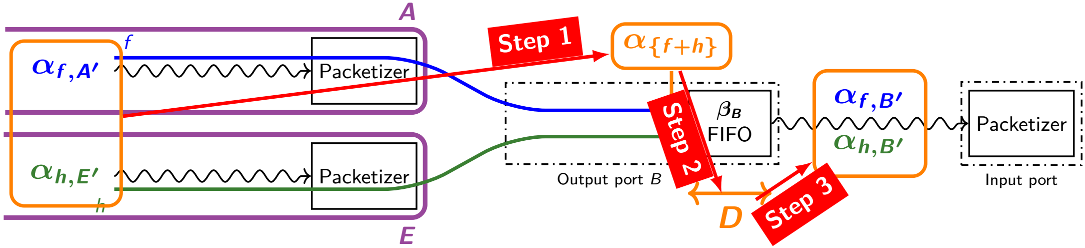

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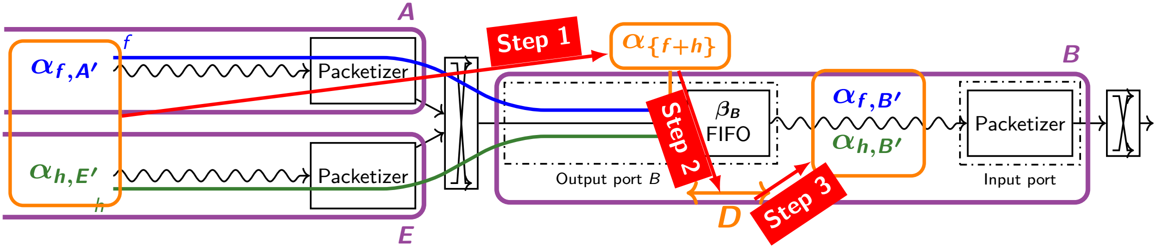

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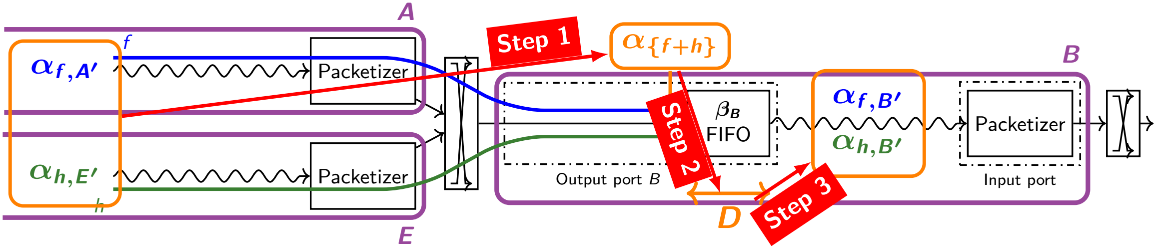
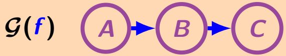


Flow Graphs



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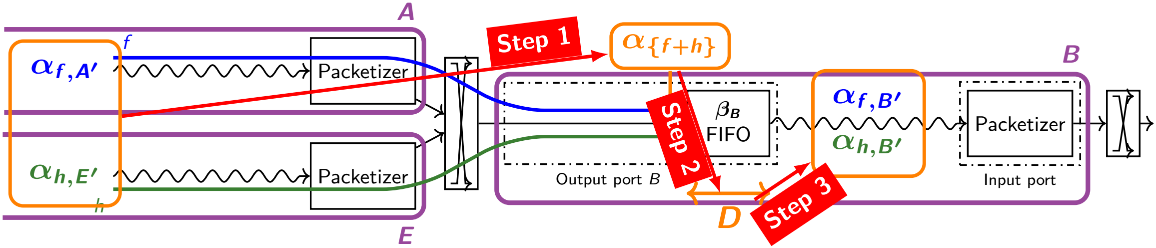

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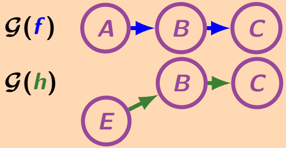

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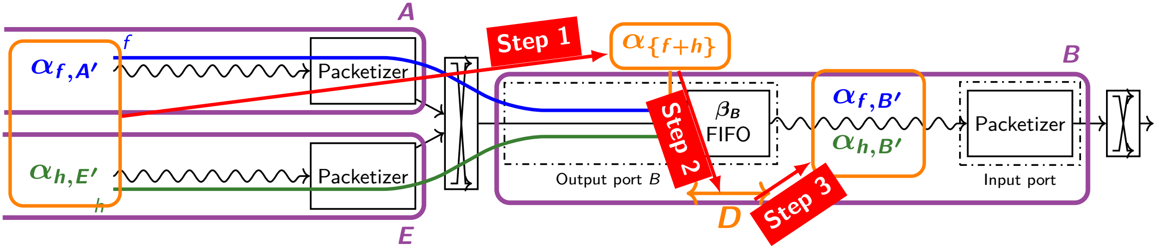
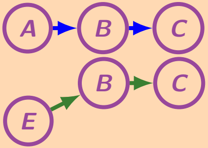


Flow Graphs

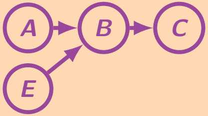
$\mathcal{G}(f)$

$\mathcal{G}(h)$



Graph Induced By Flows $\mathcal{G}$

$\mathcal{G}$



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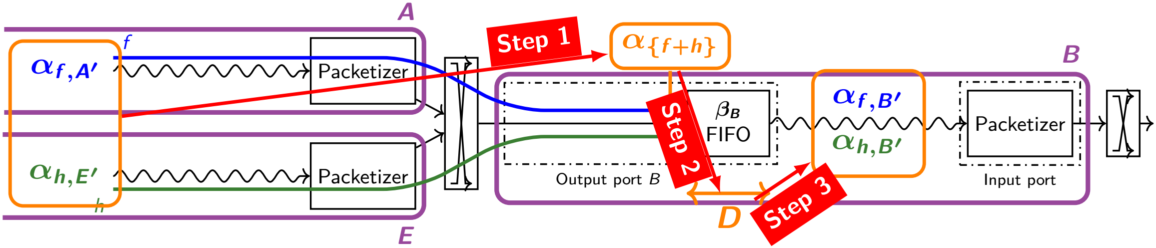

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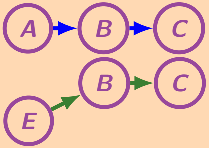

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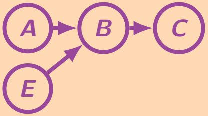
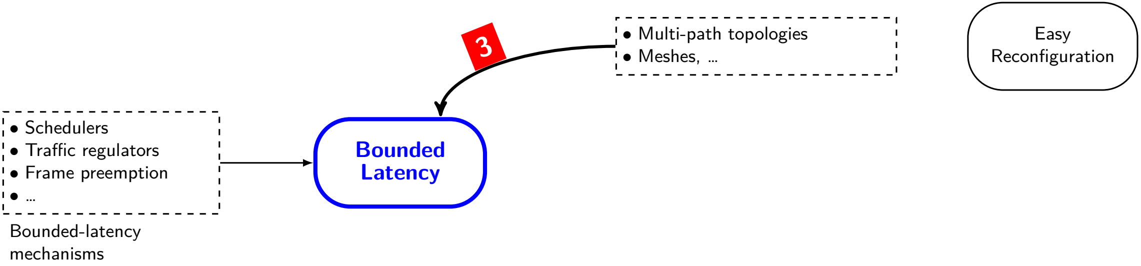
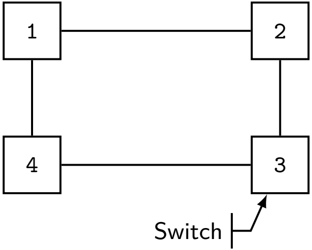


TFA is limited to networks with an **acyclic** graph $\mathcal{G}$: **feed-forward networks**.

Multi-Path Topologies



A Possible Consequence of Using Multi-Path Topologies: **Cyclic Dependencies**



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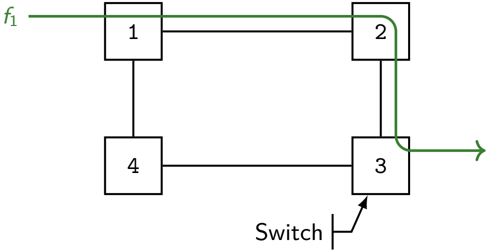

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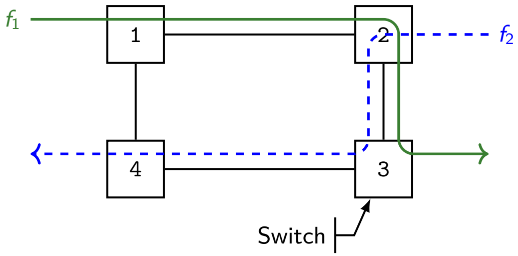

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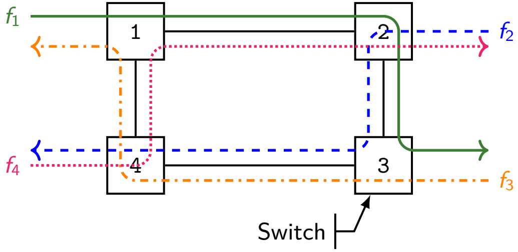

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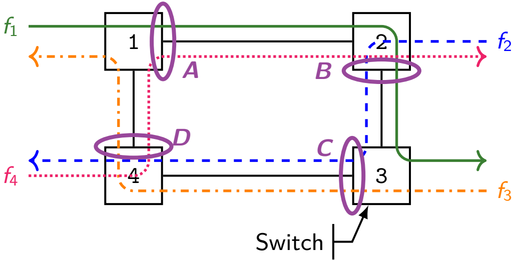

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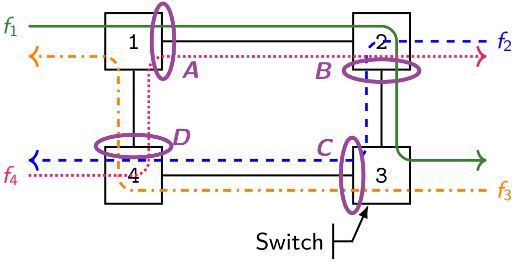
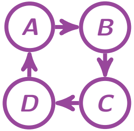


Graph induced by flows $\mathcal{G}$:



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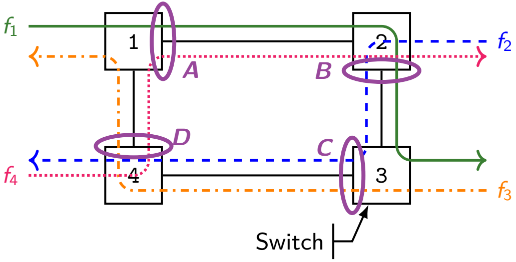

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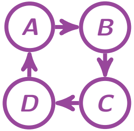
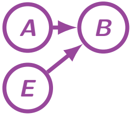


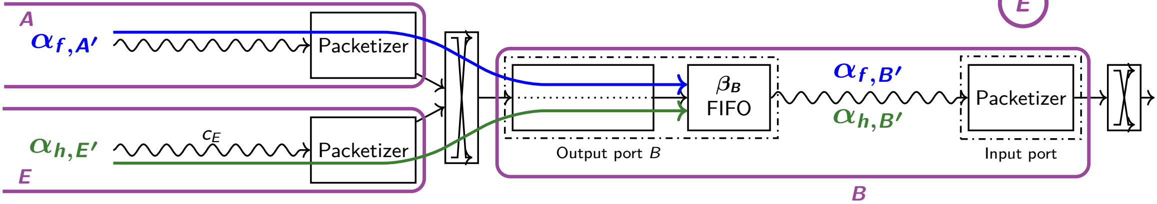
End-to-end latency bounds?

Fixed-Point Total Flow Analysis (FP-TFA)

Fixed-Point Total Flow Analysis (FP-TFA): An **Improved TFA**



FP-TFA is based on Total Flow Analysis **with improvements**



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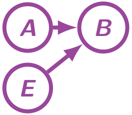

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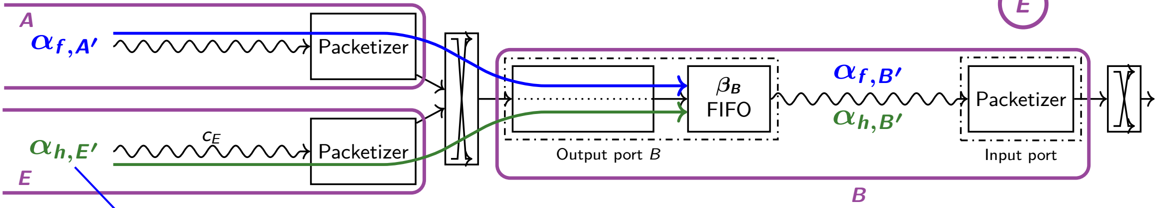
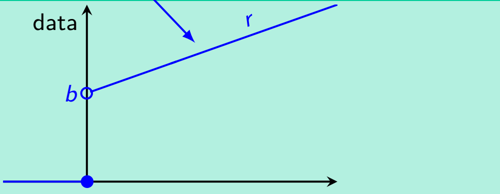


Line shaping [Mifdaoui, Leydier 2017]



– [Mifdaoui, Leydier 2017] Ahlem Mifdaoui and Thierry Leydier [Dec. 2017]. "Beyond the Accuracy-Complexity Tradeoffs of Compositional Analyses Using Network Calculus for Complex Networks". In: *10th International Workshop on Compositional Theory and Technology for Real-Time Embedded Systems (Co-Located with RTSS 2017).* Paris, France

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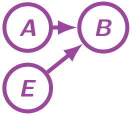

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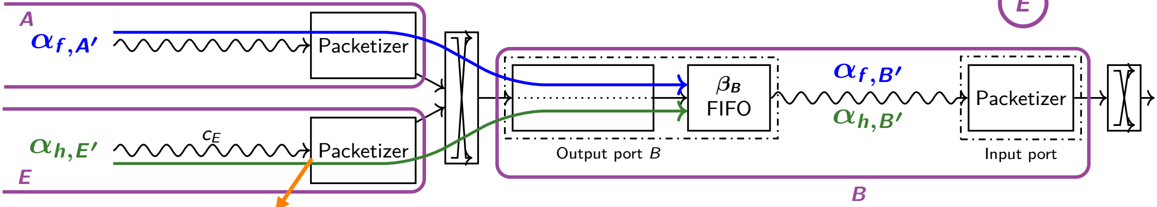

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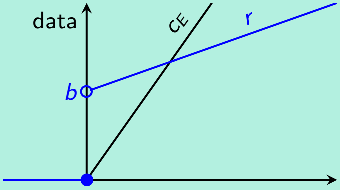

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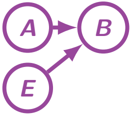

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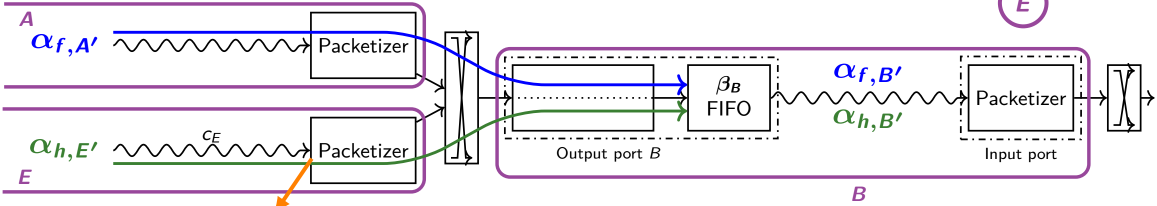

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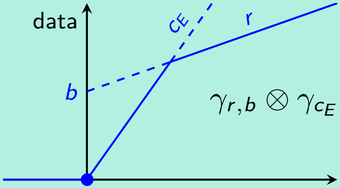

$\otimes$: min-plus convolution

$(\mathfrak{f} \otimes \mathfrak{g}) : t \mapsto \inf_{0 \leq s \leq t}\{\mathfrak{f}(t-s) + \mathfrak{g}(s)\}$

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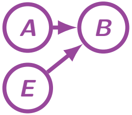

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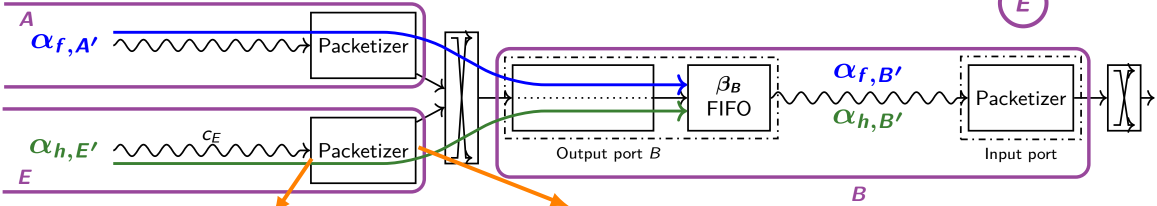

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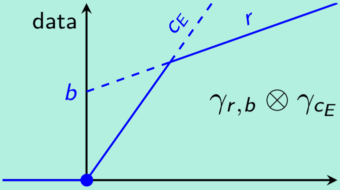

- Previous result: $+l_{max}$
- New result: $+l_{\max}\frac{r}{c_E}$

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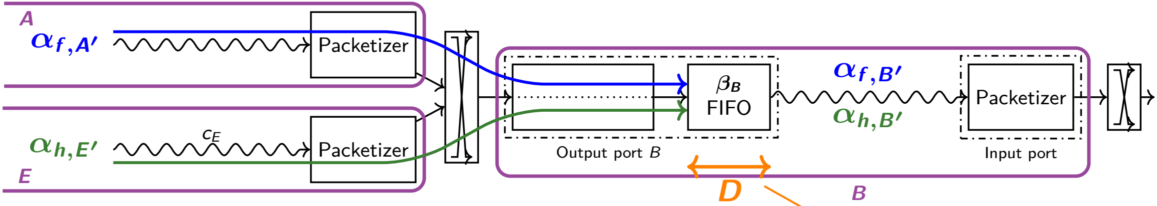

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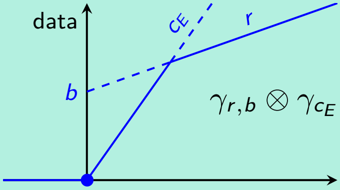

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[Mohammadpour, Stai, Le Boudec 2019]

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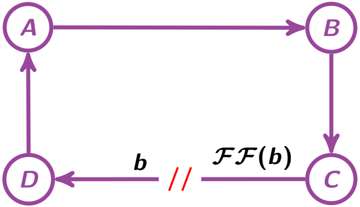
– [Mohammadpour, Stai, Le Boudec 2019] E. Mohammadpour, E. Stai, and J.-Y. Le Boudec [2019]. "Improved Delay Bound for a Service Curve Element with Known Transmission Rate". In: *IEEE Networking Letters*. DOI: 10.1109/LNET.2019.2927143

FP-TFA: A **New Fixed-Point Result** for Networks with Cyclic Dependencies

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



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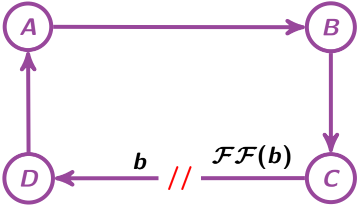

Theorem (Validity of the fixed-point)

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

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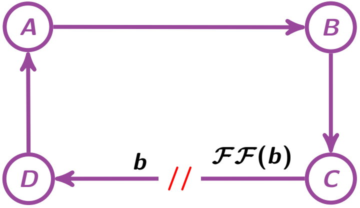

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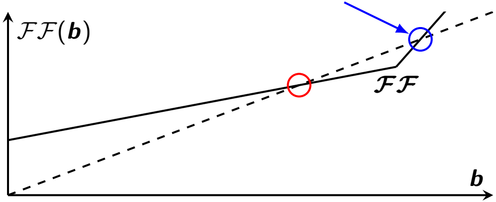
Before our result

[Bouillard, Boyer, Le Corronc 2018]



– [Bouillard, Boyer, Le Corronc 2018] Anne Bouillard, Marc Boyer, and Euriell Le Corronc [2018]. *Deterministic Network Calculus: From Theory to Practical Implementation*. Wiley. ISBN: 978-1-84821-852-9

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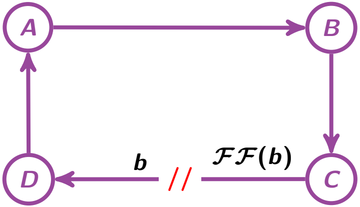

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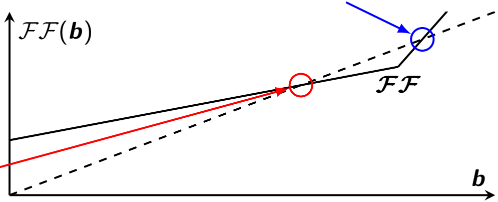

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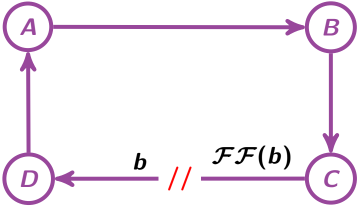

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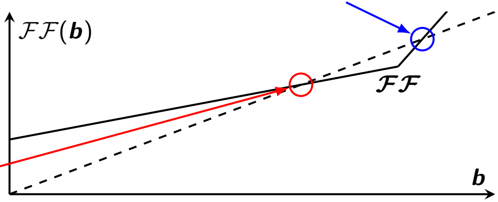


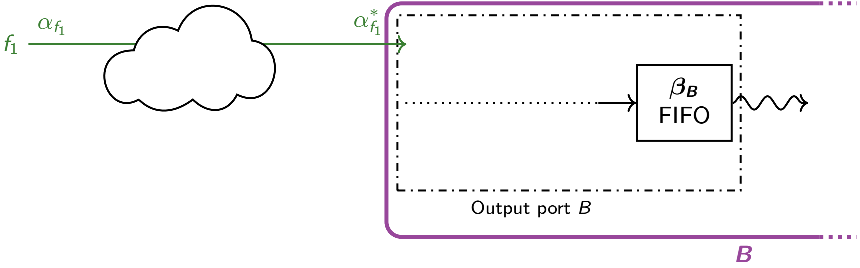
Sometimes, no fixed-point can be found!

[Andrews 2009]

There exist FIFO networks with cyclic dependencies and arbitrarily small load that are **unstable** (unbounded latencies).

– [Andrews 2009] Matthew Andrews [July 2009]. "Instability of FIFO in the Permanent Sessions Model at Arbitrarily Small Network Loads". In: *ACM Trans. Algorithms* 5.3. DOI: 10.1145/1541885.1541894

Traffic Regulators Break Cyclic Dependencies and Remove Instability Issues



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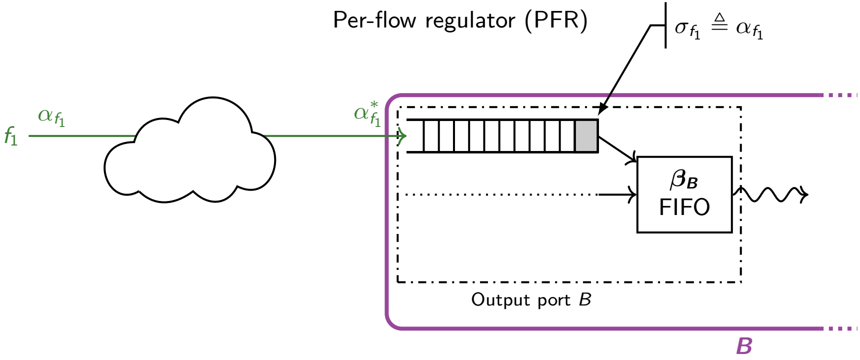

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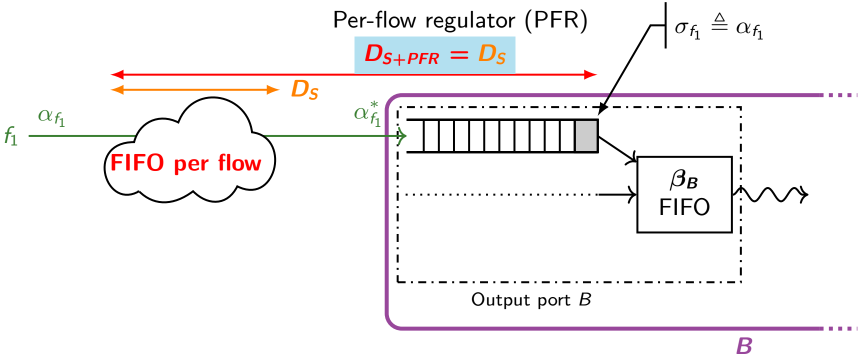

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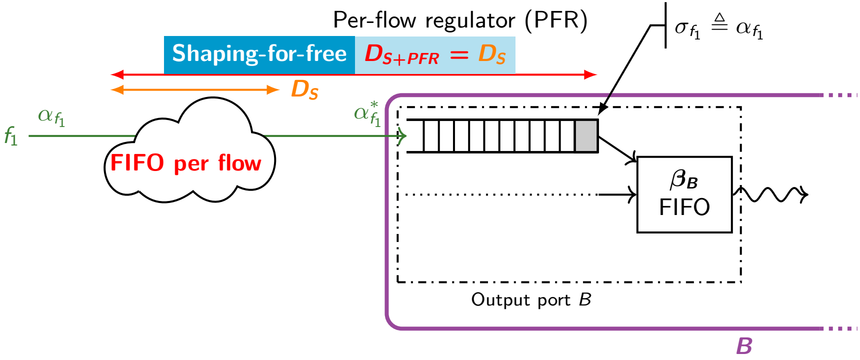

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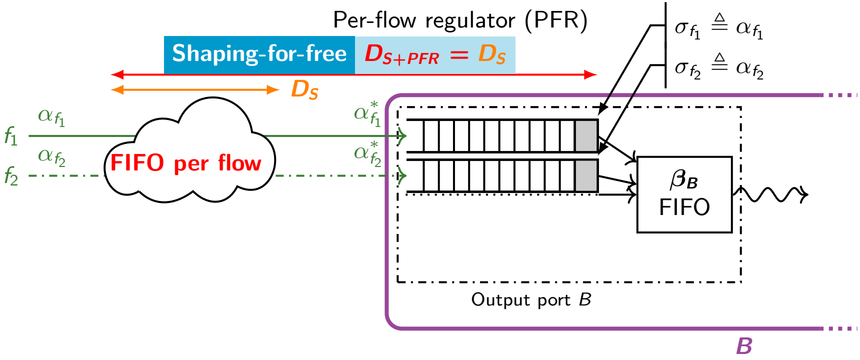

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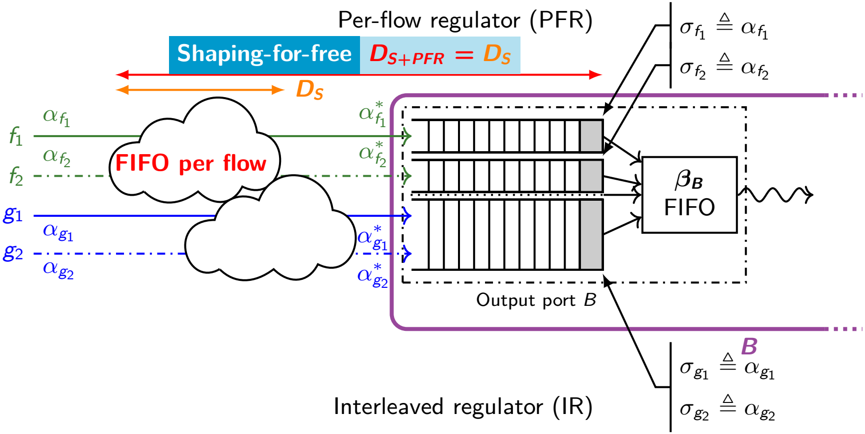

TSN *Asynchronous Traffic Shaping* (ATS)

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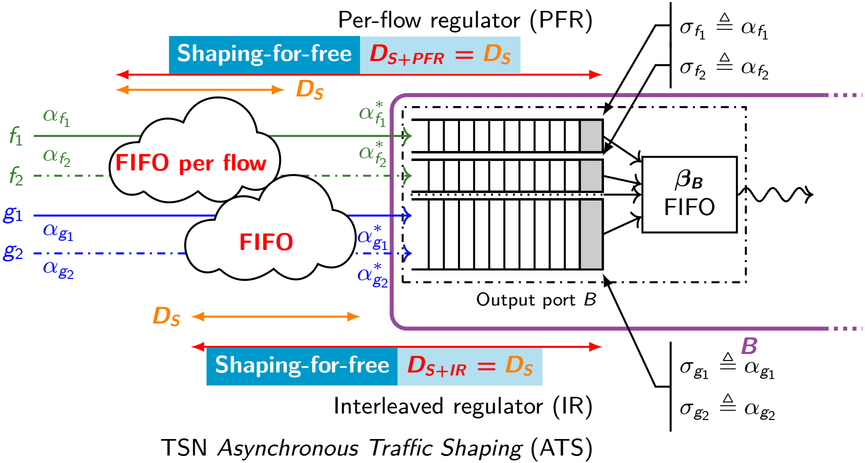

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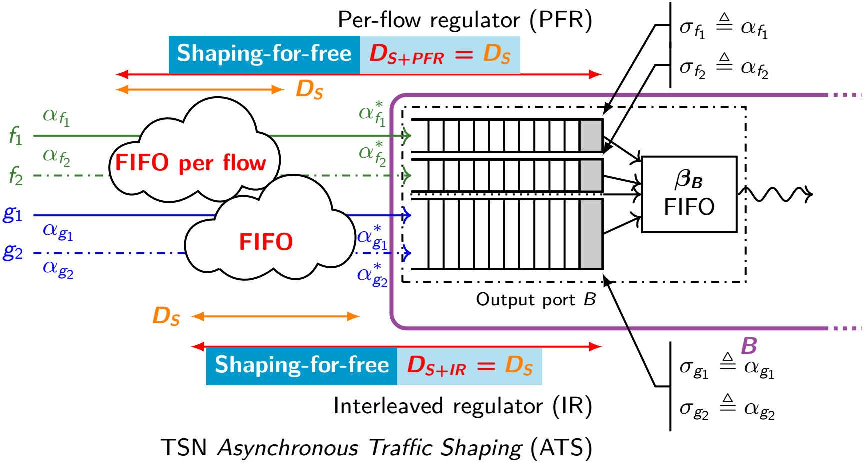


Place regulators only at few strategic places: **Low-Cost Acyclic Network (LCAN)**

Multi-path Topologies: **Our Contributions**

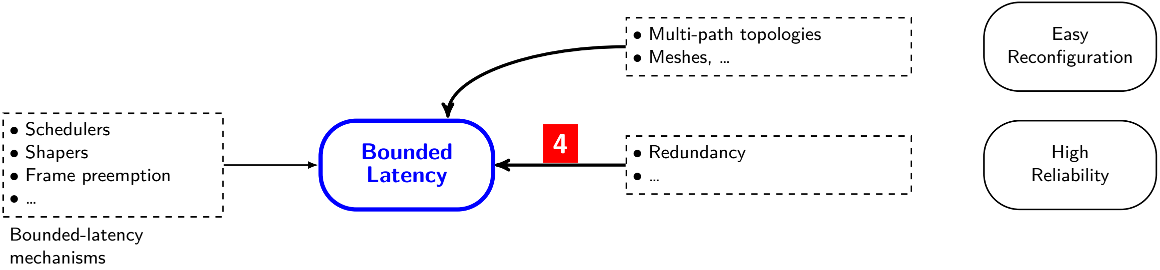
Contribution	Multipath topologies
End-to-end latency bounds	**FP-TFA**
Traffic regulators (PFRs and IRs)	LCAN

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

FP-TFA: Fixed-point total flow analysis
LCAN: Low-cost acyclic network

PFR: Per-flow regulator
IR: Interleaved regulator (=TSN ATS)

Redundancy Mechanisms

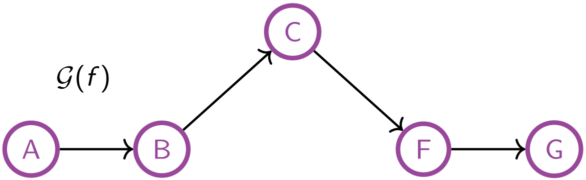


In TSN: Frame replication and elimination for redundancy [IEEE 802.1CB] (FRER)
In DetNet: Packet replication and elimination functions [RFC 8655] (**PREF**)

– [IEEE 802.1CB] "IEEE Standard for Local and Metropolitan Area Networks–Frame Replication and Elimination for Reliability" [Oct. 2017]. In: *IEEE Std 802.1CB-2017*. DOI: 10.1109/IEEESTD.2017.8091139

– [RFC 8655] Norman Finn, Pascal Thubert, Balázs Varga, and János Farkas [2019]. "Deterministic Networking Architecture". In: RFC 8655. DOI: 10.17487/RFC8655

Redundancy Relies on **Packet Replication (PRF)** and **Packet Elimination (PEF)** Functions



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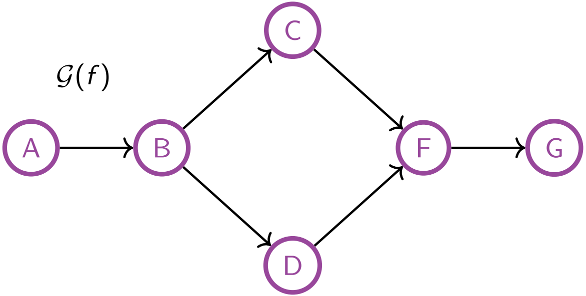

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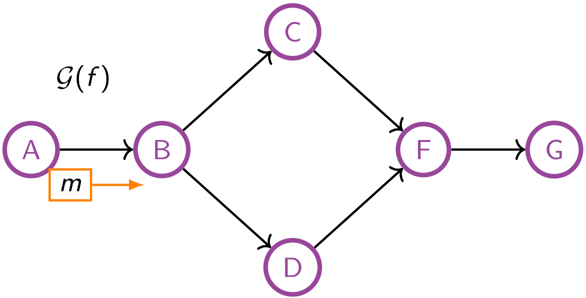

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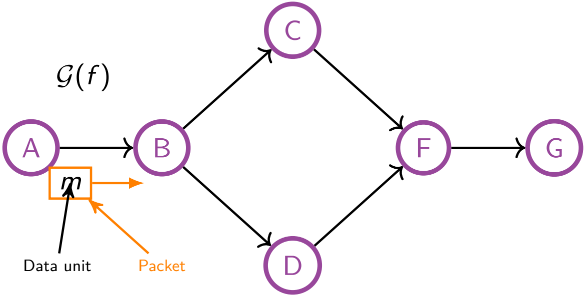

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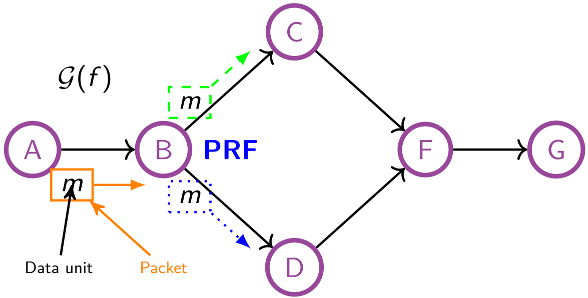

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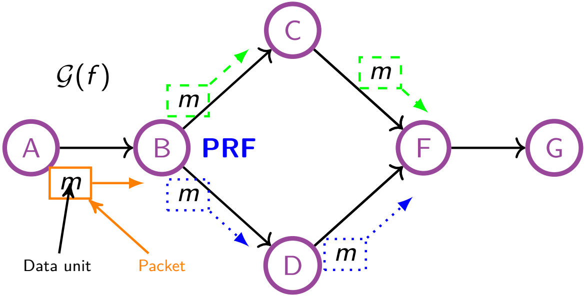

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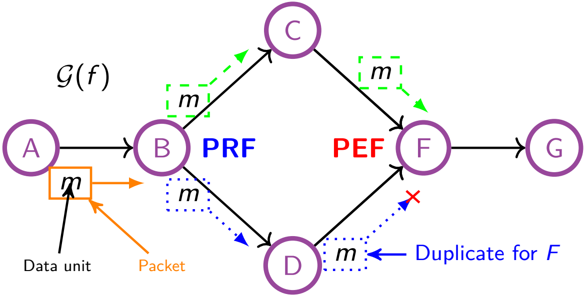

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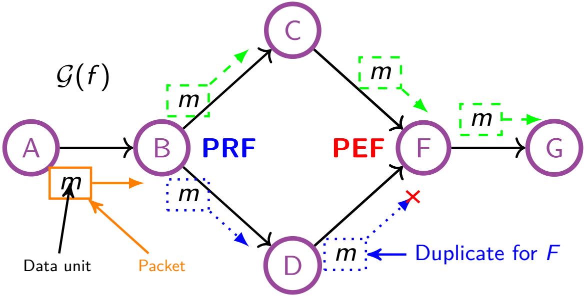

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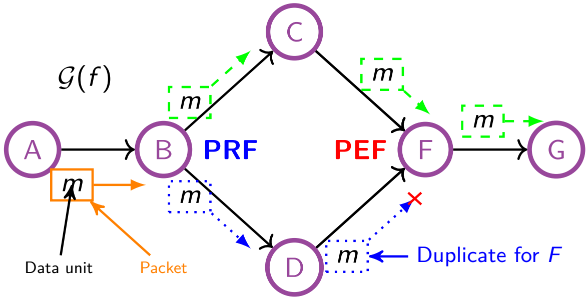

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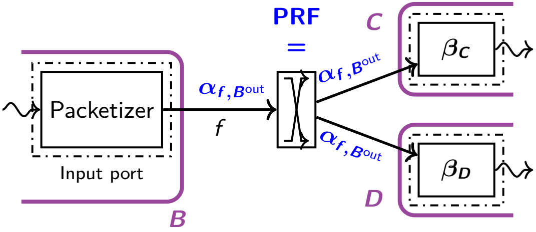

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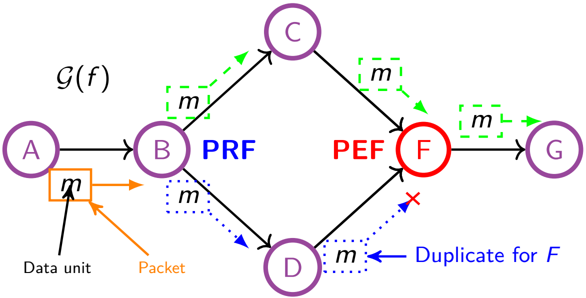

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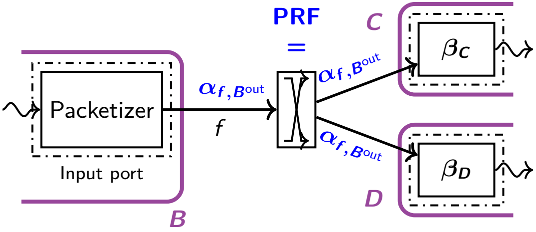
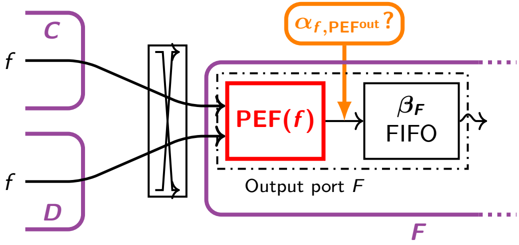
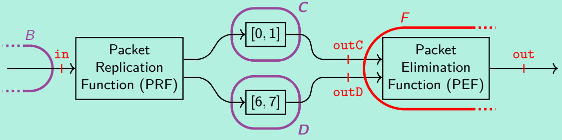
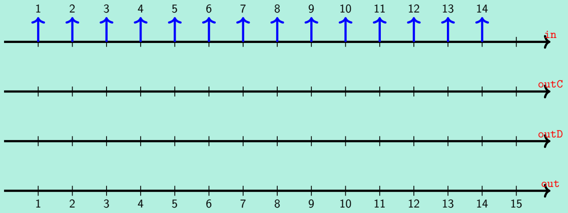




What is the **Traffic at the Output** of the PEF ? (Packet Elimination Function)

A Possible Trajectory on a Toy Example





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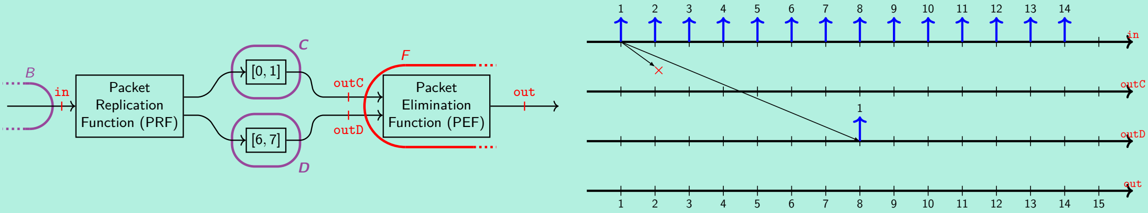

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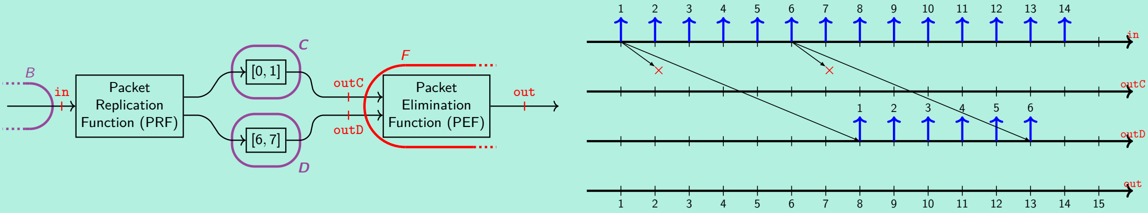

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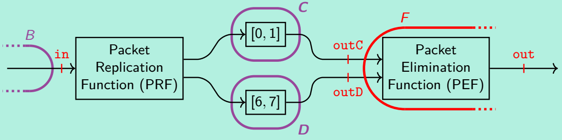

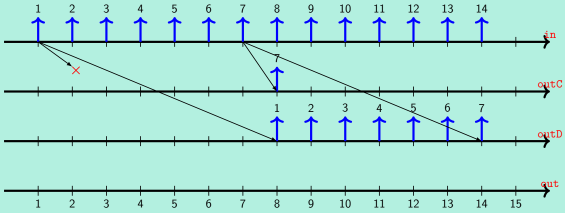

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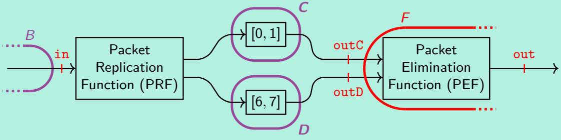

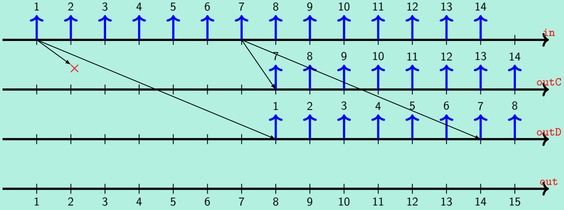

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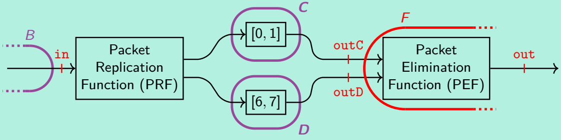

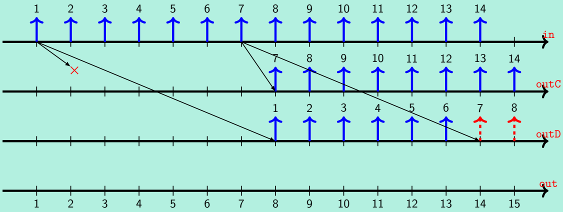

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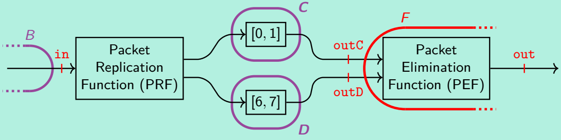

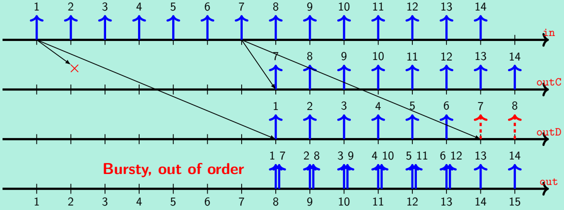

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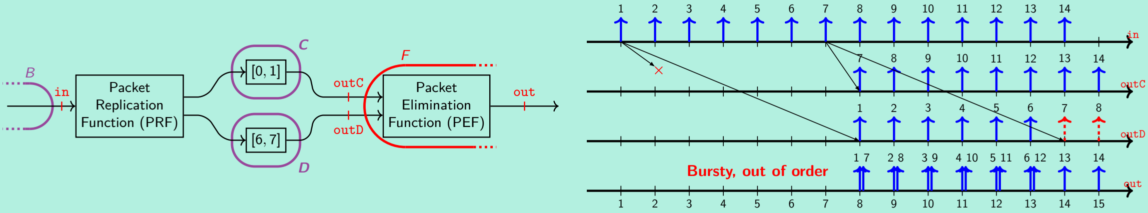

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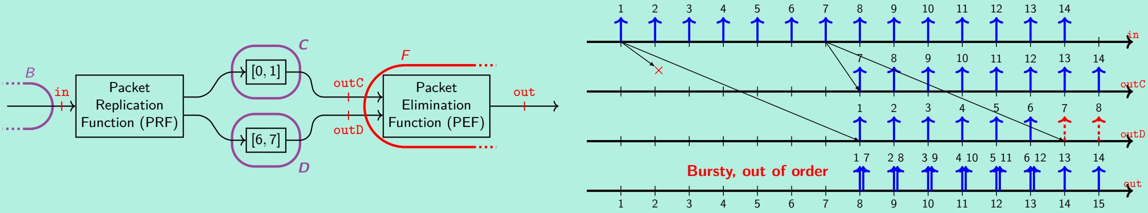

- Output of PEF bursty, mis-ordered ⇒ Can we bound the burstiness and mis-ordering at the PEF's output?
- Output bursty → leads to high delay in downstream ⇒ Place a traffic regulator after the PEF ?

An **Arrival Curve** at The Output of The PEF (Packet Elimination Function)

Theorem: PEF Output Arrival Curve

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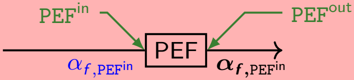
- $\alpha_{f,\mathrm{PEF}^{\mathrm{in}}}$ is an arrival curve at $\mathrm{PEF}^{\mathrm{out}}$



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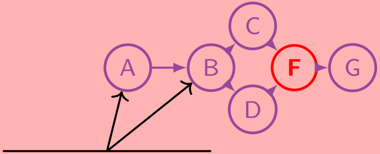

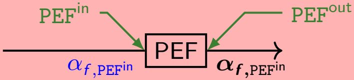

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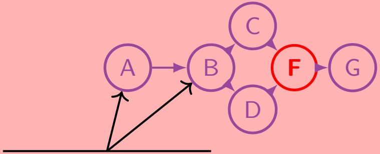

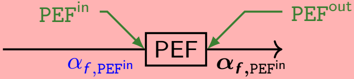

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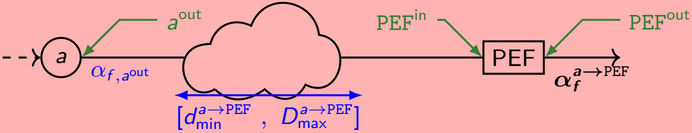

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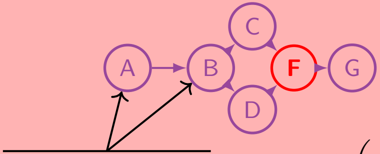

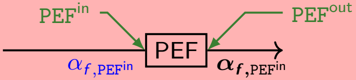

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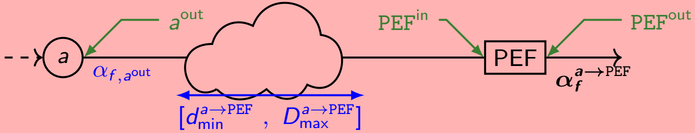

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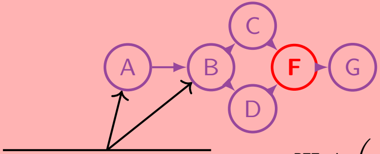

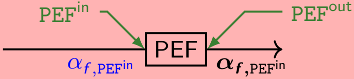

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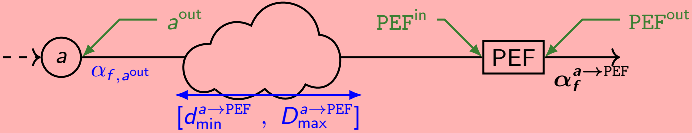
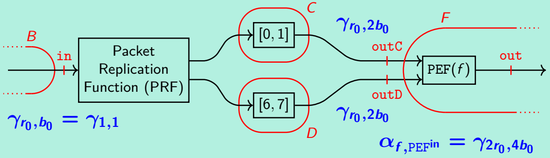


$\Rightarrow$ **Combine:** The min-plus convolution of all above arrival curves is an arrival curve at $\mathrm{PEF}^{\mathrm{out}}$.

Applying our Result to the Toy Example Provides a **Tight Output Arrival Curve**

Toy example:



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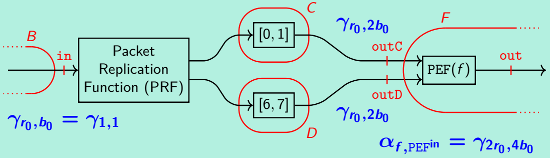

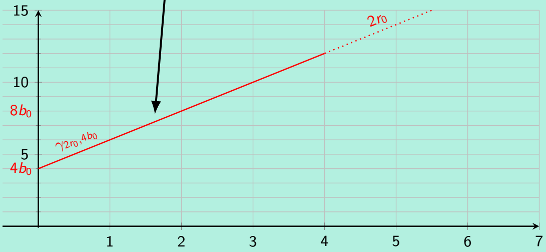

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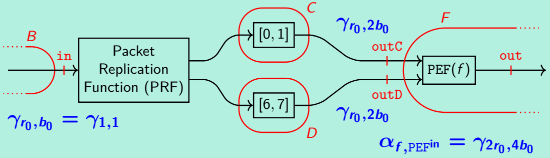

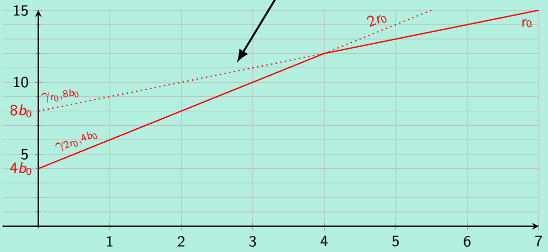

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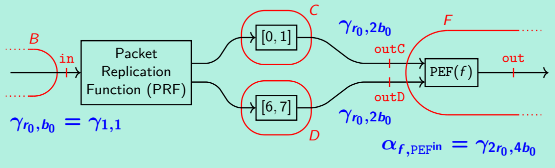

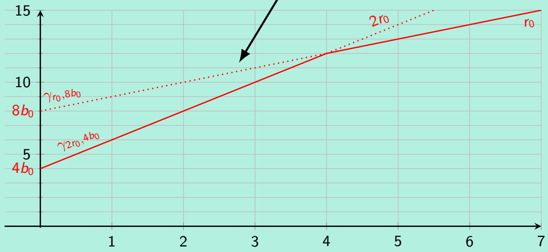

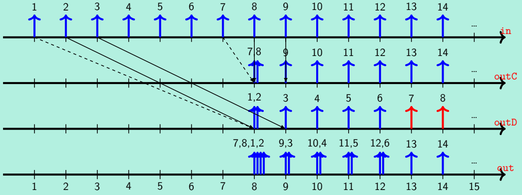

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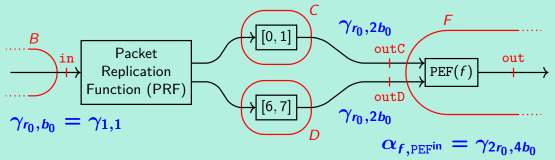

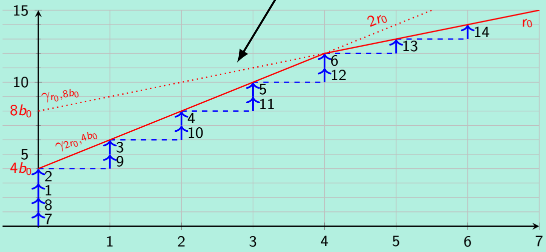

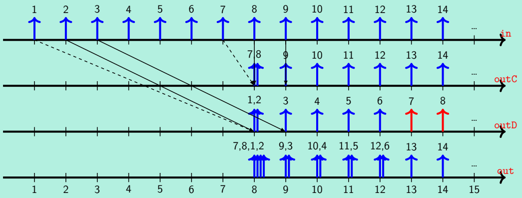

Question 1

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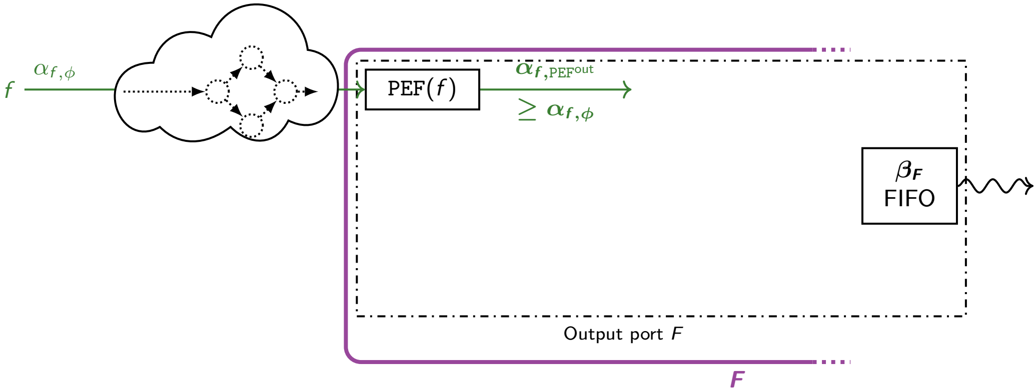
Output bursty → leads to high delay in downstream ⇒ Place a traffic regulator after the PEF ?

Combination of Traffic Regulators with Redundancy Functions: **FIFO assumption is lost**!



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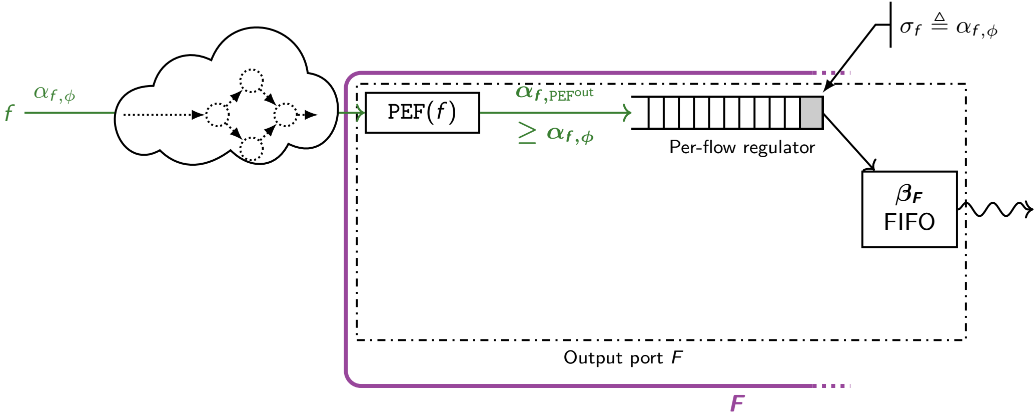

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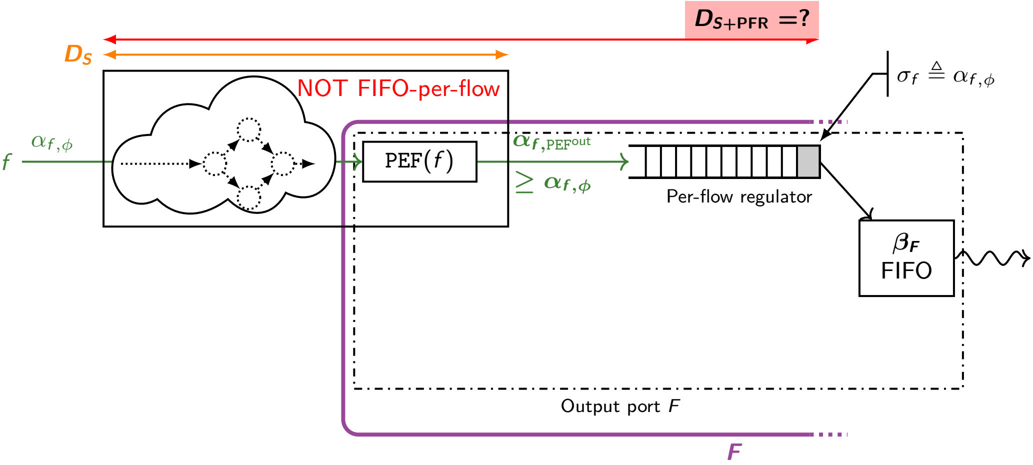
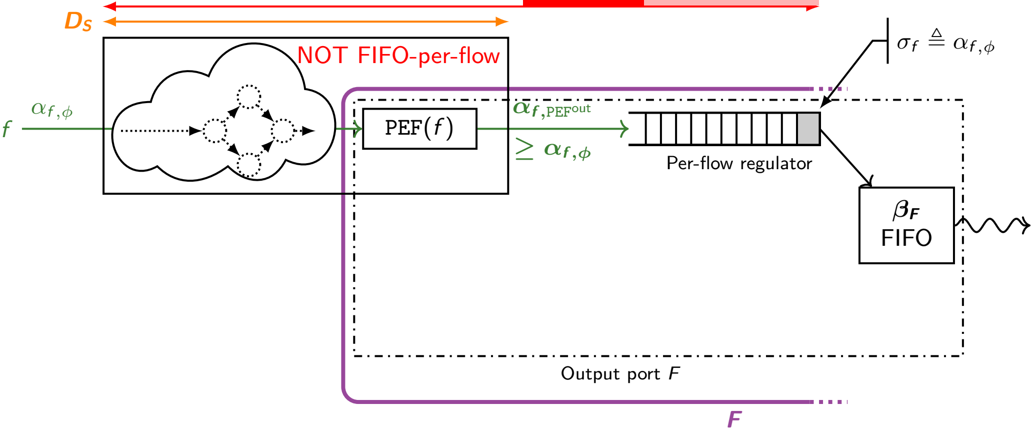
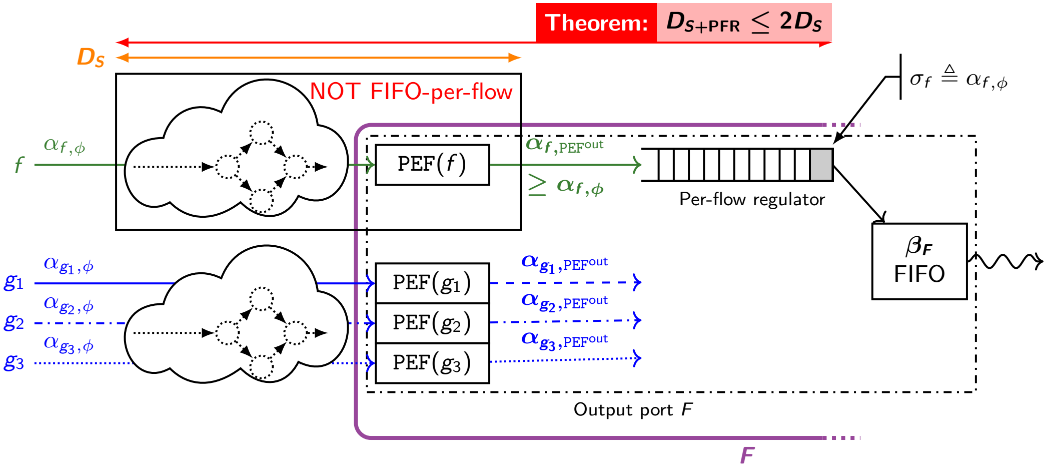


Combination of Traffic Regulators with Redundancy Functions: **FIFO assumption is lost**!

Theorem: $D_{S+\text{PFR}} \leq 2D_S$



Combination of Traffic Regulators with Redundancy Functions: **FIFO assumption is lost**!



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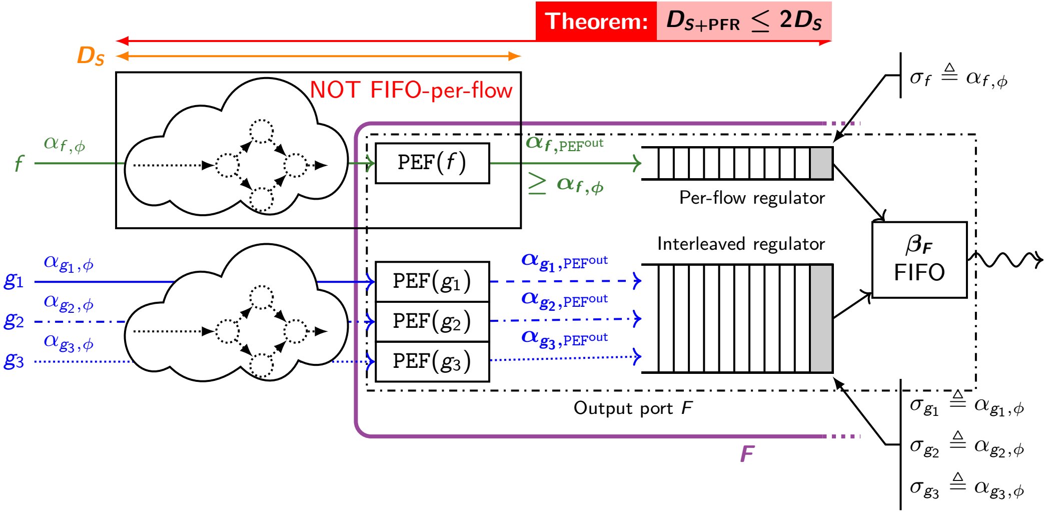

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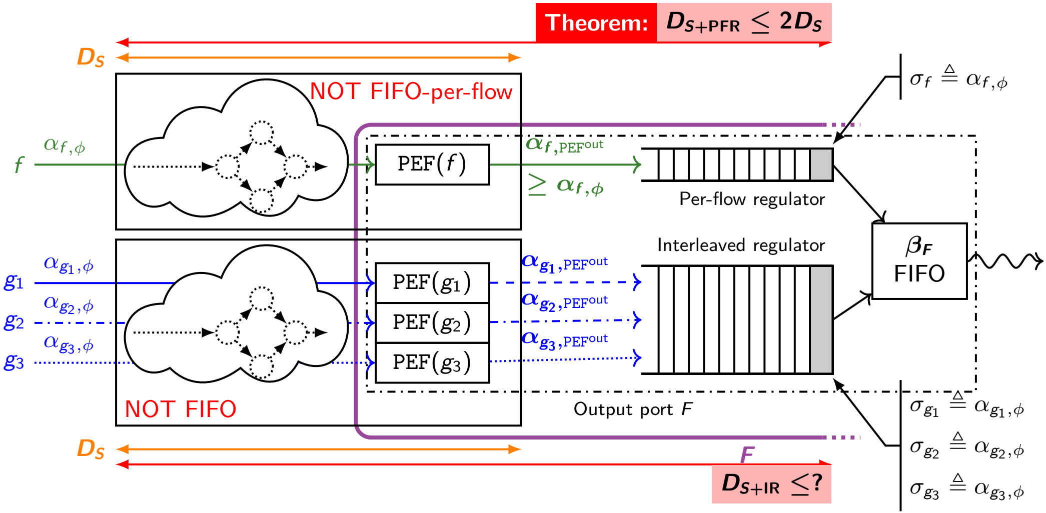

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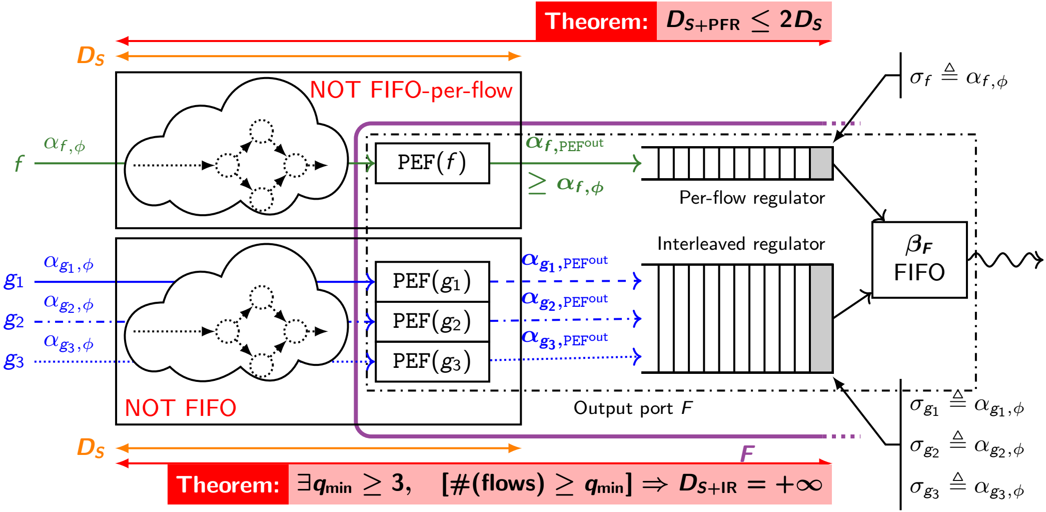
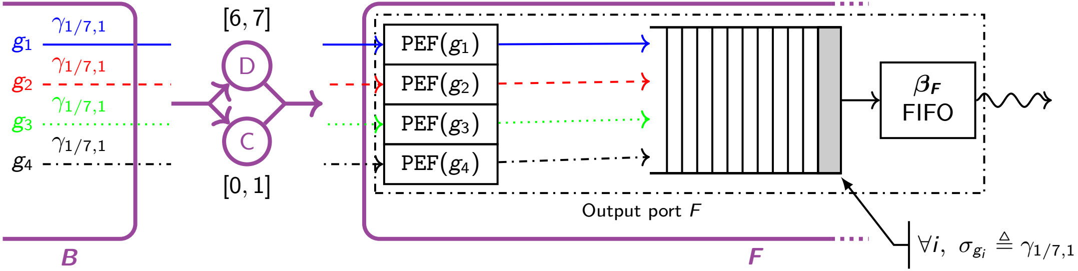


Interleaved Regulator (IR) Unstable after PEF: Intuition of the Proof



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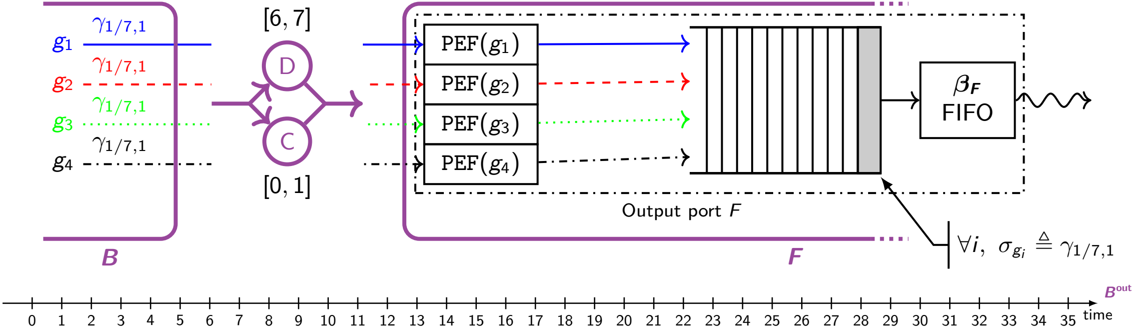

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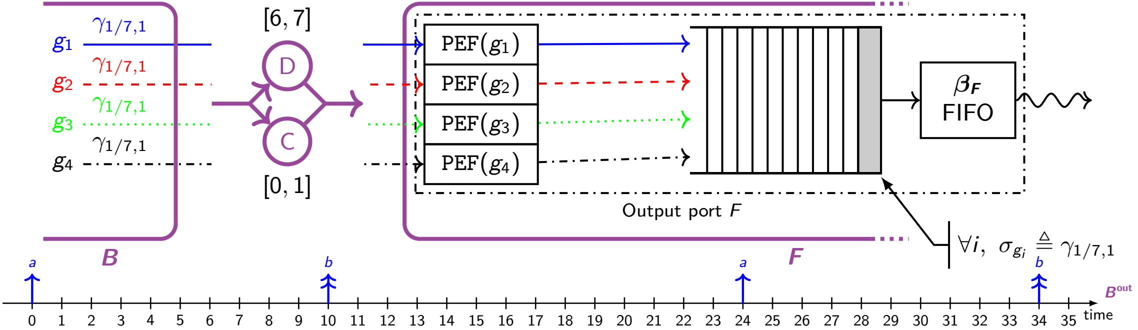

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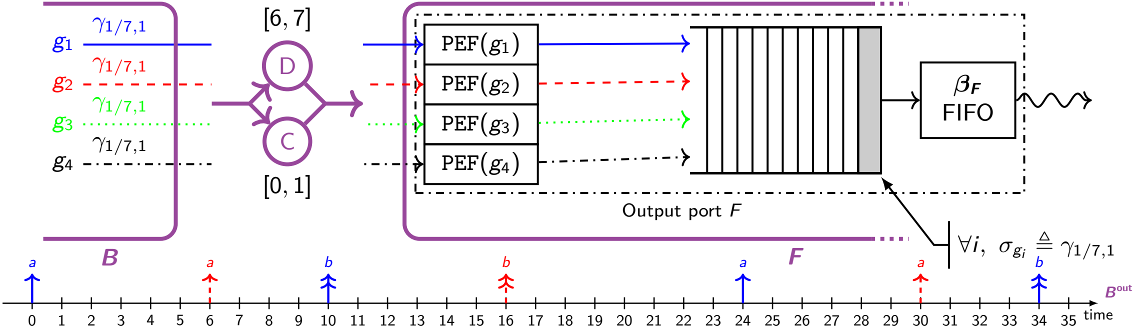

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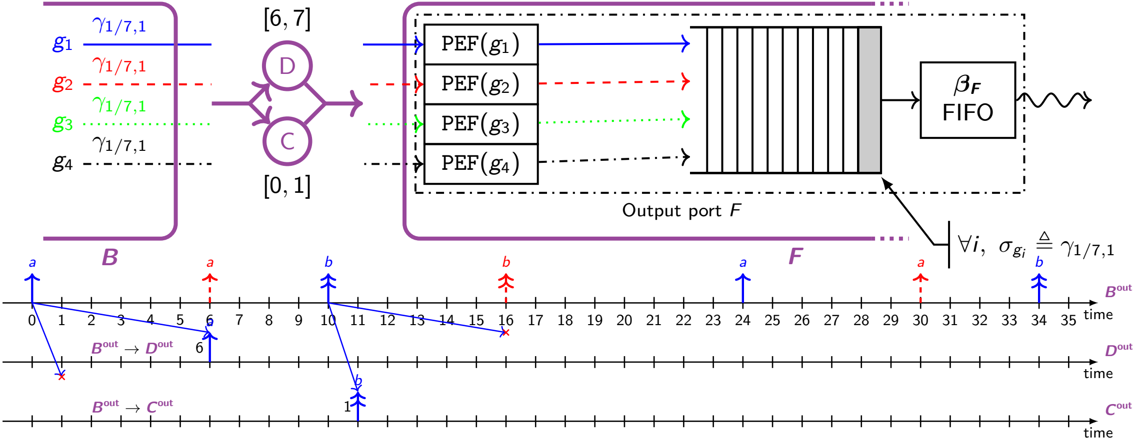

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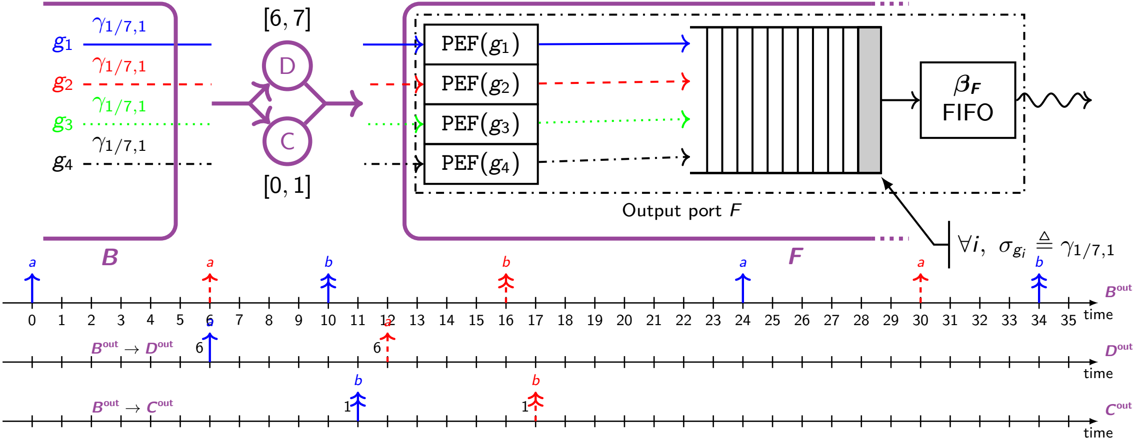

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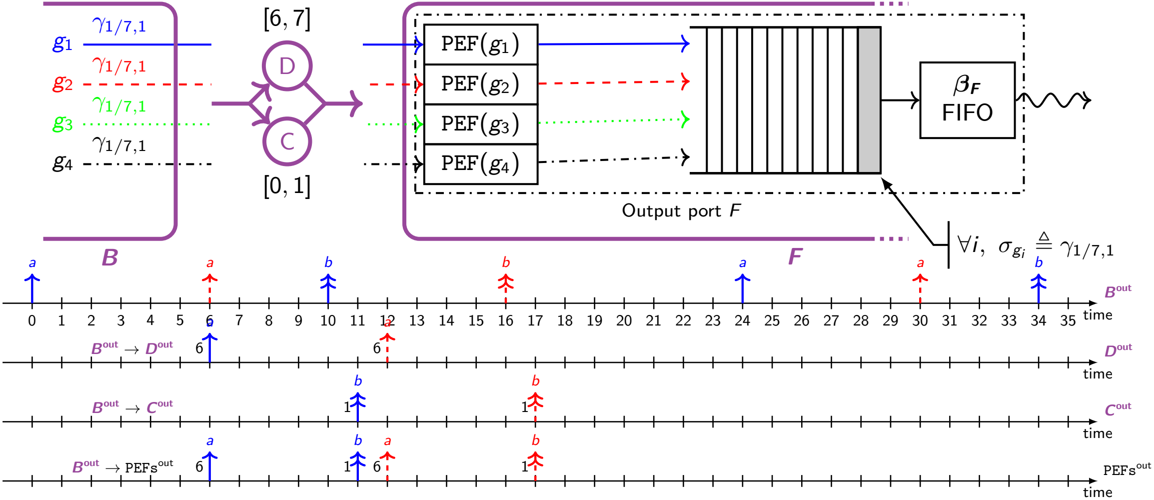

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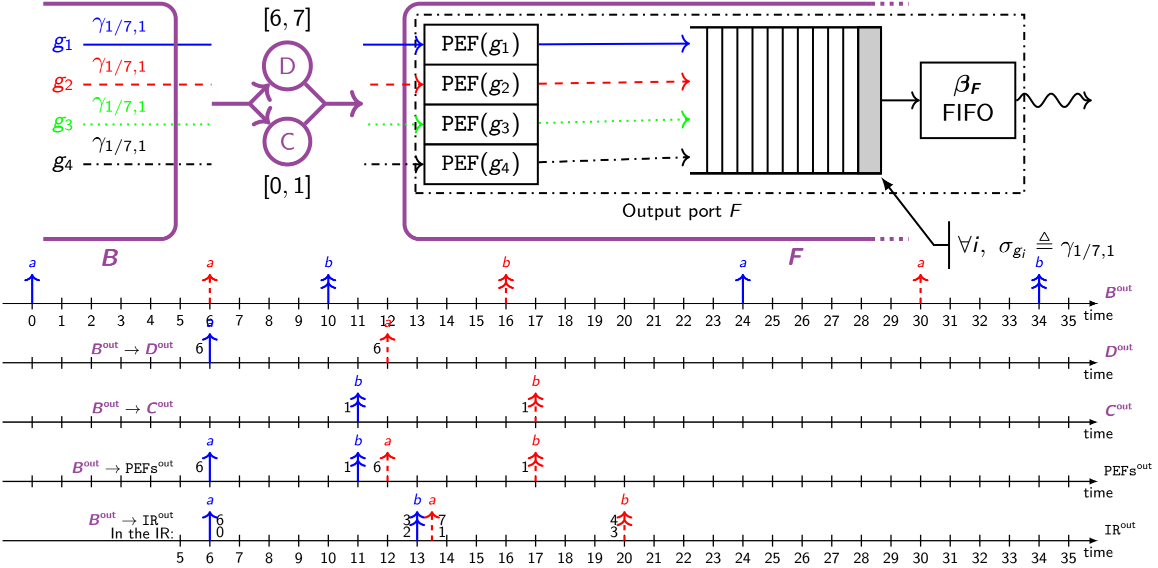

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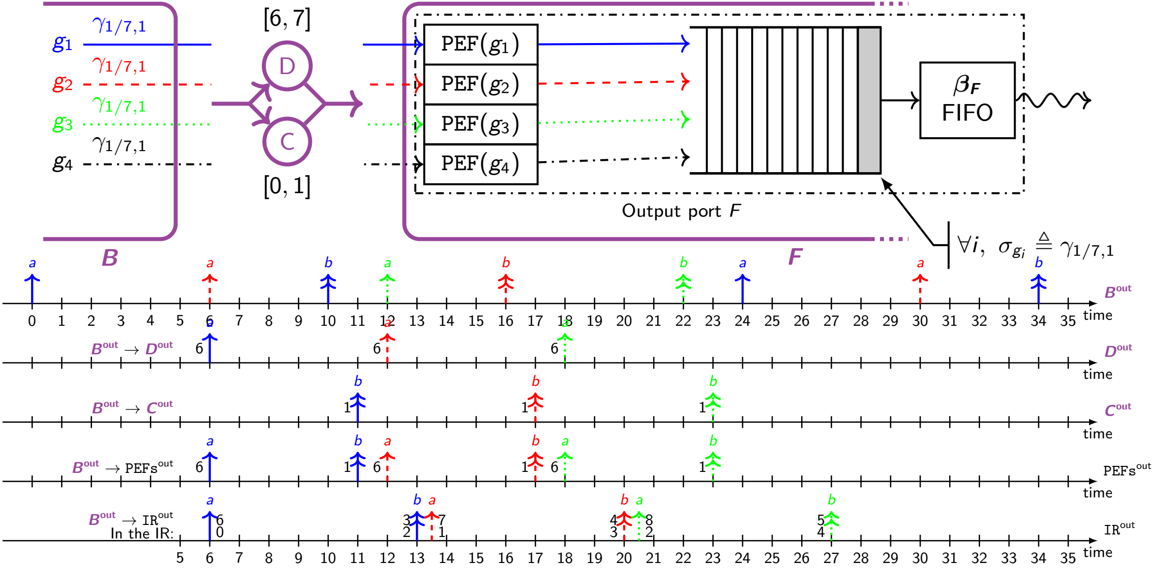

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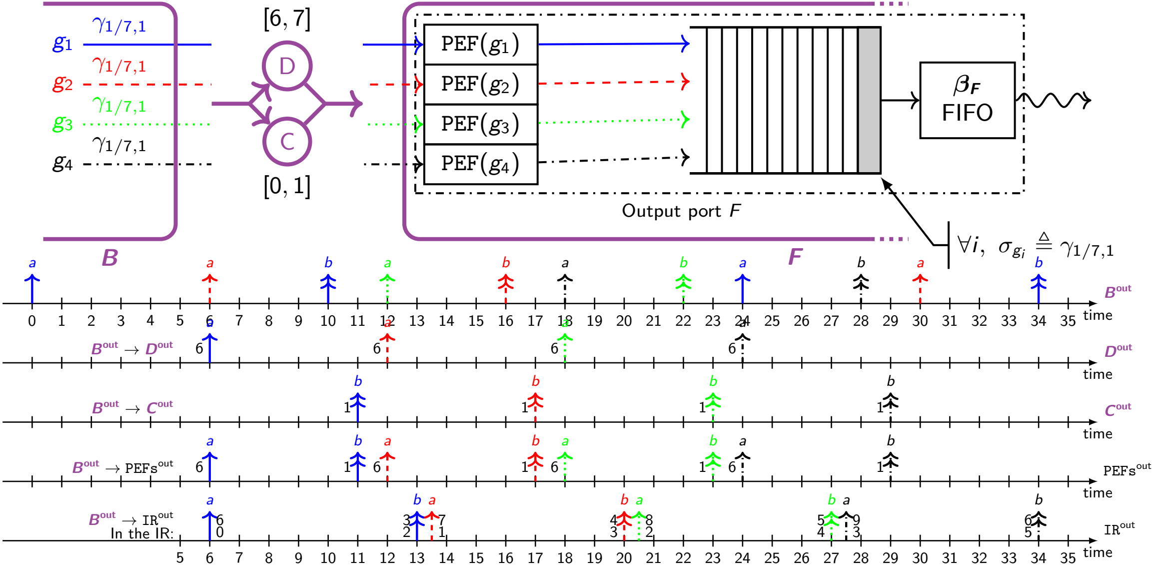

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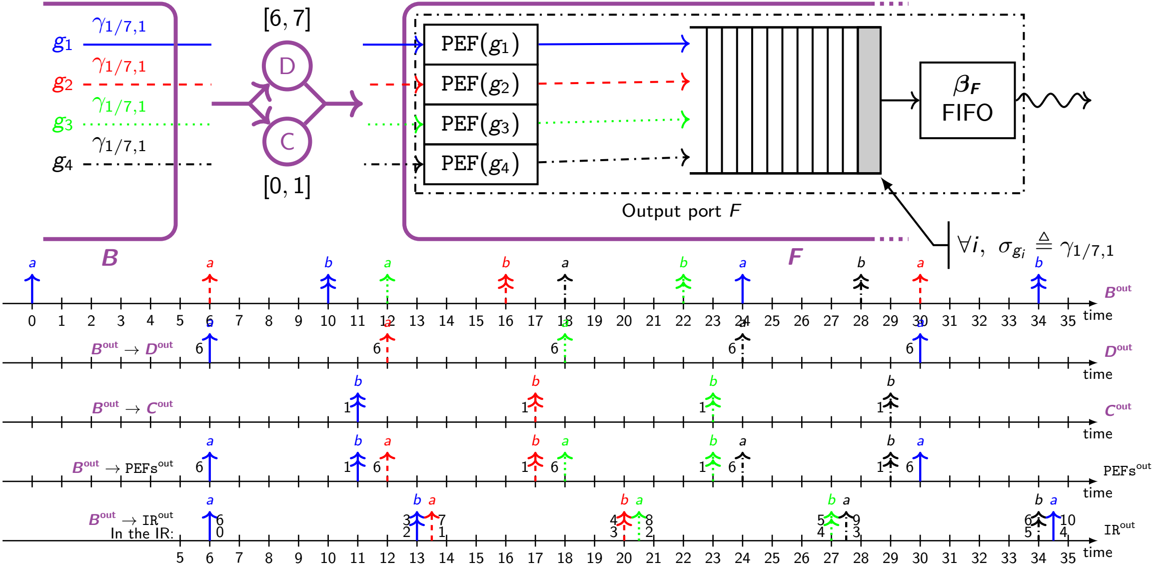


Redundancy Mechanisms: **Our Contributions**

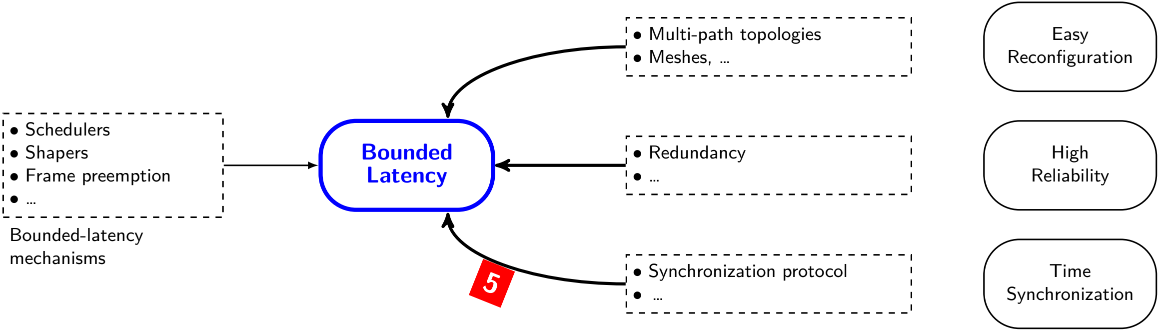
Contribution	Multipath topologies	Redundancy mechanisms
Network-calculus toolboxes		**Network-calculus model** for redundancy mechanisms
End-to-end latency bounds	**FP-TFA**	
Traffic regulators (PFRs and IRs)	LCAN	**IR Instability Result**
		Bounded penalty with PFR. Solution: POF (Packet Ordering Function)

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

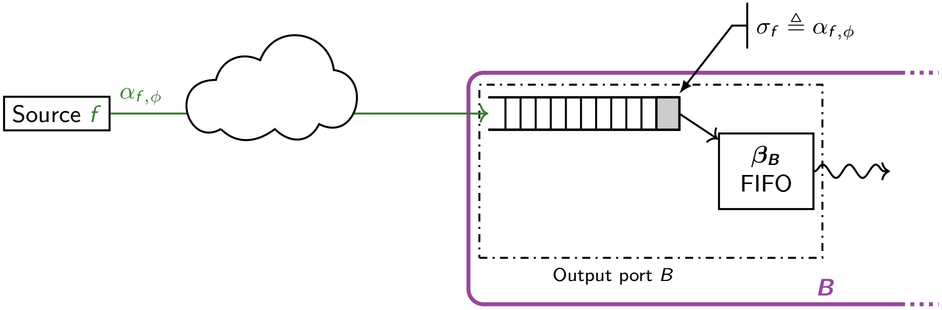
IR: Interleaved regulator (=TSN ATS)

PFR: Per-flow regulator

Time Synchronization and Clock Non-Idealities



Motivation: Systems rely on their **own Internal Clock**



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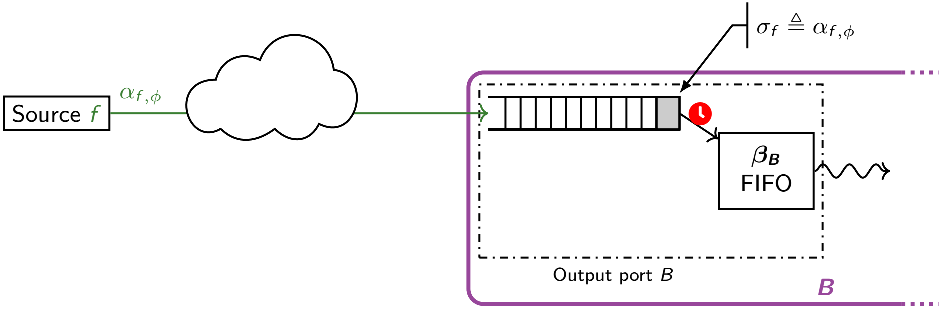

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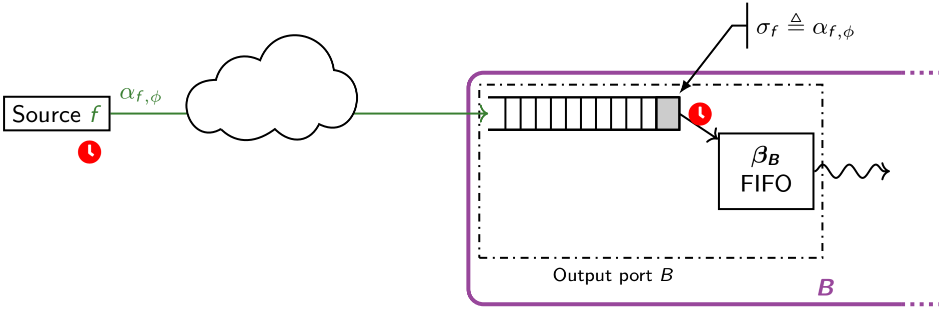

Discussions raised for TSN *Asynchronous Traffic Shaping* [IEEE 802.1Qcr]

– [IEEE 802.1Qcr] "IEEE Standard for Local and Metropolitan Area Networks–Bridges and Bridged Networks - Amendment 34" [Nov. 2020]. "IEEE Standard for Local and Metropolitan Area Networks–Bridges and Bridged Networks - Amendment 34:Asynchronous Traffic Shaping". In: *IEEE Std 802.1Qcr-2020 (Amendment to IEEE Std 802.1Q-2018 as amended by IEEE Std 802.1Qcp-2018, IEEE Std 802.1Qcc-2018, IEEE Std 802.1Qcy-2019, and IEEE Std 802.1Qcx-2020)*. DOI: 10.1109/IEEESTD.2020.9253013

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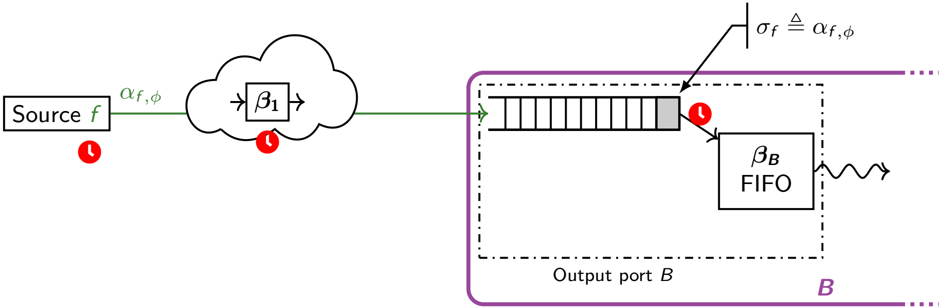

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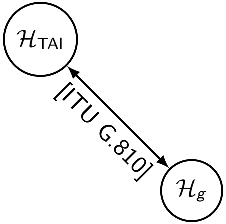
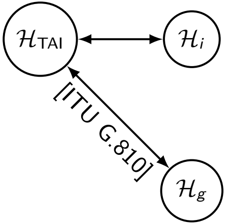
Model for Non-Synchronized Clocks



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

$\mathcal{H}_{\mathsf{TAI}}$: international atomic time ("true time")

Model for Non-Synchronized Clocks



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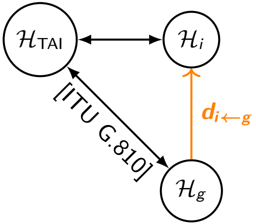

Non-synchronized model (ρ, η):

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

Parameters

ρ Clock-stability bound
η Time-jitter bound

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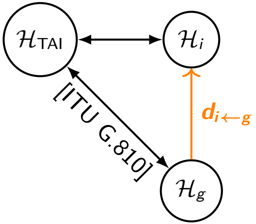
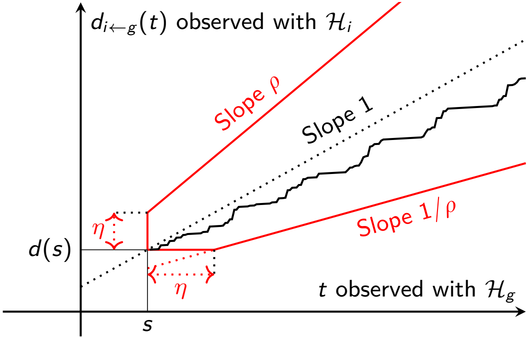


Non-synchronized model (ρ, η):

$$\forall t, s \quad \frac{1}{\rho}(t - s - \eta) \le d_{i\leftarrow g}(t) - d_{i\leftarrow g}(s) \le (t - s)\rho + \eta$$



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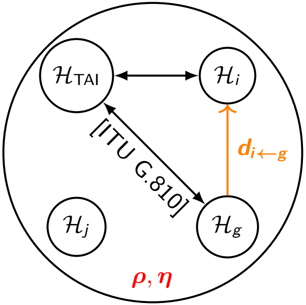

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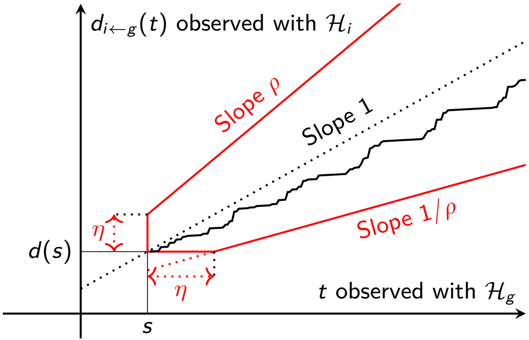

Parameters

ρ Clock-stability bound
η Time-jitter bound

In TSN [IEEE 802.1AS]

$\rho = 1 + 200\text{ppm}$
$\eta = 4\text{ns}$

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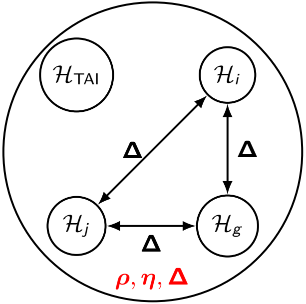
$\mathcal{H}_{\text{TAI}}$: international atomic time ("true time")

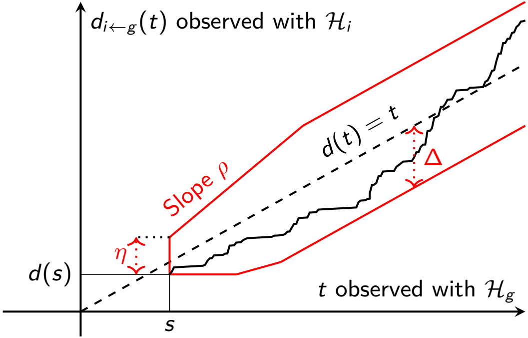
Model for Synchronized Clocks



Synchronized model (ρ, η): $\forall i, g$,

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

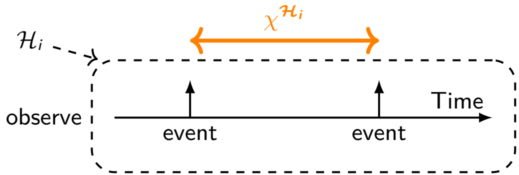
$$\forall t, \quad |d_{i \leftarrow g}(t) - t| \leq \Delta$$



Parameters	**In TSN [IEEE 802.1AS]**
ρ Clock-stability bound	$\rho = 1 + 200\text{ppm}$
η Time-jitter bound	$\eta = 4\text{ns}$
Δ Synchronization precision	$\Delta = 1\mu s$

– [IEEE 802.1AS] "IEEE Standard for Local and Metropolitan Area Networks–Timing and Synchronization for Time-Sensitive Applications" [June 2020]. In: *IEEE Std 802.1AS-2020 (Revision of IEEE Std 802.1AS-2011)*. DOI: 10.1109/IEEESTD.2020.9121845

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



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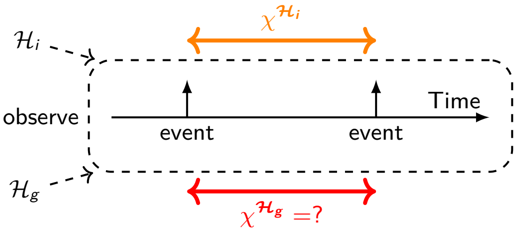

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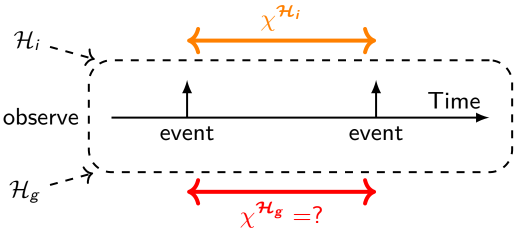
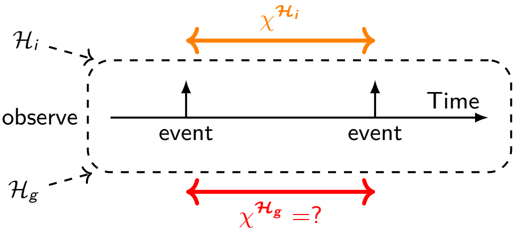


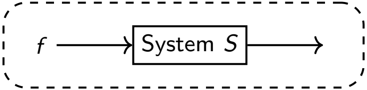
Proposition [Changing clock for a duration]

$$\max\left(0, \frac{\chi^{\mathcal{H}_i} - \eta}{\rho}, \chi^{\mathcal{H}_i} - 2\Delta\right) \leq \chi^{\mathcal{H}_g} \leq \min\left(\rho\chi^{\mathcal{H}_i} + \eta, \chi^{\mathcal{H}_i} + 2\Delta\right)$$

$\Delta \triangleq +\infty$ if non-synchronized

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





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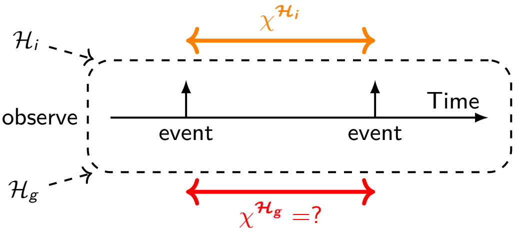
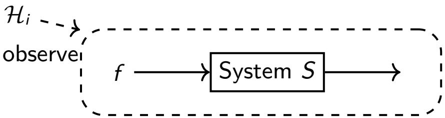


$\alpha_{f,\text{in}}^{\mathcal{H}_i}$



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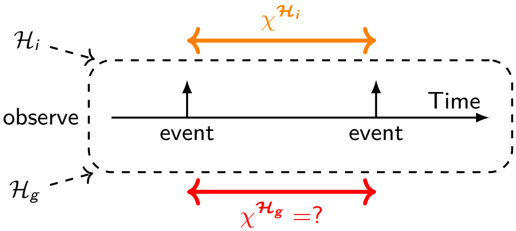

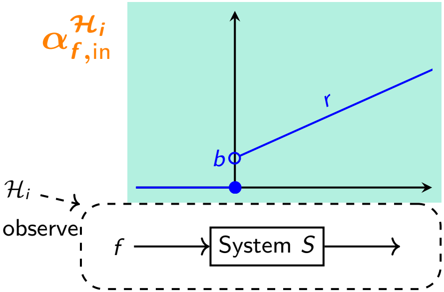

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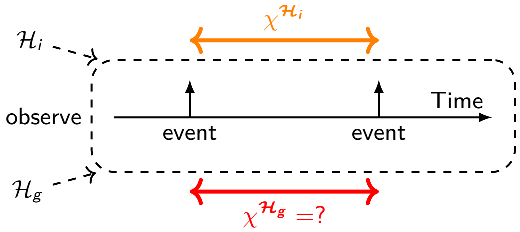

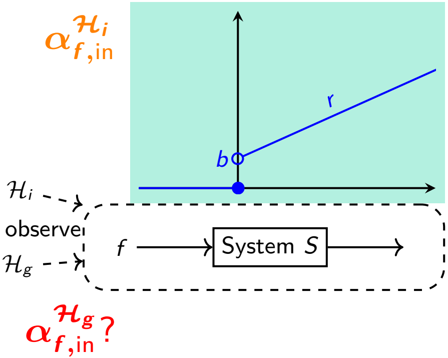

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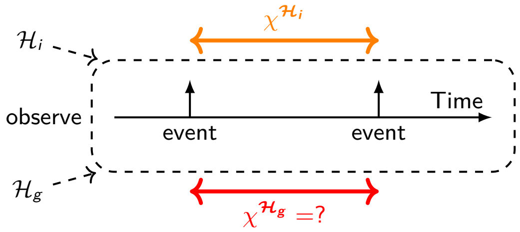

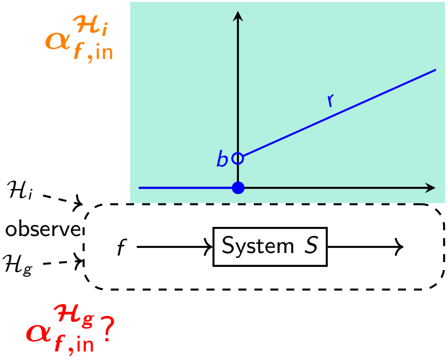

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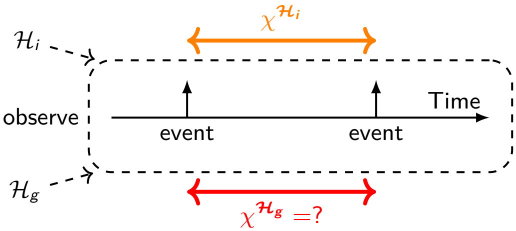
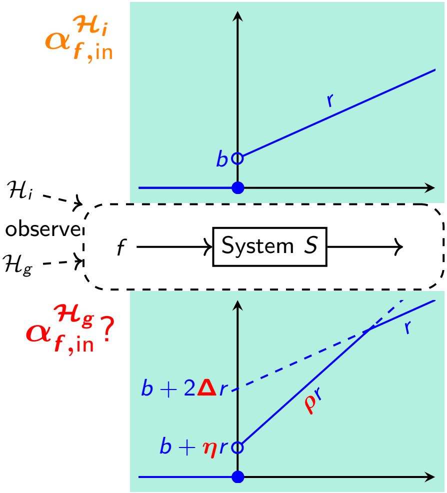
$\Delta \triangleq +\infty$ if non-synchronized

Proposition [Changing clock for an arrival curve]

$$\alpha_f^{\mathcal{H}_g} : t \mapsto \alpha_f^{\mathcal{H}_i}\left(\min\left[\rho t + \eta, t + 2\Delta\right]\right)$$

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





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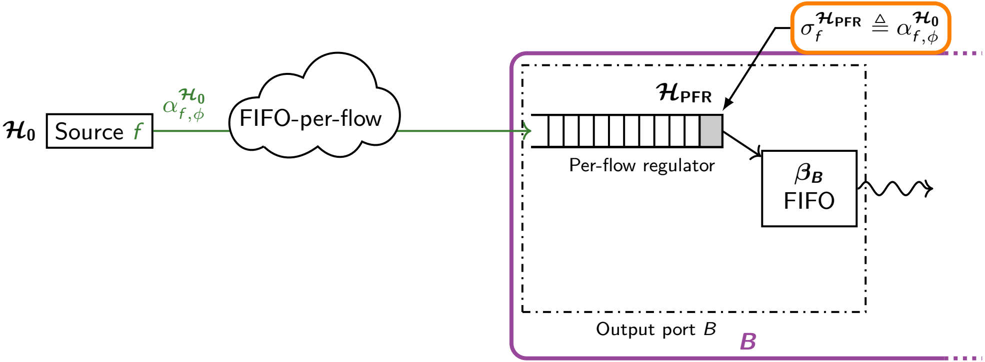
Regulators and Non-Synchronized Clocks: **Unbounded Latencies**

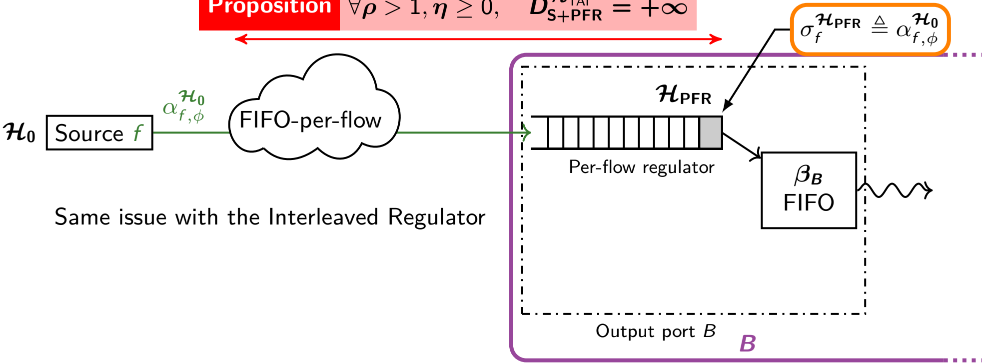


$\mathcal{H}_{TAI}$: international atomic time ("true time")

Regulators and Non-Synchronized Clocks: **Unbounded Latencies**

Non-synchronized model: ρ, η

Proposition $\forall \rho > 1, \eta \geq 0, \quad D^{\mathcal{H}_{\text{TAI}}}_{\text{S+PFR}} = +\infty$



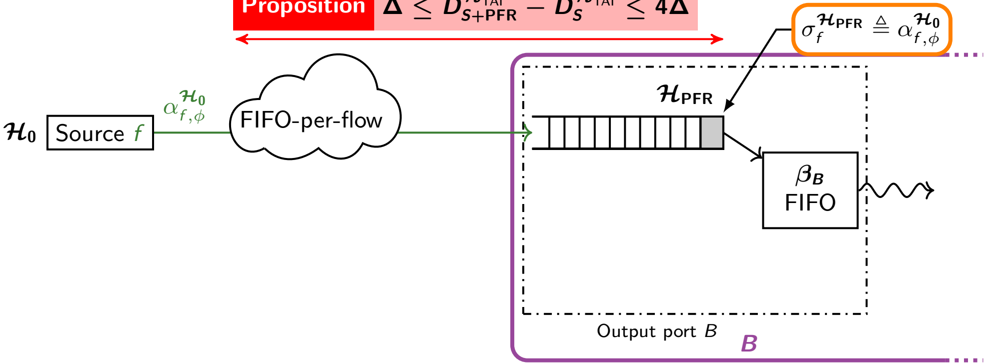
Same issue with the Interleaved Regulator

$\mathcal{H}_{\text{TAI}}$: international atomic time ("true time")

Combination of Traffic Regulators with a Time-Synchronization Protocol

Synchronized model: ρ, η, Δ

Proposition $\Delta \leq D^{\mathcal{H}_{\text{TAI}}}_{S+\text{PFR}} - D^{\mathcal{H}_{\text{TAI}}}_{S} \leq 4\Delta$



$\mathcal{H}_{\text{TAI}}$: international atomic time (“true time”)

Combination of Traffic Regulators with a Time-Synchronization Protocol

Synchronized model: ρ, η, Δ

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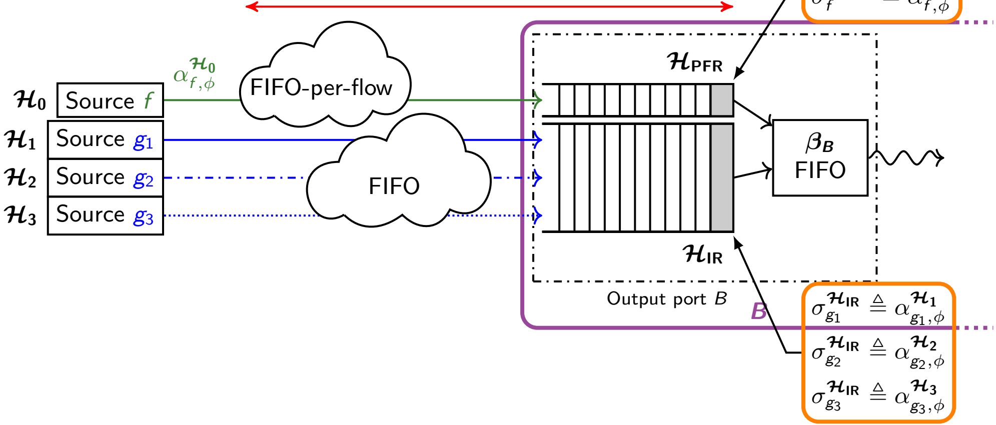

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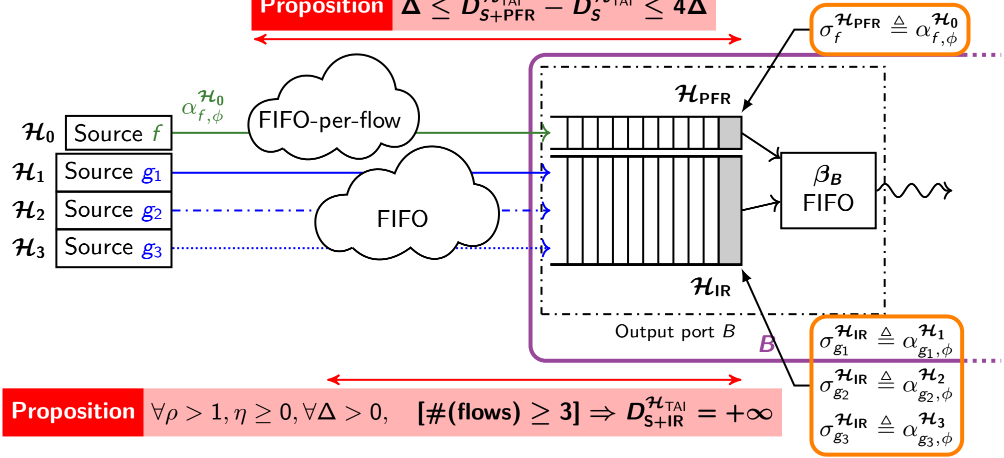

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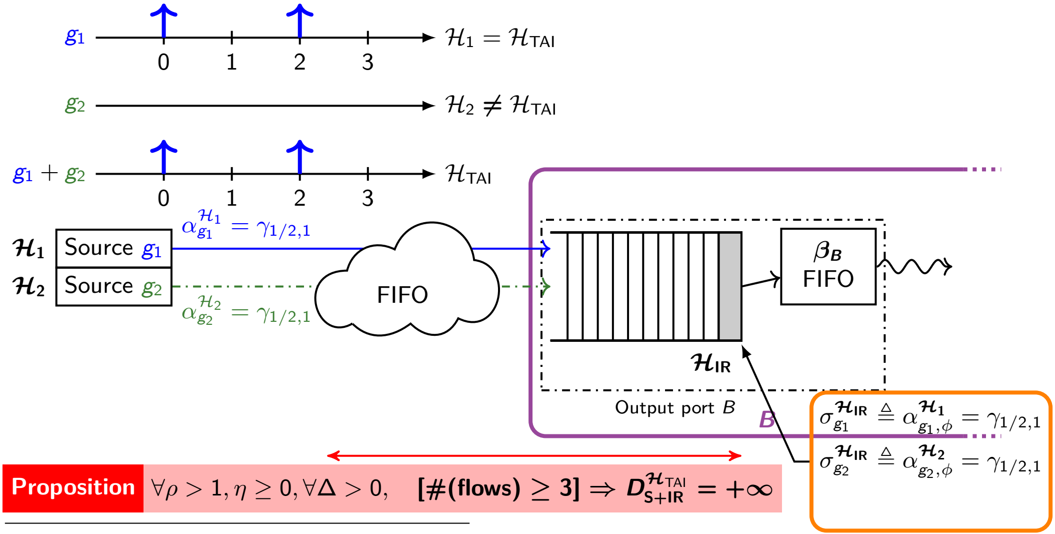
Instability of the Interleaved Regulator with non-ideal Clocks: Intuition of the proof



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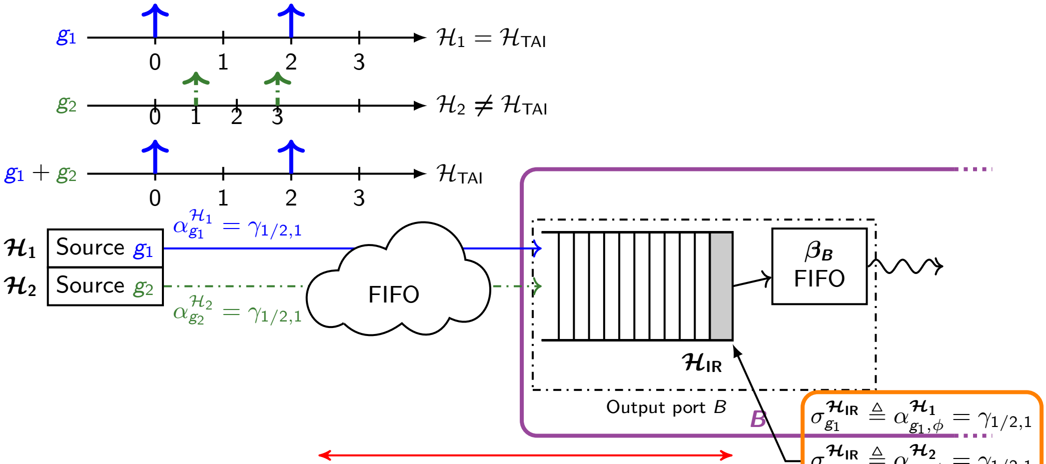

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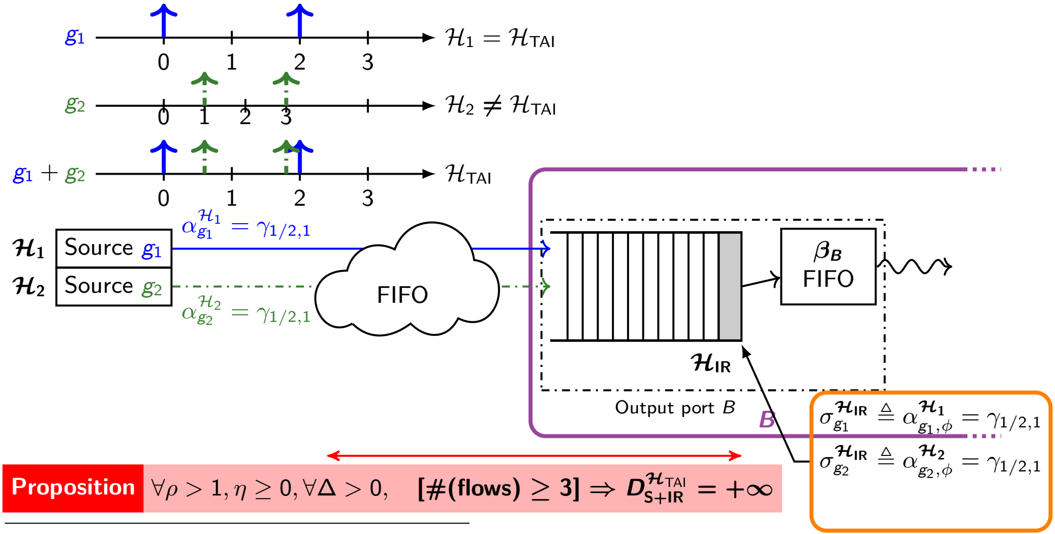

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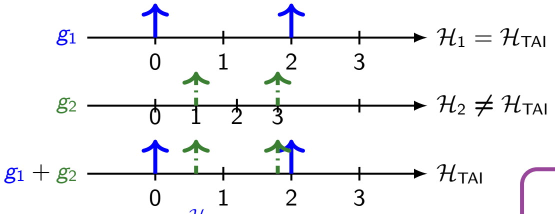
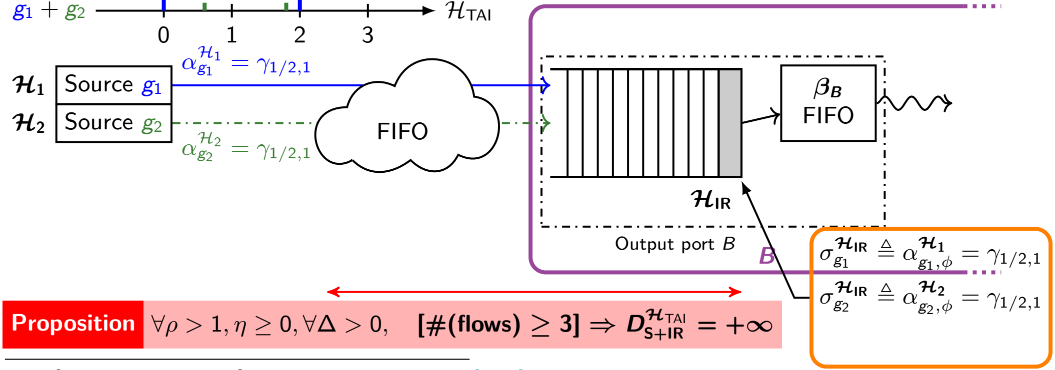


[Aguirre Rodrigo 2020]

Instability validated by simulation (ns-3)
ns-3 module for local clocks



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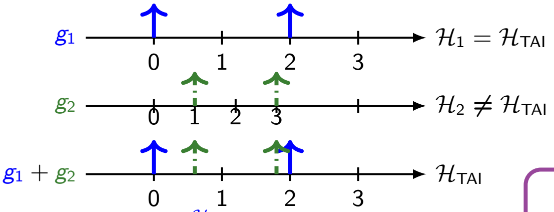

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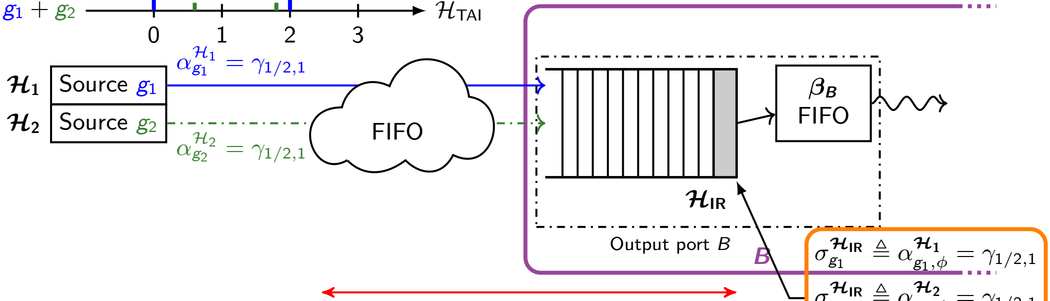

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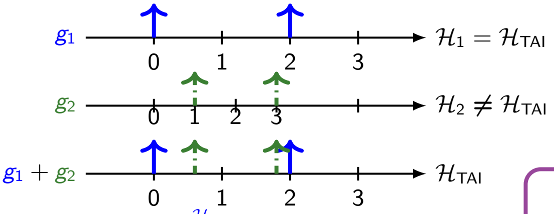

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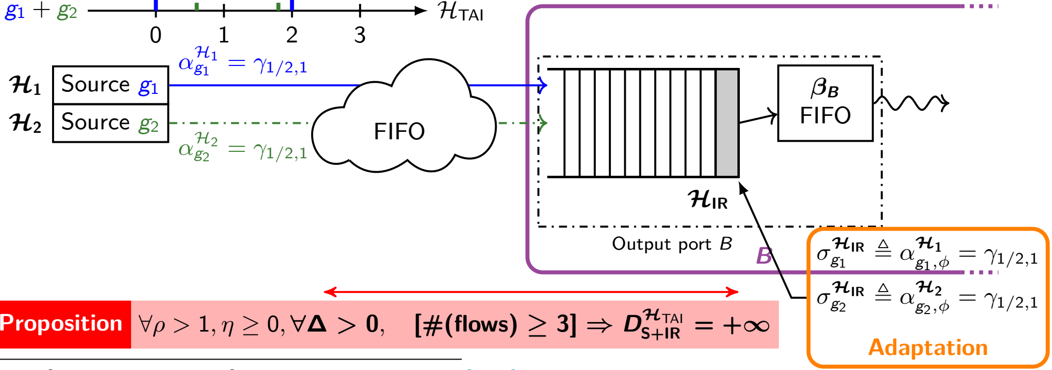

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Time Synchronization: **Our Contributions**

Contribution	Multipath topologies	Redundancy mechanisms	Time Synchronization
Network-calculus toolboxes		**Network-calculus model** for redundancy mechanisms	**Network-calculus model** for non-ideal clocks (sync/non-sync).
End-to-end latency bounds	**FP-TFA**		Two end-to-end strategies
Traffic regulators (PFRs and IRs)	LCAN	**IR Instability Results**	
		Bounded penalty with PFR. Solution: POF (Packet Ordering Function)	Bounded penalty with sync PFR. Solutions: ADAM and rate-and-burst cascade

Ludovic Thomas and Jean-Yves Le Boudec [June 9, 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

PFR: Per-flow regulator

IR: Interleaved regulator (=TSN ATS)

Experimental modular TFA, a **Tool for End-to-end Latency Bounds**

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<tr><th>Contribution</th><th>Multipath topologies</th><th>Redundancy mechanisms</th><th>Time Synchronization</th></tr>
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Application to an **Industrial Use-Case**

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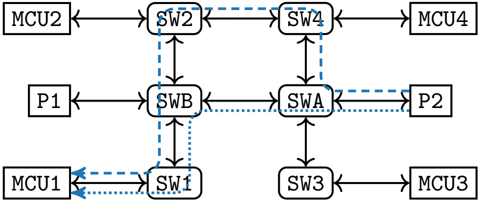
Use-Case: A **Multi-path Topology**



Based on the Volvo Core TSN Network

Nicolas Navet, Hoai Hoang Bengtsson, and Jörn Migge [Feb. 12, 2020]. "Early-Stage Bottleneck Identification and Removal in TSN Networks".

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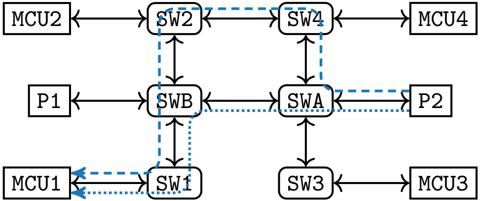

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Profile	Payload size	Period at source
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M1	92B	324μs
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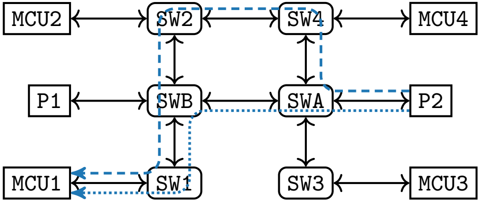

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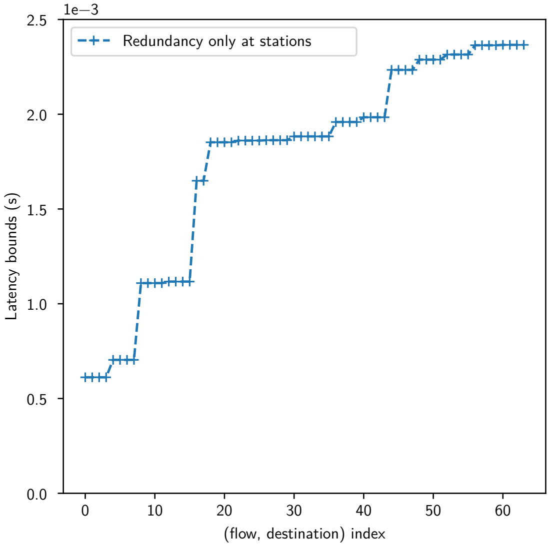
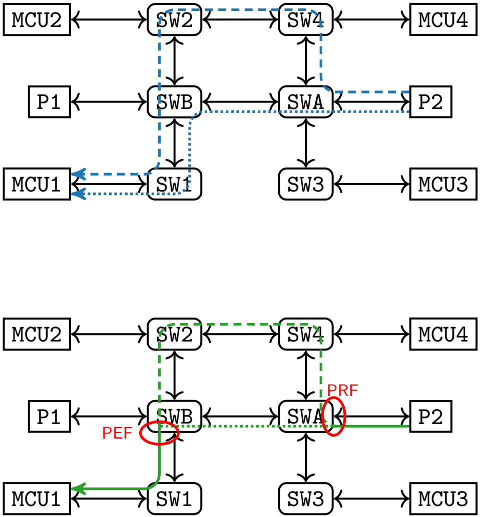
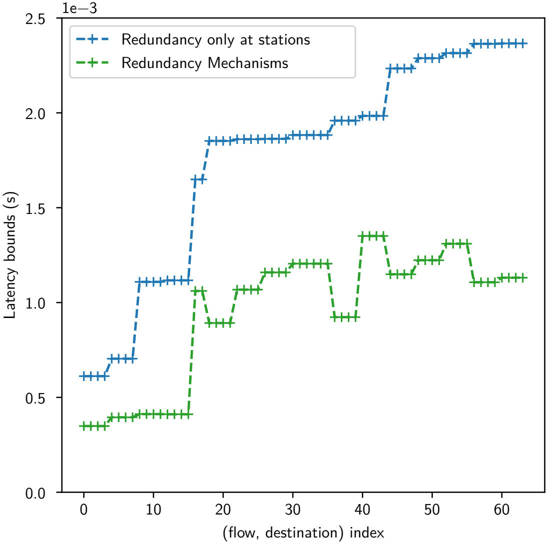
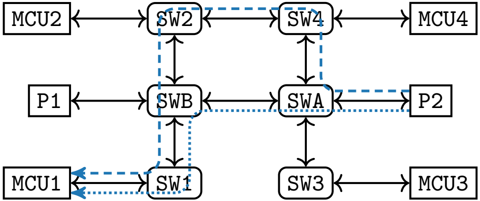


Use-Case: A **Multi-path Topology** with **Redundancy Mechanisms**

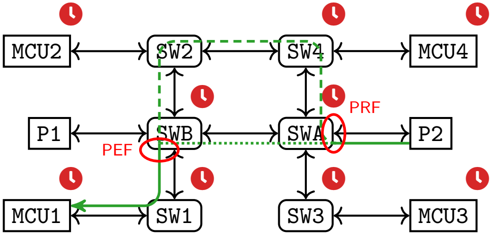


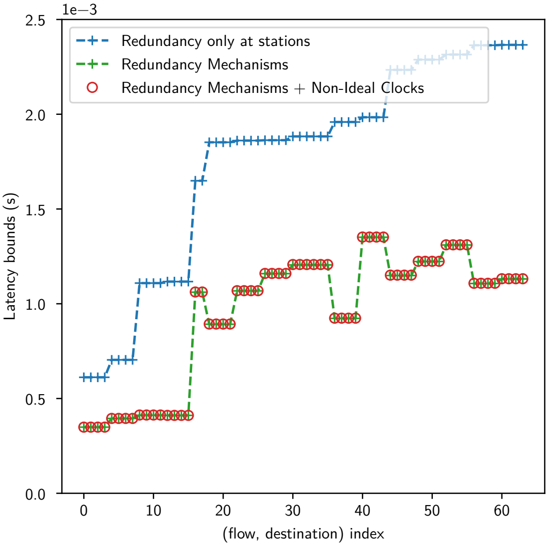


Use-Case: **Multi-path Topology** with **Redundancy Mechanisms** and **Time-Synchronization**



Tightly-synchronized $\Delta = 1\mu s$

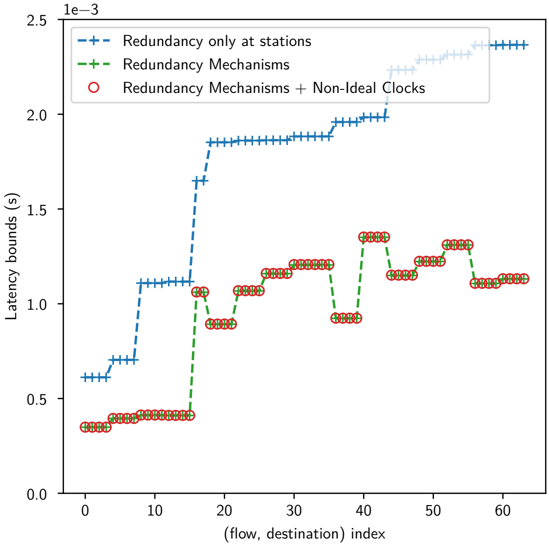




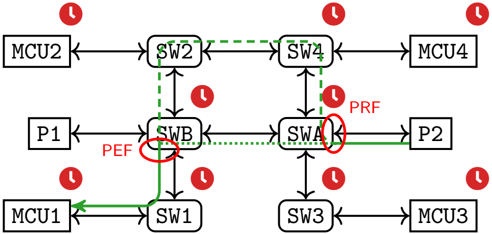
Use-Case: **Multi-path Topology** with **Redundancy Mechanisms** and **Time-Synchronization**

Take-away

- Our model provides **better latency bounds** than those that assume redundancy only at end-systems.
- Clock non-idealities can be neglected in **tightly synchronized** networks that contain **no regulator**.



Use-Case: The Effect of **TSN ATS** (Interleaved Regulator)



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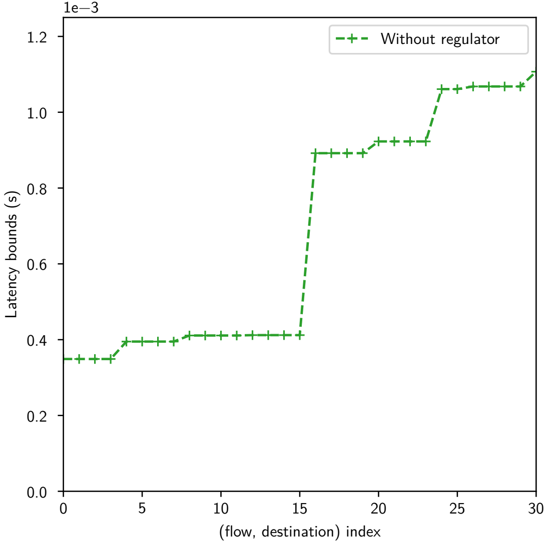

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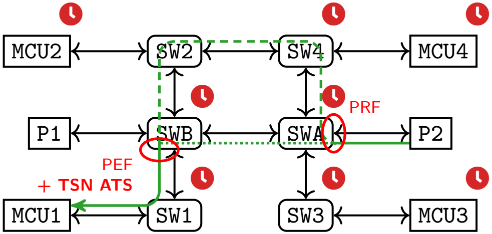

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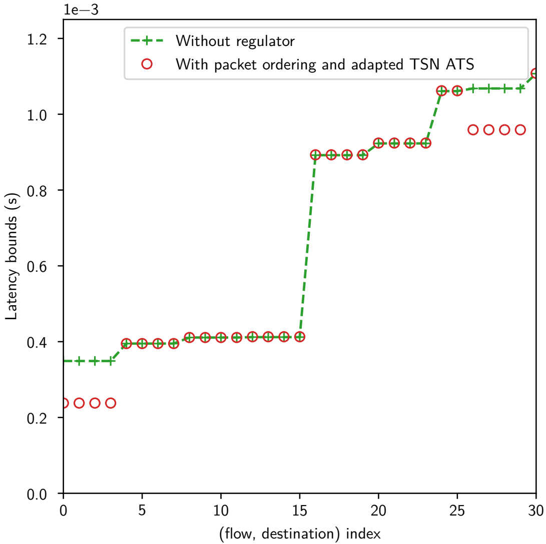

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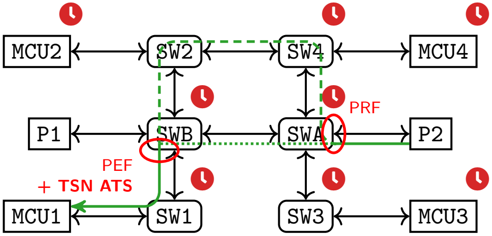

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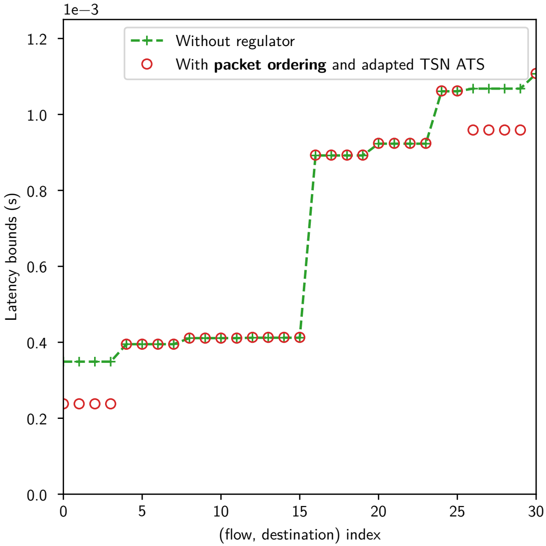

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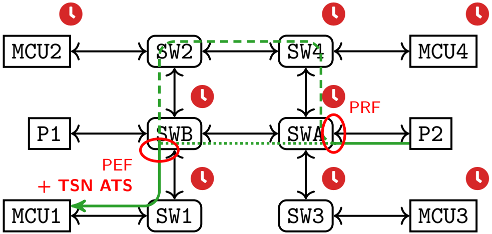

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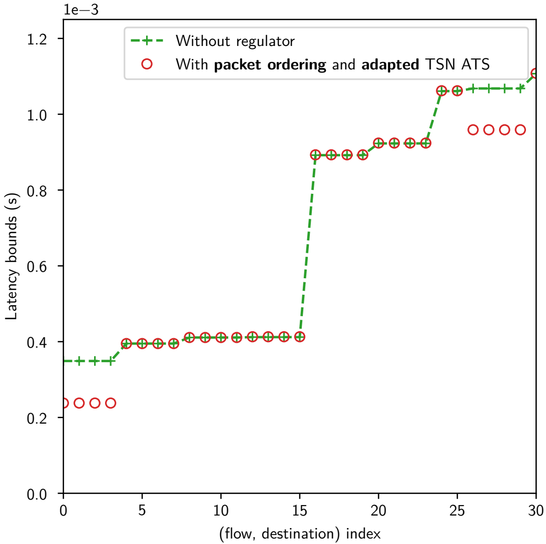

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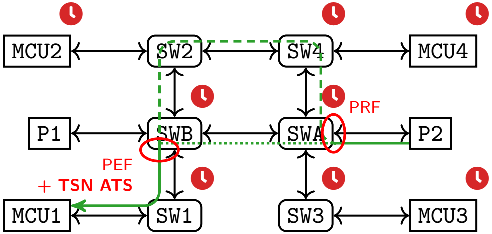

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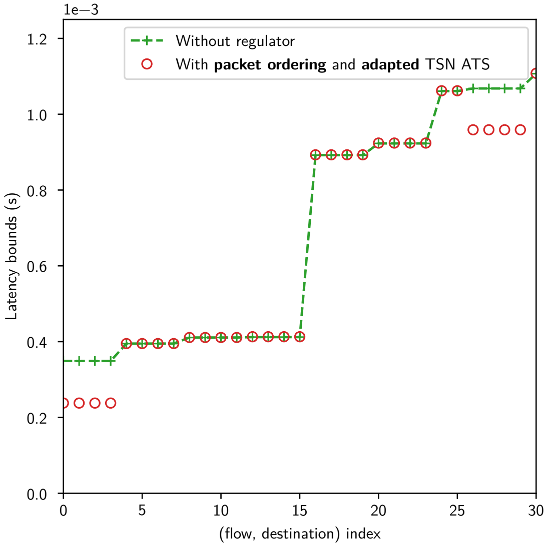

Take-away

- Redundancy and clock non-idealities **cannot be neglected** when configuring IR / TSN ATS.
- If properly configured, TSN ATS **reduce latency bounds** when combined with redundancy mechanisms.

Summary of **our contributions**

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FP-TFA: Fixed-point total flow analysis
LCAN: Low-cost acyclic network

PFR: Per-flow regulator
IR: Interleaved regulator (=TSN ATS)

Perspectives

Implement the model of redundancy mechanisms and non-ideal clocks in other compositional approaches

- Non-ideal clocks:
  - Service-curve-oriented approaches (SFA, PMOO) can benefit from the service-curve result.
  - Linear-constraints-oriented approaches can write the time models as linear constraints.
- Redundancy mechanisms: Results for service curves are missing!

SFA: Separated Flow Analysis
PMOO: Pay Multiplexing Only Once
TSN ATS: TSN Asynchronous Traffic Shaping
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The Quest for a Service Curve for TSN ATS

Does TSN ATS have a network calculus service-curve model?
⇒ Probably not (instability is too easy to achieve)

SFA: Separated Flow Analysis
PMOO: Pay Multiplexing Only Once
TSN ATS: TSN Asynchronous Traffic Shaping
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List of Publications

- 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
- Ludovic Thomas and Jean-Yves Le Boudec [June 9, 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
- 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

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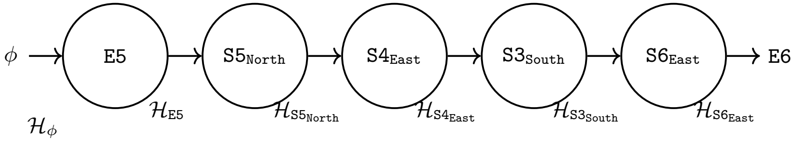
[IEEE 802.1AS] "IEEE Standard for Local and Metropolitan Area Networks–Timing and Synchronization for Time-Sensitive Applications" (June 2020). In: *IEEE Std 802.1AS-2020 (Revision of IEEE Std 802.1AS-2011)*, pp. 1–421. DOI: 10.1109/IEEESTD.2020.9121845.

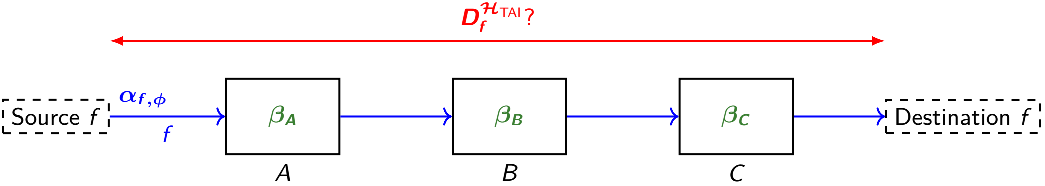
[ITU G.810] ITU (1996). "Definitions and Terminology for Synchronization Networks". In: *ITU G.810*. URL: https://www.itu.int/rec/T-REC-G.810-199608-I/en (visited on 10/14/2019).

[RFC 793] *Transmission Control Protocol* (Sept. 1981). RFC 793. DOI: 10.17487/RFC0793. URL: https://rfc-editor.org/rfc/rfc793.txt.

Computing End-to-end Latency Bounds in the True Time with TFA



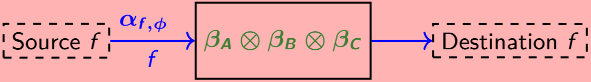
End-To-End Latency Bounds



If f is alone:

Theorem (Concatenation)

$\Leftrightarrow$



Also known as *Pay Burst Only Once* (PBOO)

$\otimes$: min-plus convolution. $(\mathfrak{f} \otimes \mathfrak{g}) : t \mapsto \inf_{0 \leq s \leq t}\{\mathfrak{f}(t-s) + \mathfrak{g}(s)\}$

The Always In TAI Strategy

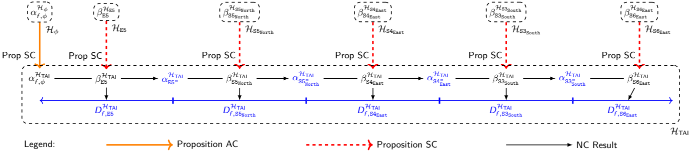
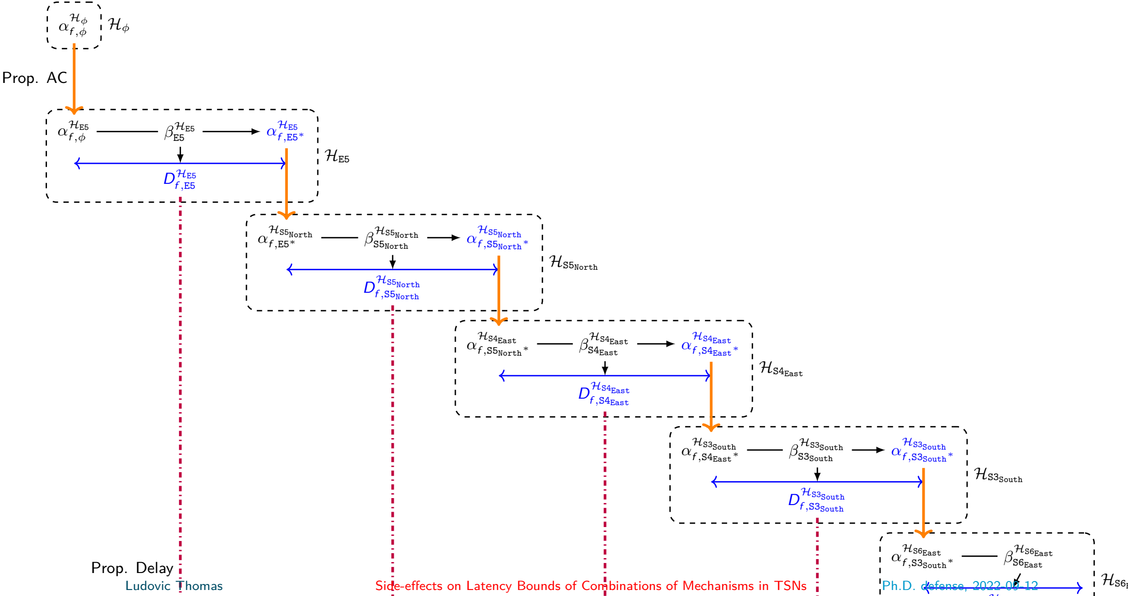


Figure: Illustration of the strategy "always in $\mathcal{H}_{\mathsf{TAI}}$" for the example

The Always In Local Time



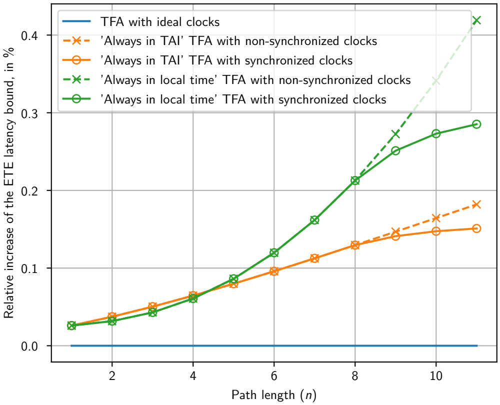
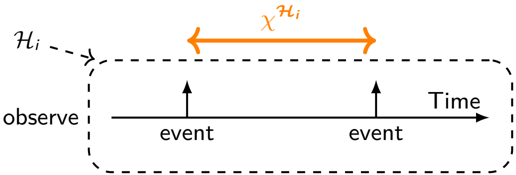


Figure: End-to-end latency bounds as a function of the path length, obtained either with the "always in TAI" strategy or with the "always in local time strategy", in synchronized and non-synchronized networks.

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



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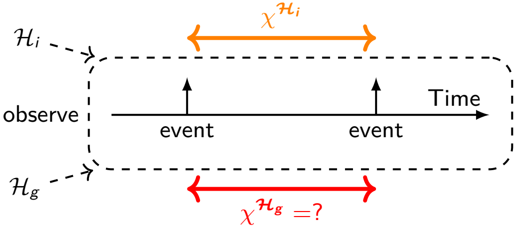

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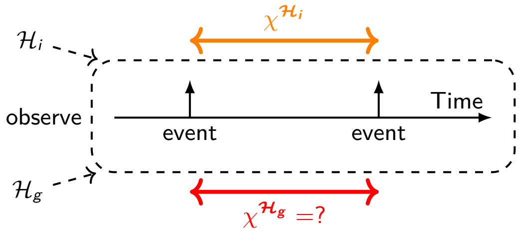

Proposition [Changing clock for a duration]

$$\max\left(0, \frac{\chi^{\mathcal{H}_i} - \eta}{\rho}, \chi^{\mathcal{H}_i} - 2\Delta\right) \le \chi^{\mathcal{H}_g} \le \min\left(\rho\chi^{\mathcal{H}_i} + \eta, \chi^{\mathcal{H}_i} + 2\Delta\right)$$

$\Delta \triangleq +\infty$ if non-synchronized

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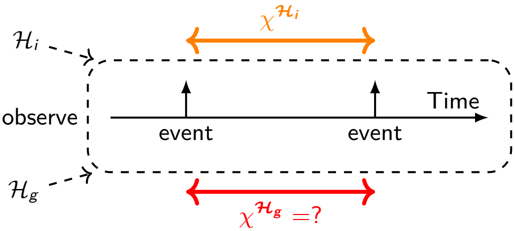

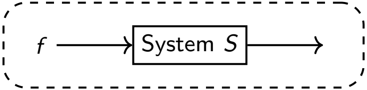

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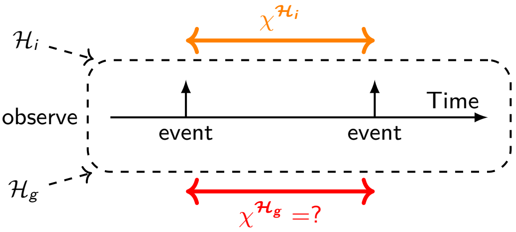
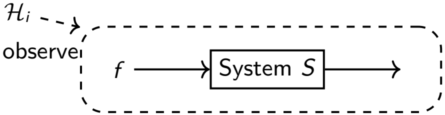


$\alpha_{f,\text{in}}^{\mathcal{H}_i}$



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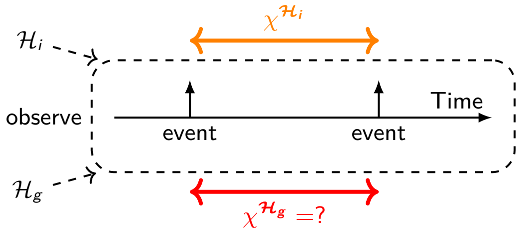

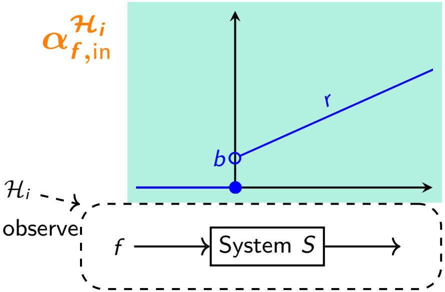

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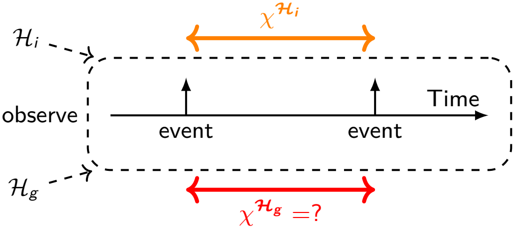

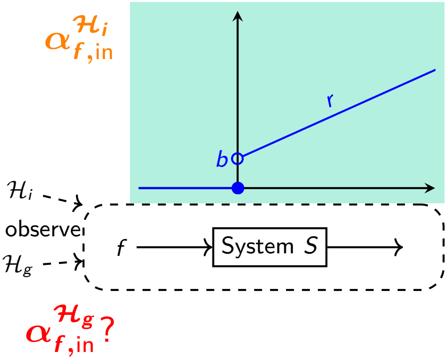

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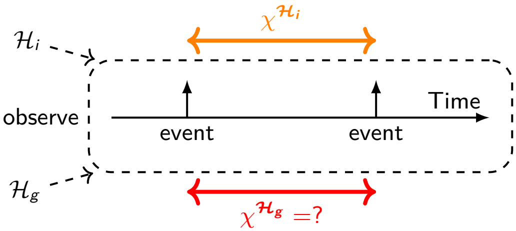

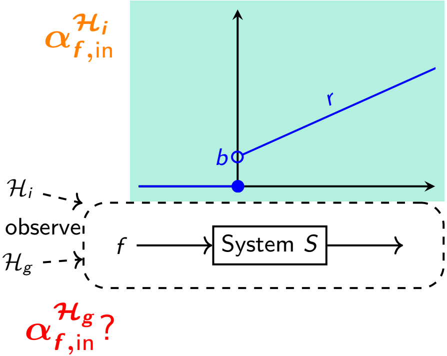

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$$\alpha_f^{\mathcal{H}_g} : t \mapsto \alpha_f^{\mathcal{H}_i}\left(\min\left[\rho t + \eta, t + 2\Delta\right]\right)$$

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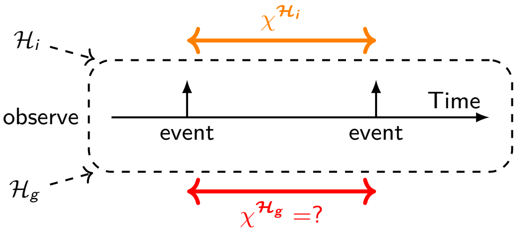

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