EPFL

Worst-case Delay Bounds in Time-Sensitive Networks with Packet Replication and Elimination

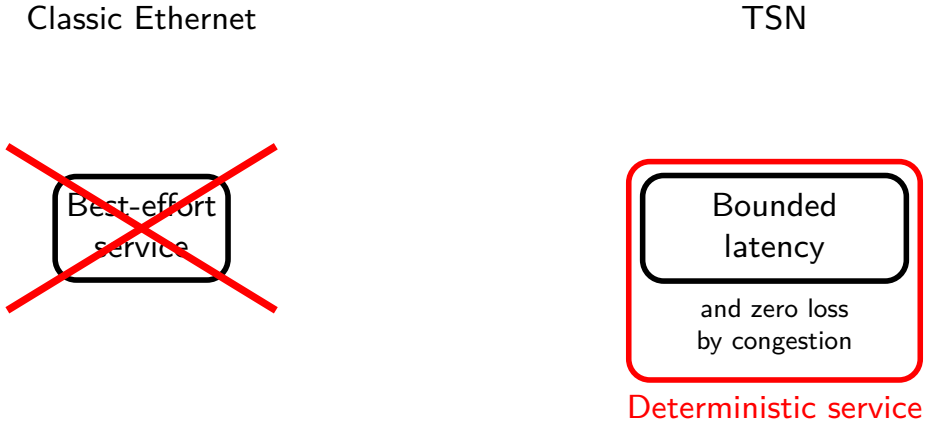
Published in *IEEE/ACM Transactions on Networking*

Ludovic Thomas, Ahlem Mifdaoui, Jean-Yves Le Boudec

STORE 19
July 12th, 2022

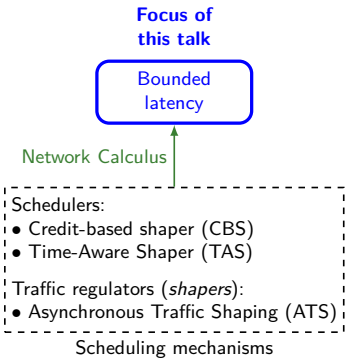
Context (1/2)

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



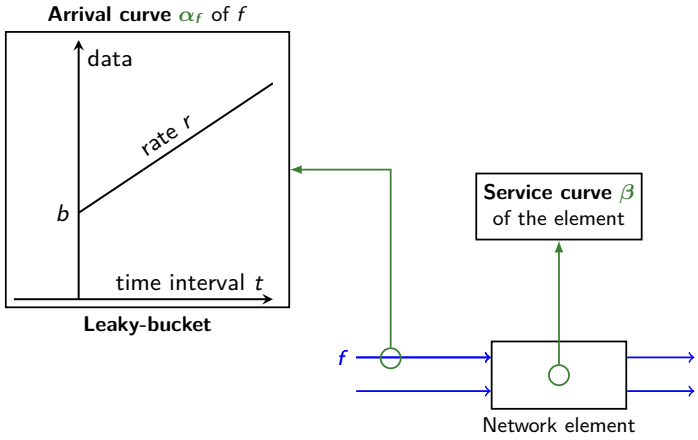
Similar ideas in **IETF deterministic networking (DetNet)** for IP and MPLS networks (layer 3)

Context (2/2)


Focus of this talk
Bounded latency
Network Calculus
Schedulers:
• Credit-based shaper (CBS)
• Time-Aware Shaper (TAS)
Traffic regulators (shapers):
• Asynchronous Traffic Shaping (ATS)
Scheduling mechanisms

Network Calculus (1/2)

A framework for obtaining **deterministic (= proven) bounds** on the **worst-case** performance metrics.

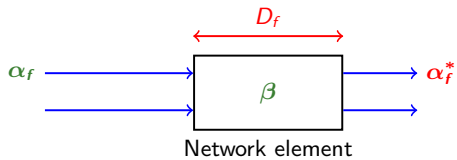


Network Calculus (2/2)

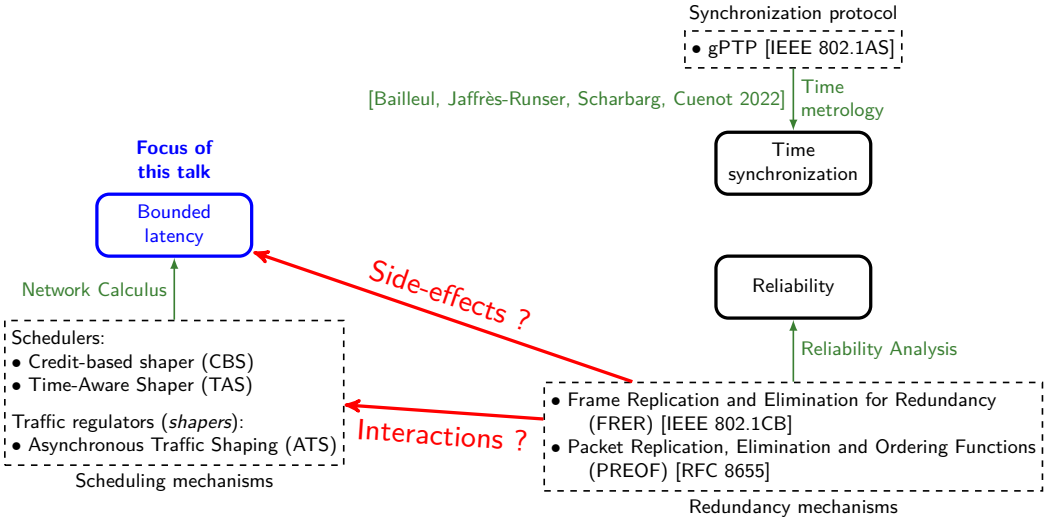
A framework for obtaining **deterministic bounds** on the **worst-case performance**.

Bounds on the

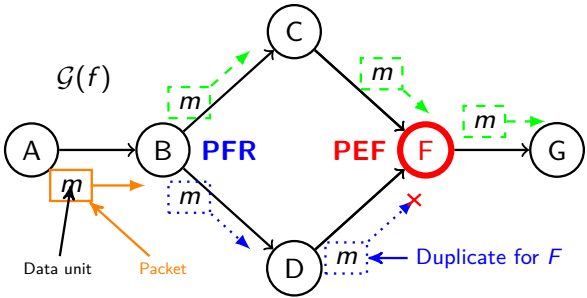
- Backlog
- Output arrival curve
- Latency



Other Services and Interactions



Redundancy: Principles and Terminology



PRF Packet Replication Function
PEF Packet Elimination Function

Assumption

The Packet Elimination Function (PEF) is correctly configured: it drops all duplicates and only them. [Maile 2022]

Content

Issues posed by PREFs (Packet Replication and Elimination Functions)

Illustration with a toy Example. Based on [IEEE 802.1CB, §C.9]

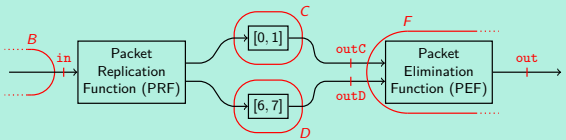
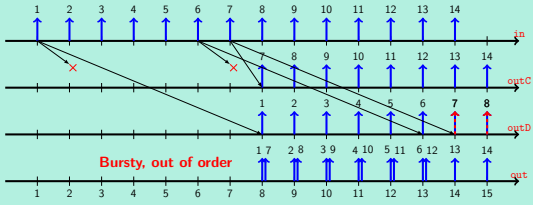


Figure: Toy example used thorough the presentation.

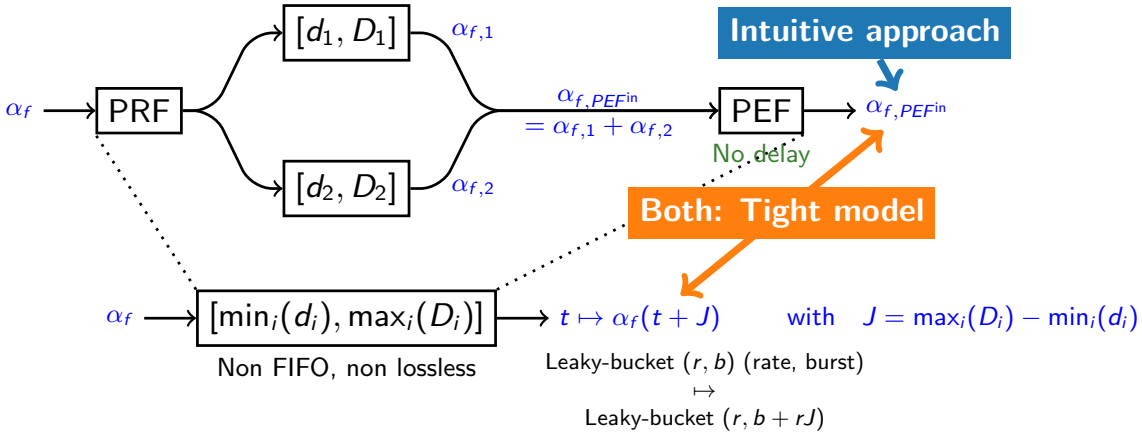


- Output of PEF bursty, mis-ordered ⇒ Can we bound the burstiness and mis-ordering at the PEF's output?
- Output mis-ordered → might violate application's requirements ⇒ Place a Packet Ordering Function (POF) ?
- Output bursty → leads to high delay in dowstream ⇒ Place a regulator (*shaper*) after the PEF ?

Question 1

Output of PEF bursty, mis-ordered $\Rightarrow$ Can we bound the burstiness and mis-ordering at the PEF's output?

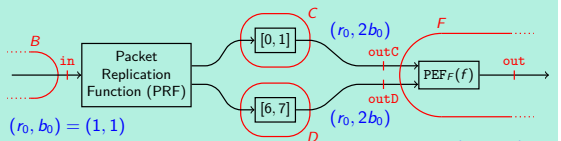
PEF Output Arrival Curve (1/3): Main Idea

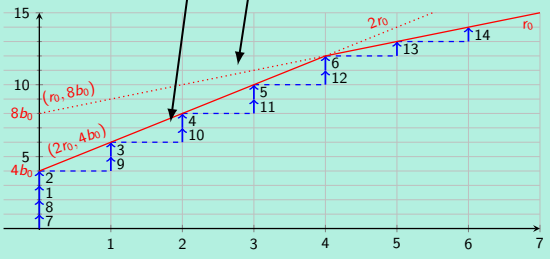


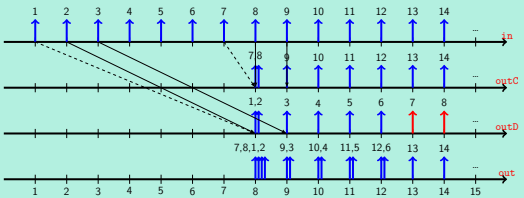
PEF Output Arrival Curve (2/3): Result is tight on the toy example.

- $\alpha_{f,\text{PEF}^{\text{in}}} = (2r_0, 4b_0)$
- $J = 7 - 0 = 0$
  $(r_0, b_0 + r_0 J) = (r_0, 8b_0)$

Toy example:

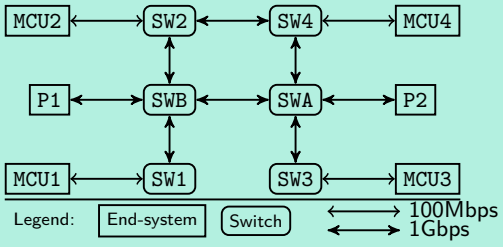




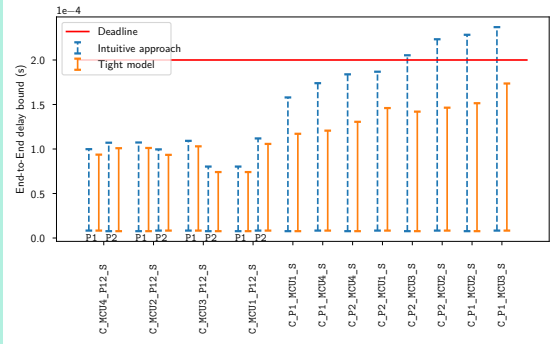


PEF Output Arrival Curve (3/3): **Tight Model**, better bounds than the **Intuitive approach**

An industrial use-case: The Volvo Core TSN Network



48 flows, 40 are redounded.



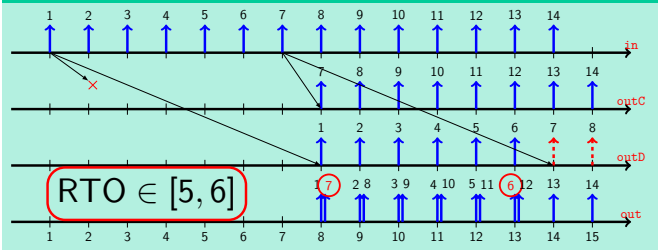
Mis-Ordering at the PEF's output

Reordering late Time Offset (RTO)

Quantifies the lateness of a data unit with respect to another one that was expected after.

[RFC 4737] [Mohammadpour, Le Boudec 2021]

Toy example



RTO after a PEF

$$\leq \left| J_{\text{source}\to\text{PEF}} - \alpha^{\downarrow}_{f,\text{source}}(2L^{\min}) \right|^{+}$$

- $\alpha^{\downarrow}_{f,\text{source}}$ lower pseudo-inverse of the arrival curve of f at its source.
- $|\cdot|^{+} = \max(0, \cdot)$

Comes from [Mohammadpour, Le Boudec 2021]

Question 1

Output of PEF bursty, mis-ordered $\Rightarrow$ Can we bound the burstiness and mis-ordering at the PEF's output?

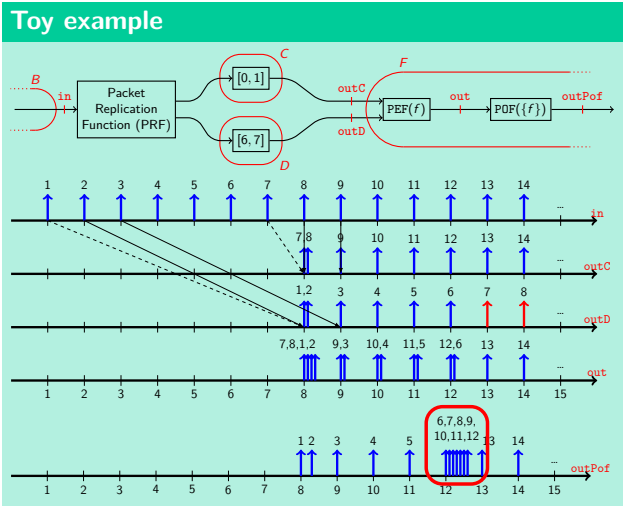
- Yes!
- Using a toolbox of network-calculus results.

Question 2

Output mis-ordered $\rightarrow$ might violate application's requirements $\Rightarrow$ Place a Packet Ordering Function (POF) ?

POF after a PEF

Toy example



Here, no data unit is lost (at least one replicate reaches the PEF).

$\Rightarrow$ The combination PEF+POF comes 'for free'. [Mohammadpour, Le Boudec 2021, Thm. 4].

BUT the output is even more bursty.

Interactions PEF and POF (3/3): Conclusion

Question 2

Output mis-ordered → might violate application's requirements ⇒ Place a Packet Ordering Function (POF) ?

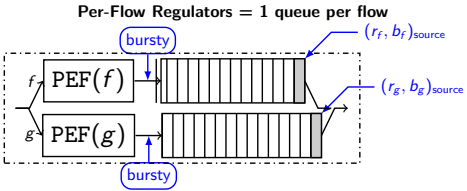
■

Configuration	Benefits	Drawbacks
PEF + POF	• Data units in order • Reordering-for-free	• Increased burstiness ⇒ higher delay bounds in downstream nodes. • Hardware complexity.

Question 3

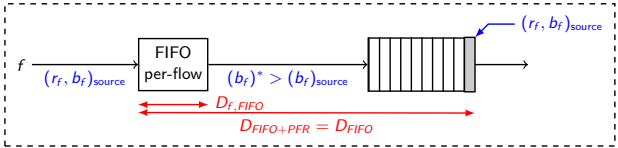
Output bursty → leads to high delay in dowstream ⇒ Place a regulator (*shaper*) after the PEF ?

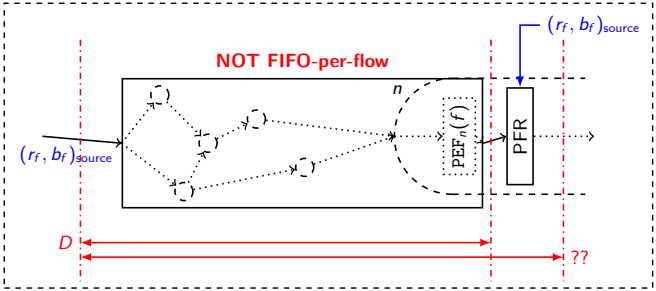
PFR after the PEF



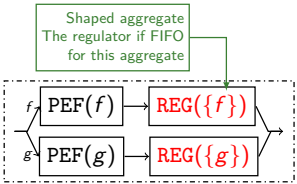
We want to correct the burstiness increase caused by the redundancy mechanisms.
I.e., we place the regulator **after** the PEF.

"Shaping for free" for **PFR**:





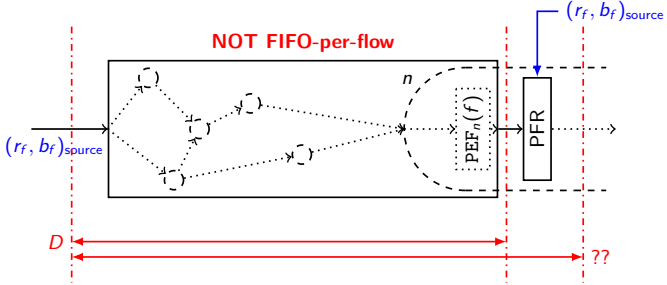
Interactions PEF and Regulators (REGs): The Per-Flow Regultor (PFR) (2/4)



Interactions PEF and Regulators (REGs): The Per-Flow Regultor (PFR) (3/4)

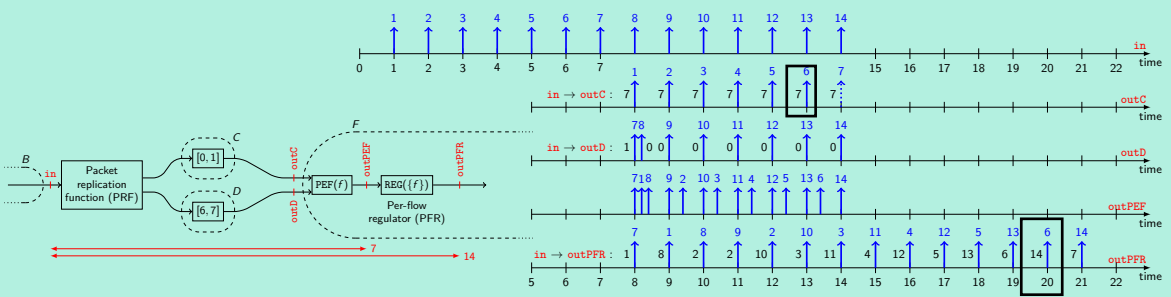
PFR after PEF

$D' \leq 2D$

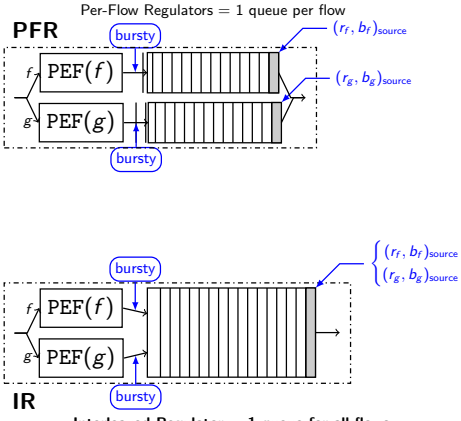


Interactions PEF and Regulators (REGs): The Per-Flow Regultor (PFR) (4/4)

Toy example

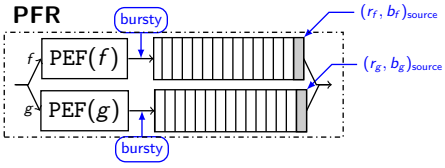


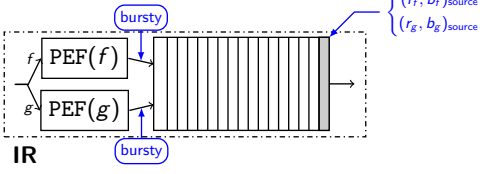
Interactions PEF and Regulators (REGs): The Interleaved Regulator (IR) (1/5)



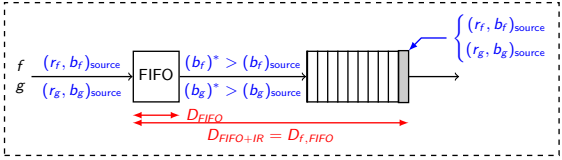
We want to correct the burstiness increase caused by the redundancy mechanisms.
I.e., we place the regulator **after** the PEF.

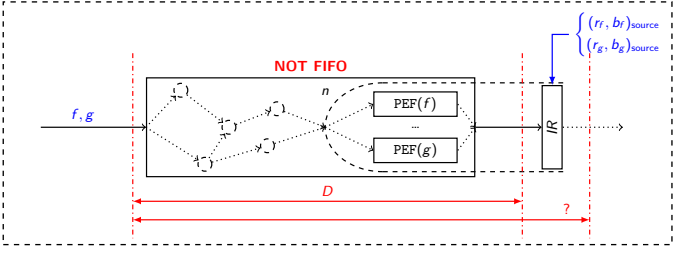
Interactions PEF and Regulators (REGs): The Interleaved Regulator (IR) (3/5)



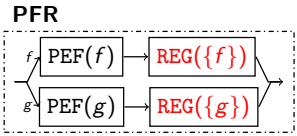


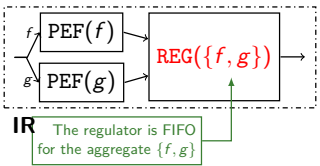
"Shaping for free" for the **IR**:





Interactions PEF and Regulators (REGs): The Interleaved Regulator (IR) (4/5)

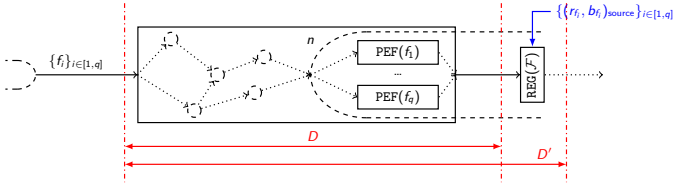




Interactions PEF and Regulators (REGs): The Interleaved Regulator (IR) (5/5)

Instability of IR after a PEF

If the interleaved regulator (IR) processes three or more redounded flows, then it can yield unbounded latencies.



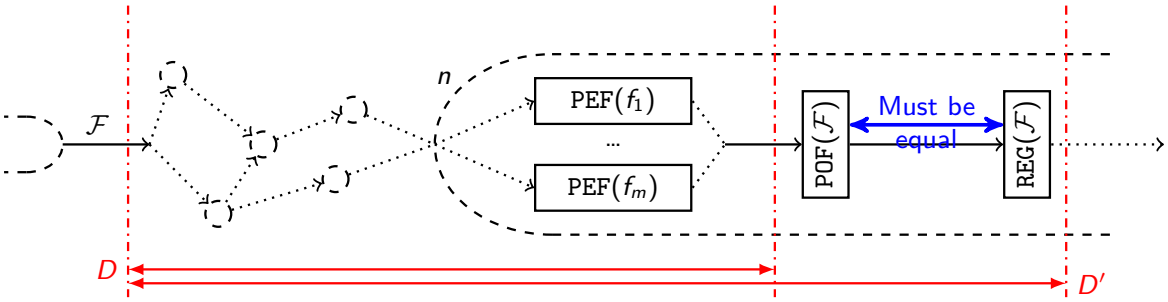
Interactions PEF and Regulators: Conclusion

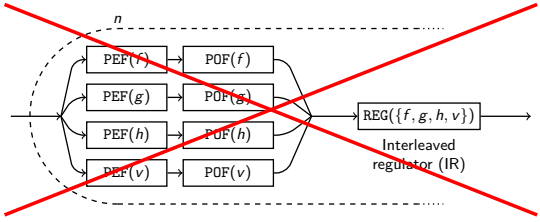
Question 3

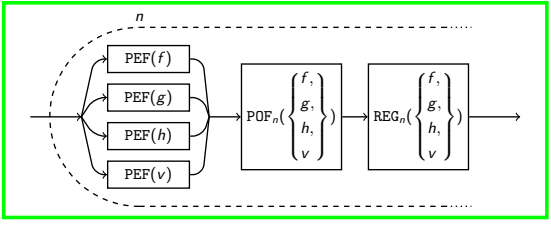
Output bursty $\rightarrow$ leads to high delay in dowstream $\Rightarrow$ Place a regulator (*shaper*) after the PEF ?

Configuration	Benefits with respect to the PEF alone	Drawbacks with respect to the PEF alone
PEF + REG	• Output traffic keeps the arrival constraints it had before the redundant section, resulting in smaller delay bounds in downstream nodes.	• Delay penalty due to mis-ordering: with PFR: delay penalty with a guaranteed maximum delay; with IR: unbounded delay. • Increased hardware complexity.

Interactions PEF + POF + REG (1/2)

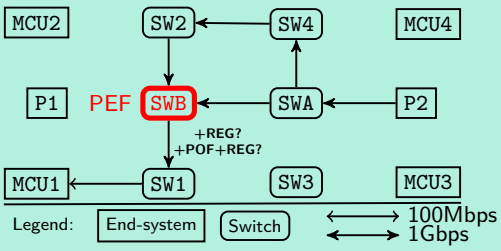


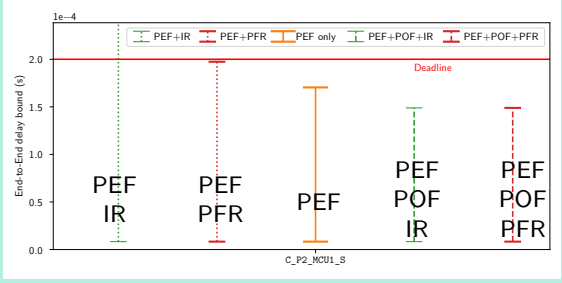




Interactions PEF + POF + REG (2/2)

On the industrial use-case: focus on one path





Conclusion

- Toolbox: output arrival curve at PEF output + re-ordering bound (+xTFA a tool implementing the results).
- Analysis of the interactions [PEF+POF], [PEF+REG] and [PEF+POF+REG]
  - POF corrects the mis-ordering but worsens the burstiness.
  - PEF+REF incurs delay penalties (unbounded with TSN ATS).
  - PEF+POF+REG is ideal, but has an hardware cost.

Announcements

The Workshop on Network Calculus (WoNeCa)

- 8th and 9th September 2022
- EPFL, Lausanne, Switzerland
- 2022.woneca.org

Bibliography I

[Bailleul, *et al.* 2022] Bailleul, Quentin et al. (June 2022). "Assessing a Precise gPTP Simulator with IEEE802.1AS Hardware Measurements". In: *11th European Congress on Embedded Real-Time Systems (ERTS 2022)*. Toulouse, France. URL: https://hal.archives-ouvertes.fr/hal-03620481.

[Maile 2022] Maile, Lisa (May 2022). "Ensuring Reliable & Predictable Behavior of IEEE 802.1CB Frame Replication & Elimination (ICC 2022)". In: *IEEE International Conference on Communications 2022*.

[Mohammadpour, Le Boudec 2021] Mohammadpour, Ehsan and Jean-Yves Le Boudec (2021). "On Packet Reordering in Time-Sensitive Networks". In: *IEEE/ACM Transactions on Networking*, pp. 1–13. ISSN: 1558-2566. DOI: 10.1109/TNET.2021.3129590.

[RFC 8655] Finn, Norman et al. (2019). "Deterministic Networking Architecture". In: RFC 8655. ISSN: 2070-1721. DOI: 10.17487/RFC8655. URL: https://www.rfc-editor.org/info/rfc8655 (visited on 06/07/2021).

[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*, pp. 1–102. DOI: 10.1109/IEEESTD.2017.8091139.

Bibliography II

[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.

[RFC 4737] Morton, Al et al. (Nov. 2006). *Packet Reordering Metrics*. RFC 4737. DOI: 10.17487/RFC4737. URL: https://rfc-editor.org/rfc/rfc4737.txt.