EPFL

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

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Time-Sensitive Networks

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

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Classic Ethernet

Best-effort service

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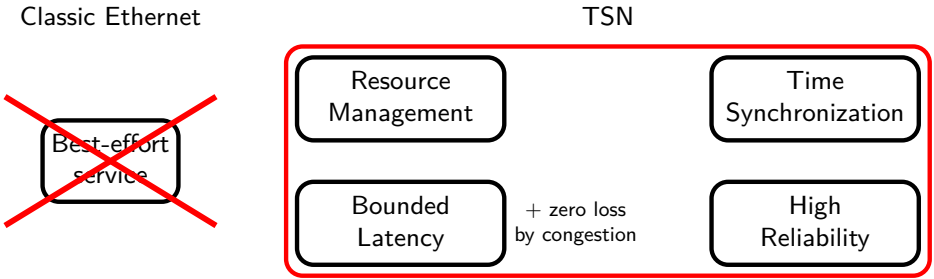

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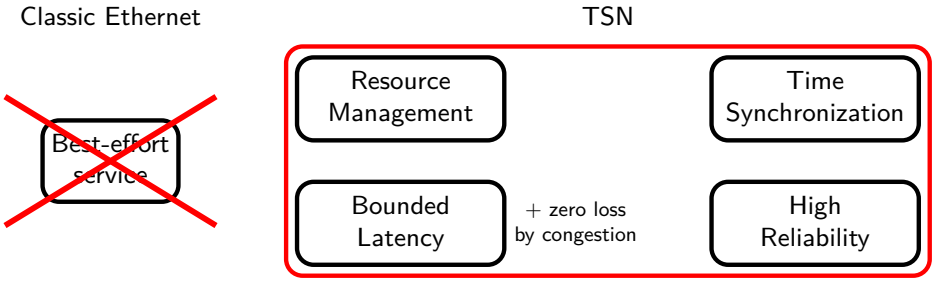

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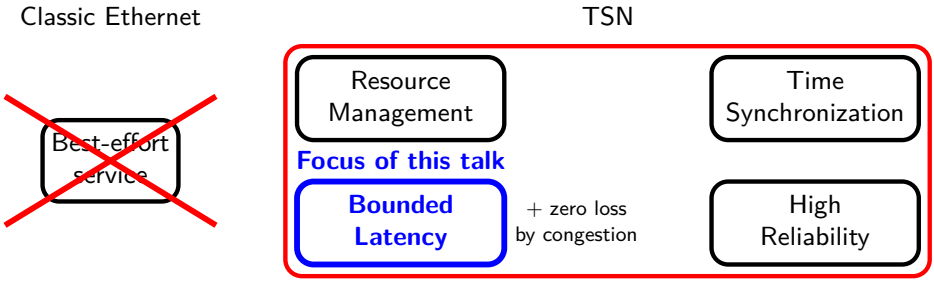

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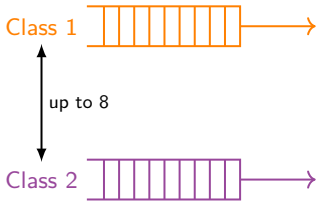

Access policy

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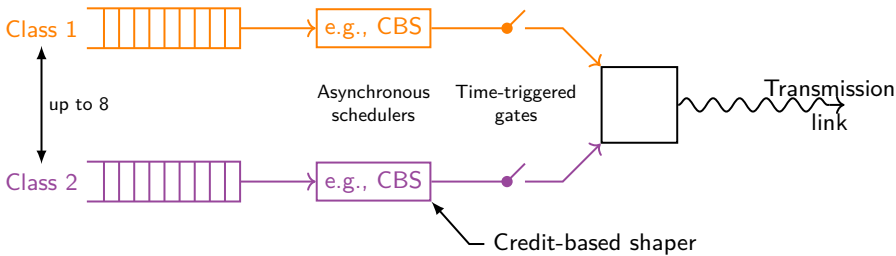

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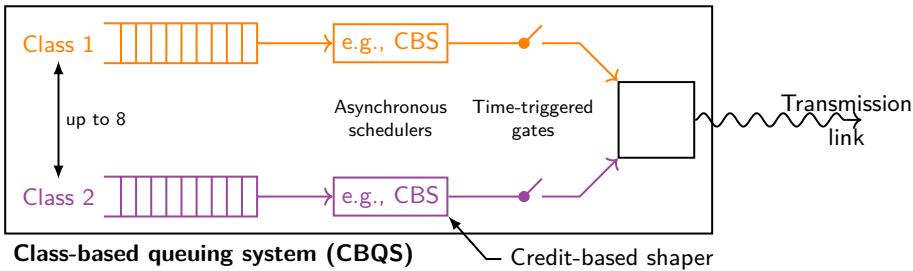

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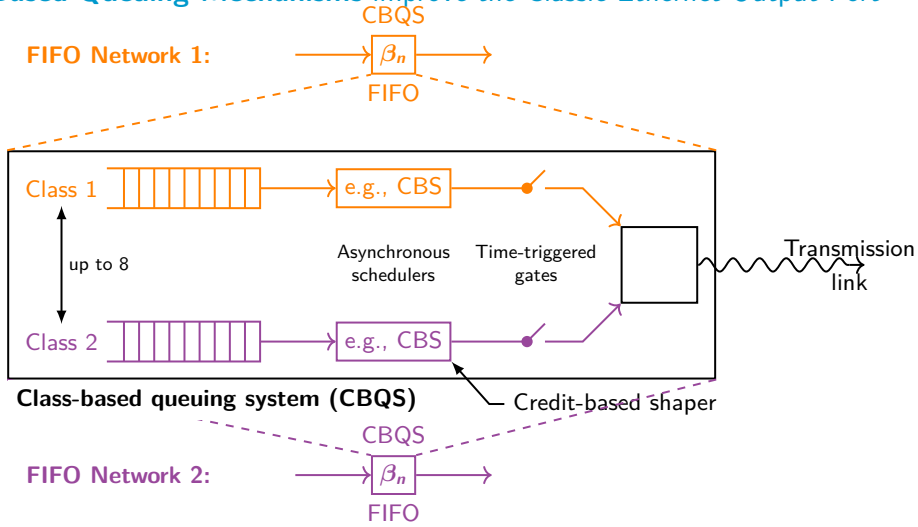

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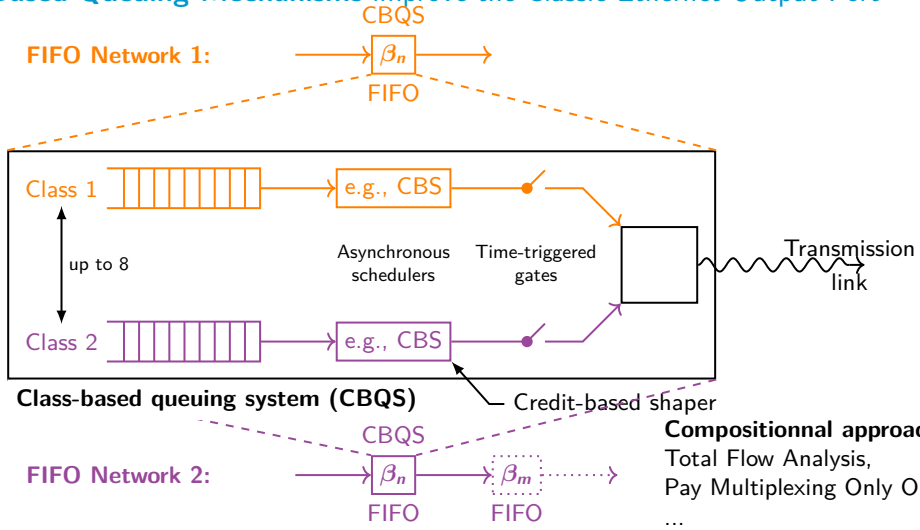
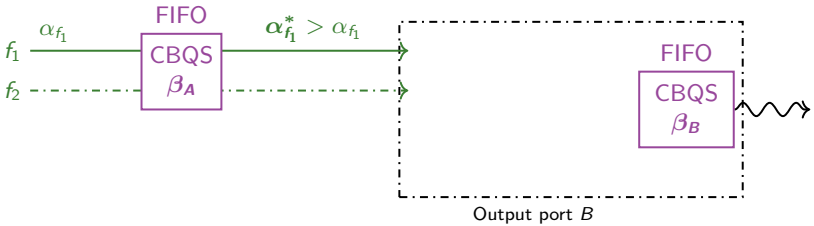


Compositionnal approaches:
Total Flow Analysis,
Pay Multiplexing Only Once,
...

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



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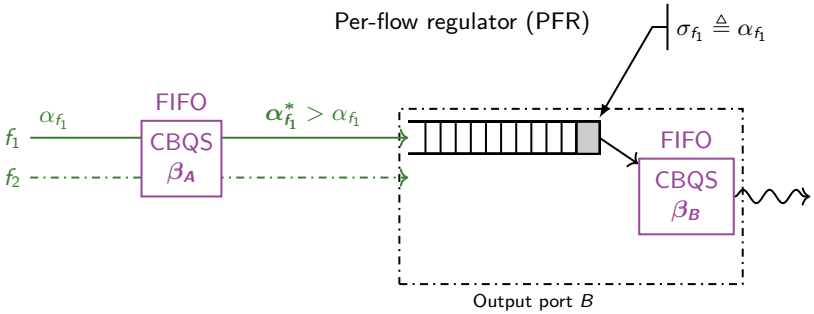

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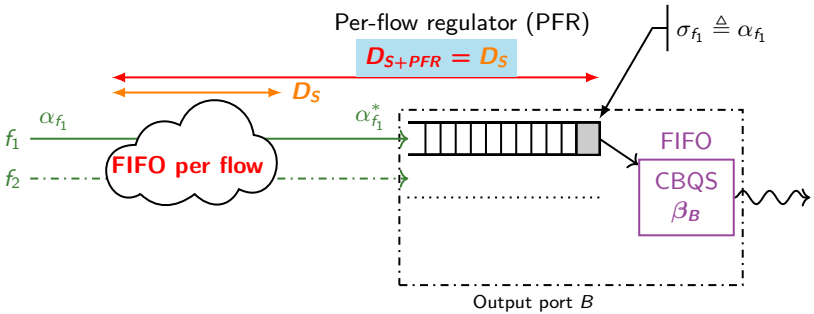

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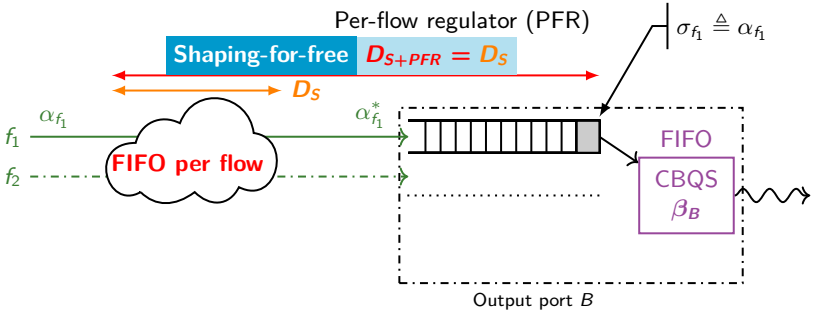

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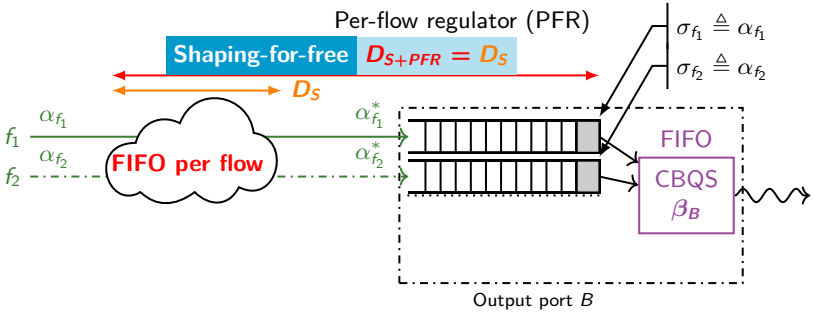

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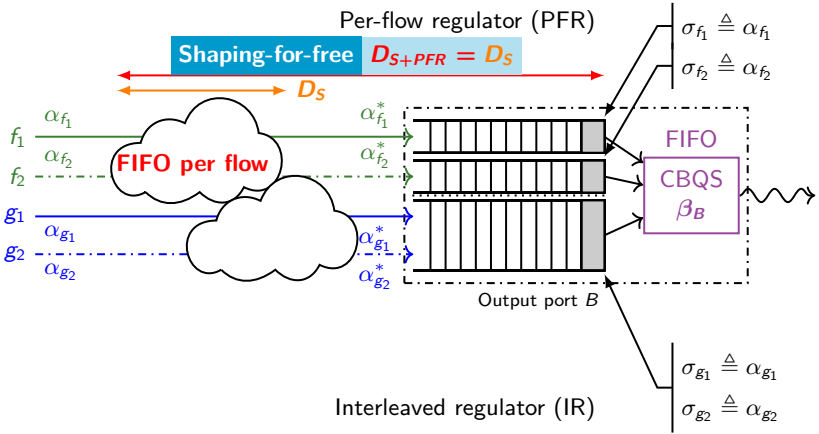

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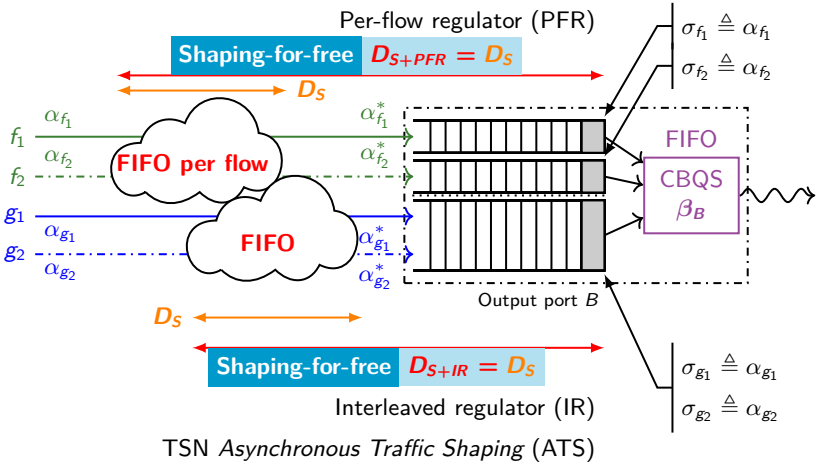

CBQS: Class-based queuing system (FIFO for the class aggregate)

Focus of this talk

Bounded Latency

Class-based queuing mechanisms:
- Asynchronous schedulers
- Time-triggered gates

Traffic regulators (*shapers*):
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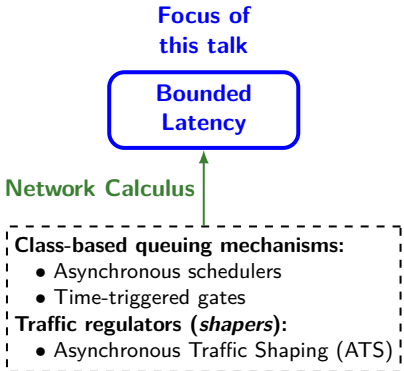
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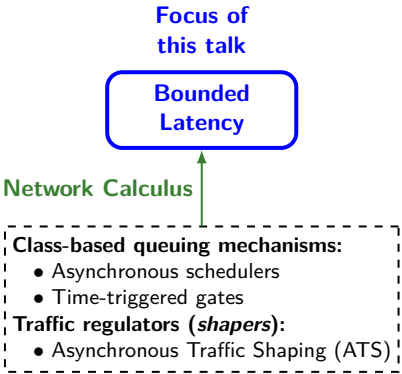
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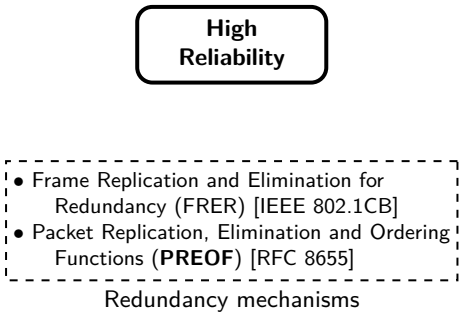
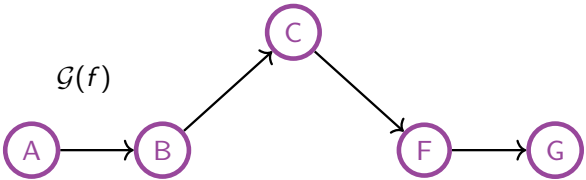

High Reliability
• Frame Replication and Elimination for Redundancy (FRER) [IEEE 802.1CB]
• Packet Replication, Elimination and Ordering Functions (PREOF) [RFC 8655]
Redundancy mechanisms

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



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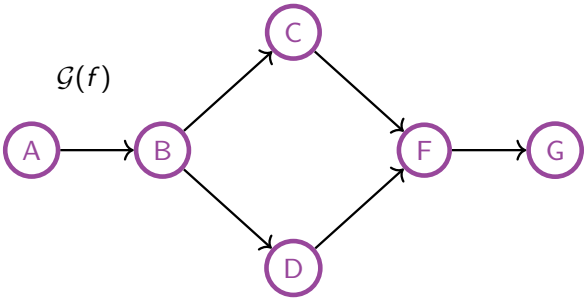

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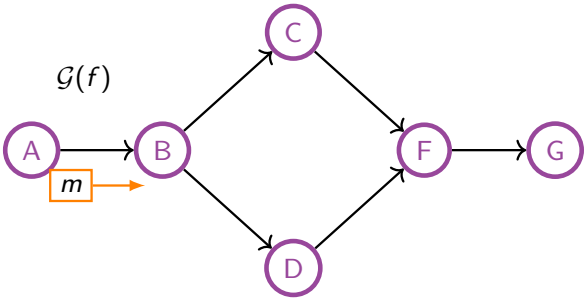

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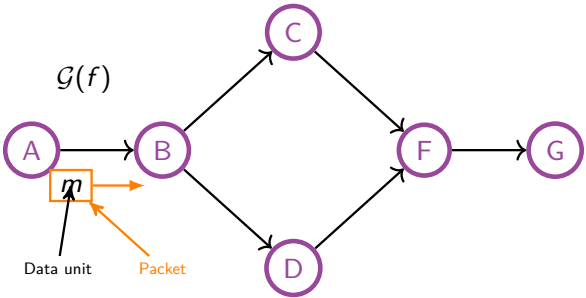

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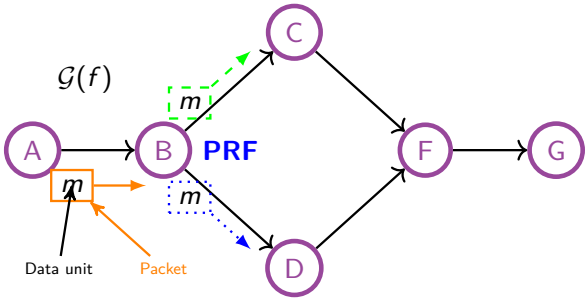

PRF Packet Replication Function (DetNet)
Stream splitting function (TSN)

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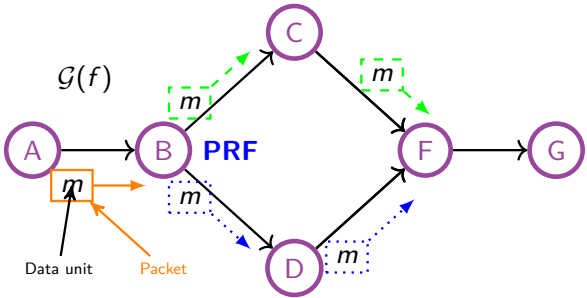

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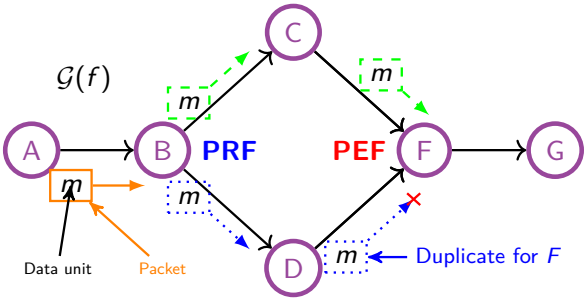

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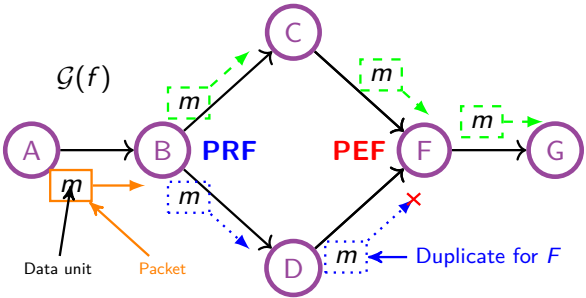

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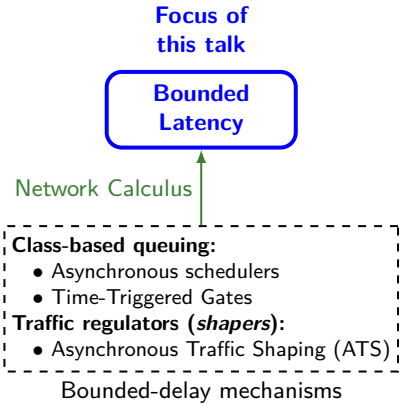

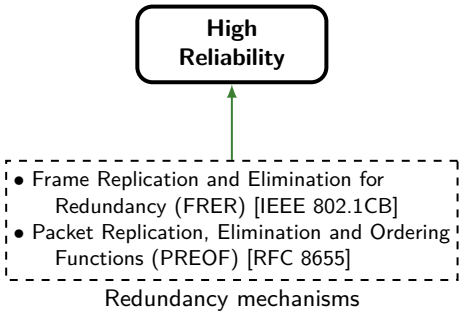

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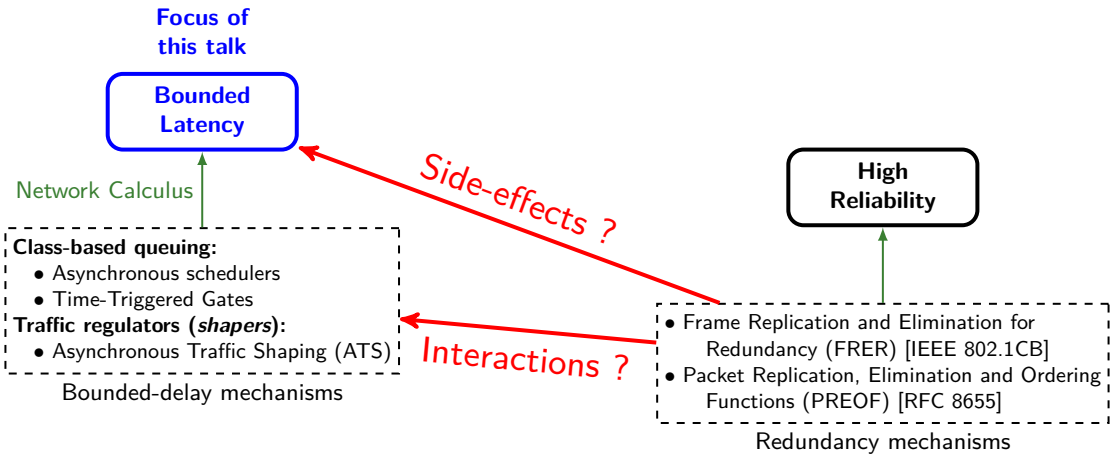

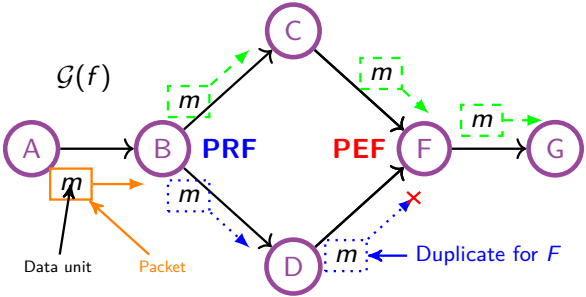

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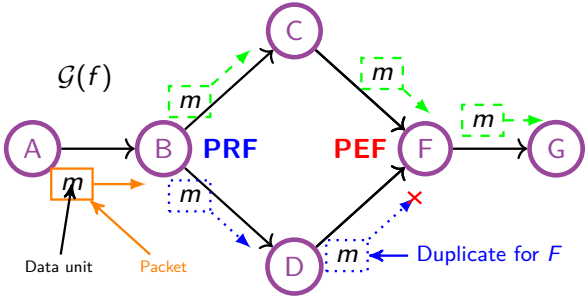

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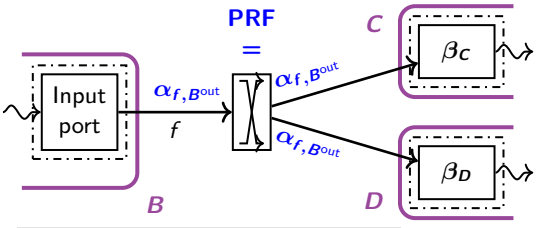

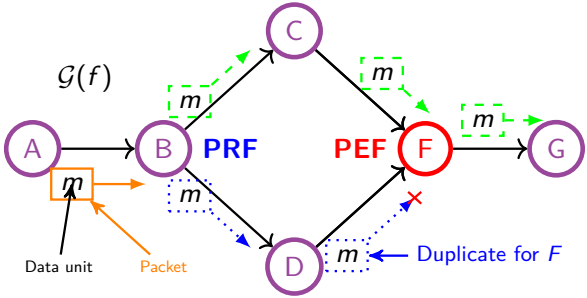

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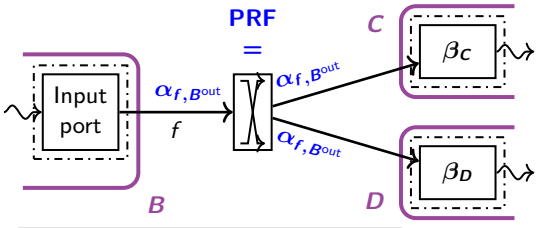

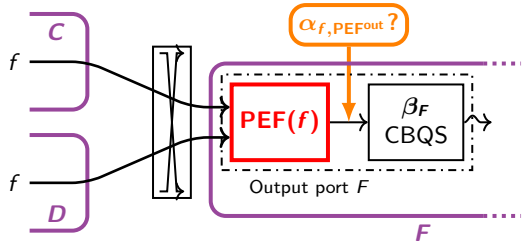

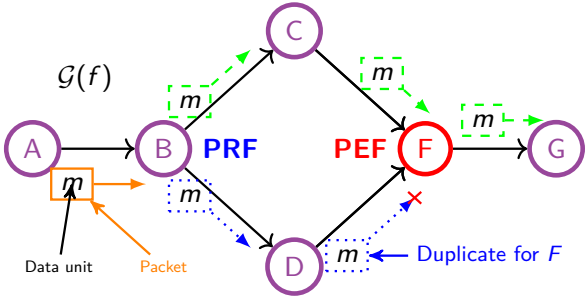

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Assumption

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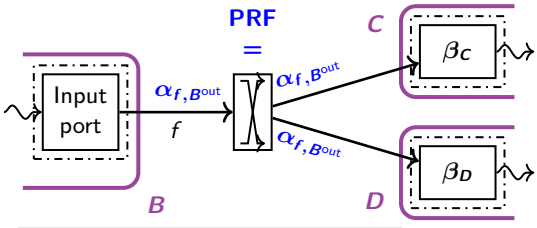

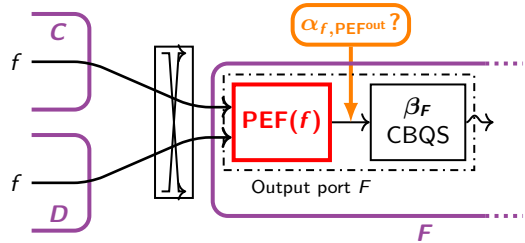

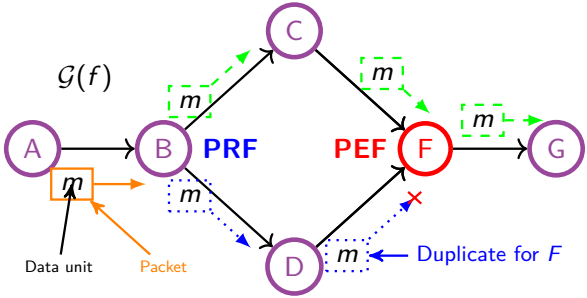

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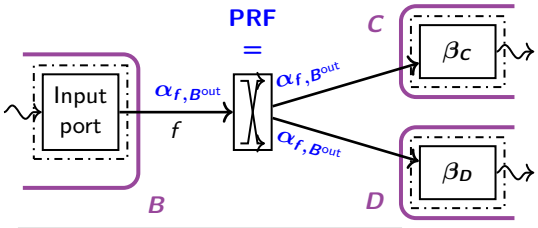
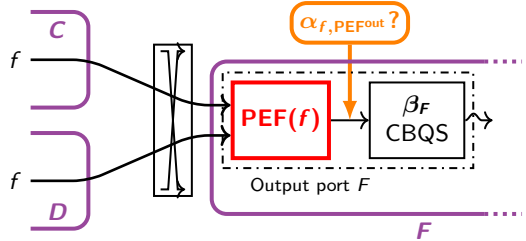
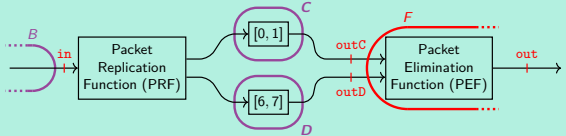


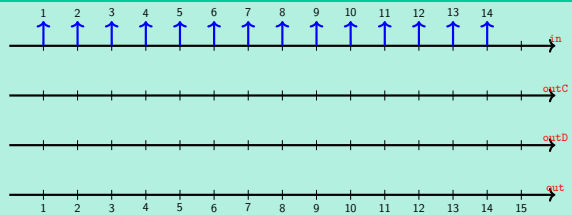


– [Maile, *et al.* 2022] Lisa Maile, Dominik Voitlein, Kai-Steffen Hielscher, and Reinhard German [May 2022]. "Ensuring Reliable and Predictable Behavior of IEEE 802.1CB Frame Replication and Elimination". In: *ICC 2022 - IEEE International Conference on Communications*. DOI: 10.1109/ICC45855.2022.9838905

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

A Possible Trajectory on a Toy Example





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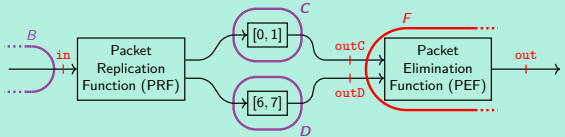

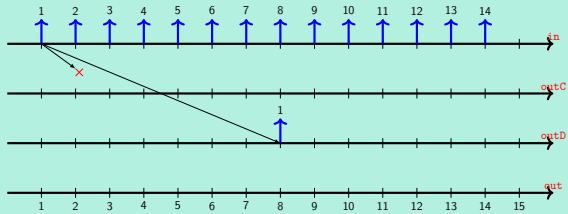

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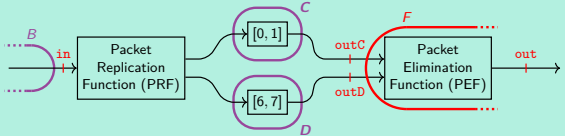

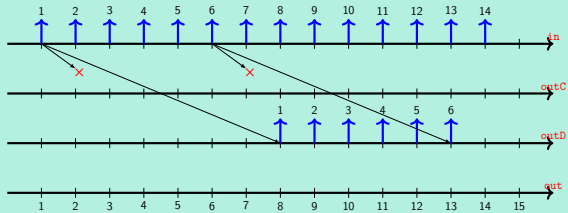

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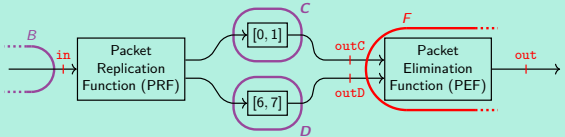

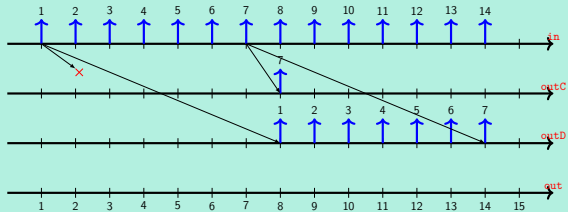

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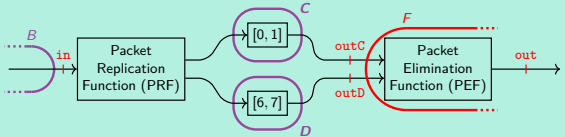

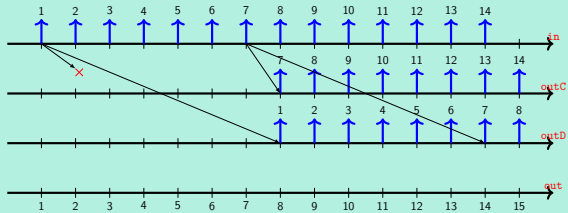

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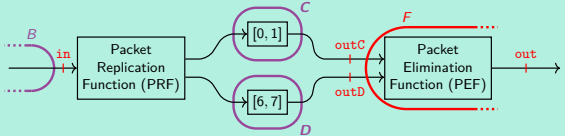

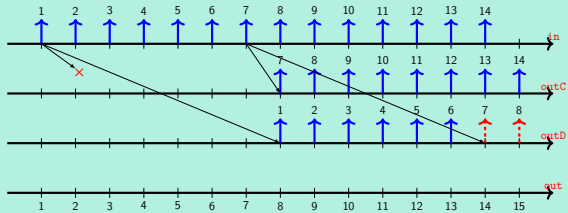

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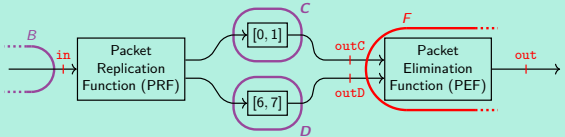

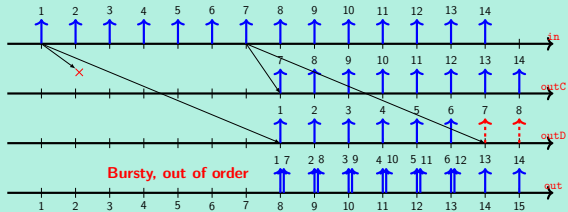

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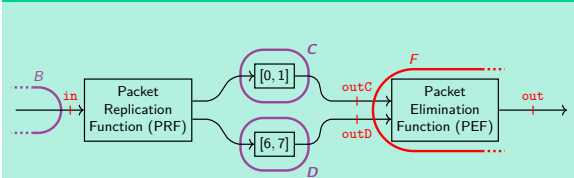

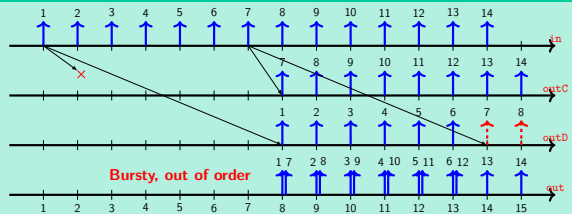

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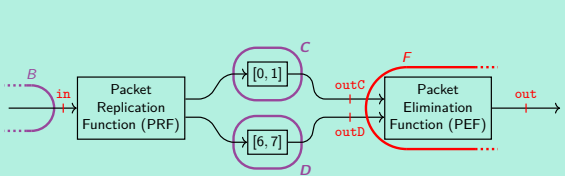

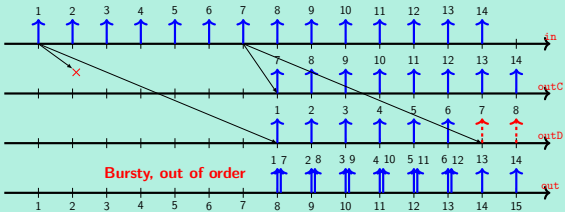

- Output of PEF bursty, mis-ordered ⇒ Can we bound the burstiness and mis-ordering at the PEF's output?
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An **Arrival Curve** at The Output of The PEF (Packet Elimination Function)

Theorem: PEF Output Arrival Curve

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Intuitive approach

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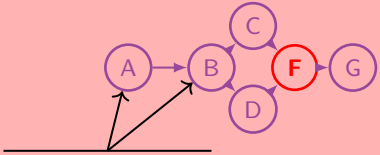

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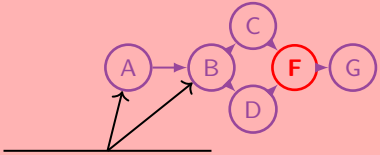

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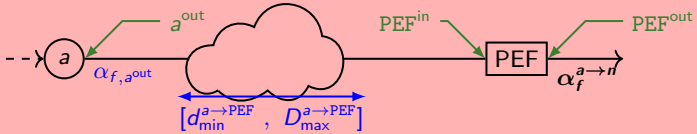

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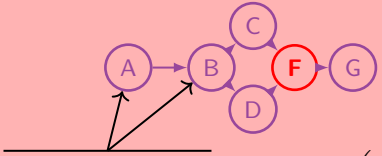

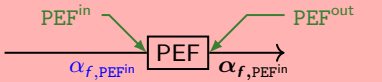

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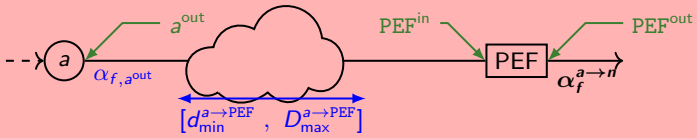
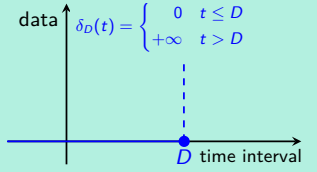


Bounded-Delay δ_D



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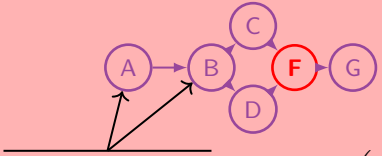

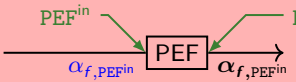

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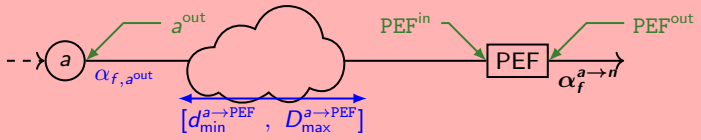

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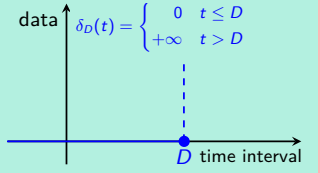
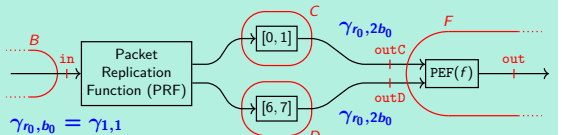


⇒ **Tight Model:** The min-plus convolution of all above arrival curves is an arrival curve at PEF^{out}.

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

Toy example:



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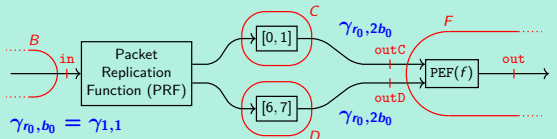

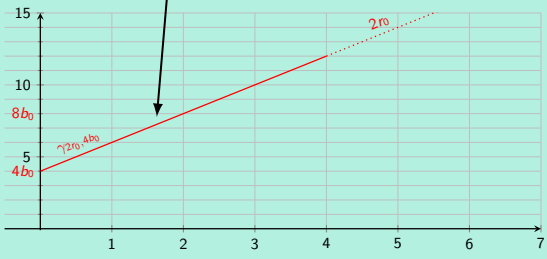

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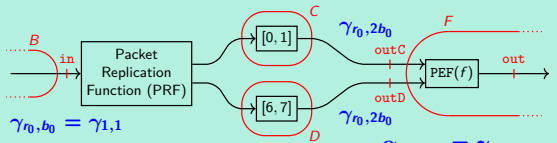

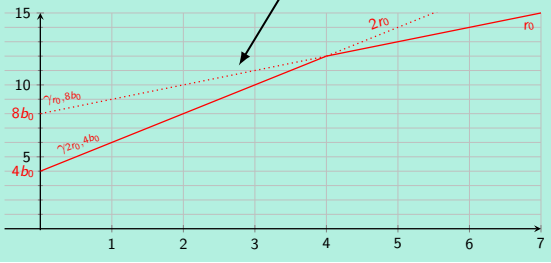

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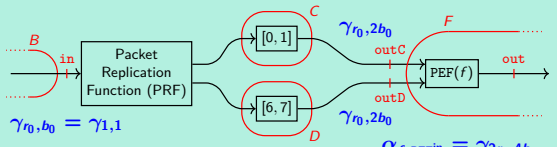

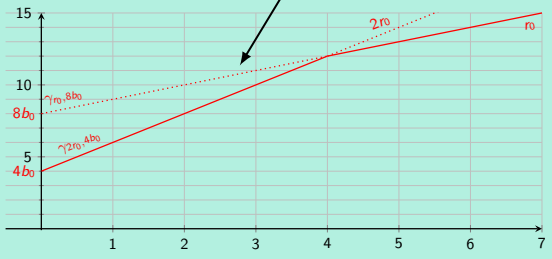

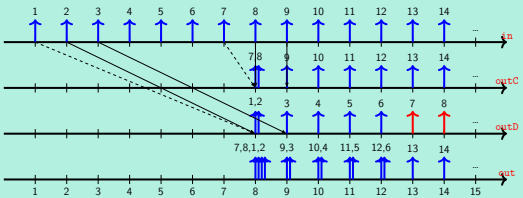

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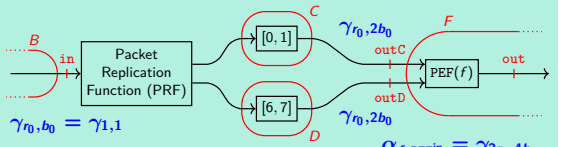
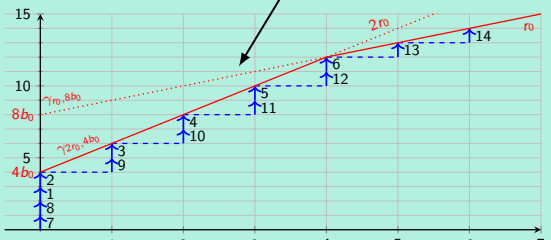
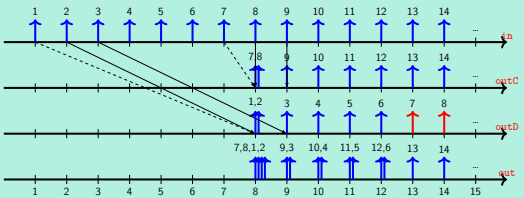
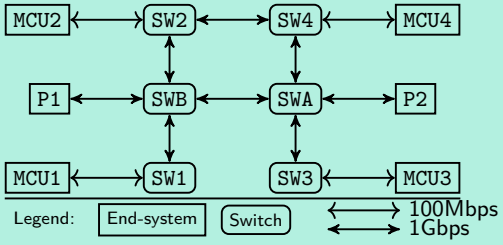




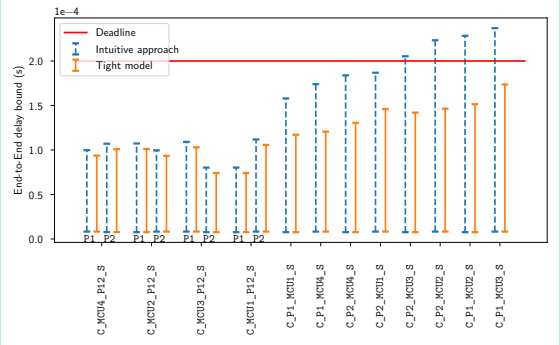


Tight Model, better bounds than the Intuitive approach

An industrial use-case: The Volvo Core TSN Network



48 flows, 40 are redounded.



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

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Question 2

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

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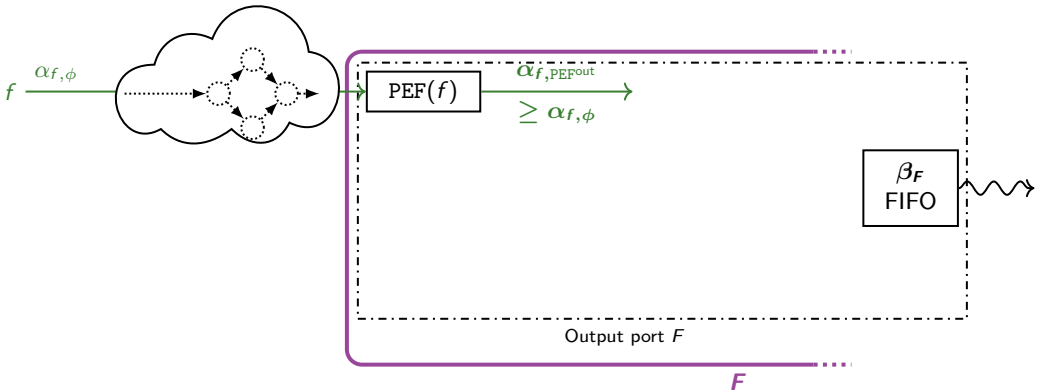

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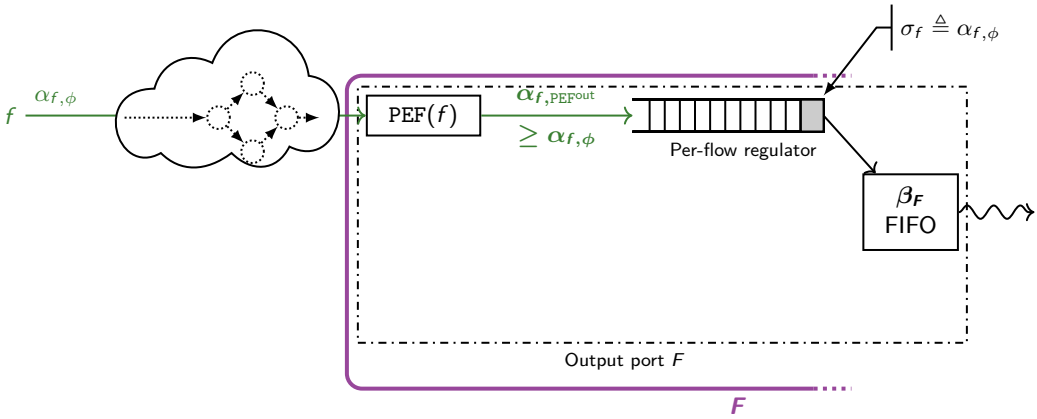

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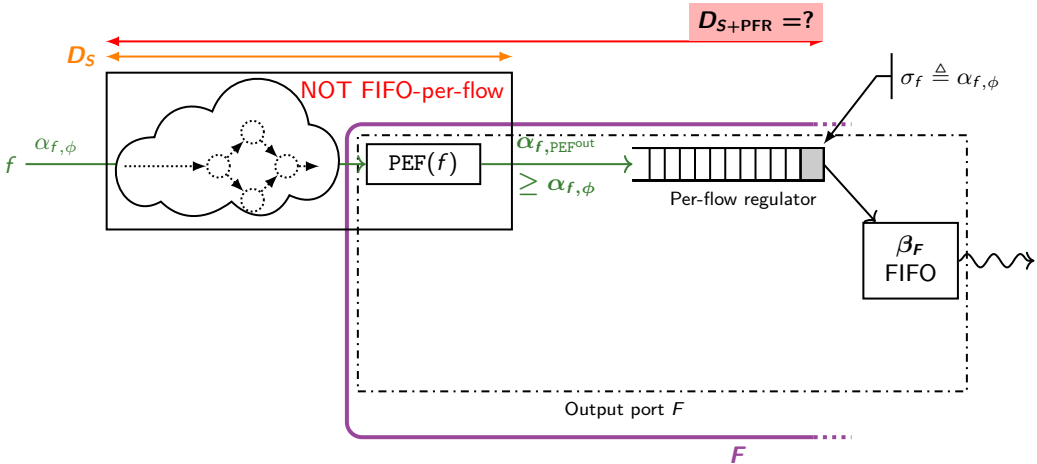

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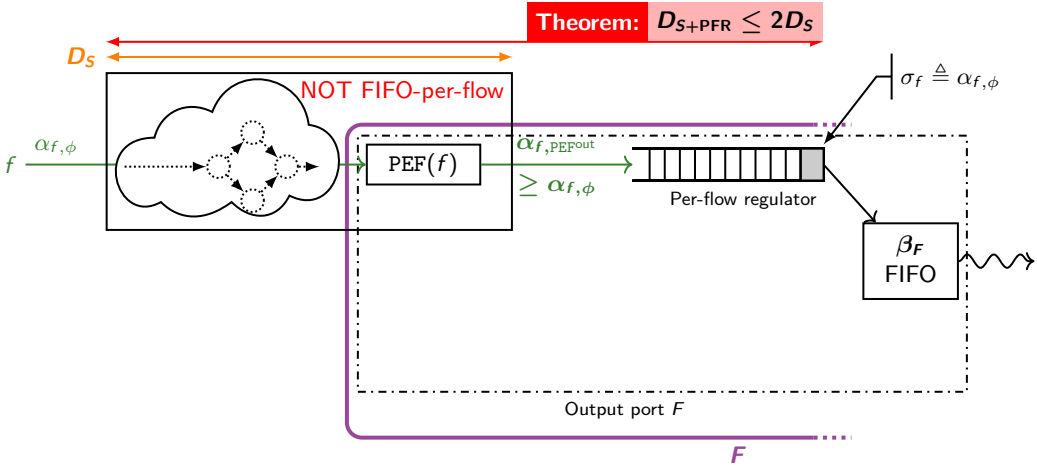

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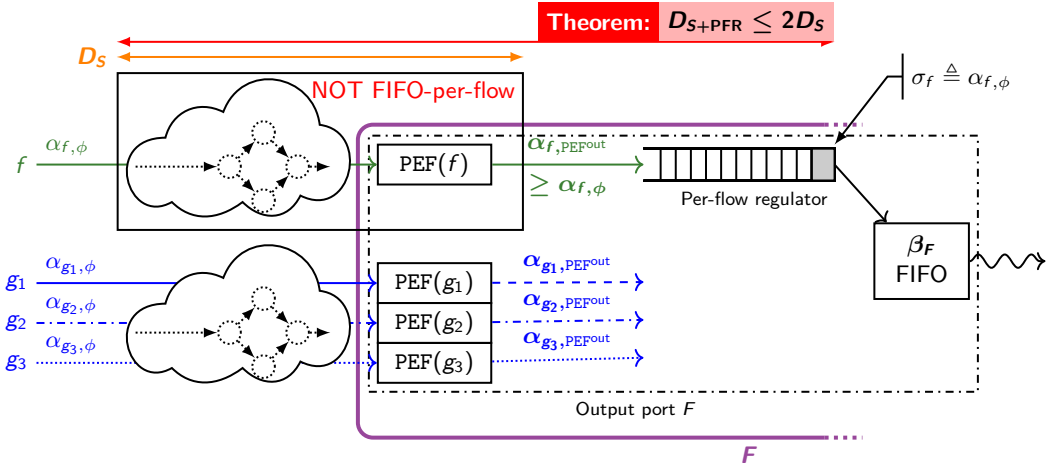

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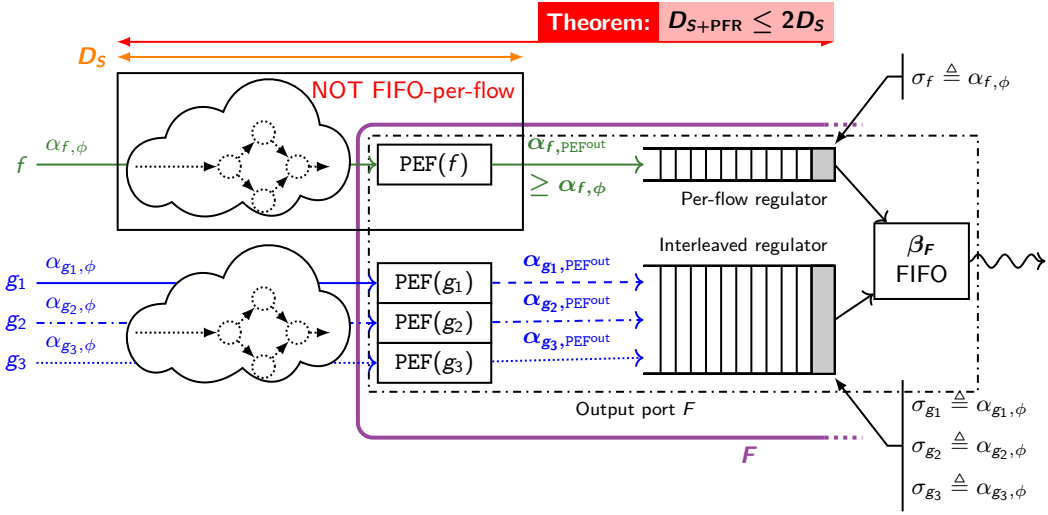

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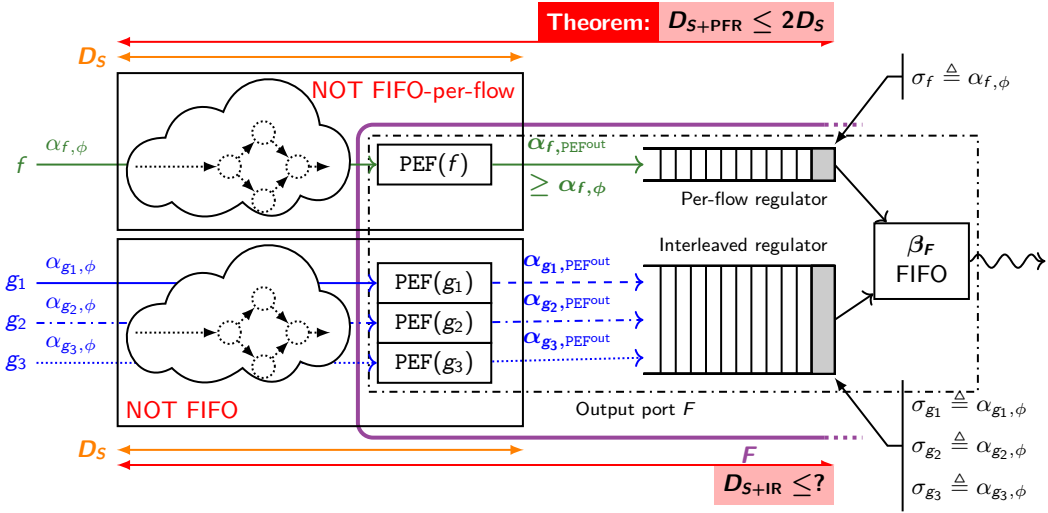

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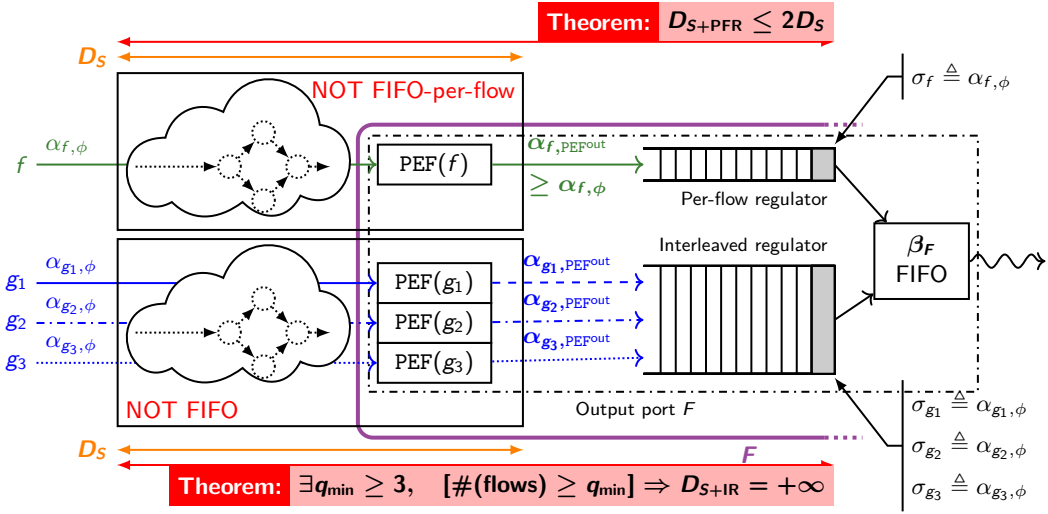
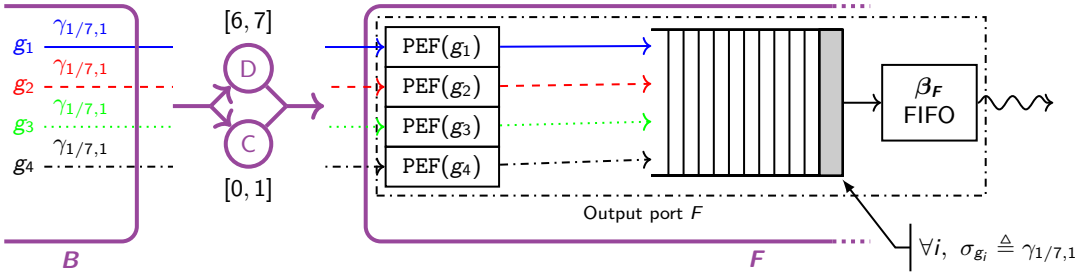


Interleaved Regulator (IR, TSN ATS) **Unstable after PEF**: Intuition of the Proof



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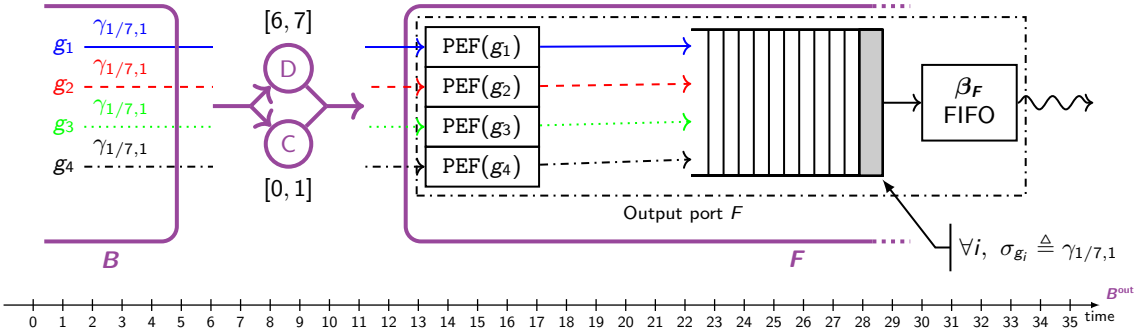

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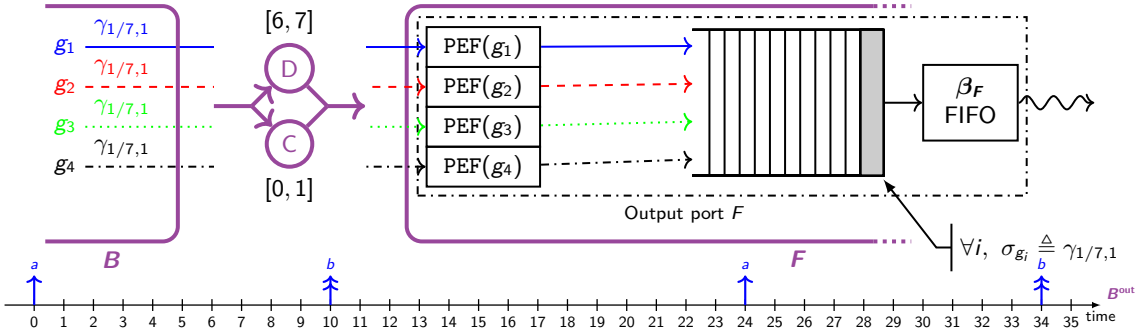

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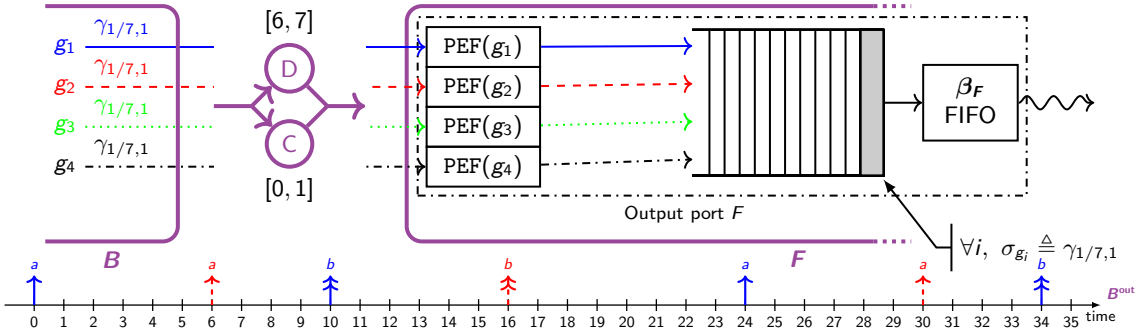

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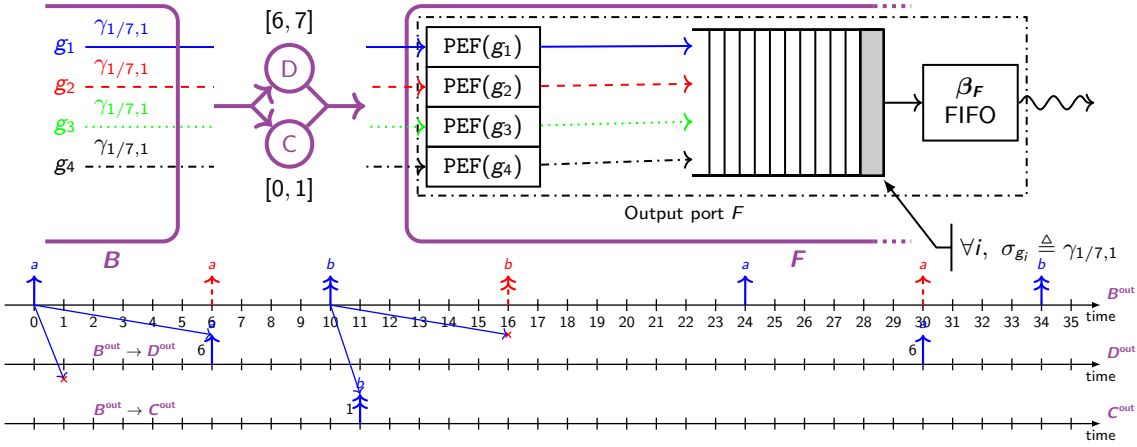

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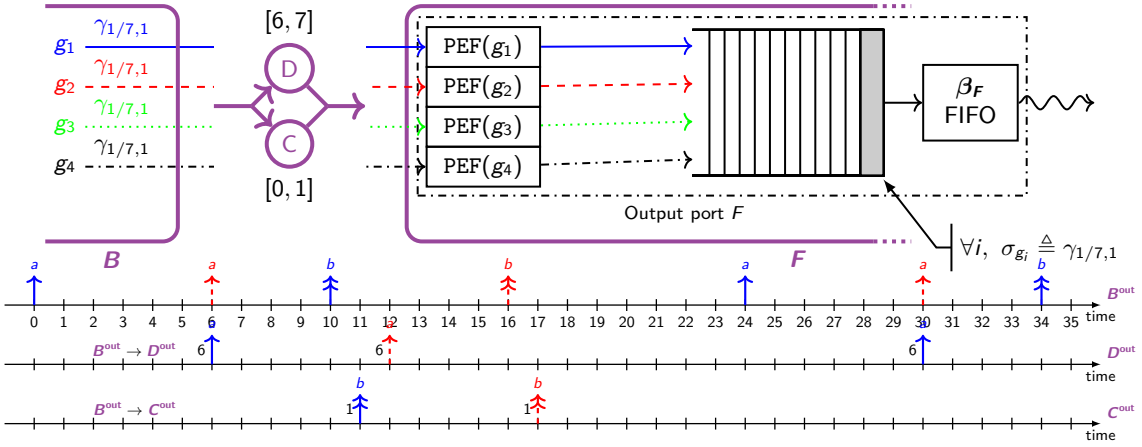

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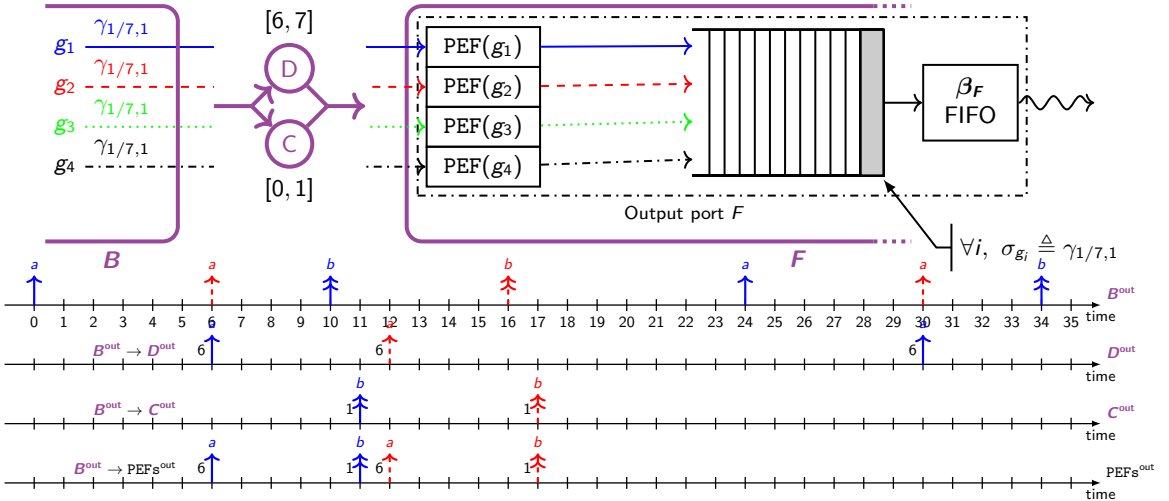

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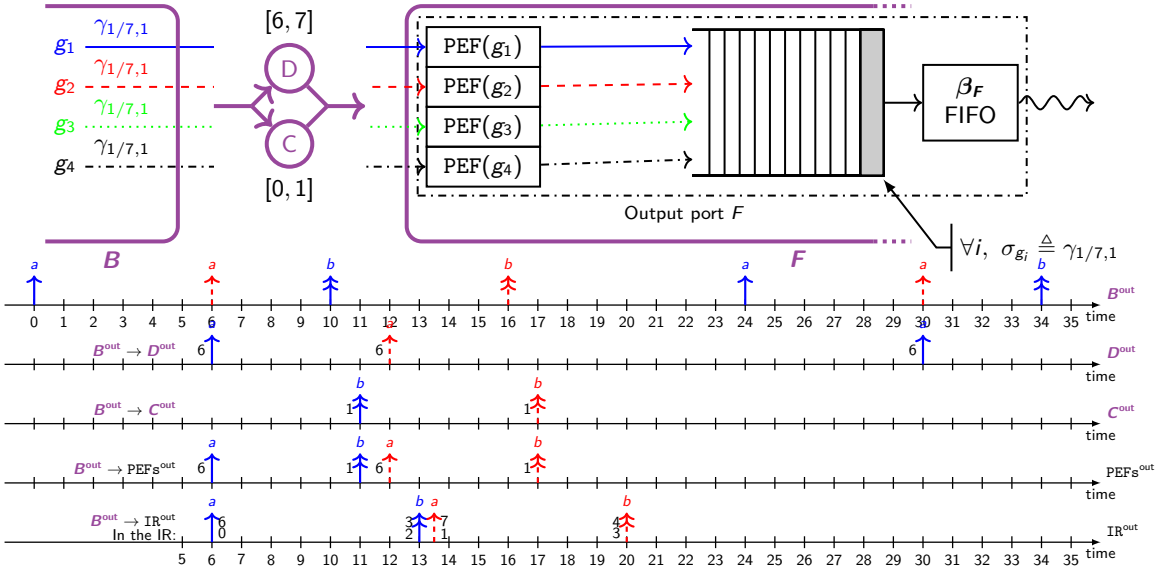

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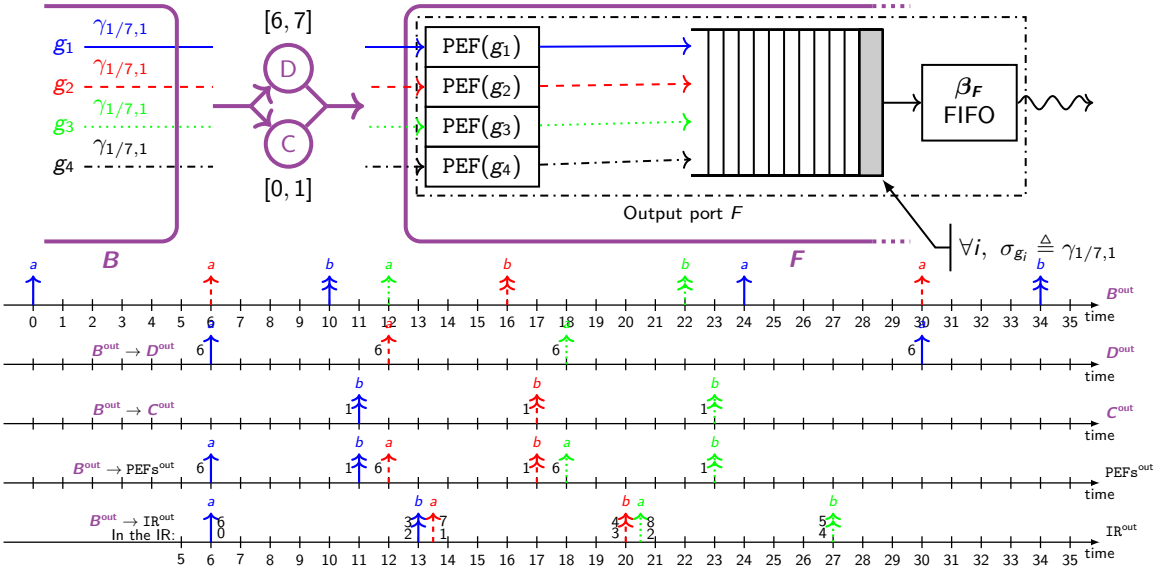

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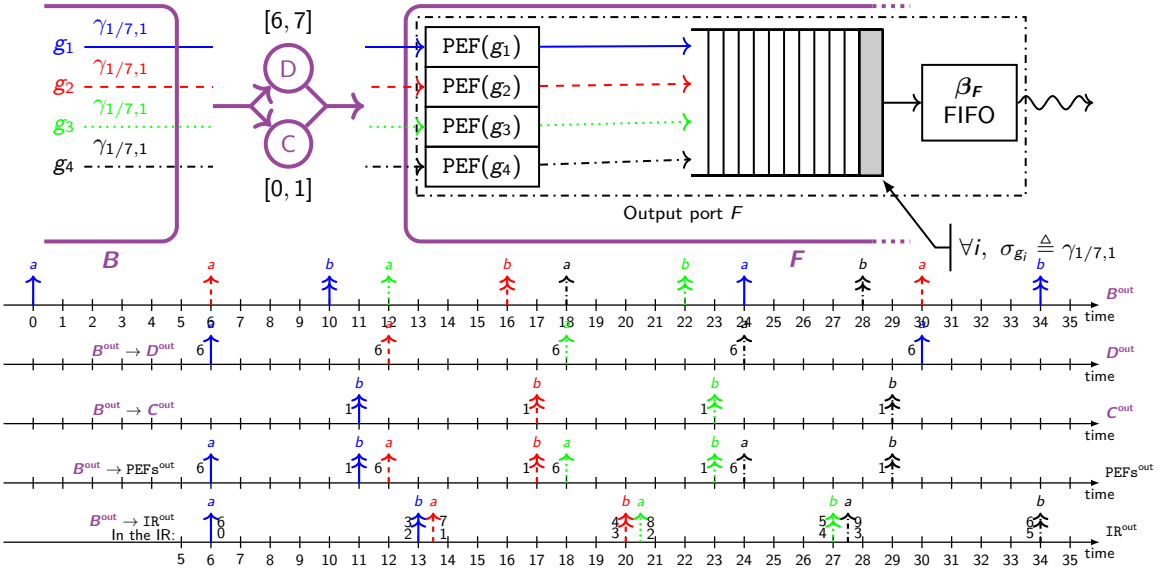

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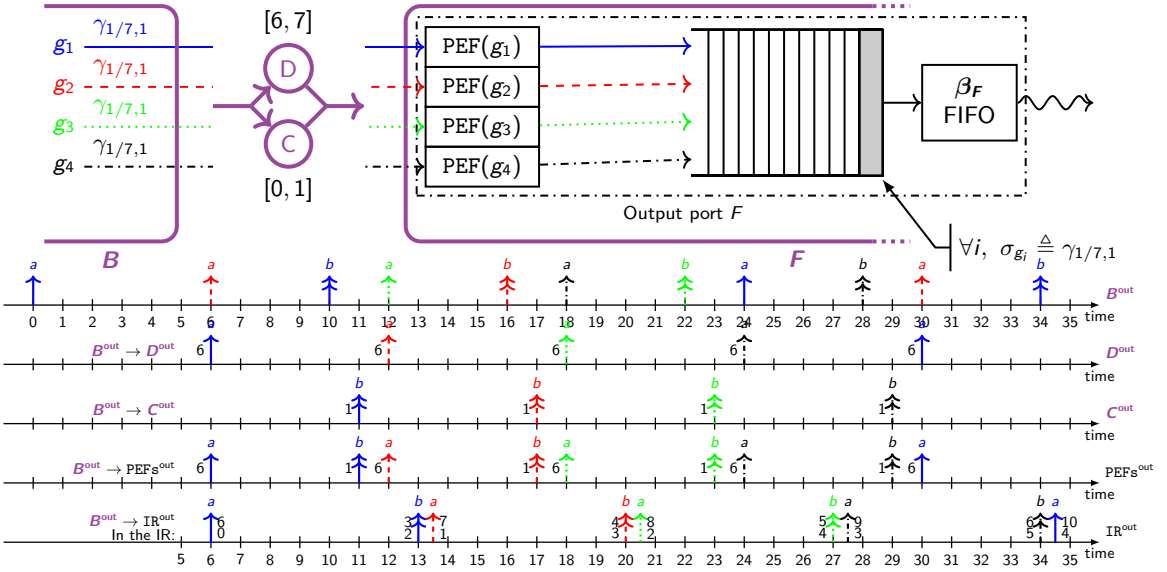

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- Output arrival curve, bound on the mis-ordering.

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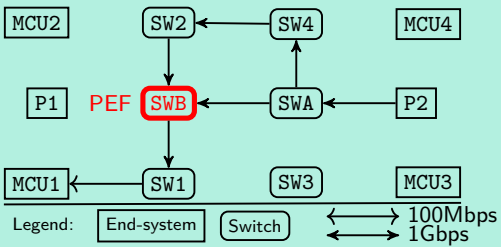
- Reordering prior to the regulator solves the issue (but only available in DetNet!)

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

Effect of IR (TSN ATS) On a Industrial Use-case with Redundancy Mechanisms

On the industrial use-case: focus on one path



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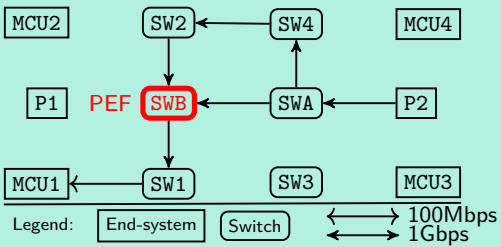

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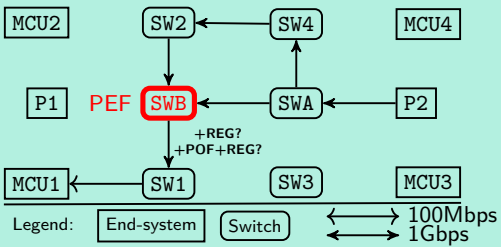

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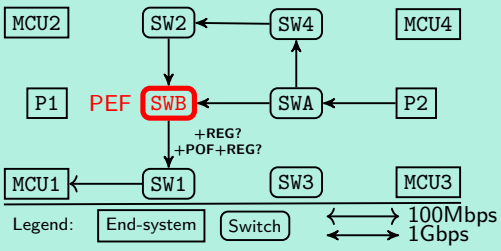

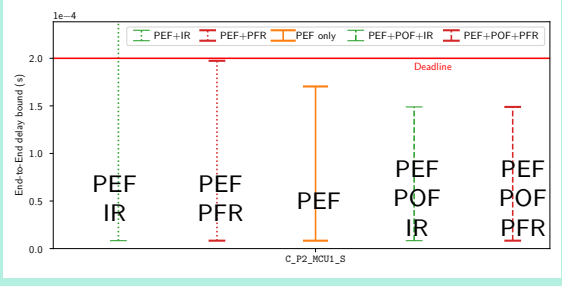

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Where is **TSN ATS** wrt to **TSN FRER** ?

The place of the Interleaved Regulator (IR) with respect to the PEF is not clear in TSN.

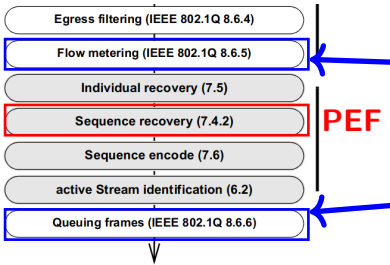

Figure: TSN FRER Pipeline [IEEE 802.1CB]

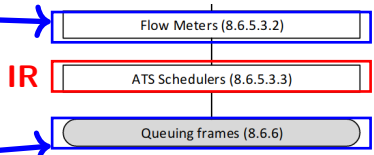

Figure: TSN ATS Pipeline (=Interleaved Regulator) [IEEE 802.1Qcr]