Network-Calculus Service Curves
of the
Interleaved Regulator

ITC 35th - Networked Systems and Services, Turin

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Time-Sensitive Networks

Public networks
(e.g., the Internet)

Time-Sensitive
Networks

Deterministic Service

Best-effort service

Bounded Latency

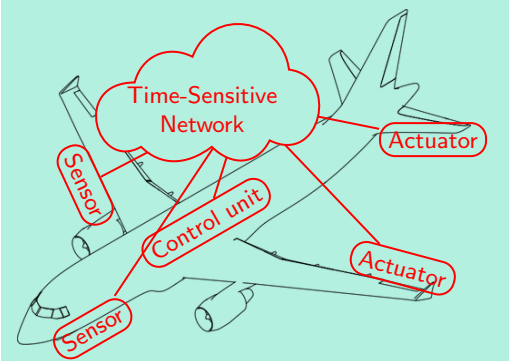
+ no loss
by congestion

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

Schedulers

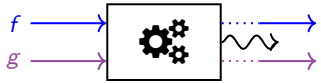
Traffic regulators (shapers)

Cyber-Physical Systems



Safety-critical applications

Schedulers: Distribute Access to a Resource



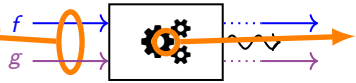
Output port
with a scheduler

Guaranteed delay/backlog bounds ?

Network Calculus: Model-Based Analysis

Arrival Curve α

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

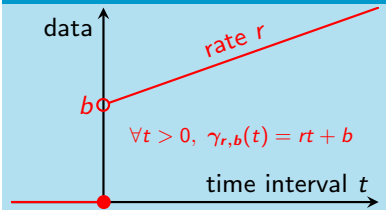


Output port with a scheduler

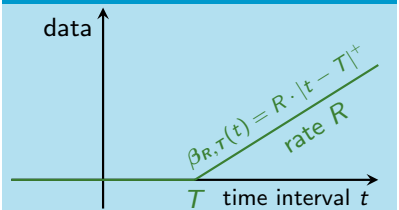
Service Curve β

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

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

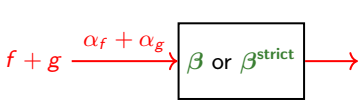


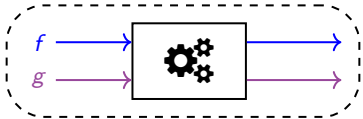
Rate-Latency $\beta_{R,T}$

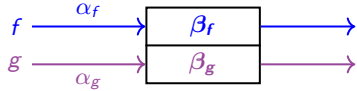


$|\cdot|^+ = \max(0, \cdot)$

Network Calculus: Provides **Worst-Case Delay Bounds**

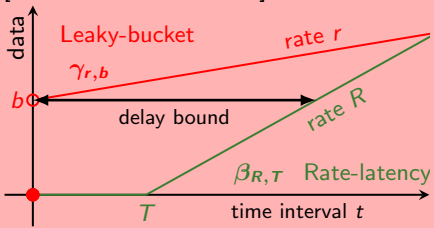






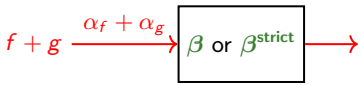
Network-calculus delay bound

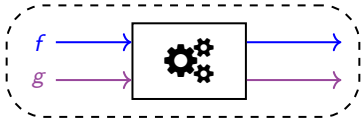
[Le Boudec, Thiran 2001]

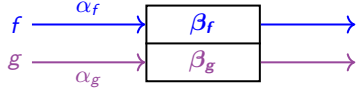


– [Le Boudec, Thiran 2001] Jean-Yves Le Boudec and Patrick Thiran [2001]. *Network Calculus*. Lecture Notes in Computer Science. Berlin, Heidelberg: Springer. DOI: 10.1007/3-540-45318-0

Network Calculus: Provides **Worst-Case Delay Bounds** of TSN networks

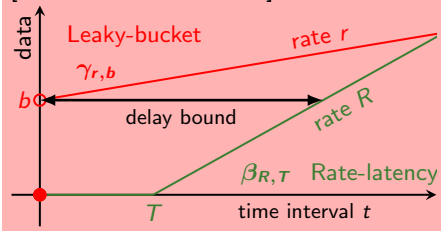






Network-calculus delay bound

[Le Boudec, Thiran 2001]



All IEEE TSN schedulers have a **Service-Curve Model** [Maile, Hielscher, German 2020].

$\Rightarrow$ A flexible, continuous, differentiable model.

$\Rightarrow$ Allows for optimization of schedulers' parameters, routing, etc. [Geyer, Bondorf 2022].

– [Maile, Hielscher, German 2020] Lisa Maile, Kai-Steffen Hielscher, and Reinhard German [May 2020]. "Network Calculus Results for TSN: An Introduction". In: *2020 Information Communication Technologies Conference (ICTC)*. DOI: 10.1109/ICTC49638.2020.9123308

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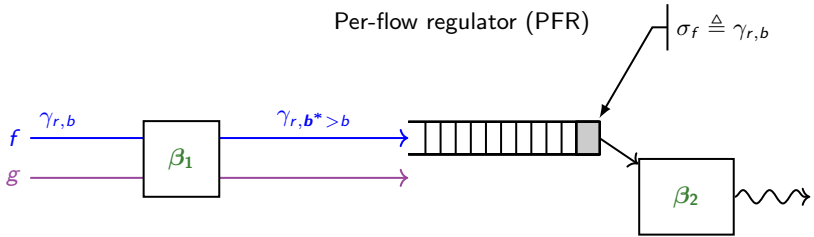
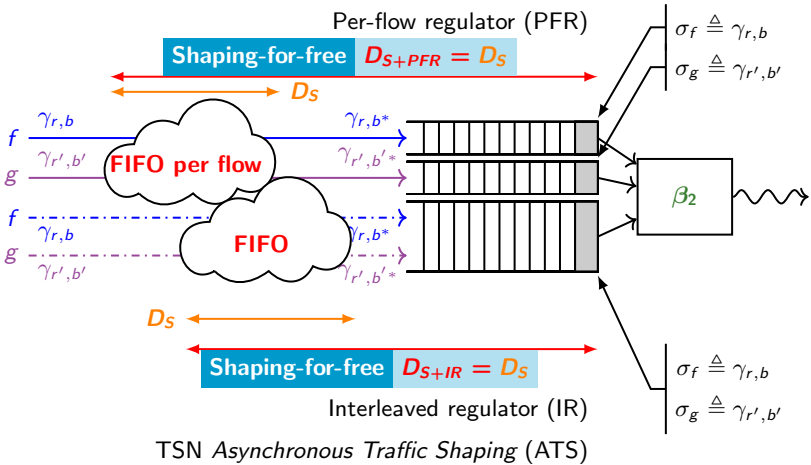
Traffic Regulators: Allow for a Per-Flow Control

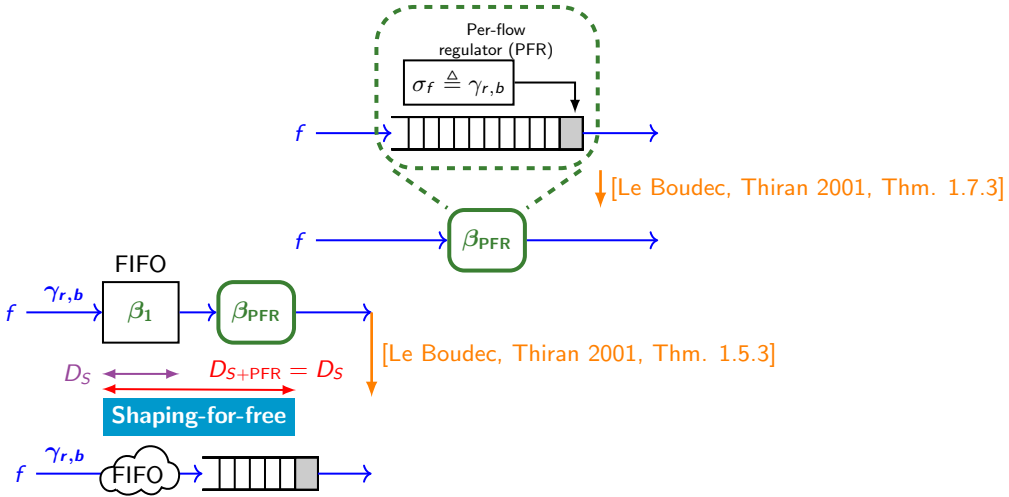


Traffic Regulators: Allow for a Per-Flow Control



FIFO: First In, First Out

The Per-Flow Regulator (PFR) has a **Service-Curve Model**



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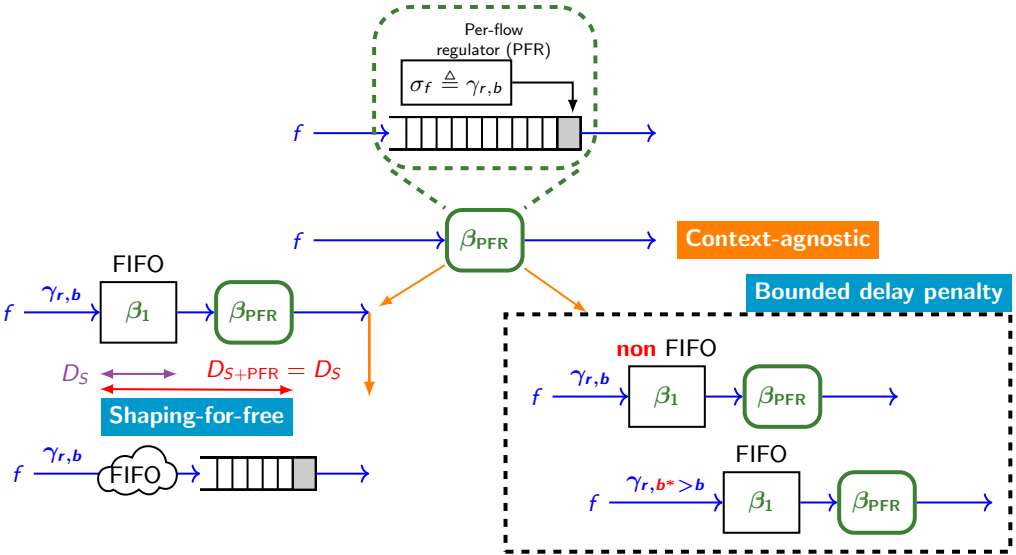
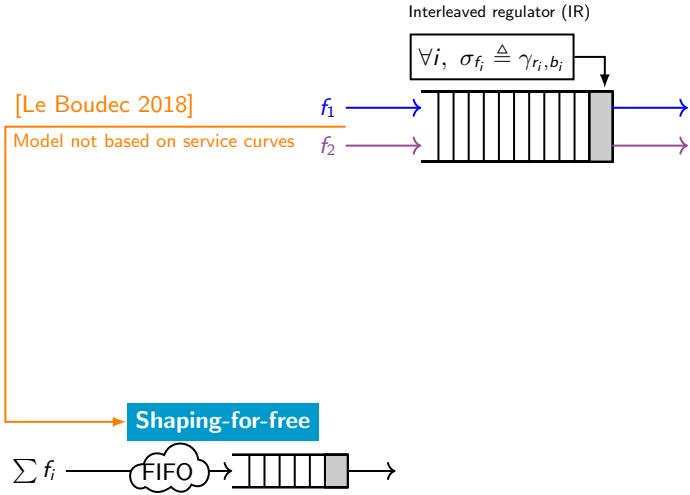
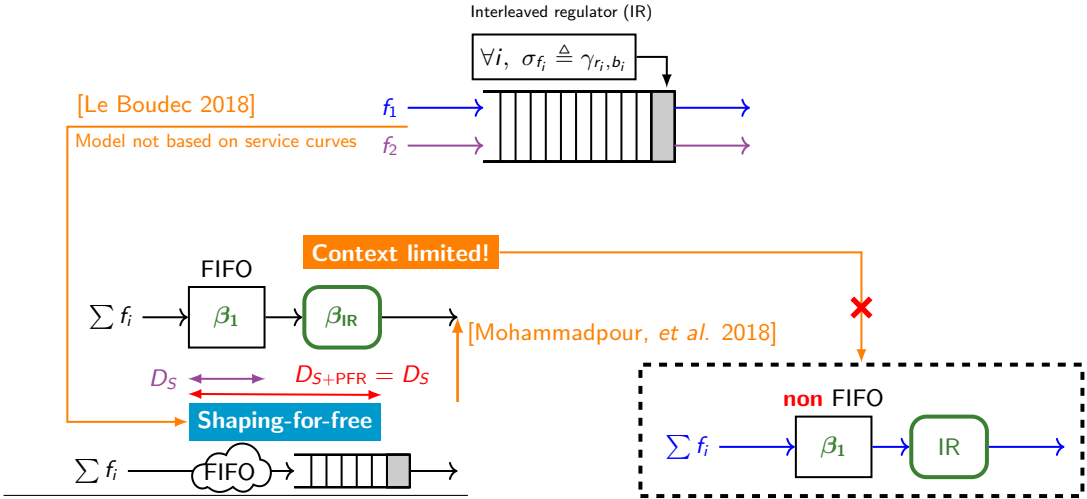
The Per-Flow Regulator (PFR) has a **Service-Curve Model**





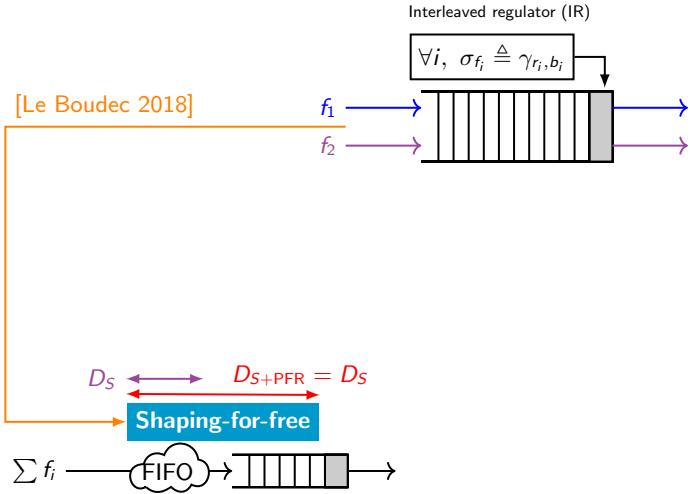
– [Le Boudec 2018] Jean-Yves Le Boudec [Dec. 2018]. "A Theory of Traffic Regulators for Deterministic Networks With Application to Interleaved Regulators". In: *IEEE/ACM Transactions on Networking* 6. DOI: 10.1109/TNET.2018.2875191

The Only Know Service-Curves for the Interleaved Regulator are **Context Limited**

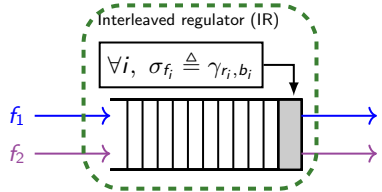


– [Mohammadpour, *et al.* 2018] Ehsan Mohammadpour, Eleni Stai, Maaz Mohiuddin, and Jean-Yves Le Boudec [Sept. 2018]. "Latency and Backlog Bounds in Time-Sensitive Networking with Credit Based Shapers and Asynchronous Traffic Shaping". In: *2018 30th International Teletraffic Congress (ITC 30)*. DOI: 10.1109/ITC30.2018.10053

The **Quest for a Service-Curve Model** for the Interleaved Regulator (IR)



The **Quest for a Service-Curve Model** for the Interleaved Regulator (IR)



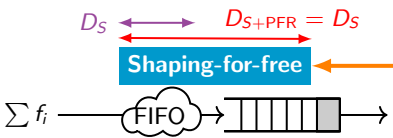
Question

Does the IR provide any context-agnostic service curves?

[Hamscher 2022]

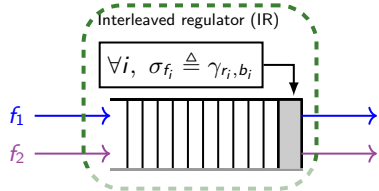
Question

Does any of them explain the shaping-for-free?



– [Hamscher 2022] Anja Hamscher [Sept. 9, 2022]. "Using Mathematical Programming to Harden Conjectures on Service Curves". [Lausanne, Switzerland]

Outline



Question 2

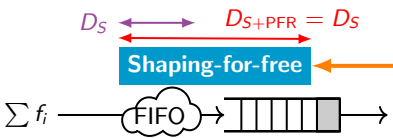
Does the IR provide any context-agnostic service curves?

Question 1

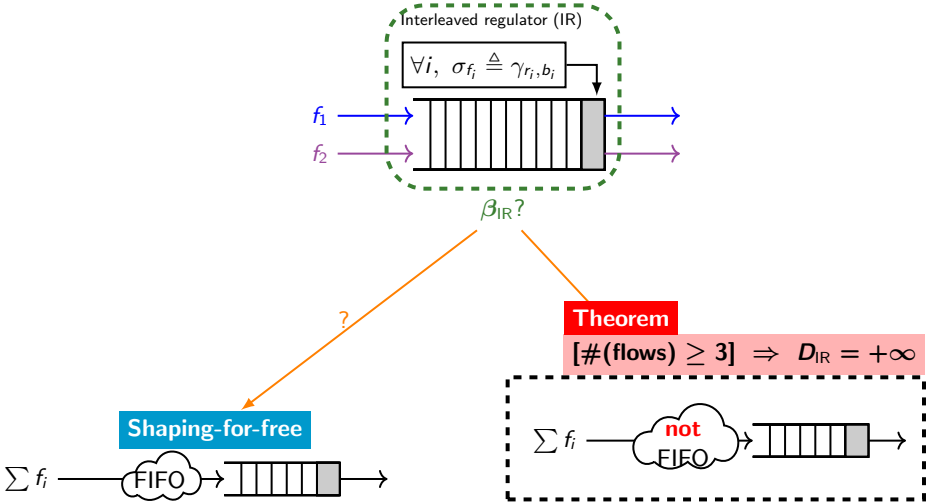
Does any of them explain the shaping-for-free?

Theorem

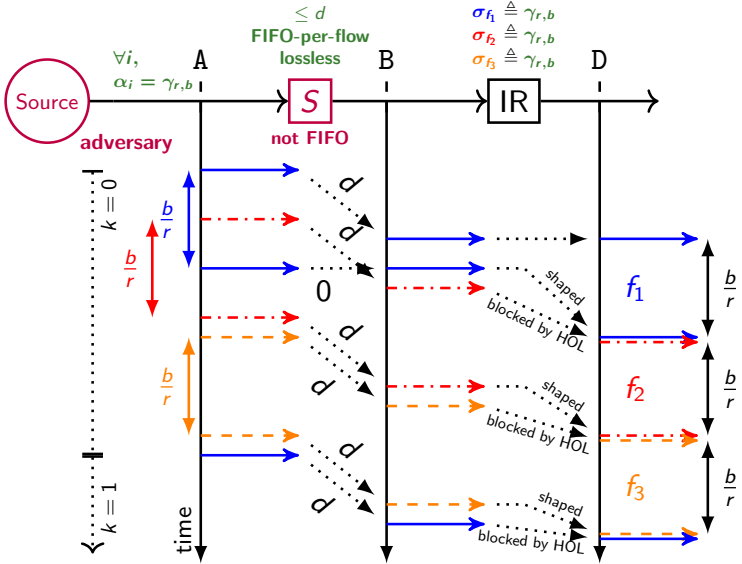
No



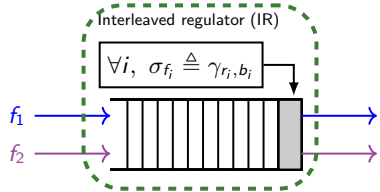
Can a Context-Agnostic Service Curve Explain the IR's Shaping-for-free?



Interleaved Regulator (IR) after non-FIFO: An **Adversarial Traffic Generation**



Context-agnostic Service Curves of the IR



Question 2

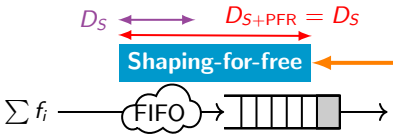
Does the IR provide any context-agnostic service curves?

Question 1

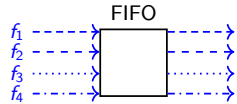
Does any of them explain the shaping-for-free?

Theorem

No



Some Properties of **FIFO Systems'** Service Curves



Type of service curve

Strict service curve β^{strict}

implies [Le Boudec, Thiran 2001, Prop. 1.3.5]

Service curve β

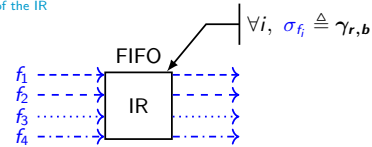
derives [Le Boudec, Thiran 2001, Prop. 6.4.1]

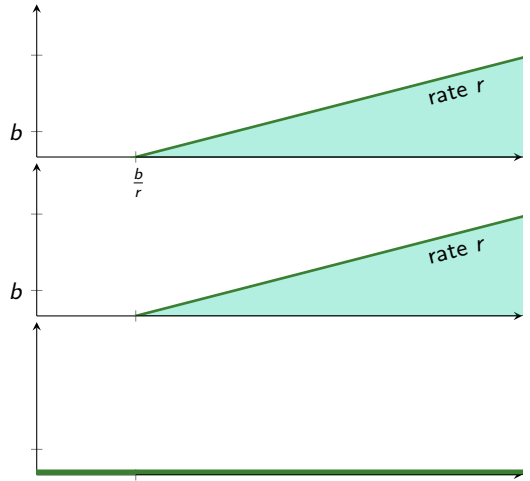
Individual service curve β_{f_1}

– [Le Boudec, Thiran 2001] Jean-Yves Le Boudec and Patrick Thiran [2001]. *Network Calculus*. Lecture Notes in Computer Science. Berlin, Heidelberg: Springer. DOI: 10.1007/3-540-45318-0

Service Curves of the Interleaved Regulator (IR)

Type of service curve	Curve exhibited in our paper
Strict service curve β^{strict}	$\beta_{r,\frac{b}{r}}$ ← Model from [Boyer 2022]
implies ↓	↓
Service curve β	$\beta_{r,\frac{b}{r}}$
derives ↓	↓
Individual service curve β_{f_1}	None $(t \mapsto 0)$



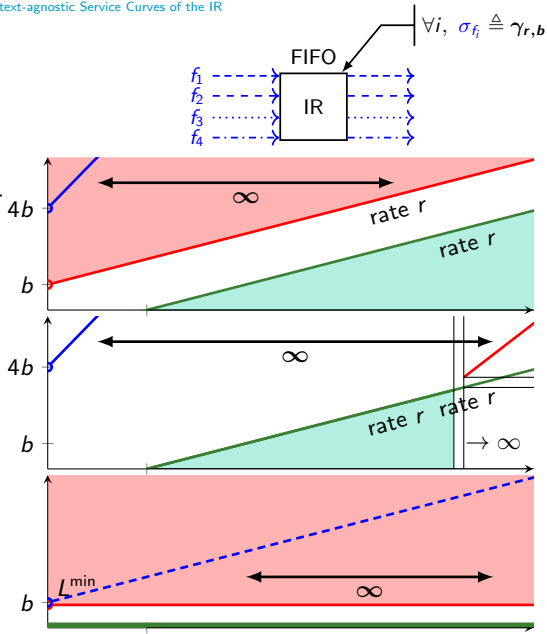


– [Boyer 2022] Marc Boyer [Sept. 2022]. "Equivalence between the Theoretical Model and the Standard Algorithm of Asynchronous Traffic Shaping".

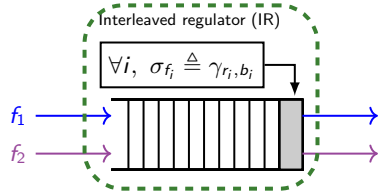
Service Curves of the Interleaved Regulator

Type of service curve	Curve exhibited in our paper	Limit
Strict service curve β^{strict}	$\beta_{r,\frac{b}{r}}$	$\forall t \geq 0,\ \beta^{\text{strict}}(t) \leq rt + b$
implies ↓	Additional argument	
Service curve β	$\beta_{r,\frac{b}{r}}$	$\liminf_{t\to+\infty} \frac{\beta(t)}{t} \leq 3r$
derives ↓		
Individual service curve β_{f_1}	None $(t \mapsto 0)$	$\forall t \geq 0,\ \beta_{f_1}(t) \leq L_{\min}$

Thm: Instability of the IR after a non-FIFO system

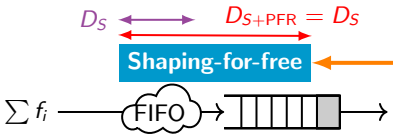


Conclusion



Question 2	Theorem(s)
Does the IR provide any context-agnostic service curves?	Yes but not helpful

Question 1	Theorem
Does any of them explain the shaping-for-free?	No



Conclusion

Summary of our contributions

- The Interleaved Regulator (IR) **can yield unbounded latencies** when placed after a non-FIFO system.
- As a consequence, **no context-agnostic service curve can explain** the shaping-for-free property of the IR.
- Drastically reduced the "grey" zone of possible service curves for the IR.

Perspectives

- Concludes the IR's service-curve quest.
- The IR's implementation inside TSN (*Asynchronous Traffic Shaping*) suffers a change-or-perish risk.

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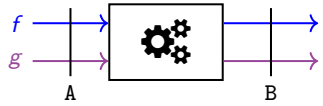
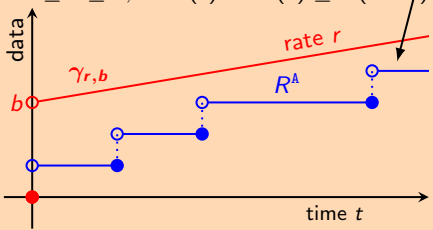
Arrival Curve and **Strict Service Curve**: Formal definitions



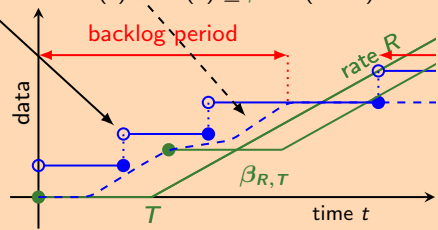
Arrival Curve α

$\forall t \geq s \geq 0, \quad R^{\mathrm{A}}(t) - R^{\mathrm{A}}(s) \leq \alpha(t-s)$

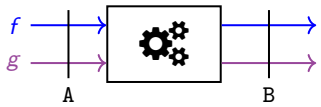


Strict Service Curve β^{strict}

$\forall]s,t] \in$ backlog period,
$R^{\mathrm{B}}(t) - R^{\mathrm{B}}(s) \geq \beta^{\mathrm{strict}}(t-s)$



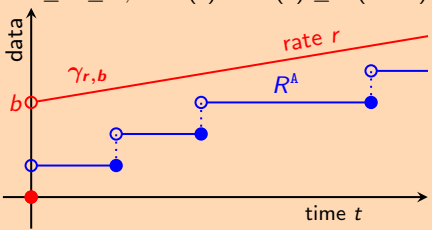
Arrival Curve and **Service Curve**: Formal definitions



min-plus convolution

Arrival Curve α

$\forall t \geq s \geq 0, \quad R^{\mathrm{A}}(t) - R^{\mathrm{A}}(s) \leq \alpha(t-s)$



Service curve β

$\forall t \geq 0, \quad R^{\mathrm{B}}(t) \geq (R^{\mathrm{A}} \otimes \beta)(t)$

$\geq \inf_{s \leq t} R^{\mathrm{A}}(t) + \beta(t-s)$