On Time Synchronization Issues in Time-Sensitive Networks with Regulators and Nonideal Clocks

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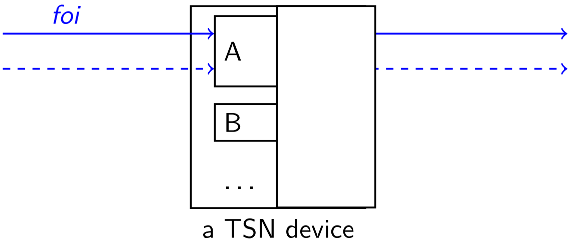
5th Workshop on Network Calculus
9 October 2020

TSN: Class-based schedulers. FIFO-per-class.



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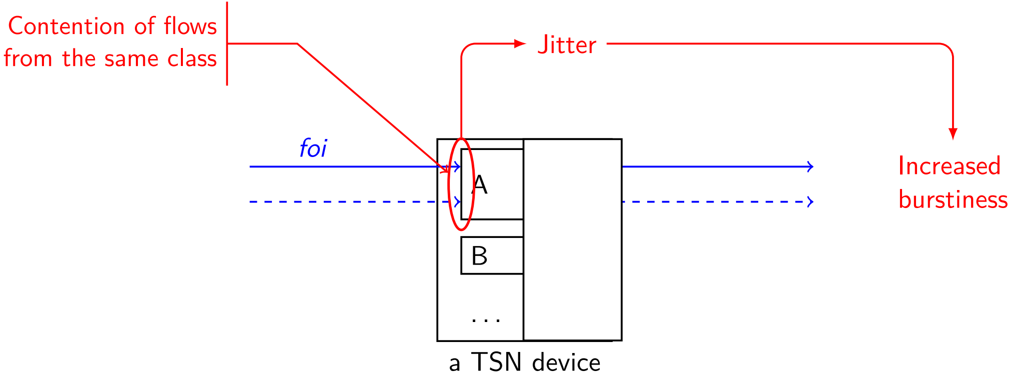

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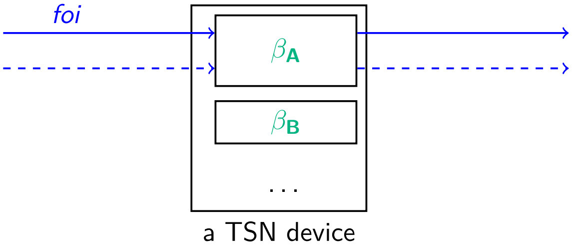
With Network Calculus (e.g. TFA [Schmitt and Zdarsky, 2006]):



TFA = Total Flow Analysis.

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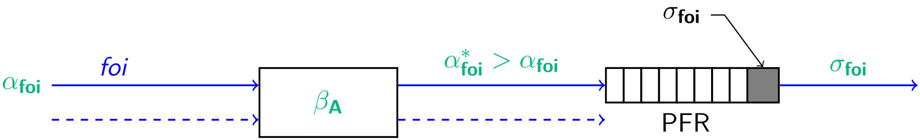
TFA = Total Flow Analysis.

Traffic Shaping with a Per-Flow Regulator (PFR)

also called Packetized Greedy Shaper [Le Boudec and Thiran, 2001, Definition 1.7.6].



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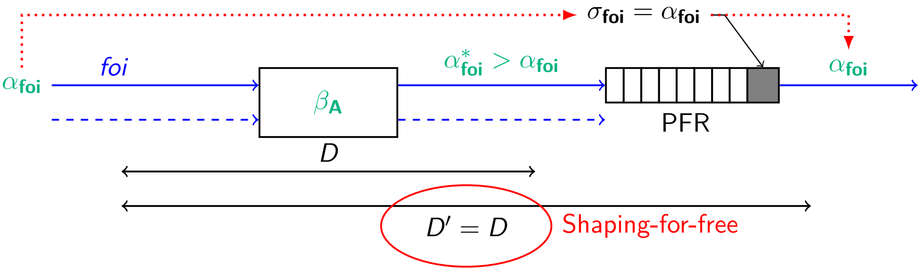
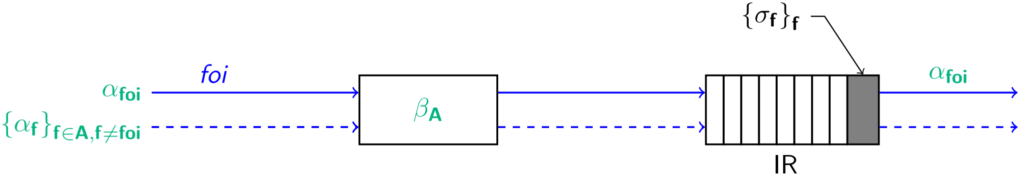


Traffic Shaping with an Interleaved Regulator (IR)

[Specht and Samii, 2016, Le Boudec, 2018]



Traffic Shaping with an Interleaved Regulator (IR)

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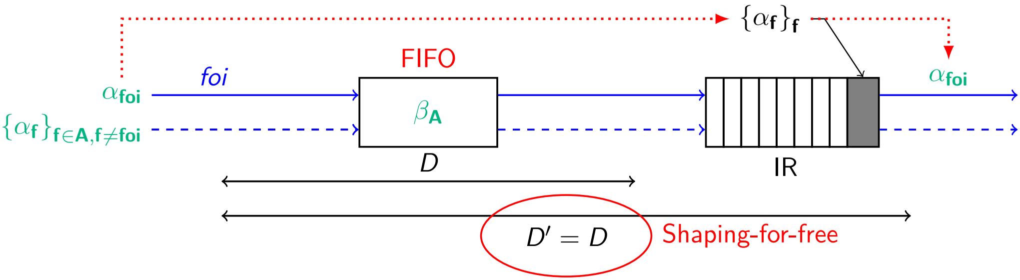

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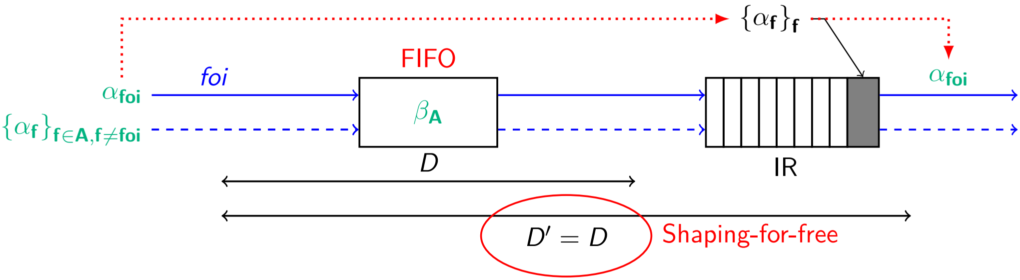
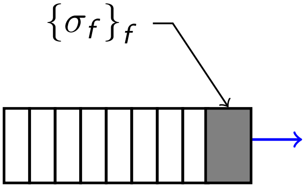


TSN Asynchronous Traffic Shaping (ATS) [IEEE, 2019] reproduces the IR in TSN.

Regulators measure **elapsed time**



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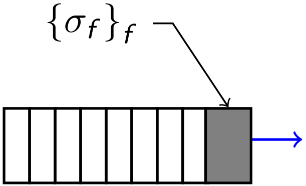
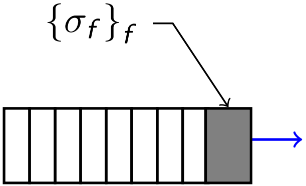


$$\forall f, \forall t, \forall s, \quad R^*(t+s) - R^*(t) \leq \sigma_f(s)$$

Regulators measure **elapsed time**



$$\forall f, \forall t, \forall s, \quad R^*(t+s) - R^*(t) \leq \sigma_f(s)$$

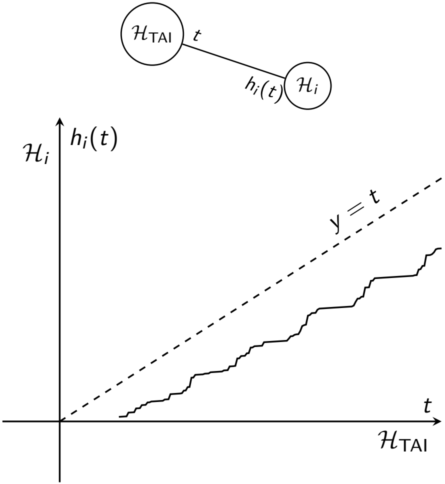
- Discussions in TSN ATS (Asynchronous Traffic Shaping) [IEEE, 2019].
- In doi:10.1145/3392145: theoretical foundations to address the problem.

Contributions

- **Time model** for $\left\{\begin{matrix}\text{non-synchronized} \\ \text{synchronized}\end{matrix}\right\}$ networks.
- A toolbox of **Network Calculus** results for $\left\{\begin{matrix}\text{non-synchronized} \\ \text{synchronized}\end{matrix}\right\}$ networks.
- Analysis of regulators $\left\{\begin{matrix}\text{PFR} \\ \text{IR}\end{matrix}\right\}$ in $\left\{\begin{matrix}\text{non-synchronized} \\ \text{synchronized}\end{matrix}\right\}$ networks.

Model for non-synchronized clocks

Definitions and terminology for synchronization networks [ITU, 1996]



$$h_i(t) - t = x_{i,0} + t y_{i,0} + w(t) + \psi(t)$$

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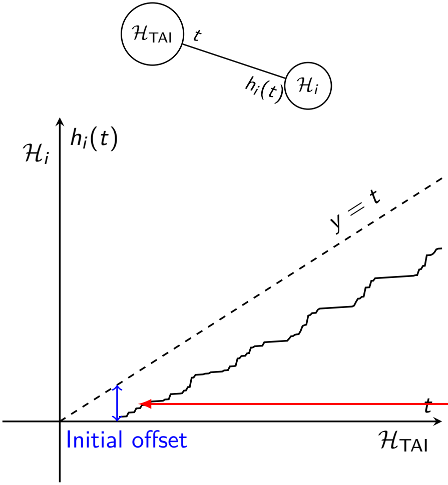

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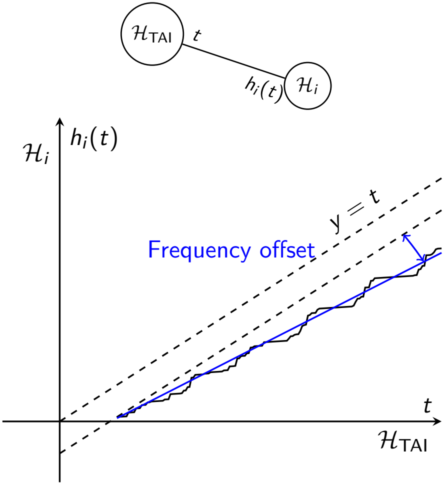

$$h_i(t) - t = x_{i,0} + ty_{i,0} + w(t) + \psi(t)$$

$\leq y_{\max} t$

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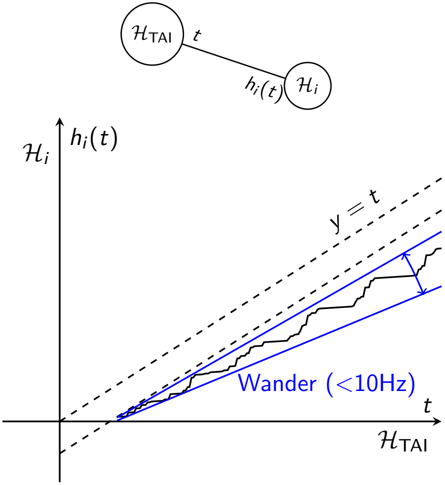

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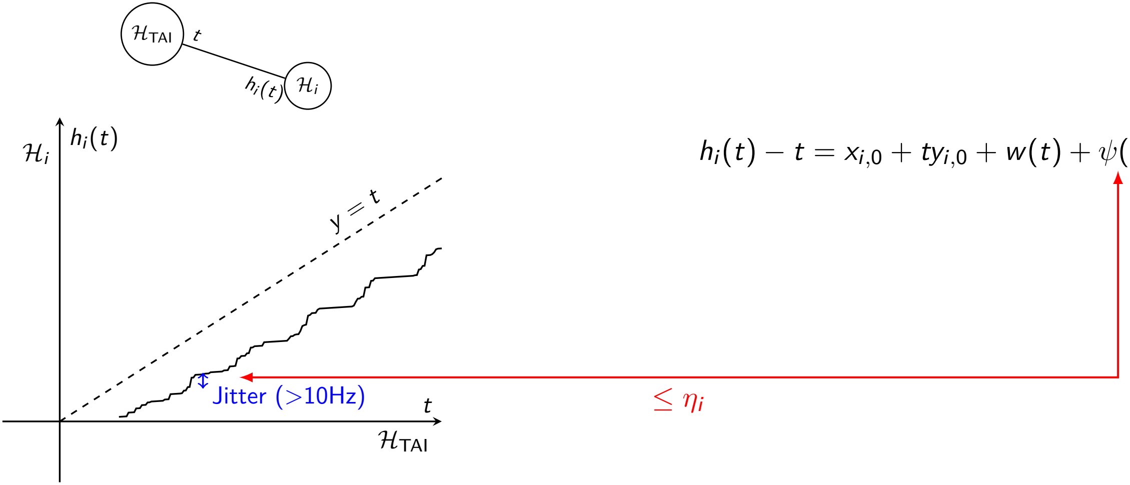

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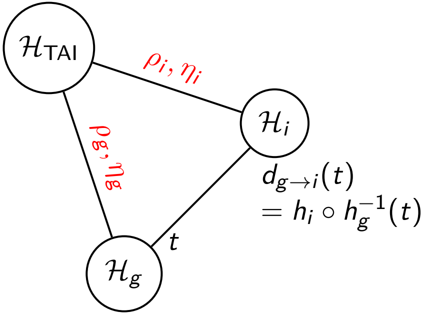

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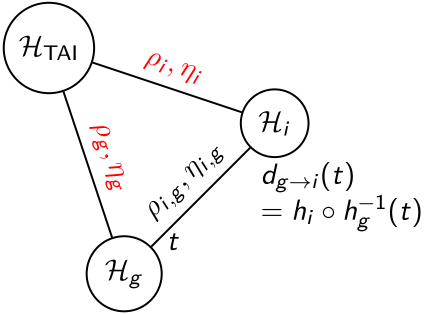

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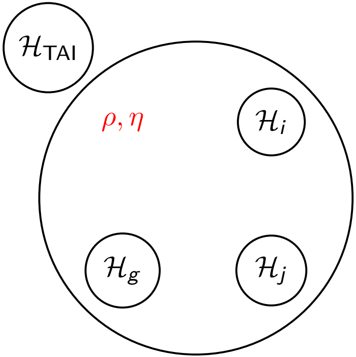
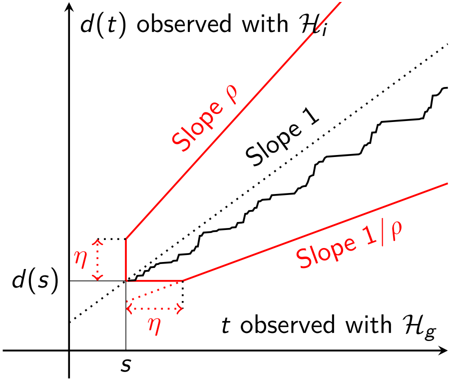


TSN: $\rho = 1 + 200ppm$
$\eta = 4ns$

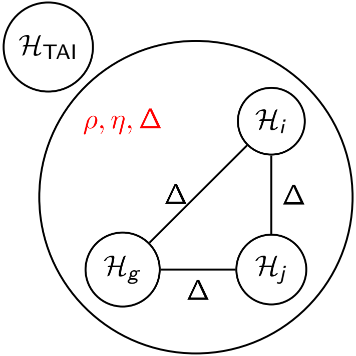
$\forall i, g$

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

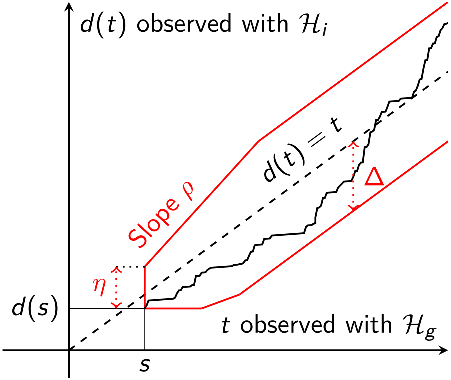


Model for synchronized clocks

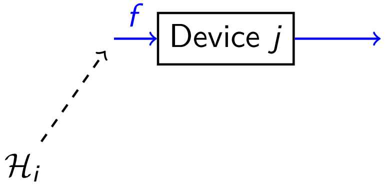
$$\forall i, g \quad \begin{cases} \frac{1}{\rho}(t - s - \eta) \leq d_{g\to i}(t) - d_{g\to i}(s) \leq (t-s)\rho + \eta \\ |d_{g\to i}(t) - t| \leq \Delta \end{cases}$$



TSN:$\Delta = 1\mu s$



Toolbox for changing the observing clock



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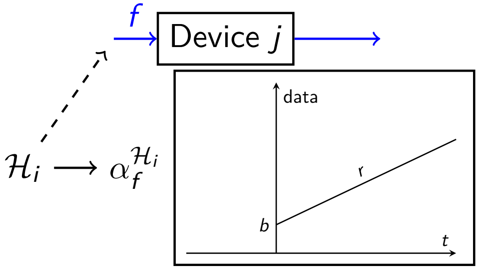

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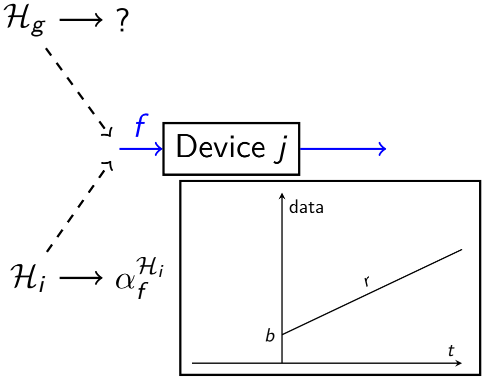
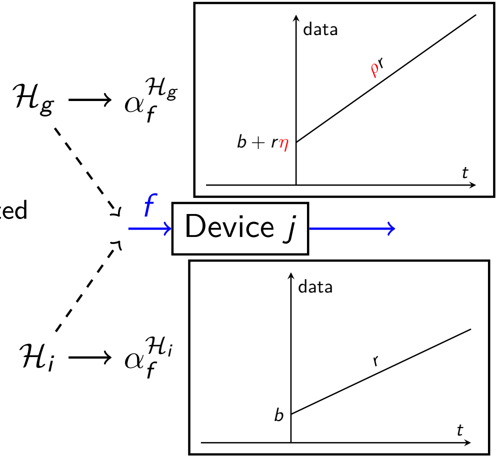


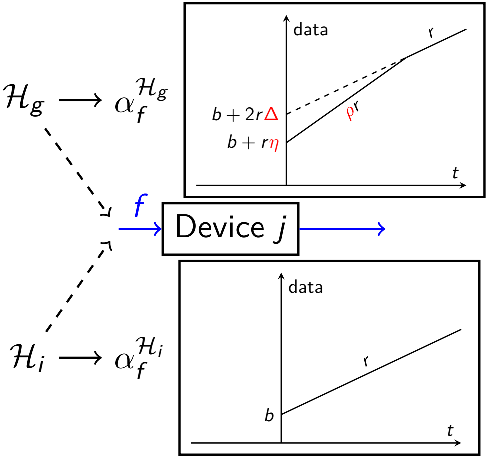
Toolbox for changing the observing clock

Non-synchronized
η, ρ



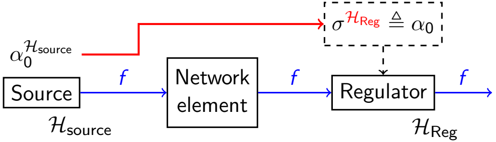
Toolbox for changing the observing clock

Synchronized
η, ρ, Δ



Instabilities with non-adapted regulators

Usual configuration of regulators
$=$ Non-adapted regulator



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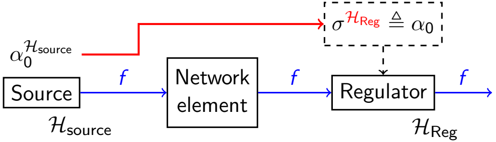

- Non-synchronized networks:

  Per-flow regulator
  Interleaved regulator
  } unstable

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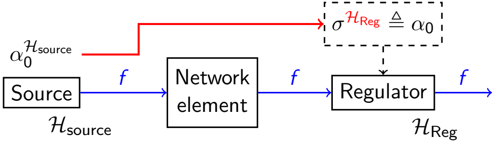


- Non-synchronized networks:

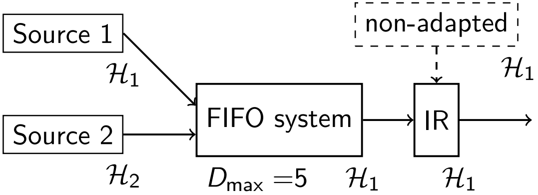
$$\left.\begin{array}{r}\text{Per-flow regulator}\\ \text{Interleaved regulator}\end{array}\right\}\text{unstable}$$

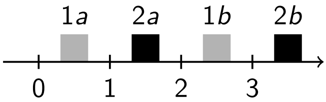
- Synchronized networks:

Per-flow regulator $\rightarrow$ penalty $[\Delta, 4\Delta]$

Interleaved regulator $\rightarrow$ **unstable** $\forall\Delta > 0$

Adversarial synchronized clocks for a non-adapted IR (=ATS) (1/3)





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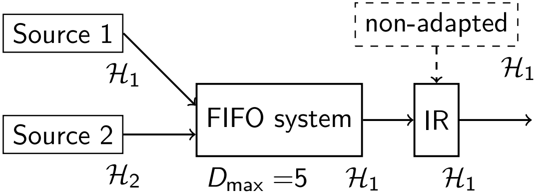
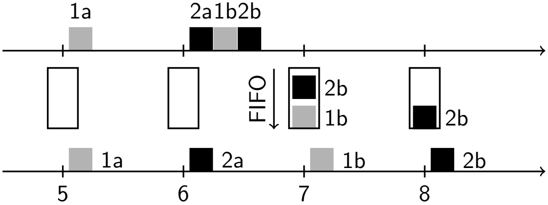
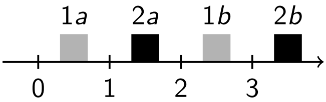
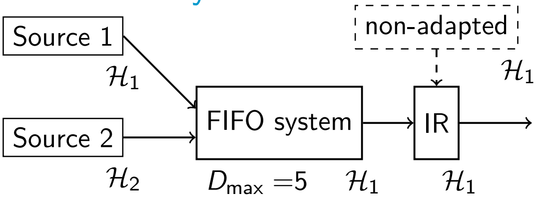
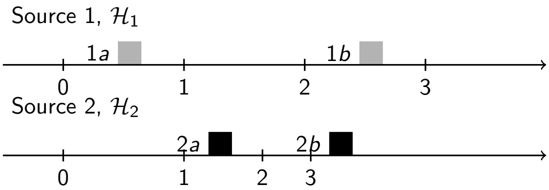




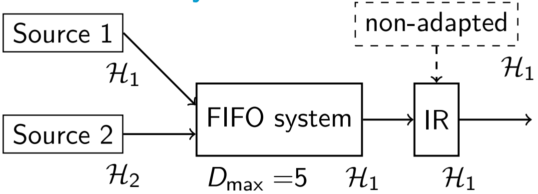


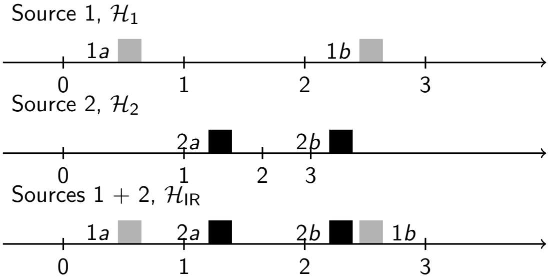
Adversarial synchronized clocks for a non-adapted IR (=ATS) (2/3)



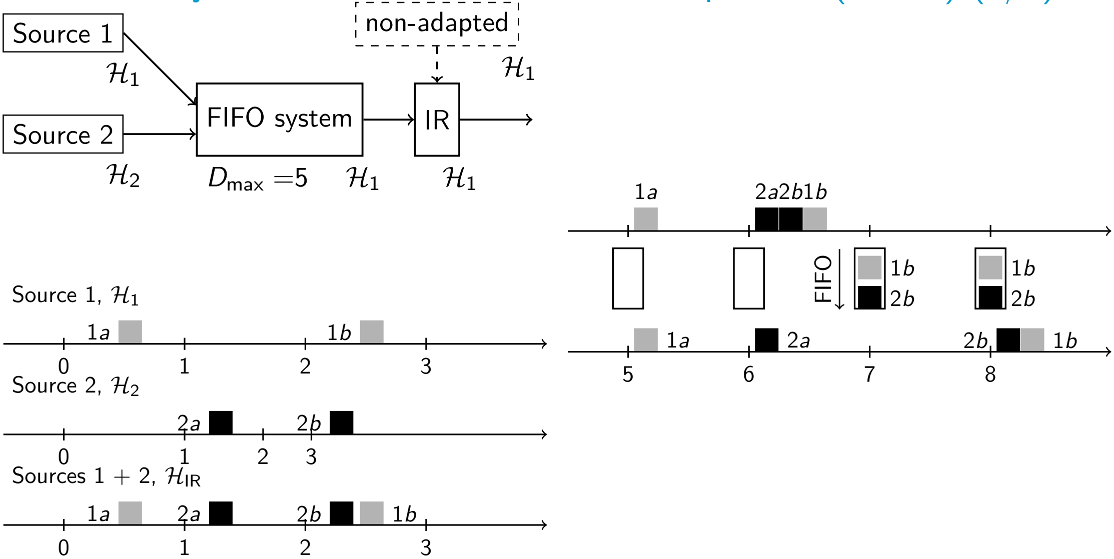


Adversarial synchronized clocks for a non-adapted IR (=ATS) (2/3)





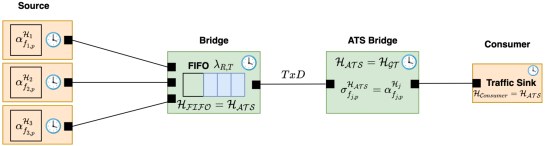
Adversarial synchronized clocks for a non-adapted IR (=ATS) (2/3)

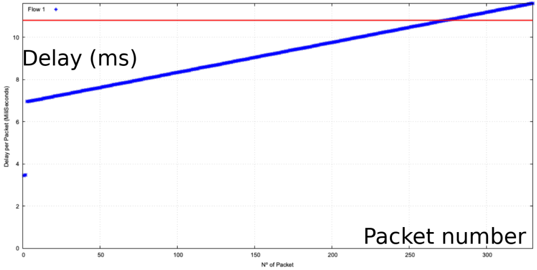


Adversarial synchronized clocks for a non-adapted IR (=ATS) (3/3)

Validation and extension through ns-3 simulations.

Example at low data rates:



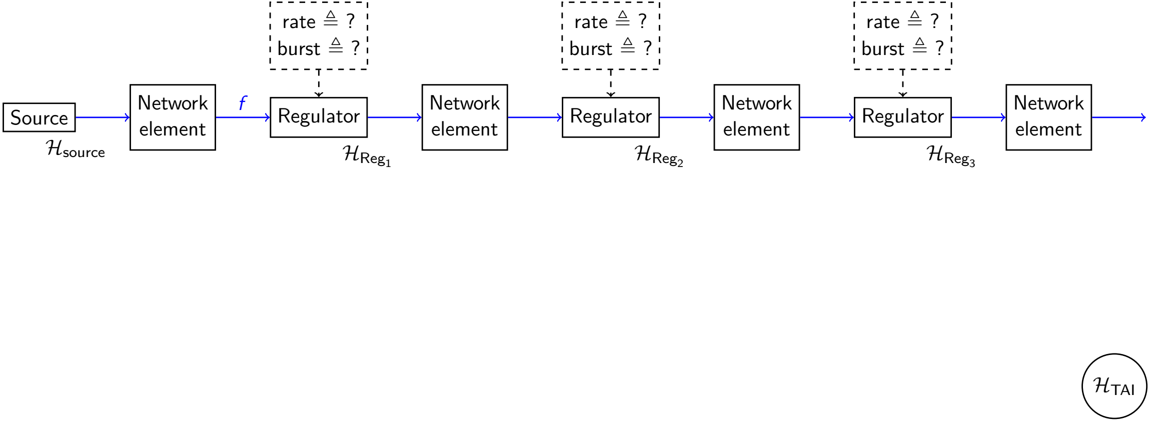


- 3 sources @ 147 kB/s
- 1 queuing element @ 437.5 kB/s
- Δ =1μs, ρ =1+100ppm
- using adversarial clocks
- $\Rightarrow$ red line is Network Calculus delay bound assuming perfect clocks

Work by Guillermo Aguirre

How to configure the regulators ?

assuming leaky-bucket-constrained flows $\forall$ flow f



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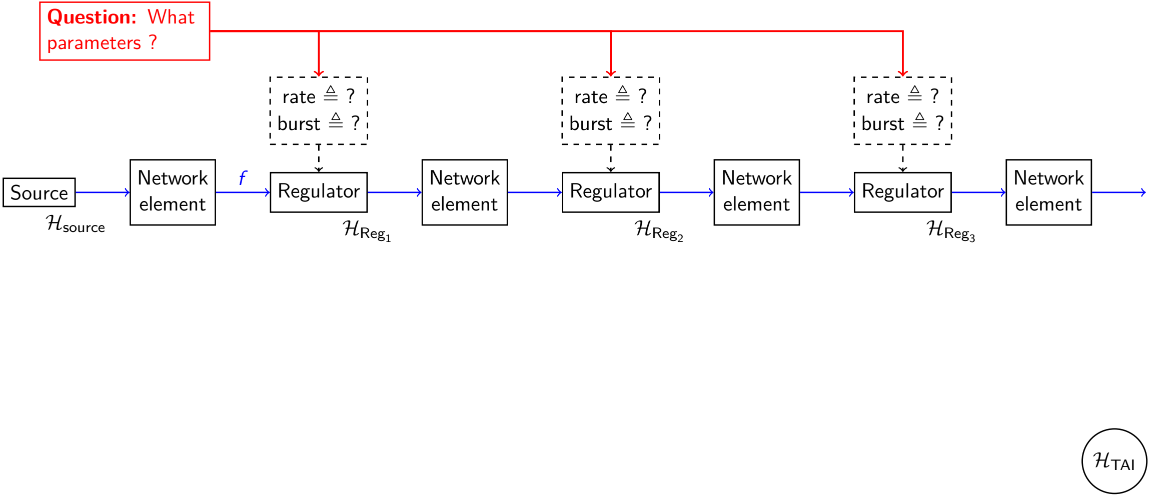

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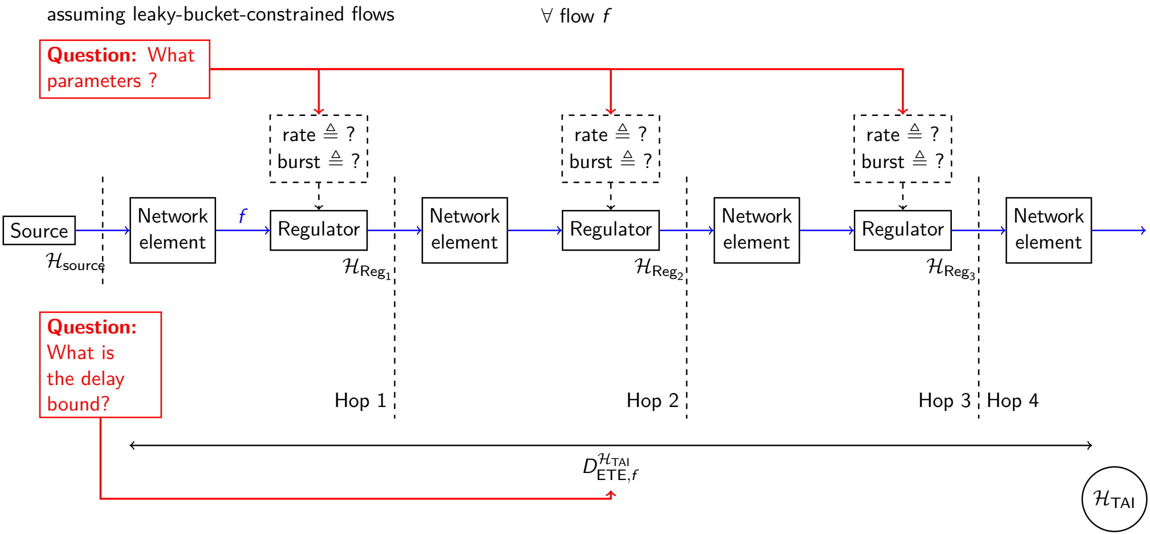
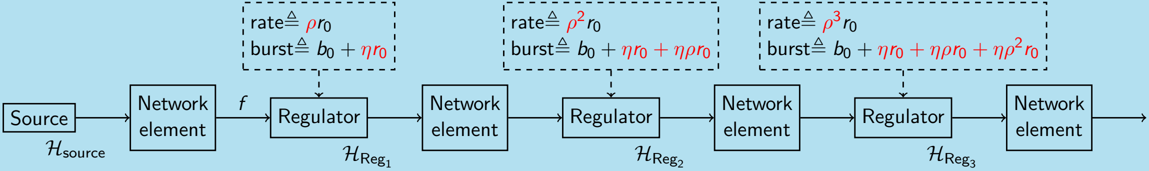


Two methods for synchronized and non-synchronized networks

Rate-and-burst cascade Works with PFR or IR



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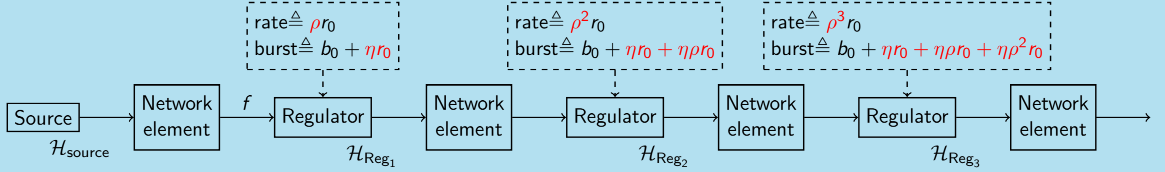
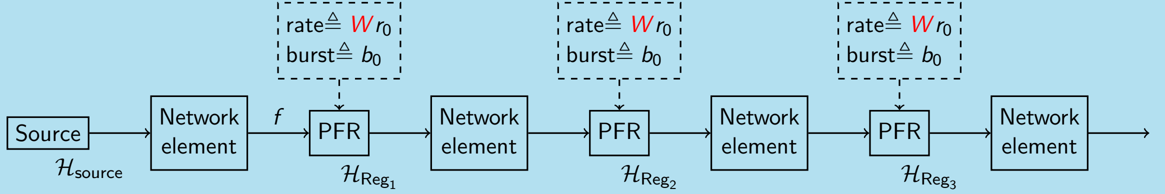
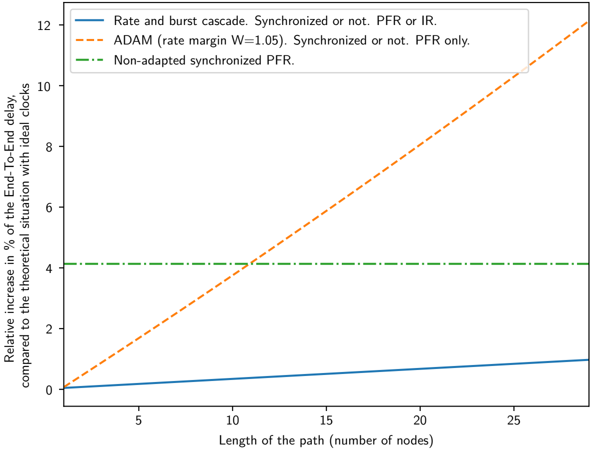


ADAM Works with PFR only



Performance comparison



Increase of the ETE delay bound wrt ideal clocks.

Conclusion

- **Time-model** for bounding the behavior of the clocks in the network.
- **Instability** of the non-adapted ATS regulator **for any** $\Delta > 0$.
- Two methods for **configuring the regulators** in a network, relying on a **Network Calculus toolbox**.

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Future work:

- Improvements on the ADAM method.
- Simulation of different (more realistic) clock models in ns-3.
- The toolbox could be of interest when studying other technologies / TSN components.

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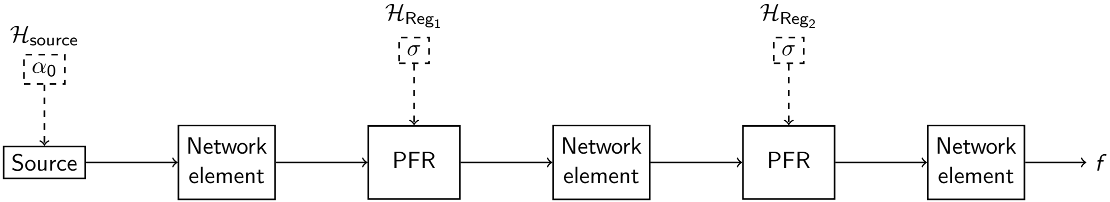
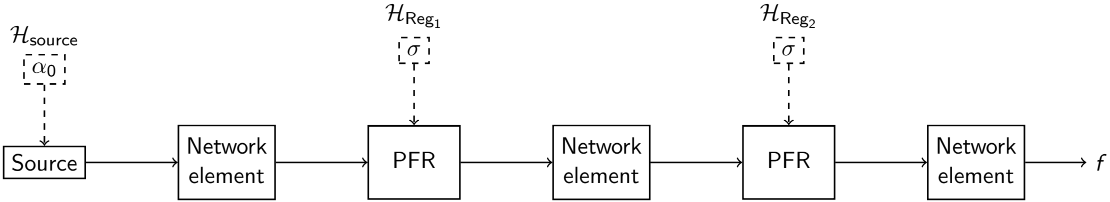
A quick look at ADAM



A quick look at ADAM

- Step 1 (per flow): arrival curve at each network element



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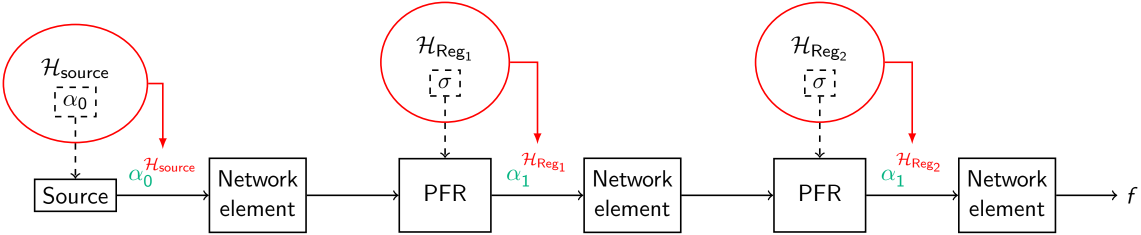
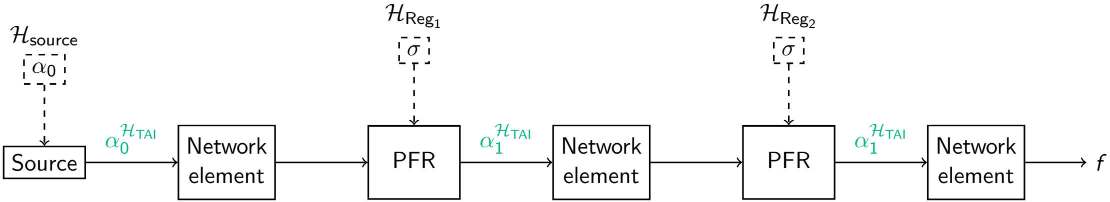


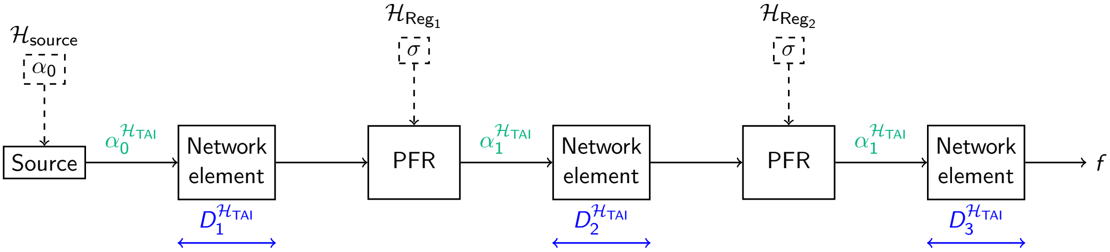
A quick look at ADAM

- Step 1 (per flow): arrival curve at each network element



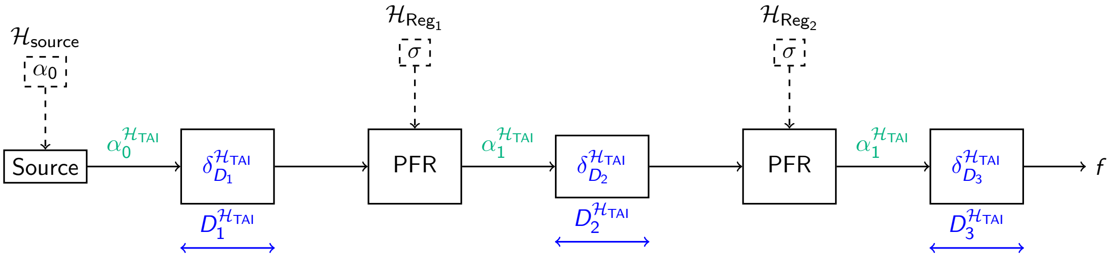
A quick look at ADAM

- Step 1 (per flow): arrival curve at each network element
- Step 2 (per node): compute delay bounds



A quick look at ADAM

- Step 1 (per flow): arrival curve at each network element
- Step 2 (per node): compute delay bounds
- Step 3 (per flow): service-curve characterization and end-to-end delay bound



A quick look at ADAM

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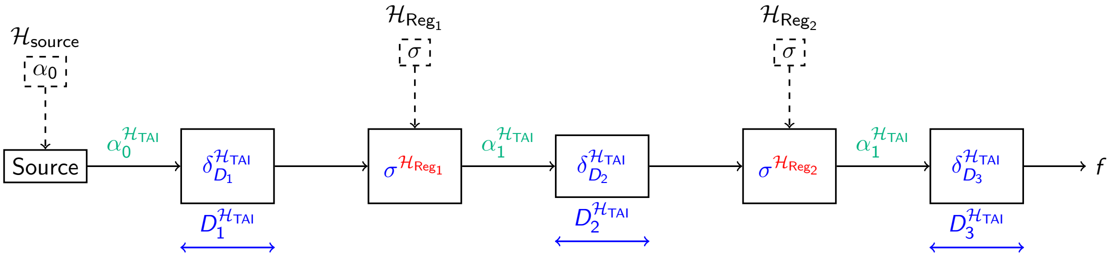

A quick look at ADAM

- Step 1 (per flow): arrival curve at each network element
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