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

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We focus on **time-sensitive networks**

- IEEE TSN
- IETF Detnet

} **Goals:**

- Bounded latency
- No losses

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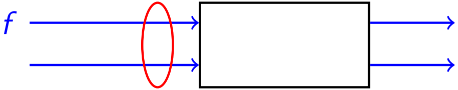
FIFO per class



Class-based network element

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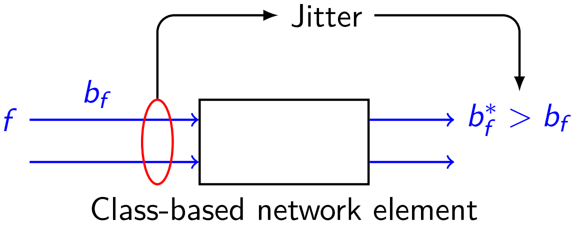
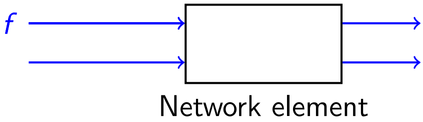


Time sensitive networks: analysis with **Network Calculus**



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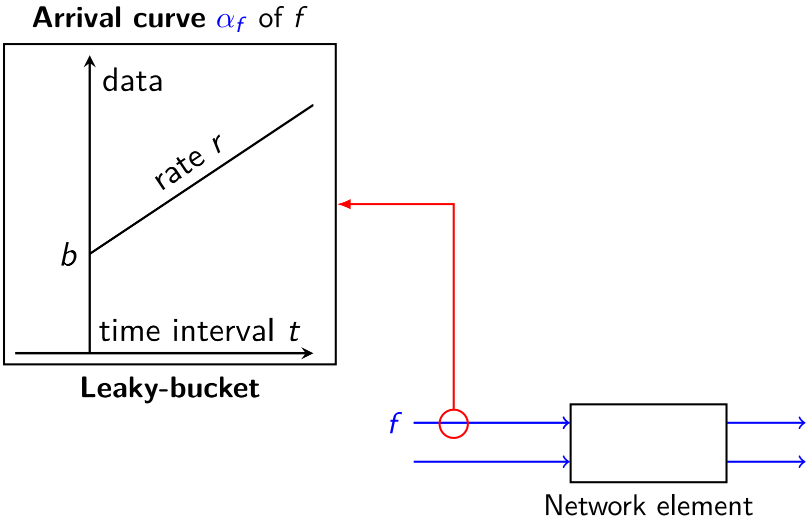

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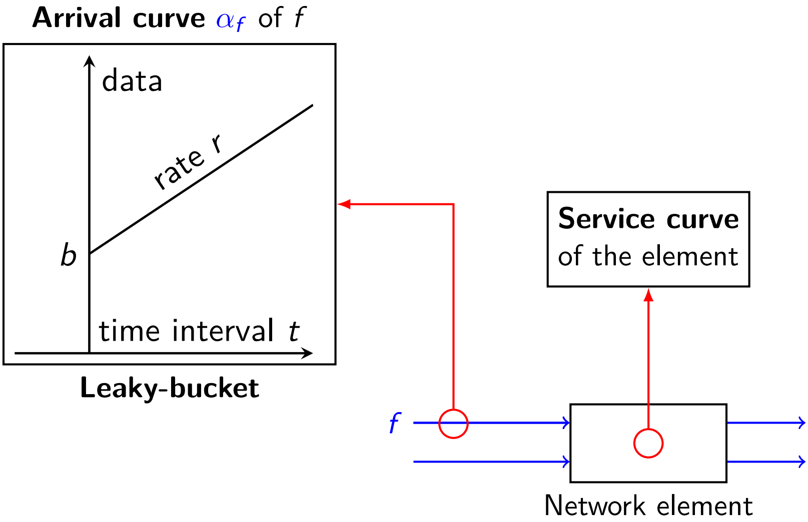
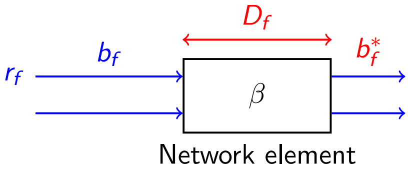


Time sensitive networks: analysis with **Network Calculus**

- Computes delay bounds
- Computes burst increase bounds

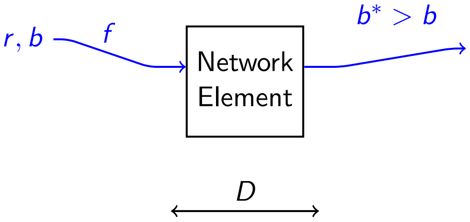


Time sensitive networks: analysis with **Network Calculus**

New: join the network calculus mailing list!

https://lists.geant.org/sympa/info/netcal-list

Tight delay bounds with **Traffic Regulators**



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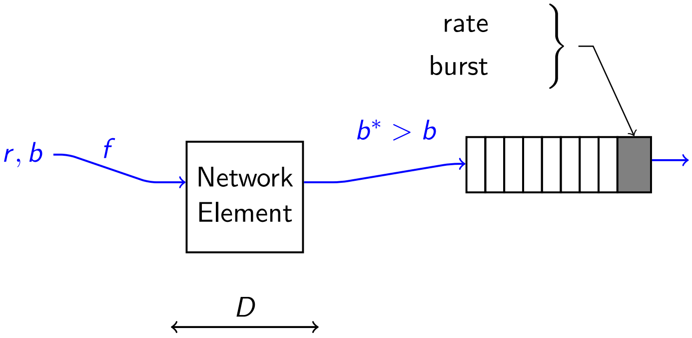

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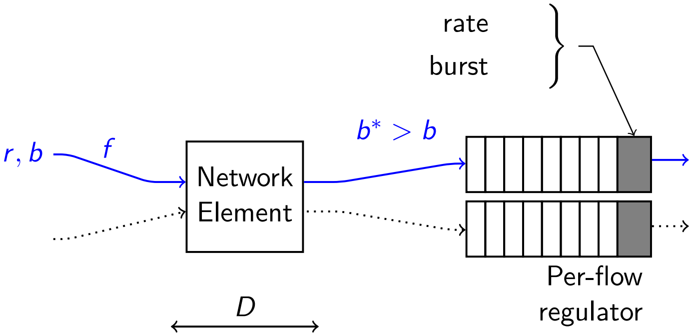

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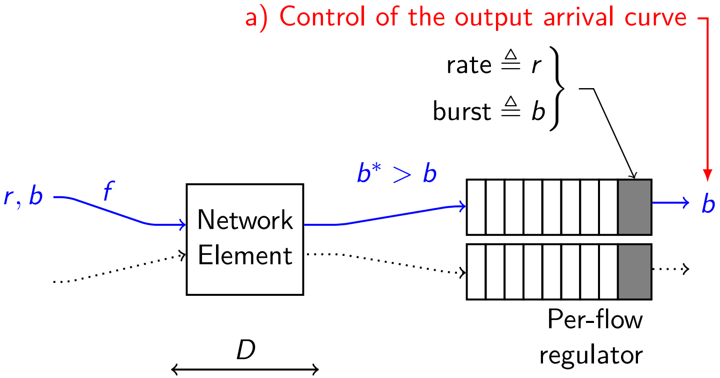

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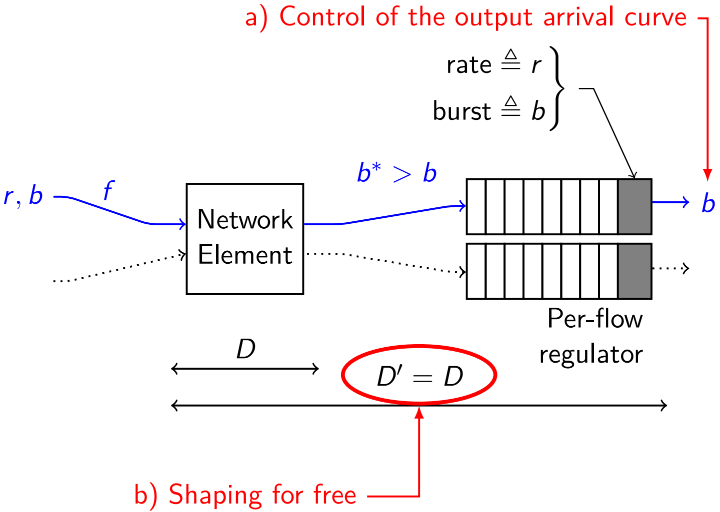

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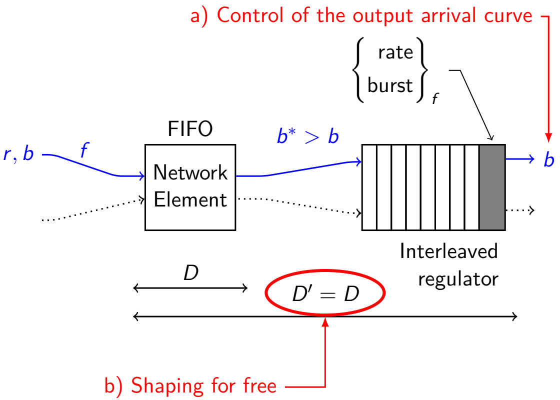

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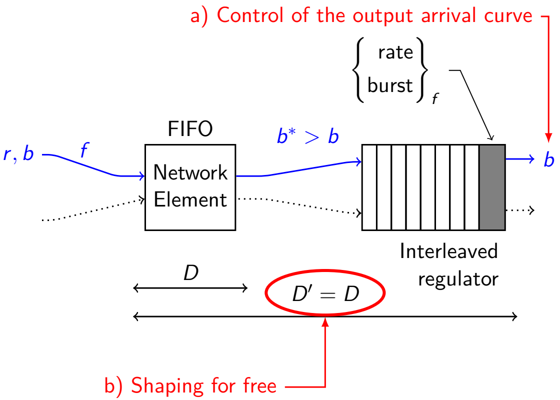
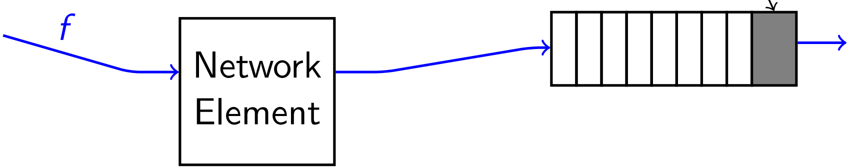


Per-flow regulator (PFR) and Interleaved Regulator (IR)

⇒ A building block of IEEE TSN, called **Asynchronous Traffic Shaping** (ATS).

Regulators measure **elapsed time**

$$\forall t,\ \text{bits}(t) \le r t + b \left\{ \begin{array}{c} \text{rate} \triangleq r \\ \text{burst} \triangleq b \end{array} \right\}$$



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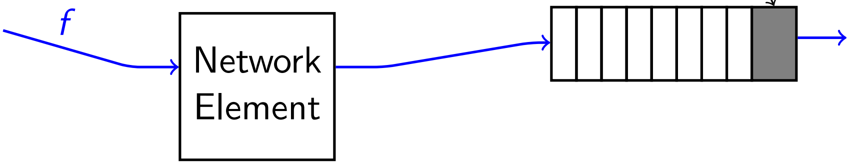


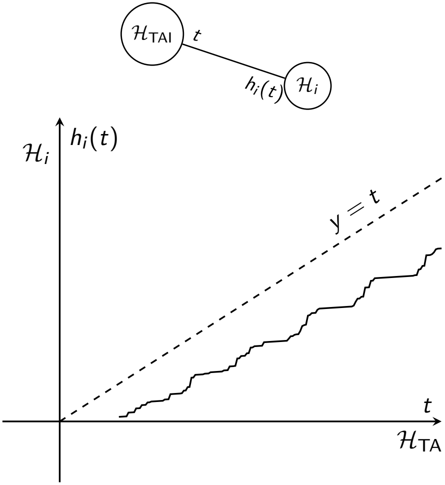
- Discussions in TSN ATS (Asynchronous Traffic Shaping) [IEEE, 2019].
- In our paper: theoretical foundations to address the problem.

Contributions

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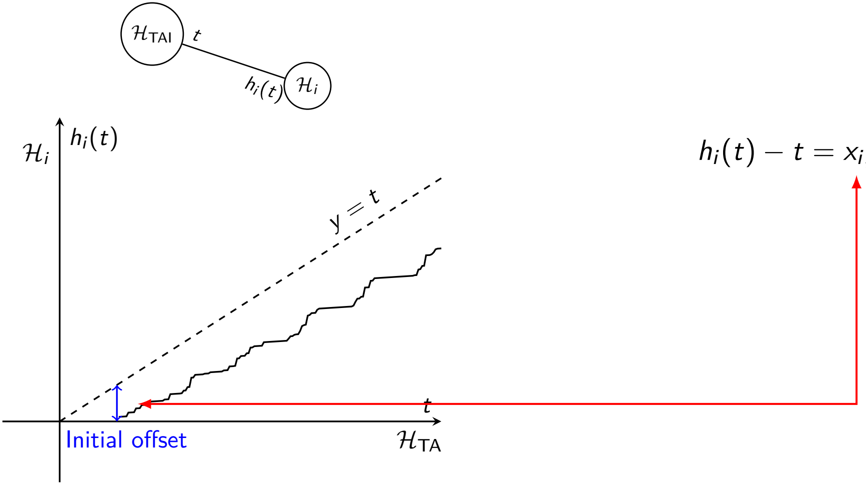

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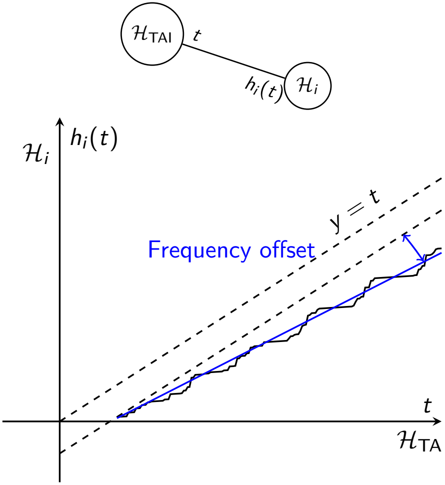

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$\leq y_{\max} t$

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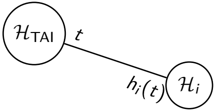

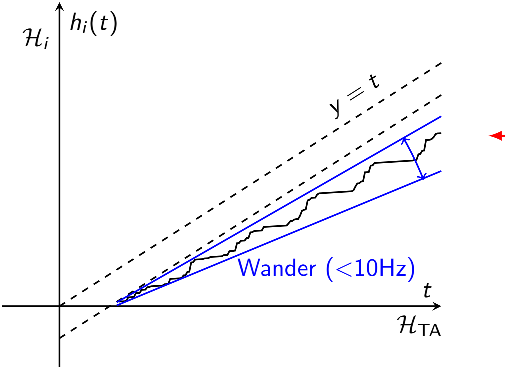

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$\leq w_i t$

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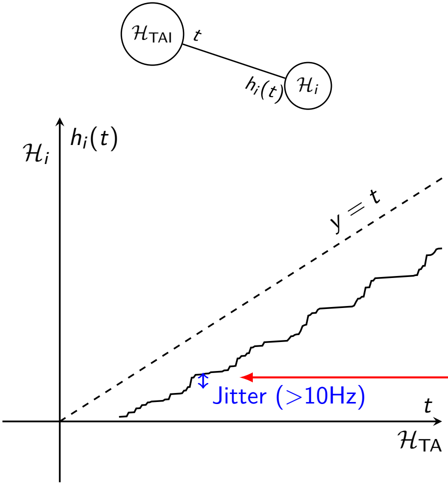

$$h_i(t) - t = x_{i,0} + ty_{i,0} + w(t) + \psi(t)$$

$\leq \eta_i$

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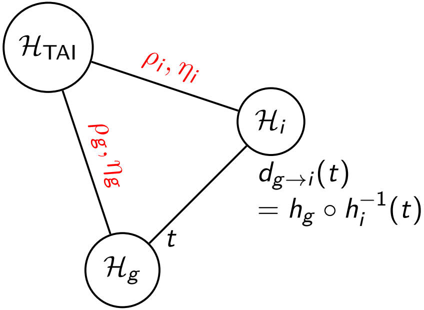

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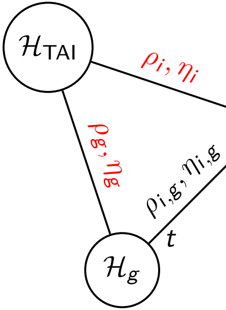
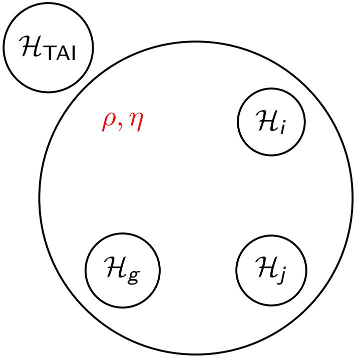


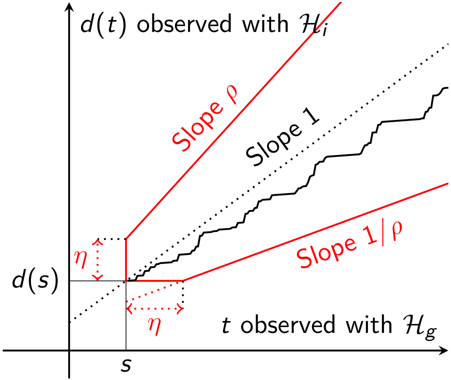
$d_{g \to i}(t)$
$= h_g \circ h_i^{-1}(t)$

Model for non-synchronized clocks



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

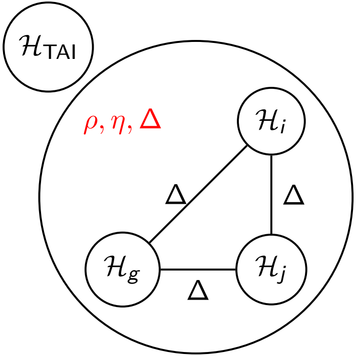
$\forall i, g$
$$\frac{1}{\rho}(t - s - \eta) \leq d_{g\to i}(t) - d_{g\to i}(s) \leq (t - s)\rho + \eta$$



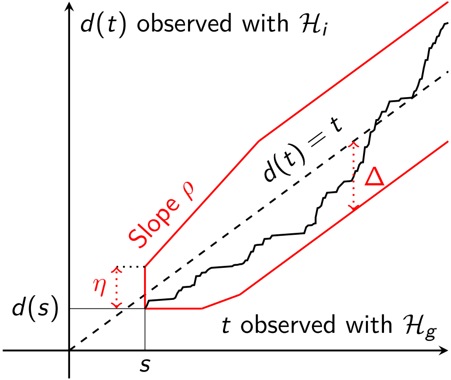
Model for synchronized clocks

$\forall i, g$

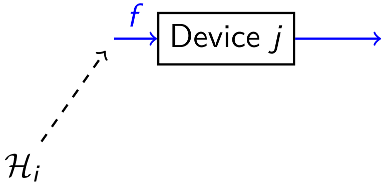
$$\begin{cases} \frac{1}{\rho}(t - s - \eta) \leq d_{g\to i}(t) - d_{g\to i}(s) \leq (t-s)\rho + \eta \\ |d_{g\to i}(t) - t| \leq \Delta \end{cases}$$



TSN:$\Delta = 1\mu s$



Toolbox for changing the observing clock



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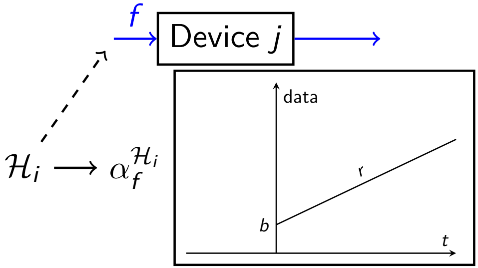

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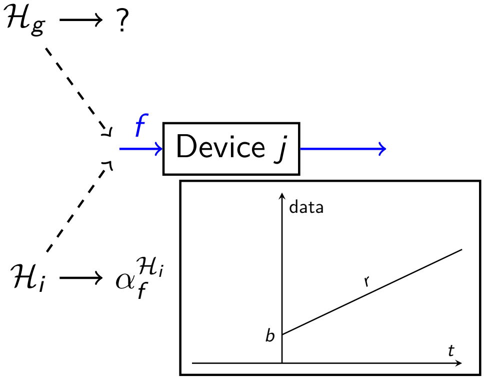
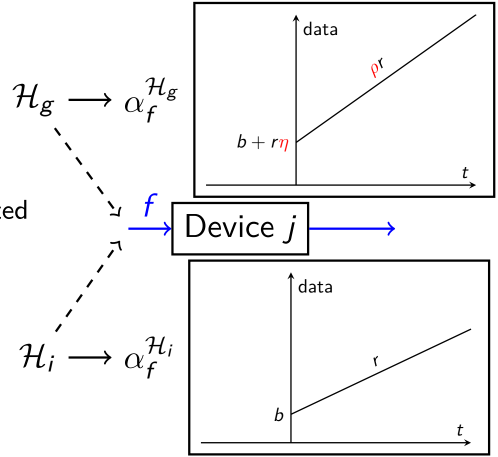


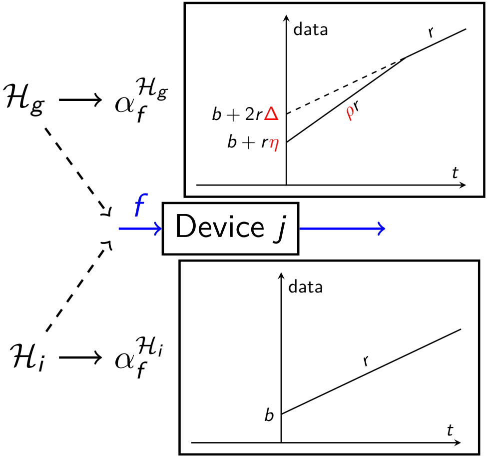
Toolbox for changing the observing clock

Non-synchronized
η, ρ



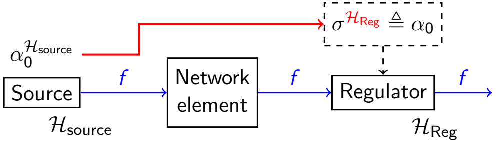
Toolbox for changing the observing clock

Synchronized
η, ρ, Δ



Instabilities with non-adapted regulators

Usual configuration of regulators
$=$ Non-adapted regulator



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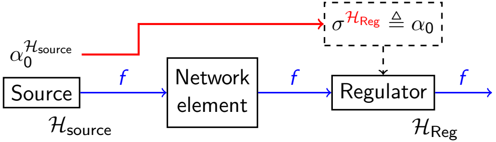

- Non-synchronized networks:
  - Per-flow regulator
  - Interleaved regulator

  } unstable

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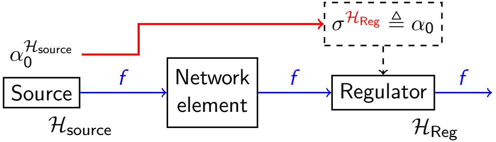
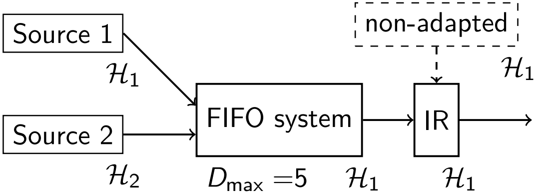
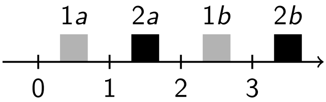


- Non-synchronized networks:
  - Per-flow regulator, Interleaved regulator } unstable
- Synchronized networks:
  - Per-flow regulator $\rightarrow$ penalty $[\Delta, 4\Delta]$
  - Interleaved regulator $\rightarrow$ **unstable** $\forall \Delta > 0$

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





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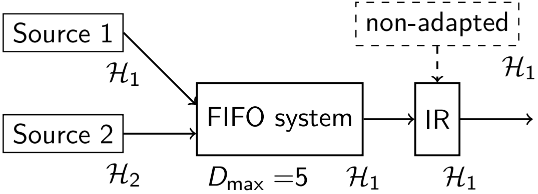
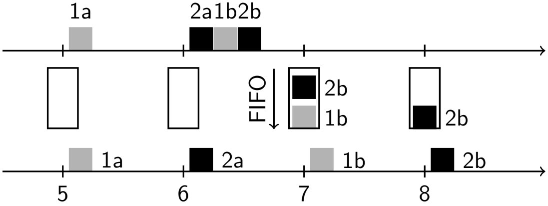
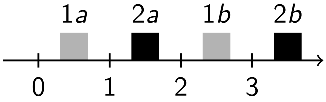
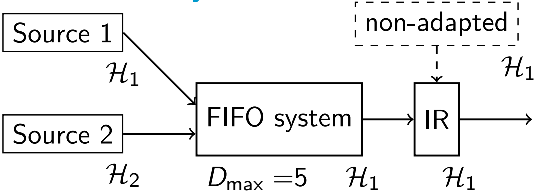
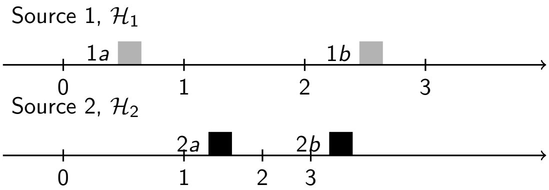






Adversarial synchronized clocks for a non-adapted IR (=ATS) (2/3)





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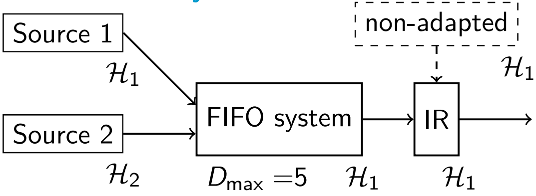

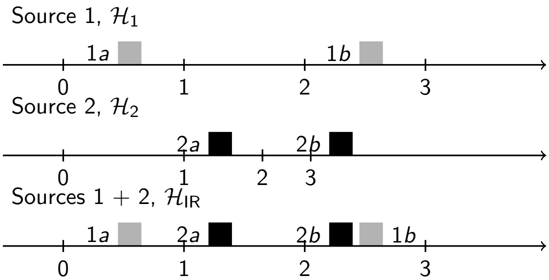

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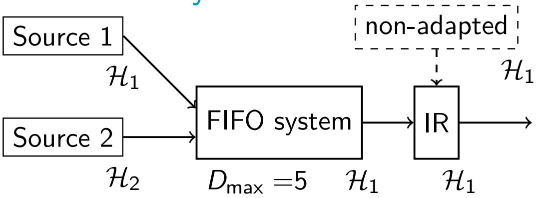
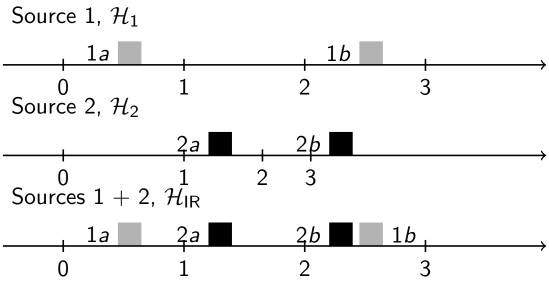
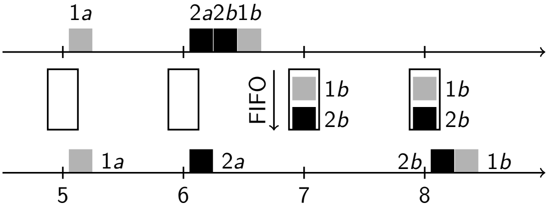


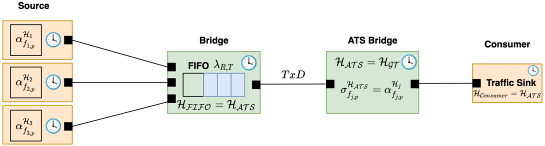


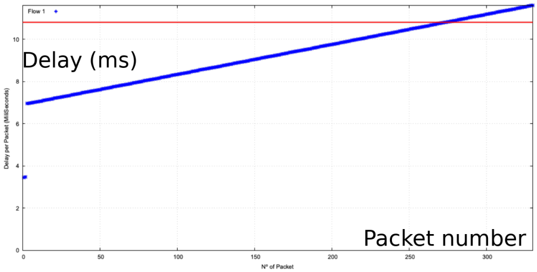


Adversarial synchronized clocks for a non-adapted IR (=ATS) (3/3)

Validation and extension through ns-3 simulations.

Example at low data rates:



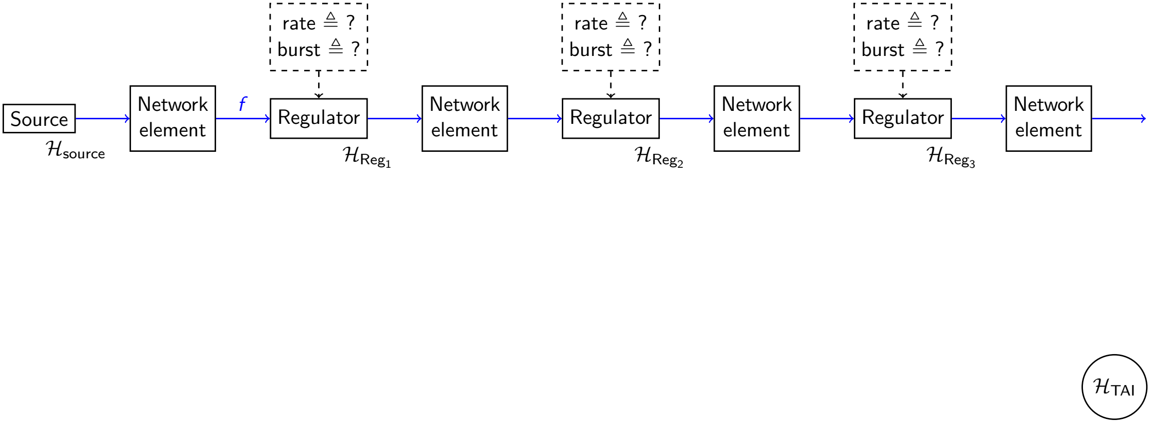


- 3 sources @ 147 kB/s
- 1 queuing element @ 437.5 kB/s
- $\Delta = 1\mu s$, $\rho = 1 + 100$ppm
- using adversarial clocks
- $\Rightarrow$ red line is Network Calculus delay bound assuming perfect clocks

Work by Guillermo Aguirre

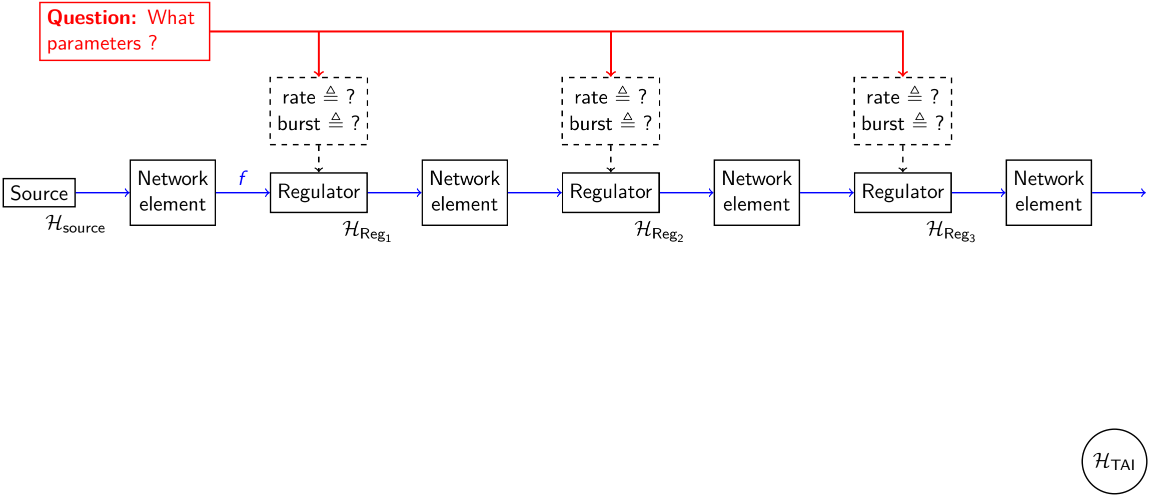
How to configure the regulators ?

$\forall$ flow f



How to configure the regulators ?

$\forall$ flow f



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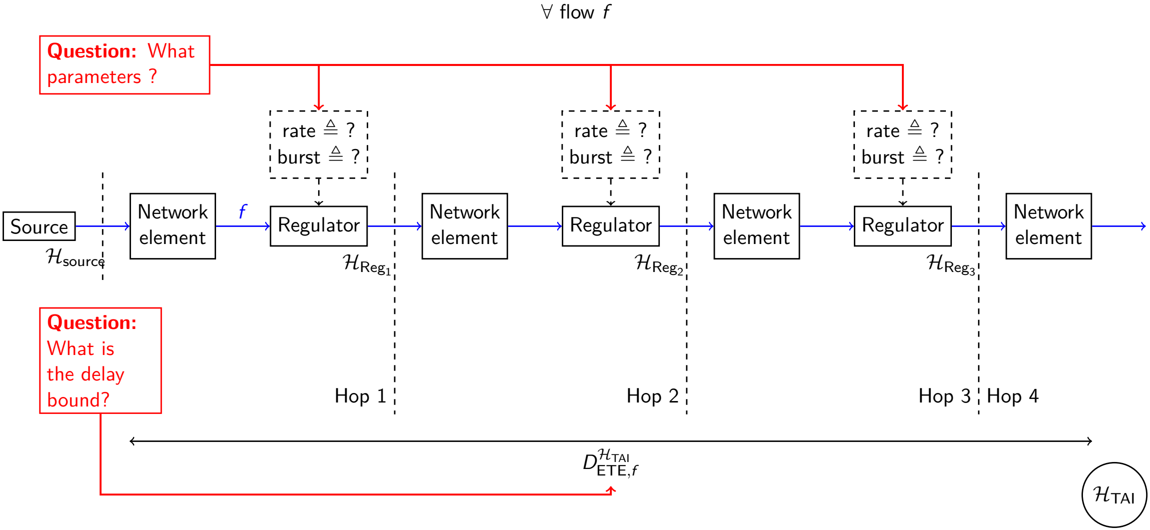
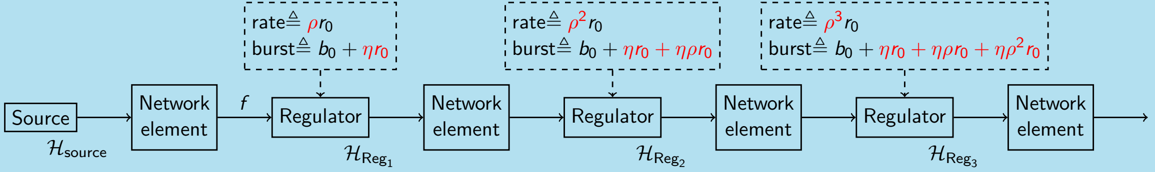


Two methods for synchronized and non-synchronized networks

Rate-and-burst cascade Works with PFR or IR



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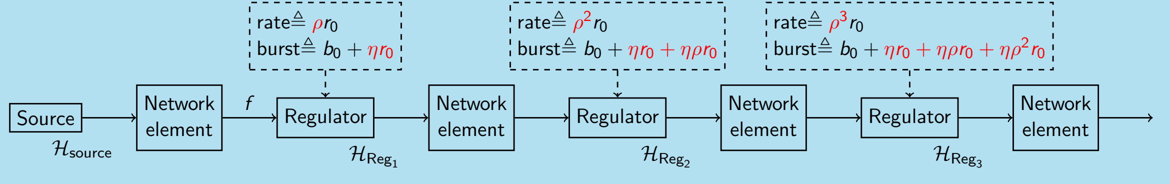
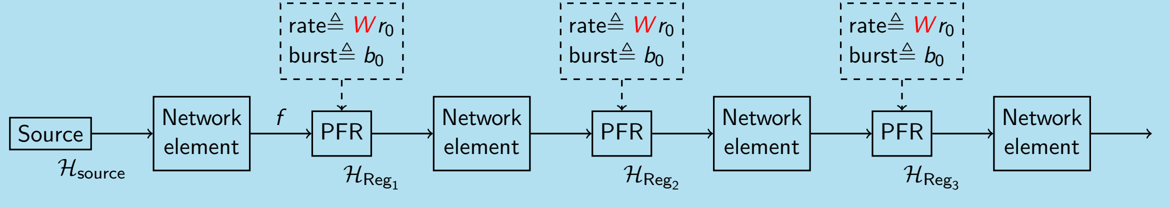
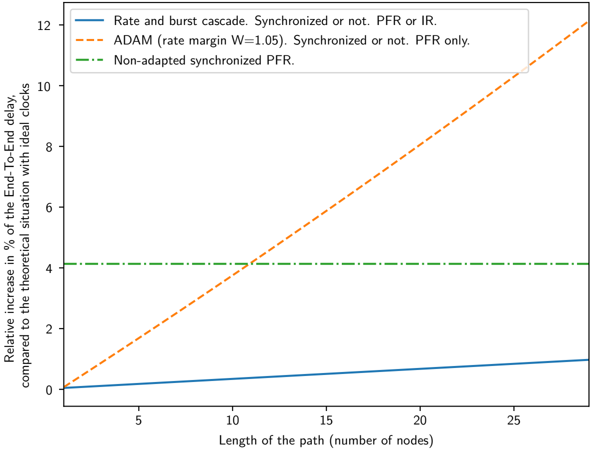


ADAM Works with PFR only



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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- Two methods for **configuring the regulators** in a network, relying on a **Network Calculus toolbox**.

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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