



Regulators, Dampers and Clock Non Idealities in Time Sensitive Networks

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<https://leboudec.github.io/leboudec/>

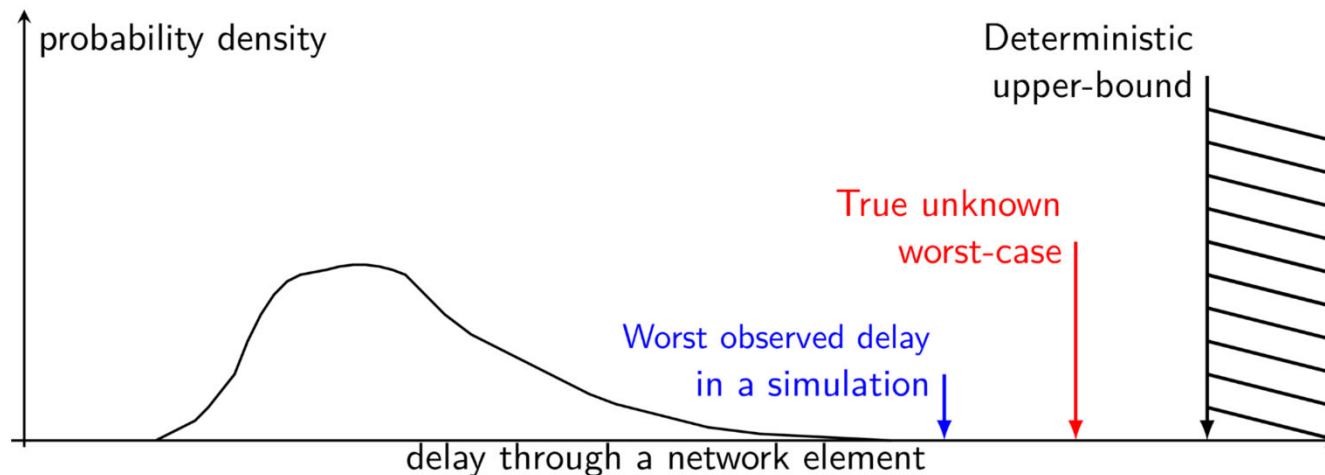
Joint work with Thomas Ludovic, ISAE, France
and Ehsan Mohammadpour, EPFL, Switzerland

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Per-Class Time Sensitive Networks

1. Flows are assigned to a small number of **classes** with different quality of service requirements
2. Every flow is **constrained at the source** by an *arrival curve* (e.g. with rate r and burstiness b , #bits sent over any interval of any duration t is $\leq rt+b$)
3. At every node, traffic of a given class is FIFO and is assured to receive a **minimum amount of service** (e.g. with rate R and latency T)

⇒ Deterministic delay, delay jitter and backlog bounds can be derived using network calculus



Burstiness Cascade

Unlike in a per-flow network, in a per-class network with FIFO inside every class, burstiness of every flow increases at every hop as a function of other flows' burstiness: e.g.

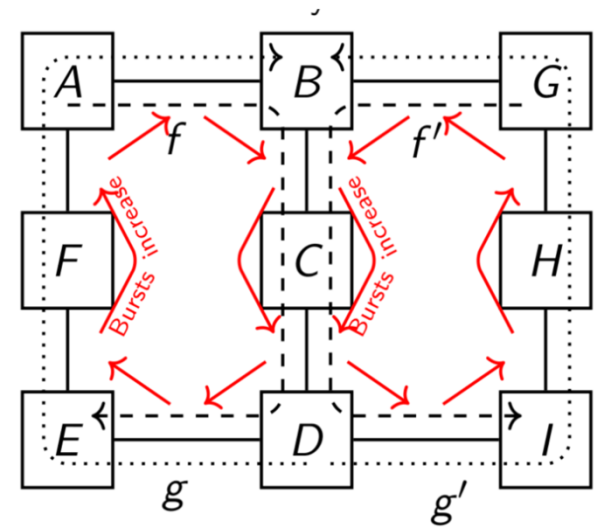
$$b_f^* = b_f + r \left(T + \frac{b_{tot} - b_f}{R} \right)$$

Increased burstiness causes increased burstiness (**cascade**).

Computing burstiness requires solving a fixpoint.

Good delay bounds depend on the topology and on the number of hops. In non-feedforward topologies, delay bounds can be bad even at medium utilizations.

[Bennett 2002].



Instability (infinite bounds) can occur even at low utilization [Andrews 2009].

Regulators in Time Sensitive Networks

Regulator (= shaper) delays packets in order to limit burstiness to a prescribed value (i.e. enforces an arrival curve constraint).

Example: Token Bucket filter (Linux tc; IEEE TSN ATS).

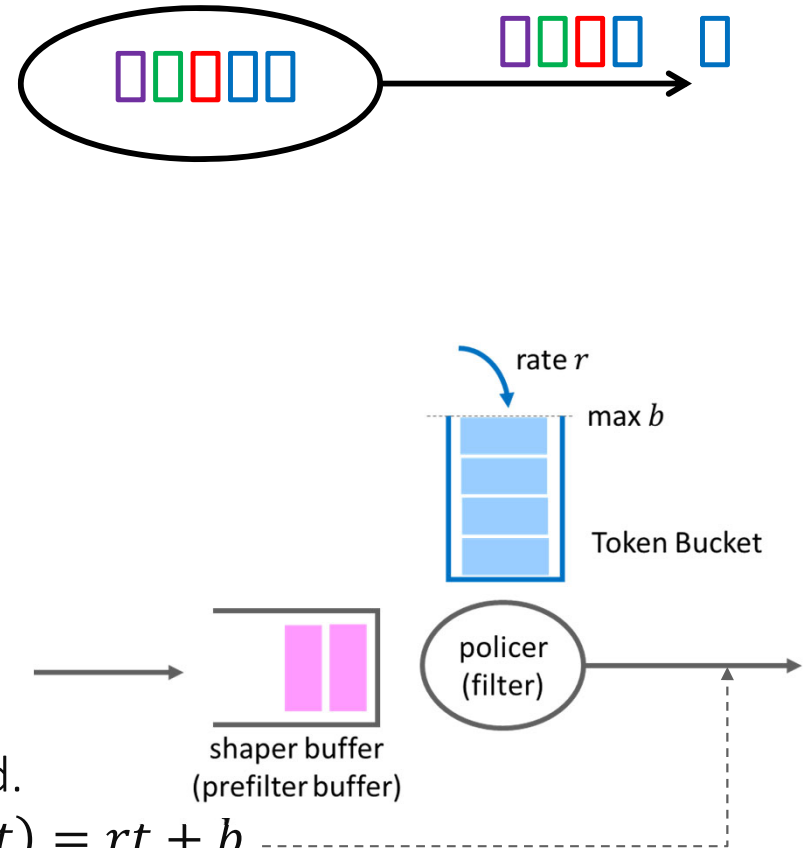
Imagine a token bucket, spontaneously replenished at rate r up to some maximum b .

In order to be released, a packet must consume same amount of tokens as its size.

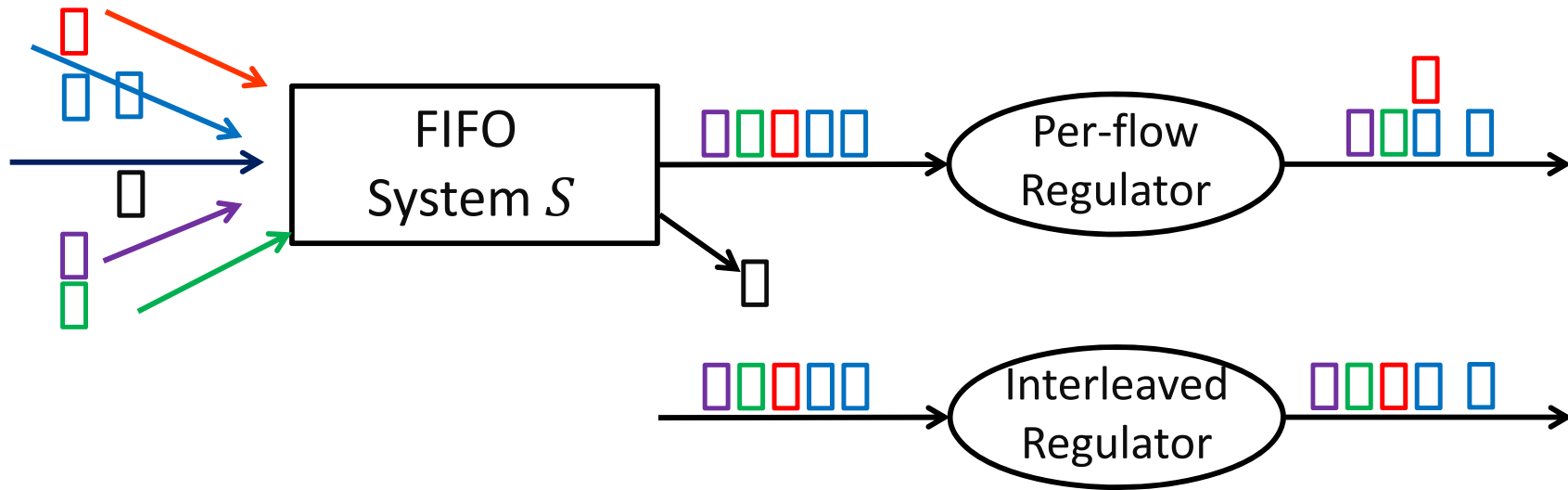
If there are not enough tokens, packet must wait.

As soon as there are enough tokens, packet is released.

This is the regulator for the arrival curve constraint $\alpha(t) = rt + b$



Regulators Avoid Cascading Burstiness in Per-Class Networks

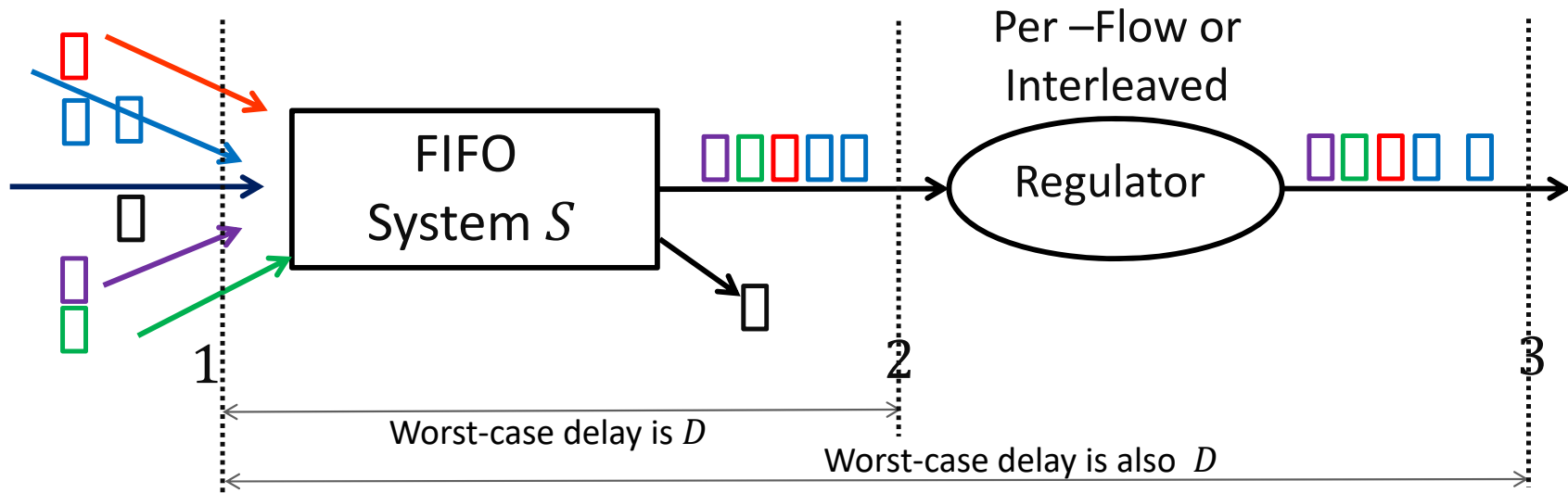


Per flow regulator: one state + one queue per flow.

Interleaved regulator: one state per flow + one global queue:

- packet at head of queue is examined against the arrival constraint (e.g. rate r_f and burstiness b_f) of its flow f ; this packet is delayed if it came too early; different flows in same queue can have different arrival constraints;
- packets not at head of queue wait for their turn to come [Specht-Samii 2016].

Regulators do not Increase Worst Case Delay



Assume S is FIFO per flow (per-flow regulator) or globally (interleaved regulator).

Assume every flow satisfies some arrival constraint at 1 (e.g. rate and burstiness) and regulators enforces same constraint at 3.

The worst case delay 1 – 3 is the same as the worst-case delay 1 – 2 [Le Boudec 2018].

Clock Non Idealities

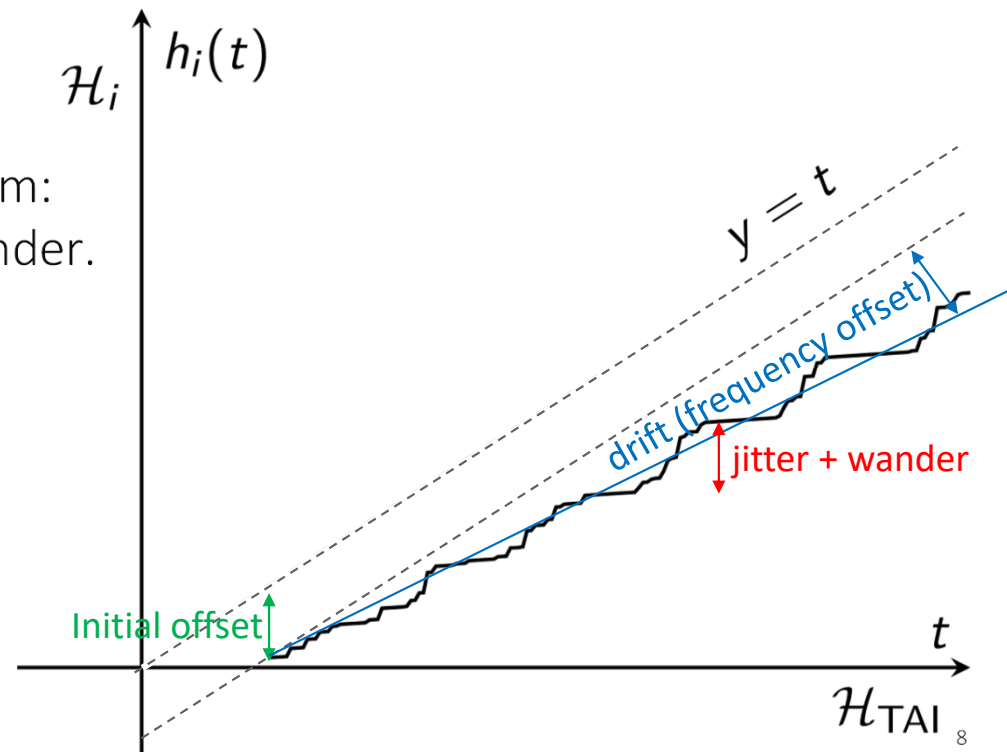
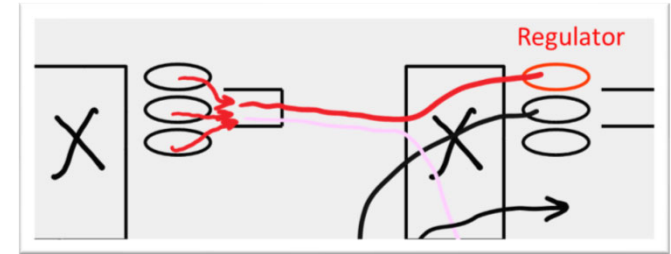
Previous theory assumes perfect time everywhere.
In reality, nodes use local clocks that are not ideal.

- **tight sync** (PTP, White Rabbit, GPS) :
timestamping error $\leq \omega \approx 10\text{ns} - 1\mu\text{s}$
- **loose sync** (NTP): $\omega \approx 1\text{ms} - 1\text{s}$
- **no sync**: timestamping error ω unbounded;
measurement of time interval on same system:
error is bounded by clock drift, jitter and wander.

[ITU 1996]

Regulators use time measurements to decide
when a packet can be released.

What is the effect of clock non ideality ?



Clock Model in Network Calculus [Thomas 2020]

A delay measurement is performed with one clock $\rightarrow d$ and with another clock $\rightarrow d'$

Time synchronization error: $d' - d \leq 2\omega$

Clock jitter and wander: $d' \leq \rho d + \eta$

This gives the constraints

$$-\min\left(\left(1 - \frac{1}{\rho}\right)d + \frac{\eta}{\rho}, 2\omega\right) \leq d' - d \leq \min((\rho - 1)d + \eta, 2\omega)$$

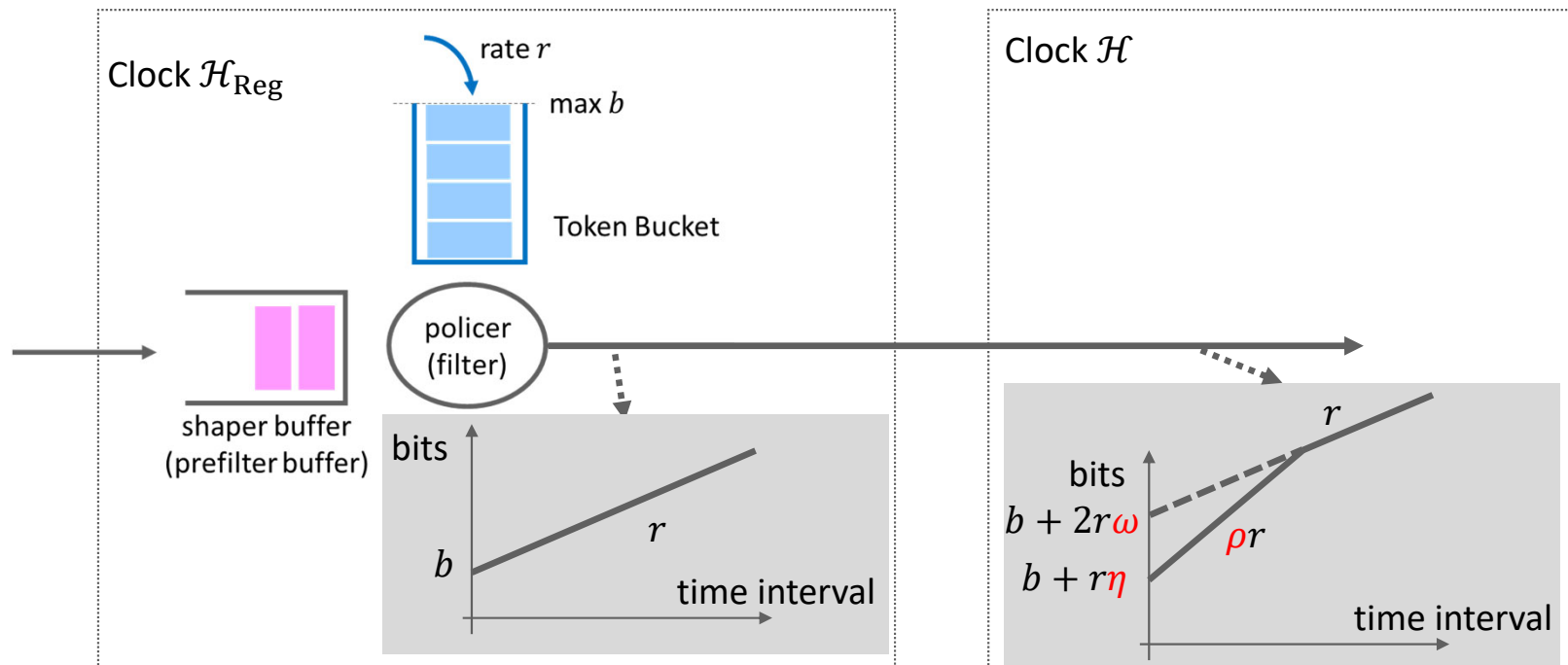
- ω = time error bound = $1\mu\text{s}$ in TSN with PTP; = $+\infty$ if no synchronization
- ρ = clock-stability bound = 1.0001; η = timing-jitter bound = 2ns (e.g. in TSN)

Model is symmetric, i.e. same inequalities if we exchange $d' \leftrightarrow d$

Change of Clock: Arrival Curves

Assume a flow satisfies a token bucket constraint (r, b) when observed with clock \mathcal{H}_{Reg} i.e. arrival curve constraint $\alpha^{\mathcal{H}_{\text{Reg}}}(t) = rt + b$

When observed with some other clock \mathcal{H} , it satisfies the arrival curve constraint $\alpha^{\mathcal{H}}(t) = \min(\rho r t + b + r\eta, rt + b + 2r\omega)$ [Thomas 2020]



Consequences for Non-Adapted Regulators

Non adapted regulator : uses same nominal arrival curve as at source.

Perfect clocks:

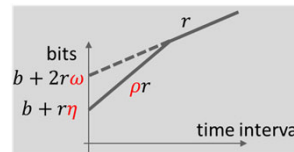
- Regulator does not increase worst-case delay

Non-synchronized network:

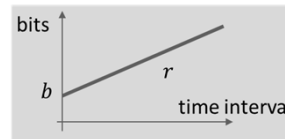
- Per-flow and interleaved regulator unstable (unbounded delay).

Synchronized network:

- Per-flow regulator incurs delay penalty up to 4ω ;
- Interleaved regulator is **unstable**.



In regulator's clock, flow satisfies this constraint at source



Source

Flow constrained by $\alpha(t) = rt + b$ in local clock

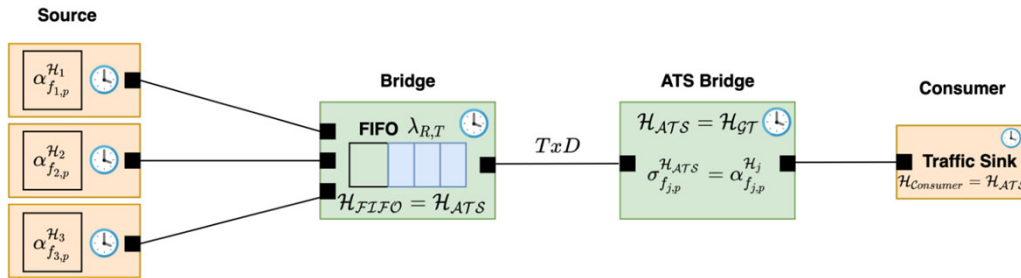
Network Elements

Non adapted Regulator (PFR or IR)

Implements constraint $\alpha(t) = rt + b$ in local clock

Synchronized clocks, Unstable non-adapted Interleaved Regulator (= IEEE TSN ATS)

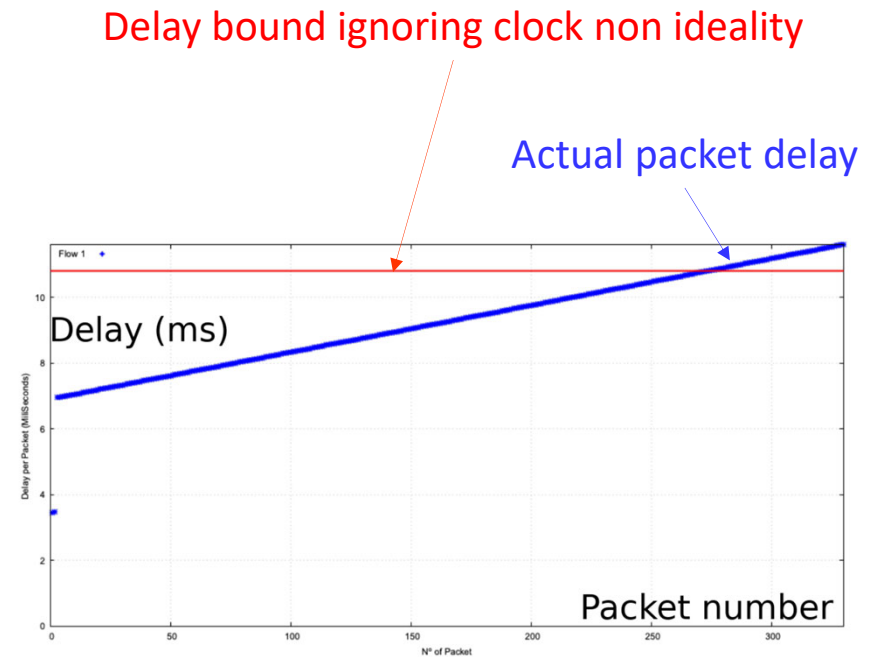
ns-3 simulations with adversarial clocks



3 sources @ 147 kb/s
 $\omega = 1\mu s, \rho = 1.0001$

Delay increases by up to $100\mu s$ per second of operation.

[Thomas 2020]



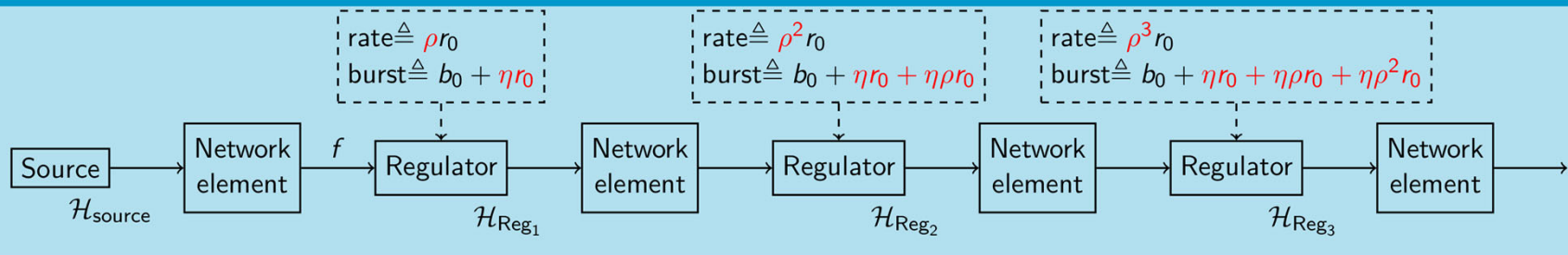
Work by Guillermo Aguirre

Regulators are sensitive to clock inaccuracies

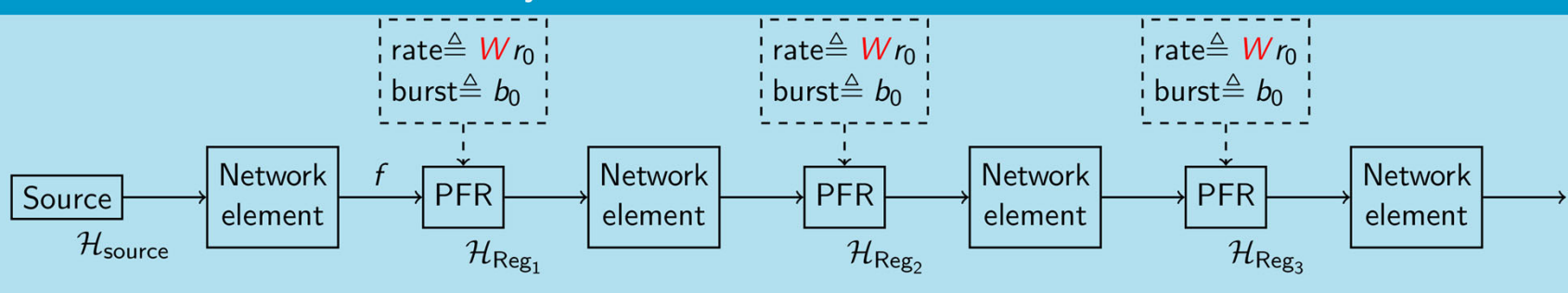
In **tightly synchronized** networks, IR must be adapted otherwise is unstable; PFR need not be adapted but increased delay due to clock inaccuracy must be accounted for. In loosely synchronized or non synchronized networks, both PFR and IR must be adapted.

Examples of
adaptation
methods

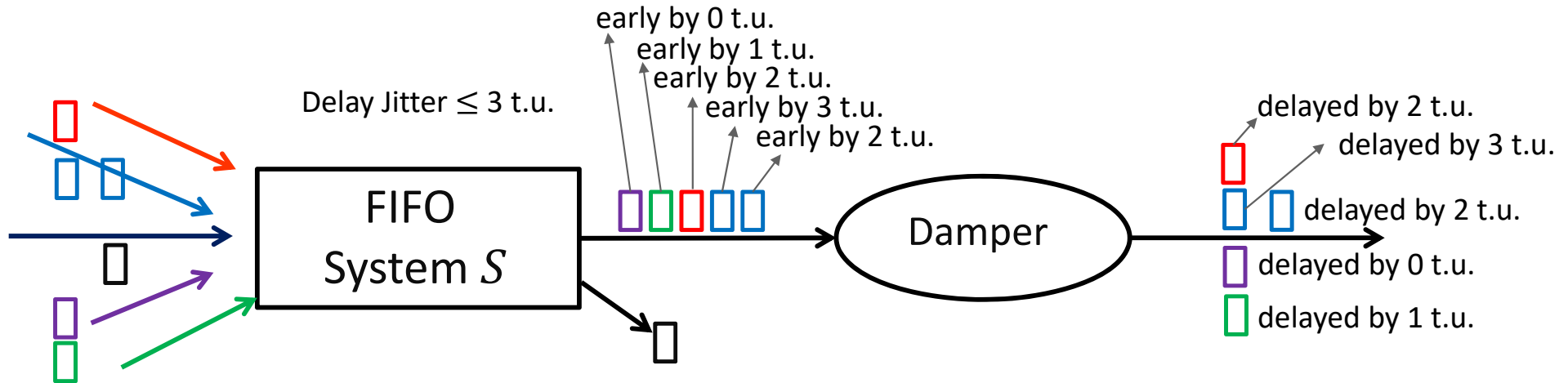
Rate-and-burst cascade Works with PFR or IR



ADAM Works with PFR only



Beyond Regulators: Dampers



Damper delays a packet by “earliness” read from packet header.

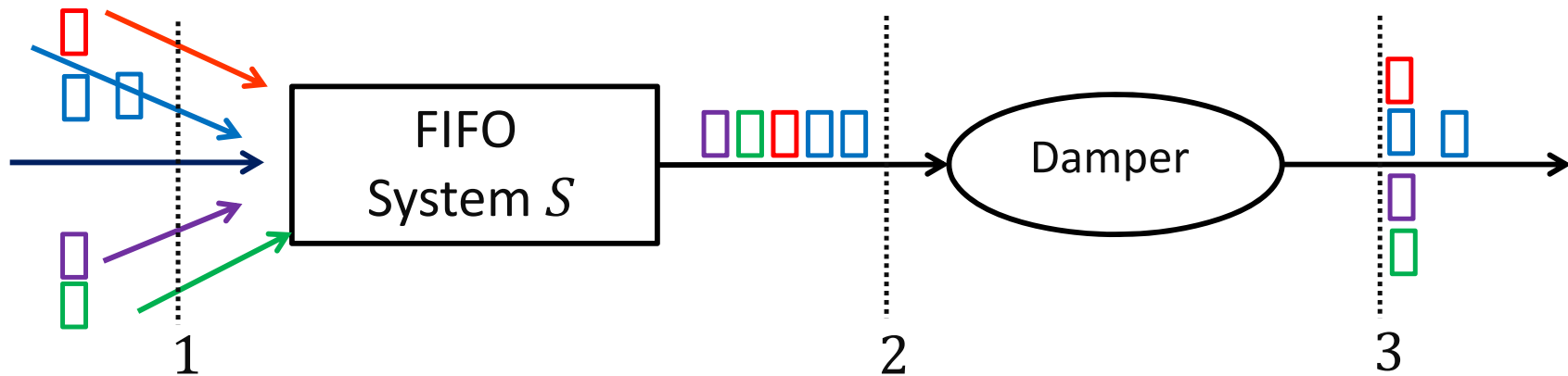
Removes (almost all) jitter.

Like a regulator, does not exist in isolation, is combined with queue at next hop.

Unlike regulator, is **stateless**.

[Cruz 1998] RCSP [Zhang 1993], RGCQ [Shoushou 2020], ATS with Jitter Control [Grigorjew 2020].

Dampers solves Burstiness Cascade Problem



Delay jitter $1 \rightarrow 3$ is 0 in theory; in practice, a small residual delay jitter $\leq \Delta$ (in true time):

At 1: assume a flow is constrained by token bucket with rate r and burstiness b (in true time);

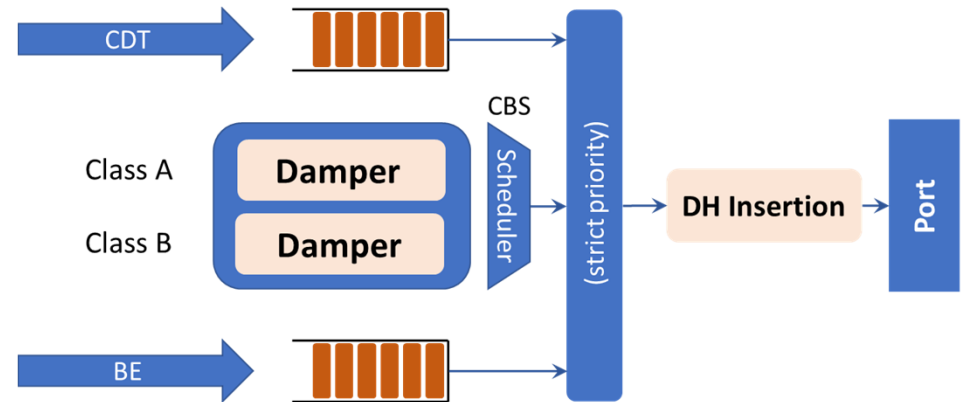
\Rightarrow At 3, same flow is constrained by token bucket with rate r and burstiness $b + r\Delta$ (in true time).

Tolerance Δ depends on jitter implementation and not on traffic
 \Rightarrow no burstiness cascade.

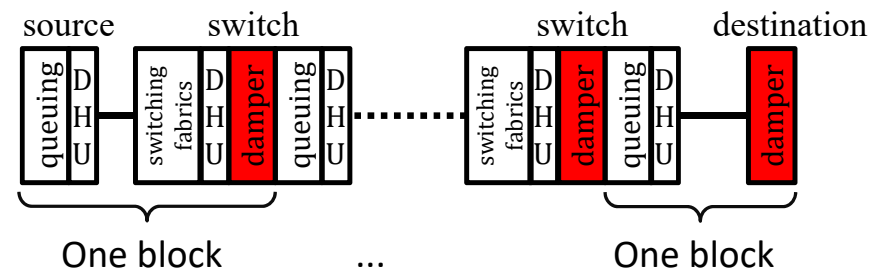
Damper in an IEEE TSN Switch

Damper replaces the FIFO queue of the credit-based shaper.

Makes packet visible to the scheduler at its theoretical eligibility time \pm some *damper tolerance*.



Damper Header inserted on the transmission line.



Example: RCSP damper;

with clock model in [Thomas 2020] : residual jitter

1.264 μ s per block, with or without clock synchronization

timing accuracy and clock non idealities contributes to 262 ns [Mohammadpour 2021].

Conclusion

Time Sensitive Networks require deterministic, proven delay, jitter and backlog bounds.

Network Calculus provides theory and tools for computing such bounds and for understanding operation of regulators. We extended it to account for clock non-idealities.

Regulators must be adapted to account for clock non-idealities.

Beyond regulators, dampers are stateless and are less affected by clock non-idealities.

References

- [Andrews 2009] Andrews, M., 2009. Instability of FIFO in the permanent sessions model at arbitrarily small network loads. ACM Transactions on Algorithms (TALG), 5(3), pp.1-29.
- [Bennett 2002] Bennett, J.C., Benson, K., Charny, A., Courtney, W.F. and Le Boudec, J.Y., 2002. Delay jitter bounds and packet scale rate guarantee for expedited forwarding. IEEE/ACM Transactions on networking, 10(4), pp.529-540.
- [Cruz 1998] Cruz, R.L., 1998, March. SCED+: Efficient management of quality of service guarantees. In Proceedings. IEEE INFOCOM'98, IEEE.
- [Grigorjew 2020] Grigorjew, A., Metzger, F., Hoßfeld, T., Specht, J., Götz, F.J., Chen, F. and Schmitt, J., 2020. Asynchronous Traffic Shaping with Jitter Control. <https://opus.bibliothek.uni-wuerzburg.de>
- [ITU-T-1996] Definitions and terminology for synchronization networks. ITU-T G.810.
- [Le Boudec-Thiran 2001] Le Boudec, J.Y. and Thiran, P., 2001. Network calculus: a theory of deterministic queuing systems for the internet (Vol. 2050). Springer Science & Business Media. <https://leboudec.github.io/netcal/>
- [Le Boudec 2018] Le Boudec, J.Y., 2018. A theory of traffic regulators for deterministic networks with application to interleaved regulators. IEEE/ACM Transactions on Networking, 26(6), pp.2721-2733.
- [Mohammadpour 2018] Mohammadpour, E., Stai, E., Mohiuddin, M. and Le Boudec, J.Y., 2018, September. Latency and backlog bounds in time-sensitive networking with credit based shapers and asynchronous traffic shaping. In 2018 30th International Teletraffic Congress (ITC 30) (Vol. 2, pp. 1-6). IEEE.
- [Mohammadpour 2021] Ehsan Mohammadpour and Jean-Yves Le Boudec, “Analysis of Dampers in Time-Sensitive Networks with Non-ideal Clocks”, 2021, [arxiv:2109.02757](https://arxiv.org/abs/2109.02757).
- [Shoushou 2020] R. Shoushou, L. Bingyang, M. Rui, W. Chuang, J.-Y. Le Boudec, E. Mohammadpour, and A. El Fawal, “A method for sending data packets and network equipment,” China Patent, Jul., 2020
- [Specht-Samii 2016] Specht, J. and Samii, S., 2016, July. Urgency-based scheduler for time-sensitive switched ethernet networks. In 2016 28th Euromicro Conference on Real-Time Systems (ECRTS) (pp. 75-85). IEEE.
- [Thomas 2020] Thomas, L. and Le Boudec, J.Y., 2020. On Time Synchronization Issues in Time-Sensitive Networks with Regulators and Nonideal Clocks. Proc. ACM Sigmetrics 2020, 4(2), pp.1-41.
- [Zhang 1993] Zhang, H. and Ferrari, D., 1993, March. Rate-controlled static-priority queueing. In IEEE INFOCOM'93 The Conference on Computer Communications, Proceedings (pp. 227-236). IEEE.