Time Sensitive Networks, Network Calculus and Clock Non-idealities

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LORIA Colloquium, Nancy, 2024 October 17

Abstract: Time Sensitive Networks offer guarantees on worst-case delay, worst-case delay variation and zero congestion loss. They find applications in many areas such as factory automation, embedded and vehicular networks, audio-visual studio networks, and in the front-hauls of cellular wireless networks. In this talk we will describe how network calculus can be used to analyze time sensitive networks. We will also explain why clock non-idealities matter and how to take them into account.

Contents

1. Time Sensitive Networks

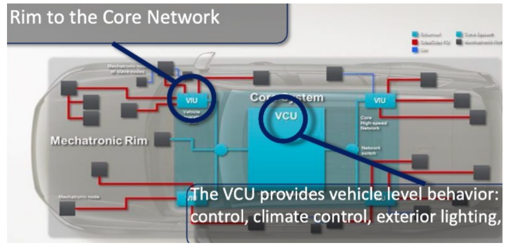
= deterministic service: upper bounds on end-to-end delay and delay-jitter + zero congestion loss.

Congestion control with feedback is not an option here.

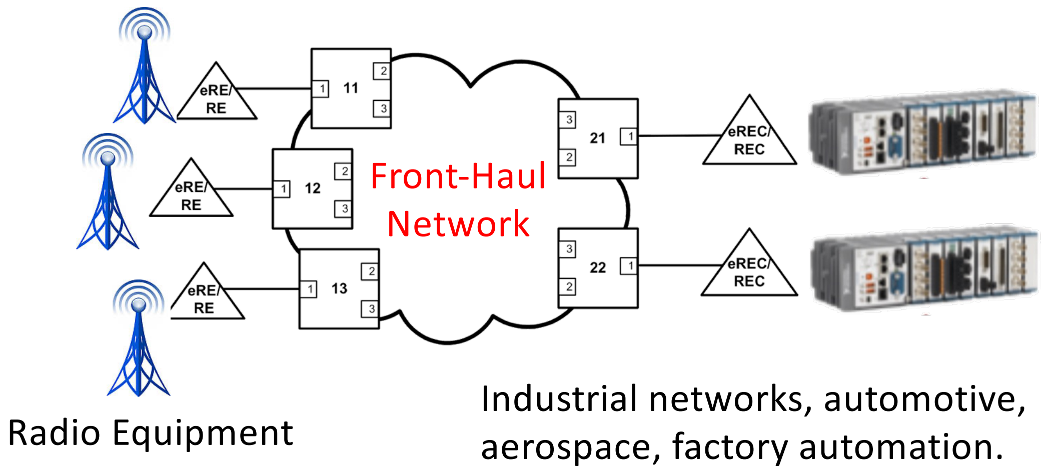
Proven bounds are required.

Standardization:

MAC-layer networks: IEEE TSN (Time Sensitive Networking)
IP and MPLS networks: IETF Detnet (Deterministic Networking)



From [Navet et al,2020]



Industrial networks, automotive, aerospace, factory automation.
Studio networking
Front-haul of cellular networks
Distributed games
Low latency on-demand video

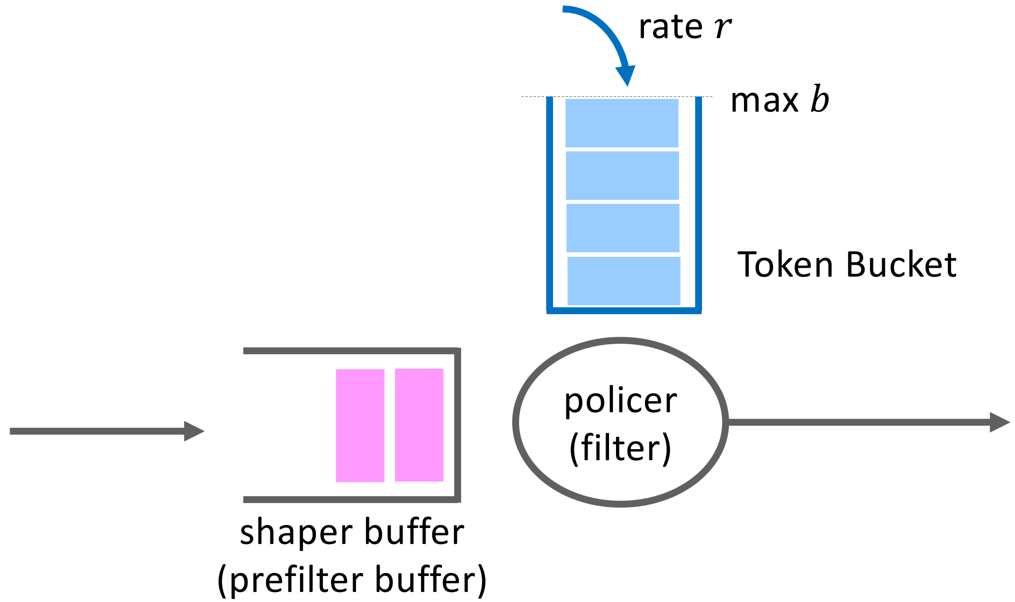
How can a Network Offer a Deterministic Service ?

1. Every flow is constrained at source

   e.g. source is periodic

   e.g. source is limited by a token bucket filter with rate r and burstiness b

   $\rightarrow$ number of bits sent over any interval of any duration t is $\leq rt+b$ (*arrival curve* constraint) (T-SPEC)



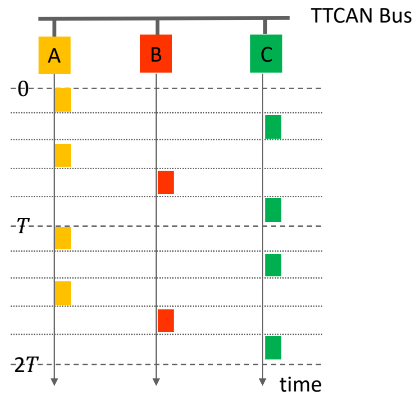
Imagine a token bucket, spontaneously replenished at rate r up to maximum b (called the "burst")

A released packet must consume same amount of tokens as its size, else waits until enough tokens are available.

```
tc qdisc add dev eth0 root tbf rate 1mbit burst 32kbit …
```

How can a Network Offer a Deterministic Service ?

1. Every flow is constrained at source



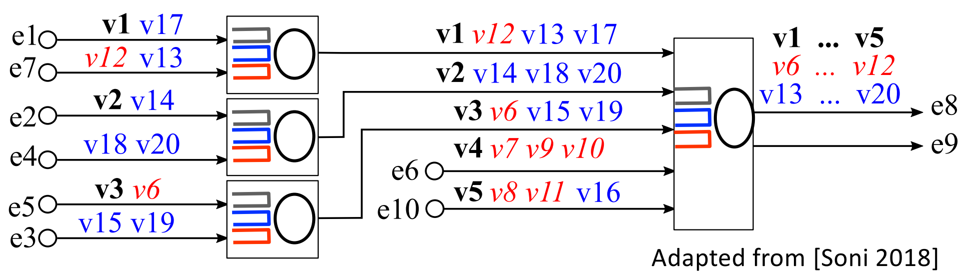
2. The network nodes offer a guaranteed service to flows or classes of flows

   synchronous: e.g Time Triggered CAN bus: every flow is scheduled on bus (not our focus today)

   asynchronous: e.g. switch/router network

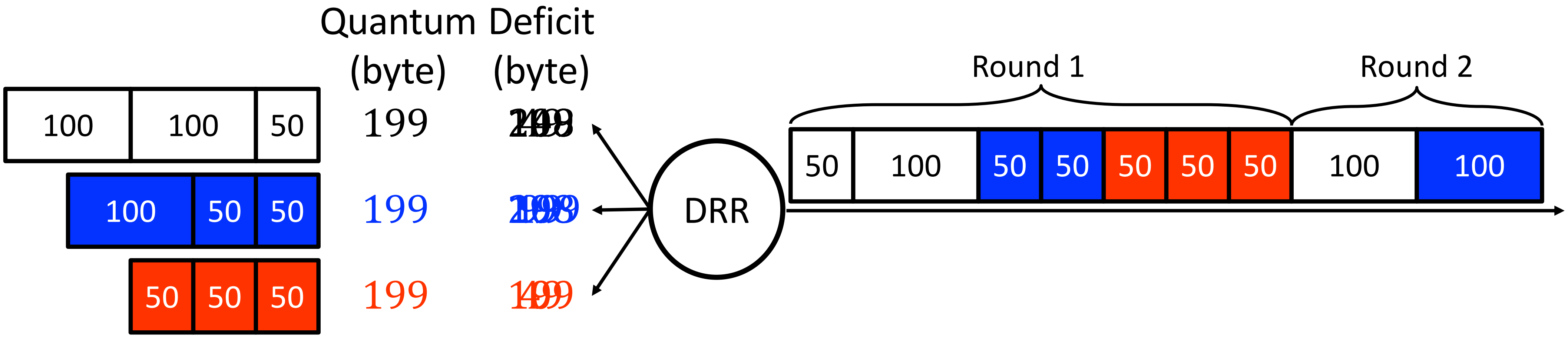
   a) Flows are assigned to a small number of classes with different quality of service requirements

   b) At every node, traffic of a given class is FIFO; a scheduler shares bandwidth and buffer between classes



Adapted from [Soni 2018]

Example of Scheduler: Deficit Round Robin (DRR) [Shreedhar 1996]



Implemented in Linux class based queuing **tc qdisc ... add drr [quantum** bytes **]**

Operation: Each queue (= each class) is given a quantum.

An infinite loop of rounds visits queues.

When a queue is visited its deficit is increased by the quantum.

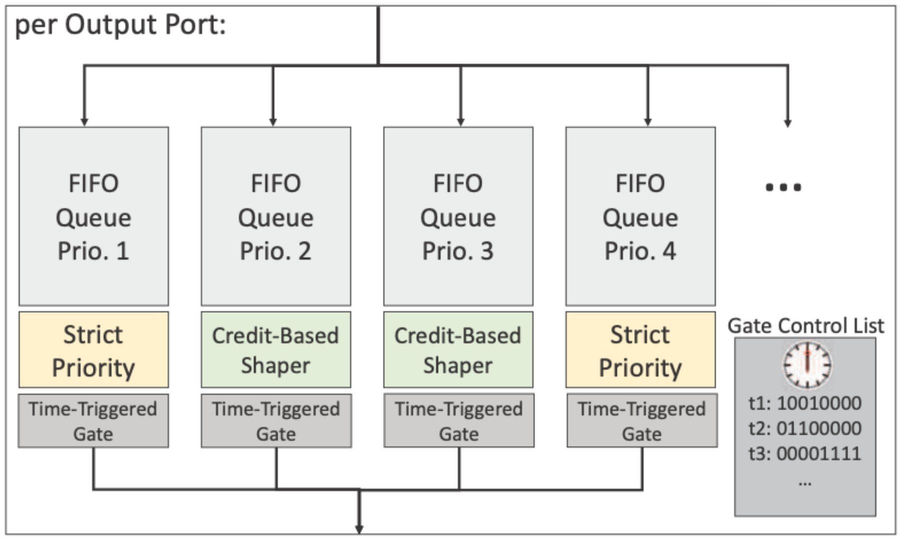
Service for this queue stops if 1) deficit is smaller than head-of-line packet or 2) queue becomes empty (in which case deficit is reset).

$\Rightarrow \approx$ Bandwidth is allocated to every class in proportion of the quantum.

Other Schedulers

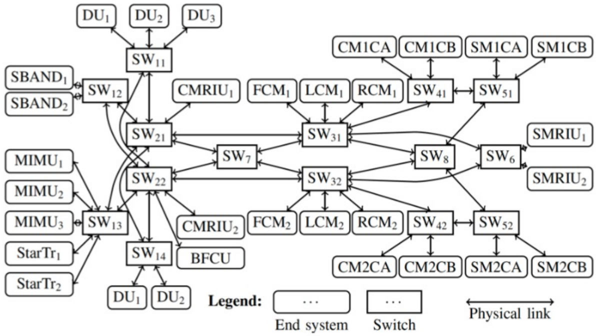
- Weighted Fair Queuing and all variants of Generalized Processor Sharing (such as DRR)
- Audio Visual Bridging (AVB) / Credit Based Shaper (CBS)
- Burst Limiting Shaper
- Time Aware Shaper
- Static Priority

Etc.



Typical IEEE TSN scheduler. From [Maile 2020]

They can be combined.

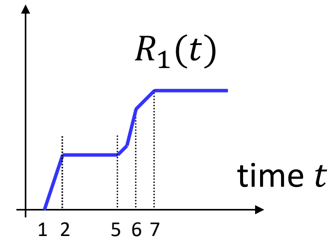


From [Zhao 2018]

Given source constraints and schedulers, what are the worst-case delay, jitter and backlog ?

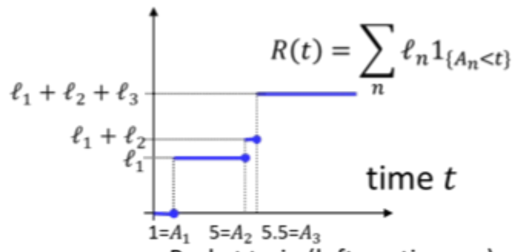
2. Analysis of Deterministic Networks uses Network Calculus

- Flows are modelled with cumulative arrival functions, $R(t)$, non-decreasing with $R(0) = 0$, or, for packetized flows, with point processes (packet trains) (A, ℓ)

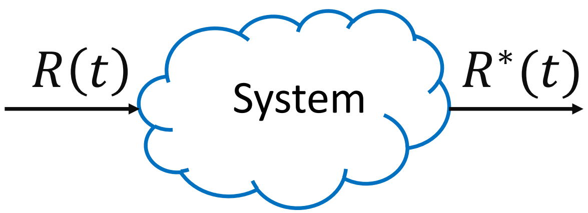


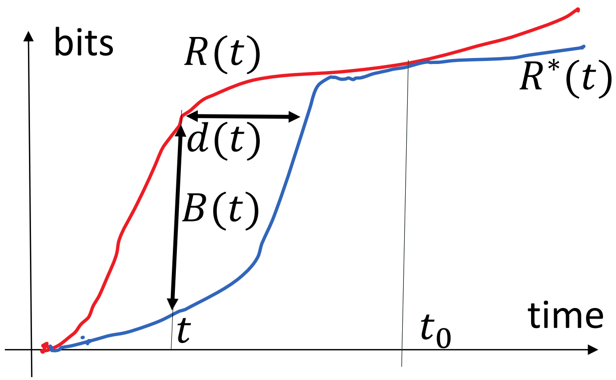
Fluid model (continuous)

- Delay and backlog are derived



Packet train (left continuous)





$d(t) = \inf\{d \text{ s.t. } R(t) \le R^*(t+d)\}$
(horizontal deviation)

Arrival Curves

Flow with cumulative function $R(t)$ has α as (maximal) arrival curve if

$$R(t) - R(s) \leq \alpha(t-s) \text{ for any } t \geq s \geq 0$$

where α is a monotonic nondecreasing function $\mathbb{R}^+ \rightarrow [0, +\infty]$

α can be assumed sub-additive ($\alpha(s+t) \leq \alpha(s) + \alpha(s)$).

This is equivalent to $R \leq R \otimes \alpha$, where $\otimes$ denotes min-plus convolution:

$$(f_1 \otimes f_2)(t) = \inf_{s \geq 0} \left(f_1(s) + f_2(t-s) \right)$$

and, for a point process model, to

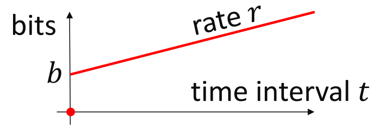
$$A_n - A_m \geq \alpha^{\downarrow}(\ell_m + \cdots + \ell_n), \forall m, n, 1 \leq m \leq n$$

where $\alpha^{\downarrow}$ is the lower-pseudo inverse of α.

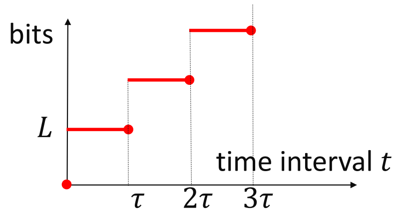
E.g. for $\alpha(t) = rt + b$, $\alpha^{\downarrow}(x) = \frac{(x-b)^+}{r}$

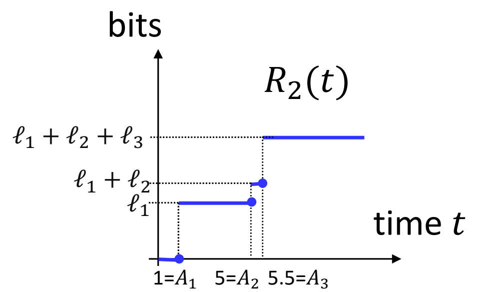
[Le Boudec 2018]

token bucket constraint (r, b)
with rate r and burst b:
$\alpha(t) = rt + b$



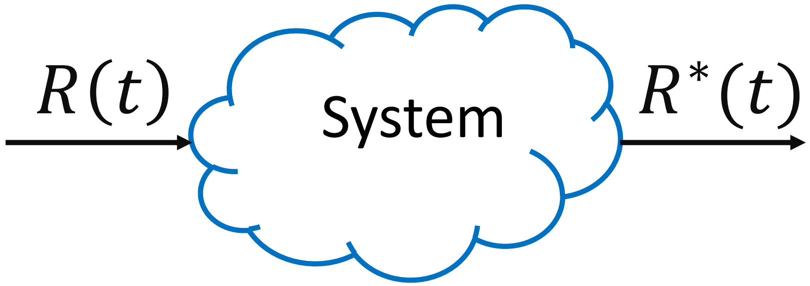
periodic stream of packets of size $\leq$ L: $\alpha(t) = L\left\lceil \frac{t}{\tau} \right\rceil$





Packet train (left continuous)

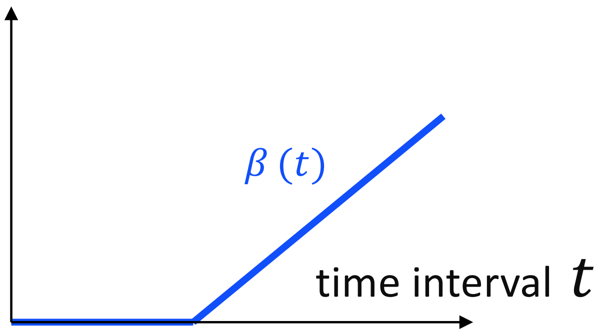
Service Curve

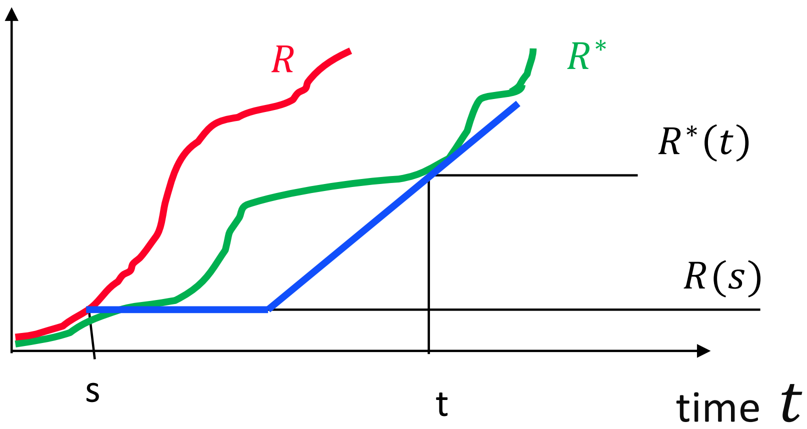


System offers to this flow a (minimal) service curve β if $\boxed{R^* \geq R \otimes \beta}$, i.e. :

$$\forall t \geq 0, \exists s \in [0, t]: R^*(t) \geq R(s) + \beta(t - s)$$

where β is a function : $\mathbb{R}^+ \rightarrow \mathbb{R} \cup \{+\infty\}$

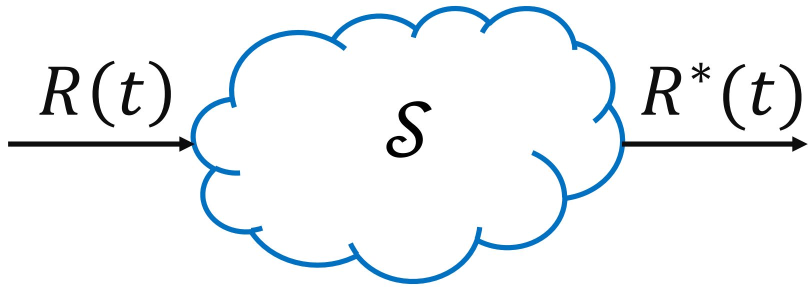




[Le Boudec 1996, Chang 1997, Bouillard 2018]

Strict Service Curve

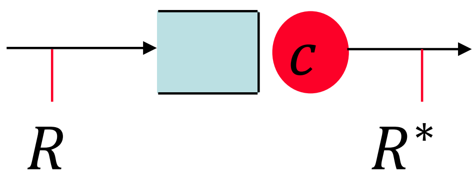
System $\mathcal{S}$ offers to a flow a strict service curve β if for any $s < t$ inside a backlogged period, i.e. such that $R^*(u) < R(u), \forall u \in (s,t]$, we have $R^*(t) - R^*(s) \geq \beta(t-s)$



$\mathcal{S}$ is typically a single queuing point

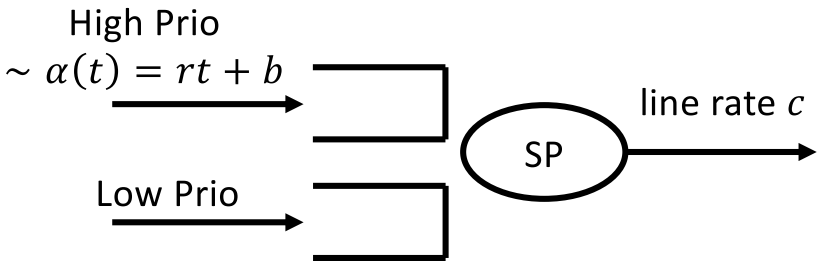
β is a strict service curve $\Rightarrow$ β is a service curve but converse is not true.

Example: constant rate server with line rate c has strict service curve $\beta(t) = ct$

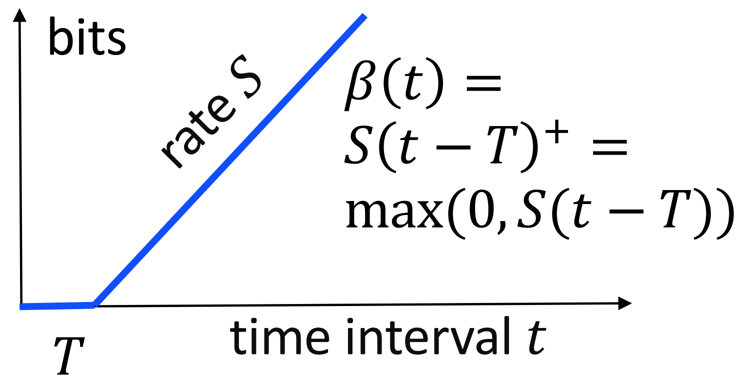


Example: Non-preemptive Static Priority

High prio: $\beta_H(t) = (ct - MTU_L)^+$
(strict service curve)
(MTU_L = max packet size, low prio)



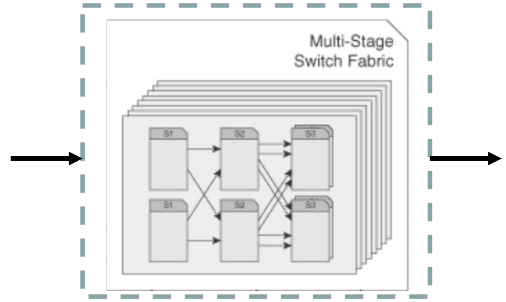
Low prio: when high priority constrained by $\alpha(t) = rt + b, r < c$:
$\beta_L(t) = ((c-r)t - b)^+$ (not a strict service curve)
$\beta'_L(t) = \left((c-r)t - b - MTU_L\right)^+$ (strict service curve)
[Bouillard 2018]



A function of the form $\beta(t) = S(t-T)^+$ is called rate-latency, with rate S and latency T

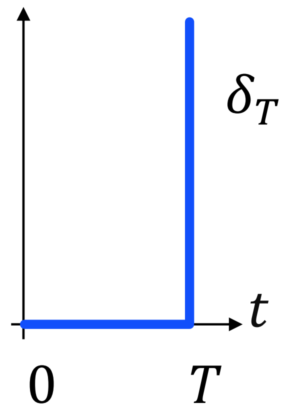
Bounded Delay Element

Sometimes it is convenient to model a system as a black box with known delay upper bound T.



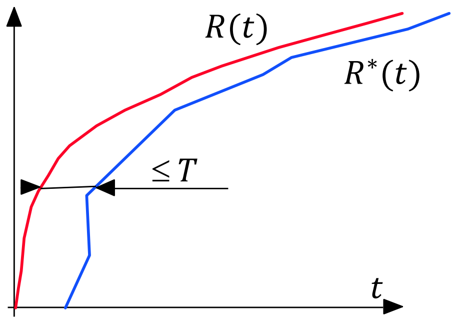
delay $\in [1\mu s, 10\mu s]$

For a node that is FIFO for this flow: delay $\leq T \iff$ nodes offers to this flow a service curve δ_T



$\delta_T(t) = 0$ if $t \leq T$
$\delta_T(t) = +\infty$ if $t > T$

Not a strict service curve



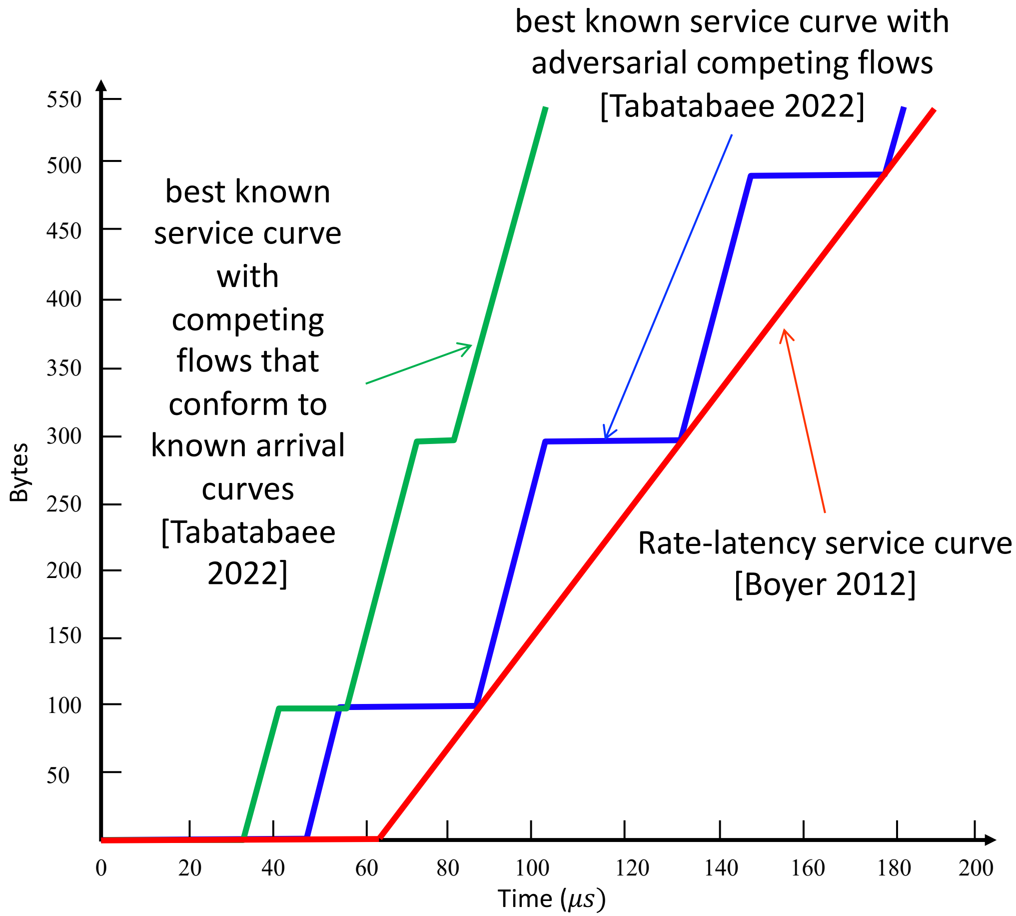
Example: Deficit Round Robin

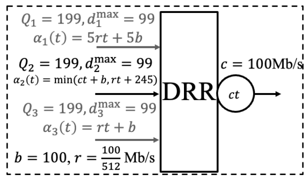
- DRR offers to flow i a rate-latency strict service curve $\beta_i(t) = R_i(t - T_i)^+$

$$\text{with } R_i = \frac{Q_i}{\sum_j Q_j} c, \quad T_i = \frac{\bar{Q}_i + \bar{L}_i}{c} + L_{\max,i}\left(\frac{1}{R_i} - \frac{1}{c}\right), \; \bar{Q}_i = \sum_{j \neq i} Q_j, \;\; \bar{L}_i = \sum_{j \neq i} L_{\max,j}$$

and c is the line rate [Boyer 2012].

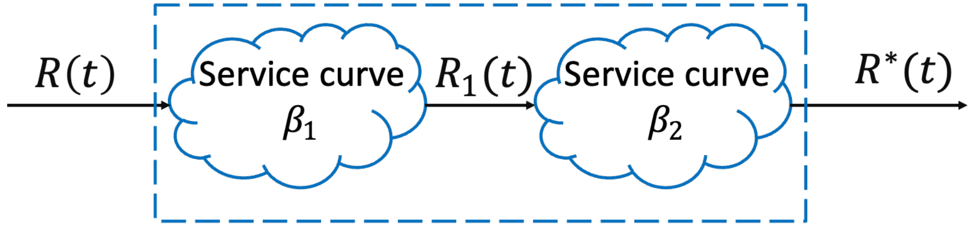
- Can be improved esp. if competing flows are constrained [Tabatabaee 2022]





- Other examples: Packetized Generalized Processor Sharing, RFC 2212, IEEE AVB, IEEE TSN, etc. [De Azua 2014] [Bouillard 2018]

Concatenation



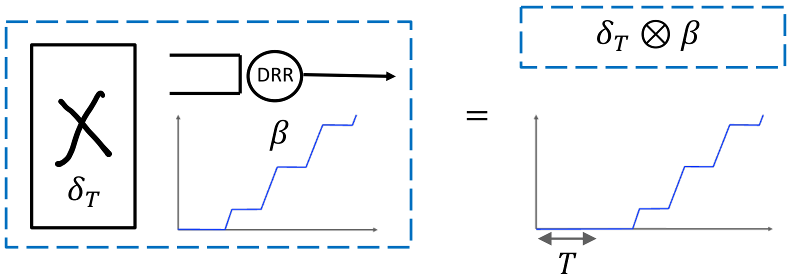
$\beta = \beta_1 \otimes \beta_2$

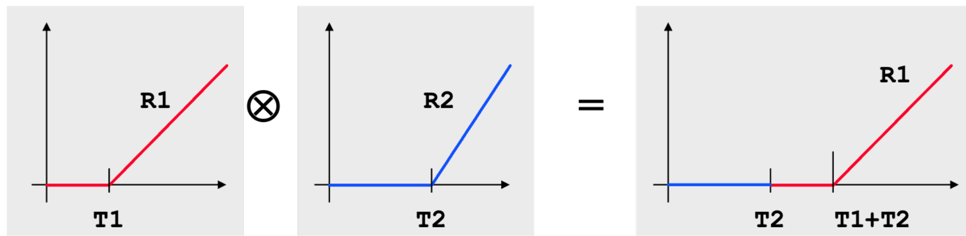
$R^* \geq R_1 \otimes \beta_2 \geq (R \otimes \beta_1) \otimes \beta_2 = R \otimes (\beta_1 \otimes \beta_2)$

Concatenation of service curve elements β_1, β_2 has service curve $\beta_1 \otimes \beta_2$

Examples:

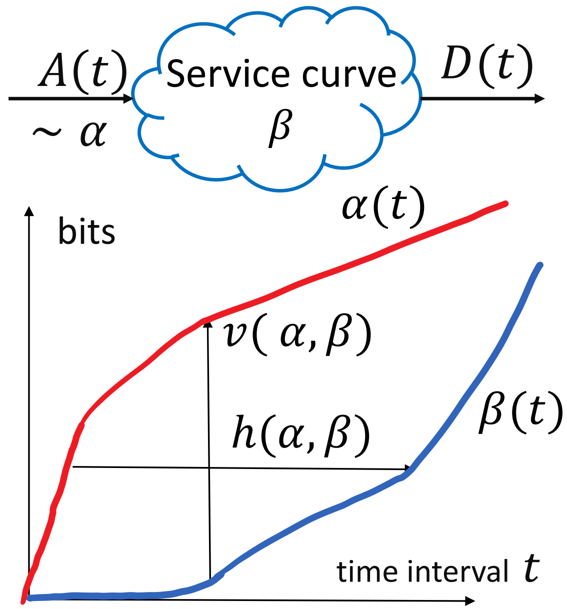
- scheduler with service curve β combined with bounded delay element has service curve $\beta \otimes \delta_T$
- If β_i is rate-latency R_i, T_i then the concatenation $\beta = \beta_1 \otimes \beta_2$ is rate-latency $R = \min(R_1, R_2)$ and $T = T_1 + T_2$





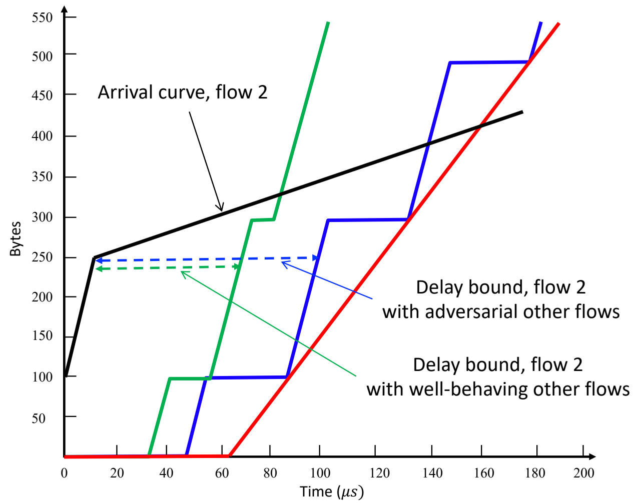
Three Tight Bounds

1. backlog $\leq v(\alpha,\beta) = \sup_t \big(\alpha(t) - \beta(t)\big)$
2. if FIFO for this flow, delay $\leq h(\alpha,\beta)$
3. output is constrained by arrival curve
$$\alpha^*(t) = \sup_{u\geq 0}\big(\alpha(t+u) - \beta(u)\big)$$
i.e. $\alpha^* = \alpha \oslash \beta$ (deconvolution)



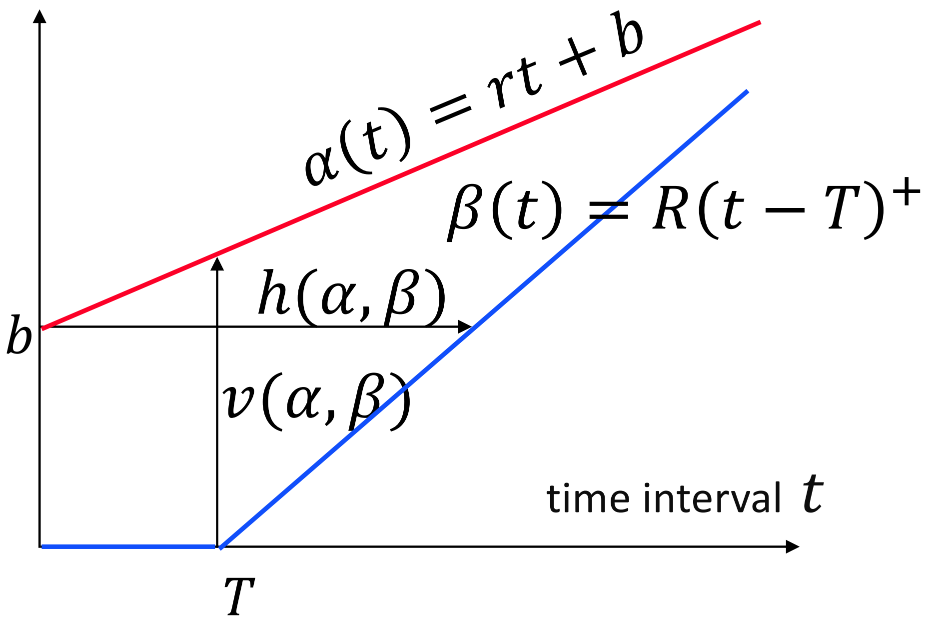
Jitter bound = $h(\alpha,\beta) -$ delay lower bound

Delay bound can be improved to $h(\alpha - L_{min}, \beta) + \frac{L_{min}}{c}$ if we know line rate c of server [Mohammadpour 2019]



Industrial tools perform these computations.

Example



One flow, constrained by one token bucket is served in a network element that offers a rate latency service curve

Assume $r \leq R$

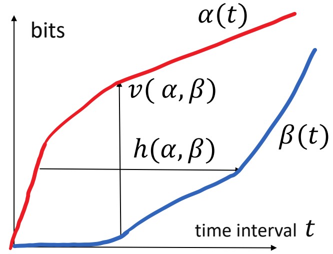
Backlog bound: $b + rT$

Delay bound: $\frac{b}{R} + T$

Output arrival curve:

$$\alpha^*(t) = rt + b^*$$

with $b^* = b + rT$



Network calculus uses arrival curves and service curves to derive delay and backlog bounds.

Single node analysis follows immediately.

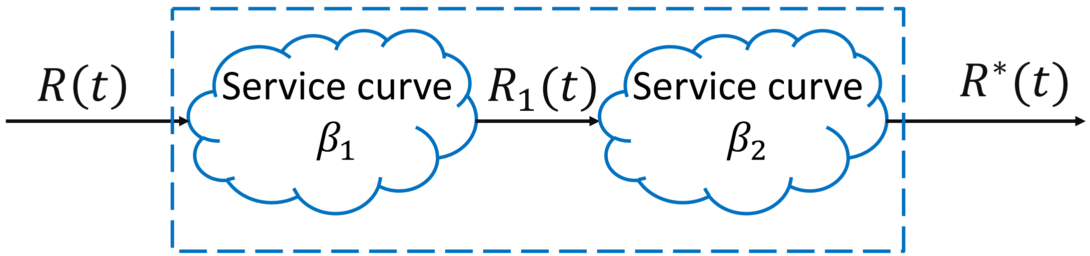
How about network analysis ?

3. Network Analysis

Per-flow network:

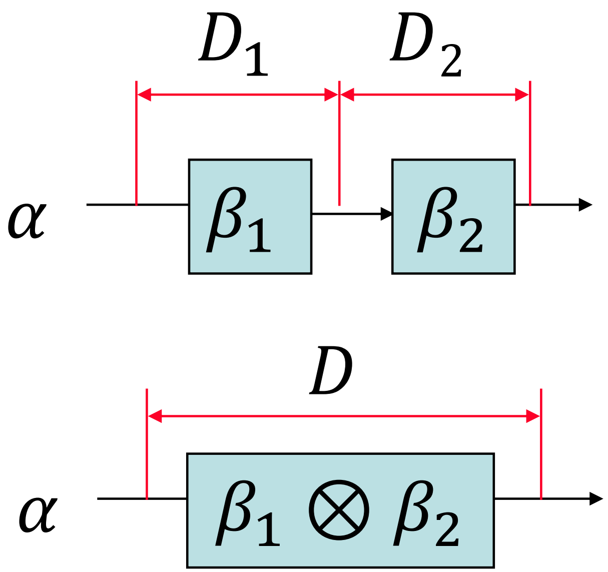
network nodes offer guarantees to individual flows
e.g. IETF IntServ

Solution: apply concatenation result



$$\boxed{\beta = \beta_1 \otimes \beta_2}$$

Pay Bursts Only Once



$$\alpha(t) = rt + b$$
$$\beta_1(t) = R(t - T_1)^+$$
$$\beta_2(t) = R(t - T_2)^+$$
$$r \leq R$$

In per-flow Network:
one flow constrained *at source* by α

end-to-end delay bound computed *node-by-node* (also accounting for increased burstiness at node 2):

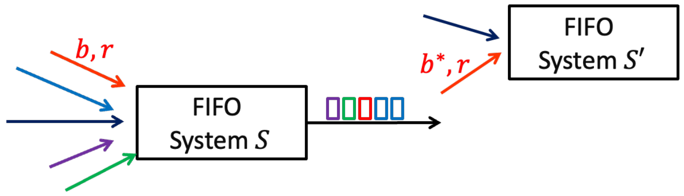
$$D_1 + D_2 = \frac{2b + rT_1}{R} + T_1 + T_2$$

computed *by concatenation:*

$$D = \frac{b}{R} + T_1 + T_2$$

i.e. worst cases cannot happen simultaneously

FIFO Per-Class Networks



Most time sensitive networks are FIFO per-class:

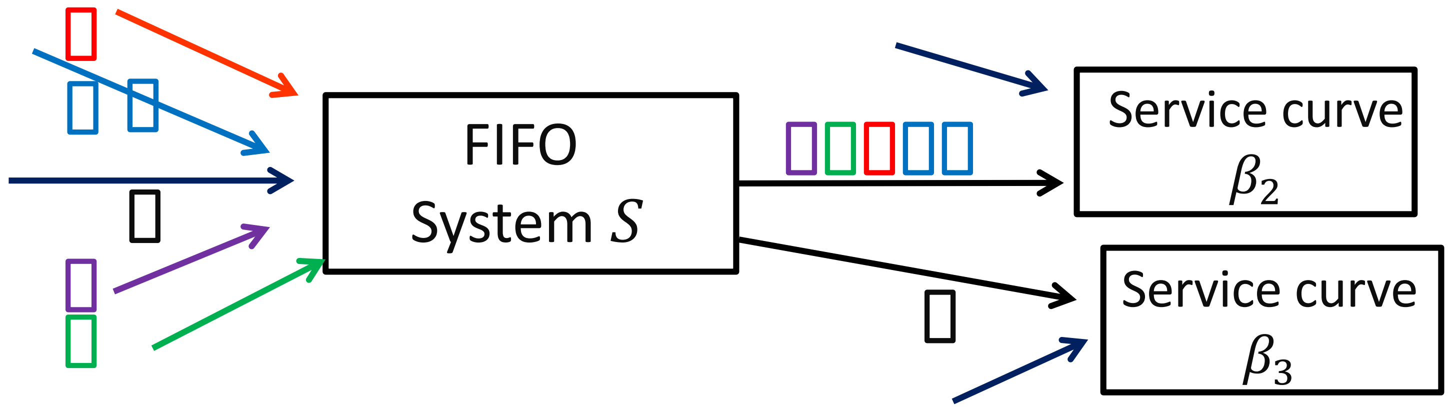
- flows are assigned to classes
- schedulers (such as DRR) separate classes and provide service guarantee to the aggregate of all flows of this class
- Inside a class, service is FIFO
- flows are constrained at sources by arrival curves

Using service curves, such a network can be analyzed per-class

→ one separate FIFO network model per class

Global analysis can also be performed iteratively [Tabatabaee 2023c]

FIFO Networks



this shows only one class;

the service curves are offered to aggregate of all flows.

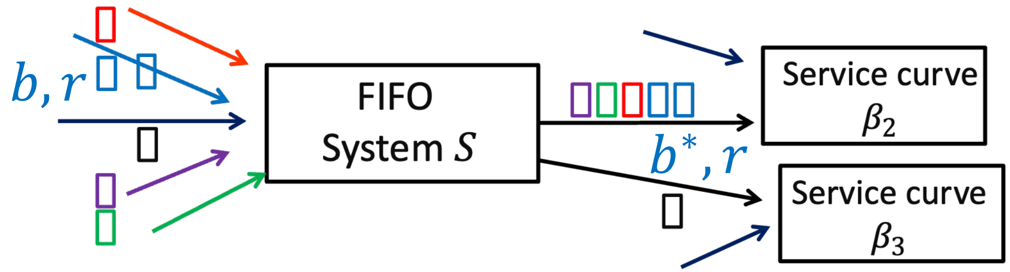
Flows merge and split, no simple result as in per-flow networks.

Feedforward networks: obtaining worst-case delay is NP-hard [Bouillard 2010]

Can be computed with ELP (Exponential Linear Programming) [Bouillard 2014]

- service curve, arrival curve and FIFO are expressed as constraints in a linear program
- super-exponential complexity

Total Flow Analysis (TFA [Schmitt 2006], TFA++ [Mifdaoui 2017])



Simple, commonly used method to analyze a generic deterministic network

- Sources are constrained by token buckets

a) Propagated burstiness of flow inside the network is computed by
$$b^* = b + r \times (\text{delay bound between source and here})$$

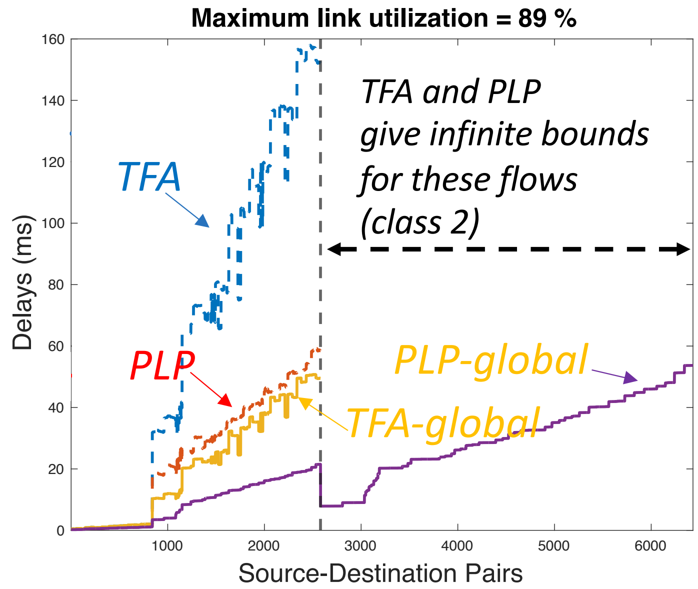
b) Delay at every node uses single node network calculus + propagated burstinesses.

End-to-end delay bound is sum of nodal bounds on path

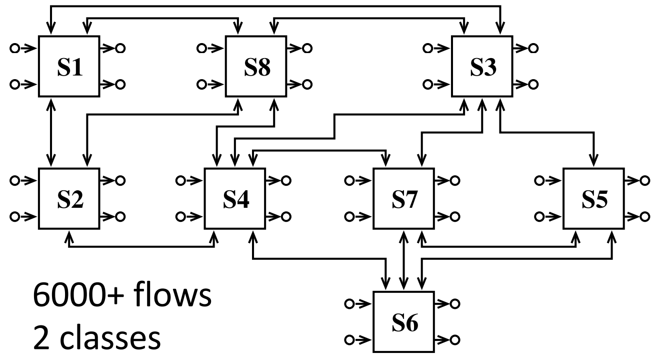
- In a feedforward network of depth d, start at edge nodes and stop in d iterations
- In a generic network, iterate a) and b) at all nodes until convergence to a fixpoint or move to infinity. If convergence, the bounds are valid. If divergence, we don't know. [Thomas 2019, Plassart 2022]
- Optimizations for case with many periodic flows and many different periods [Tabatabaee 2023a]

Polynomial Linear Programming (PLP)

- PLP (Polynomial Linear Programming) [Bouillard 2022]: relaxation of ELP, with polynomial complexity, uses TFA (and other) bounds as constraints, applies to generic topologies. Usually much better than TFA.
- Refinements analyze all classes together (limited inter-class interference) [Tabatabaee 2023c].



- Other methods : SFA [Schmitt 2006, Grieu 2004], PMOO, LUDB [Fidler 2003, Lenzini 2006, Bondorf 2017,Geyer 2022] do not apply to generic topologies;



6000+ flows
2 classes
[Tabatabaee 2023c]

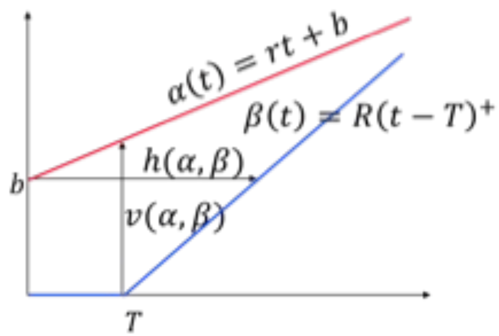
- Tools: DISCO [Schmitt 2006], WoPaNets [Mifdaoui 2010], Pegase [Boyer 2010]

Stability of a FIFO Network

Every flow $f \in \mathcal{F}$ constrained by $\alpha_f(t) = r_f t + b_f$ at source. Route of flow f is fixed. $F_i \subset \mathcal{F}$ is the set of flows passing through node i. Every node $i \in \mathcal{I}$ is FIFO and offers to the aggregate of flows $f \in F_i$ a service curve $\beta_i(t) = R_i(t - T_i)^+$. Load factor $u = \max_i \left(\frac{\sum_{f \in F_i} r_f}{R_i} \right)$. $\mathcal{F}, \mathcal{I}$ finite. Network underloaded: $u < 1$; overloaded: $u > 1$; critical: $u = 1$.

One network instance $= (\mathcal{F}, r, b, F, \mathcal{I}, R, T)$ is stable if there is a bound on all delays (or backlogs), that is valid for any execution trace of the network.

- An overloaded FIFO network is not stable. A feed-forward network that is underloaded or critical is stable.
- For any $\varepsilon > 0$ there is an unstable underloaded FIFO network with load factor $u < \varepsilon$ [Andrews 2009]
- Every underloaded ring is stable [Tassiulas 1996].



When PLP or TFA does not converge, it may be that network is truly unstable or not.

Stability conditions are still an open research issue.

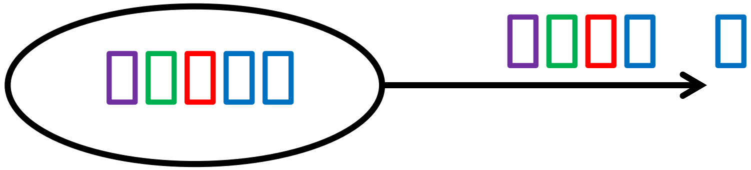
In per-flow networks, deterministic Network analysis is as simple as single node.

In per-class networks and arbitrary topologies, algorithms typically require finding fixpoints (with e.g. TFA or PLP).

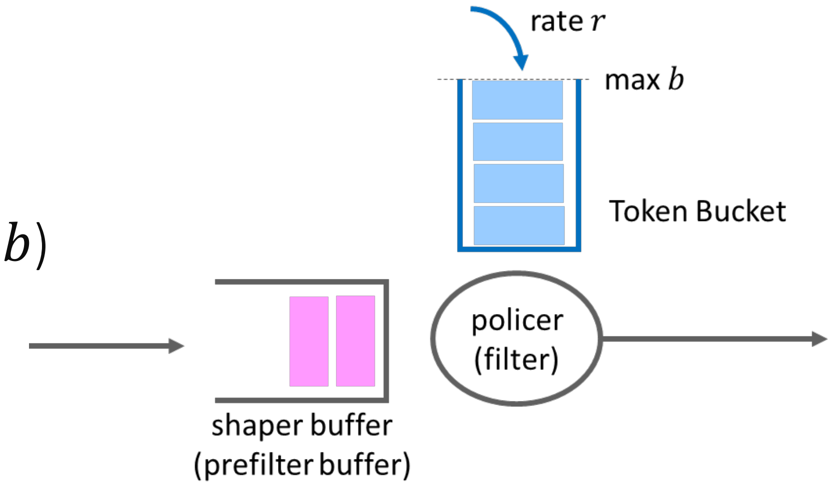
Underloaded networks may be unstable.

4. Regulators

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



Non work-conserving.



Example: Token Bucket regulator
(regulator for the arrival curve constraint $\alpha(t) = rt + b$)

Typically placed at source / network edge to protect deterministic network from misbehaving sources

Can also be used inside the network

Cascading Burstiness

In a per-flow network, burstiness of a flow increases linearly with number of hops, but pay-bursts-only allows to still have good delay bounds.

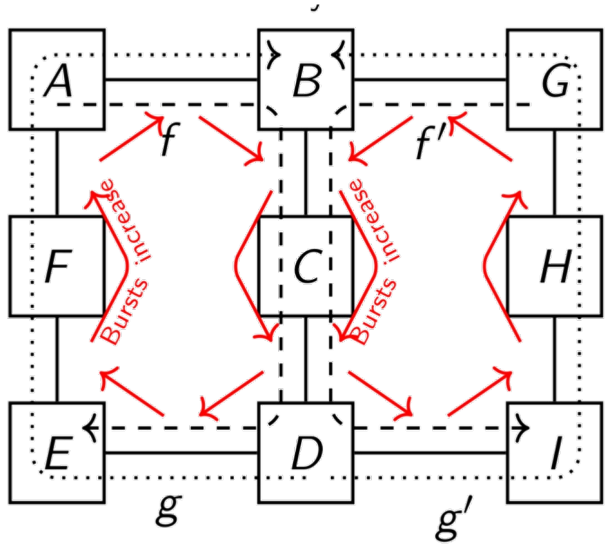
In per-class networks, burstiness of every flow increases at every hop as a function of other flows' burstiness:

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

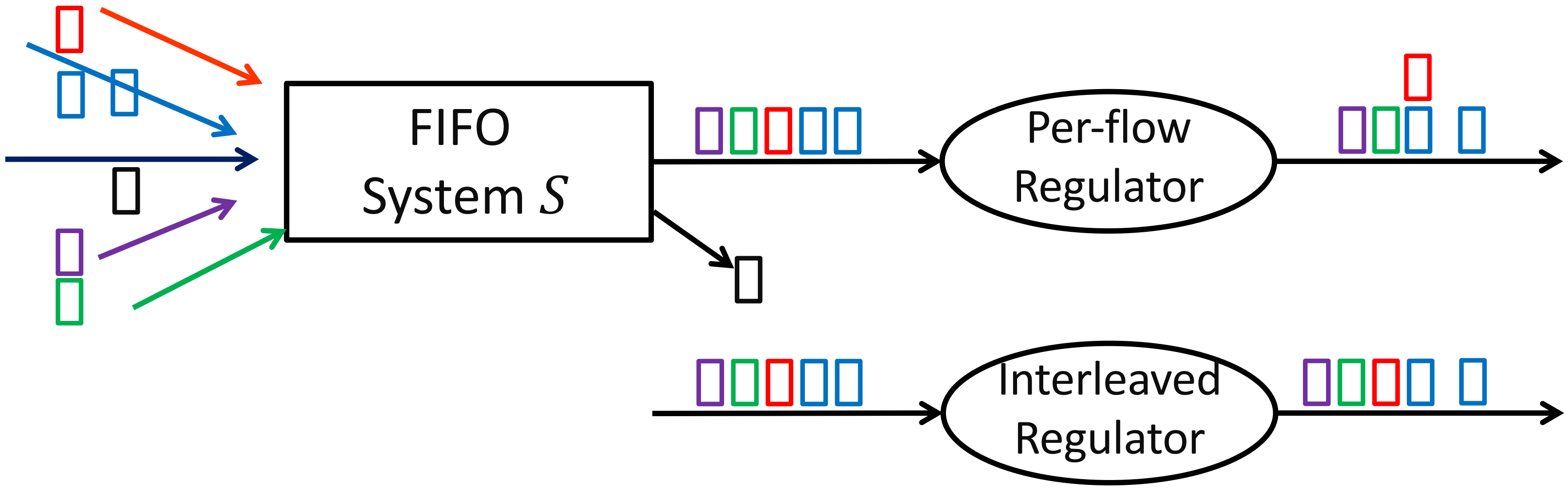
Increased burstiness causes increased burstiness (cascade).

Propagated burstiness is computed by PLP / TFA as solution to a fixpoint problem.

Cyclic dependencies are root cause for bad worst-case delays.



Regulators Avoid Cascading Burstiness in Per-Class Networks

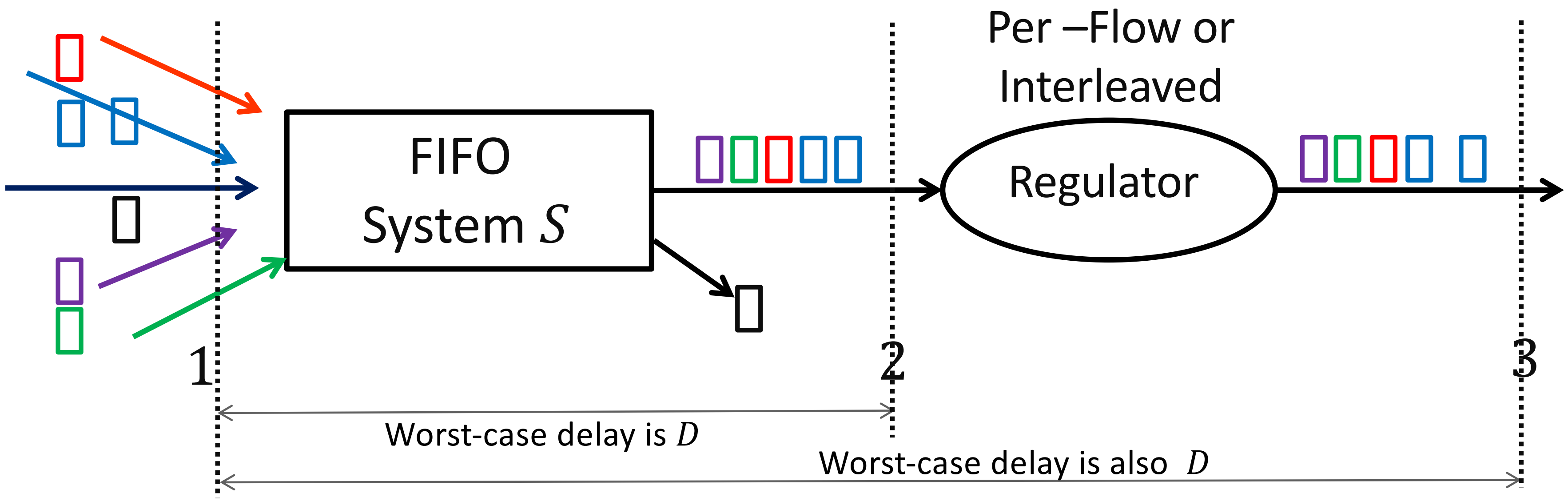


Per flow regulator: one state + one queue per flow.

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 2016].

Regulators do not Increase Worst Case Delay



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

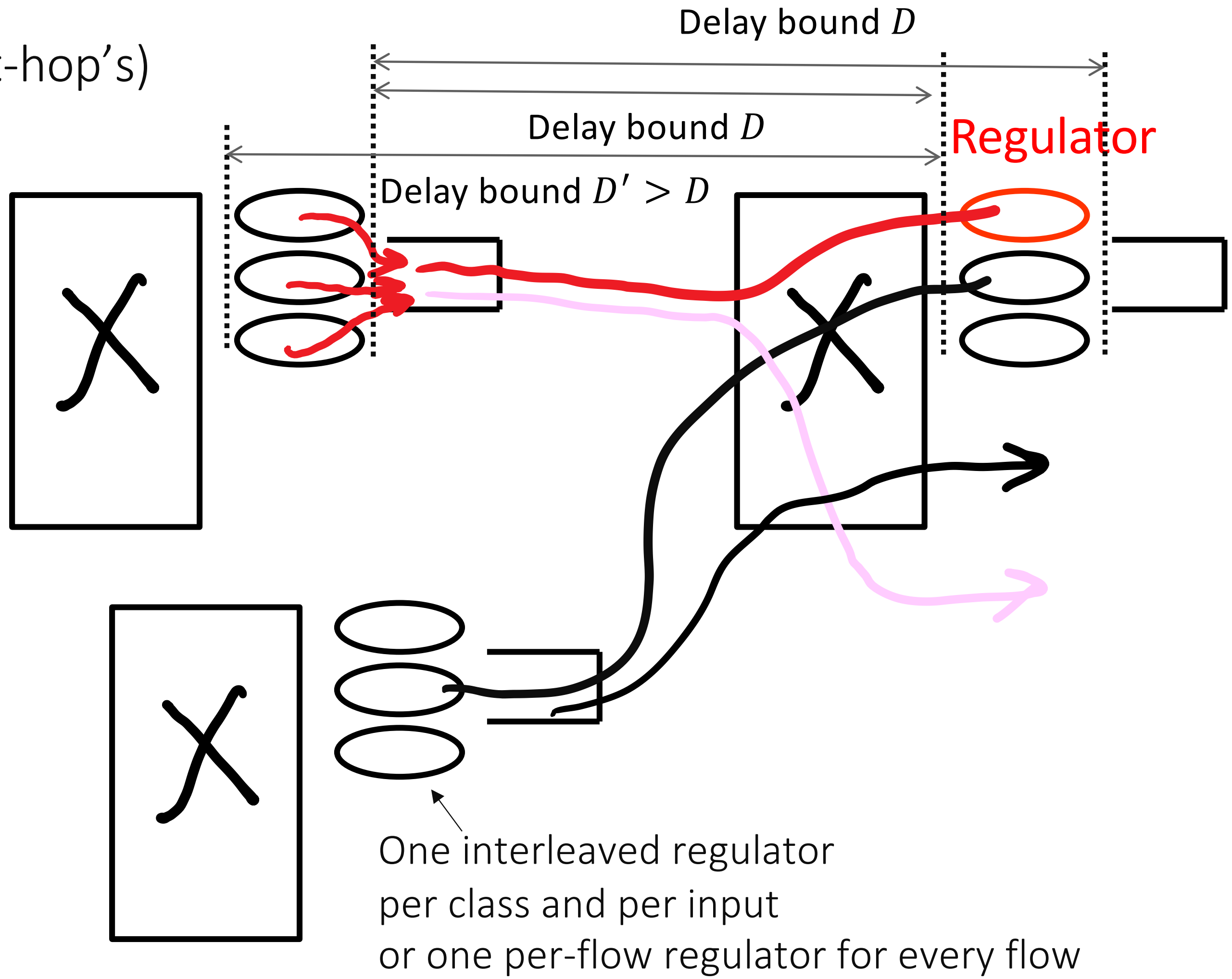
Assume every flow satisfies some arrival constraint at 1 (e.g. rate and burstiness) and regulators enforces same constraint at 3.

The worst case delay $1 - 3$ is the same as the worst-case delay $1 - 2$ [Le Boudec 2018]. (Reshaping-for-free property)

Network With Regulators [IEEE TSN ATS]

- Regulators are integrated in (next-hop's) queuing system.
- Worst case end-to-end queuing delay can ignore regulators. Worst-case delay at one regulator is absorbed by delay bound at previous hop.
- Queuing delay and backlog at every hop can be computed using single node analysis.
- Underloaded network is always stable.

[Mohammadpour 2018]



Deterministic networks use regulators at edge to protect determinism

Can also be deployed internally to avoid burstiness increase / to simplify network analysis

Re-shaping is for free (w.r. to worst-case delay)

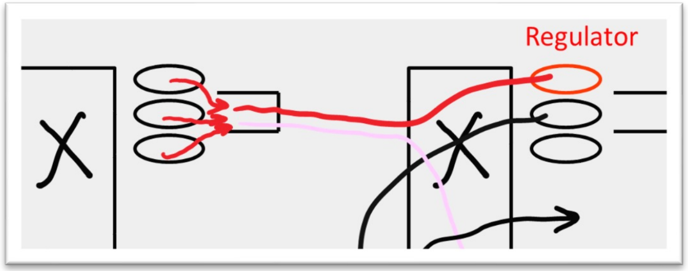
5. Clock Non Idealities

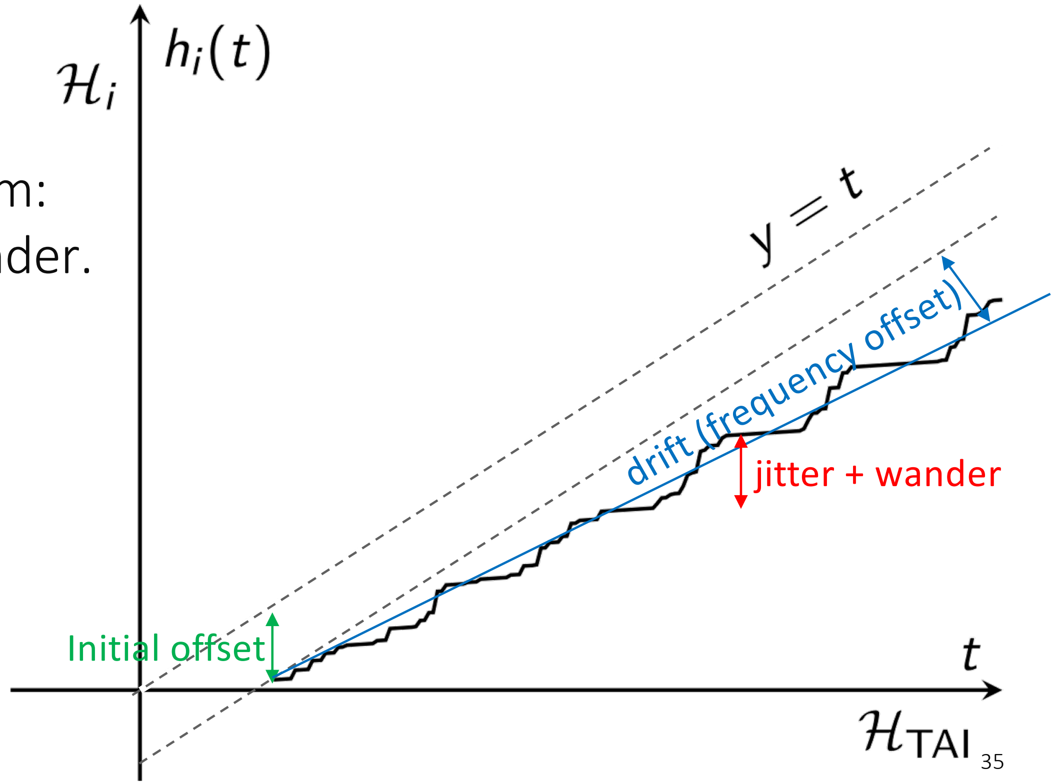
Previous theory assumes perfect time everywhere.

In reality, nodes use local clocks that are not ideal.

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

[ITU-T 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]

Measurement of a time interval 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 change-of-clock inequalities

$$\boxed{\max\left(0, \frac{d-\eta}{\rho}, d - 2\omega\right) \leq d' \leq \min(\rho d + \eta, d + 2\omega)}$$

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

Relative error on estimation of delays is, in general, $\approx 10^{-4}$, i.e. negligible. However there are some corner cases.

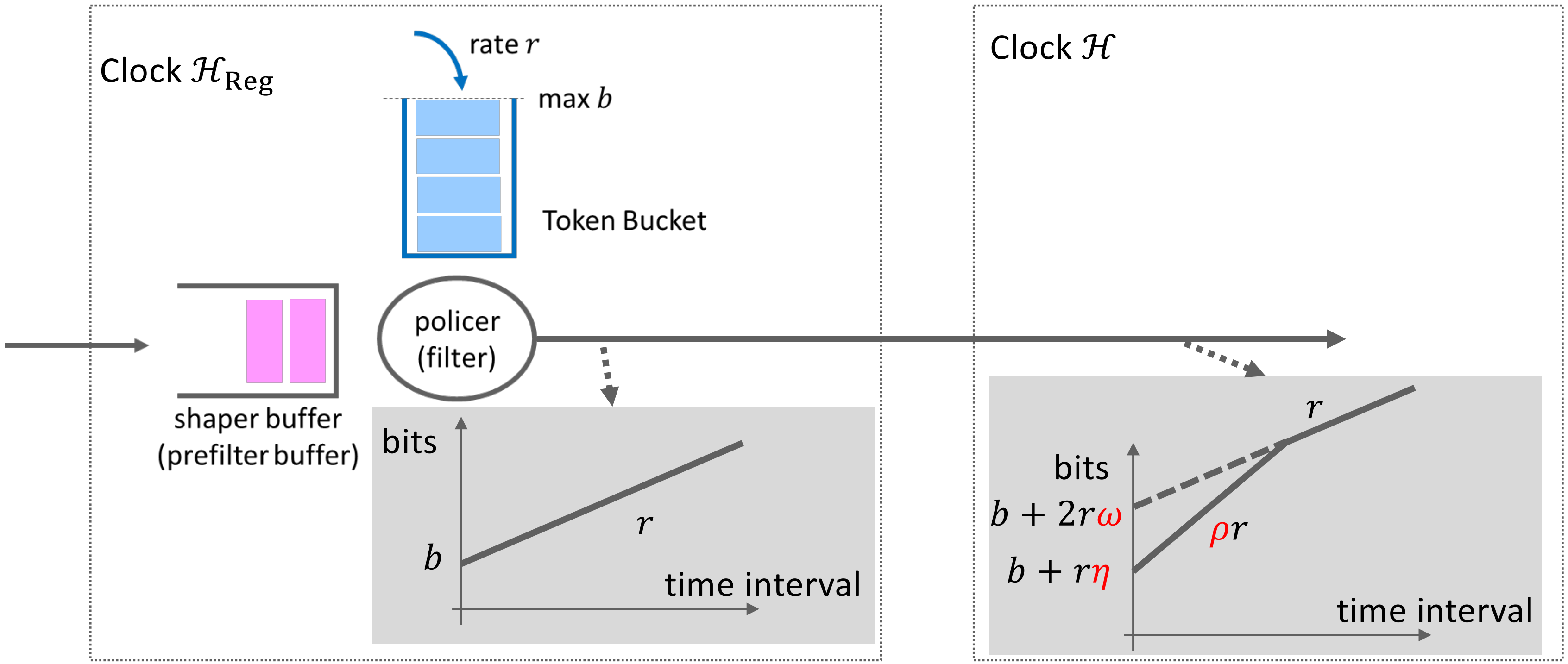
$\omega =$ time error bound
= 1μs in TSN with PTP;
= $+\infty$ if no synchronization

$\rho =$ clock-stability bound
=1.0001 (e.g. in TSN)

$\eta =$ timing-jitter bound
= 2ns (e.g. in TSN)

Change of Clock: Arrival Curves

Assume a flow satisfies a token bucket constraint (r, b) when observed with clock $\mathcal{H}_{\text{Reg}}$
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
$\alpha^{\mathcal{H}}(t) = \min(\rho rt + b + r\eta, rt + b + 2r\omega)$



Consequences for Non-Adapted Regulators [Thomas 2020]

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

Perfect clocks:

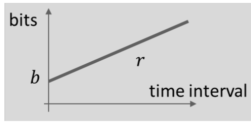
- Regulator does not increase worst-case delay

Non-synchronized network:

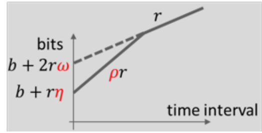
- Per-flow and interleaved regulator unstable (unbounded delay).

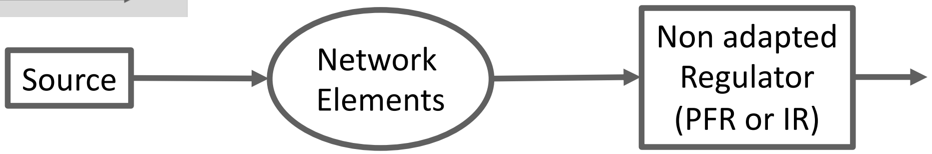
Synchronized network:

- Per-flow regulator incurs delay penalty up to 4ω;
- Interleaved regulator is unstable
  $\Rightarrow$ must be adapted,
  e.g. with rate-and-burst cascade



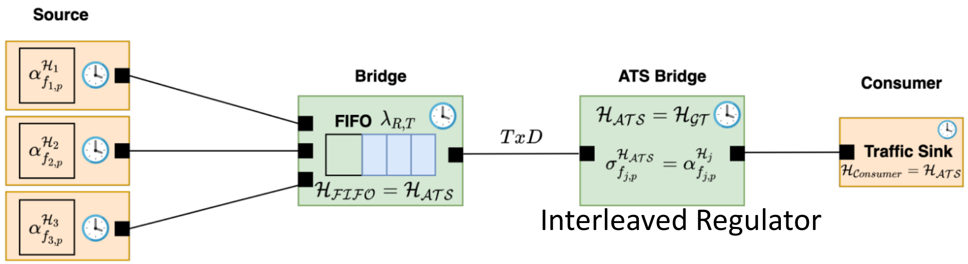
In regulator's clock, flow satisfies this constraint at source



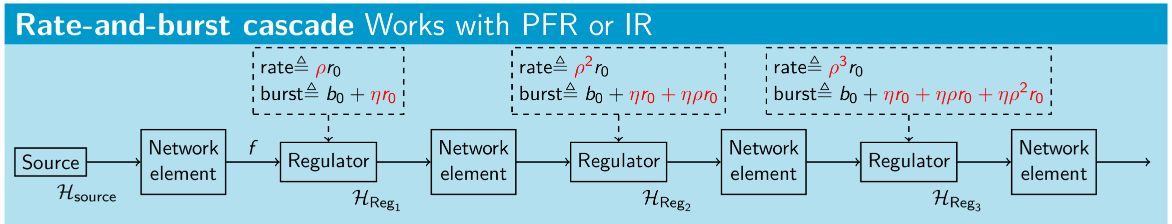


Flow constrained by $\alpha(t) = rt + b$ in local clock

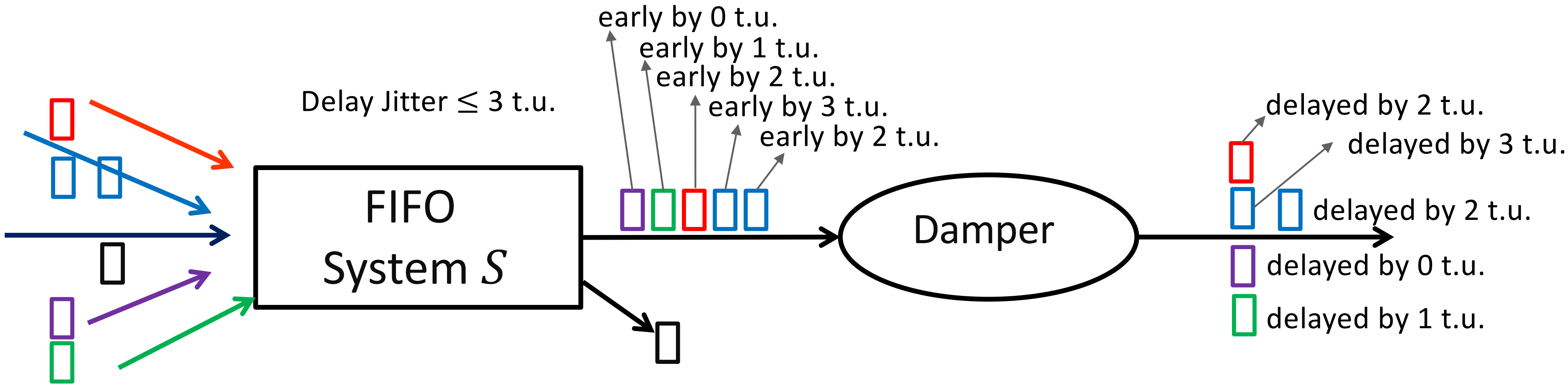
Implements constraint $\alpha(t) = rt + b$ in local clock



Ns3 simulation – Guillermo Aguirre and Ludovic Thomas
3 sources @ 147 kb/s, $\omega = 1\mu$s, $\rho = 1.0001$; Delay increases by up to 100μs per second.



Dampers



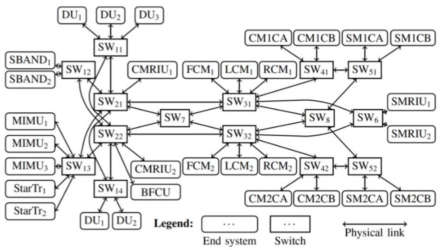
Damper delays a packet by “earliness” read from packet header.

Removes most of jitter, with some residual jitter dependent on tolerance, not on traffic $\Longrightarrow$ also removes burstiness cascade.

Non work-conserving. Like a per-flow regulator, does not exist in isolation, is combined with queue at next hop.

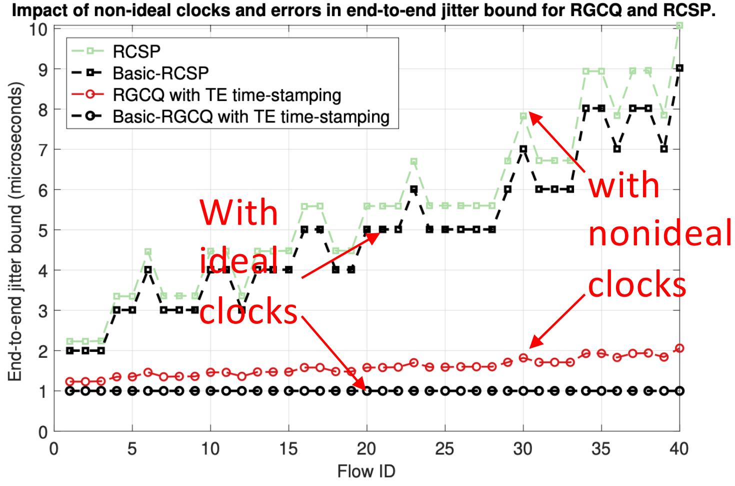
Unlike regulator, is stateless.
[Cruz 1998] RCSP [Zhang 1993], RGCQ [Shoushou 2020], ATS with Jitter Control [Grigorjew 2020].

Consequences for Dampers

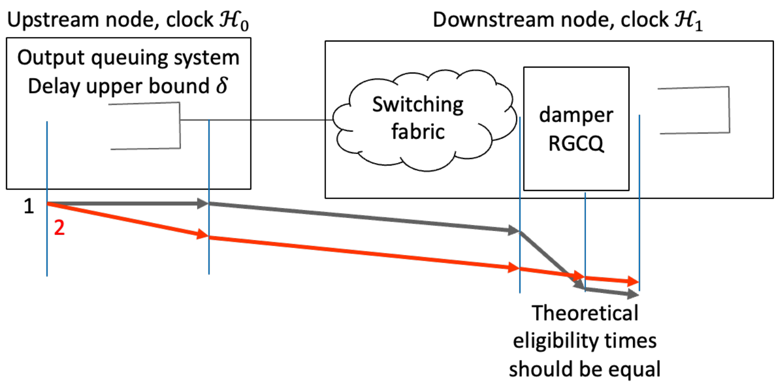


Residual jitter is somehow affected by clock inaccuracies

Impact of non-ideal clocks and errors in end-to-end jitter bound for RGCQ and RCSP.



Timing inaccuracies may lead to mis-ordering



Two consecutive packets should be released by damper at ca. the same time, timing inaccuracies may lead to inversion of order

⇒ Some dampers enforce per-flow packet order (e.g. FOPLEQ, ATS with Jitter Control [Grigorjew 2020]) - work properly only if all network elements are FIFO per flow

[Mohammadpour 2022]

Clock non idealities can easily be accounted for in a network calculus analysis

Both for synchronized and non-synchronized networks

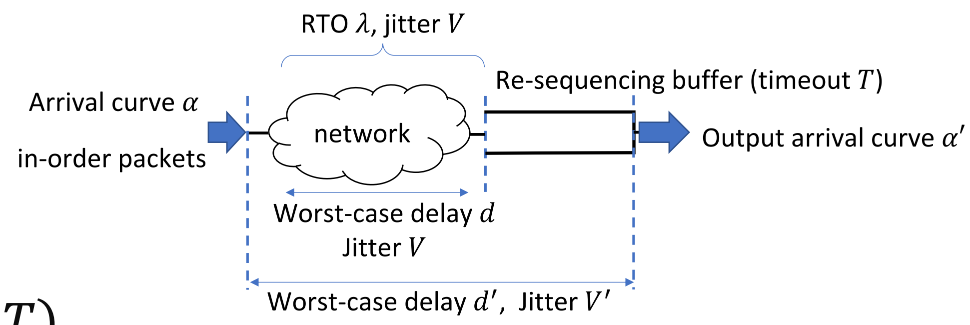
Arrival curves and delay bounds are (very slightly) affected, but dampers and regulators are dramatically affected and need to provision safety mechanisms

6. More Bells and Whistles

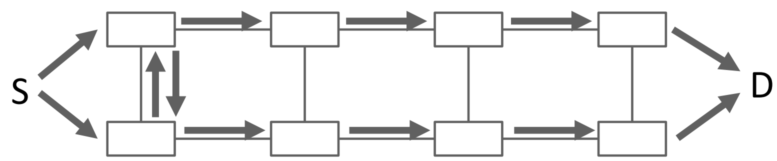
Packet re-ordering due to e.g. multi-paths, packet replication, dampers.

⇒ Re-sequencing buffers are used. Network calculus was extended to account for them [Mohammadpour 2021]

- Lossless network:
  $d' = d, V' = V$ and $\alpha'(t) = \alpha(t + V)$
  (re-sequencing is for free)
- Lossy network:
  $d' = d + T, V' = V + T$ and $\alpha'(t) = \alpha(t + V + T)$.



Packet replication and removal is used to repair non-congestion losses. It causes causes mis-ordering and increases burstiness. Network calculus was extended to account for this [Thomas 2022]



Any combination of failures that leaves at least one path up is masked (“0 msec repair”) [IEEE 802.1CB]

Stochastic Network Calculus ...

nb bits observed in $[s, t)$

Stochastic arrival curves [Ciucu 2012]

$$\text{SBB: } \forall s \le t, \sigma > 0\text{: } \mathbb{P}(\boxed{A(s,t)} > f(t-s) + \sigma) \le \varepsilon(\sigma)$$

$$\text{S}^2\text{BB: } \forall t, \sigma > 0\text{: } \mathbb{P}\left(\sup_{s \le t} A(s,t) > f(t-s) + \sigma\right) \le \varepsilon(\sigma)$$

$$\text{S}^3\text{BB: } \forall \sigma > 0\text{: } \mathbb{P}\left(\sup_{s \le t} A(s,t) > f(t-s) + \sigma\right) \le \varepsilon(\sigma)$$

S^2BB obtains $\mathbb{P}(Q(t) \le b)$ for any arbitrary t [Vojnovic 2003].

S^3BB obtains $\mathbb{P}(\forall t, Q(t) \le b)$

cannot apply nontrivially to ergodic processes, but applies to periodic sources [Tabatabaee2023b]

Stochastic service [Jiang 2008, Fidler 2015, Nikolaus 2019] uses MGF bounds. [Zhang 2022] models wireless links.

Tools

- The DiscoDNC is an academic Java implementation of the network calculus framework.[10]
- The RTC Toolbox is an academic Java/MATLAB implementation of the Real-Time calculus framework, a theory quasi equivalent to network calculus.[4][11]
- The CyNC[12] tool is an academic MATLAB/Symulink toolbox, based on top of the RTC Toolbox. The tool was developed in 2004-2008 and it is currently used for teaching at Aalborg university.
- The RTaW-PEGASE is an industrial tool devoted to timing analysis tool of switched Ethernet network (AFDX, industrial and automotive Ethernet), based on network calculus.[13]
- The WOPANets is an academic tool combining network calculus based analysis and optimization analysis.[14]
- The DelayLyzer is an industrial tool designed to compute bounds for Profinet networks.[15]
- DEBORAH is an academic tool devoted to FIFO networks.[16]
- NetCalBounds is an academic tool devoted to blind & FIFO tandem networks.[17][18]
- NCBounds is a network calculus tool in Python, published under BSD 3-Clause License. It considers rate-latency servers and token-bucket arrival curves. It handles any topology, including cyclic ones.[19]
- The Siemens Network Planner (SINETPLAN) uses network calculus (among other methods) to help the design of a PROFINET network.[20]
- experimental modular TFA (xTFA) is a Python code, support of the PhD thesis of Ludovic Thomas[21]
- Panco is a Python code that computes network calculus bounds with linear programming methods.
- Saihu is a Python interface that integrates three worst-case network analysis tools: xTFA, DiscoDNC, and Panco.
- CCAC is an SMT-solver based tool to verify the performance properties of congestion control algorithms (CCAs) using a network-calculus-like model

sampled on 2024 September 11 from https://en.wikipedia.org/wiki/Network_calculus

Conclusion

Time Sensitive Networks require deterministic, proven bounds on delay, jitter, backlog and re-ordering.

Network Calculus provides a rigorous theory and software tools for computing such bounds and for understanding operation of regulators, dampers, re-sequencing buffers or packet elimination functions.

Clock non-idealities can easily be incorporated. Regulators and dampers are affected, other systems not.

Stochastic Network calculus promises to apply to wireless networks.

Thank You !

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