# Time Sensitive Networks, Network Calculus and Clock Non-idealities

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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.

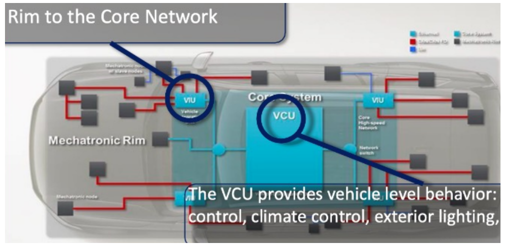
# Contents

# 1. Time Sensitive Networks

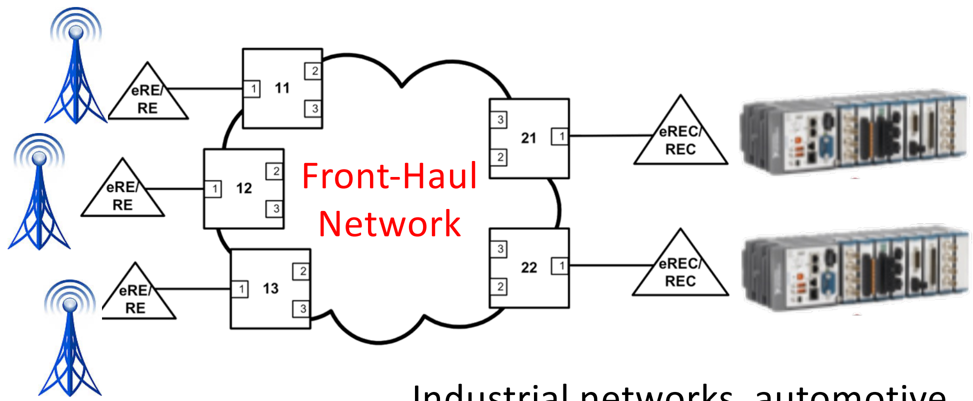
= deterministic service: upper bounds on end-to-end delay and delay-jitter + zero congestion loss.

Congestion control with feedback is not an option here.

Proven bounds are required.




From [Navet et al,2020]




Radio Equipment

**Standardization**:

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

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 ?

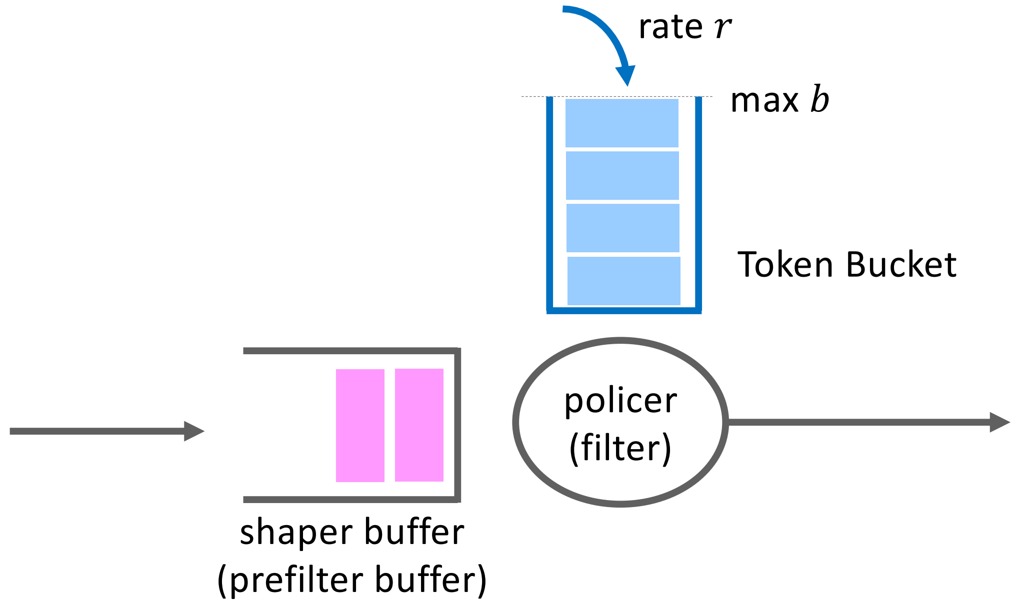
1. Every flow is constrained at source

   e.g. source is periodic

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

   → number of bits sent over any interval of any duration $t$ is $\leq rt+b$

   (*arrival curve* constraint) (T-SPEC)



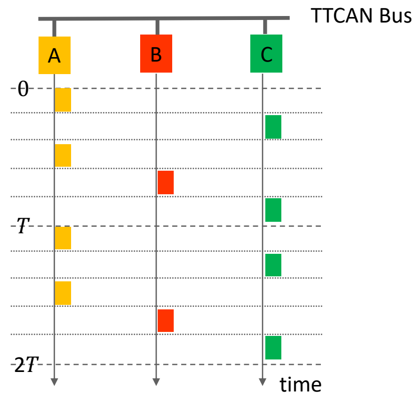

*Imagine* a token bucket, spontaneously replenished at rate $r$ up to maximum $b$ (called the "burst")

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

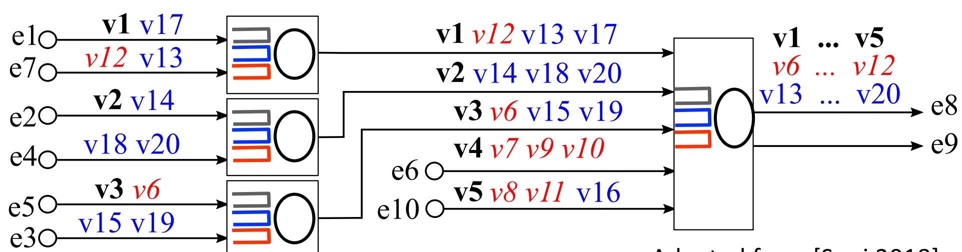



2. The network nodes offer a guaranteed service to flows or classes of flows

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

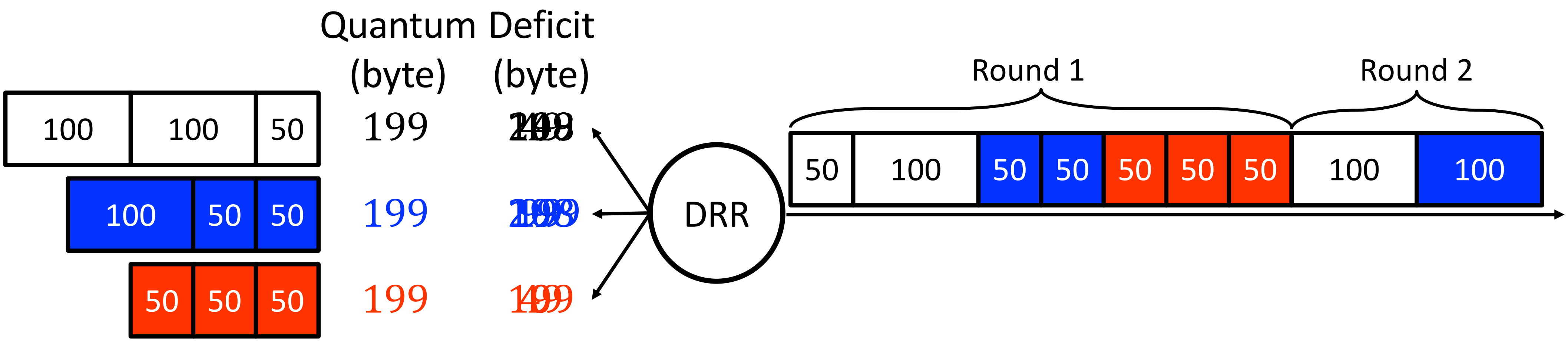
   asynchronous: e.g. switch/router network

   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.

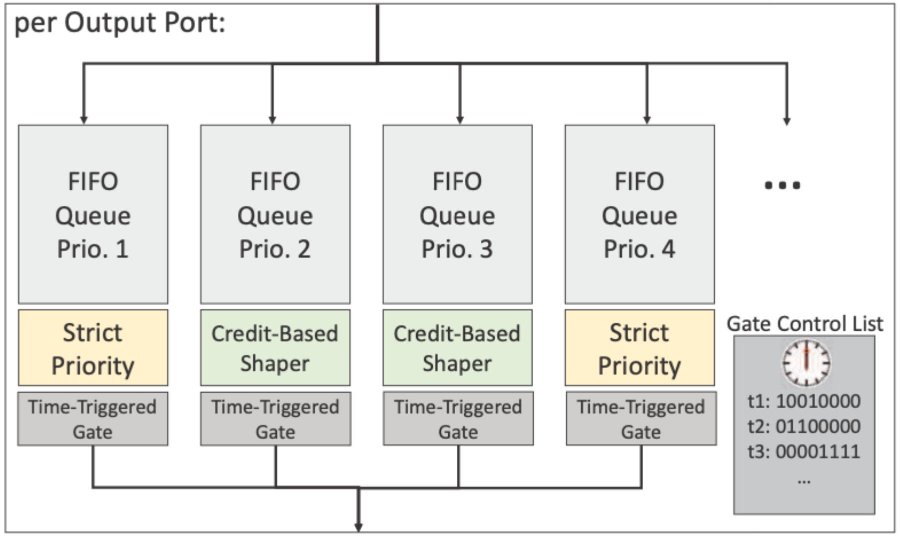
Service for this queue stops if 1) deficit is smaller than head-of-line packet or 2) queue becomes empty (in which case deficit is reset).

⇒ ≈ Bandwidth is allocated to every class in proportion of the quantum.

# Other Schedulers

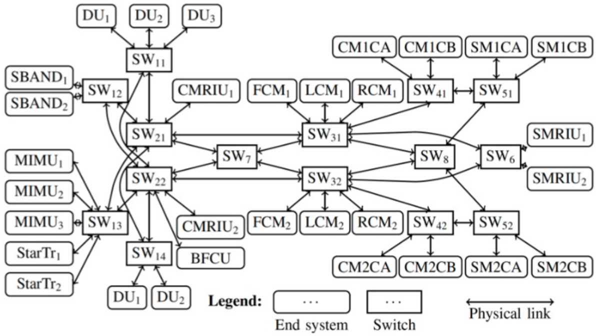
- Weighted Fair Queuing and all variants of Generalized Processor Sharing (such as DRR)
- Audio Visual Bridging (AVB) / Credit Based Shaper (CBS)
- Burst Limiting Shaper
- Time Aware Shaper
- Static Priority

Etc.




Typical IEEE TSN scheduler. From [Maile 2020]

They can be combined.

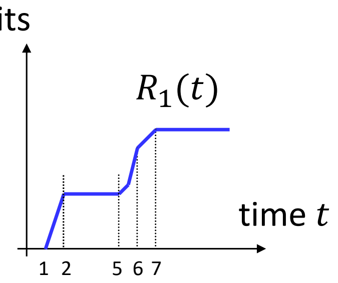



From [Zhao 2018]

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

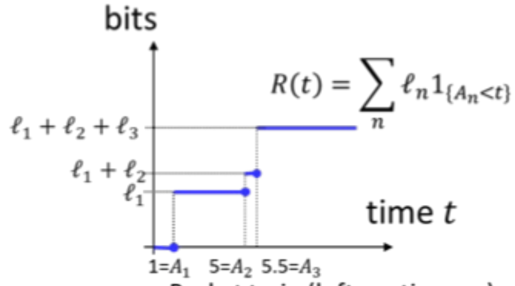
# 2. Analysis of Deterministic Networks uses Network Calculus

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

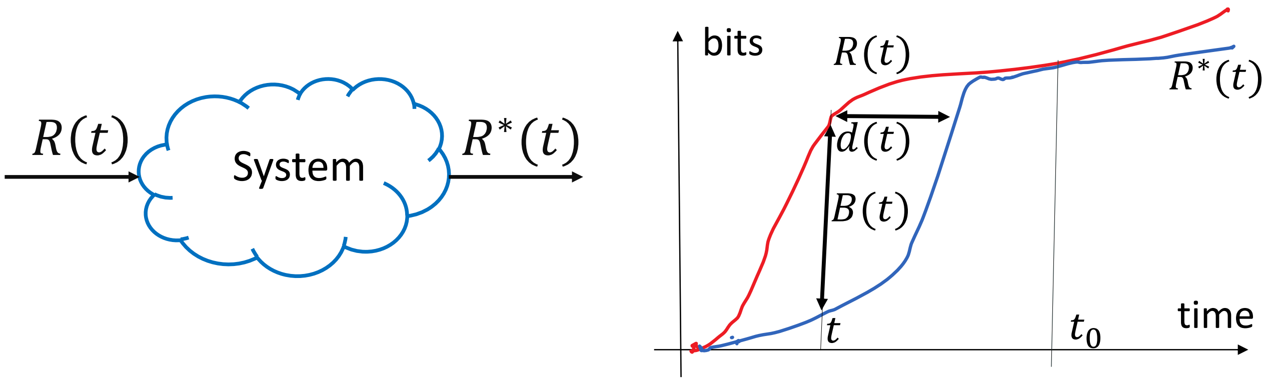


Fluid model (continuous)

- 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 $\alpha$ as (maximal) arrival curve if

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

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

$\alpha$ 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

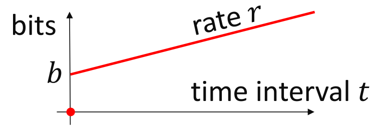
$$A_n - A_m \geq \alpha^{\downarrow}(\ell_m + \cdots + \ell_n), \forall m, n, 1 \leq m \leq n$$

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

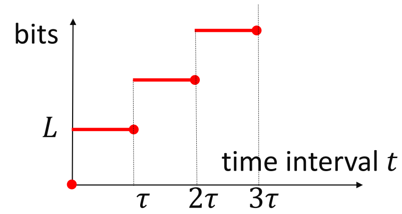
E.g. for $\alpha(t) = rt + b$, $\alpha^{\downarrow}(x) = \frac{(x-b)^+}{r}$

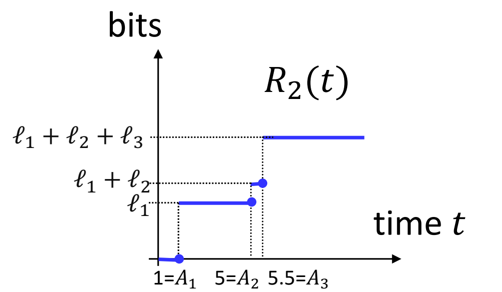
[Le Boudec 2018]

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



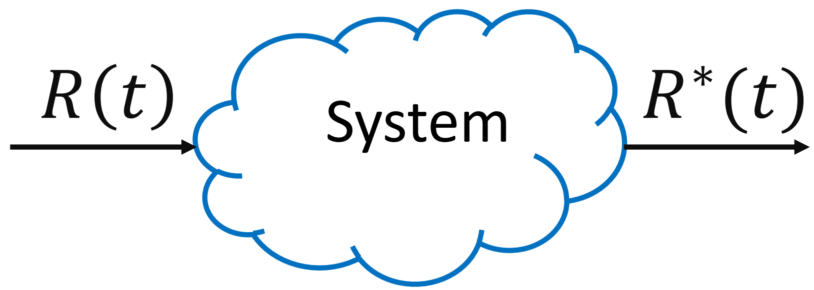

periodic stream of packets of size $\leq L$: $\alpha(t) = L \left\lceil \frac{t}{\tau} \right\rceil$




Packet train (left continuous)

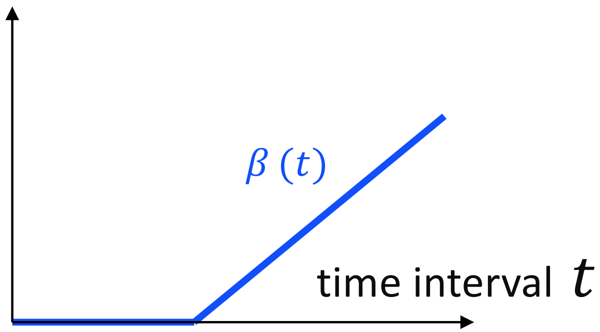
## Service Curve

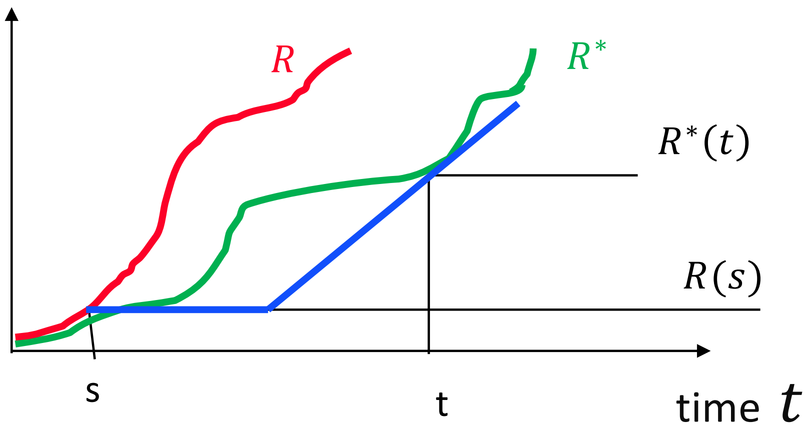



System offers to this flow a (minimal) service curve $\beta$ if $R^* \geq R \otimes \beta$ , i.e. :

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

where $\beta$ is a function : $\mathbb{R}^+ \to \mathbb{R} \cup \{+\infty\}$

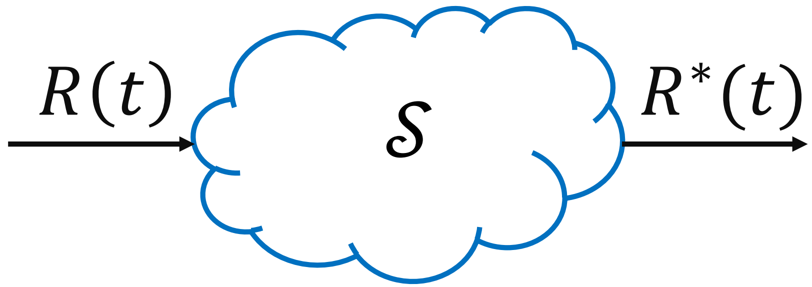



[Le Boudec 1996, Chang 1997, Bouillard 2018]

## Strict Service Curve

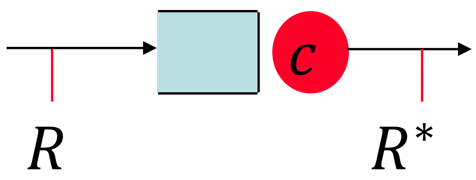
System $\mathcal{S}$ offers to a flow a strict service curve $\beta$ if for any $s < t$ inside a backlogged period, i.e. such that $R^*(u) < R(u), \forall u \in (s, t]$, we have $R^*(t) - R^*(s) \geq \beta(t - s)$




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

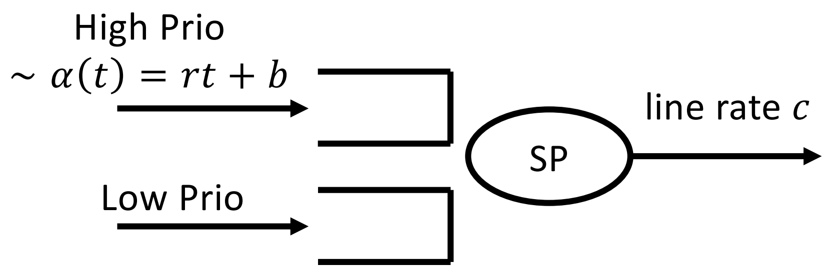
$\beta$ is a strict service curve $\Rightarrow$ $\beta$ is a service curve but converse is not true.

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

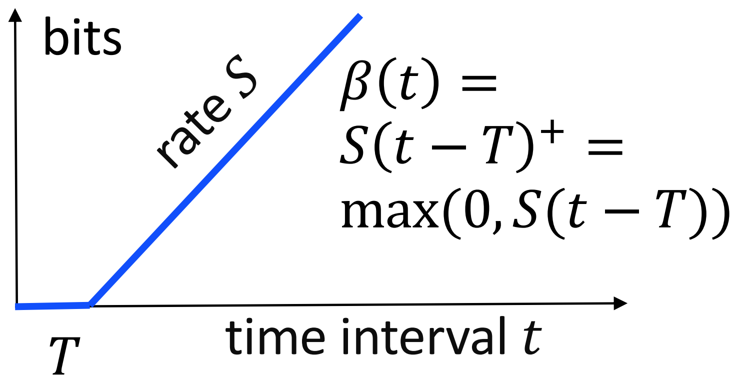


# Example: Non-preemptive Static Priority

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

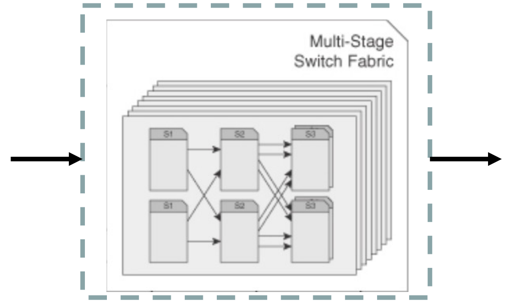



Low prio: when high priority constrained by $\alpha(t) = rt + b, r < c$:
$\beta_L(t) = ((c - r)t - b)^+$ (not a strict service curve)
$\beta'_L(t) = \left((c - r)t - b - MTU_L\right)^+$ (strict service curve)
[Bouillard 2018]




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

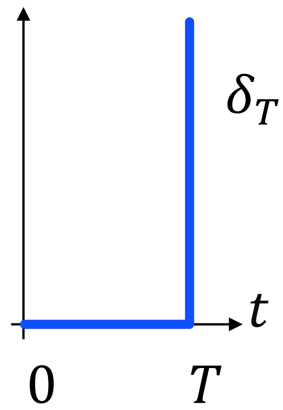
# Bounded Delay Element




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

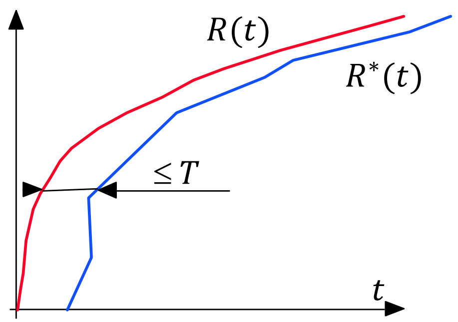
Sometimes it is convenient to model a system as a black box with known delay upper bound $T$.

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




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

Not a strict service curve

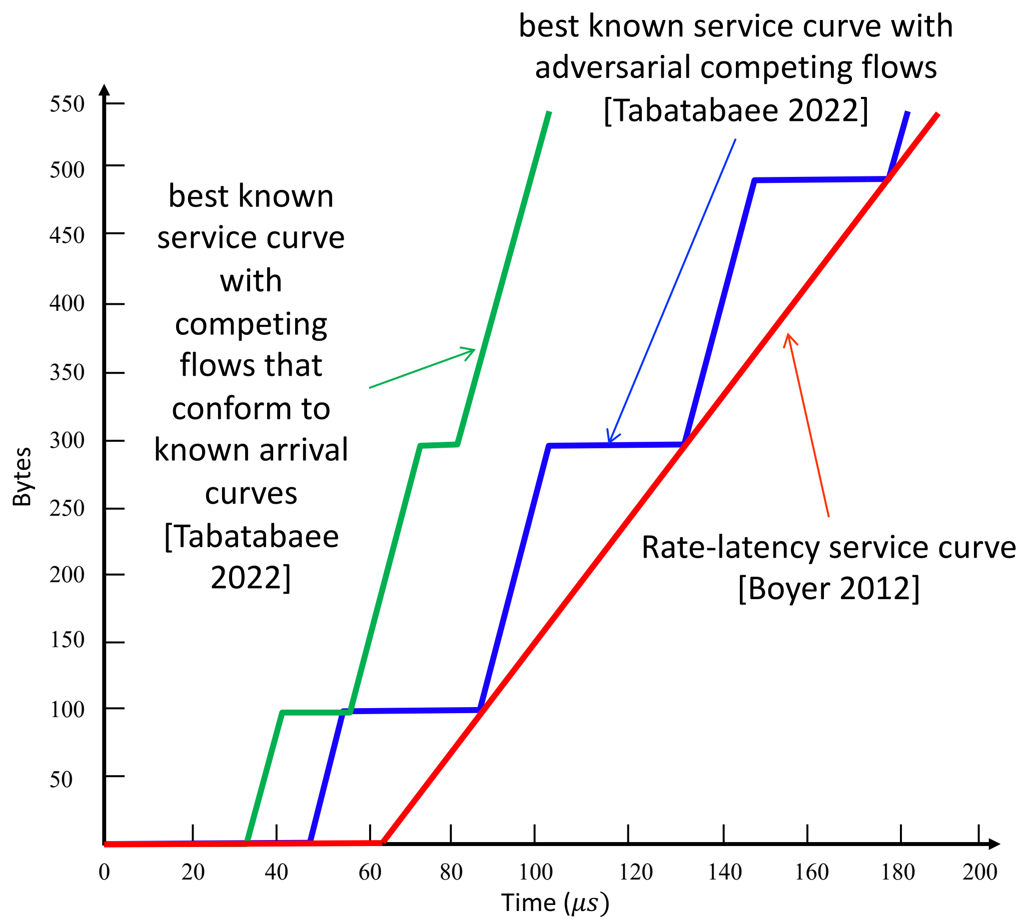


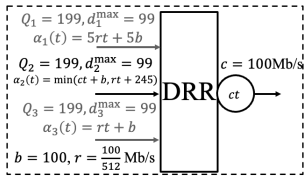
# Example: Deficit Round Robin

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

  with $R_i = \frac{Q_i}{\sum_j Q_j} c, \quad T_i = \frac{\bar{Q}_i + \bar{L}_i}{c} +$ $L_{\max,i}(\frac{1}{R_i} - \frac{1}{c}),\ \bar{Q}_i = \sum_{j \neq i} Q_j,\ \ \bar{L}_i = \sum_{j \neq i} L_{\max,j}$ and $c$ is the line rate [Boyer 2012].

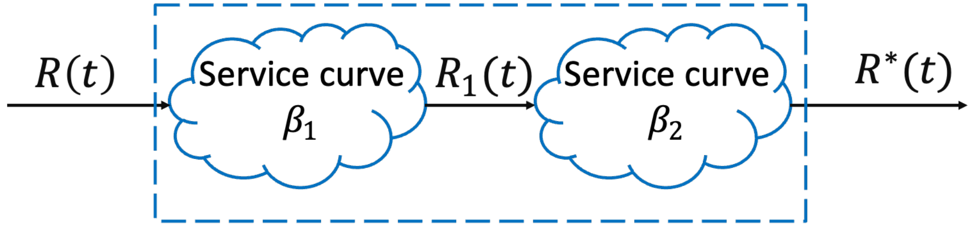
- Can be improved esp. if competing flows are constrained [Tabatabaee 2022]




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

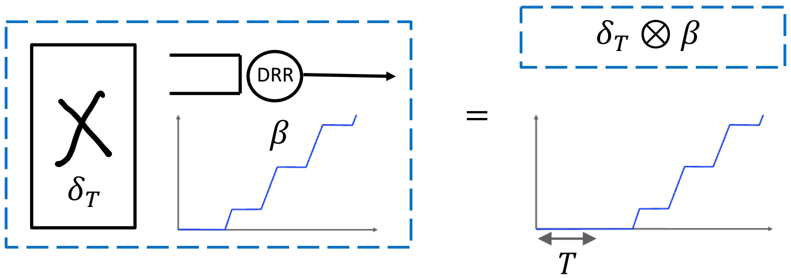
# Concatenation




$$\beta = \beta_1 \otimes \beta_2$$

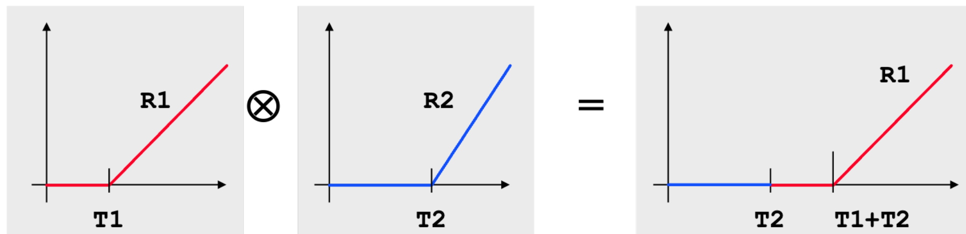
$$R^* \geq R_1 \otimes \beta_2 \geq (R \otimes \beta_1) \otimes \beta_2 = R \otimes (\beta_1 \otimes \beta_2)$$

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




Examples:

- scheduler with service curve $\beta$ combined with bounded delay element has service curve $\beta \otimes \delta_T$
- If $\beta_i$ 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 $T = T_1 + T_2$

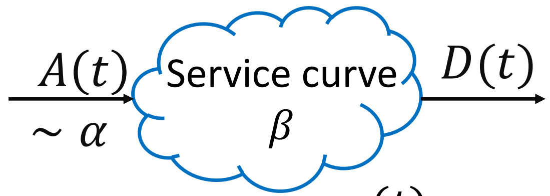


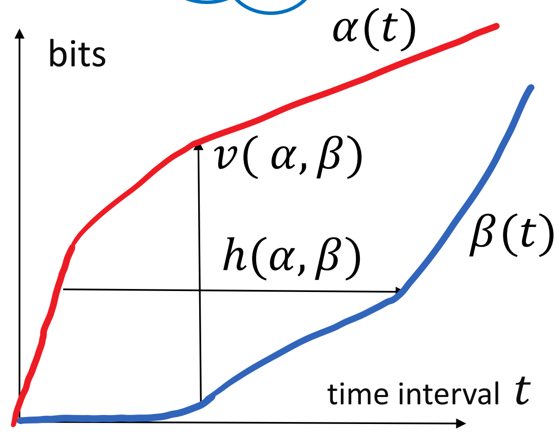
# Three Tight Bounds

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

$$\alpha^*(t) = \sup_{u\geq 0}\big(\alpha(t+u) - \beta(u)\big)$$

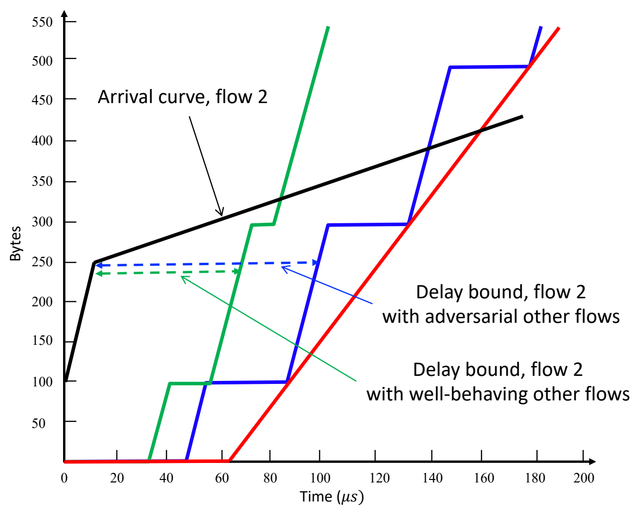
i.e. $\alpha^* = \alpha \oslash \beta$ (deconvolution)



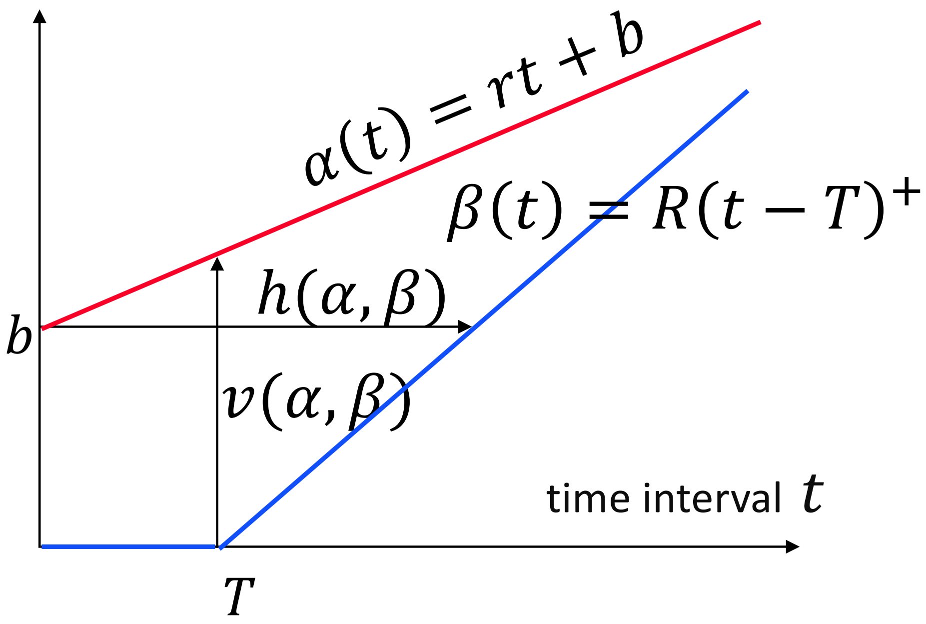

Jitter bound = $h(\alpha,\beta)$ − delay lower bound

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 $r \leq R$

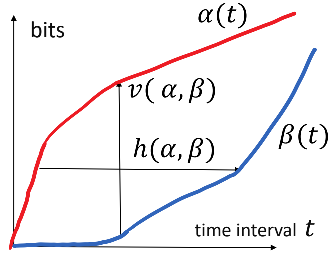
Backlog bound: $b + rT$

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.

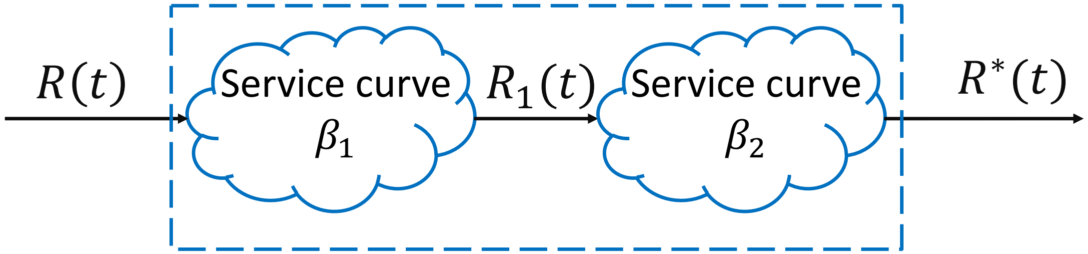
How about network analysis ?

# 3. Network Analysis

Per-flow network:

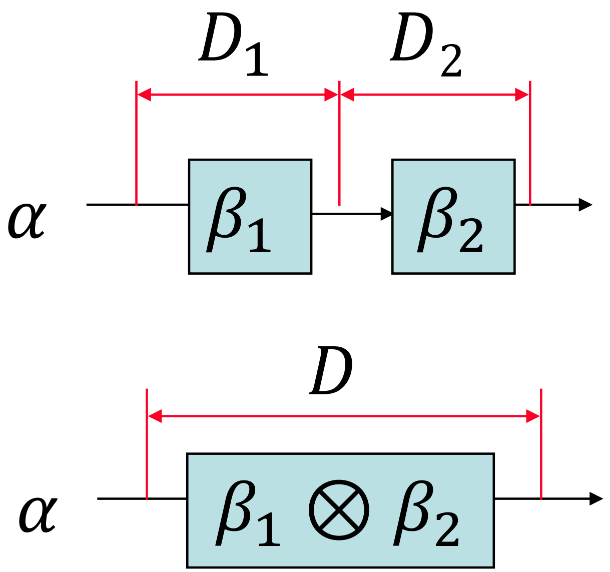
network nodes offer guarantees to individual flows
e.g. IETF IntServ

Solution: apply concatenation result




$$\beta = \beta_1 \otimes \beta_2$$

# 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 $\alpha$

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

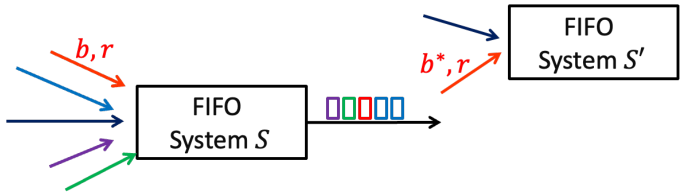
$$D_1 + D_2 = \frac{2b + rT_1}{R} + T_1 + T_2$$

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:

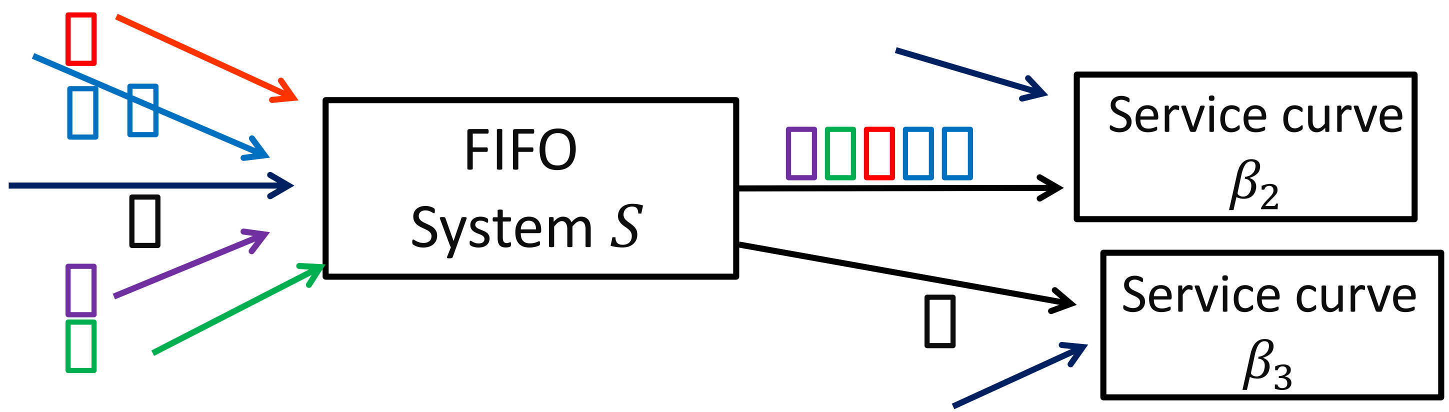
- flows are assigned to classes
- schedulers (such as DRR) separate classes and provide service guarantee to the aggregate of all flows of this class
- Inside a class, service is FIFO
- flows are constrained at sources by arrival curves

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.

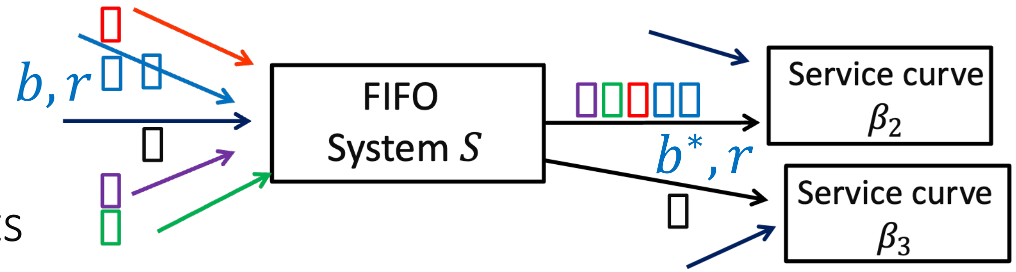
Flows merge and split, no simple result as in per-flow networks.

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 e.g. by token buckets

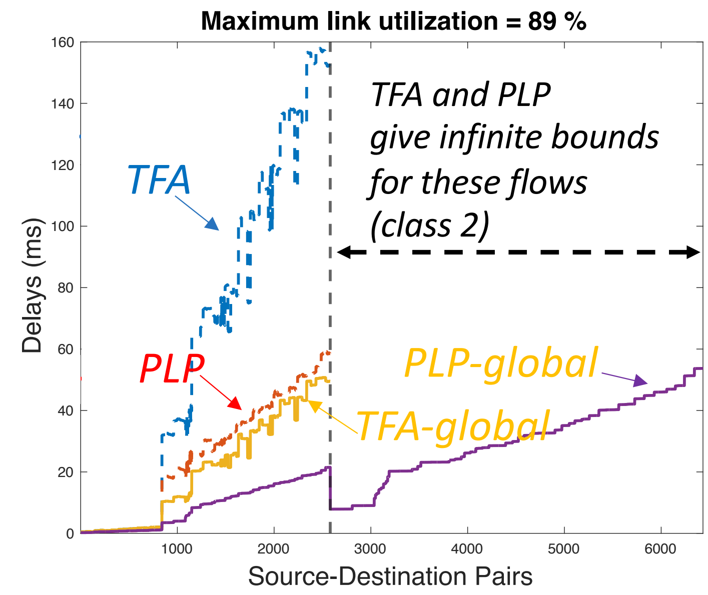
a) Propagated burstiness of flow inside the network is computed by
$b^* = b + r \times (\textbf{delay bound between source and here})$

b) Delay at every node uses single node network calculus + propagated burstinesses.
End-to-end delay bound is sum of nodal bounds on path

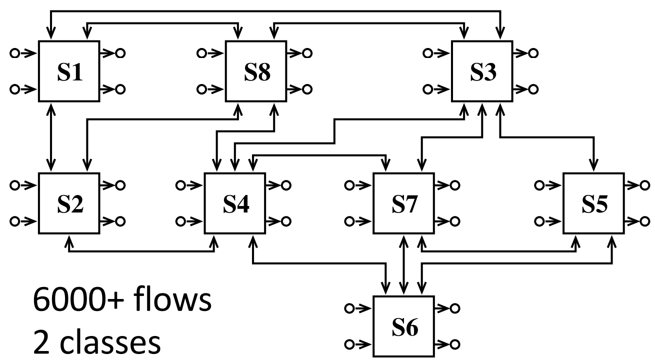
- In a feedforward network of depth $d$, start at edge nodes and stop in $d$ iterations
- In a generic network, iterate a) and b) at all nodes until convergence to a fixpoint or move to infinity. If convergence, the bounds are valid. If divergence, we don't know. [Thomas 2019, Plassart 2022]
- Optimizations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

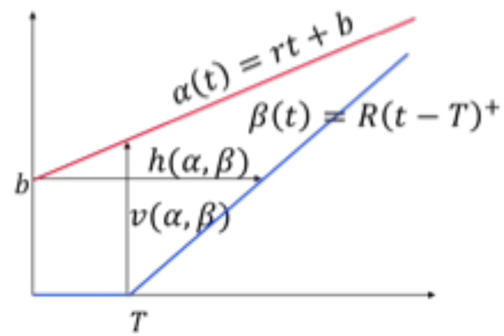
- Tools: DISCO [Schmitt 2006], WoPaNets [Mifdaoui 2010], Pegase [Boyer 2010], Saihu [Tsai 2024]

# 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.

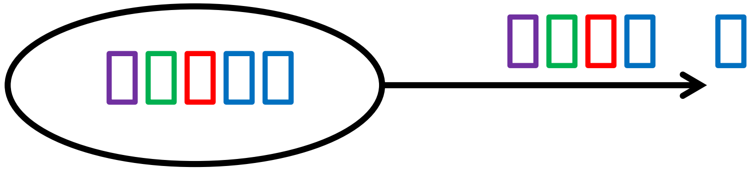
Stability conditions are still an open research issue.

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).

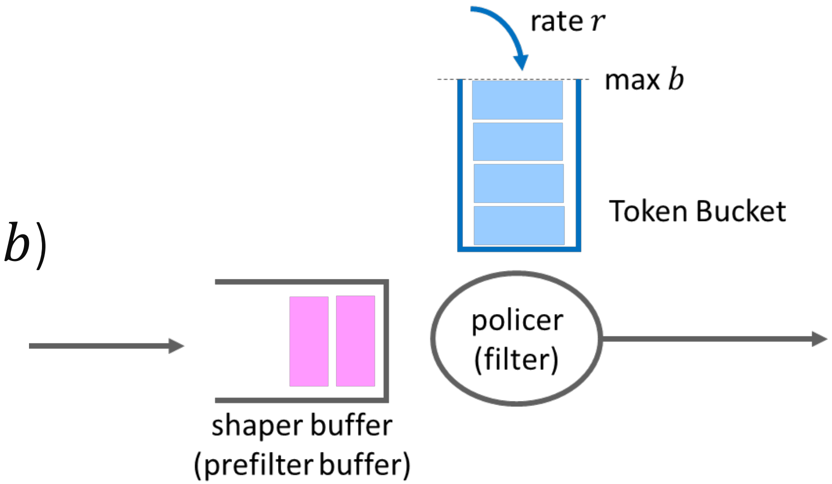
Underloaded networks may be unstable.

# 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.

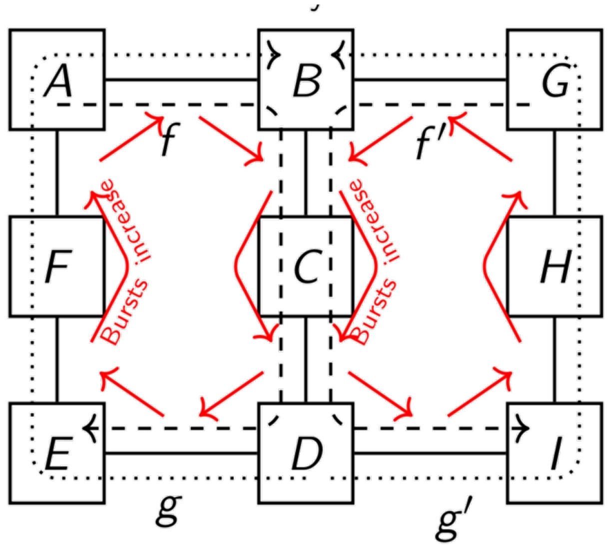
In per-class networks, burstiness of every flow increases at every hop as a function of other flows' burstiness:

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

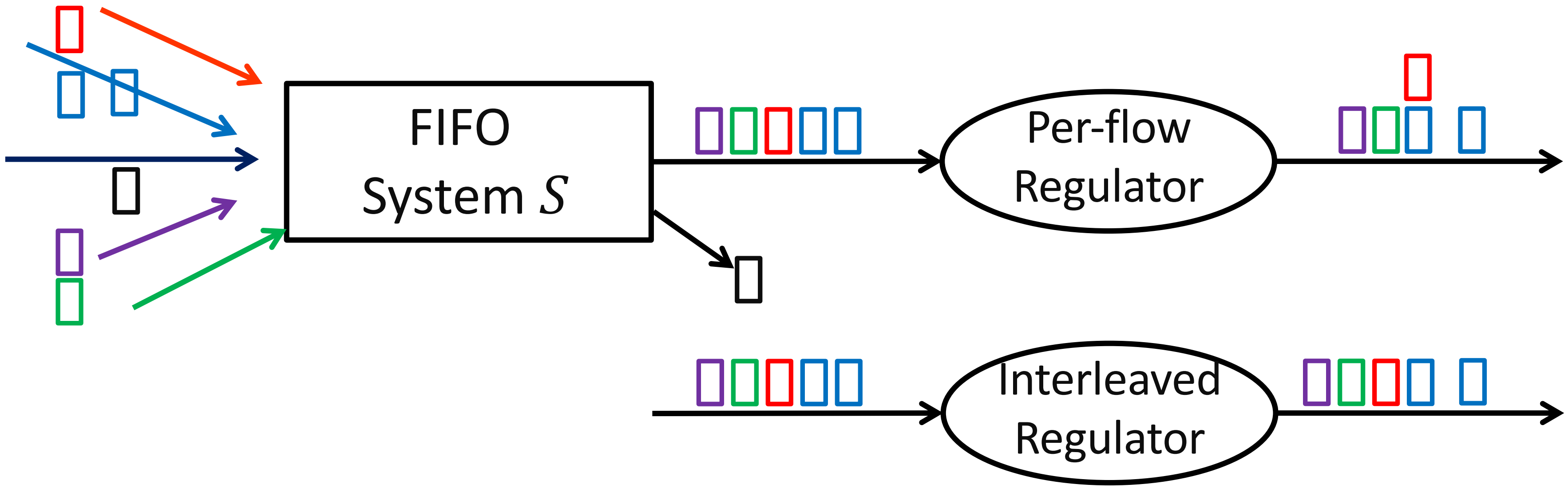
Increased burstiness causes increased burstiness (cascade).

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

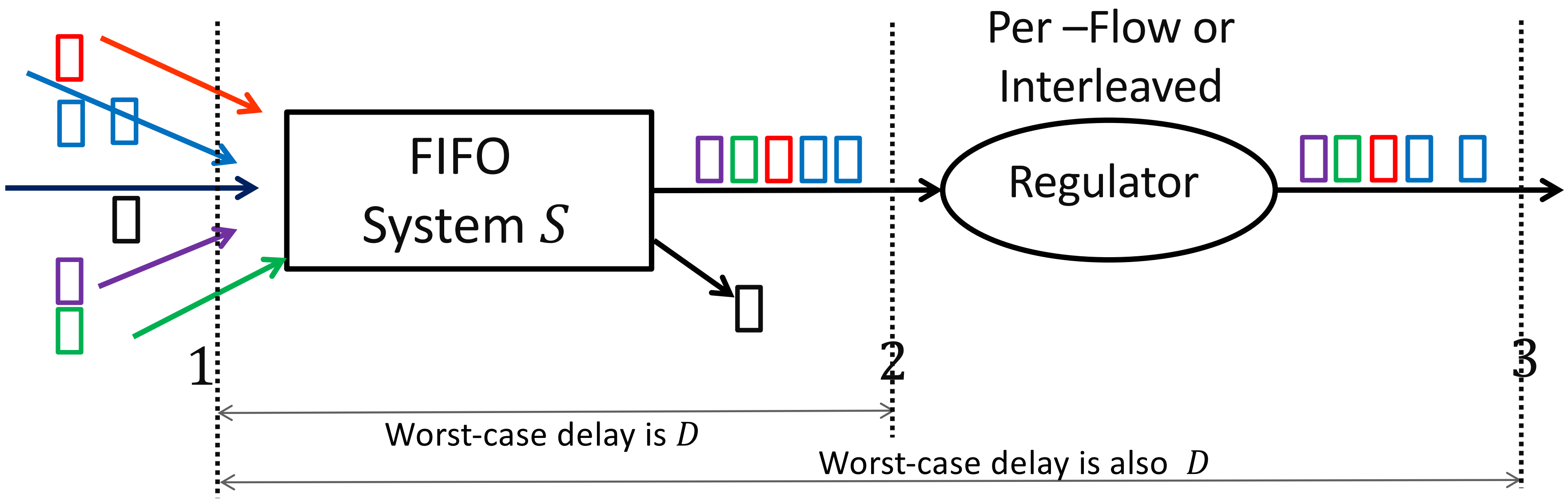



Per flow regulator: one state + one queue per flow.

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).

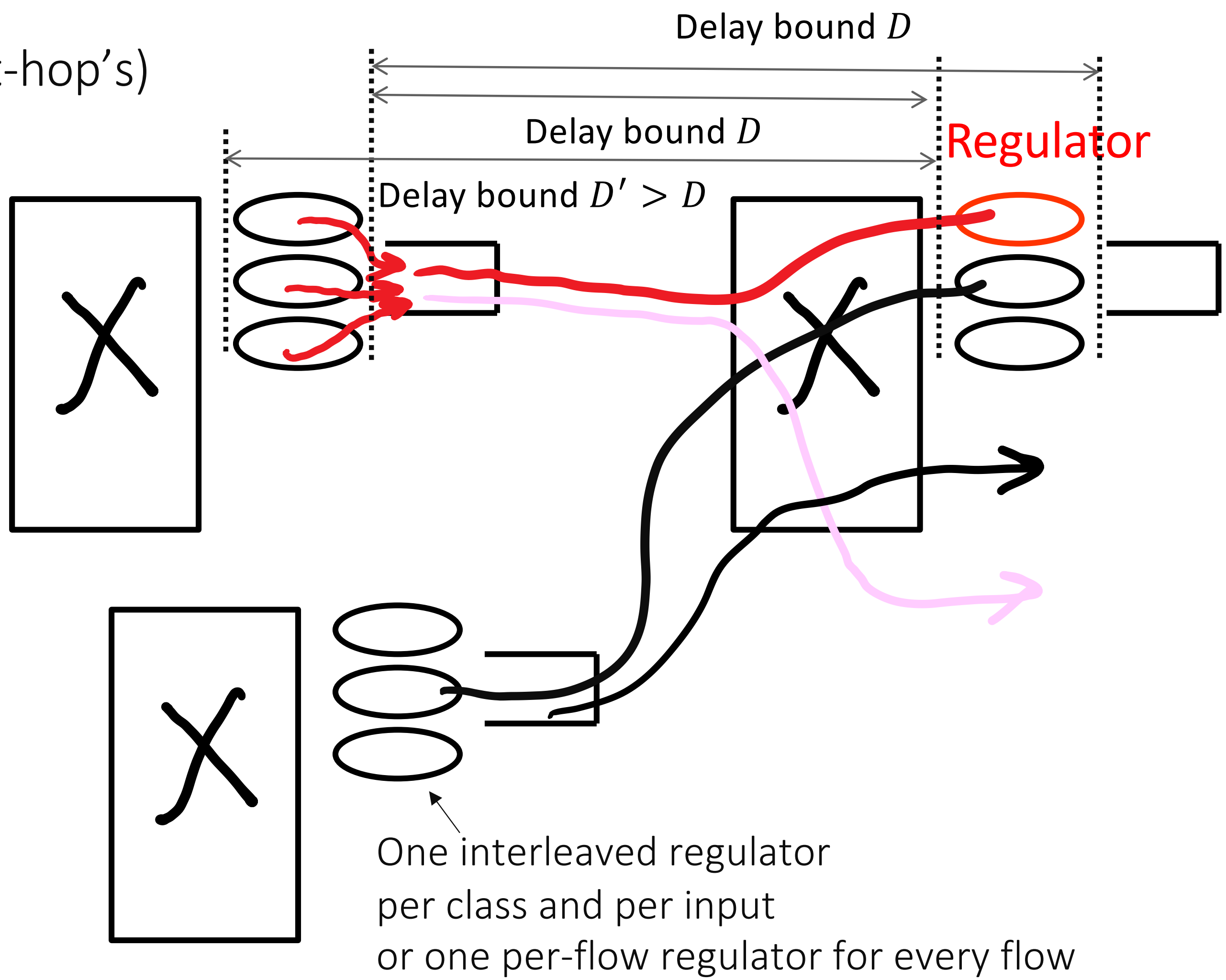
Assume every flow satisfies some arrival constraint at $1$ (e.g. rate and burstiness) and regulators enforces same constraint at $3$.

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)

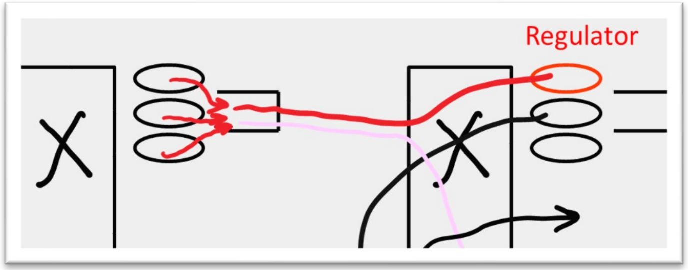
# 5. Clock Non Idealities

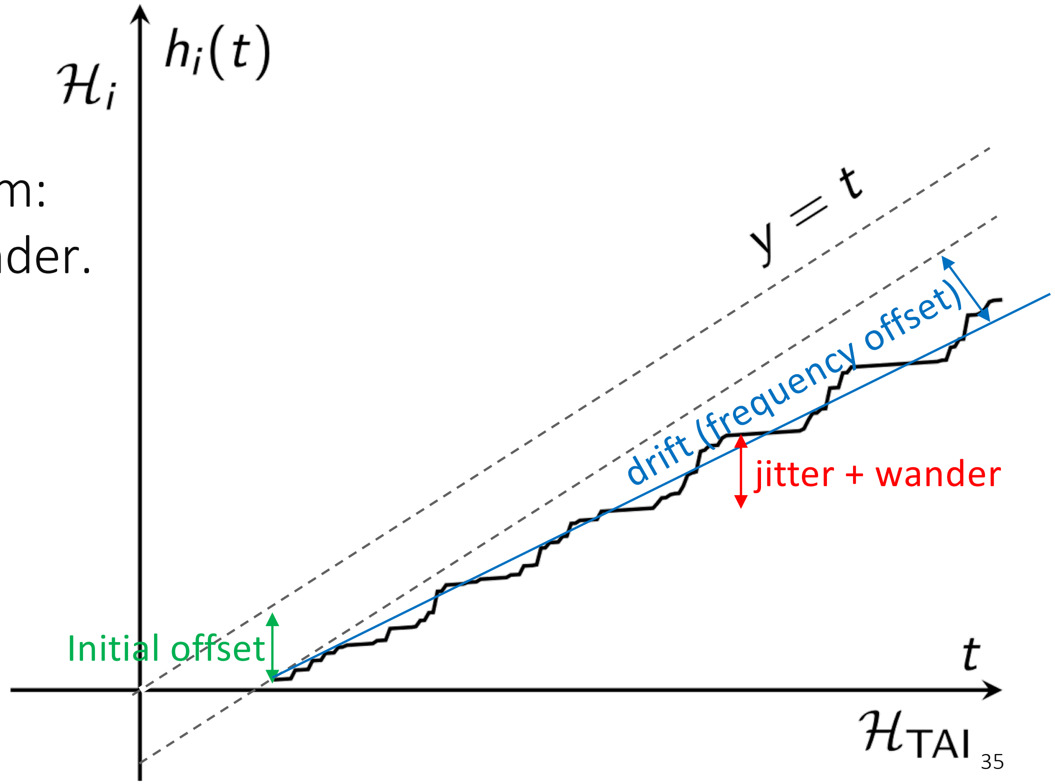
Previous theory assumes perfect time everywhere.

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

- tight sync (PTP, White Rabbit, GPS) : timestamping error $\leq \omega \approx$ 10ns–1$\mu$s
- loose sync (NTP): $\omega \approx$ 1ms – 1s
- no sync: timestamping error $\omega$ 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

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

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.

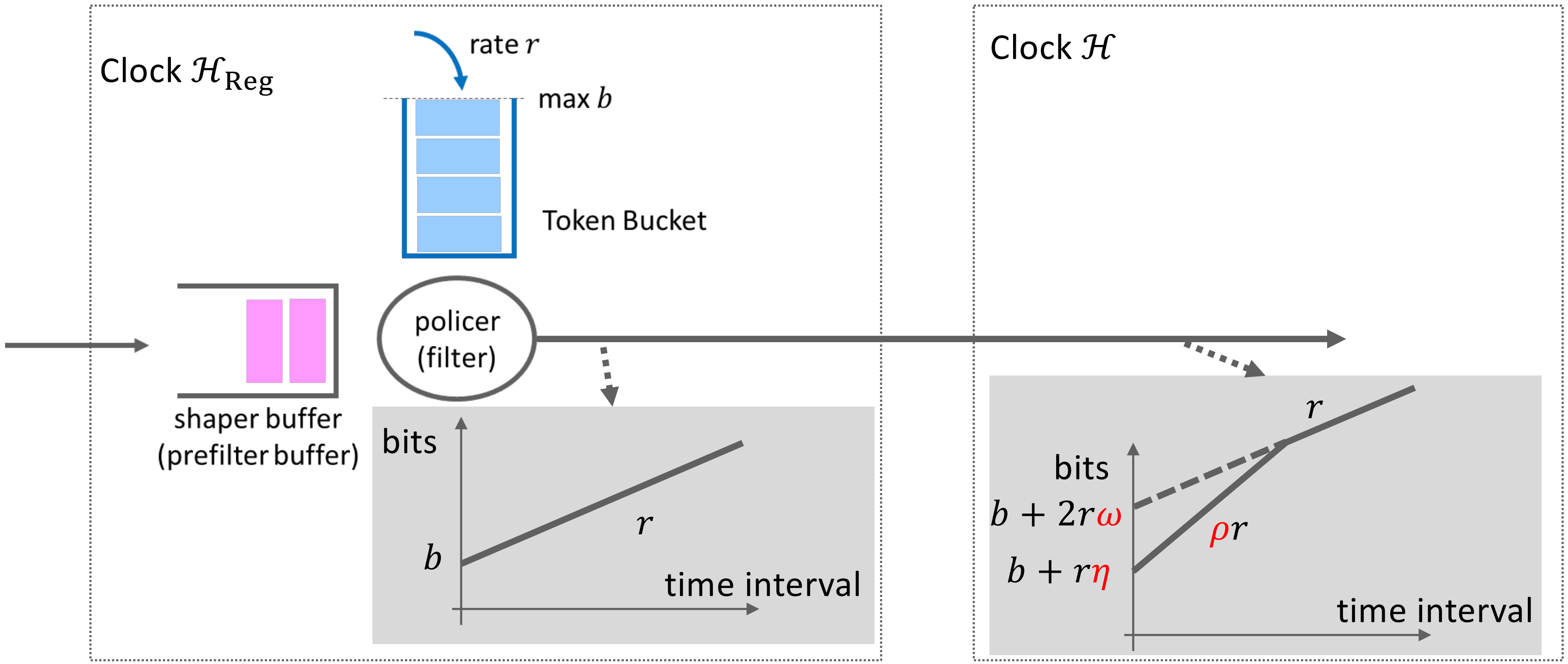
$\omega =$ time error bound
= 1$\mu$s in TSN with PTP;
= $+\infty$ if no synchronization

$\rho =$ 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:**

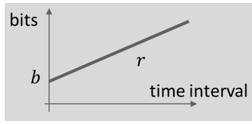
- Regulator does not increase worst-case delay

**Non-synchronized network:**

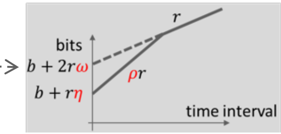
- Per-flow and interleaved regulator unstable (unbounded delay).

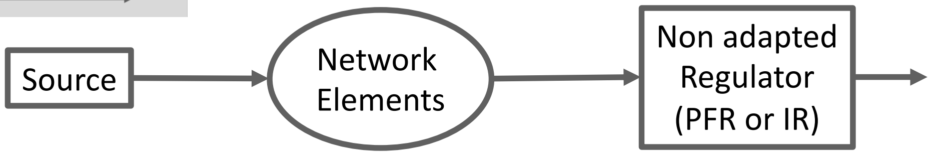
**Synchronized network:**

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



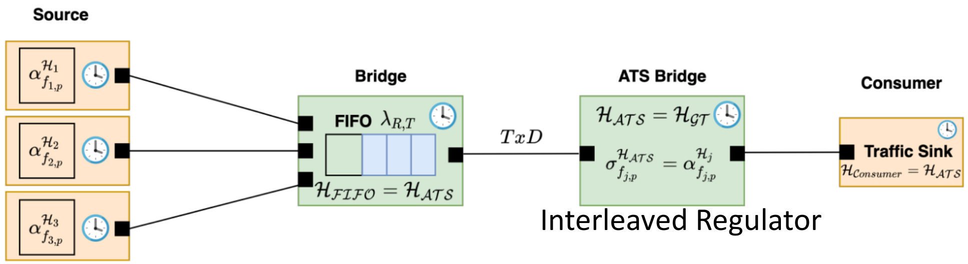

In regulator's clock, flow satisfies this constraint at source



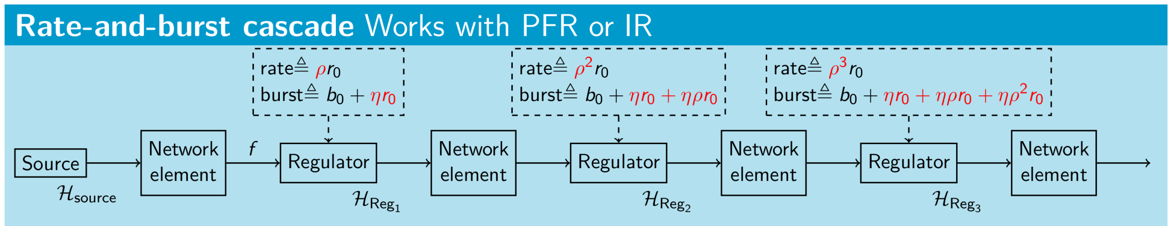

Flow constrained by $\alpha(t) = rt + b$ in local clock

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

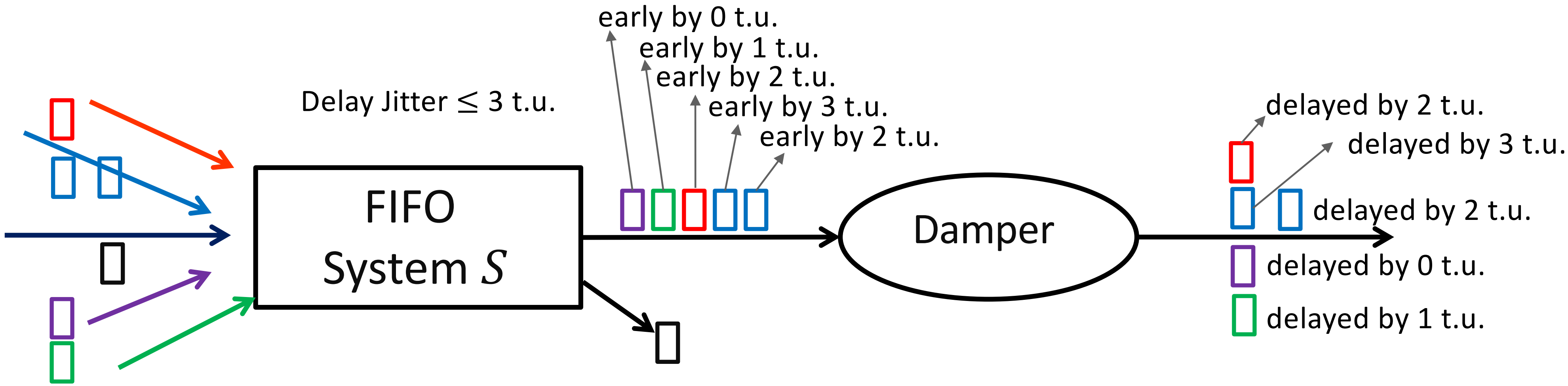



Interleaved Regulator

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



# Dampers




Damper delays a packet by "earliness" read from packet header.

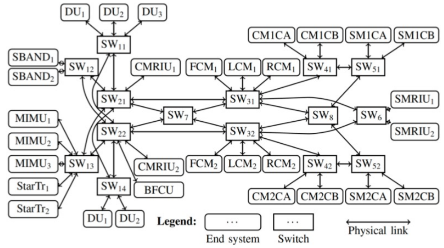
Removes most of jitter, with some residual jitter dependent on tolerance, not on traffic ⟹ also removes burstiness cascade.

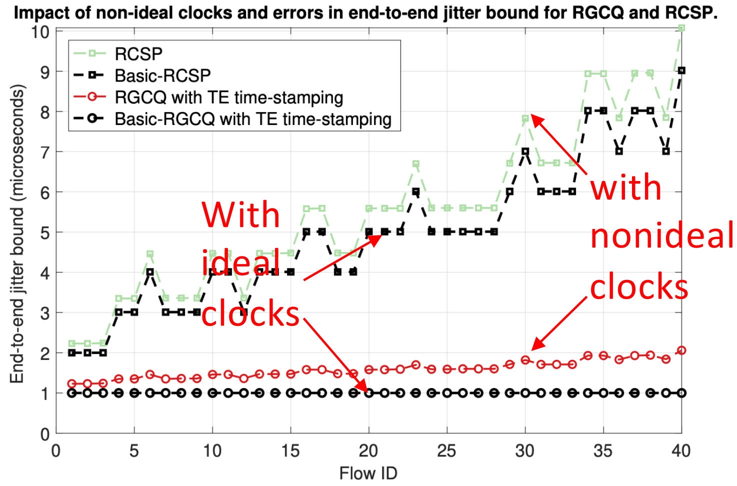
Non work-conserving. Like a per-flow regulator, does not exist in isolation, is combined with queue at next hop.

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

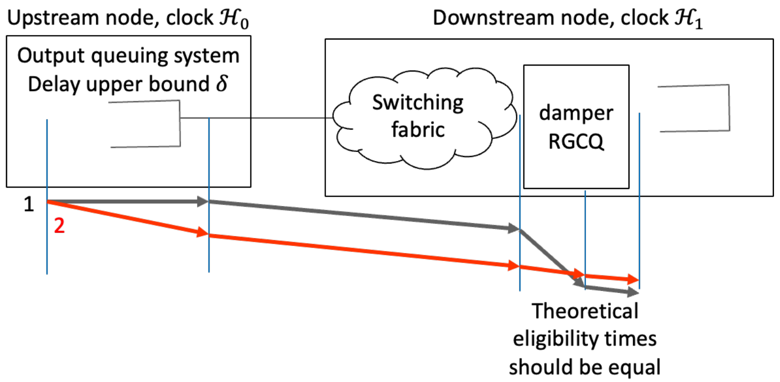
# Consequences for Dampers

Residual jitter is somehow affected by clock inaccuracies






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

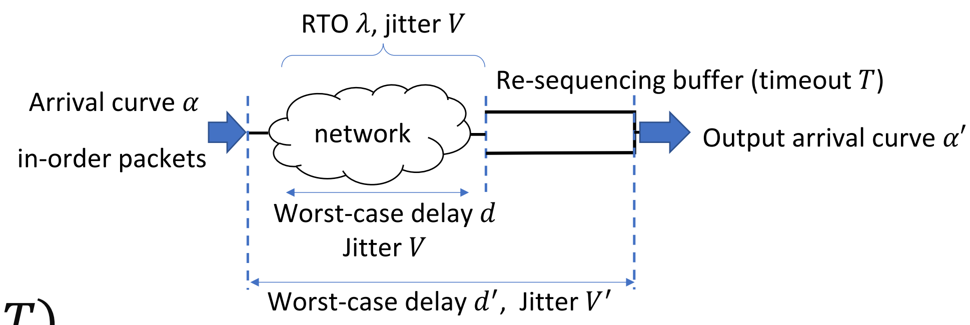
Arrival curves and delay bounds are (very slightly) affected, but dampers and regulators are dramatically affected and need to provision safety mechanisms

# 6. More Bells and Whistles

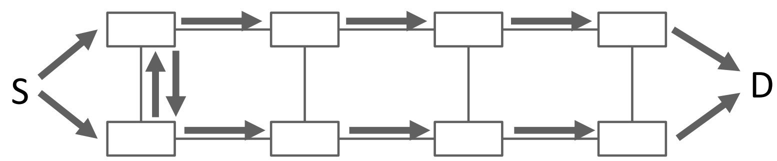
Packet re-ordering due to e.g. multi-paths, packet replication, dampers.

⇒ 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]

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

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

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

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

$\text{S}^3\text{BB}$ 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 !

References are in the online version.

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