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Time Sensitive Networks, Network Calculus and Clock Non-idealities

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Slides available at https://leboudec.github.io/leboudec/resources/lebSlides.html

Title: Time Sensitive Networks, Network Calculus and Clock Non-idealities

Abstract: Time Sensitive Networks offer guarantees on worst-case delay, worst-case delay variation and zero congestion loss; in addition, they provides mechanisms for packet duplication in order to hide residual losses due to transmission errors. 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 with components such as packet ordering and duplicate removal functions, schedulers, regulators and dampers. We will also explain why clock non-idealities matter, and will describe how to take them into account.

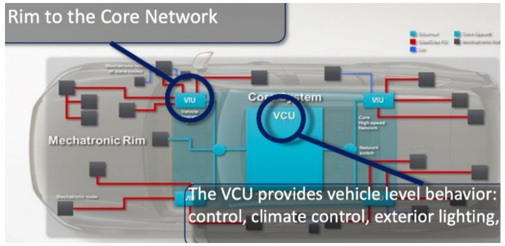
Contents

1. Time Sensitive Networks

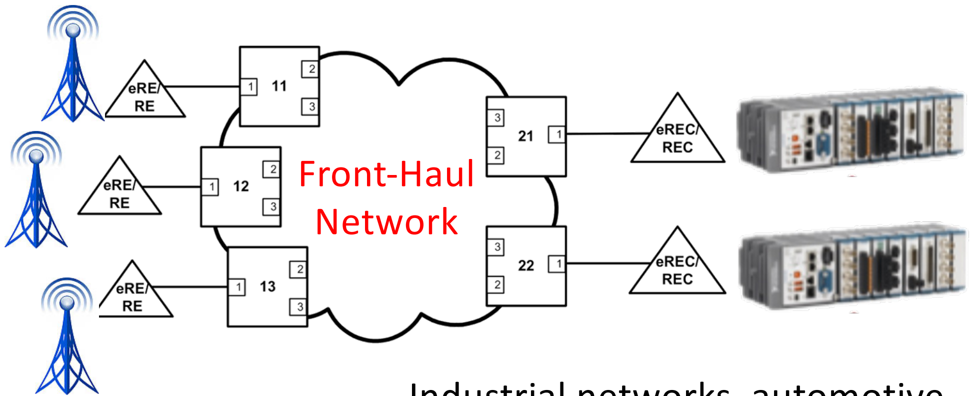
= deterministic service: upper bounds on end-to-end delay and delay-jitter + zero congestion loss.

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

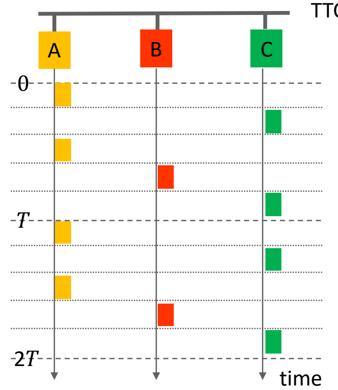
Distributed games

Low latency on-demand video

How can a Network Offer a Deterministic Service ?

1. Every flow is constrained at source (*arrival curve* constraint) (T-SPEC)
2. The network nodes offer a guaranteed service to flows or classes of flows

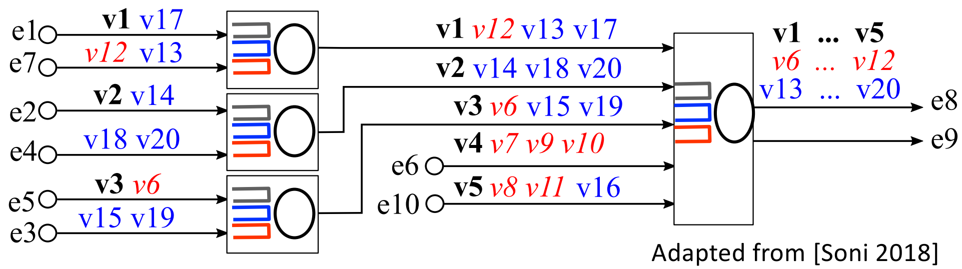
synchronous: e.g Time Triggered CAN bus: every flow is scheduled on bus (not our focus today)



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 (e.g. Deficit Round Robin (DRR) [Shreedhar 1996], Credit Based Shaper (CBS, TSN))

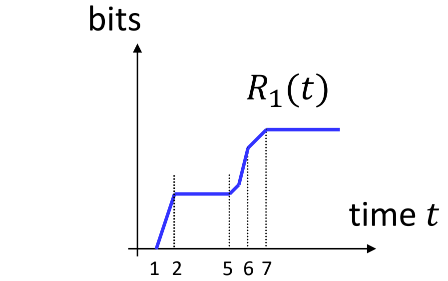


Adapted from [Soni 2018]

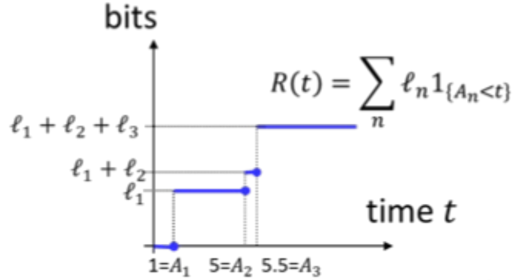
Analysis of Deterministic Networks uses Network Calculus

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

- 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)

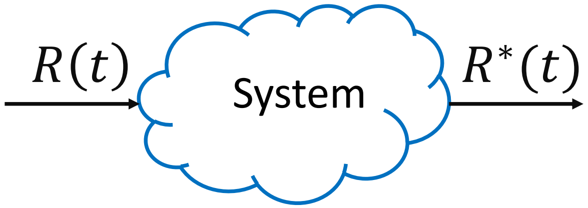


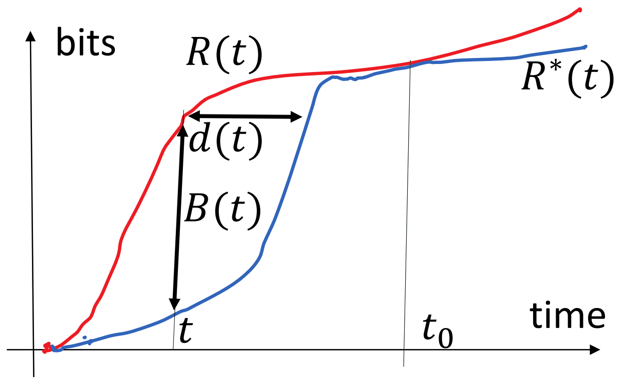
Fluid model (continuous)



Packet train (left continuous)

- Delay and backlog are derived





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

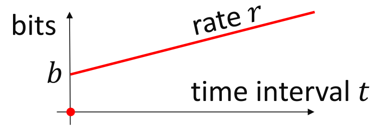
$$A_n - A_m \geq \alpha^{\downarrow}(\ell_m + \cdots + \ell_n), \forall m, n, 1 \leq m \leq n$$

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

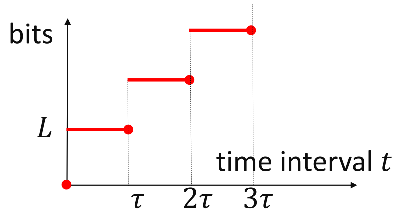
E.g. for $\alpha(t) = rt + b$, $\alpha^{\downarrow}(x) = \frac{(x-b)^+}{r}$

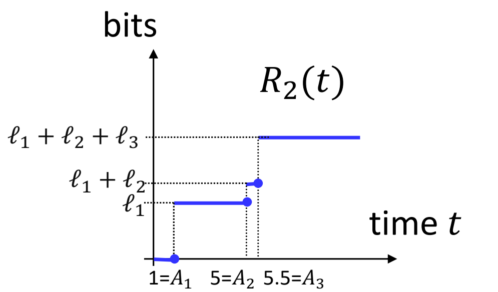
[Le Boudec 2018]

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



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

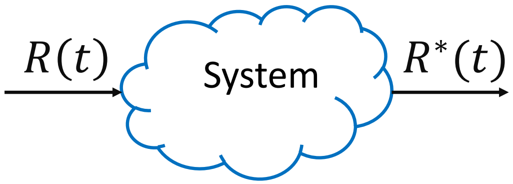




Packet train (left continuous)

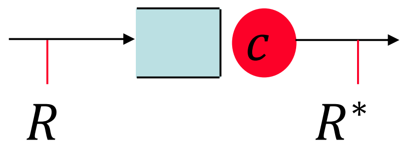
Service Curves

System offers to (R, R^*)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 : $\mathbb{R}^+ \rightarrow \mathbb{R} \cup \{+\infty\}$.



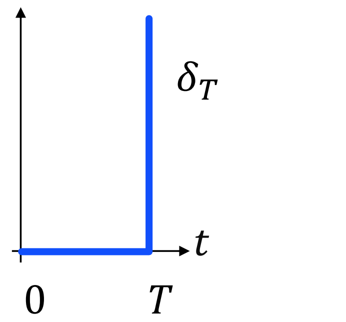
System $\mathcal{S}$ offers to a flow a strict service curve β if for any $s < t$ in a backlogged period, we have $R^*(t) - R^*(s) \geq \beta(t - s)$

$\mathcal{S}$ is typically a single queuing point; example: constant rate server with line rate c has strict service curve $\beta(t) = ct$



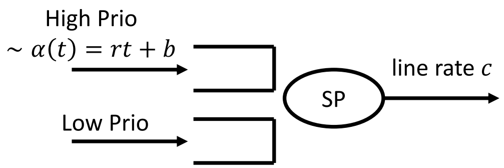
β is a strict service curve $\Rightarrow \beta$ is a service curve; converse is not true.

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 $\leq T \;\Leftrightarrow\;$ node offers to this flow a service curve δ_T. Not a strict service curve.



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

Examples of Service Curves



MTU_L = max packet size, low prio

Static Priority (non-pre-emptive).

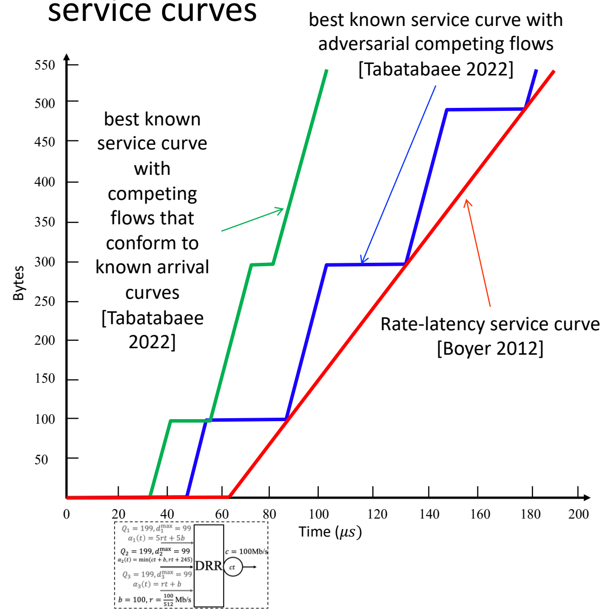
High prio: $\beta_H(t) = (ct - MTU_L)^+$ (strict service curve)

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)

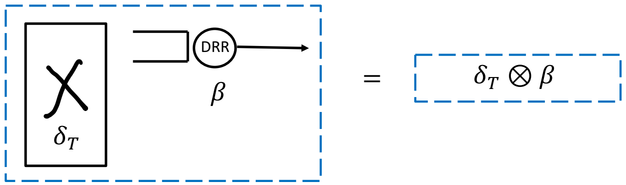
$\beta'_L(t) = \left((c - r)t - b - MTU_L\right)^+$ (strict service curve)

Deficit Round Robin (DRR) service curves



Service curve characterizations exist for most schedulers used in time-sensitive networks: CBS, DRR, IEEE AVB, etc.

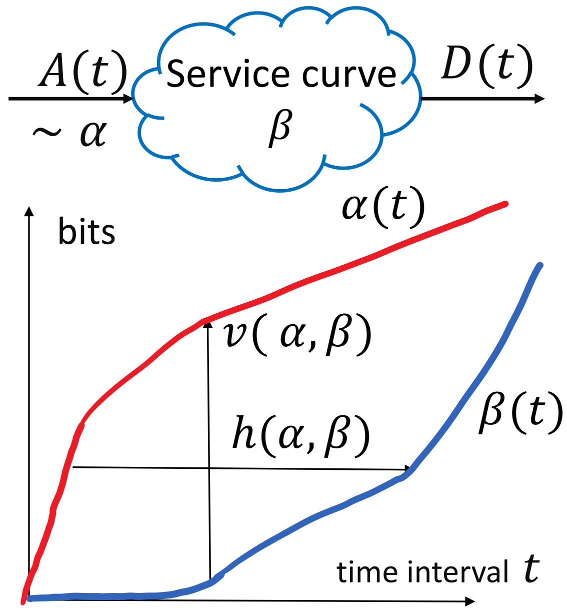
Concatenation of service curve elements β_1, β_2 has service curve $\beta_1 \otimes \beta_2$



[De Azua 2014] [Bouillard 2018] [Tabatabaee 2022]

Three Tight Bounds

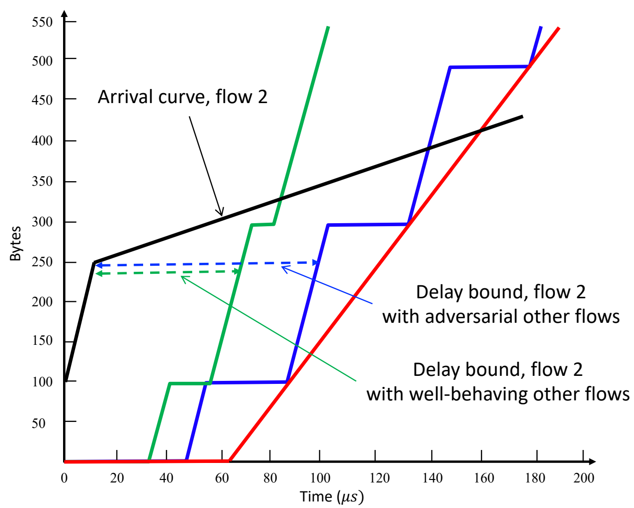
1. backlog $\leq v(\alpha, \beta) = \sup_t \big(\alpha(t) - \beta(t)\big)$
2. if FIFO for this flow, delay $\leq h(\alpha, \beta)$
3. output is constrained by arrival curve
   $$\alpha^*(t) = \sup_{u \geq 0} \big(\alpha(t+u) - \beta(u)\big)$$
   i.e. $\alpha^* = \alpha \oslash \beta$ (deconvolution)



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.



2. Network Analysis: Per-flow Networks

Per-flow network: network nodes offer guarantees to individual flows, e.g. IETF IntServ.
Solution: apply concatenation of service curves.

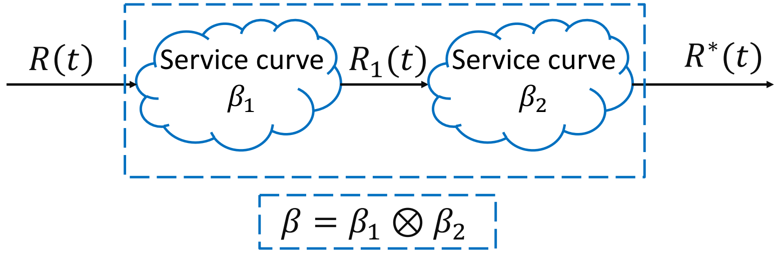
Pay bursts only once: end-to-end delay bound computed *node-by-node* (also accounting for increased burstiness at node 2):

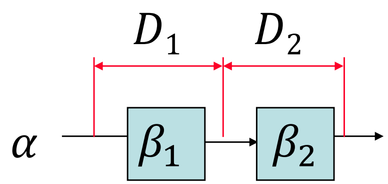
$$D_1 + D_2 = \frac{2b + rT_1}{R} + T_1 + T_2$$

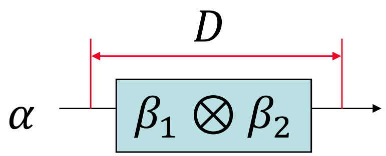
computed *by concatenation:*

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

i.e. worst cases cannot happen simultaneously

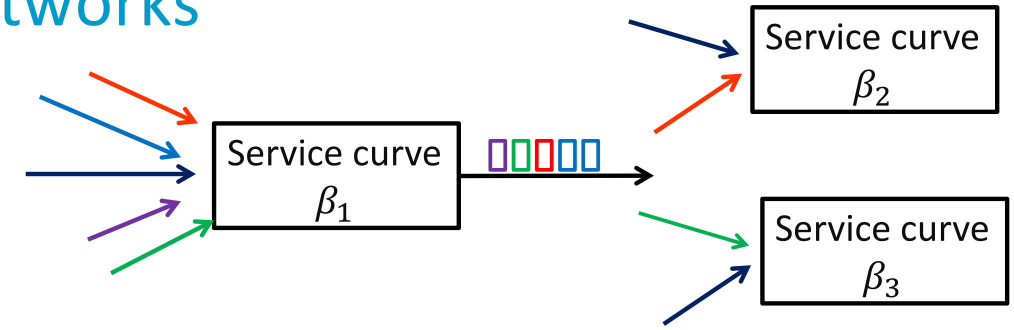






$$\alpha(t) = rt + b$$
$$\beta_1(t) = R(t - T_1)^+$$
$$\beta_2(t) = R(t - T_2)^+$$
$$r \le R$$

Network Analysis: FIFO Per-Class Networks



Most time-sensitive networks are FIFO per class; schedulers (such as DRR) separate classes; service guarantee is to the aggregate of all flows of this class.

Service curves → analyze one separate FIFO network model per class.

Analysis of a FIFO (single class) network is NP-hard [Bouillard 2010]. Worst-case delays can be computed with ELP (Exponential Linear Programming) [Bouillard 2014].

Total Flow Analysis (TFA) and Polynomial Linear Programming (PLP)

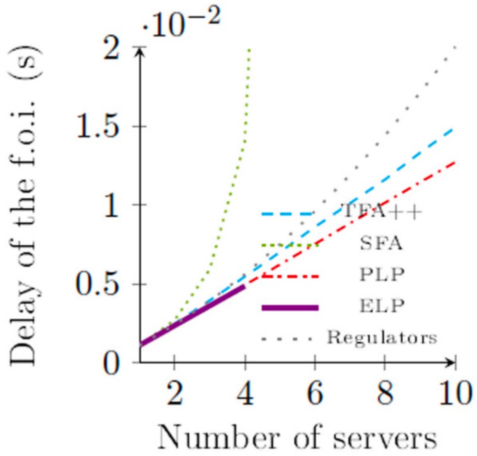
Total Flow Analysis (TFA [Schmitt 2006], TFA++ [Mifdaoui 2017])

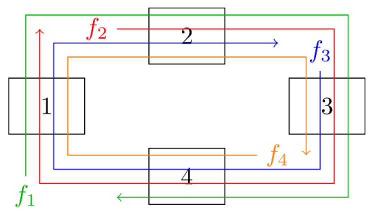
a) Propagated arrival curve of flow inside the network is computed by
$$\alpha^*(t) = \alpha(t + \textbf{delay jitter bound between source and here})$$

b) Delay at every node is computed from propagated arrival curves. 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 bound are valid. If divergence, we don't know. [Thomas 2019, Plassart 2022,Tabatabaee 2023].

PLP (Polynomial Linear Programming): relaxation of ELP, with polynomial complexity, uses TFA (and other) bounds as constraints, applies to generic topologies. Generally provides better bounds and stability region than TFA but is more complex and limited to concave arrival curves and convex service curves. [Bouillard 2022].





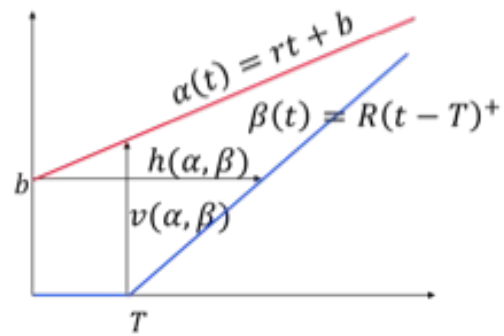
From [Bouillard 2022]

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.

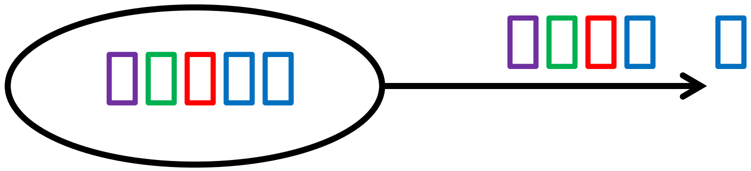
- An overloaded FIFO network is not stable. A feed-forward network that is underloaded or critical is stable.
- For any $\varepsilon > 0$ there is an unstable underloaded FIFO network with load factor $u < \varepsilon$ [Andrews 2009]
- Every underloaded ring is stable [Tassiulas 1996].



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.

3. Regulators

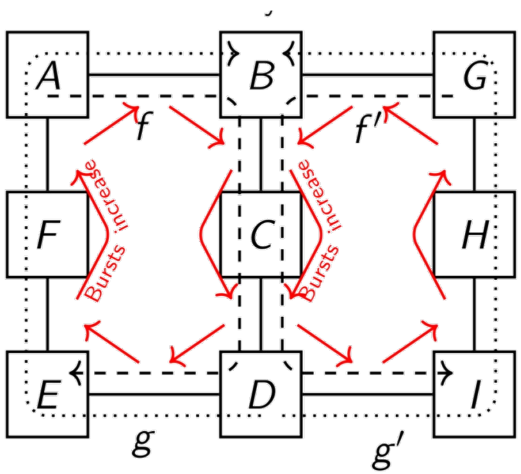


Regulator (= shaper) delays packets in order to limit burstiness to a prescribed value (i.e. enforces an arrival curve constraint). Example: Token Bucket regulator.

Typically placed at network edge to protect from misbehaving sources.

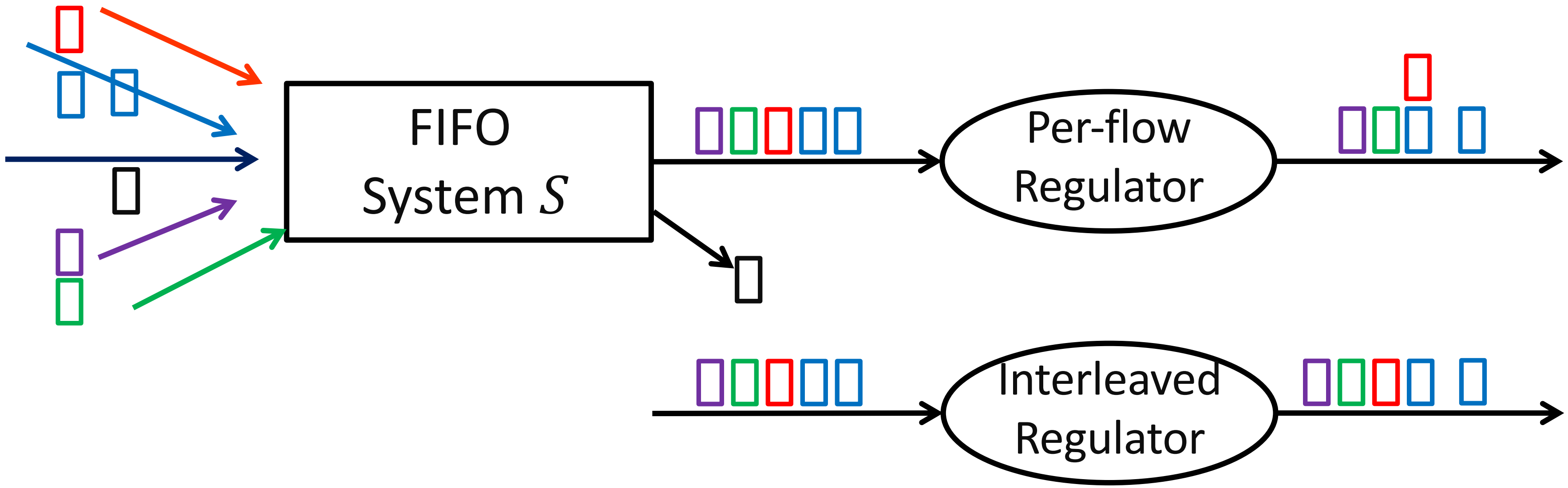
In per-class networks, burstiness of every flow increases at every hop as a function of other flows' burstiness. Increased burstiness causes increased burstiness (cascade).

Propagated burstiness is computed by PLP / TFA as solution to a fixpoint problem. Cyclic dependencies may cause bad delays.



Regulators can be used to reduce burstiness or even break cyclic dependencies [Thomas 2019].

Regulators Avoid Cascading Burstiness in Per-Class Networks

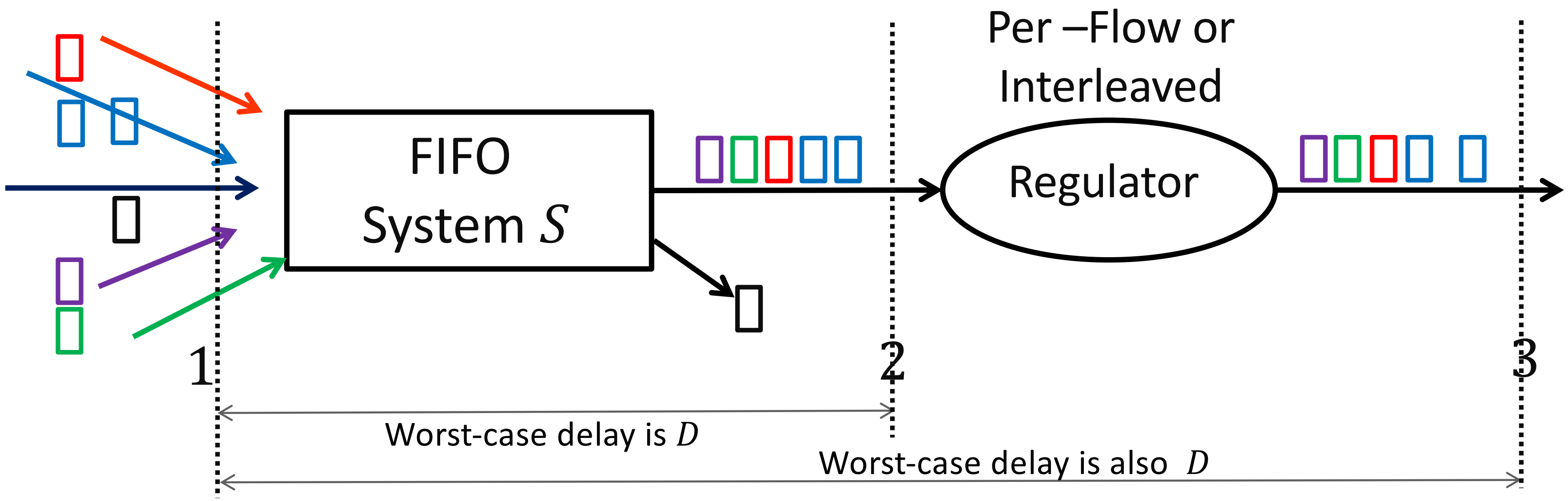


Per flow regulator: one state + one queue per flow.

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



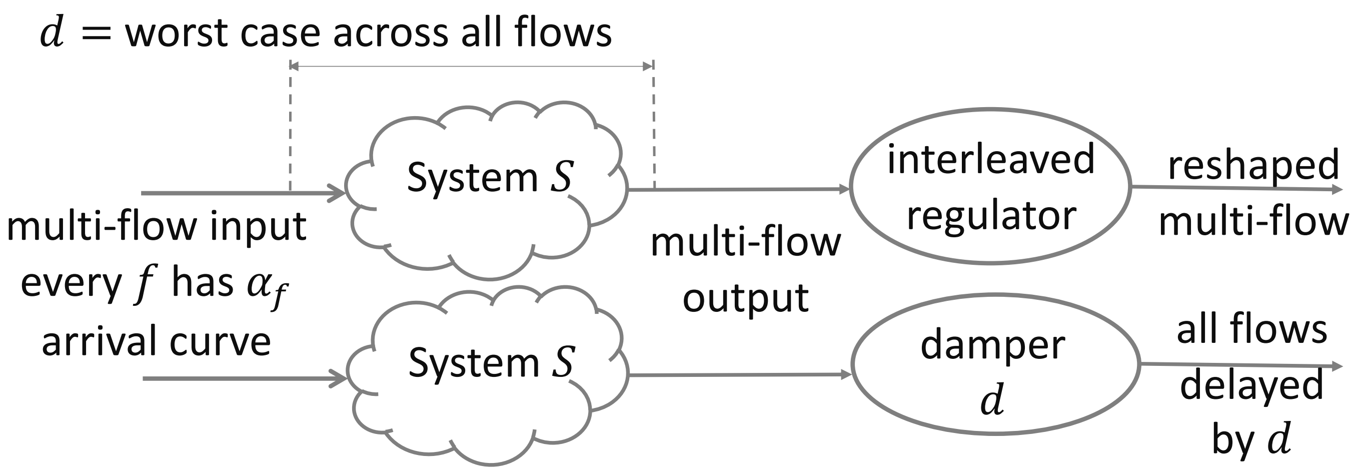
Assume S is FIFO per flow (per-flow regulator) or globally (interleaved regulator).

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).

⇒ Used in Time Sensitive Networks where regulators break cyclic dependencies

Proof



- The interleaved regulator is the minimal FIFO system that delivers output flows $\sim\alpha_f, \forall f$.
- Replace minimal regulator by **damper** [Verma et al 1991]:
  Damper forces total delay of input to be exactly d; Damper is causal and FIFO if d is $\geq$ worst-case delay through S.
- Damper delivers output flows $\sim\alpha_f, \forall f$ $\Rightarrow$ multi-flow output delayed by d is no earlier than reshaped multi-flow.

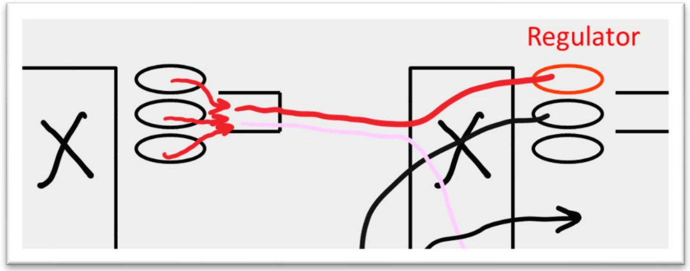
4. Clock Non Idealities

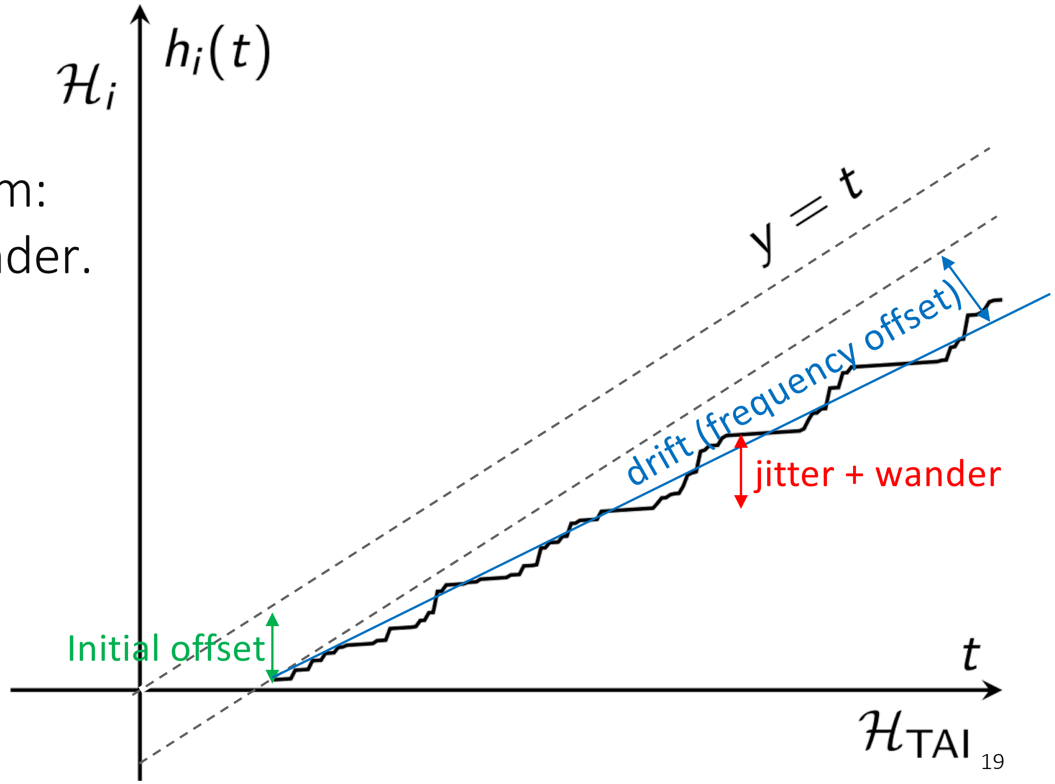
Previous theory assumes perfect time everywhere.

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

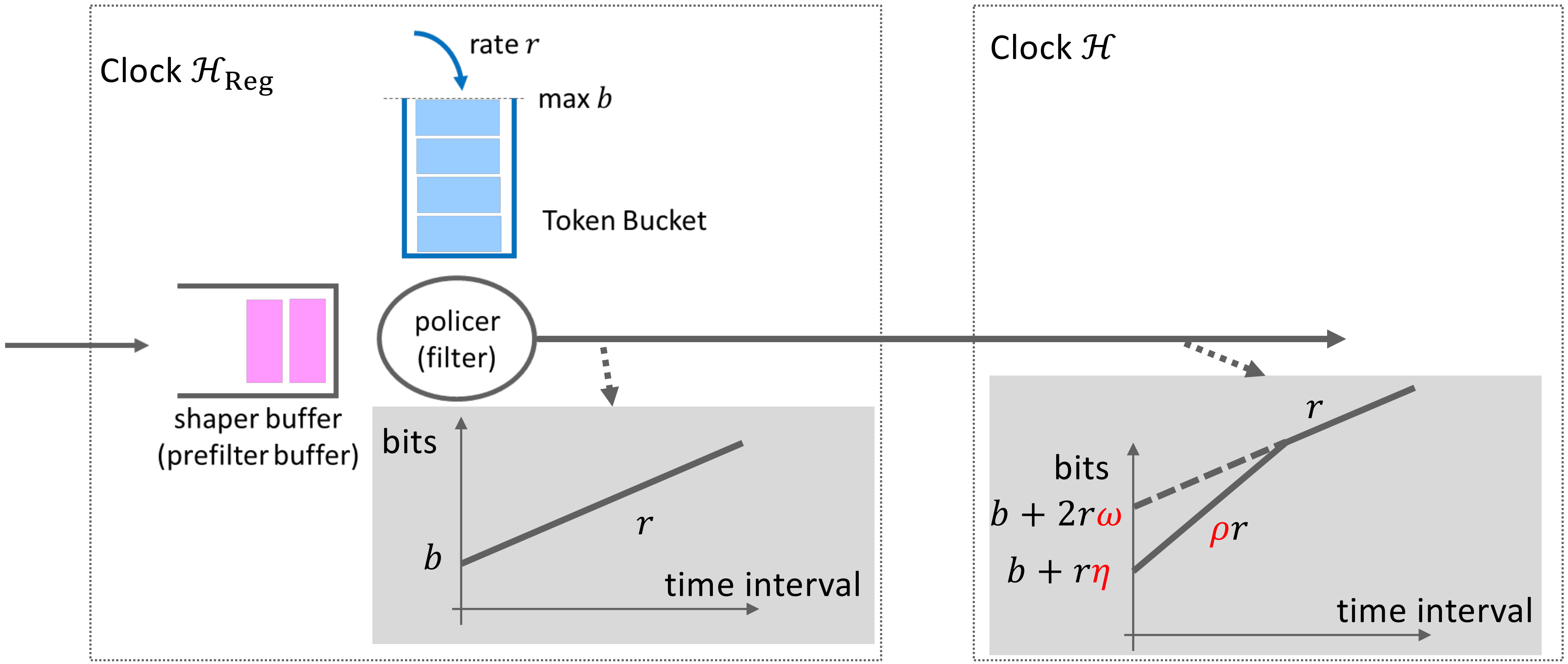
$\rho =$ clock-stability bound
=1.0001 (e.g. in TSN)

$\eta =$ 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 $\mathcal{H}_{\mathrm{Reg}}$ i.e. arrival curve constraint $\alpha^{\mathcal{H}_{\mathrm{Reg}}}(t) = rt + b$

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:

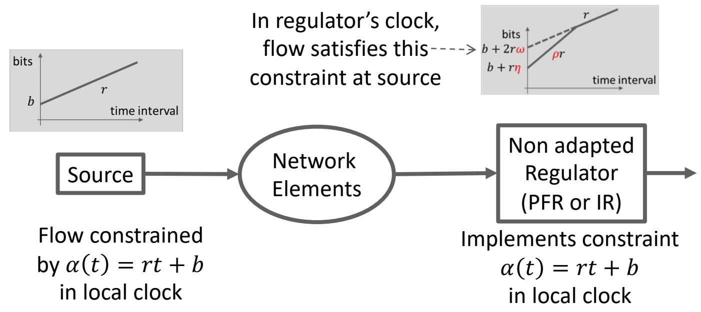
- Regulator does not increase worst-case delay

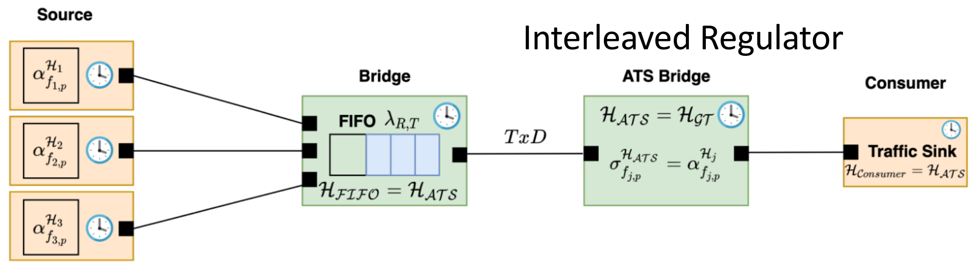
Non-synchronized network:

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

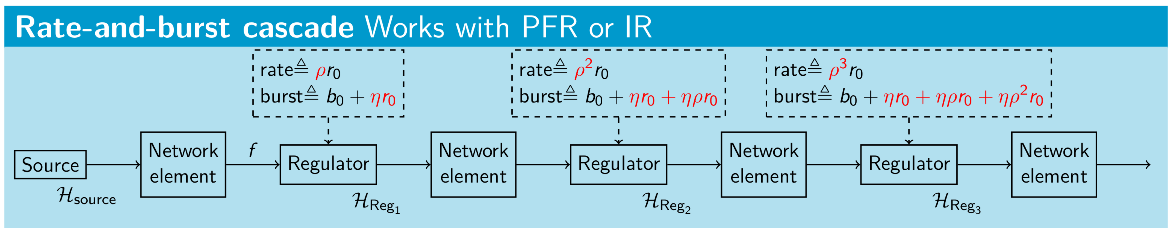
Synchronized network:

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





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 of operation.

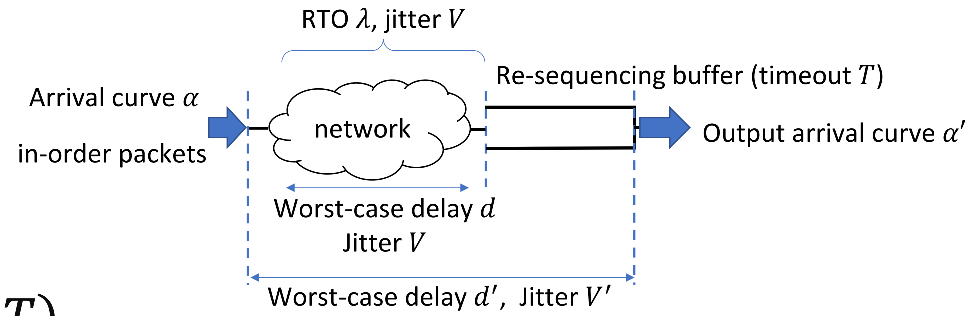


5. Other Bells and Whistles

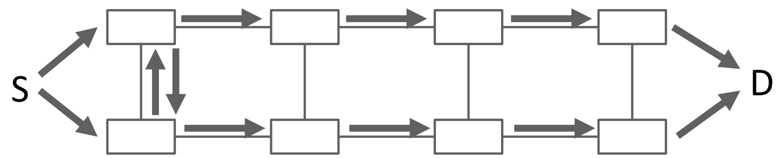
Packet re-ordering occurs due to multi-paths and packet replication.

⇒ 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]

Towards Stochastic Network Calculus …

Stochastic arrival curves [Ciucu 2012]

$$\mathrm{SBB}\text{: } \forall s \le t, \sigma > 0\text{: } \mathbb{P}(A(s,t) > f(t-s) + \sigma) \le \varepsilon(\sigma)$$
$$\mathrm{S^2BB}\text{: } \forall t, \sigma > 0\text{: } \mathbb{P}\left(\sup_{s \le t} A(s,t) > f(t-s) + \sigma\right) \le \varepsilon(\sigma)$$
$$\mathrm{S^3BB}\text{: } \forall \sigma > 0\text{: } \mathbb{P}\left(\sup_{s \le t} A(s,t) > f(t-s) + \sigma\right) \le \varepsilon(\sigma)$$

$\mathrm{S^2BB}$ can be obtained from Hoefding bounds for independent, arrival-curve constrained sources [Vojnovic 2003] – metric is $\mathbb{P}(Q(t) \le\ b)$, obtains significant statistical multiplexing gain.

$\mathrm{S^3BB}$ cannot apply nontrivially to ergodic processes, but applies for example to periodic sources, can apply to $\mathbb{P}(\forall t, Q(t) \le b)$

Stochastic service [Jiang 2008, Fidler 2015, Nikolaus 2019] uses MGF bounds. Could be used to model wireless links. Hard to obtain tight bounds.

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]

copied on 2023 March 4 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 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 are dramatically affected, other systems not.

Stochastic Network calculus promises to apply to wireless networks.

Thank You !

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