Application of Network Calculus to the TSN Problem Space

Jean-Yves Le Boudec[1,2,3]

EPFL

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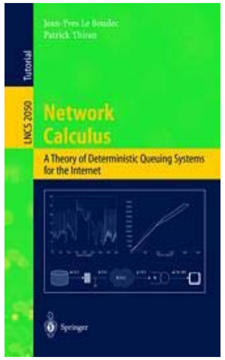
[1] https://people.epfl.ch/105633/research

[2] http://smartgrid.epfl.ch

[3] IP Parallel Redundancy Protocol https://github.com/LCA2-EPFL/iprp

What is Network Calculus ?

A theory and tools to compute bounds on queuing delays, buffers, burstiness of flows, etc



C.S. Chang, R. Cruz, JY Le Boudec, P. Thiran, …

For deterministic networking, per-flow and per-class queuing, asynchronous traffic

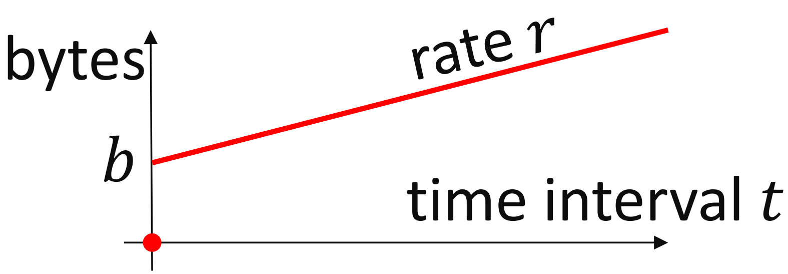
Derive system equations ⇒ formal proofs

Arrival Curve

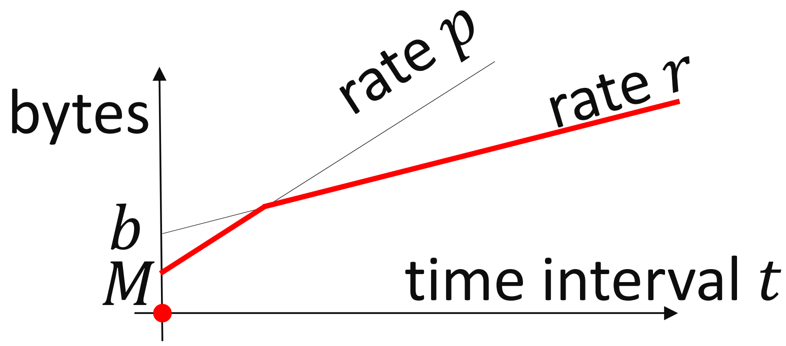
For a flow, at an observation point

Flow is constrained by arrival curve $\alpha()$ iff the amount of basic data units (e.g. bytes) observed in *any interval* of duration t is $\leq \alpha(t)$

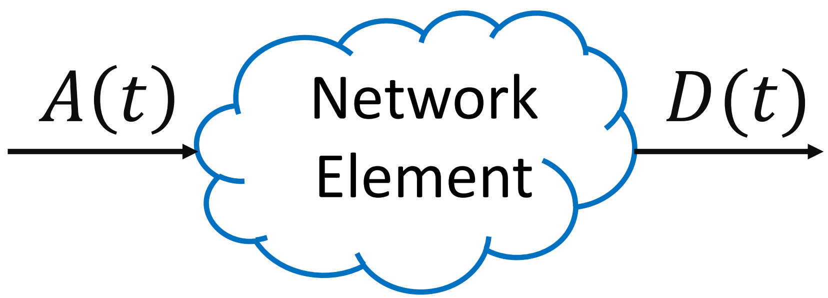
token bucket with rate r and burst b: $\alpha(t) = rt + b$



token bucket + peak rate p and MTU M: $\alpha(t) = \min(pt + M, rt + b)$



Service Curve

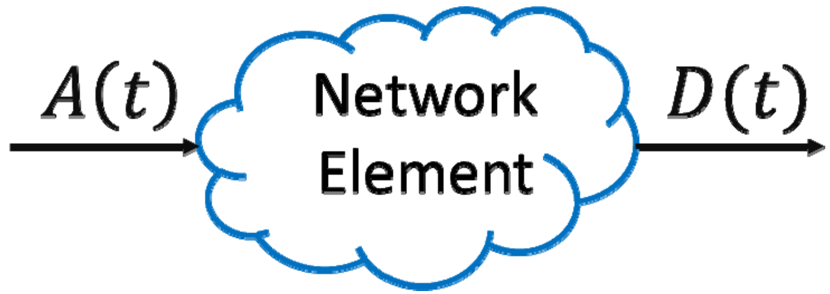


$A(t), D(t)$: amount of basic data units observed in $[0, t]$

Network element offers to this flow a service curve $\beta()$ if

$$\forall t \geq 0, \exists s \in [0, t]: D(t) \geq A(s) + \beta(t - s)$$

Service Curve Example



Rate-latency service curve :

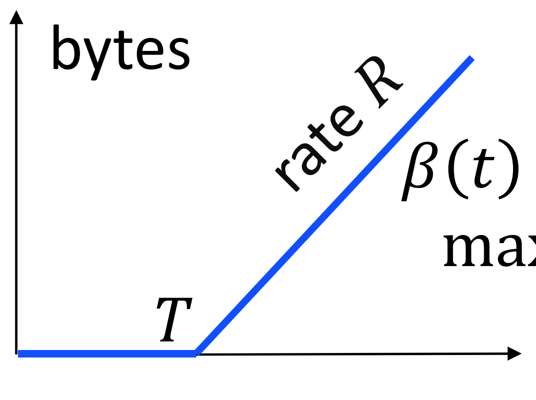
$$\beta(t) = R(t - T)^{+}$$

Models many schedulers: DRR, PGPS, RFC 2212, etc.

Example: service received by a high priority flow (no pre-emption):

$R =$ line rate

$T = \frac{1}{R} \times MTU$ of low priority packets



$$\beta(t) = R(t - T)^{+} = \max(0, R(t - T))$$

$$D(t) = A(s) + \beta(t - s)$$

for some s

(e.g. $s =$ beginning of busy period)

Service Curve Example:
Non Pre-emptive Priority

One server of rate C, two priorities

Every high priority flow f is leaky bucket controlled (r_f, b_f)

Let $r_H = \sum_{f\in H} r_f$, $b_H = \sum_{f\in H} r_f$

Then if $r_H < C$ the aggregate of all low priority flows receives a rate-latency service curve $\beta(t) = R(t-T)^+$with

$$R = C - r_H, T = \frac{b_H}{C - r_H}$$

[Le Boudec and Thiran 2001, Section 1.3]

Service Curve Example: AVB / CBS

The aggregate of all flows (streams) served in one server as AVB class A receives a rate-latency service curve $\beta(t) = R(t-T)^+$

with

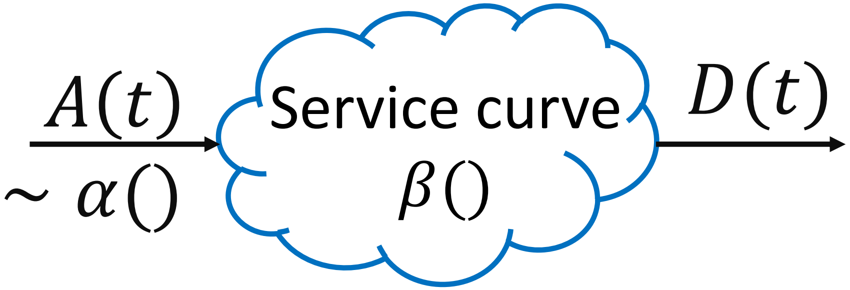
$$R = \frac{id_A\, C}{id_A - sd_A}, T = \frac{l_{\max}^n}{C}$$

Similar results for class B

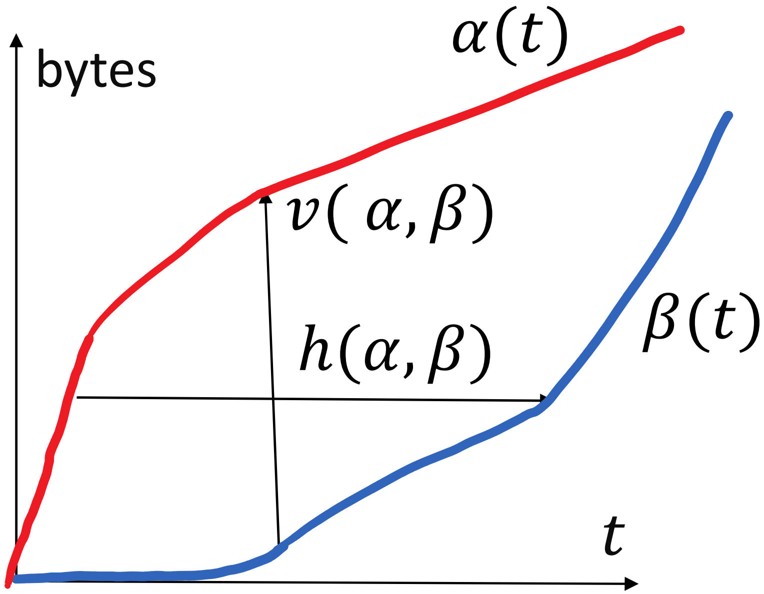
[Ruiz-Boyer 2014]

id_A = idle slope, sd_A = send slope, $l_{\max}^n$ = max packet size other than class A

Basic Results: 3 Tight Bounds

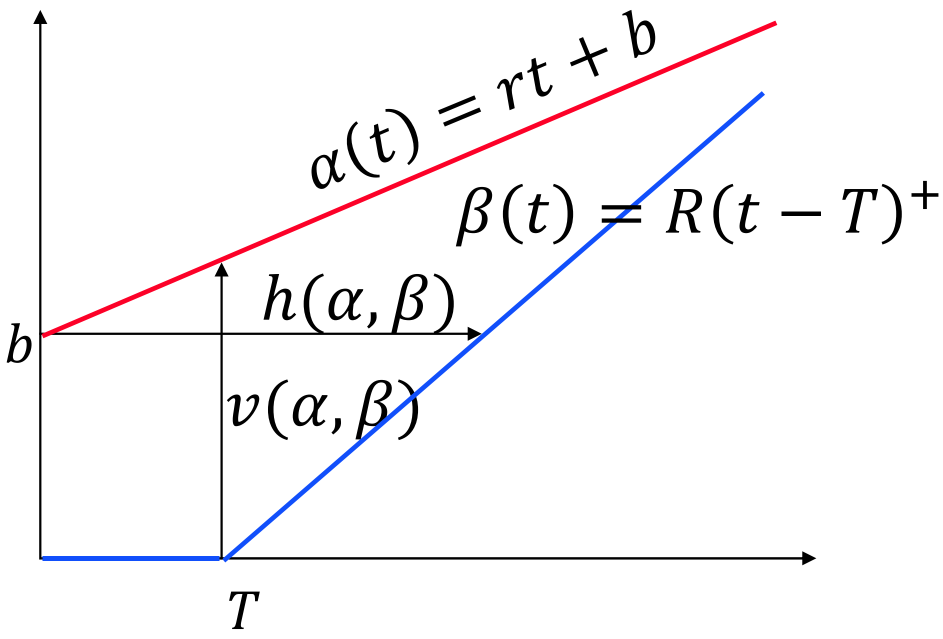


Flow is constrained by arrival curve $\alpha()$; served in network element with service curve $\beta()$. Then



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

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

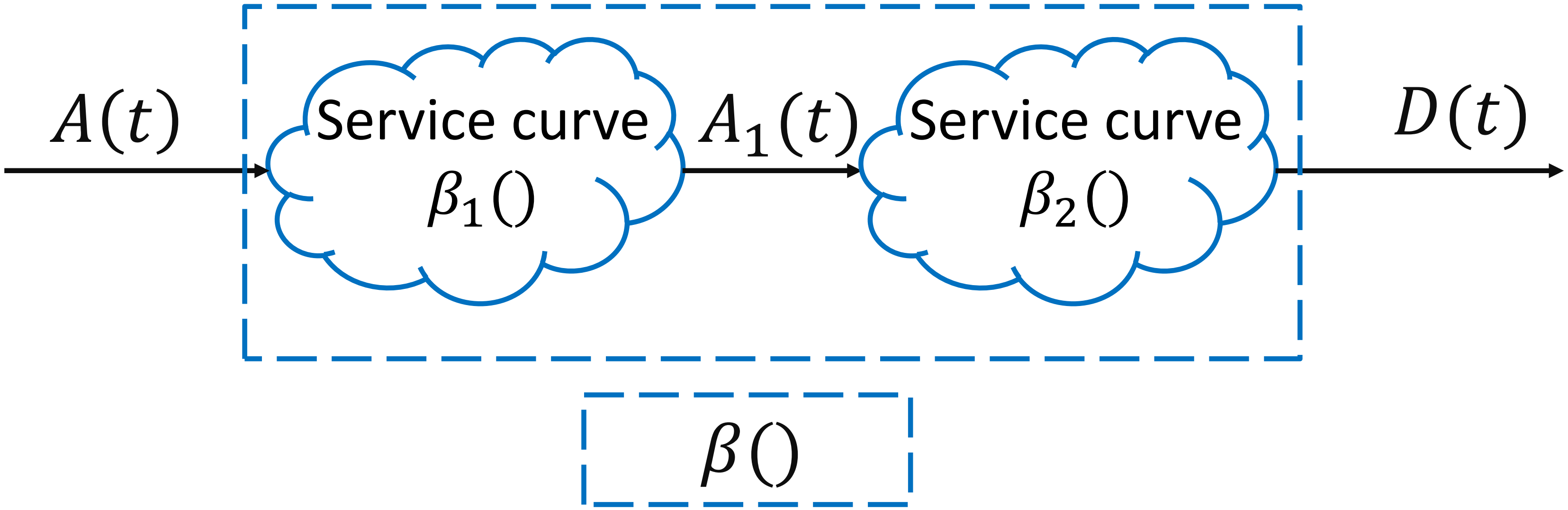
Output arrival curve:

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

with $b^* = b + rT$

(burstiness b is increased by rT)

Concatenation, Per-Flow Networks



A flow is served in series, network element i offers service curve $\beta_i()$.
The concatenation offers to flow the service curve $\beta()$ defined by

$$\beta(t) = \inf_{s \geq 0} \left(\beta_1(s) + \beta_2(t-s)\right)$$

Min-Plus Convolution

$$\beta(t) = \inf_{s \geq 0} \left(\beta_1(s) + \beta_2(t-s)\right)$$

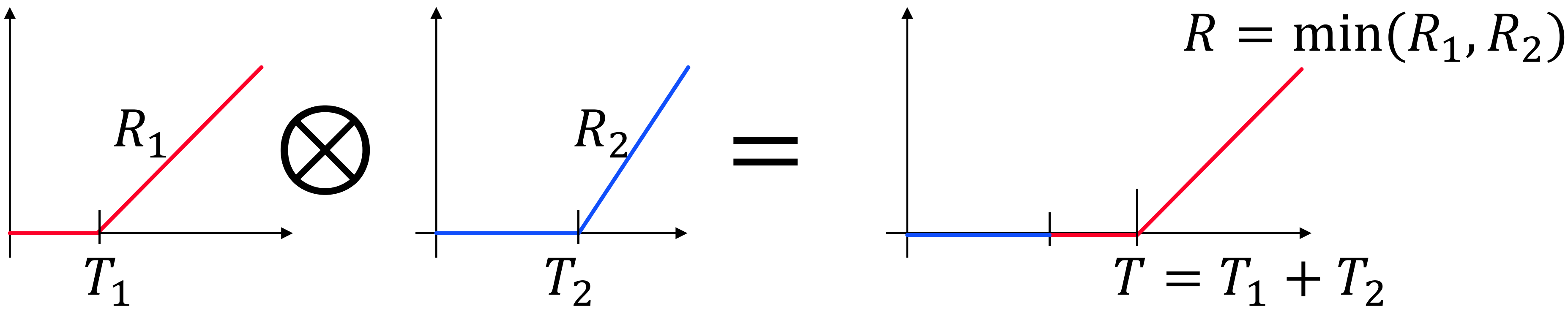
$$\beta = \beta_1 \otimes \beta_2$$

This operation is called *min-plus convolution*. It has the same nice properties as usual convolution; e.g.

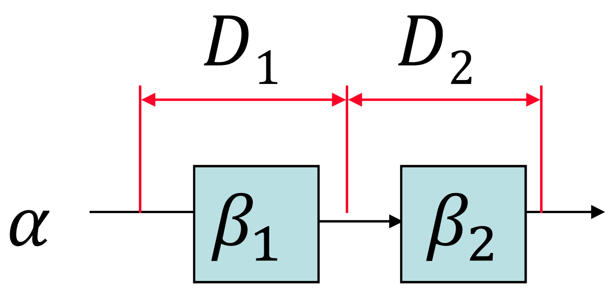
$$(\beta_1 \otimes \beta_2) \otimes \beta_3 = \beta_1 \otimes (\beta_2 \otimes \beta_3)$$

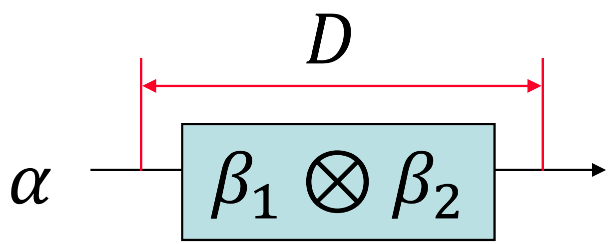
$$\beta_1 \otimes \beta_2 = \beta_2 \otimes \beta_1$$

It can be computed easily: e.g.



Pay Bursts Only Once in Per-Flow Networks





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

one flow constrained *at source* by $\alpha()$

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

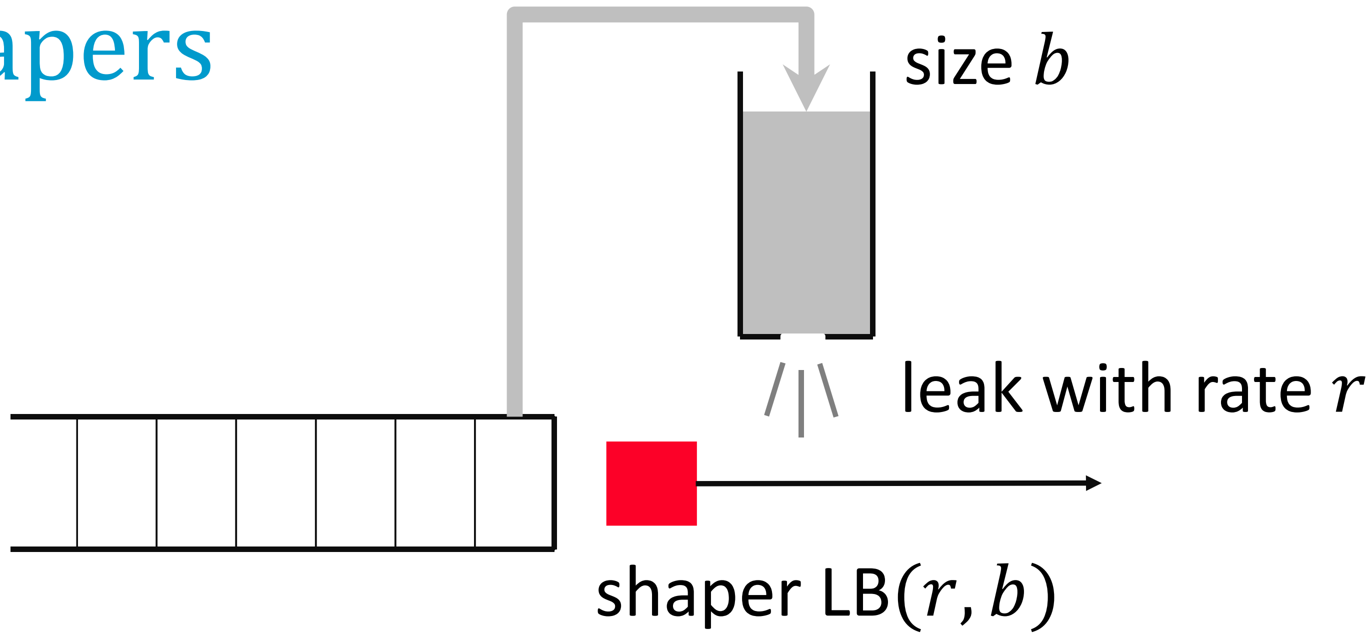
$$D_1 + D_2 = \frac{2b + rT_1}{R} + T_1 + T_2$$

computed *by concatenation:*

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

i.e. worst cases cannot happen simultaneously – concatenation captures this !

Shapers

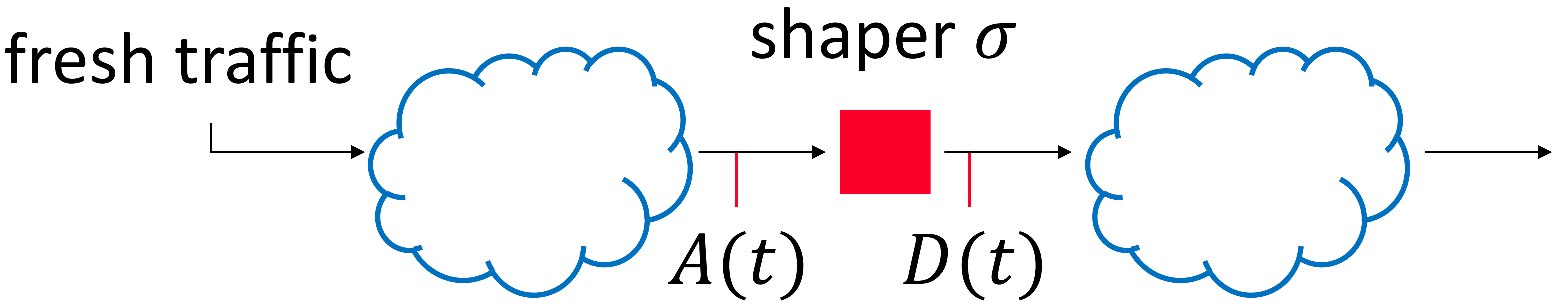


Burstiness increases as flows traverse network elements - Shapers are used to reduce burstiness

Shaper delays packets so that output conforms to arrival curve σ

Example: $\sigma(t) = rt + b$ leaky bucket shaper (r, b) releases a packet only if there is space to put an equivalent amount of fluid into bucket

The Mathematics of Per-Flow Shapers



For leaky bucket flow shaper

min-plus equation:

$$D(t) = \min_{0 \le s \le t} \left(A(t-s) + rs + b \right) \qquad (1)$$

max-plus equation

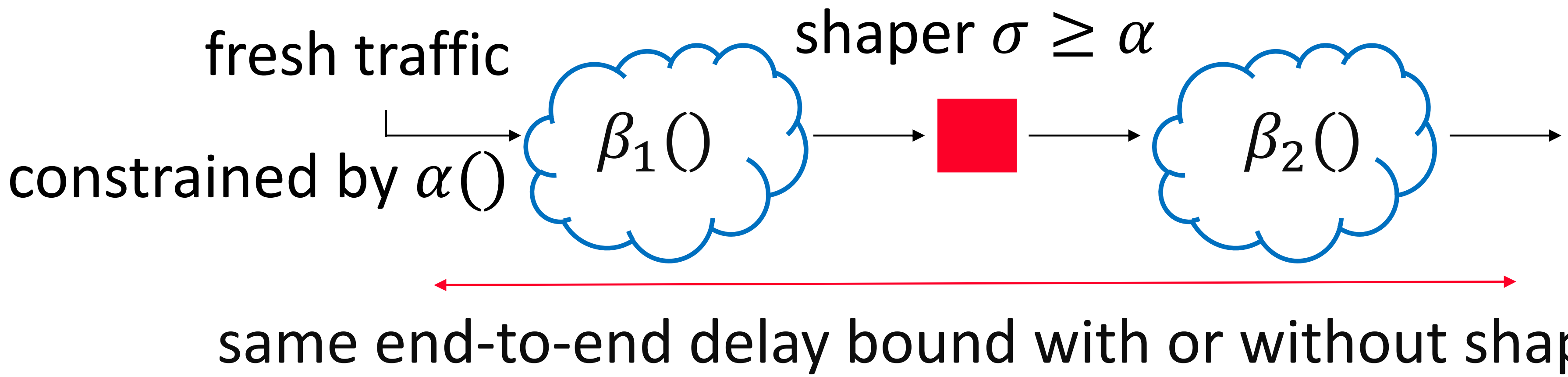
$$D_n = \max_{1 \le m \le n-1} \left(D_m + \frac{L_m + \cdots + L_n - b}{r} \right) \vee A_n \vee D_{n-1} \qquad (2)$$

A_n : arrival time of n^{th} packet, D_n : departure time (at shaper), ∨ = operator notation for max
$A(t)$ = total nb of bytes seen on arrival at shaper in $[0, t]$, $D(t)$ seen on departure

Per-Flow Re-Shaping is For Free

Per-flow re-shaping does not increase worst-case end-to-end delay

(per flow = (TSN) per stream)



Per Class Networks

A set S of flows, each constrained by leaky bucket r_f, b_f are aggregated into one class; $r_{tot} = \sum_{f \in S} r_f$, $b_{tot} = \sum_{f \in S} b_f$

At one node, this class receives a rate-latency service curve R, T (e.g. priority node, DRR, AVB, CBS). FIFO inside the class; $r_{tot} \leq R$

delay bound for any packet of any flow in S: $D = \frac{b_{tot}}{R} + T$

backlog bound for the aggregate of whole S: $B = b_{tot} + r_{tot} T$

output arrival curve for flow f is leaky bucket r_f, b_f^* with

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

[Le Boudec-Thiran 2001, Section 6.4]

Cascading Burstiness

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

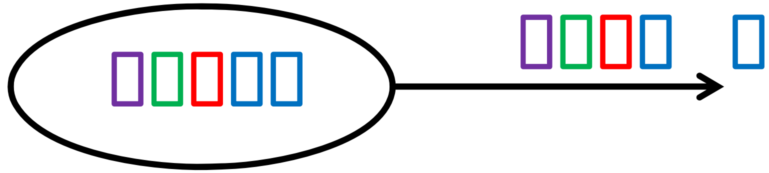
$$b_f^* = b_f + r\left(T + \frac{b_{tot} - b_f}{R}\right)$$

Increased burstiness causes increased burstiness (cascade).

Good delay bounds depend on the topology and on the number of hops. In non-tree topologies, delay bounds are generally bad even at low utilizations and small numbers of hop.
[Bennett et al 2002]

Avoiding Cascading Burstiness in Per-Class Networks

Solution 1: re-shape every flow at every hop (per-flow shaping)
Solves the problem but defeats the purpose of per-class network.

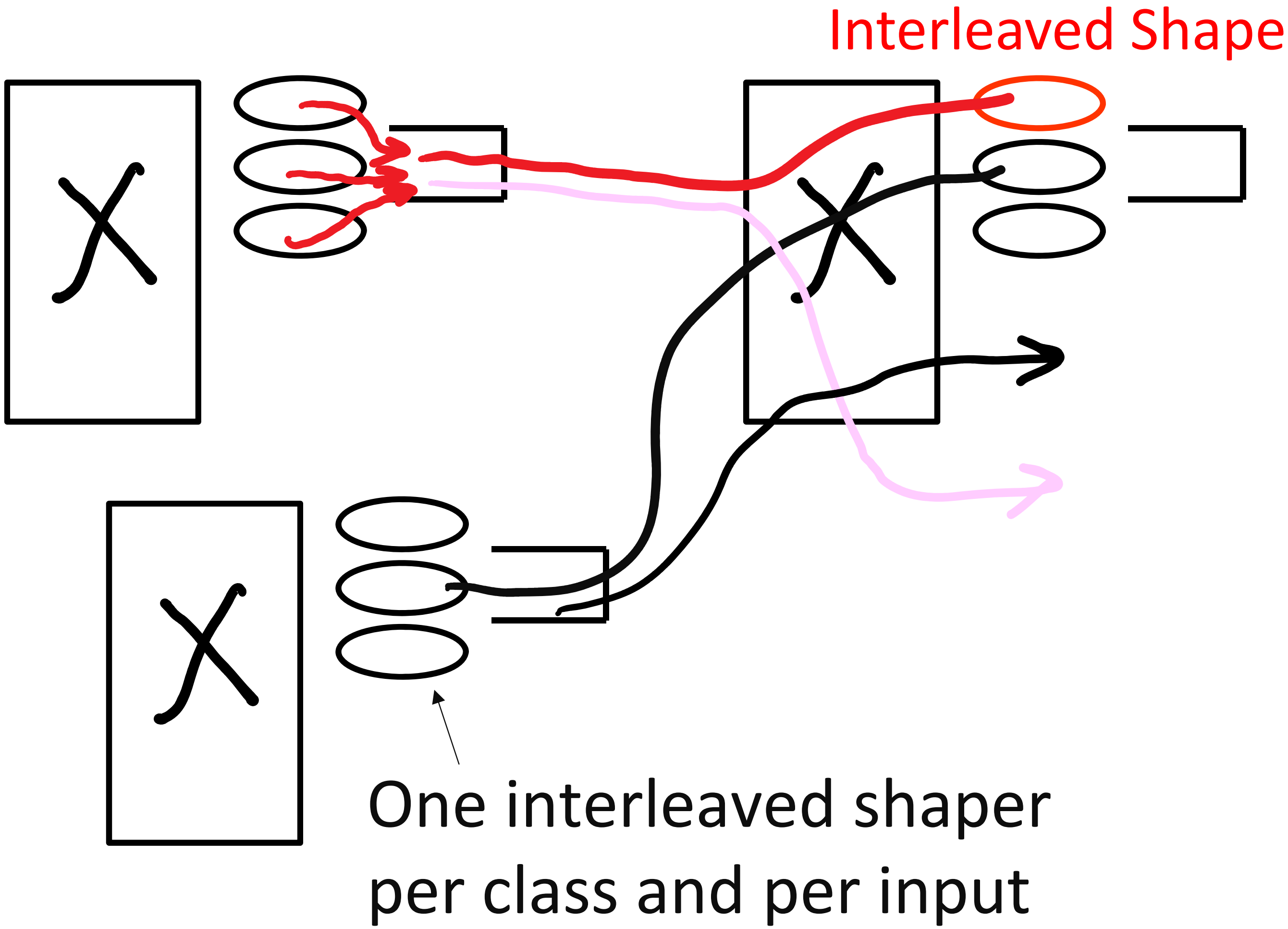


Solution 2: Interleaved shaper

- FIFO queue of all packets of all flows in class
- packet at head of queue is examined versus arrival curve of its flow; this packet is delayed if it came too early
- packets not at head of queue wait for their turn to come

[Specht-Samii 2016]

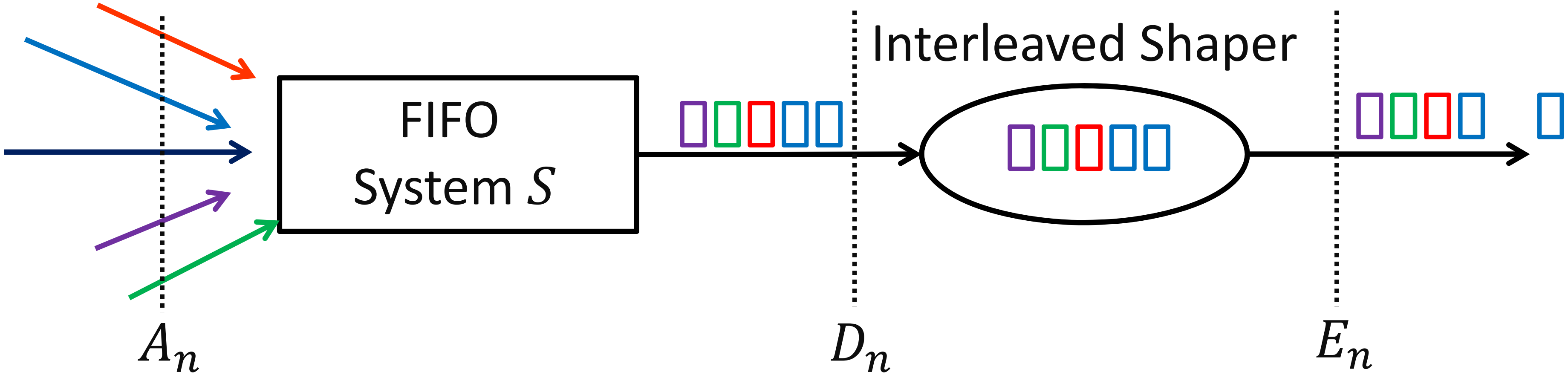
Network With Interleaved Shaper [Specht-Samii 2016]



Output of interleaved shaper is shaped per flow ⇒ delay bound at next server is controlled – no cascading

Question:
what is the delay
due to interleaved shaper ?

Interleaved Shaping Does Not Increase Worst Case Delay



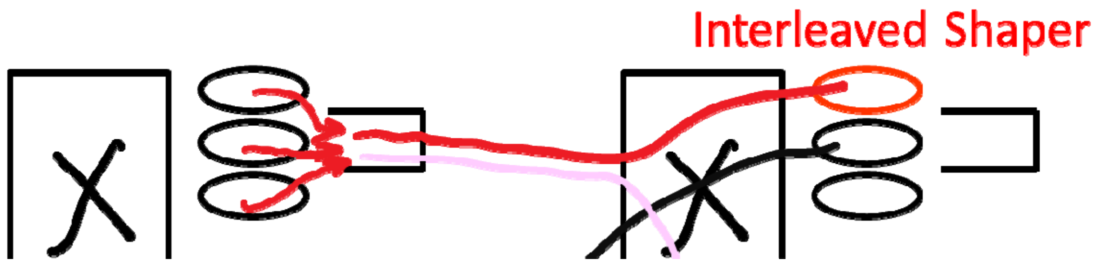
A_n = arrival time of n^{th} packet (numbered in arrival order)

Every flow f is shaped before input to S with parameters (r_f, b_f)

Output of S is fed to interleaved shaper with parameters (r_f, b_f) for flow f

Theorem: $\sup_n (D_n - A_n) = \sup_n (E_n - A_n)$ [Proof in appendix]

Implications for TSN



- Worst case end-to-end queuing delay can ignore interleaved shapers. Delay bound at one interleaved shaper is absorbed by delay at previous hop
- Queuing delay at every hop (without shaper) can be computed with e.g. by $D = \frac{b_{tot}}{R} + T$ where R, T is rate-latency service curve allocated to the class and b_{tot} is the sum of burstiness enforced by the interleaved shaper at this node.
- Worst case delay at one node cannot ignore interleaved shaper. ⇒ Worst case end-to-end delay is generally less than sum of per-hop delays.

Conclusions

Network Calculus can

- help understand some physical properties of deterministic networks (e.g. pay bursts only once, per flow reshaping does not increase end-to-end delay bound, interleaved shaper can delay can be ignored)
- provide formal guarantees on extreme delays that are hard to reach by simulation or by ad-hoc analysis,
- provide a simple language to abstract a node without prescribing an implementation.

Future Work ?

Obtain service curve characterization of TSN/other schedulers and shapers.

Formally prove end-to-end bounds.

Quantify of improvement to end-to-end delay-bounds by exporting service curves instead of per-node delay-bounds.

Explore implications for path computation and setup (distributed, centralized).

Propose and test abstract node models.

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Proof of Theorem 1

The interleaved shaper releases packet n at time $E_n = \max \{D_n, E_{n-1}, F_n\}$, where F_n is the earliest possible time allowed by the leaky bucket constraints (see Eq. (2)):

$$F_n = \max_{1 \le j \le k-1} \left(E_{i_j} + \frac{L_{i_j} + \cdots + L_{i_k} - b_f}{r_f} \right)$$

with: $i_1, i_2, \dots, i_k = n$ indices of packets of flow f in the global packet sequence and f = flow of packet n. Using the operator notation ∨ for maximum, this gives

$$E_n = D_n \vee E_{n-1} \vee \left(E_{i_1} + \frac{L_{i_1} + \cdots + L_{i_k} - b_f}{r_f} \right) \vee \cdots \vee \left(E_{i_{k-1}} + \frac{L_{i_{k-1}} + L_{i_k} - b_f}{r_f} \right) \quad (3)$$

Call d the worst case delay at FIFO system S and prove by induction on n that $E_n \le d + A_n$. Obviously this holds for $n = 1$ (first packet is not delayed by shaper). Now assume $E_m \le d + A_m$ for $m < n$. We will prove that every terms in right-handside of (3) is $\le d + A_n$.

- the first term is D_n; $D_n \leq d + A_n$ by definition of d
- the second term is E_{n-1} ; $E_{n-1} \leq d + A_{n-1}$by induction hypothesis; furthermore, $A_{n-1} \leq A_n$ by definition of the arrival times A_n; thus $E_{n-1} \leq d + A_n$
- the third and following terms are of the form $E_{i_j}+\frac{L_{i_j}+\cdots+L_{i_k}-b_f}{r_f}$; now $E_{i_j}\leq d + A_{i_j}$by induction hypothesis. Furthermore, the input to system S is leaky-bucket constrained per flow. Thus (by Eq (2)):

  $$A_{i_j}+\frac{L_{i_j}+\cdots+L_{i_k}-b_f}{r_f} \leq A_{i_k} = A_n$$

  It follows that the third term is $\leq d + A_{i_j} + \frac{L_{i_j}+\cdots+L_{i_k}-b_f}{r_f} \leq d + A_n$

QED