Latency and Backlog Bounds in Time-Sensitive Networking with Credit Based Shapers and Asynchronous Traffic Shaping

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Time Sensitive Networking(TSN)

- **Time Sensitive Networking (TSN)**: An IEEE standard of the 802.1 Working Group defining mechanisms for:
  - bounded end-to-end latency
  - zero packet loss

- Hardness of end-to-end delay calculation in TSN with per-class queuing
  - Burstiness cascade caused by per-class queuing
  - Dependency loop issue

Reshaping at every node

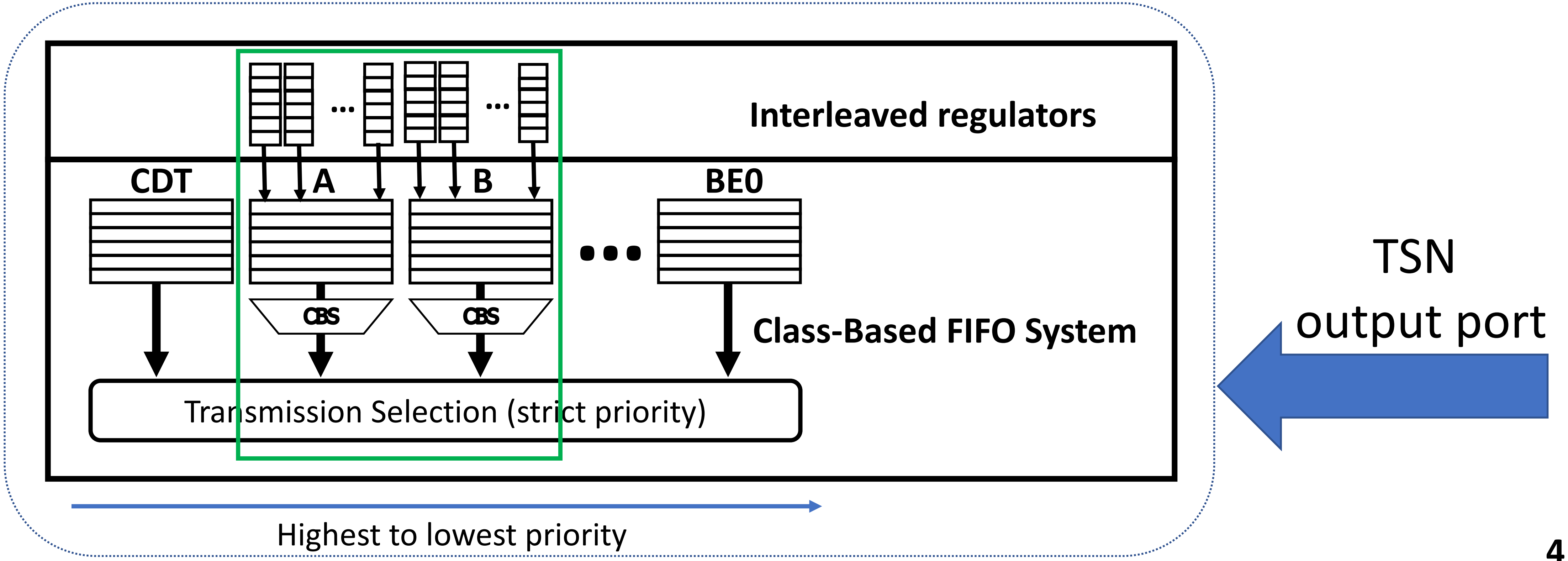
Reshaping solution

- **Interleaved regulator**: Called **Asynchronous Traffic Shaping** (P802.1Qcr) in the context of IEEE TSN. An interleaved regulator reshapes individual flows, while doing **aggregate queuing** and not per-flow queuing.

- Addition of interleaved regulator makes the calculation of end-to-end latency tractable; as in every node, each flow can be treated as a fresh one.

System Model - Architecture of considered TSN Node

- Contention occurs only at the **output port**
- Input ports and switching fabrics are modeled as **variable delays** with known bounds
- We focus on classes A and B which queues are using CBS and ATS
- All classes are **non-preemptive**



System Model - Interleaved Regulation

Interleaved Regulation

Aggregate queuing, per-flow regulation

Queuing policy

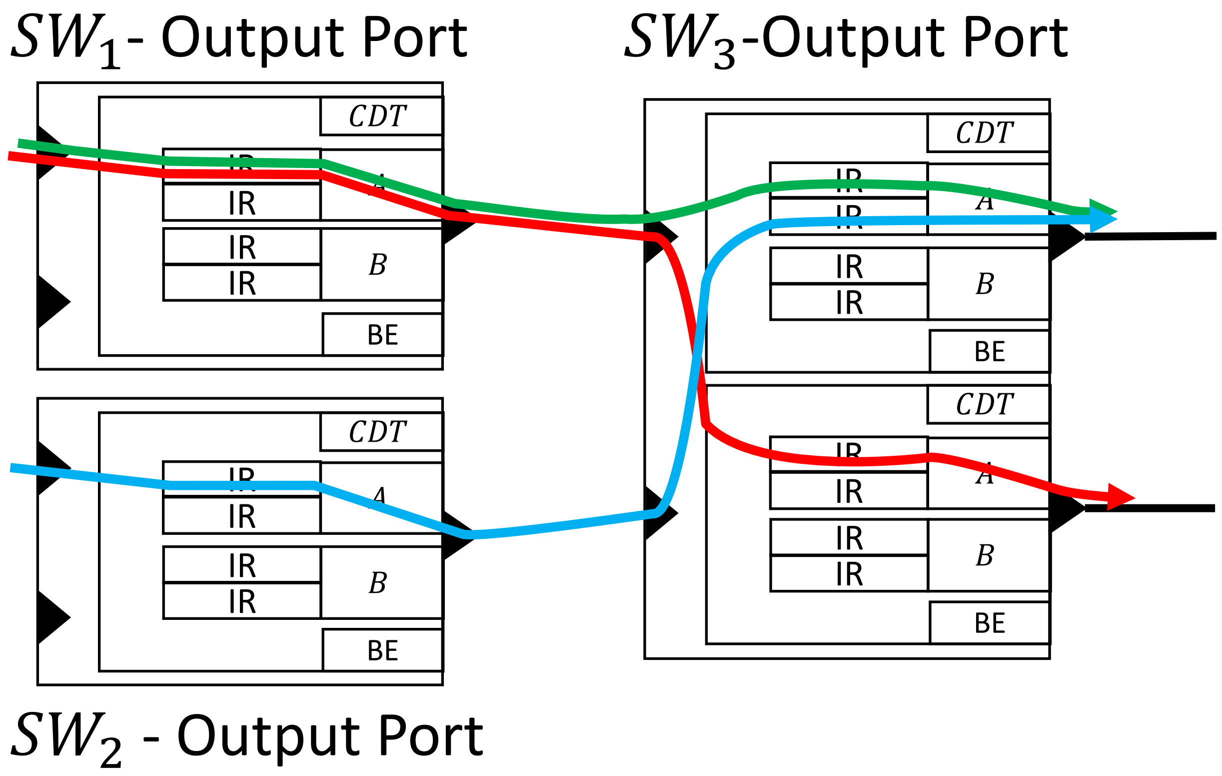
two flows share the same queue if:

- Going to the same output port, and
- Having the same class, and
- Coming from the same input port.

Type of Regulation

+ Length Rate Quotient (LRQ)

+ Leaky Bucket (LB)



System Model - Type of Regulation

LRQ (r)

A_n: arrival time of packet n

E_n: eligibility time of packet n

l_i: length of packet i, $(l_i \leq L)$

$$E_n = \max\left(A_n, E_{n-1} + \frac{l_{n-1}}{r}\right)$$

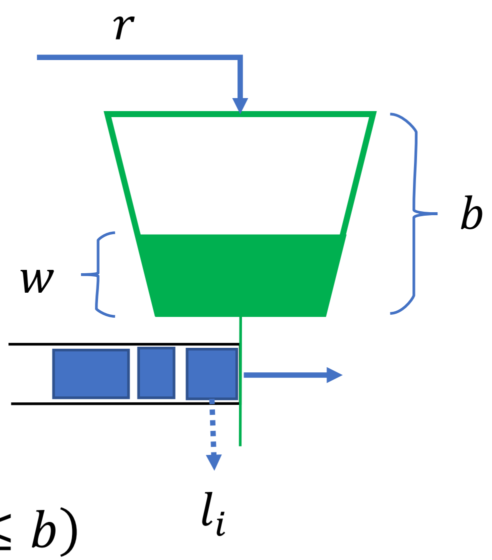
It is a case of g-regularity [Chang and Lin, 1998]:

$$\boldsymbol{\forall m < n\text{: } E_n \geq E_m + g(l_m + \cdots + l_{n-1})}$$

Where for LRQ, $g(x) = \frac{x}{r}$.

LB (r, b)

It is a shaper with shaping curve $rt + b$.



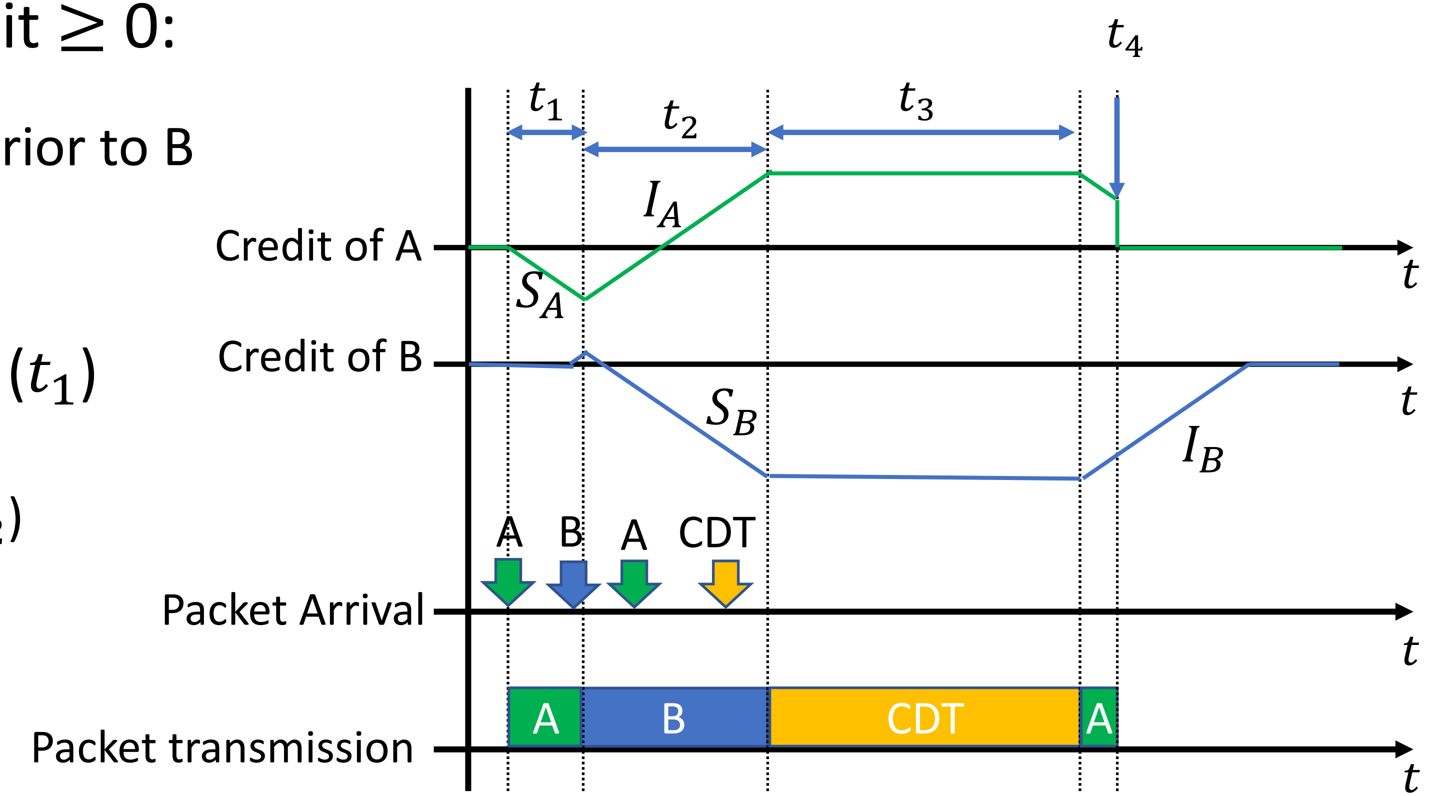
l_i: length of packet i, $(l_i \leq b)$

If $l_i \leq w$: packet i is eligible, $w -= l_i$

w is increasing with rate r $(w \leq b)$

System Model - Credit Based Shaper (CBS)

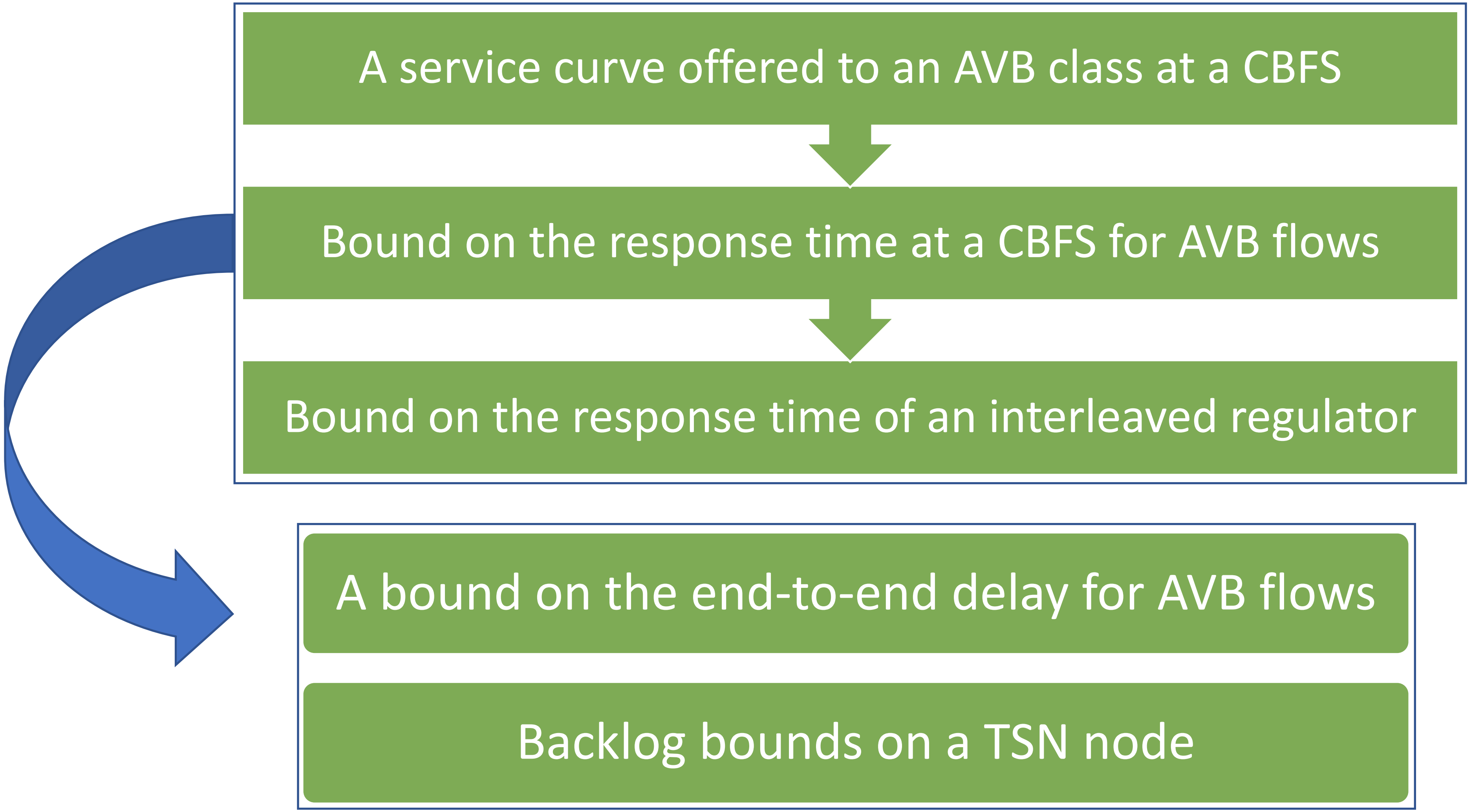
- Keeps a separate credit counter for class A and B
- Packets can be transmitted, if credit ≥ 0:
  - Subject to priority, where class A is prior to B
- Credit modification:
  - **Decreases** in packet transmission (t_1)
  - **Increases** when:
    - no transmission and backlog $\neq 0$ (t_2)
    - Credit < 0
  - **Freezes** in CDT transmission (t_3)
  - **Resets** when backlog becomes zero and Credit ≥ 0 (t_4)



Assumptions

- Each flow has its own regulation policy (LRQ or LB)
- The regulation policy for each flow is the same at all hops
- Flows are regulated at the source nodes
- Control Data Traffic (CDT) has known affine arrival curve at every hop

Contributions



Service curve property for classes A and B at a CBFS

- An extension of minimal service curve computed in [De Azua and Boyer, 2014]

Theorem 1-A: *A rate-latency service curve offered to* ***class A*** *by CBFS, assuming CDT has an affine arrival curve (r,b), is:*

$$T^A = \frac{1}{c-r}(\bar{L}^A + b + \frac{r\bar{L}}{c})$$

$$R^A = \frac{I^A(c-r)}{I^A - S^A}$$

Theorem 1-B: *A rate-latency service curve offered to* ***class B*** *by CBFS, assuming CDT has an affine arrival curve (r,b), is:*

$$T^B = \frac{1}{c-r}(L^{BE} + L^A - \frac{\bar{L}^A I^A}{S^A} + b + \frac{r\bar{L}}{c})$$

$$R^B = \frac{I^B(c-r)}{I^B - S^B}$$

c = line rate

L^A *= max. pkt. Len. of A*

L^B *= max. pkt. Len. of B*

L^{BE} *= max. pkt. Len. of BE*

I^A *= CBS Idle slope (A)*

S^A *= CBS send slope (A)*

I^B *= CBS Idle slope (B)*

S^B *= CBS send slope (B)*

$\bar{L}^A = \max(L^B, L^{BE})$

$\bar{L} = \max(L^A, L^B, L^{BE})$

Novel Bound on Response time of CBFS for classes A and B

***Theorem 2**: An upper bound on the response time of CBFS for flow f of class A is:*

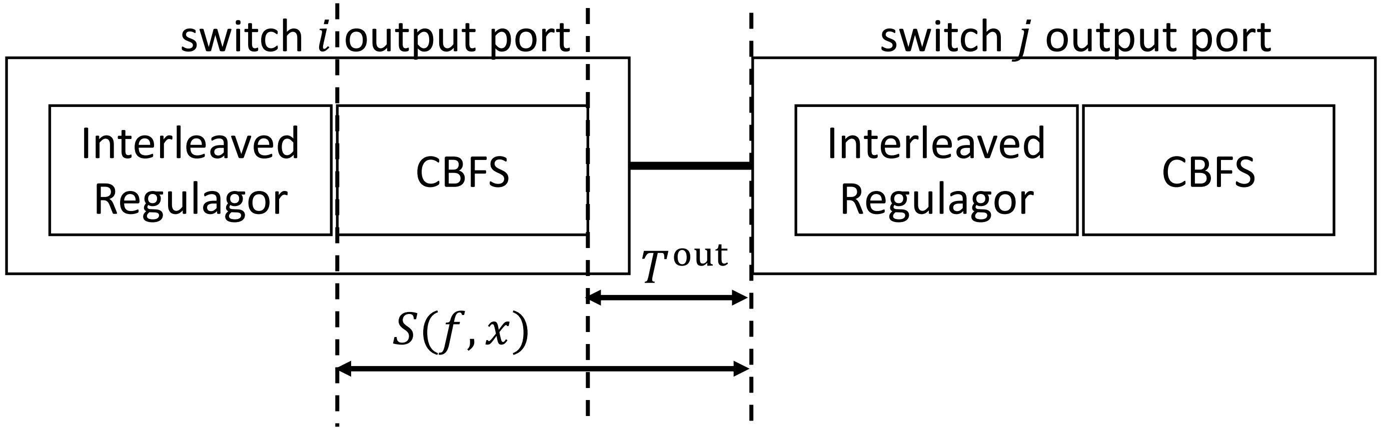
$$S(f,A) = T^A + \frac{b^{\text{tot},A} - \psi_f}{R^x} + \frac{\psi_f}{c} + T^{\text{var,max}}$$

Where:

$\psi_f = L_f$ (*maximum packet length of flow* f), *if flow is LRQ-regulated,*

$\psi_f = M_f$ (*minimum packet length of flow* f), *if flow is LB-regulated.*

Similar formula is obtained for class B.



c = line rate

(T^A, R^A) = *CBFS service curve params of class* x

$$b^{\text{tot},A} = \sum_{f' \text{ of class } A} b_{f'}$$

$$T^{\text{out}} = T^{\text{tran}} + T^{\text{var}}$$

$$T^{\text{var}} \in [T^{\text{var,min}}, T^{\text{var,max}}]$$

Comparison with Classical Network Calculus results

- From classical network calculus results, an upper bound on CBFS response time of class A is:

$$S'(A) = T^A + \frac{b^{\text{tot},A}}{R^A} + T^{\text{var,max}}$$

  - FIFO system
  - Shaped input flows
  - Known service curve

$$S(f,x) = T^A + \frac{b^{\text{tot},A} - \psi_f}{R^A} + \frac{\psi_f}{c} + T^{\text{var,max}}$$

- This work offers better bound ($S(f,A) \leq S'(A)$):
  - $S'(A) - S(f,A) = \psi_f \left(\frac{1}{R} - \frac{1}{c}\right) \geq 0$

  Made possible by:

  \+ **max-plus representation of regulator**

  \+ **Known packet transmission time**

- This work offers per-flow bound, while classical NC does not.

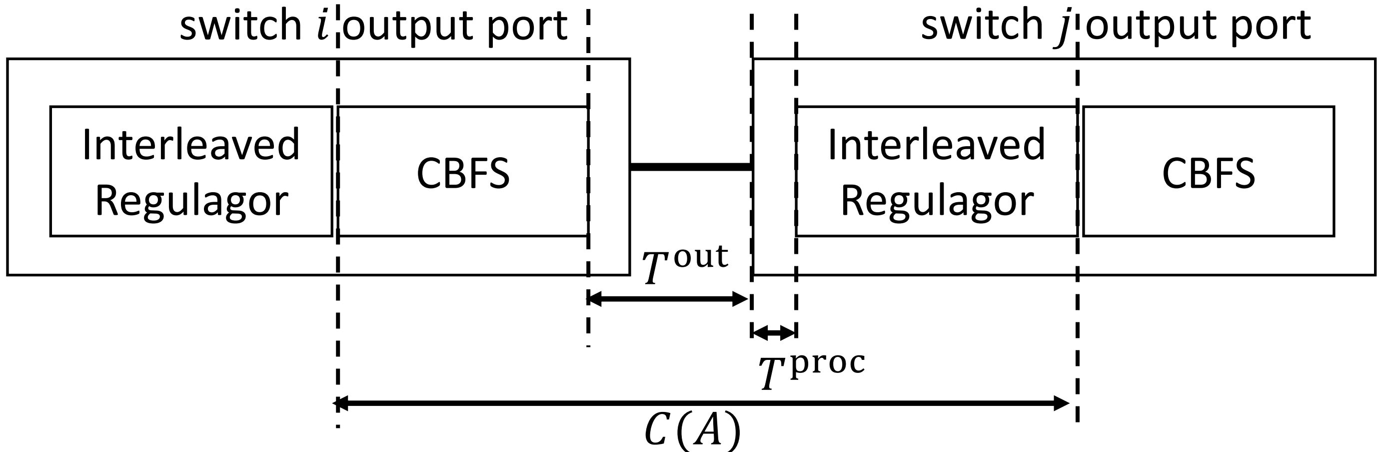
Bound on Response time of CBFS-IR pair for classes A and B

- Interleaved regulator comes for free [Le Boudec, 2018][Specht and Samii, 2016]; thus:

***Corollary 1**: An upper bound on the response time of the combination of a CBFS-IR of class A is:*

$$C(A) = \sup_{f' \in F}\{S(f', A)\} + T^{\text{proc,max}}$$
$$= T^A + \frac{b^{\text{tot},A}}{R^A} + \sup_{f' \in F}\left\{\frac{\psi_{f'}}{c} - \frac{\psi_{f'}}{R^A}\right\} + T^{\text{var,max}} + T^{\text{proc,max}}$$

Similar formula is obtained for class B.



c = line rate

(T^A, R^A) = *CBFS service curve params of class A*

$$b^{\text{tot},A} = \sum_{f' \text{ of class } x} b_{f'}$$

$$T^{\text{out}} = T^{\text{tran}} + T^{\text{var}}$$

$$T^{\text{var}} \in [T^{\text{var,min}}, T^{\text{var,max}}]$$

$$T^{\text{proc}} \in [T^{\text{proc,min}}, T^{\text{proc,max}}]$$

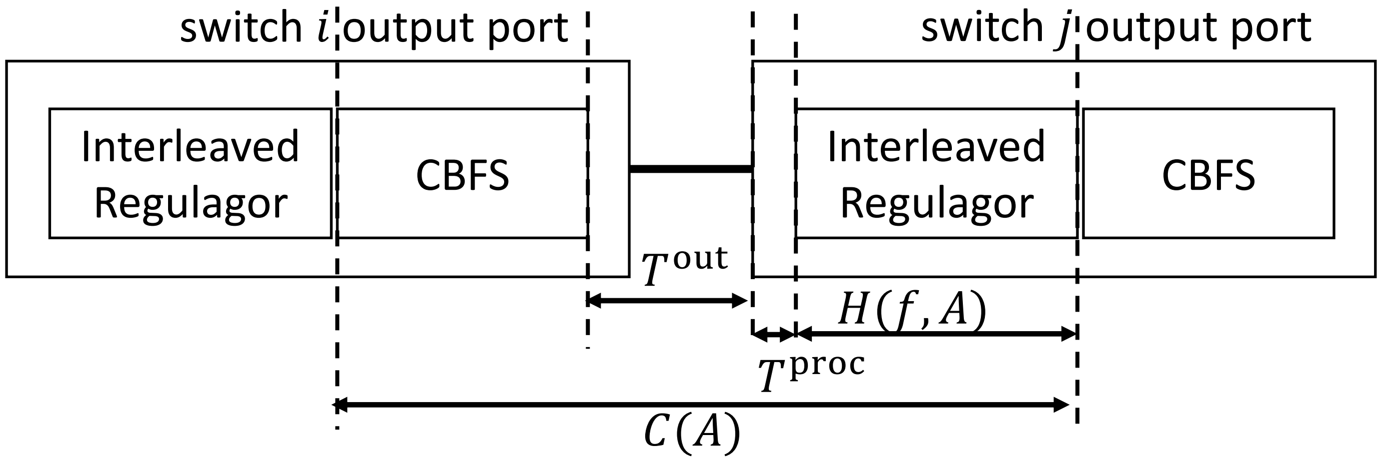
$$\psi_f = \begin{cases} L_f & LRQ - reg \\ M_f & LB - reg \end{cases}$$

Bound on Response time of IR for classes A and B

***Theorem 3**: An upper bound on the response time of an interleaved regulator for flow f of class A is:*

$$H(f,A) = C(A) - \frac{M_f}{c} + T^{\text{var,min}} + T^{\text{proc,min}}$$

Similar formula is obtained for class B.



c = line rate

(T^A, R^A) *= CBFS service curve params of class A*

$$b^{\text{tot,A}} = \sum_{f' \text{ of class } x} b_{f'}$$

M_f: Min. packet length

$T^{\text{out}} = T^{\text{tran}} + T^{\text{var}}$

$T^{\text{var}} \in [T^{\text{var,min}}, T^{\text{var,max}}]$

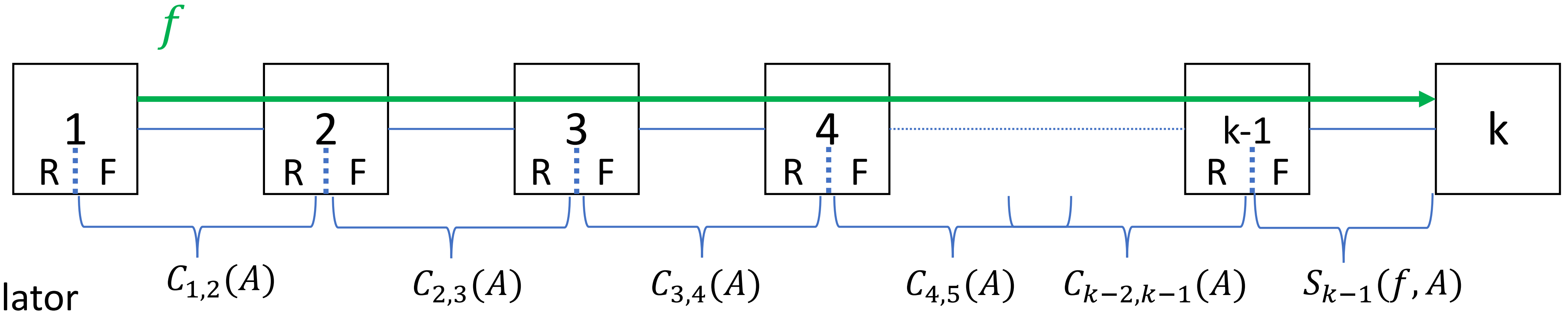
$T^{\text{proc}} \in [T^{\text{proc,min}}, T^{\text{proc,max}}]$

Bound on End-to-end delay for classes A and B

***Corollary 2**: An upper bound on the end-to-end delay of a flow f of class A, is:*

$$D(f, A) = \sum_{i=1}^{k-2} C_{i,i+1}(A) + S_{k-1}(f, A)$$

Similar formula is obtained for class B.

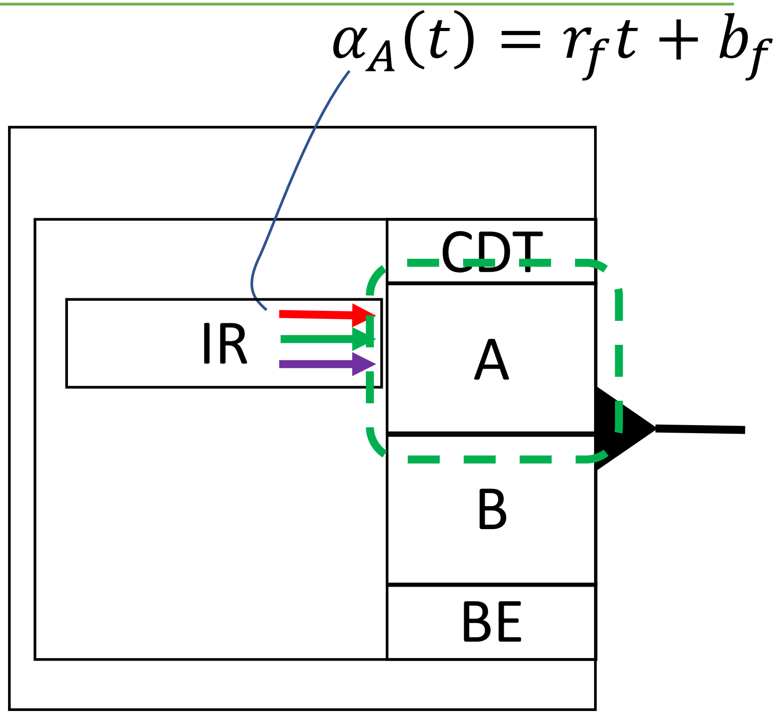


R: Regulator
F: CBFS

Backlog bound- CBFS for class A and B

- Bound on number of bits in the CBFS

- Regulated input flows to the CBFS
- Known rate-latency service curve (R,T)



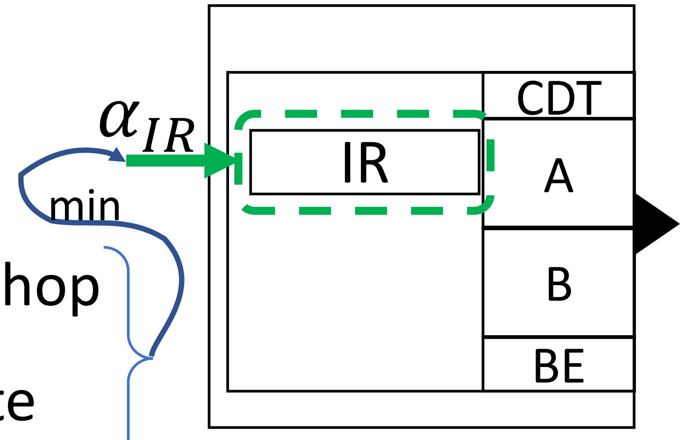
Backlog bound CBFS for class A:

$$B_{CBFS}^{A} = \sum_{f\ of\ class\ A} b_f + T^A \sum_{f\ of\ class\ A} r_f$$

Similar formula is obtained for class B.

Backlog bound- Interleaved Regulator of class A and B

- Bound on number of bits in the interleaved regulator



- Output arrival curve of previous hop
- Arrival curve enforced by line rate
- Service curve from known latency bound ($\delta_D(t)$)

Backlog bound of interleaved regulator of class A:

$$B_{IR}^{A} = \min\left(cD^A + \sup_{f \in F}\{L_f\}, r_s D^A + b_s + r_s\left(T^A + \frac{b_w}{R^A}\right)\right)$$

Similar formula is obtained for class B.

c = line rate

(T^A, R^A) *= CBFS service curve params of class A*

D^A= delay bound on IR

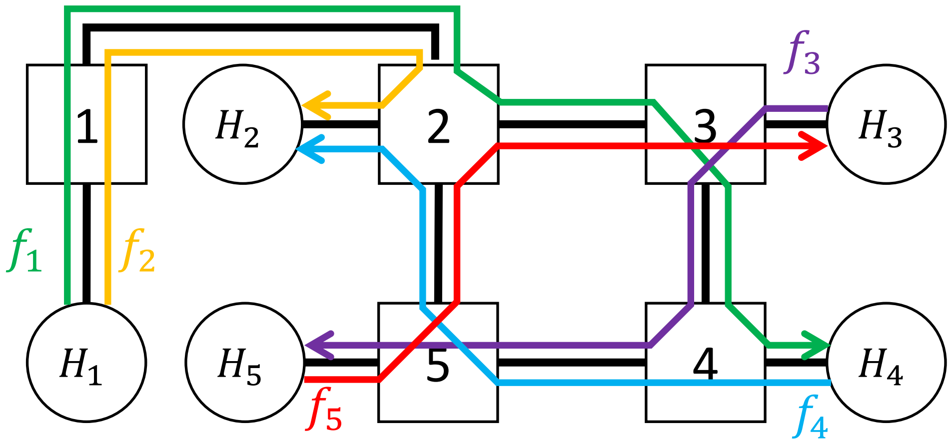
L_f: Max. packet length

(r_s, b_s)= affine arrival curve params of the flows using considered IR, sharing the same CBFS in previous hop

b_w= total burstiness of flows not using the same IR, sharing the same CBFS in previous hop

Case study 1 - Network setup and flows

- On each output port:
  - CBFS classes: CDT, A, BE
  - Line rate: 100 $Mbps$
  - CDT traffic with affine arrival curve $(r = 20\ Mbps, b = 4\ kb)$
  - Best Effort traffic with maximum packet length 2 kb
  - CBS parameters: $I_A = 50\ Mbps, S_A = -50\ Mbps$

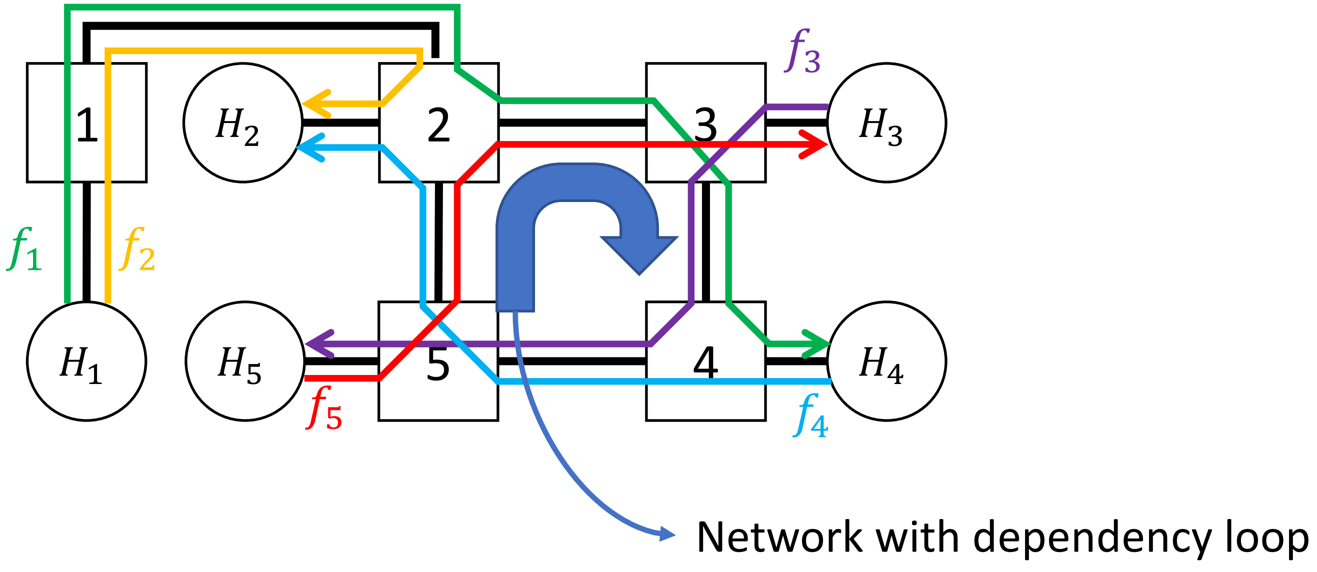


LRQ-regulated

Flow	Rate ($Mbps$)	Packet len. (kb)
f_1	20	1
f_2	20	2
f_3	20	2
f_4	20	2
f_5	20	2

Case study 1 – Numerical results on end-to-end delay bound

- We can calculate end-to-end delay bound for any link utilization ≤ 1
- This is not correct for other techniques without regulation
- End-to-end delay bound of flow f_1 of class A: $D(f_1, A) = 700\ \mu s$

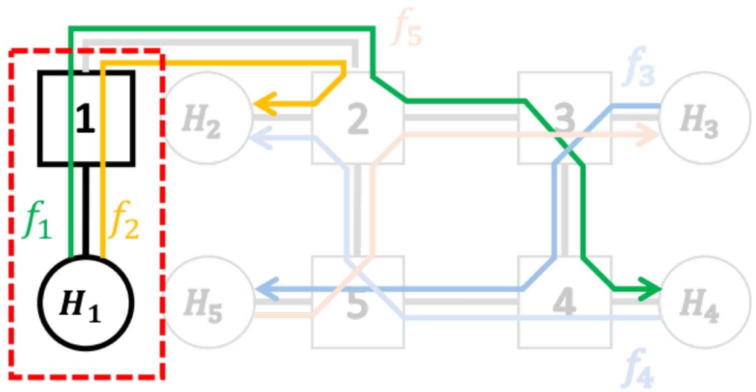


LRQ-regulated

Flow	Rate $(Mbps)$	Packet len. (kb)
f_1	20	1
f_2	20	2
f_3	20	2
f_4	20	2
f_5	20	2

Case study 1 – Numerical results on response times

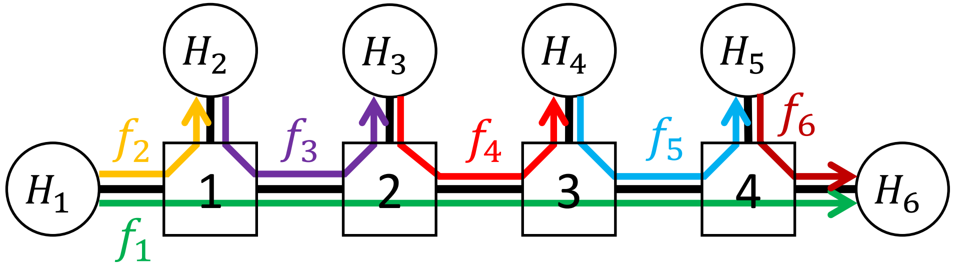
- Adversarial simulation is done by trial and error
- The numerical results show clues on tightness of the bounds
- Proving the tightness is still an ongoing project…



Bound on	Simulation	Theoretical
CBFS response time of H_1	$140\ \mu s$	$S(f_1, A) = 140\ \mu s$
IR response time at 1	$130\ \mu s$	$H(f_1, A) = 130\ \mu s$
CBFS-IR response time $(H_1 - 1)$	$140\ \mu s$	$C_{H_1,1}(A) = 140\ \mu s$

Case study 2- E2E delay tightness; Comparing with sum of per-node delay bound

- The numerical results show clues on tightness of the bounds
  - Theoretical: $D(f_1, A) = 700\ \mu s$
  - Simulation: $700\ \mu s$
- Proving the tightness is still an ongoing project…



- Sum of per-node delay bound ≥ Our E2E delay bound
  - Bound on delay of node i: $d_i^{f_1,A} = H(f_1, A) + S(f_1, A)$
  - $d_{H_1}^{f_1,A} = 0 + 140 = 140\ \mu s$
  - $d_i^{f_1,A} = 130 + 140 = 270\ \mu s\ (i = 1,2,3,4)$
  - $D_{pn}(f_1, A) = \sum_{i \in path} \left(d_i^{f_1,A}\right) = 1220\ \mu s$

$$D_{pn}(f_1, A) = 1220\ \mu s \gg 700\ \mu s = D(f_1, A)$$

LRQ-regulated

Flow	Rate ($Mbps$)	Packet len. (kb)
f_1	20	1
f_2	20	2
f_3	20	2
f_4	20	2
f_5	20	2
f_6	20	2

Conclusion

- We obtain a service curve offered to AVB classes
- Novel upper bound on response time of CBFS for AVB flows
  - The bound is better than classical network calculus results
- Upper bound on response time of interleaved regulator for each flow
- Upper bound on per-flow end-to-end delay
  - The bound is better than sum of per-node delay bound
- Backlog bounds in a TSN node

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References

- **[1]** E. Mohammadpour, E. Stai, M. Mohiuddin, and J.-Y. Le Boudec, “ End-to-end Latency and Backlog Bounds in Time-Sensitive Networking with Credit Based Shapers and Asynchronous Traffic Shaping,” *arXiv:1804.10608 [cs.NI]*, 2018. [Online]. Available: https: //arxiv.org/abs/1804.10608/
- **[2]** J.-Y. Le Boudec, “A Theory of Traffic Regulators for Deterministic Networks with Application to Interleaved Regu- lators,” *arXiv:1801.08477 [cs]*, Jan. 2018. [Online]. Available: http://arxiv.org/abs/1801.08477/, (Accessed:09/02/2018).
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