Analysis of TSN for Industrial Automation based on Network Calculus

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Purpose

- Share a paper from our team with the group
  - <<Analysis of TSN for Industrial Automation based on Network Calculus>>
  - Network calculus theory, industrial automation network modeling, and simulation results.
  - https://ieeexplore.ieee.org/document/8869053

- Discuss the idea of using network calculus to calculate the **worst-case latency bound** for industrial automation scenarios.
  - Vital for using asynchronous/non-time-based methods, e.g., SP with CBS or ATS.
  - What is the challenge? Where is the gap?

Network calculus theory

- Traffic characteristics / traffic constraints (TSpec in TSN) → arrival curve
- Device's capability (bandwidth, queuing and shaping, reservation) → service curve

→ The bound.

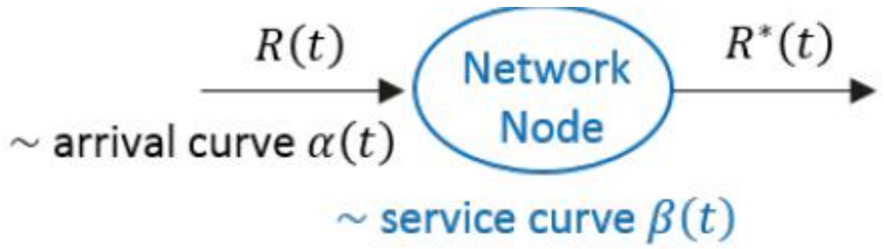


Fig. 3. Two-port network model of a TSN relay node

$$R(s+t) - R(s) \leq \alpha(t), \quad \forall\ s \geq 0,\ t \geq 0 \qquad (1)$$

$$R^*(t) \geq R \otimes \beta(t) = \inf_{s}\{R(s)+\beta(t-s)\}, \quad \forall\ 0 \leq s \leq t \quad (2)$$

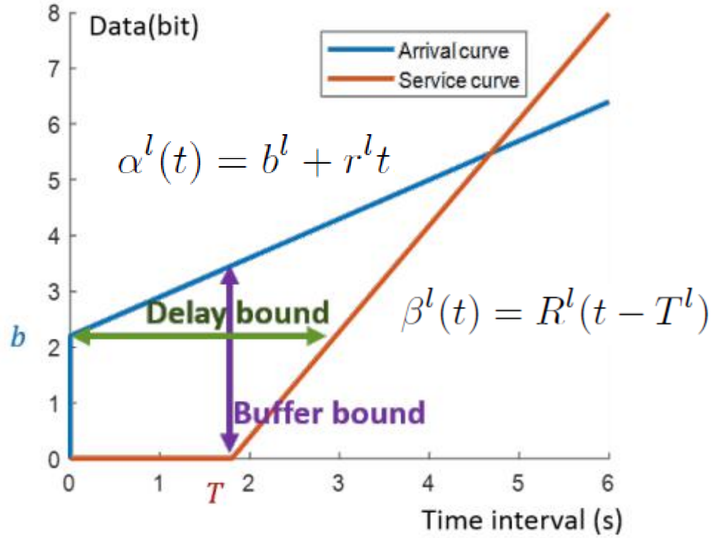


Fig. 4. Computation of backlog bound and delay bound.

Network calculus theory

CDT: Control Data Traffic

- The queuing and forwarding method: SP+CBS

TRAFFIC CLASS DEFINITION

	Priority	Traffic Class	Traffic constraint
highest →	1	CDT	Token bucket
	2	SR Class A	Token bucket
	3	SR Class B	Token bucket
lowest →	4	BE	

$$\alpha^l(t) = b^l + r^l t$$

$$\beta^l(t) = R^l(t - T^l)$$

For CDT,

$$R^{CDT} = c$$

$$T^{CDT} = \frac{b_h - b_f + L^{\bar{h}}}{c}$$

For SR Class A,

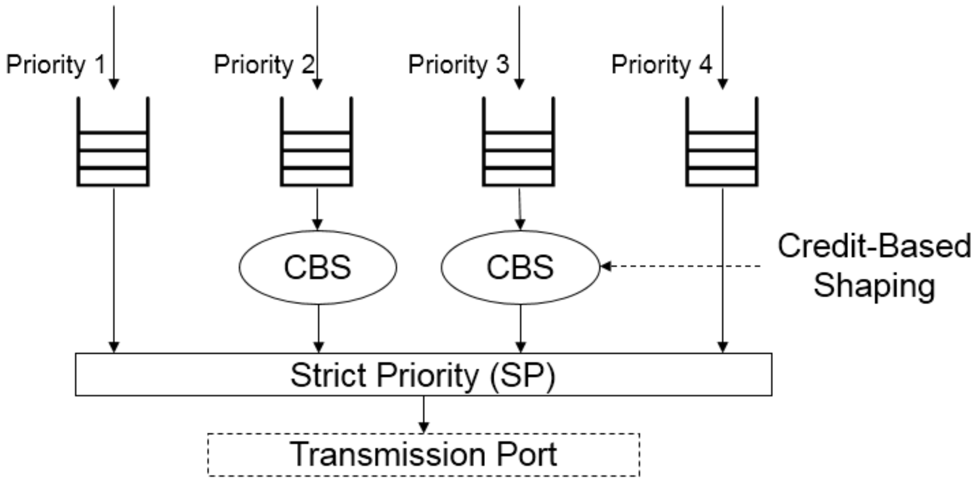
$$R^A = \frac{I^A(c - r_h)}{c}$$

$$T^A = \frac{L^{\bar{A}} + b_h + \frac{r_h L^{\bar{h}}}{c}}{c - r_h}$$

For SR Class B,

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

$$T^B = \frac{L^{BE} + L^A + \frac{L^{\bar{A}} I^A}{c - I^A} + b_h + \frac{r_h L^{\bar{h}}}{c}}{c - r_h}$$



- One hop latency bound: $D_{i,j} = T^l + \frac{b^l - L_{\min,f}}{R^l} + \frac{L_{\min,f}}{c}$
- End-to-end latency bound: the sum of per-hop latency bound along the path.

The network calculus math in this paper mainly refers to J-Y. Le Boudec and E. Mohammadpour's research.

Industrial automation network modeling

- Topology, flows, and shapers.

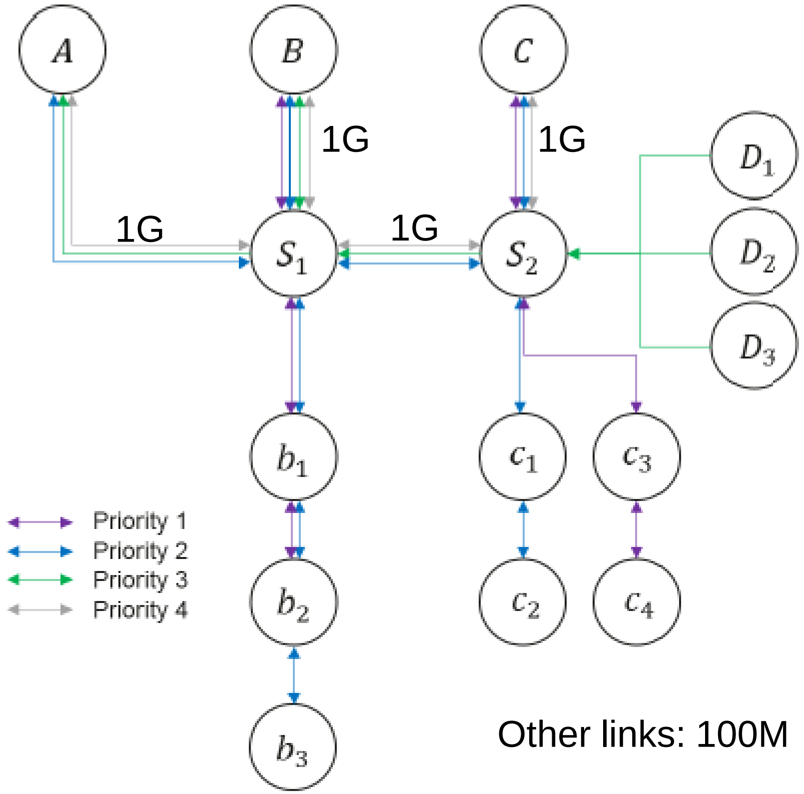


Fig. 5. Simulation topology

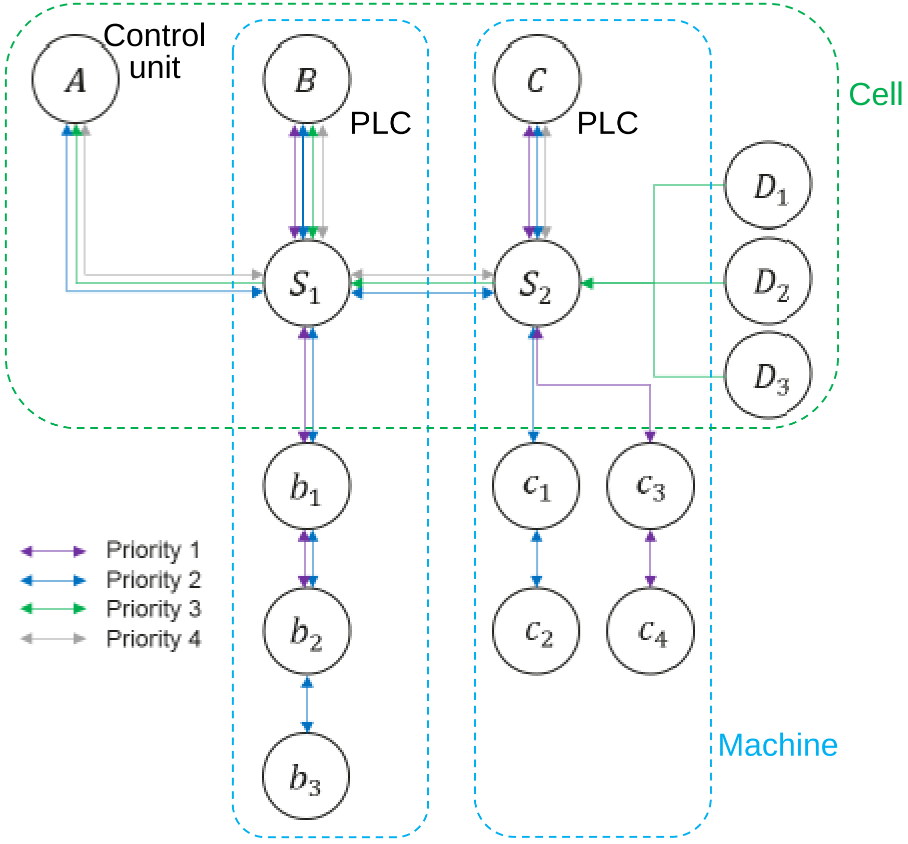
FLOW DESCRIPTION

Flow path	Traffic Type	Forwarding	Priority
p_1: B, S_1, b_1 p_2: B, S_1, b_1, b_2 p_3: b_1, S_1, B p_4: b_2, b_1, S_1, B p_5: C, S_2, c_3 p_6: C, S_2, c_3, c_4 p_7: c_3, S_2, C p_8: c_4, c_3, S_2, C	Isochronous	CDT (SP)	1
p_9: B, $_1$, S_2, C p_{10}: C, S_2, S_1, B p_{11}: A, S_1, B p_{12}: B, S_1, A p_{13}: A, S_1, S_2, C p_{14}: C, S_2, S_1, A p_{15}: C, S_2, c_1 p_{16}: C, S_2, c_1, c_2 p_{17}: c_1, S_2, C p_{18}: c_2, c_1, S_2, C p_{19}: b_3, b_2, b_1, S_1, B p_{20}: B, S_1, b_1, b_2, b_3	Cyclic	SR Class A (CBS)	2
p_{21}: D_1, S_2, C p_{22}: D_2, S_2, S_1, A p_{23}: D_3, S_2, S_1, B	A/V	SR Class B (CBS)	3
p_{24}: A, S_1, B p_{25}: B, S_1, A p_{26}: A, S_1, S_2, C p_{27}: C, S_2, S_1, A	BE	BE (SP)	4

Most of the information used for modeling is referenced to past 60802 contributions and 60802 use case draft.

Industrial automation network modeling

- Topology, flows, and shapers.



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FLOW DESCRIPTION

Flow path	Traffic Type	Forwarding	Priority	
p_1: B, S_1, b_1 p_2: B, S_1, b_1, b_2 p_3: b_1, S_1, B p_4: b_2, b_1, S_1, B	Isochronous	CDT (SP)	1	Lmax=0.8kb T=2ms (cycle time)
p_5: C, S_2, c_3 p_6: C, S_2, c_3, c_4 p_7: c_3, S_2, C p_8: c_4, c_3, S_2, C				Lmax=0.8kb T=1ms (cycle time)
p_9: B, $_1$, S_2, C p_{10}: C, S_2, S_1, B p_{11}: A, S_1, B p_{12}: B, S_1, A p_{13}: A, S_1, S_2, C p_{14}: C, S_2, S_1, A p_{15}: C, S_2, c_1 p_{16}: C, S_2, c_1, c_2 p_{17}: c_1, S_2, C p_{18}: c_2, c_1, S_2, C p_{19}: b_3, b_2, b_1, S_1, B p_{20}: B, S_1, b_1, b_2, b_3	Cyclic	SR Class A (CBS)	2	Lmax=0.8kb T=10ms
p_{21}: D_1, S_2, C p_{22}: D_2, S_2, S_1, A p_{23}: D_3, S_2, S_1, B	A/V	SR Class B (CBS)	3	Lmax=12kb r=1Mbps
p_{24}: A, S_1, B p_{25}: B, S_1, A p_{26}: A, S_1, S_2, C p_{27}: C, S_2, S_1, A	BE	BE (SP)	4	Lmax=12kb

IdleSlopeA=50%Bandwidth

IdleSlopeB=25%Bandwidth

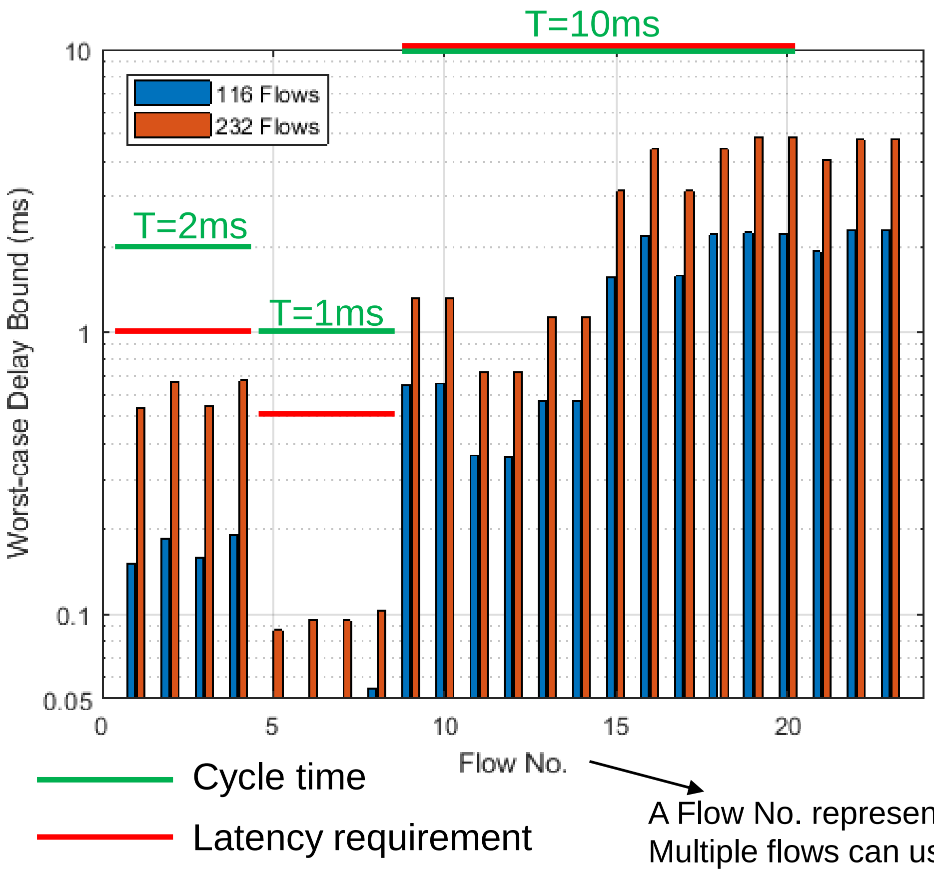
Most of the information used for modeling is referenced to past 60802 contributions and 60802 use case draft.

Simulation results

- The worst-case latency bound result with different bandwidth usage (i.e., different number of flows).

➢ Assuming that the latency requirement is 50%*T (cycle time) for all isochronous traffic, and is T for all cyclic traffic, then the result satisfies the requirement.

➢ Generally, the latency requirement could be tighter for isochronous cyclic real-time traffic and looser for cyclic real-time traffic.



A Flow No. represents a flow path.
Multiple flows can use a same path.

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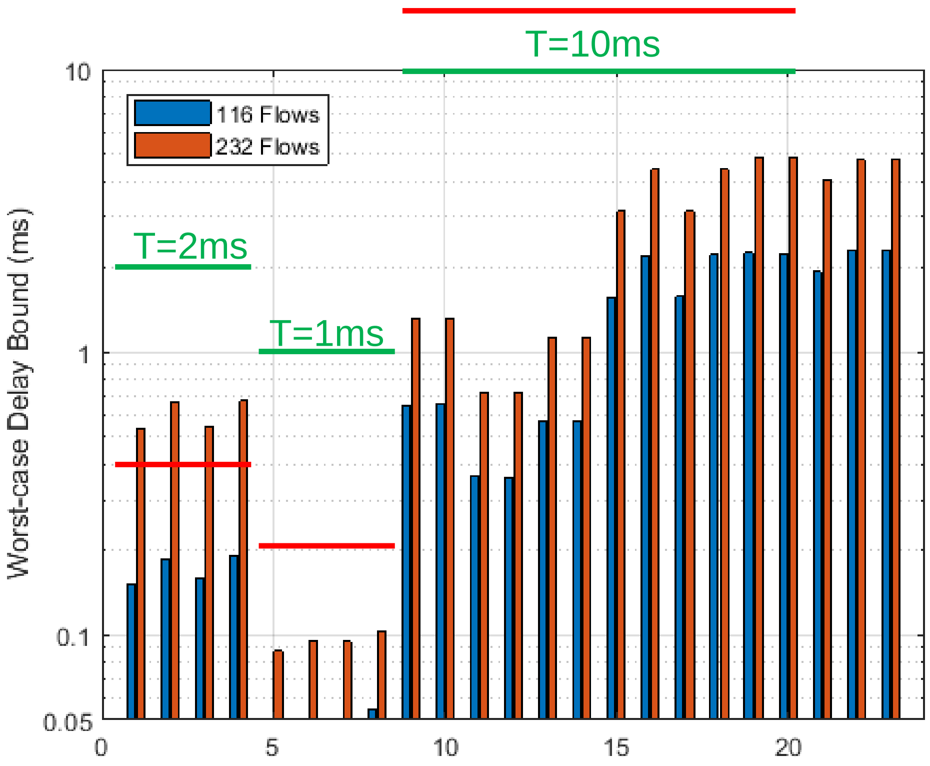
➢ Generally, the latency requirement could be tighter for isochronous cyclic real-time traffic and looser for cyclic real-time traffic.

➢ If the latency requirement is 20%*T for isochronous traffic,,, oops!

➢ What if there are even more flows, or more hops, or…



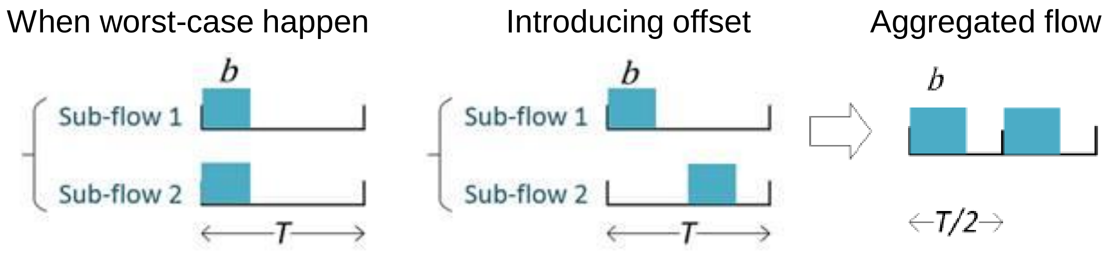
Cycle time

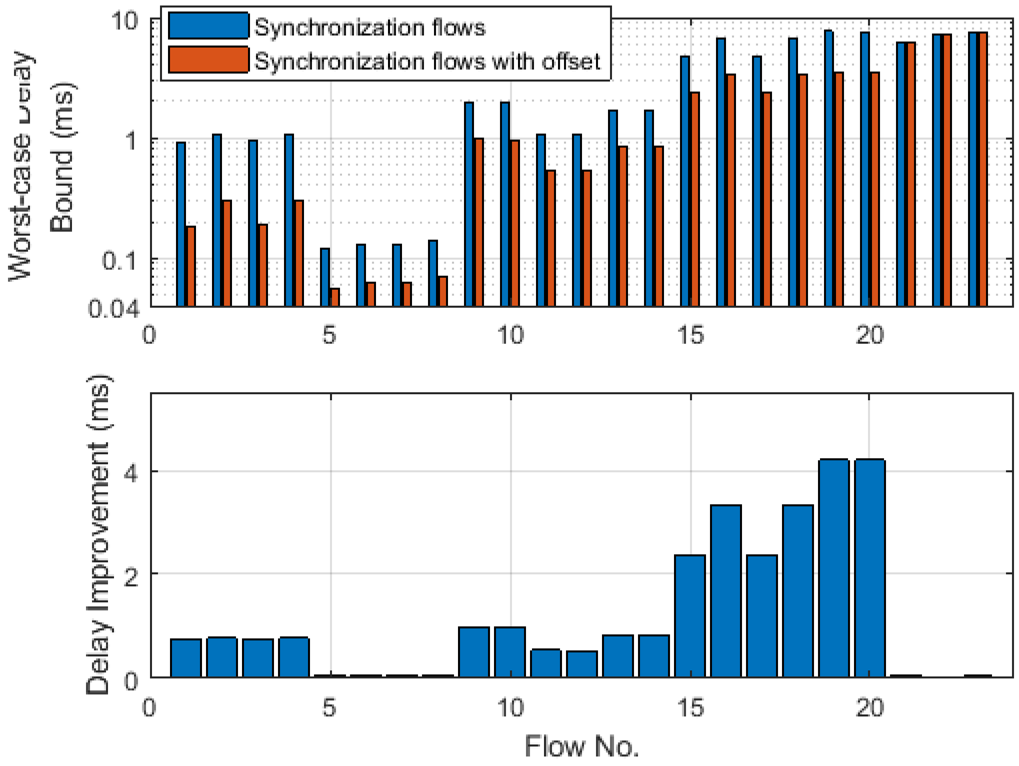
Latency requirement

A Flow No. represents a flow path. Multiple flows can use a same path.

Simulation results

- Introducing offset to periodic traffic can get a better/tighter worst-case latency bound.





➢ To avoid the worst-case, control loops of tasks with identical cycle time can use different cycle time offset.

- Of course, there are many other ways to get a better/tighter worst-case latency bound.

Better: to make the actual worst-case latency less.
Tighter: to make the calculated worst-case latency bound closer to the actual worst-case latency (reduce pessimism).

Discussion

- As in real industrial automation scenarios, the number of flows and nodes can be much larger than the model used in this paper, will network calculus still be able to provide a useful result of latency bound?
  - How to improve the NC math to get a tighter bound while the calculating complexity is acceptable?
  - How is the performance of ATS, or CBS/ATS combines with TAS?
  - How to optimize the parameter configuration of shapers?
  - Are there any better ways to describe a flow besides “b+rt”?

- Besides,
  - Any other thoughts and concerns about using network calculus to calculate the worst-case latency bound for industrial automation scenarios?
  - How to make the industrial automation network modeling closer to the real case?

Hope to get feedback from the group.

Thank you