Worst-case Delay Bounds in Time-Sensitive Networks with Packet Replication and Elimination

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IEEE time-sensitive networking (TSN): the Ethernet for safety-critical applications (layer 2)

Classic Ethernet

TSN

- Bounded latency
- and zero loss by congestion

Deterministic service

Similar ideas in IETF deterministic networking (DetNet) for IP and MPLS networks (layer 3)
Focus of this talk

Bounded latency

Network Calculus

Schedulers:
- Credit-based shaper (CBS)
- Time-Aware Shaper (TAS)

Traffic regulators (shapers):
- Asynchronous Traffic Shaping (ATS)
Network Calculus (1/2)

A framework for obtaining \textbf{deterministic (\(=\) proven) bounds} on the \textbf{worst-case} performance metrics.

- **Arrival curve** \(\alpha_f\) of \(f\)
- **Service curve** \(\beta\) of the element

The diagram illustrates the relationship between data, rate, time interval, and the leaky-bucket service curve. The network element is depicted as being affected by the service curve and the arrival curve.
Network Calculus (2/2)

A framework for obtaining **deterministic bounds** on the **worst-case performance**.

Bounds on the
- Backlog
- Output arrival curve
- Latency
Other Services and Interactions

Focus of this talk

Bounded latency

Network Calculus

Synchronization protocol

- gPTP [IEEE 802.1AS]

[Thomas, Mifdaoui, Le Boudec]

Time synchronization

Time metrology

Scheduling mechanisms

- Credit-based shaper (CBS)
- Time-Aware Shaper (TAS)

Traffic regulators (shapers):
- Asynchronous Traffic Shaping (ATS)

Reliability

- Frame Replication and Elimination for Redundancy (FRER) [IEEE 802.1CB]
- Packet Replication, Elimination and Ordering Functions (PREOF) [RFC 8655]

Reliability Analysis

Side-effects ?

Interactions ?

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Time-Sensitive Networks with Packet Replication and Elimination

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Redundancy: Principles and Terminology

**Assumption**

The Packet Elimination Function (PEF) is correctly configured: it drops all duplicates and only them. [Maile 2022]
Content

1 Introduction

2 Issues posed by PREFs (Packet Replication and Elimination Functions)

3 Question 1: Burstiness and mis-ordering bounds?

4 Question 2: POF after PEF?

5 Question 3: REG after the PEF?

6 Interactions PEF + POF + REG
Issues posed by PREFs (Packet Replication and Elimination Functions)

Illustration with a toy Example. Based on [IEEE 802.1CB, §C.9]

- Output of PEF bursty, mis-ordered ⇒ Can we bound the burstiness and mis-ordering at the PEF’s output?
- Output mis-ordered → might violate application’s requirements ⇒ Place a Packet Ordering Function (POF)?
- Output bursty → leads to high delay in downstream ⇒ Place a regulator (shaper) after the PEF?
Question 1: Burstiness and mis-ordering bounds?

Output of PEF bursty, mis-ordered \(\Rightarrow\) Can we bound the burstiness and mis-ordering at the PEF's output?
PEF Output Arrival Curve (1/3): Main Idea

**Intuitive approach**

\[ \alpha_f = \alpha_{f,1} + \alpha_{f,2} \]

No delay

**Both: Tight model**

\[ t \mapsto \alpha_f (t + J) \]

with \( J = \max_i(D_i) - \min_i(d_i) \)

Non FIFO, non lossless

Leaky-bucket \((r, b)\) (rate, burst)

\[ \mapsto \text{Leaky-bucket } (r, b + rJ) \]
PEF Output Arrival Curve (2/3): Result is tight on the toy example.

- $\alpha_{f,\text{PEF}_{\text{in}}} = (2r_0, 4b_0)$
- $J = 7 - 0 = 0$
- $(r_0, b_0 + r_0 J) = (r_0, 8b_0)$

Toy example:

![Diagram of PEF Output Arrival Curve]
PEF Output Arrival Curve (3/3): **Tight Model**, better bounds than the **Intuitive approach**

**An industrial use-case: The Volvo Core TSN Network**

48 flows, 40 are redounded.
Mis-Ordering at the PEF’s output

Reordering late Time Offset (RTO)
Quantifies the lateness of a data unit with respect to another one that was expected after.

[RFC 4737] [Mohammadpour, Le Boudec 2021]

Toy example

\[ \text{RTO} \in [5, 6] \]

\[ \text{RTO after a PEF} \]
\[ \leq \left| J_{\text{source} \to \text{PEF}} - \alpha^\dagger_{f, \text{source}} (2L_{\text{min}}) \right|^+ \]

- \( \alpha^\dagger_{f, \text{source}} \) lower pseudo-inverse of the arrival curve of \( f \) at its source.
- \( | \cdot |^+ = \max(0, \cdot) \)

Comes from [Mohammadpour, Le Boudec 2021]
Question 1
Output of PEF bursty, mis-ordered ⇒ Can we bound the burstiness and mis-ordering at the PEF’s output?
- Yes!
- Using a toolbox of network-calculus results.

Question 2
Output mis-ordered → might violate application’s requirements ⇒ Place a Packet Ordering Function (POF)?
**POF after a PEF**

**Toy example**

Here, no data unit is lost (at least one replicate reaches the PEF).

⇒ The combination PEF+POF comes ‘for free’.

[Mohammadmour, Le Boudec 2021, Thm. 4].

**BUT** the output is even more bursty.
Interactions PEF and POF (3/3): Conclusion

Question 2

Output mis-ordered → might violate application’s requirements ⇒ Place a Packet Ordering Function (POF)?

| Configuration | Benefits | Drawbacks |
|---------------|----------|-----------|
| PEF + POF     | • Data units in order  
• Reordering-for-free | • Increased burstiness  
⇒ higher delay bounds in downstream nodes.  
• Hardware complexity. |

Question 3

Output bursty → leads to high delay in downstream ⇒ Place a regulator (shaper) after the PEF?
PFR after the PEF

Per-Flow Regulators = 1 queue per flow

We want to correct the burstiness increase caused by the redundancy mechanisms. i.e., we place the regulator after the PEF.

"Shaping for free" for PFR:

NOT FIFO-per-flow
Interactions PEF and Regulators (REGs): The Per-Flow Regulator (PFR) (2/4)

Shaped aggregate
The regulator if FIFO
for this aggregate

\[\text{PEF}(f) \xrightarrow{f} \text{REG}\{\{f\}\} \xrightarrow{g} \text{PEF}(g) \xrightarrow{g} \text{REG}\{\{g\}\}\]
Interactions PEF and Regulators (REGs): The Per-Flow Regulator (PFR) (3/4)

**PFR after PEF**

\[ D' \leq 2D \]

\[ \text{NOT FIFO-per-flow} \]

\[ (r_f, b_f)_{\text{source}} \]
Interactions PEF and Regulators (REGs): The Per-Flow Regulator (PFR) (4/4)

Toy example
Interactions PEF and Regulators (REGs): The Interleaved Regulator (IR) (1/5)

We want to correct the burstiness increase caused by the redundancy mechanisms. 
I.e., we place the regulator after the PEF.
Interactions PEF and Regulators (REGs): The Interleaved Regulator (IR) (3/5)

PEF

(f)

(r_f, b_f)_{source}

(g)

(r_g, b_g)_{source}

IR

bursty

bursty

D\text{FIFO}

D_{\text{FIFO} + IR} = D_{f, \text{FIFO}}

“Shaping for free” for the IR:

\begin{align*}
\left( r_f, b_f \right)_{source} & > \\
\left( r_g, b_g \right)_{source} & > \\
( & )_{source}
\end{align*}

NOT FIFO

\text{IR}

\text{PEF}(f)

\text{PEF}(g)

\text{bursty}

\text{bursty}

\text{D}
Interactions PEF and Regulators (REGs): The Interleaved Regulator (IR) (4/5)
Instability of IR after a PEF

If the interleaved regulator (IR) processes three or more redounded flows, then it can yield unbounded latencies.
Question 3: REG after the PEF? Interactions PEF and Interleaved Regulator (IR)

Interactions PEF and Regulators: Conclusion

**Question 3**

Output bursty $\rightarrow$ leads to high delay in downstream $\Rightarrow$ Place a regulator (*shaper*) after the PEF?

| Configuration | Benefits with respect to the PEF alone | Drawbacks with respect to the PEF alone |
|---------------|--------------------------------------|---------------------------------------|
| PEF + REG     | • Output traffic keeps the arrival constraints it had before the redundant section, resulting in smaller delay bounds in downstream nodes. | • Delay penalty due to mis-ordering: with PFR: delay penalty with a guaranteed maximum delay; with IR: unbounded delay. • Increased hardware complexity. |
Interactions PEF + POF + REG (1/2)

\[ \text{Must be equal} \]

\[ \text{Interleaved regulator (IR)} \]

\[ \text{Interactions PEF + POF + REG} \]
Interactions PEF + POF + REG (2/2)

On the industrial use-case: focus on one path

Legend:
- End-system
- Switch

100Mbps 1Gbps

End-to-End delay bound (s)

Deadline

PEF+IR PEF+PFR PEF only PEF+POF+IR PEF+POF+PFR

C_P2_MCU1_S
Conclusion

- Toolbox: output arrival curve at PEF output + re-ordering bound (+xTFA a tool implementing the results).

- Analysis of the interactions [PEF+POF], [PEF+REG] and [PEF+POF+REG]
  - POF corrects the mis-ordering but worsens the burstiness.
  - PEF+REF incurs delay penalties (unbounded with TSN ATS).
  - PEF+POF+REG is ideal, but has an hardware cost.
Announcements

The Workshop on Network Calculus (WoNeCa)

- 8th and 9th September 2022
- EPFL, Lausanne, Switzerland
- 2022.woneca.org
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