Application of Network Calculus for Reliable and Predictable Behavior of IEEE 802.1CB Frame Replication and Elimination in Time-Sensitive Networks

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Applying Network Calculus?

“It is up to the user to [...] match the needs of the particular network [...]”
*IEEE 802.1CB-2017 Standard*

Typical use of Network Calculus:
- Derive worst-case queuing delay.
- Eliminate buffer overflow.

New area of application:
- IEEE 802.1CB-2017 – Frame Replication and Elimination for Reliability (FRER):
  - Configure save duplicate elimination.
Limitations of the IEEE 802.1CB-2017 standard

- Choosing match or vector recovery algorithm
- Configuring the length of the sequence history
- Setting timer values to reset the sequence history
- Studying the length of bursts in case of link failure
Stream Characteristics (IEEE Std 802.1Qat):

- Class Measurement Interval (CMI)
- Maximum Interval Frames (MIF)
- and Maximum Frame Size (MFS)

A stream sends at most $MIF$ packets during an interval of length $CMI$. Each packet is smaller or equal to $MFS$.

Network Characteristics:

- lowest delay of fastest path $d_{BC}$ (best-case)
- highest delay of slowest path $d_{WC}$ (worst-case)
- reception window: $\Delta d = d_{WC} - d_{BC}$
Different View on Network Delays

- **Best-Case Delay:** Processing → Propagation → Transmission
- **Worst-Case Delay:** Processing → Propagation → Transmission → Queuing

Thomas et al. [2]
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Match recovery algorithm

Problem Description

Match Recovery Algorithm (MRA)

- stores only highest sequence number received
- only eliminates duplicates with this sequence number
- forwards all other packets

requires intermittent streams:
the difference between arriving sequence numbers may not exceed one
Identify intermittent streams

- all copies of a packet must arrive before the next sequence number can arrive at the eliminating device
Match recovery algorithm

Evaluation

different $\Delta d$

$CMI > \Delta d$

$\#\text{Duplicates} = 0$

$\#\text{Duplicates} > 0$
Match recovery algorithm
Central / NC versus Decentral / Standard

Different Path Length

IEEE 802.1BA-2021 Standard

\[
D_{u,v,0} = D_{\text{proc}}^{u,v} + D_{t}^{u,v} + \frac{L_{\text{max}}}{C} \\
+ \left( \frac{\text{idSL}_{u,v,0}}{C} \cdot \frac{C}{\text{CM1} - D_{t}^{u,v}} \right) \cdot \frac{C}{\text{idSL}_{u,v,0}}
\]
Match recovery algorithm
Central / NC versus Decentral / Standard

different Path Length

Δd > CMI

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12
Limitations of the IEEE 802.1CB-2017 standard

- Choosing match or vector recovery algorithm
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Vector Recovery Algorithm (VRA)

- defines an interval of sequence numbers

\[ \text{RecovSeqNum} \pm (\text{frerSeqRcvyHistoryLength} - 1) \]

- within this interval:
  - new packets are accepted
  - duplicates are eliminated
  - higher sequence numbers than \text{RecovSeqNum} lead to an update of \text{RecovSeqNum}

- outside this interval
  - all packets are discarded

**Problem Description**

Vector recovery algorithm: History Length

**default** \( \text{frerSeqRcvyHistoryLength} = 2 \)
Define \textit{frerSeqRcvyHistoryLength} (short: \(L\))

- the worst integer number of overlapping sequence numbers is
\[
N = \left\lceil \frac{\Delta d}{\mathrm{CMI}} \right\rceil + 1
\]

- However, only the reception of new packets triggers a shift of the sequence history, which leads to
\[
L > \frac{\Delta d}{\mathrm{CMI}} + 1
\]
Vector recovery algorithm: History Length

Evaluation

\[ L > \frac{\Delta d}{CMI} + 1 \]
different Path Length

Factor 2
Limitations of the IEEE 802.1CB-2017 standard

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**SequenceRecoveryReset** function

- FRER triggers a reset after a period of time in which no packets have been accepted
- too short: duplicates passed
- too long: valid packets discarded (from interrupted connections)

**SequenceRecoveryReset**\(\text{Reset MSec (short: } R)\)**

- save: \( R > \Delta d \)
- optimal: \( R = \Delta d + CMI \)
Reset Timer Configuration

Evaluation

\[ R = \Delta d + CMI \]

\[ R > \Delta d \]

<table>
<thead>
<tr>
<th>Timeout in ( \mu s )</th>
<th>50</th>
<th>75</th>
<th>100</th>
<th>150</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>500</th>
<th>600</th>
</tr>
</thead>
<tbody>
<tr>
<td>#Duplicates</td>
<td>99</td>
<td>99</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>#Passed</td>
<td>99</td>
<td>99</td>
<td>99</td>
<td>99</td>
<td>99</td>
<td>99</td>
<td>98</td>
<td>97</td>
<td>96</td>
</tr>
<tr>
<td># Resets</td>
<td>198</td>
<td>101</td>
<td>99</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>
Limitations of the IEEE 802.1CB-2017 standard

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Burst Size Prediction

Problem Description

Burst dimensioning after link failure

- transmission errors occur on the fastest path
- faster path resumes transmission: slower paths continue to transmit, new packets from fast path

Burst dimensioning after link failure

- for a duration of $\Delta d$
  - arrival rate doubles
  - burstiness doubles

\[ n_{max} = \max \left( 2 \cdot \left\lfloor \frac{\Delta d}{CMI} \right\rfloor - 1, 0 \right) \]

also refer to L. Thomas et al. [2]
Comparison Evaluation

<table>
<thead>
<tr>
<th>#Nodes</th>
<th>Path A/B</th>
<th>2/2</th>
<th>4/2</th>
<th>8/2</th>
<th>12/2</th>
<th>16/2</th>
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</thead>
<tbody>
<tr>
<td>Network Calculus $\Delta d$</td>
<td>37.5</td>
<td>164.4</td>
<td>419.4</td>
<td>675.7</td>
<td>933.5</td>
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Network Calculus Configuration

<table>
<thead>
<tr>
<th>History Length</th>
<th>2</th>
<th>3</th>
<th>5</th>
<th>7</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>#Passed</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>#Rogue</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Default Values

<table>
<thead>
<tr>
<th>History Length</th>
<th>2</th>
<th>2</th>
<th>2</th>
<th>2</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>#Passed</td>
<td>100</td>
<td>100</td>
<td>72</td>
<td>72</td>
<td>72</td>
</tr>
<tr>
<td>#Rogue</td>
<td>0</td>
<td>0</td>
<td>90</td>
<td>90</td>
<td>90</td>
</tr>
</tbody>
</table>
Central Admission Control for TSN/CBS using NC

- online flow reservation, no re-configuration of reserved flows
- deadline guarantees and zero buffer overflow (with NC)
- routing and prioritization
- definition of IdleSlopes
- future work: automatic configuration of FRER devices


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Conclusion

- IEEE 802.1CB-2017 seeks to add reliability to critical traffic in TSN

- four critical configurations of the IEEE 802.1CB-2017 TSN standard

- proofed solutions, theoretically and in simulation

- safe configuration possible with NC

- hope that these considerations will be helpful in future standardization processes
Thank you!
