Choosing the Right TSN Tools to meet a Bounded Latency

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Preamble

• This presentation was originally presented at the Sep 2019 IEEE Ethernet & IP Tech Day conference in Detroit and subsequently at the Feb 2020 Automotive Ethernet Congress in Munich

• An article is available that covers this presentation at:

  • https://www.allaboutcircuits.com/industry-articles/choosing-the-right-tsn-tools-to-meet-a-bounded-latency/

• The goal of this presentation was to:
  - Simplify the latency equations for the selected TSN shapers so that some quick evaluation of what shaper may be appropriate for a given bounded latency can be made
  - Propose a queue model showing how the various shapers may be used together for automotive
The Need

➢ Ethernet’s high speeds saves wires in Zonal networks
➢ And Zonal networks bring new requirements that (TSN) solves
   ➢ Multiple Domains using the same wire
   ➢ Yet each Domain needs to know its data will get delivered in the needed maximum time – as it no longer has its own dedicated wire!
➢ How to guarantee & plan the maximum bounded latency for each flow is the focus of this presentation
Overview

➢ This presentation focuses on the TSN standards that affect bounded latency of flows through the Automotive Ethernet network

➢ It briefly lists the unique problems each of these Time Sensitive Networking (TSN) standards solves & the relative ‘costs’ of using each tool

➢ Based on these numbers, a per-hop metric is proposed, to help determine which TSN tool should be used and when

➢ This tool usage order, makes the job of “Engineering” the network easier via the step-by-step process described
List of Available TSN Tools for Controlling Latency

<table>
<thead>
<tr>
<th>Standard’s Name:</th>
<th>Also Known As:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strict Priority</td>
<td>802.1p-1998 / QoS</td>
</tr>
<tr>
<td>Forwarding &amp; Queueing for Time-Sensitive Streams</td>
<td>802.1Qav-2009 / Credit Based Shaper or FQTSS</td>
</tr>
<tr>
<td>Enhancements for Scheduled Traffic</td>
<td>802.1Qbv-2015 / Time Aware Shaper</td>
</tr>
<tr>
<td>Frame Preemption</td>
<td>802.1Qbu-2016 &amp; 802.3br-2016</td>
</tr>
</tbody>
</table>

Note: IEEE 802.1 TSN is constantly doing new work so new tools will become available in products.

Known ones are: Cyclic Queueing & Forwarding, 802.1Qch; & Asynchronous Traffic Shaping, 802.1Qcr
The Shaper Standards:

What Problems the Standards Solve & How They were Envisioned to be Used
Strict Priority Shaper (Strict) – 802.1p-1998

- Priority solves the problem that some frames are more important than others
- It was needed so Network Management could work
- Management frames had to get through in order to be able to fix Network problems – thus their placement in the top Traffic Class
- The Strict hardware selector is defined as: “Frames are selected from the corresponding queue for transmission only if all queues corresponding to numerically higher values of traffic class … are empty at the time of selection.”
Credit Based Shaper (CBS) – 802.1Qav-2009

- CBS solves the problem that long bursts of data are really bad for the Bridges
- It was needed so Reserved frames are not dropped
- It caps the bandwidth a queue can transmit with hardware
- It de-bursts flows in hardware so that optimized software stacks that try to burst can be used (for streams that are not self-shaping)
  - I.e., audio from a USB drive vs. audio from a microphone or radio
  - It allows very small bursts of data to ‘catch-up’ due to momentary interference so the Reserved data rate can be maintained
- In AVB, PCP 2,3 are re-mapped above Mgmt since they can’t use 100% of the wire
Time Aware Shaper (TAS) – 802.1Qbv-2015

➢ TAS delivers the theoretically lowest possible latency for scheduled periodic data
➢ It uses significant bandwidth, so is best used as a last resort
➢ Transmission Gates are added for ALL queues just before the Strict Priority Selector

➢ Following a defined periodic schedule, the gates on the queues are opened or closed for a period of time – allowing critical traffic to pass without interference
➢ ALL queues are time-gated, but really only 1 or 2 queues are actually “Scheduled” and the “non-Scheduled” queues are left open during the remainder of the time
➢ Any TC can be used for “critical” scheduled traffic (TC 2 in the figure)
Preemption – 802.1Qbu-2016 & 802.3br-2016

- Preemption delivers very low latency for a limited set of non-scheduled data
- Preemption gains the most on slow data links (≤ 100 Mb/s)
- Two 802.3 MACs are used, a new one for “preemptable” traffic (pMAC) and the old one for “express” preemption traffic (eMAC)
- Only 1 level of preemption is supported & frames < 127 bytes can’t be preempted
- 802.1 allows connection of each TC queues to either MAC – if more than one queue connects to a MAC, the Strict selector algorithm is assumed
- In the figure, TC 1 is effectively above all the other TC’s since it can preempt them!
The Shaper Standards: Their Metrics
## Latency TSN Tool Comparison

<table>
<thead>
<tr>
<th>TSN Tool</th>
<th>Silicon Complexity</th>
<th>Engineering Complexity¹</th>
<th>Wire Efficiency²</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strict Priority</td>
<td>Low</td>
<td>Easy</td>
<td>100%</td>
<td>Needed component, but it is not deterministic by itself</td>
</tr>
<tr>
<td>Credit Based Shaper</td>
<td>Medium</td>
<td>Easy</td>
<td>100%</td>
<td>All CBS queues are deterministic + next highest TC (for Mgmt)</td>
</tr>
<tr>
<td>Time Aware Shaper</td>
<td>Medium</td>
<td>Hard (&gt;1 TC) Medium (1 TC)</td>
<td>- Guard band - Idle opens</td>
<td>All TAS queues are deterministic</td>
</tr>
<tr>
<td>Frame Preemption³</td>
<td>High</td>
<td>Medium but only 1 level deep</td>
<td>- Fragment overhead</td>
<td>Fragmentation can affect determinism on the other flows</td>
</tr>
</tbody>
</table>

1: Engineering Complexity is the expected user difficulty or effort, needed to get proper results
2: Wire Efficiency is how much data can go down the wire – this includes critical data and background data
3: Note: Preemption is the only standard that requires support on both sides of the wire
Per Hop Latency – Credit Based Shaper

➢ Class A \( \approx t_{\text{Interval}} + t_{\text{MaxFrameSize}} \)
  - \( t_{\text{Interval}} \) = observation interval of the Class (125 uSec for AVB – but can be changed)
  - \( t_{\text{MaxFrameSize}} \) = the maximum size of an interfering frame + gaps, etc.
  - This is a good rule-of-thumb equation that results in slightly higher numbers than the equation in 802.1BA-2011 subclause 6.5

➢ Class B \( \approx t_{\text{Interval}} + t_{\text{MaxFrameSize}} + t_{\text{TimeForAllHigherFrames}} \)
  - \( t_{\text{TimeForAllHigherFrames}} \) = the time to transmit all Class A frames (+ gaps, etc.) for the duration of Class B’s \( t_{\text{Interval}} \) (which is typically multiple Class A \( t_{\text{Intervals}} \))

➢ Class C \( \approx t_{\text{Interval}} + t_{\text{MaxFrameSize}} + t_{\text{TimeForAllHigherFrames}} \)
  - Where \( t_{\text{TimeForAllHigherFrames}} \) includes Class A & Class B frames

➢ Etc.
Per Hop Latency – Credit Based Shaper – part 2

- Class A \approx t_{\text{Interval}} + t_{\text{MaxFrameSize}}
  - For a 64 byte frame in a 125uSec observation interval the worst case # is:
    - On a 100BASE link \approx 125 \text{ uSec} + 124 \text{ uSec} = 249 \text{ uSec per hop}
    - On a 1000BASE link \approx 125 \text{ uSec} + 13 \text{ uSec} = 138 \text{ uSec per hop}
  - The observation interval is a significant portion of these latencies
    - Lower worst case latency numbers are possible on 1000BASE links by using shorter observation intervals, but it can’t go below the time of \( t_{\text{MaxFrameSize}} \)
    - But lowering this number reduces latency at the cost of Reservation capacity
      - 1000 vs 100 is either 10x lower latency or 10x the capacity or somewhere in between

Note: The simplified equation on the previous page is useful for calculating the worst case latency range for a fully loaded (i.e., 75% bandwidth allocation) on a Class A link. A scheduling tool needs to use the equation that is in IEEE 802.1BA. Also see: http://www.ieee802.org/1/files/public/docs2011/ba-boiger-per-hop-class-a-wc-latency-0311.pdf
Per Hop Latency – Time Aware Shaper

➢ Store & Forward with Gate Open \( \approx t_{\text{Device}} + t_{\text{FrameSize}} \)
  ➢ \( t_{\text{Device}} \) = the delay through a Store & Forward bridge
  ➢ Good Rule-of-Thumb is 2 x 512 bit times + Cable delay
  ➢ or 10.5 uSec for 100BASE & 1.5 uSec for 1GBASE
  ➢ \( t_{\text{FrameSize}} \) = the size of the frame passing through the bridge

➢ For a 64 byte frame the worst case # is:
  ➢ On a 100BASE link \( \approx 10.5 \text{ uSec} + 5.2 \text{ uSec} = 15.7 \text{ uSec per hop} \)
  ➢ On a 1000BASE link \( \approx 1.5 \text{ uSec} + 0.5 \text{ uSec} = 2.0 \text{ uSec per hop} \)
Per Hop Latency – Frame Preemption

➢ Store & Forward w/ Preemption ≈ \( t_{Device} + t_{FrameSize} + t_{Framelet} \)
  ➢ \( t_{Device} \) = the delay through a Store & Forward bridge
    ➢ Good Rule-of-Thumb is 2 x 512 bit times + Cable delay
    ➢ or 10.5 uSec for 100BASE & 1.5 uSec for 1GBASE
  ➢ \( t_{FrameSize} \) = the size of the frame passing through the bridge
  ➢ \( t_{Framelet} \) = 127 bytes + overhead, max size interfering frame that can’t be preempted

➢ For a 64 byte frame the worst case # is:
  ➢ On a 100BASE link ≈ 10.5 uSec + 5.2 uSec + 11.8 uSec = 27.5 uSec per hop
  ➢ On a 1000BASE link ≈ 1.5 uSec + 0.5 uSec + 1.2 uSec = 3.2 uSec per hop

Note: Preemption requires support on both sides of the wire
## Latency TSN Tool Comparison in Lowest Latency Order

<table>
<thead>
<tr>
<th>TSN Tool</th>
<th>Engineering Complexity</th>
<th>Wire Efficiency</th>
<th>Worst Case Latencies – 1st Order Approximation</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time Aware Shaper</td>
<td>Hard (&gt;1 TC)</td>
<td>- Guard band</td>
<td>15.7 uSec FE Hop 2.0 uSec GE Hop</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Medium (1 TC)</td>
<td>- Idle Opens</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frame Preemption</td>
<td>Medium but only 1 level deep</td>
<td>- Fragment overhead</td>
<td>27.4 uSec FE Hop 3.2 uSec GE Hop</td>
<td>3</td>
</tr>
<tr>
<td>Credit Based Shaper</td>
<td>Easy</td>
<td>100%</td>
<td>249 uSec FE Hop 138 uSec GE Hop</td>
<td>1</td>
</tr>
<tr>
<td>Strict Priority</td>
<td>Easy</td>
<td>100%</td>
<td>Can't determine</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Note: FE = 100BASE, GE = 1000BASE

Reasons for the Rankings:

1 = Multiple queues can be used with different observation intervals/latencies
2 & 3 = Assuming only 1 TC is used for very limited, very critical traffic only
2 is more available than 3 in products, supports lower latencies & has a more deterministic effect on the impacted Reserved flows
The Shaper Standards: Which Tool to Use First
Proposed Tool Usage Order

➢ Process the critical flows in smallest to highest allowed latency order
➢ First ensure the total bandwidth through any link is not more than 75% loaded with these flows
  ➢ This # could go a bit higher, but 60% to 75% is a good place to start
➢ Start with the Credit Based Shaper
  ➢ Select an Observation Interval that is as large as possible that delivers the required latency over the path(s) the flow uses
  ➢ If the default 125 uSec Observation Interval is too long, reduce it, but don’t go < 125 uSec on 100BASE links
  ➢ If that doesn’t work, use Time Aware Shaping &/or Preemption as last resorts
    ➢ As these are limited resource that are less wire efficient
    ➢ Subtract any wire efficiency loss as used bandwidth toward the 75% critical flow limit
Proposed Tool Usage Order – part 2

➢ Multiple Credit Based Shaper’s w/increasing Observation Intervals can be used – More than two Classes can be used if needed!
   ➢ Start by loading each Class no more than 20% of the link’s bandwidth
   ➢ Keep in mind that the sum total of ALL Reserved flows, & their frame (IFG, etc.) & scheduler overhead (Qbv & Qbu), must not exceed 75% of any one link’s bandwidth
   ➢ If this happens, try an alternate path for the flow
   ➢ 60% may be a better starting number so that new flows can fit in easier
      ➢ CAN network loading is typically started at 50% so new messages can be added
         ➢ To fix bugs & oversites
         ➢ And to add new features

➢ Network Mgmt must be the highest non-CBS Traffic Class
➢ The remaining “non-Reserved” flows will use the remainder of the unused bandwidth in a Best Effort fashion
Summary
Summary & Proposed Queueing Model

➢ These standards are designed to work together
➢ Multiple different data delivery requirements/latencies can be supported on the same wire
➢ The Credit Based Shaper is not limited to just Audio & Video data & it is not limited to the AVB Profile’s plug-&-play parameters
➢ There is a current limit of 8 Priority Code Points (PCP) that are effectively used to indicate the “type of service” a flow needs
➢ Automotive networks are Engineered, but let the hardware enforce the needed guarantees to make the job much simpler
Disclaimers

➢ This is a really hard concept that has been simplified so that an easy starting point on which shaper to use for a target flow can be made

➢ The listed latency numbers are in the correct range but they are still estimates. For example:
   ➢ A generic bridge delay is used vs. the actual delay in the specific bridge being used
   ➢ All latency numbers use 64 byte data frames. In most cases, larger data frames will impact the latency numbers.
   ➢ 127 byte non-preemptable frames is clear to understand & is a good 1st order approximation
   ➢ Cable delay is mostly ignored – which is approximately 80ns for 15 meters
   ➢ Look at the referenced presentations & others on the same subject in the same areas

➢ As a rule-of-thumb for link speed conversion in a bridge:
   ➢ For MaxFrameSize & Framelet use the egress link speed, for FrameSize use the ingress link speed and for Device use the faster link speed of the two
## IEEE 802.1 Automotive AVB and TSN Standards Handout

<table>
<thead>
<tr>
<th>Standards</th>
<th>Transport</th>
<th>Synchronization</th>
<th>Stream Reservation</th>
<th>Quality of Service</th>
<th>Redundancy</th>
<th>Security</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AVB</strong></td>
<td>1722-2011</td>
<td>802.1AS-2011</td>
<td>802.1Qat-2010 SRP (now Q clause 35)</td>
<td>802.1Qav-2009 Credit Based Shaper (now Q clause 34)</td>
<td>-</td>
<td>802.1X-2010 802.1Xbx-2014 802.1Xck-2018 Network Access</td>
</tr>
<tr>
<td>802.1BA-2011</td>
<td>The AVB Profile</td>
<td>gPTP</td>
<td>802.1AS-2011 Redundant gPTP</td>
<td>802.1Qcc-2018 Enhanced SRP 802.1Qca-2015 Path Control &amp; Reservation</td>
<td>802.1CB-2017 Frame Replication &amp; Elimination 802.1AS-2020 Redundant gPTP</td>
<td>802.1AEcg-2017 (end-to-end) MACSec</td>
</tr>
<tr>
<td>1722-2016 Media Transport Protocol</td>
<td>802.1AS-2020 Redundant gPTP</td>
<td>802.1Qcc-2018 Enhanced SRP</td>
<td>802.1Qb-2015 Time Aware Shaper 802.1Qbu-2016 &amp; 802.3br-2016 Preemption 802.1Qch-2017 Cyclic Queue Forwarding 802.1Qcr Asynchronous Shaping</td>
<td>802.1CB-2017 Frame Replication &amp; Elimination 802.1AS-2020 Redundant gPTP</td>
<td>802.1Qci-2017 Policing 802.1AEcg-2017 (end-to-end) MACSec</td>
<td></td>
</tr>
</tbody>
</table>

### Notes
- Standards without an appended year are not completed yet.
- Updated 1-2020

**TSN**

- 1722-2016 Media Transport Protocol
- Adds CAN, FlexRay, LIN, + more Audio/Video Transports
- 802.1AS-2011 gPTP
- 802.1AS-2020 Redundant gPTP
- 802.1AS-2011 gPTP
- 802.1Qat-2010 SRP (now Q clause 35)
- 802.1Qav-2009 Credit Based Shaper (now Q clause 34)
- 802.1Qb-2015 Time Aware Shaper
- 802.1Qbu-2016 & 802.3br-2016 Preemption
- 802.1Qch-2017 Cyclic Queue Forwarding
- 802.1Qcr Asynchronous Shaping
- 802.1CB-2017 Frame Replication & Elimination
- 802.1AS-2020 Redundant gPTP
- 802.1X-2010 Network Access
- 802.1Xbx-2014 Network Access
- 802.1Xck-2018 Network Access
- 802.1AEcg-2017 (end-to-end) MACSec
# IEEE 802.3 Automotive Ethernet PHY Standards Handout

<table>
<thead>
<tr>
<th>MAC Interface</th>
<th>10 Mbit/s</th>
<th>100 Mbit/s</th>
<th>1000 Mbit/s</th>
<th>2500 Mbit/s</th>
<th>10 Gbit/s</th>
<th>Next</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MAC Interface</strong></td>
<td>SNI, xMII/SGMII OC-SGMII</td>
<td>xMII/SGMII OC-SGMII</td>
<td>xGMII/SGMII OC-SGMII 1000BASE-X</td>
<td>OC-SGMII 2500BASE-X</td>
<td>USXGMII XFI</td>
<td>?</td>
</tr>
<tr>
<td><strong>Media Interface</strong></td>
<td>Single Twisted Pair</td>
<td>Digital/SERDES</td>
<td>Digital/SERDES</td>
<td>Digital/SERDES</td>
<td>Digital/SERDES</td>
<td>?</td>
</tr>
<tr>
<td><strong>Media Interface Standards</strong></td>
<td>802.3cg-2019 10BASE-T1S 15m Point to Point 25m Multi-Drop 10BASE-T1L 1000m Point to Point</td>
<td>802.3bw-2015 100BASE-T1 15m Point to Point</td>
<td>802.3bp-2016 1000BASE-T1 15m Point to Point</td>
<td>802.3ch 2500BASE-T1 15m Point to Point</td>
<td>802.3ch 10GBASE-T1 15m Point to Point</td>
<td>?</td>
</tr>
</tbody>
</table>

Media Interface (PHY) Standards without an appended year are not completed yet. Updated 1-2020