

# TIME-SENSITIVE NETWORKING INDUSTRIAL IOT

Software and Services Group  
IoT Developer Relations, Intel

# AGENDA

802 Networks and why “best effort” is not enough

Changing the Goals of Networking

- Audio/Video Bridging
- Industrial Control Constraints

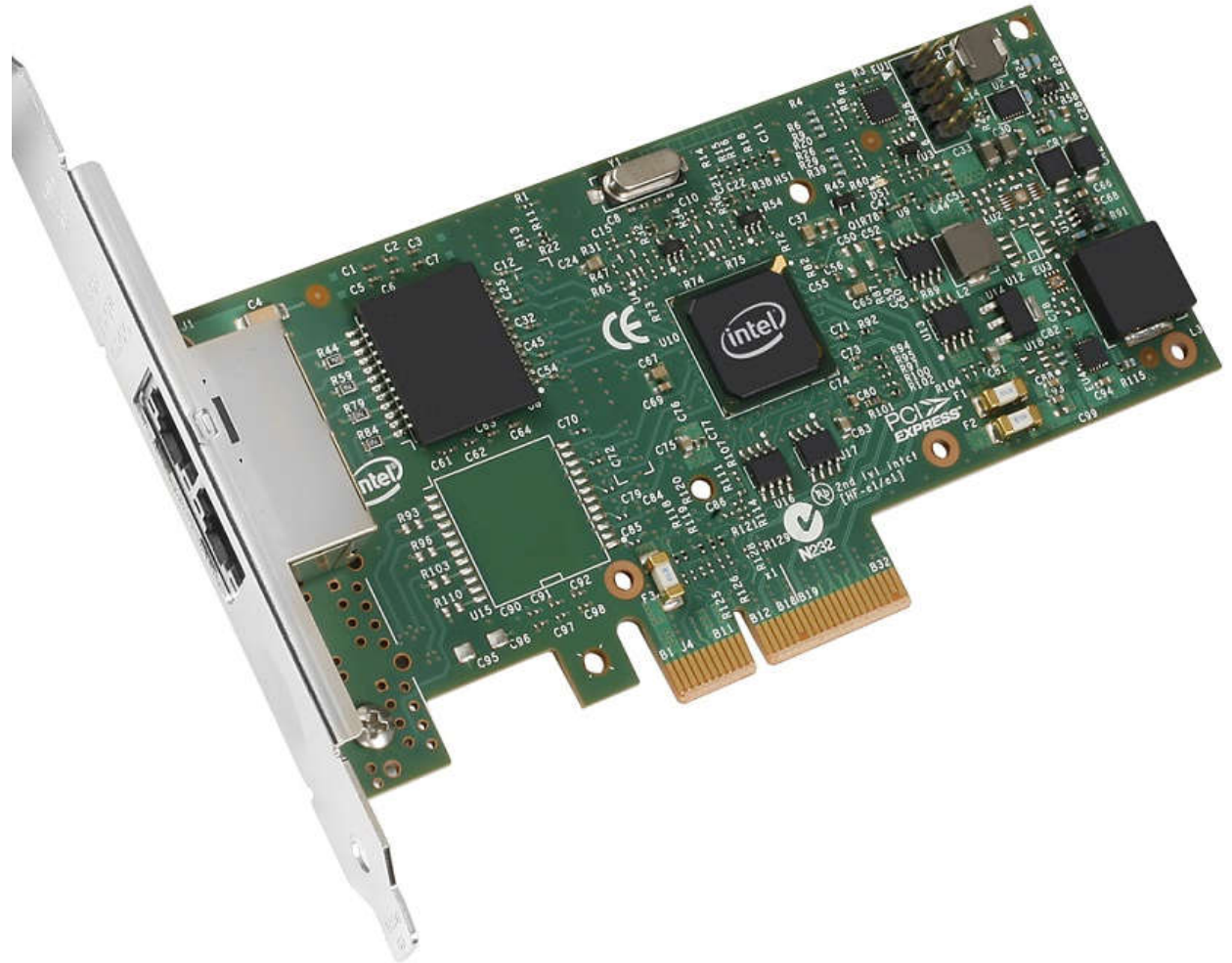
How TSN Networking meets the New Requirements

- Time-Synchronization
- Scheduling and Traffic Shaping
- Allocation of Dedicated “Streams” or network paths

Applications for Embedded Systems

# Intel® Ethernet Controller I210

- The Intel® Ethernet Controller I210 is a single port, compact, low power component that supports GbE designs.
- Supports 802.1Qav which includes Timing and Synchronization for time specific applications (802.1AS), Stream Reservation (SR) protocol to guarantee the sources needed for Audio/Video Streams, Forwarding and queuing enhancements of TSN (802.1Qav)



# CURRENT GOALS OF 802 NETWORKING

- Current Ethernet Networking (Internet and LANs) evolved from competing standards.
  - ARCnet, Token Rings, X.25, etc ...
- The important metrics where average latency and maximizing throughput for bulk data transfers
- The basic operational idea is “best-effort delivery”
- Anything that needs better QoS used point-to-point communications
  - IEEE 1394, Profinet, Modbus, Canbus, EtherCAT
- Most solutions are proprietary and not compatible with 802 communications.

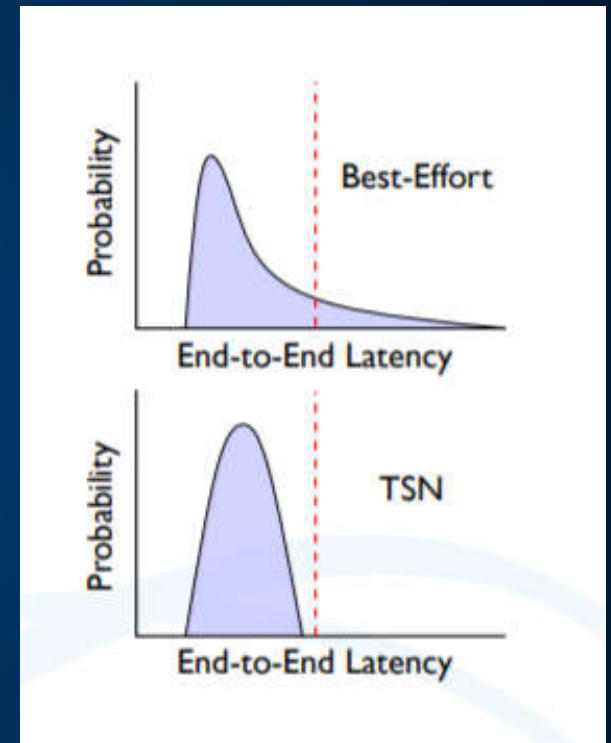
# CHANGING THE GOALS OF 802 NETWORKS

What does “Time” mean in Time-Sensitive Networks?

- The new metric is maximum delay, not average delay (no best-effort delivery)
- Time must be coordinated between all actors on the TSN Network.
- Time means deterministic and scheduled traffic
- Time means guaranteeing reserved routing of priority traffic streams

Converged critical control and best-effort data traffic over standard Ethernet (The compatibility requirement)

Bounded Delays and Scheduling are required for TSN



# EVERYTHING OLD IS NEW AGAIN

## Packet Switched Networking

- Excellent use of resources, high adaptive and resilient to network outage
- Timing is sacrificed

## Before Packet Switched Networking

- Telecom used circuit switched networks. Factories still use CSNs
- **Circuit switching** establishes a dedicated communications channel through the network before the nodes may communicate.

## Time-Sensitive Networking is a return to Circuit Switching

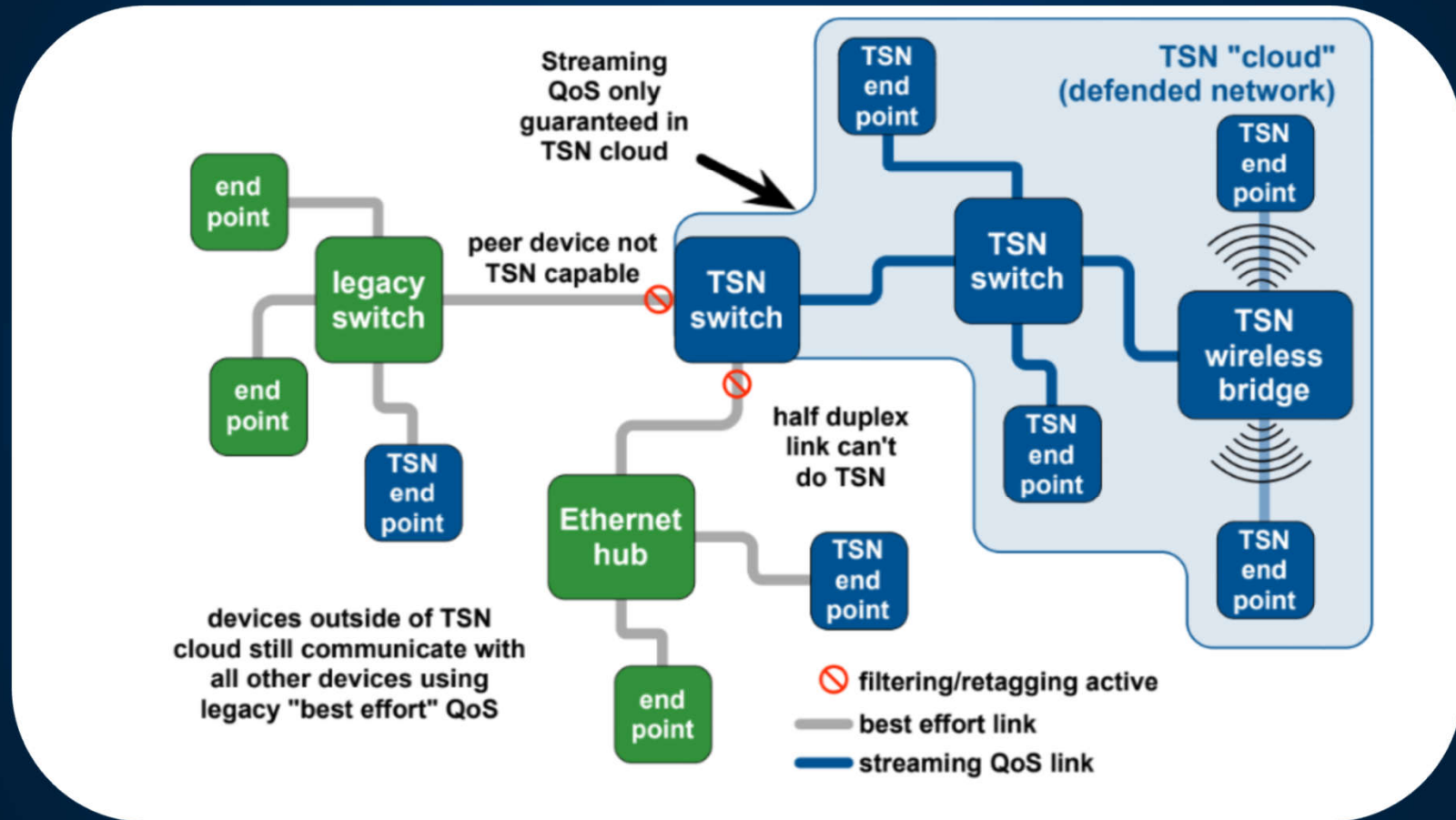
- In TSN dedicated channels are called “streams”
- Information is still packetized and is compatible with 802 Networking



# TSN HIGH LEVEL GOALS

- Establish a network-wide precision clock reference
- Real-time – Guaranteed latency, low-jitter and zero congestion loss for all critical control loops. Control loops can have different rates.
- All priority traffic is scheduled and delays are bounded and small
- Deterministic mechanism to separate normal traffic and TSN traffic, control of traffic shaping QoS
- Immunity – Critical traffic is immune to effects of converged, non-critical traffic
- Convergence – Reducing complexity and costs converging networks
- Open, Interoperable Standard – truly open standard, hence IEEE 802.1 and other relevant groups to ensure long-term viability and innovation
- And so ... the IEEE 802.1 Time-Sensitive Networking Group was established  
<http://www.ieee802.org/1/pages/tsn.html>

# INTEGRATION OF TSN AND NON-TSN NETWORKS





# TSN IS A TOOLBOX OF STANDARDS

Base Standards	IEEE Std. 802.1Q™-2018 : Bridges and Bridge Networks (e.g. VLAN) IEEE Std. 802.1AB™-2016 : Link Layer Discovery Protocol (LLDP) IEEE Std. 802.1AX™-2016: Link Aggregation
Time Synchronization	IEEE Std. 802.1AS™-Rev : generalized Precision Time Protocol (gPTP)
Scheduling Methods	IEEE Std. 802.1Qav™-2009 : Credit-based shaper IEEE Std. 802.1Qbv™-2015 : Transmission gate scheduling IEEE Std. 802.1Qbu™-2016 & IEEE Std. 802.3br™-2016 : Frame Preemption IEEE Std. 802.1Qch™-2017 : Cyclic Queuing and Forwarding
Reliability	IEEE Std. 802.1Qca™-2015 : Path Control and Reservation IEEE Std. 802.1CB™-2017 : Frame Replication & Elimination IEEE Std. 802.1Qci™-2017 : Per-stream Filtering & Policing
Resource Management	IEEE Std. 802.1Qat™-2010 : Stream Reservation Protocol IEEE Std. 802.1Qcc™-2018 : SRP Enhancements and Performance Improvements IEEE Std. 802.1Qcp™-2018: YANG model

# THE WORKING GROUPS

Description of Working Group	IEEE Standard	Extensions and Notes
Forwarding and Queuing Enhancements for Time-Sensitive Streams	802.1Qav	P802.1Qbu - Frame Preemption P802.1Qbv - Priority Queuing, Time-Gated Queuing
Distributed Stream Reservation Protocol (SRP)	802.1Qat	P802.1Qcc - preemption, scheduling, centralized control
Time Synchronization	802.1AS	All end-points, switches, bridges, etc... have the same wall-clock time
Audio Video Bridging (AVB) Systems	802.1BA	And Industrial Sensor and Actuator systems

Time-Sensitive Networking (TSN) is a set of standards under development by the Time-Sensitive Networking task group of the [IEEE 802.1](#) working group.<sup>[1]</sup>

# WE WILL REVIEW THESE 802.1 SUB-STANDARDS

[IEEE 802.1ASrev](#): Timing and synchronization (mechanisms for faster fail-over of clock grandmasters)

[IEEE 802.1Qbv](#): Time-aware shaping (per-queue based)

[IEEE 802.1Qav](#): Credit Base Traffic Shaping

[IEEE 802.1Qbu](#): Frame pre-emption

[IEEE 802.1CB](#): Redundancy (frame replication and elimination)

[IEEE 802.1Qcc](#): Enhancements and improvements for stream reservation

[IEEE 802.1Qca](#): Path control and reservation (based on IEEE802.1aq; IS-IS)

[IEEE 802.1Qch](#): Cyclic queuing and forwarding

[IEEE 802.1Qci](#): Per-stream filtering and policing

[IEEE 802.1CM](#): Time-sensitive networking for fronthaul

# TIME PROPAGATION THROUGH MASTER/SLAVE CLOCKS 802.1AS

All TSN systems participate in a native IEEE 802 layer 2 profile of the IEEE 1588v2 Precision Time Protocol

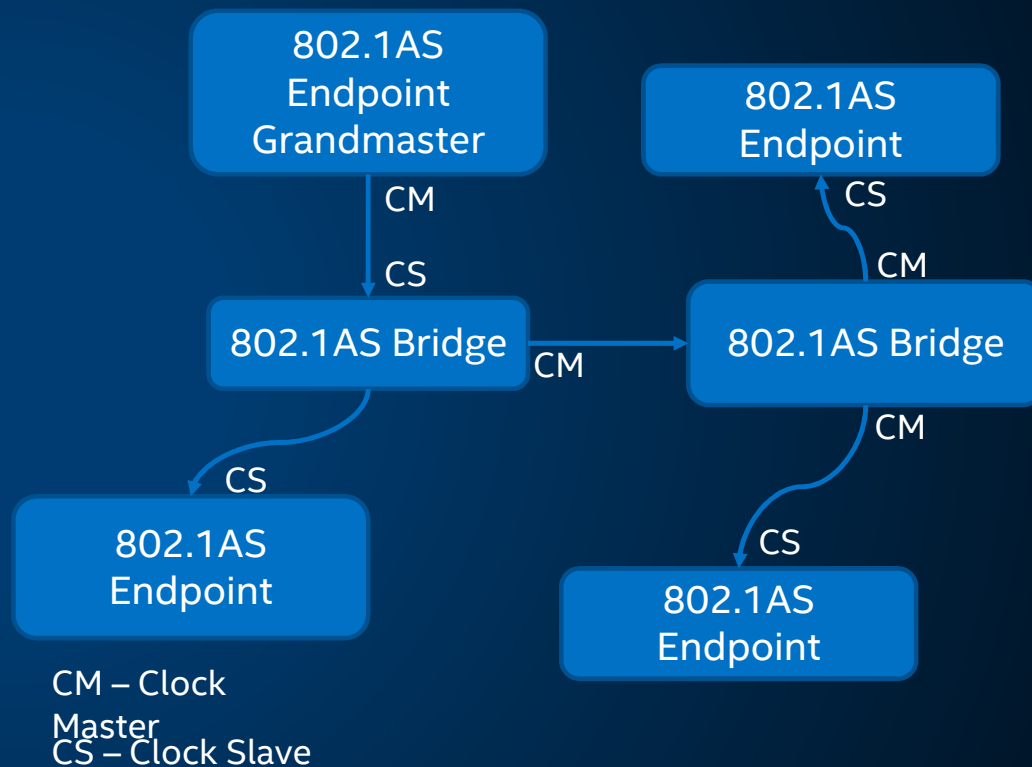
Creates a hierarchical master-slave architecture for clock distribution

A clock that connects only to one LAN is called an **Ordinary Clock**

A clock that connects to two or more LANs is called a **Boundary Clock**

A clock is elected, called the Grandmaster, and its time is synchronized to the rest of the network

Allows multiple stream to be synchronized



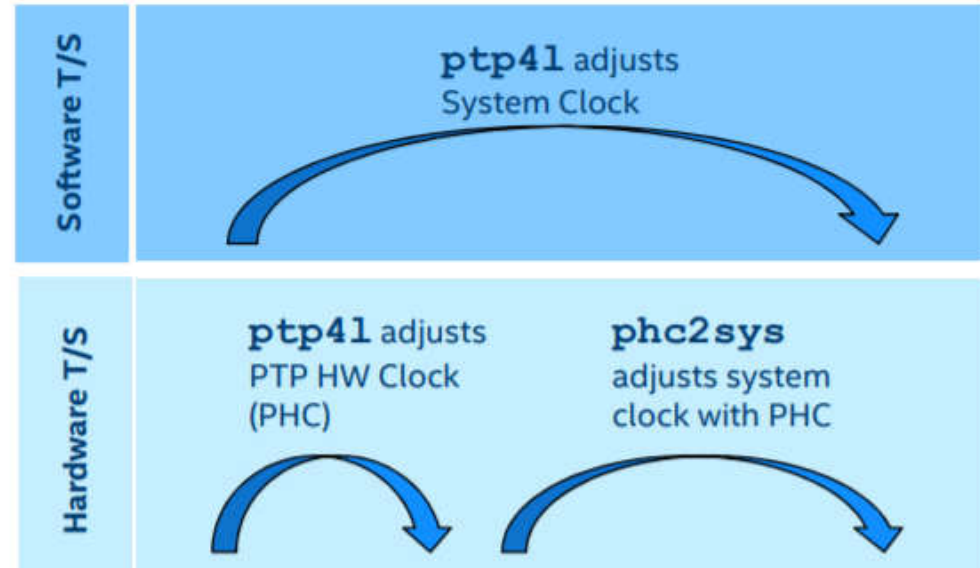
802.1AS™-2011 : Generalized Precision Time Protocol (gPTP)

# Overview of Linuxptp Project

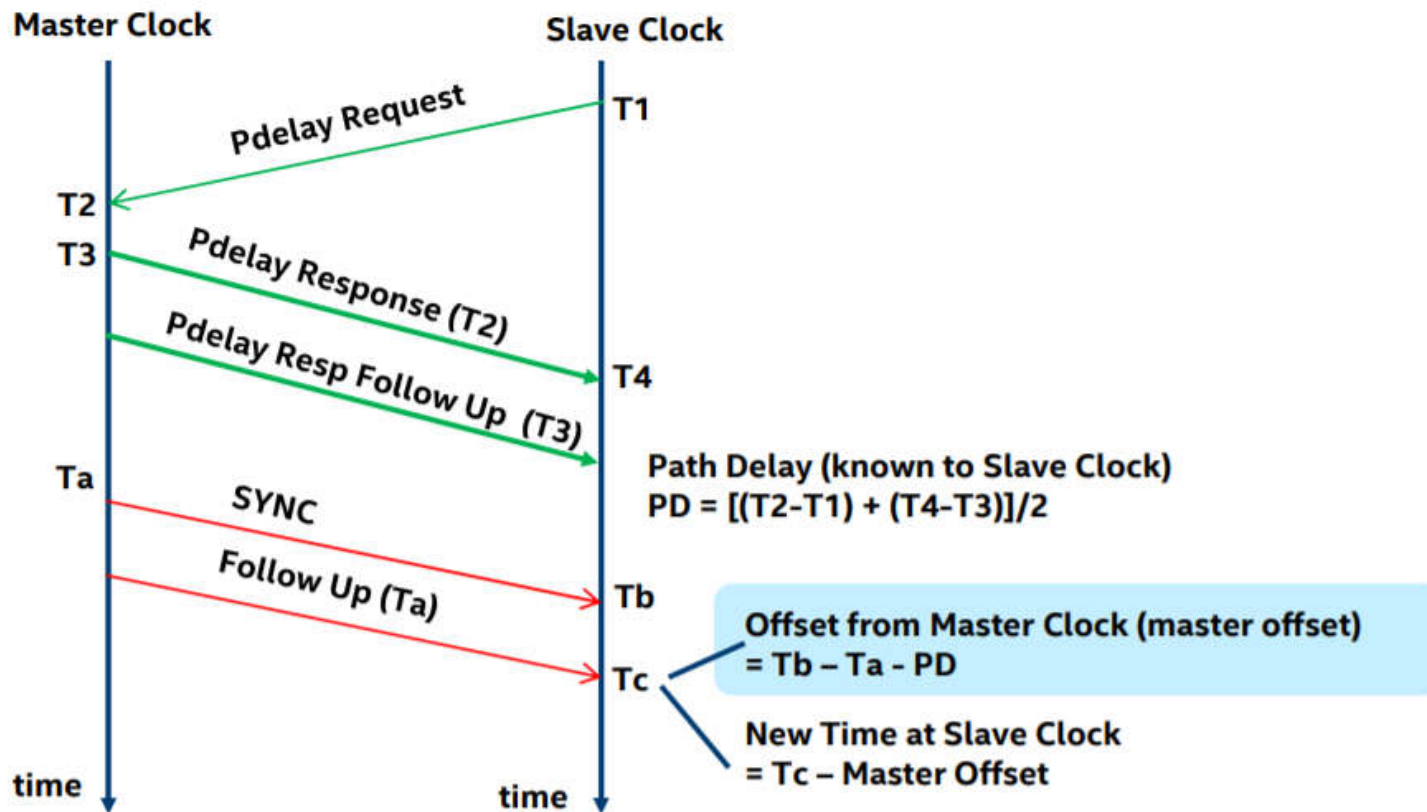
## PTP4L & PHC2SYS

Linuxptp Project provides software daemons:

- **ptp4l**
  - PTP Message over L2, UDP (IPv4 or IPv6)
  - Hardware & Software Timestamping
  - Synchronize distributed PHC clocks
  - IEEE1588 and compatible with IEEE 802.1AS
- **phc2sys**
  - Synchronize System Clock (CLOCK\_REALTIME) to PTP Hardware Clock (PHC)



# PTP4L





## PTP4L LOG AT SLAVE CLOCK

```
ptp4l[61720.627]: selected /dev/ptp0 as PTP clock
ptp4l[61720.628]: port 1: INITIALIZING to LISTENING on INIT_COMPLETE
ptp4l[61720.628]: port 0: INITIALIZING to LISTENING on INIT_COMPLETE
ptp4l[61722.021]: port 1: new foreign master e8ea6a.ffff.0938e8-1
ptp4l[61726.022]: selected best master clock e8ea6a.ffff.0938e8
ptp4l[61726.022]: port 1: LISTENING to UNCALIBRATED on RS_SLAVE
ptp4l[61728.355]: master offset      -1207 s0 freq  +2406 path delay      -7
ptp4l[61729.355]: master offset      -1287 s2 freq  +2326 path delay      -6
ptp4l[61729.356]: port 1: UNCALIBRATED to SLAVE on MASTER CLOCK SELECTED
ptp4l[61730.356]: master offset      -1284 s2 freq  +1042 path delay      -7
ptp4l[61731.356]: master offset         5 s2 freq  +1946 path delay     -11
ptp4l[61732.356]: master offset       408 s2 freq  +2350 path delay     -32
ptp4l[61733.356]: master offset       386 s2 freq  +2451 path delay     -32
ptp4l[61734.356]: master offset       241 s2 freq  +2422 path delay     -11
ptp4l[61735.356]: master offset       143 s2 freq  +2396 path delay      -7
ptp4l[61736.357]: master offset        83 s2 freq  +2379 path delay      -7
ptp4l[61737.357]: master offset        33 s2 freq  +2354 path delay      -8
ptp4l[61738.357]: master offset         6 s2 freq  +2337 path delay      -8
ptp4l[61739.357]: master offset         0 s2 freq  +2332 path delay     -11
```

- 1 Offset from Master Clock
- 2 S0: unlock  
S1: clock step  
S2: locked
- 3 PHC Frequency Adjustment (pbb)
- 4 Path Delay values between Master and Slave Clocks

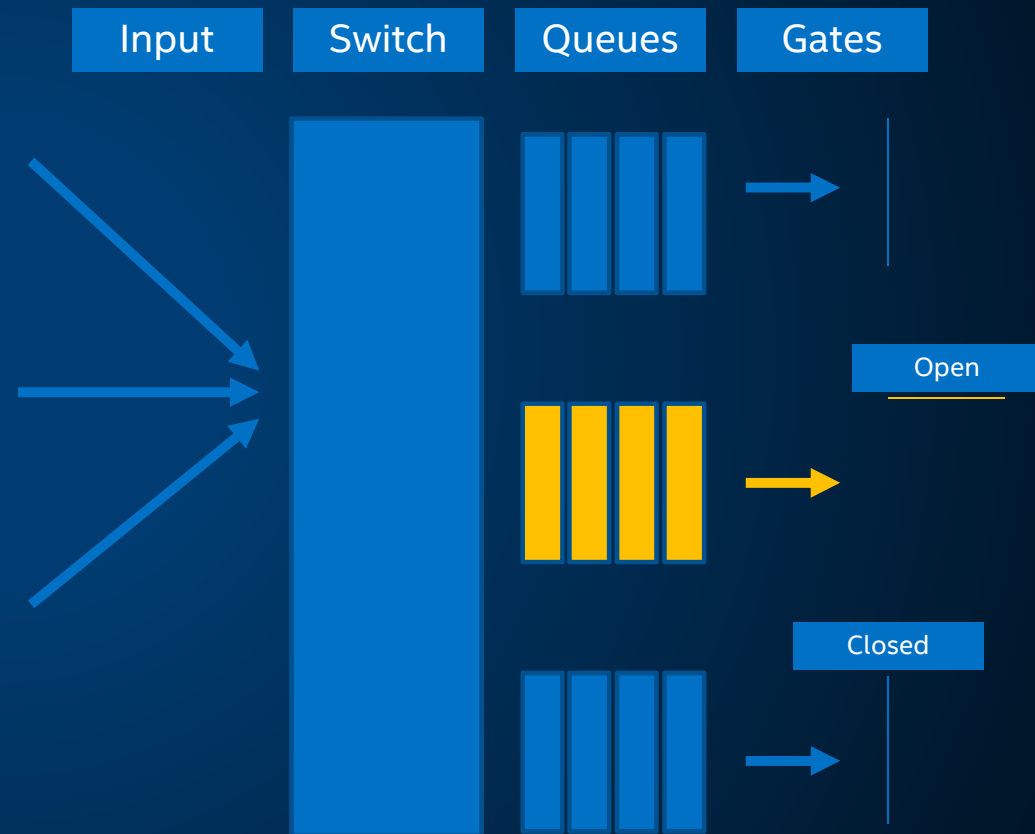
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# 802.1QBV™-2015 : TRANSMISSION GATE SCHEDULING

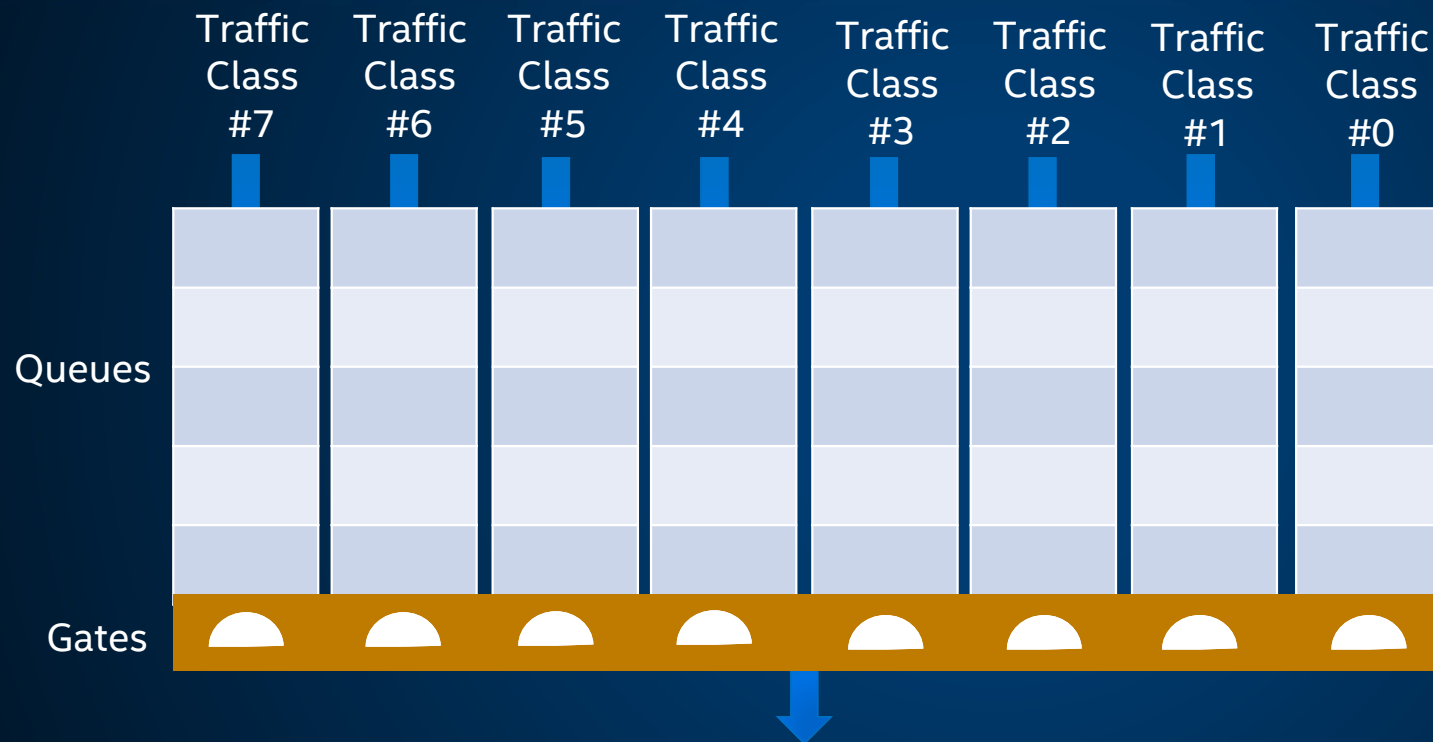
The IEEE 802.1Qbv standard is at the core of TSN and defines up to 8 queues per port for forwarding traffic.

Frames are assigned to queues based on Quality of Service (QoS) priority.

The time-aware shaper (TAS) blocks all ports except one based on an time schedule in order to prevent delays during scheduled transmission.



# SCHEDULING BRIDGE (PER EGRESS PORT)



Example:  
Cycle Time = 1 ms

$\mu s$	7	6	5	4	3	2	1	0
10	•	•	•	•	•	•	•	•
0								
40	•	•	•	•	•	•	•	•
0								
50	•	•	•	•	•	•	•	•
0								

<http://www.ieee802.org/1/pages/802.1bv.html>

# 802.1QAV™-2009 : CREDIT-BASED SHAPER

To enable bandwidth reservation for time sensitive traffic, IEEE 802.1Qav describes:

Using VLAN tag encoded priority to map to bandwidth reserved streams

A controlled bandwidth queue draining algorithm called Credit-Based Shaper (CBS).



In essence, CBS spaces out time-sensitive traffic as far as possible while ensuring the traffic bandwidth reserved for time-sensitive traffic is guaranteed.

# 802.1QBU™-2016 & IEEE STD. 802.3BR™-2016 : FRAME PREEMPTION

IEEE 802.1Qbu solves an issue of 802.1Qbv, which guarantees that critical messages are protected against interference from other network traffic but does not necessarily result in optimal bandwidth usage or minimal communication latency. If these factors matter **frame pre-emption** is used in order to interrupt the transmission of long frames in favor of high-priority frames. As soon as the high-priority traffic is through the remaining part of the interrupted frame can be transmitted. This procedure allows for optimal bandwidth utilization of background traffic when used with TAS and **enables low-latency communication in non-scheduled networks.**

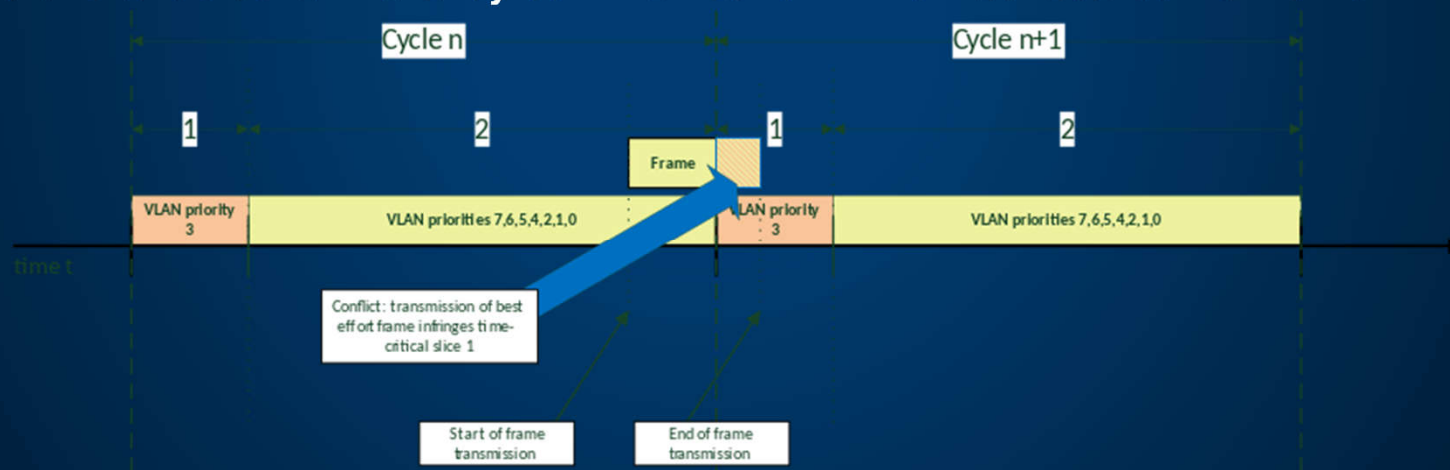


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# 802.1CB™-2017: FRAME REPLICATION & ELIMINATION

IEEE 802.1CB describes a standard for a redundancy management mechanism (similar to HSR and PRP). Messages are copied and are communicated in parallel over disjoint paths through the network. At the receiver end redundant duplicates are eliminated to create one seamless stream of information.

This method ensures high availability for data sent over TSN networks.



# 802.1QAT™-2010 : STREAM RESERVATION PROTOCOL

Stream Reservation Protocol (SRP) is an amendment to the IEEE 802.1Q standard (standardized separately as 802.1Qat) to provide end-to-end management of resource reservations for data streams requiring guaranteed Quality of Service (QoS) in Local Area Networks (LANs).

The protocol allows stream endpoints to register their willingness to "Talk" or "Listen" to specific streams, and it propagates that information through the network. All bandwidth reservation operations are performed on a physical Ethernet port basis.

Provides a signaling protocol to enable the end-to-end management of resource reservation for QoS guaranteed streams.

Handles the registration, deregistration, and retention of resource reservation information in relevant network elements that require latency and bandwidth guarantees.

# IDENTIFYING STREAMS IN A TSN NETWORK

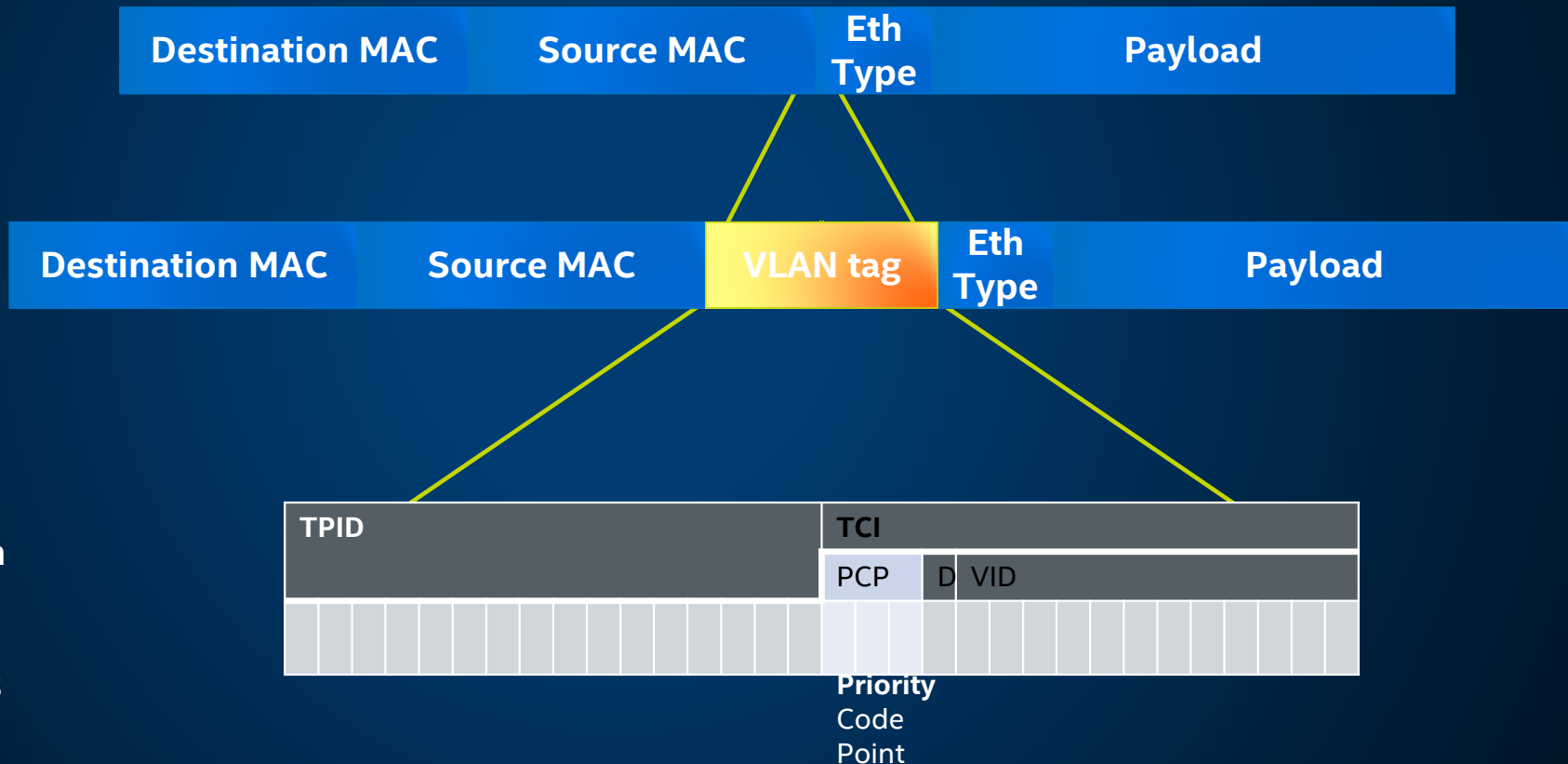
TSN uses three types of identifying labels:

**Stream ID**  
a 48-bit EUI-48  
(usually the MAC source address)

**Traffic Class**  
determined by the  
3 priority bits

**Stream Destination**  
address  
The MAC  
destination address  
and VLAN ID

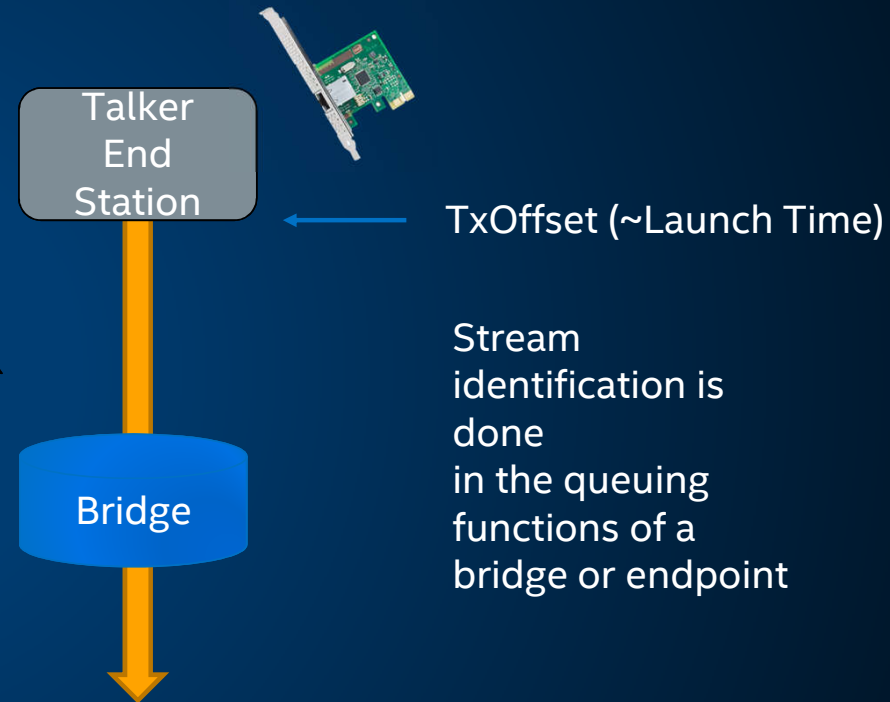
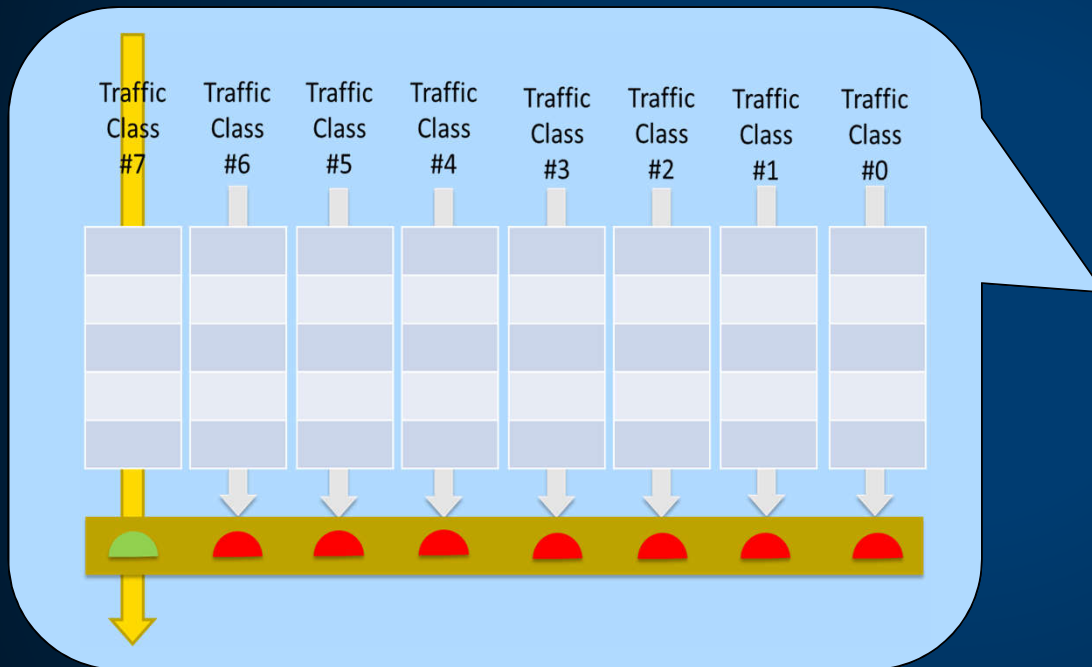
Ethernet Frame



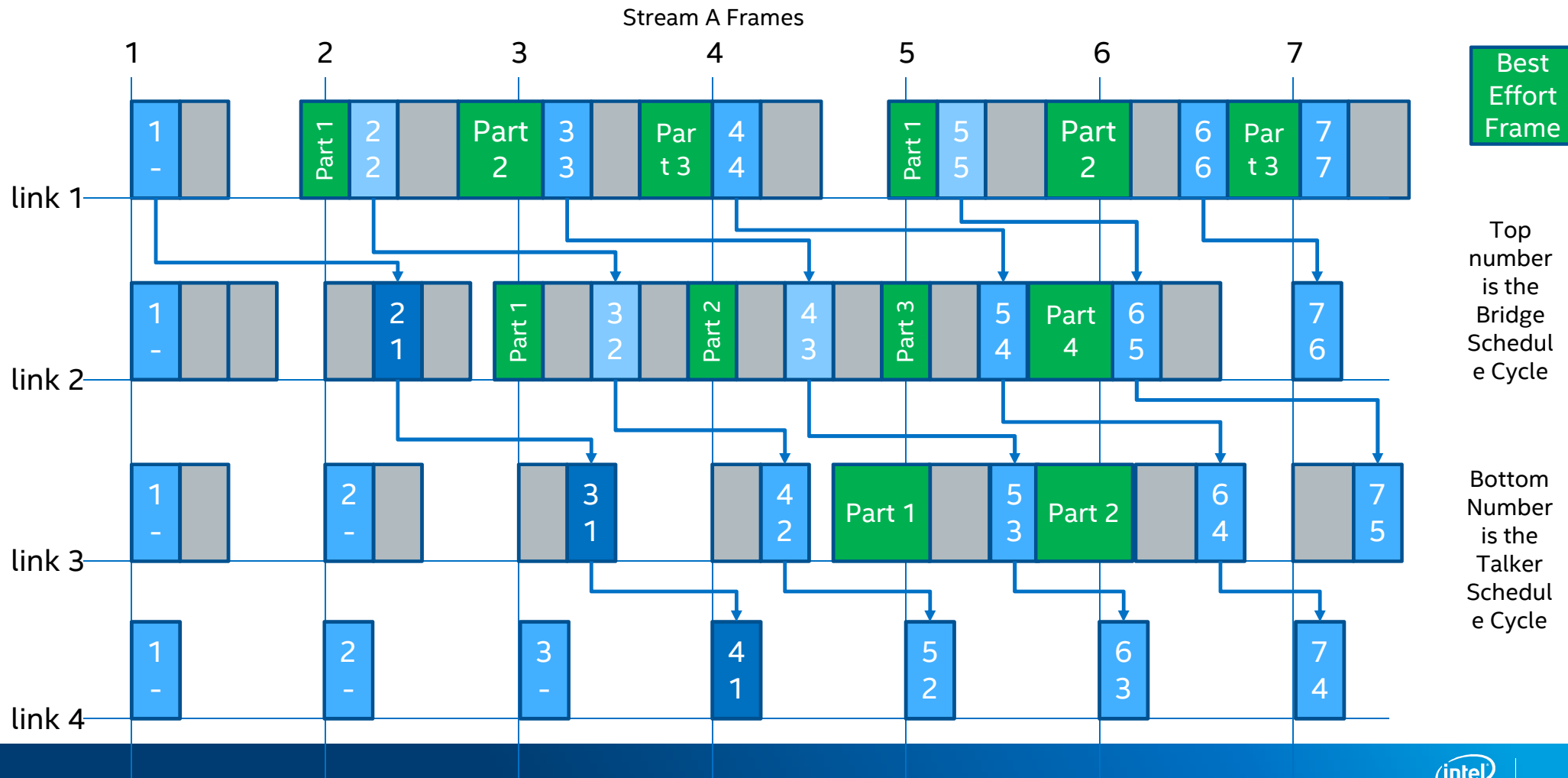
# 802.1QCC™-2018 : SRP ENHANCEMENTS AND PERFORMANCE IMPROVEMENTS

With IEEE 802.1Qcc there is also a standard which improves existing reservation protocols such as SRP (Stream Reservation Protocol) in order to meet requirements of professional, industrial, consumer and automotive markets. This includes support for more streams, configurable SR (stream reservation) classes and streams, improved description of stream characteristics, support for Layer 3 streaming, deterministic stream reservation convergence as well as UNI (User Network Interface) for routing and reservations. This method further enables central configuration models for dynamic scheduling of TSN networks and allows standard, consistent setting of TSN schedules in switches from various vendors.

# SCHEDULING END STATION



# 802.1QCH™-2017 : CYCLIC QUEUING AND FORWARDING



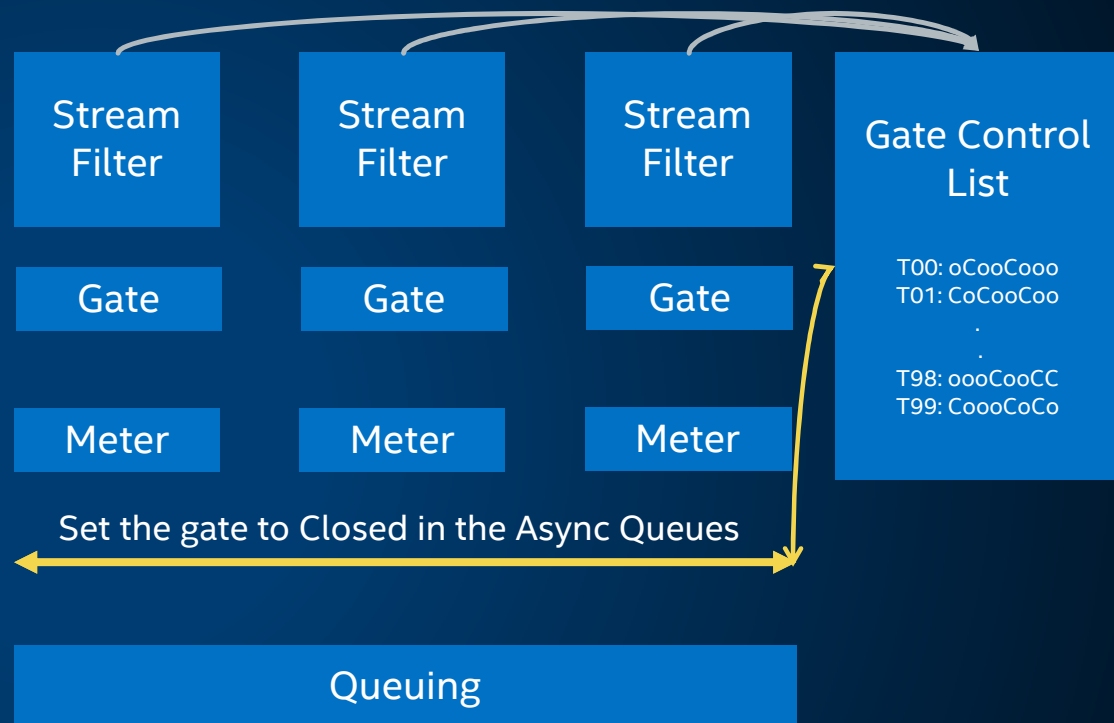
# 802.1QCA™-2015: PATH CONTROL AND RESERVATION

This standard uncovers redundant paths through the network by collecting topological information to ensure bandwidth control and data stream redundancy in the future.



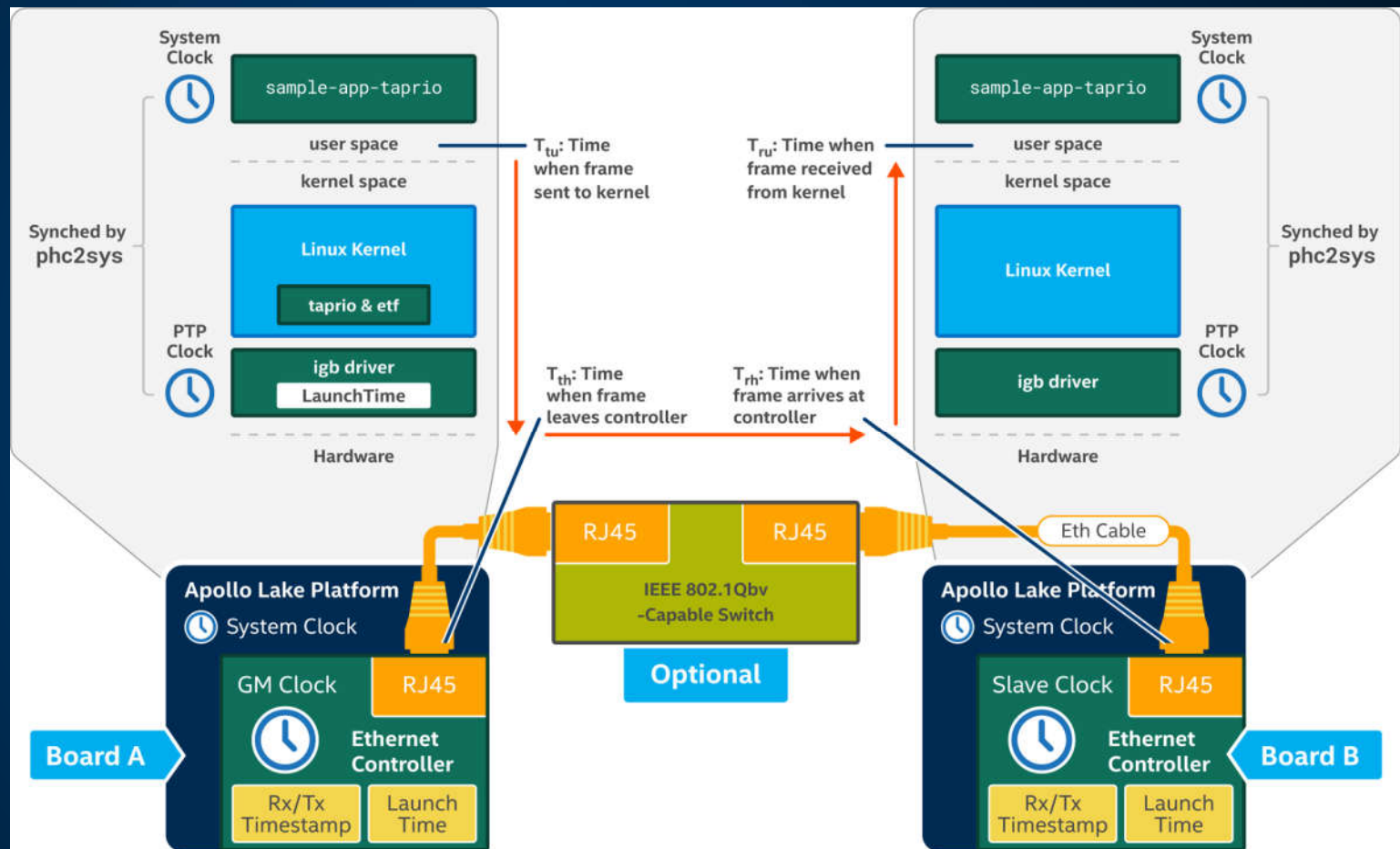
# 802.1QCI™-2017: PER-STREAM FILTERING & POLICING

- Policy for blocking streams that are misbehaving
- Can force the gate status to closed. Configure either that a stream, several streams, or all traffic is dropped. It should be possible trigger the "force gate closed" by all defined mechanisms that detect misbehavior (e.g. max SDU, RED, blocked by stream gate). The gate instances associated with a "force gate closed" event, triggered by a particular detected misbehavior of a link partner, should be configurable.



# THREE LABS TO COMPARE TSN TRAFFIC

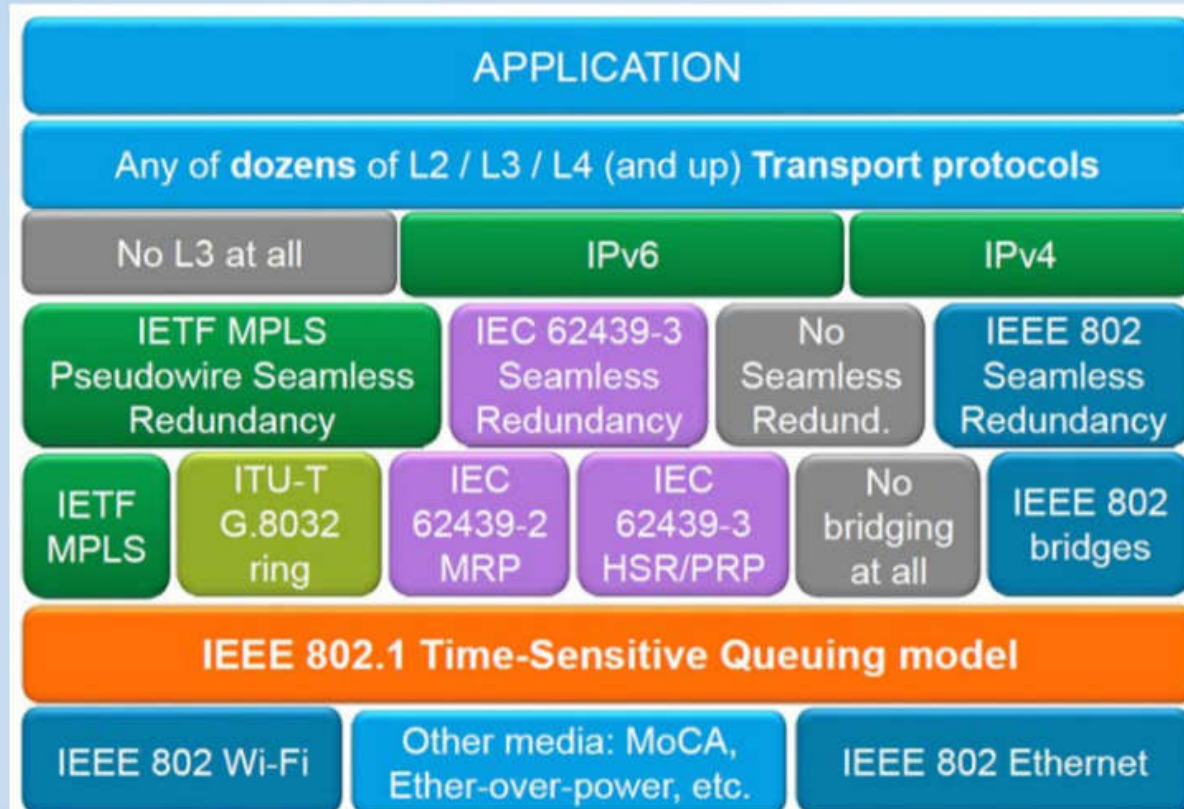
- IEEE 802.1Qbv Demo 3 Scenario 1: Without Time-Aware Traffic Scheduling or LaunchTime
- IEEE 802.1Qbv Demo 3 Scenario 2 Time-Aware Traffic Scheduling Enabled
- IEEE 802.1Qbv Demo 3 Scenario 3 Time-Aware Traffic Scheduling and LaunchTime Enabled



# TERMINOLOGY FOR THE LABS

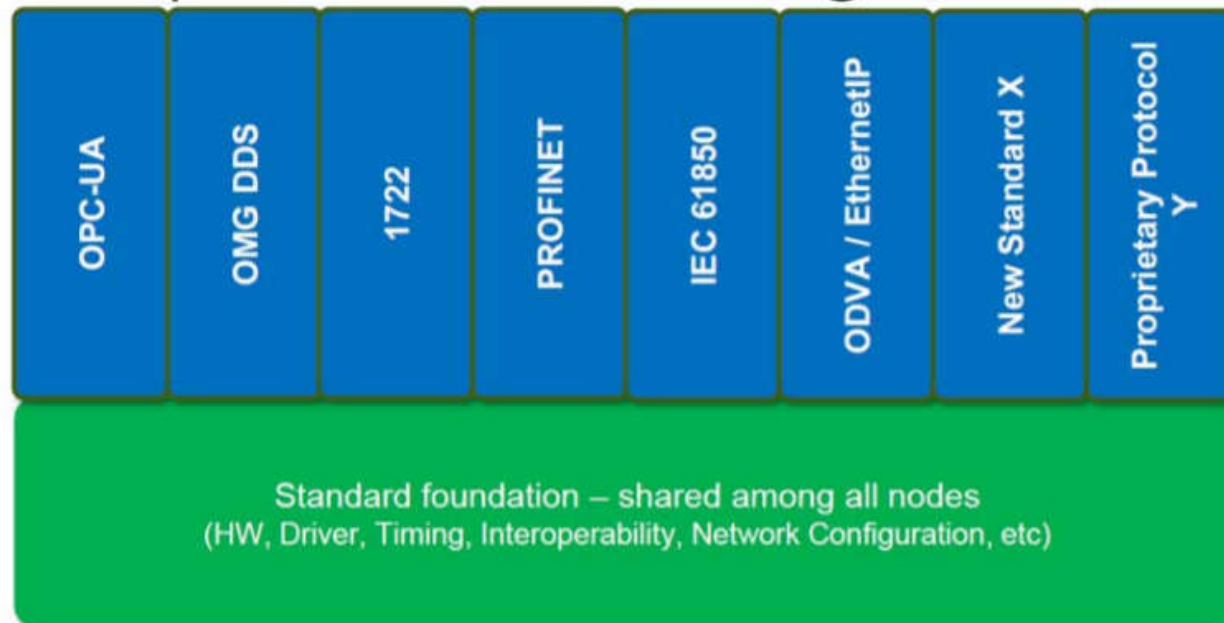
- mqprio- Multiqueue Priority Qdisc
- taprio - Time Aware Priority Shaper
- tc - show/manipulate traffic control settings
- ptp4l - Precision Time Protocol (PTP) daemon
- phc2sys - synchronize two clocks using ptp4l
- iperf3 - bandwidth measurement tool

# Deterministic Data Plane Menu



- Source: Norm Finn (Cisco) TSNA'15 - The Magic of Layering, Support for Routers in Time Sensitive Networks.pdf

# TSN-based protocols – Sharing the wire



**Key Idea:** AVnu can provide value for industrial markets by endorsing foundational TSN services in support of multiple industrial protocols.

- Source: Dan Sexton (GE) TSNA'15 - Industrial; Converging Control, Monitoring, and Enterprise Networks to Support Flexible Manufacturing.pdf