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

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.

CHALLENGES TO REAL-TIME NETWORKING

No two clock run at the same rate

Complex software gives rise to uncertainty and latency

Networks outages and unpredictability make guarantees difficult

NTP can sync to sub ms in best cases

PTP is a better protocol for sub

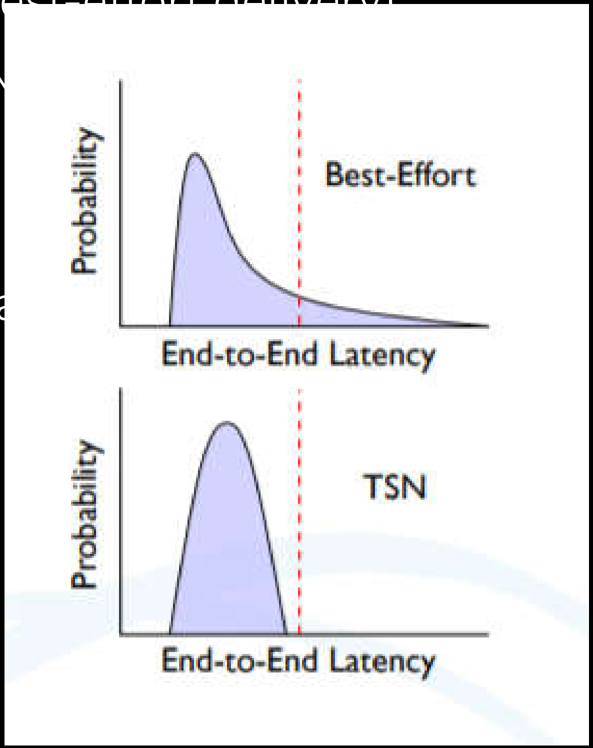
CHANGING THE GOALS OF 802 NETWORKS

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 N
- Time means deterministic and scheduled traffic
- Time means guaranteeing reserved routing of priority traffi

Converged critical control and best-effort data traffic over sta
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.

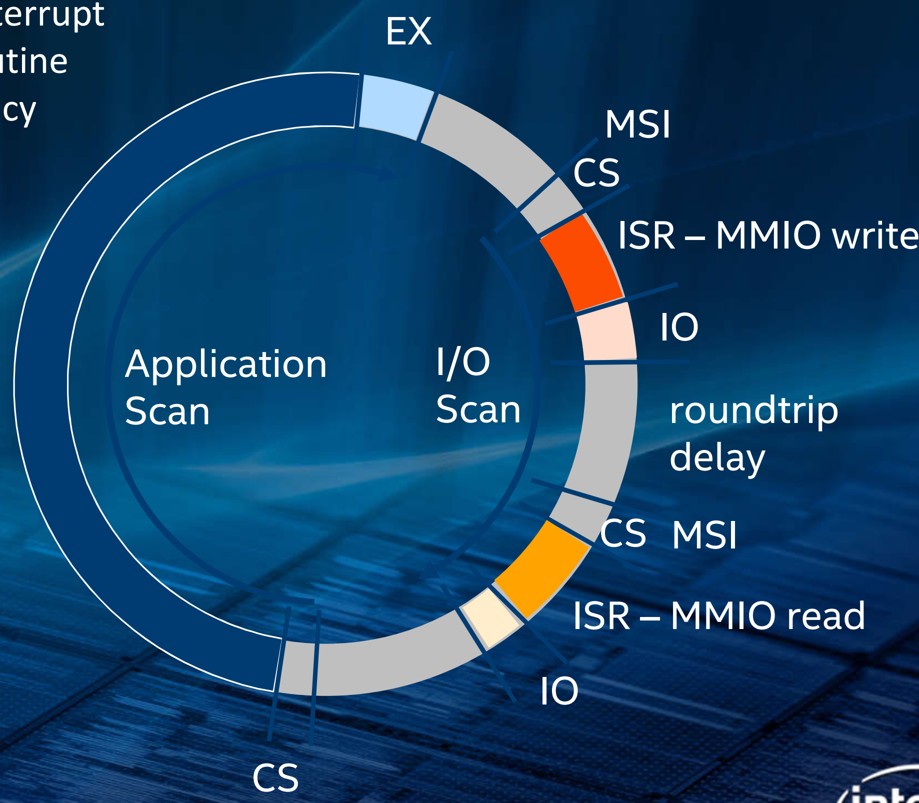
Time-Sensitive Networking is a return to Circuit Switching

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

REAL-TIME SOFTWARE: THE CONTROL LOOP

- Control Loop
  - Acquire data
  - Process
  - Actuate
- Event Driven and Periodic

MSI: Message Signaled Interrupt
ISR: Interrupt Service Routine
CS: Context Switch Latency
IO: I/O Jitter
Ex: Execution Time Jitter



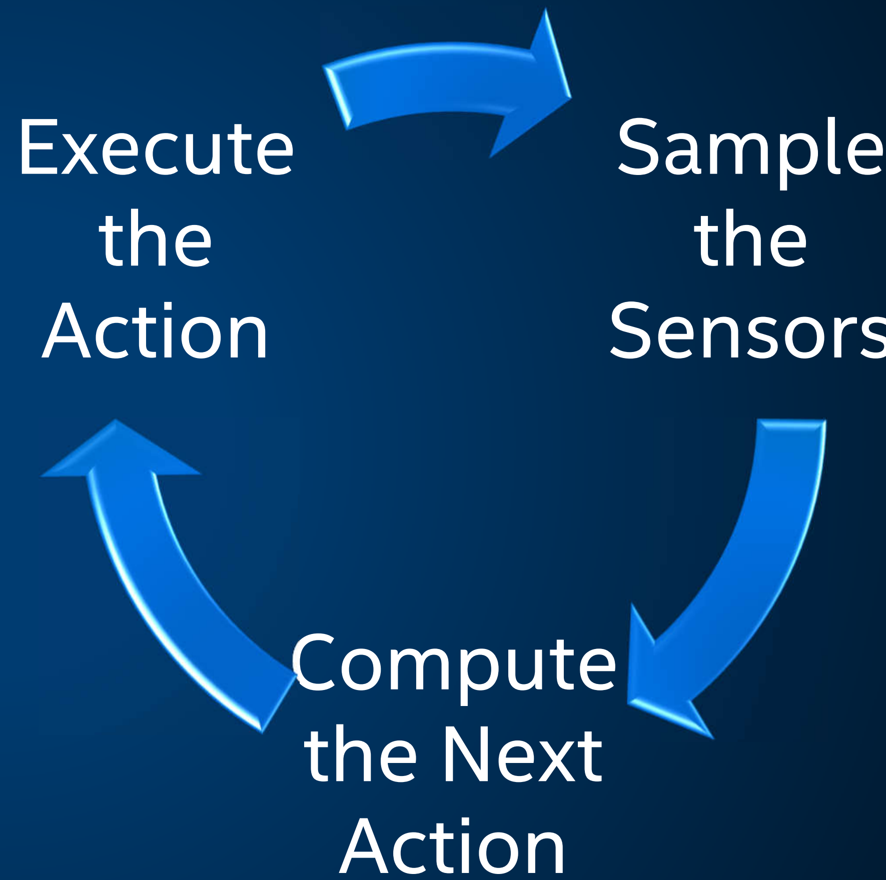
RTLinux applications consist of threads, interrupt handlers, “main” kernel processes, and user processes.

THE CONTROL LOOP

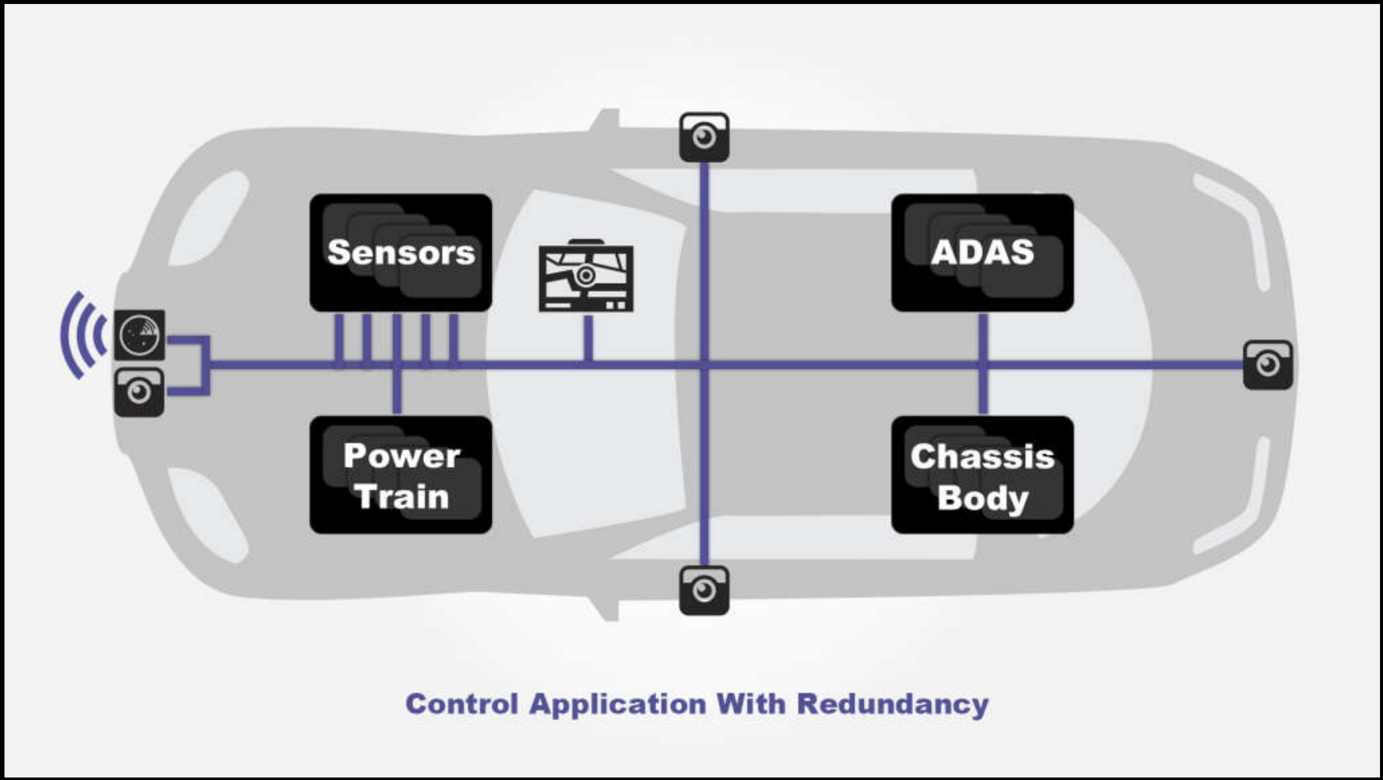
The move from physical to electronic synchronization has create the idea of the control loop

- Sample the sensor data
- Compute the next action
- Activate the action

Cycle Times of <100s of milliseconds to <250 µseconds are common



Time Sensitive Networking will Create a Single Networked Bus in Cars where Systems are Currently Separate



Time Sensitive Networking will Create a Single Networked Bus in Cars where Systems are Currently Separate

Control Loops for Industrial Manufacturing

Fujitsu Group and Intel jointly developed a solution using sensors and video to reduce the error rate of products manufactured in their business notebook and table factories

https://www.intel.com/content/dam/www/public/us/en/documents/case-studies/real-time-iot-tracking-manufacturing-case-study.pdf

TSN HIGH LEVEL GOALS

Establish a network-wide precision clock reference

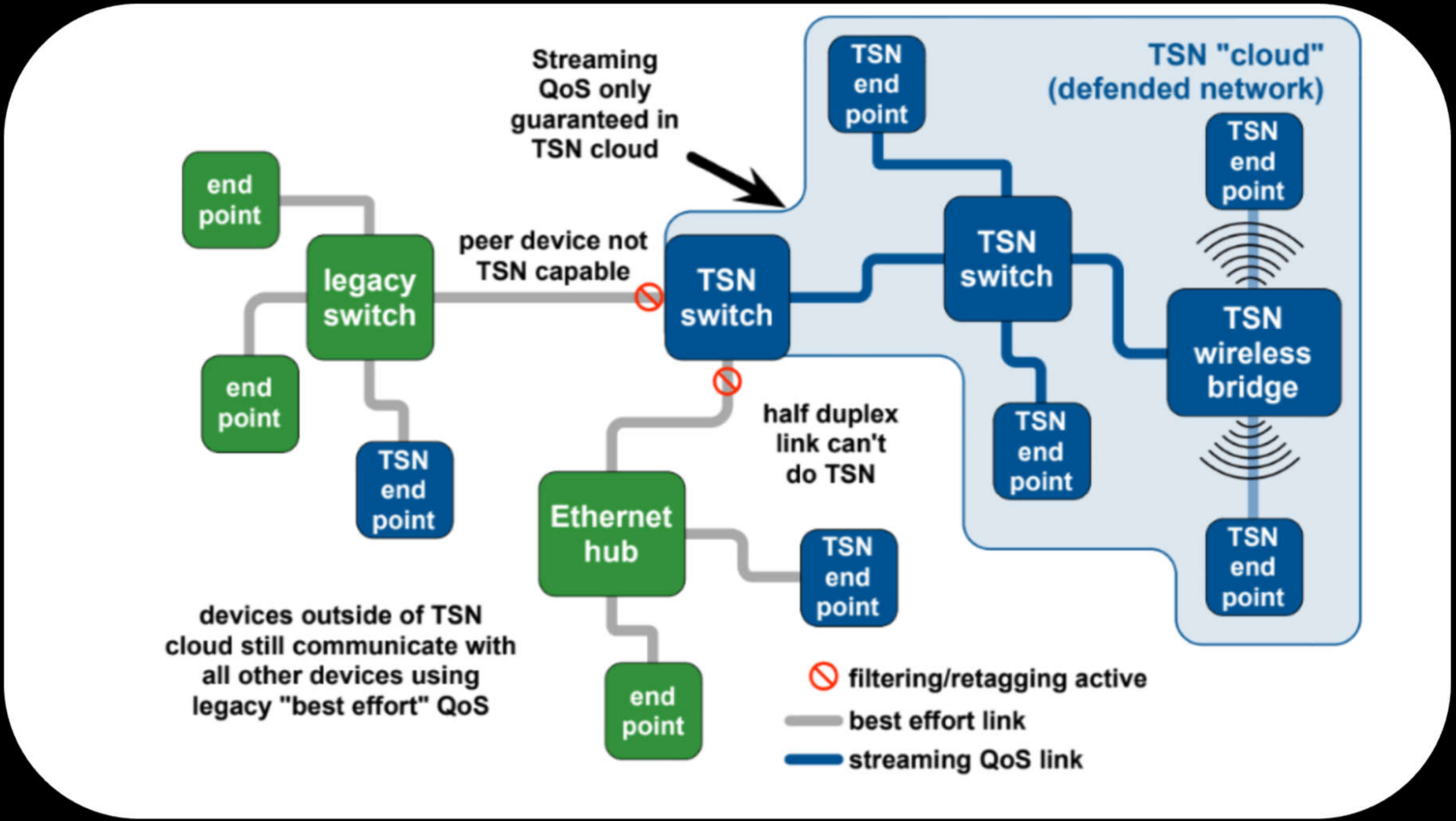
All priority traffic is scheduled and delays are bounded and small

Deterministic mechanism to separate normal traffic and TSN traffic, control of traffic shaping QoS

Built as an extension to the IEEE 802 Networking Standards

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™-2011 : generalized Precision Time Protocol (gPTP)
Bounded Low	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

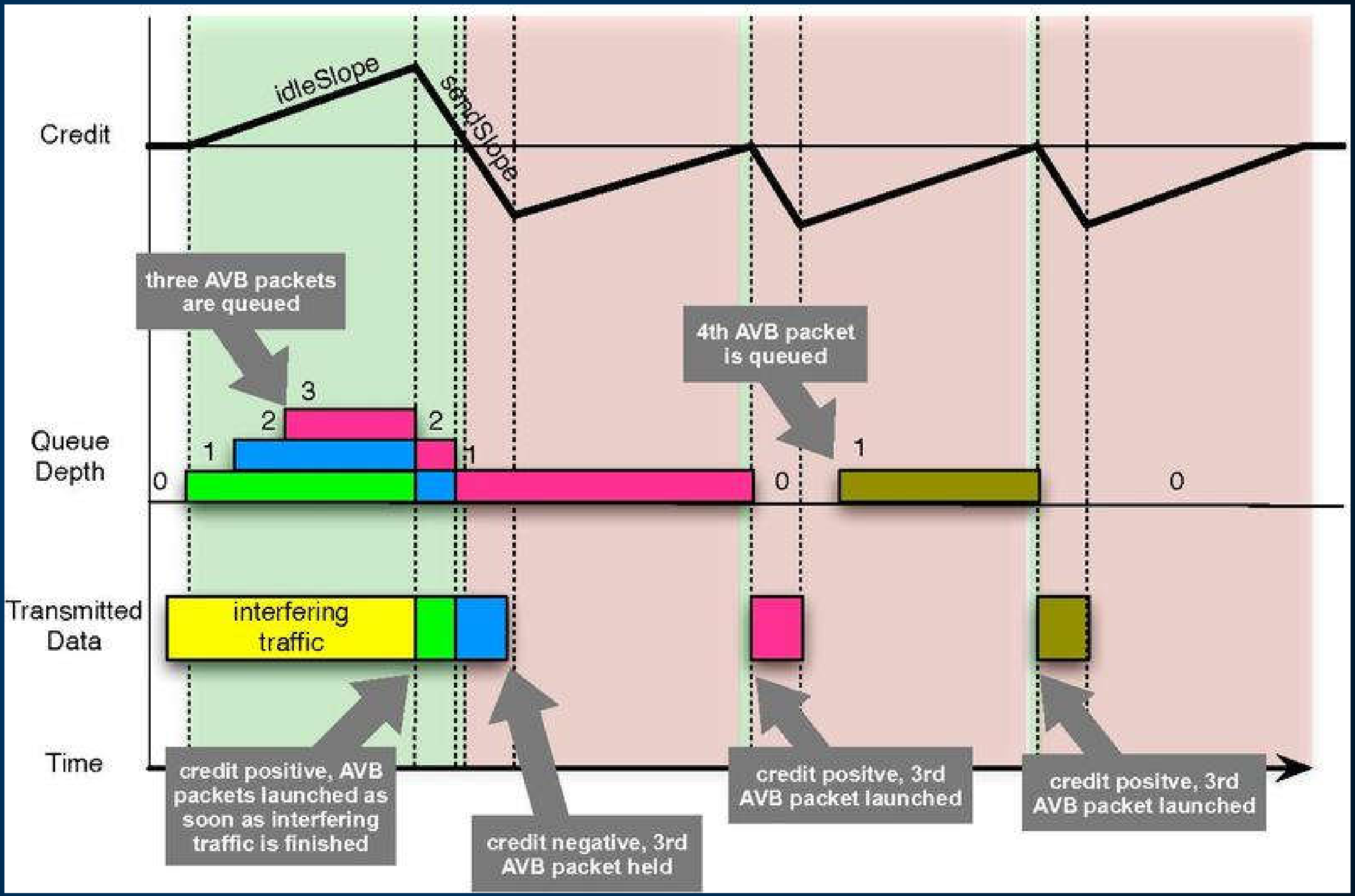
Description of Working Group	IEEE Standard	Extensions and Notes
Forwarding and Queuing Enhancements for Time-Sensitive Streams	802.1Qav	P802.1Qbu - Frame Preemption P802.1Qbv - Priority Queuing, Time-Gated Queuing
Distributed Stream Reservation Protocol (SRP)	802.1Qat	P802.1Qcc - preemption, scheduling, 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.[1]

802.1QAV™-2009 : CREDIT-BASED SHAPER

Credit-based fair queuing is a computationally efficient alternative to fair queueing.

Credit is accumulated to network queues as they wait for service, and credit is spent while they are being serviced.

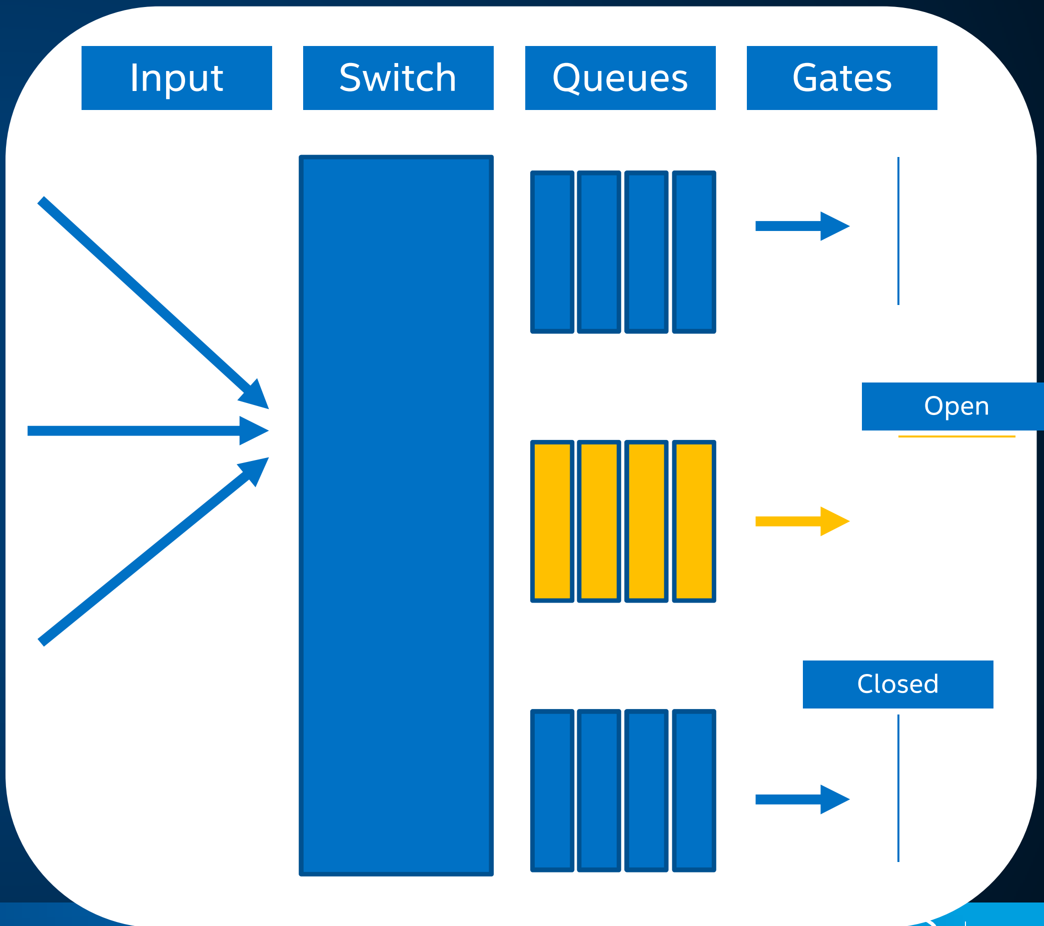


802.1QBV™-2015 : TRANSMISSION GATE SCHEDULING

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.



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 favour 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 utilisation of background traffic when used with TAS and **enables low-latency communication in non-scheduled networks**.

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.

802.1CB™-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.

802.1Qci™-2017 : Per-Stream Filtering & Policing

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.

Four sources of packet delay

Bridge delay (d_{proc}):

- check bit errors
- determine egress port

Queuing (d_{queue}):

- time waiting at egress port for transmission
- depends on congestion level of output link

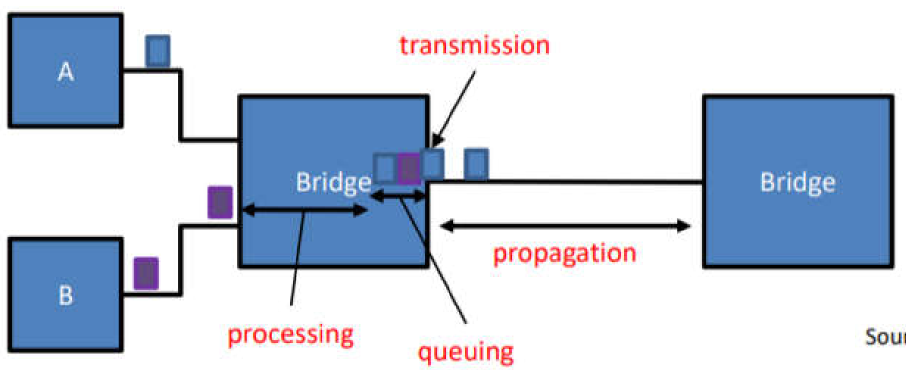
Transmission (d_{trans}):

- store-and-forward vs. cut-through delay
- time to send bits into link

Propagation (d_{prop}):

- time that it takes a signal change to propagate through the communication media from a node to the next node

$$\boxed{d_{bridge} = d_{proc} + d_{queue} + d_{trans} + d_{prop}}$$



Source: James F. Kurose, Keith W. Ross: Computer Networking

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.

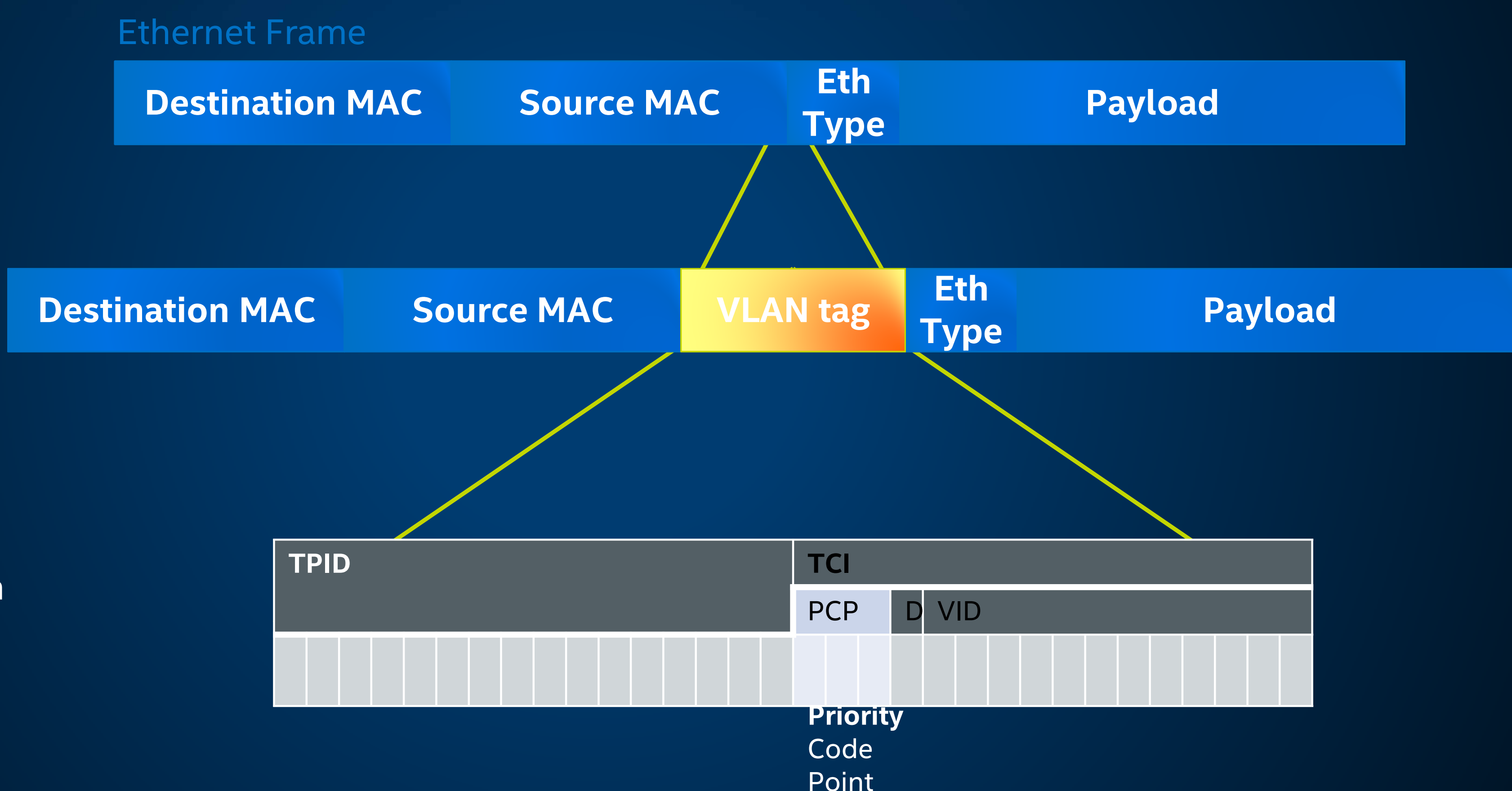
IDENTIFYING STREAMS IN A TSN NETWORK

TSN uses three types of identifying labels:

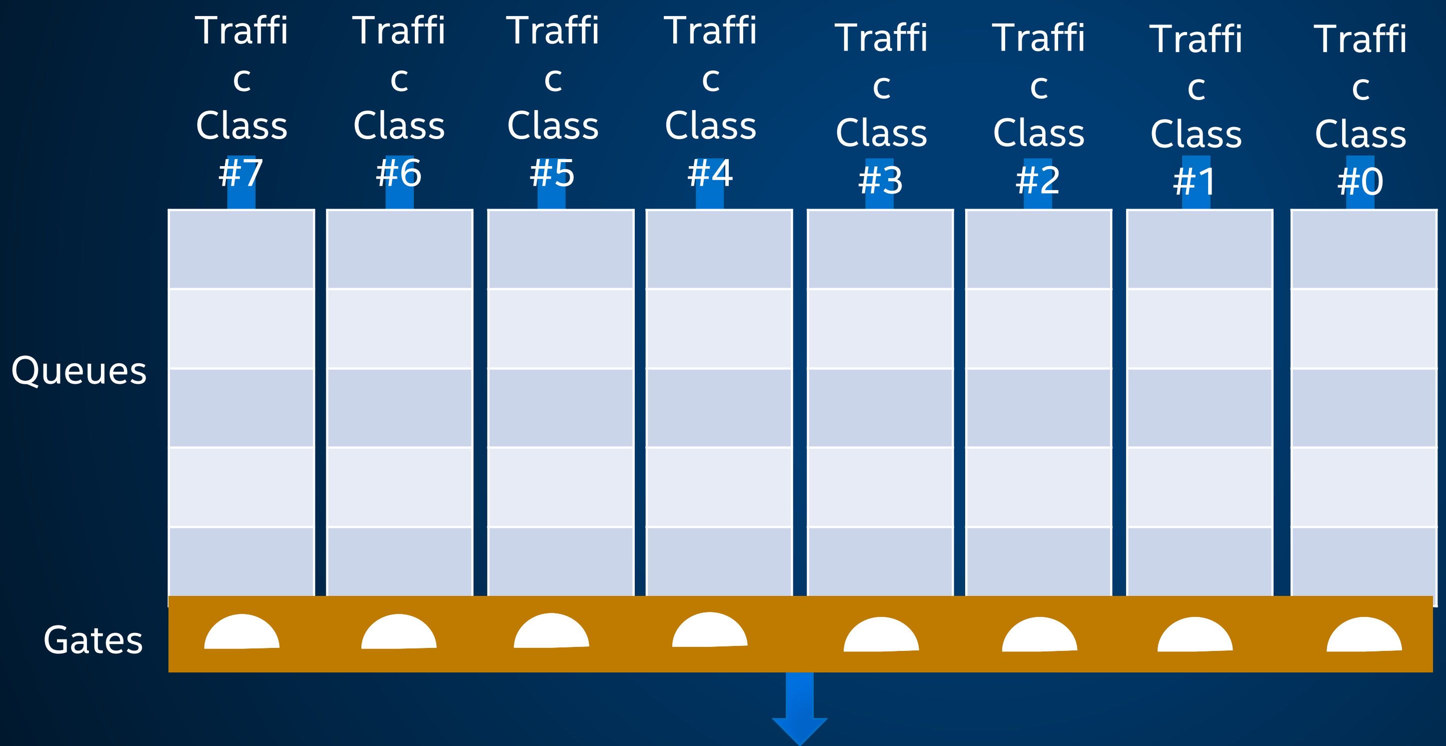
Stream ID
a 48-bit EUI-48 (usually the MAC source address)

Traffic Class
determined by the 3 priority bits

Stream Destination address
The MAC destination address and VLAN ID



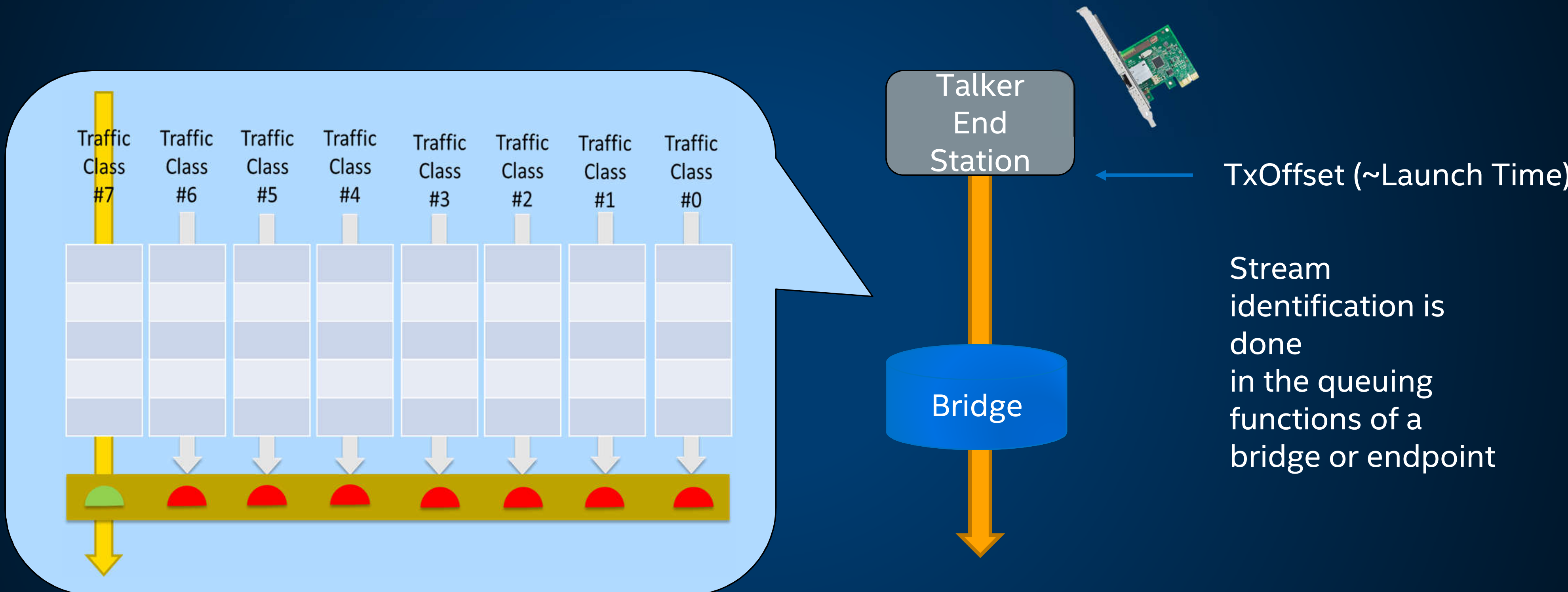
SCHEDULING BRIDGE (PER EGRESS PORT)



Example:
Cycle Time = 1 ms

µs	7	6	5	4	3	2	1	0
100	●	●	●	●	●	●	●	●
400	●	●	●	●	●	●	●	●
500	●	●	●	●	●	●	●	●

SCHEDULING END STATION



Stream
identification is
done
in the queuing
functions of a
bridge or endpoint

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

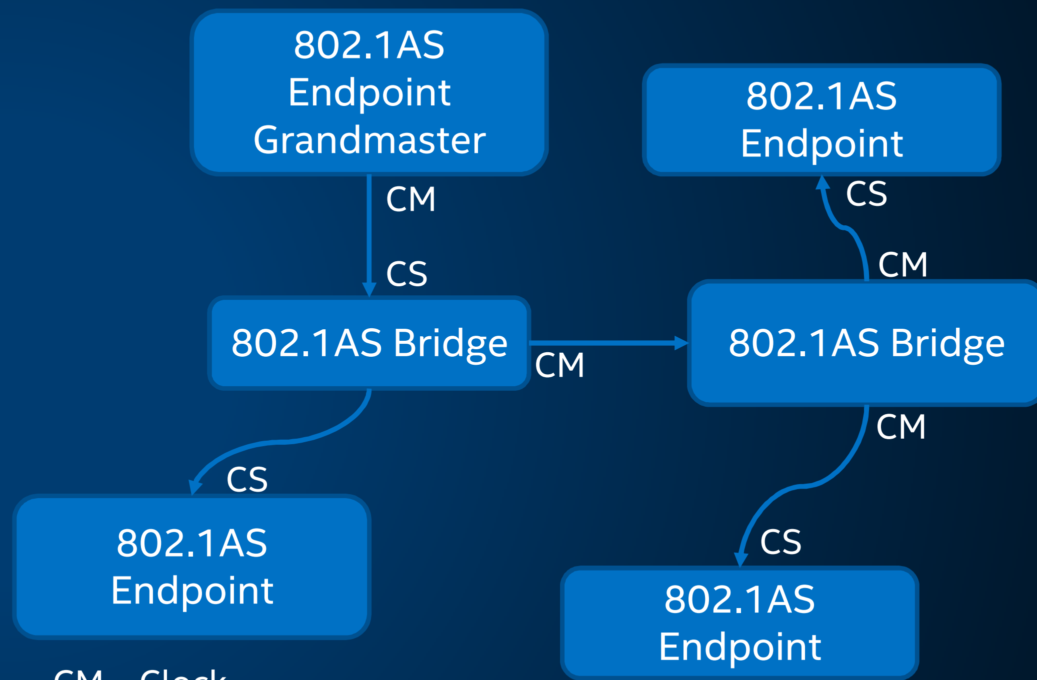
Creates a hierarchical master-slave architecture for clock distribution

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

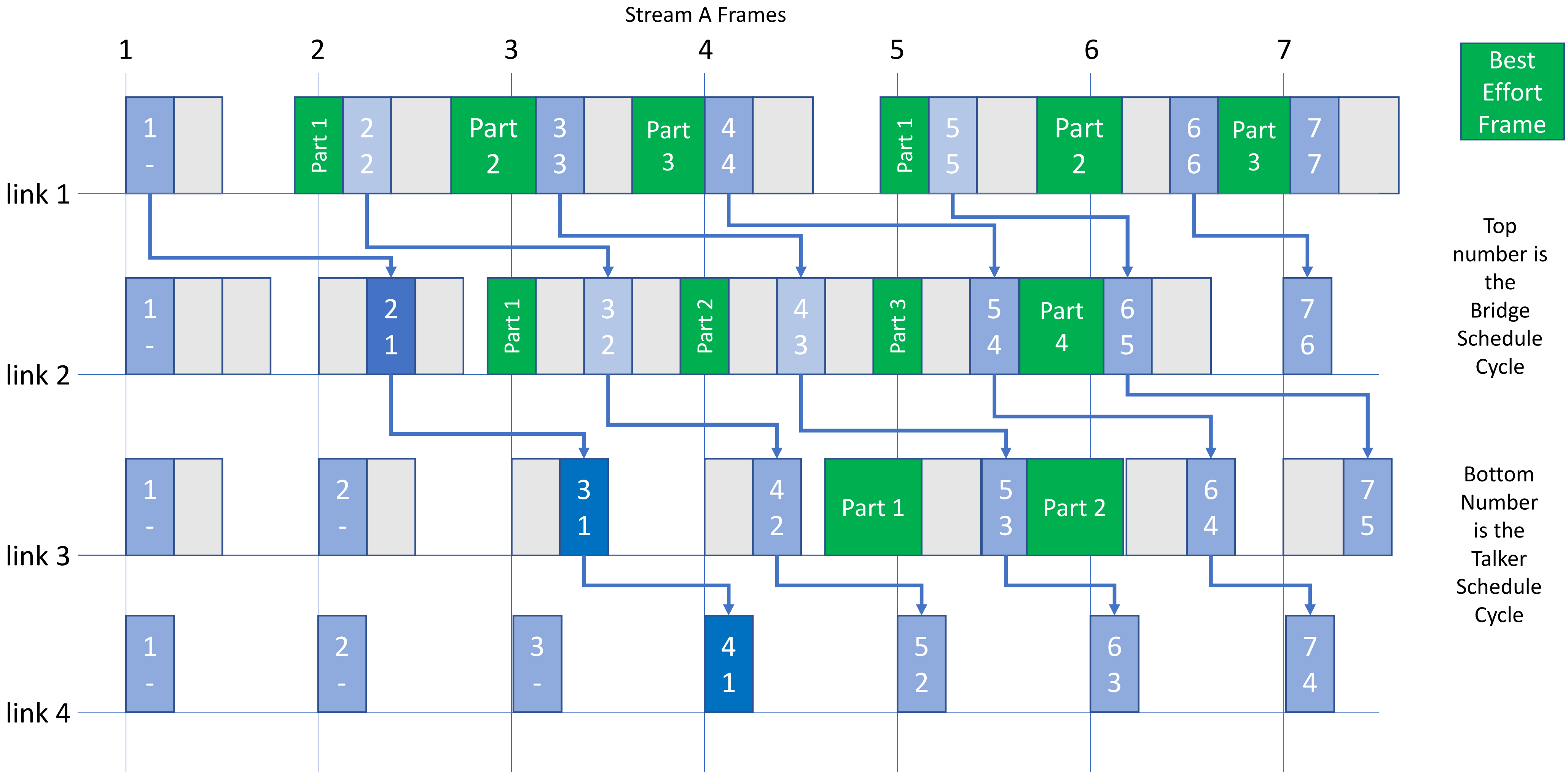
Allows multiple stream to be synchronized



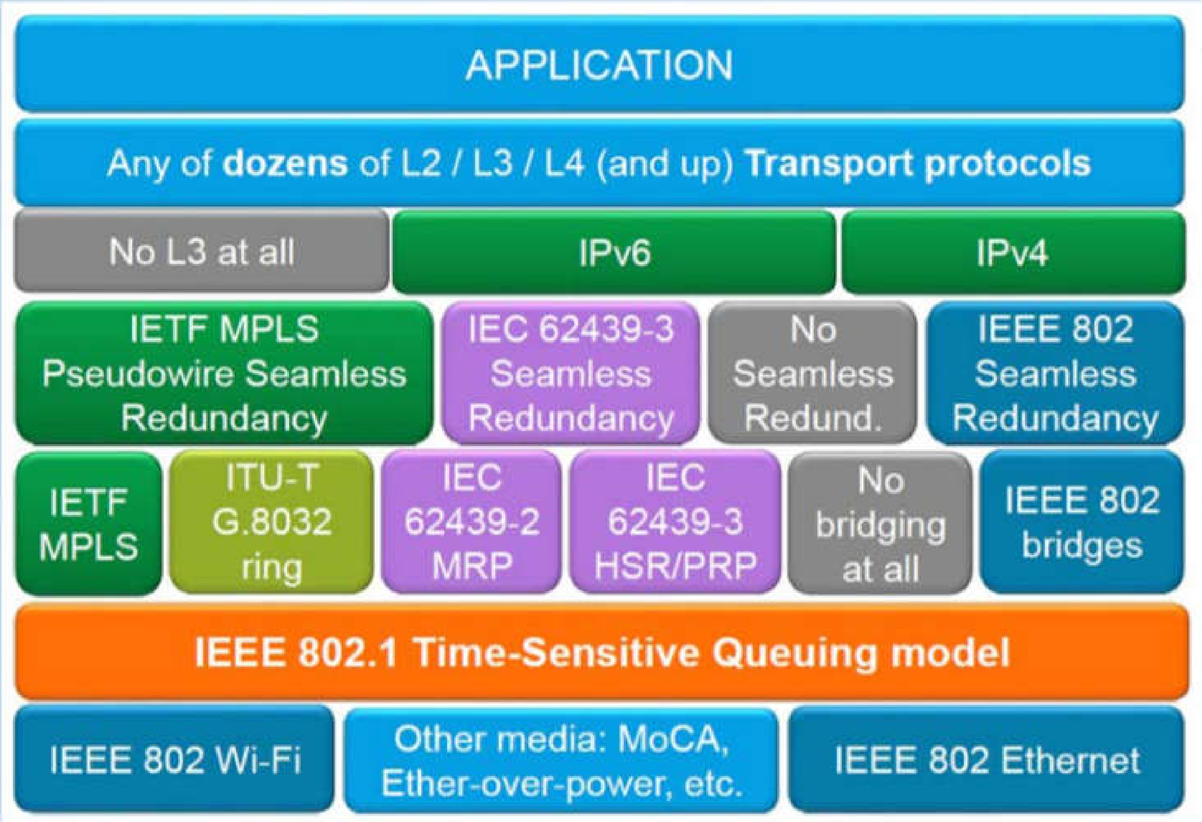
CM – Clock Master
CS – Clock Slave

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

802.1Qch™-2017 : Cyclic Queuing and Forwarding

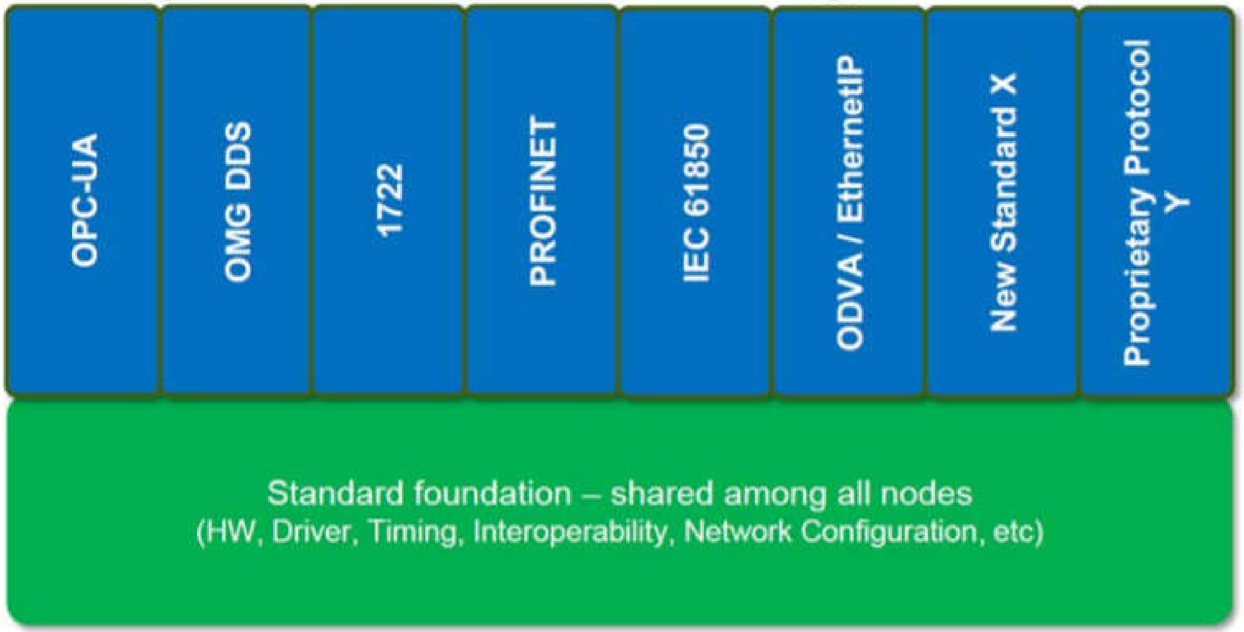


Deterministic Data Plane Menu



- 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