Time-Sensitive Networking

Moderator: Glenn Parsons

Speakers:

János Farkas, Silvana Rodrigues, Jordon Woods, Max Turner, Abdul Jabbar

Abstract

Imagine the opportunities possible if networking was instant and reliable, between people and things that matter, when and where it matters most.

Time-Sensitive Networking (TSN) makes it possible to carry data traffic of time-critical applications over a network shared by various kinds of applications having different Quality of Service (QoS) requirements. TSN provides guaranteed data transport with bounded low latency, low delay variation, and extremely low data loss. By reserving resources for critical traffic, and applying various queuing and shaping techniques, TSN achieves zero congestion loss for critical data traffic. This, in turn, allows TSN to guarantee a worst-case end-to-end latency for critical data.

These features make TSN applicable and economical for various use cases in the digital transformation. TSN can be used in various verticals, e.g., in industrial automation networks being developed for smart factories, in cellular networks, in networks for critical machine-to-machine communication, for new networking approaches in vehicles including support for autonomous driving, and many more, with a constantly expanding list.

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Workshop outline

- IEEE 802.1 Architecture and Bridging
- Fundamentals of Time-Sensitive Networking (TSN)
- Time Synchronization
- TSN Profile for Industrial Automation
- TSN Profile for Automotive
- TSN Profile for Aerospace

Speakers

- Glenn Parsons

- János Farkas

- Silvana Rodrigues

- Jordon Woods

- Max Turner

- Abdul Jabbar

Introduction to IEEE 802.1 Architecture and Bridging

Glenn Parsons

IEEE 802 reference model

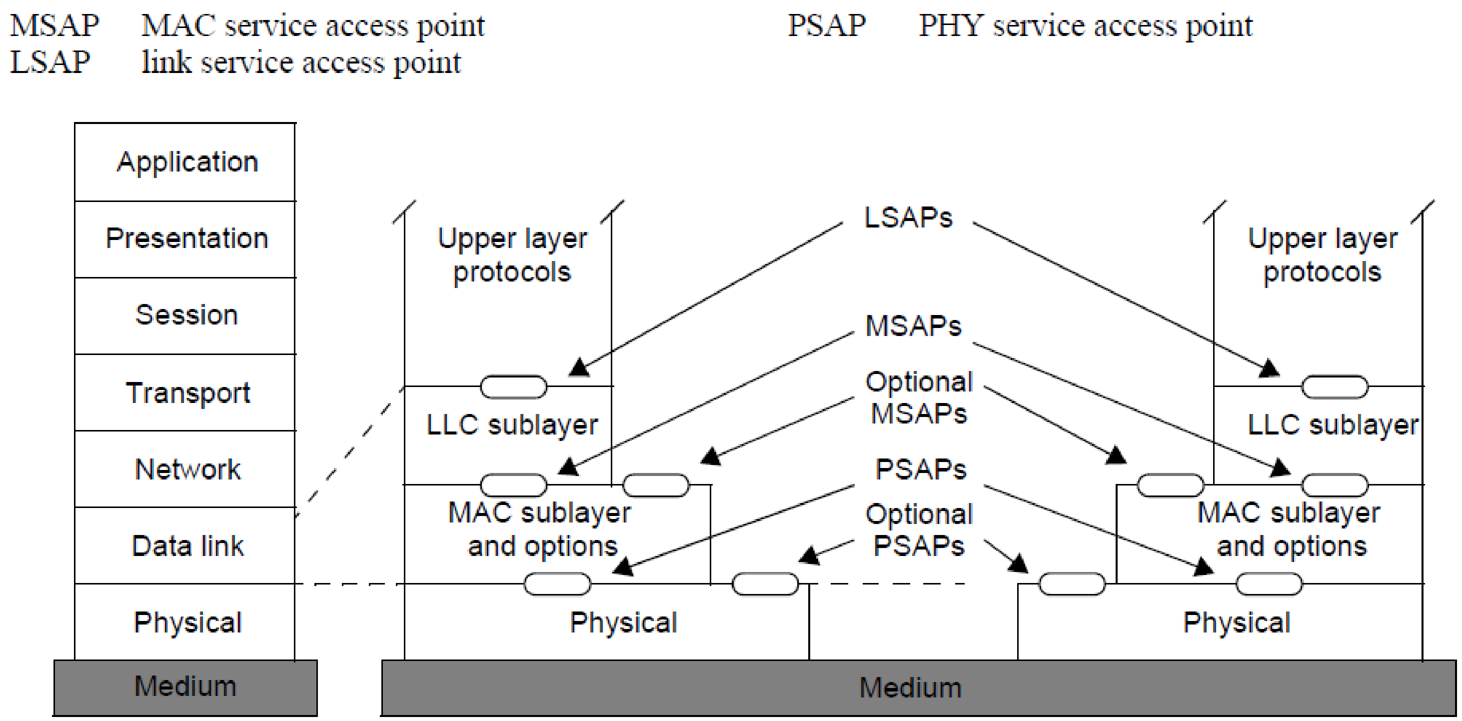


Figure 3 - IEEE Std 802

- <u>Current IEEE 802 family of working groups</u>
- 802.1 Bridging and Architecture
- 802.3 Ethernet
- 802.11 Wireless LAN (WLAN)
- 802.15 Wireless Personal Area Network (WPAN)
- 802.16 Broadband Wireless Access (BWA)
- 802.21 Media Independent Handover
- 802.22 Wireless Regional Area Networks (WRAN)

Bridging ties it together

IEEE Std 802.1AC specifies the MAC Service provided by all IEEE 802 LANs

IEEE Std 802.1Q specifies interworking among IEEE 802 LANs by bridging at the MAC sublayer

- Interworking can be heterogeneous (across different 802 technologies).
- MAC frames are forwarded (or filtered) based on address and Virtual LAN information in the MAC frame.
- Control Plane is the “bridge brain” and is separated from the Data Plane

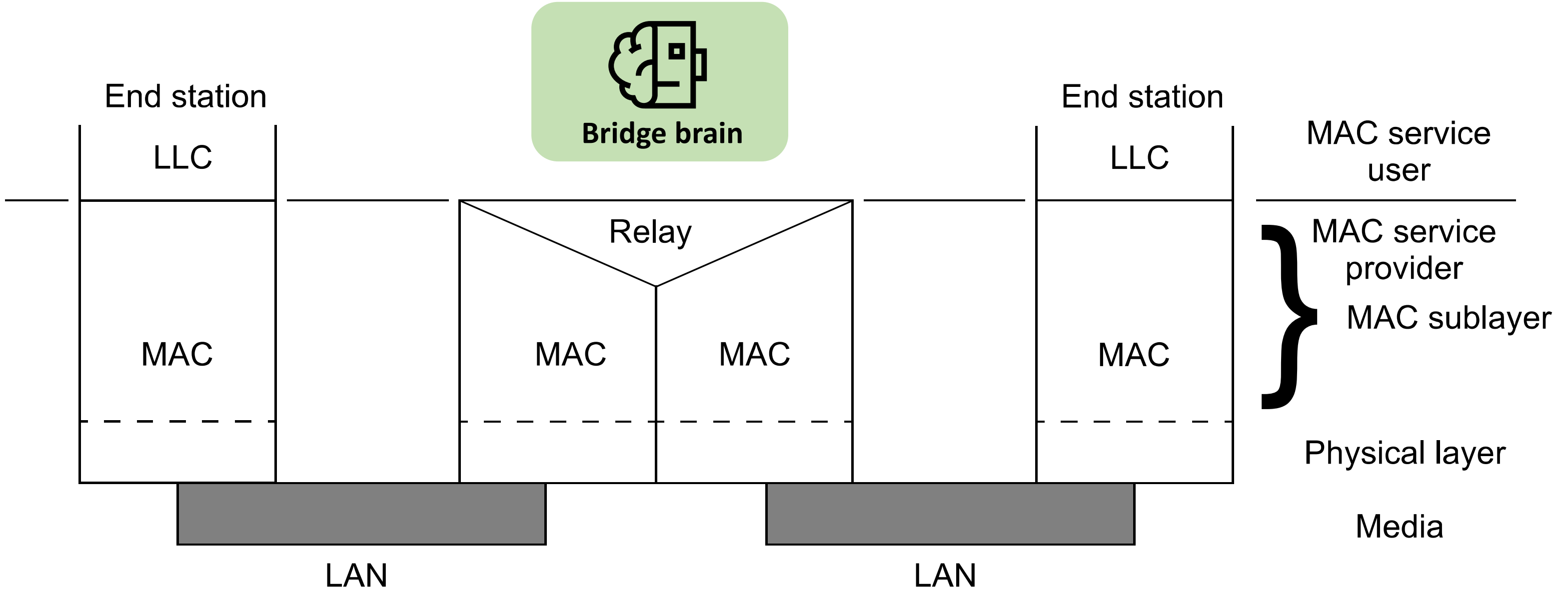


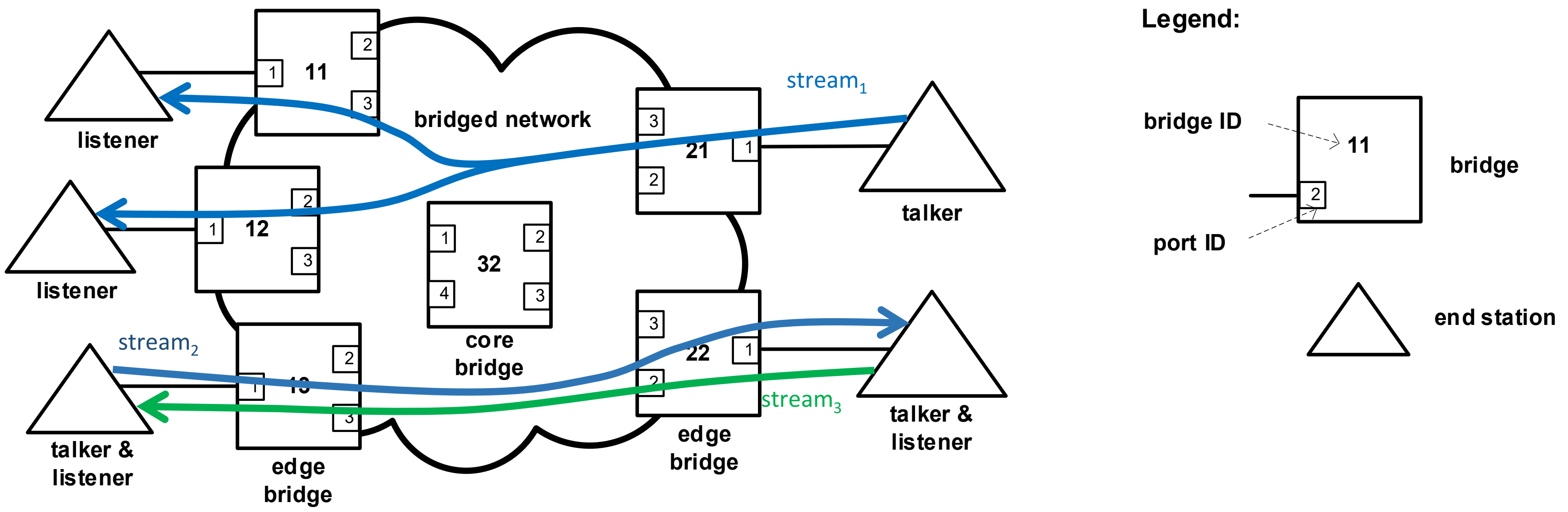
Figure 7 - IEEE Std 802

Fundamental Components

From the IEEE Std 802.1Q perspective, the world is divided into two types of devices: bridges and end stations

- Talker: The end station that is the source or producer of a stream
- Listener: The end station that is the destination, receiver, or consumer of a stream

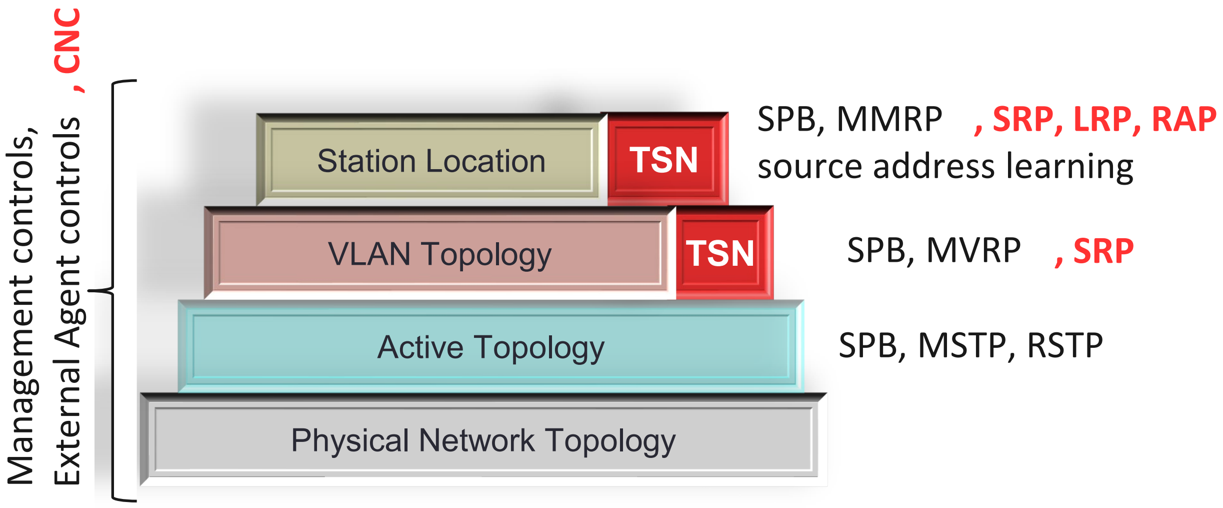
Stream: A unidirectional flow of data from a Talker to one or more Listeners



VLAN Bridging is the foundation

TSN extends IEEE 802.1 bridging

Bridging basics still apply!



SRP: Stream Reservation Protocol
LRP: Link-local Registration Protocol
RAP: Resource Allocation Protocol

RSTP: Rapid Spanning Tree Protocol
MSTP: Multiple Spanning Tree Protocol
SPB: Shortest Path Bridging
MVRP: Multiple VLAN Registration Protocol
MMRP: Multiple MAC Registration Protocol

Introduction to Time-Sensitive Networking

János Farkas

Digital Transformation through IEEE 802.1 TSN

Some Use Cases (incomplete)

IEEE 802.1 Time-Sensitive Networking (TSN)

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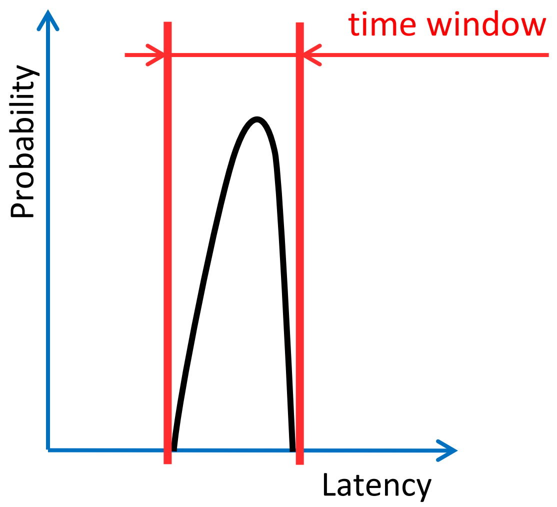
The Right Packet at The Right Time

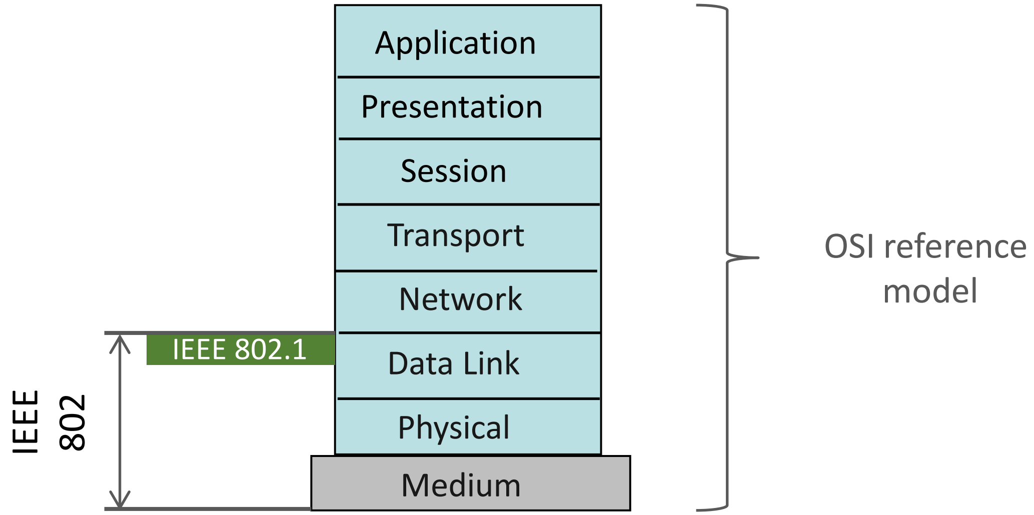
Deterministic data packet delivery

- Data packet delivery within a time window without loss or delay due to congestion or errors



TSN is a set of standards specified by IEEE 802 to provide deterministic data transfer in packet networks, e.g., in Layer 2 bridged networks

- All the benefits of open IEEE SA standards
- Standard Ethernet: IEEE Std 802.3



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TSN Time-Sensitive Networking Powered by IEEE 802

TSN Components and Profiles

Audio Video Bridging [802.1BA/Revision]	Fronthaul [802.1CM/de]	Industrial Automation [IEC/IEEE 60802]	Automotive In-Vehicle [P802.1DG]	Service Provider [P802.1DF]	Aerospace Onboard [IEEE P802.1DP / SAE AS6675]

TSN Components

(Tools of the TSN toolset)

Time synchronization:
Timing and Synchronization [802.1AS-2020] (a profile of IEEE 1588)
Hot Standby [P802.1ASdm]
YANG [P802.1ASdn]
Inclusive Terminology [P802.1ASdr]
Support for half duplex [P802.1ASds]

→ Synchronization

High availability / Ultra reliability:
Frame Replication and Elimination [802.1CB]
Path Control and Reservation [802.1Qca]
Per-Stream Filtering and Policing [802.1Qci]
Hot Standby [P802.1ASdm]

→ Reliability

Bounded low latency:
Credit Based Shaper [802.1Qav]
Frame Preemption [802.1Qbu & 802.3br]
Scheduled Traffic [802.1Qbv]
Cyclic Queuing and Forwarding [802.1Qch]
Asynchronous Traffic Shaping [802.1Qcr]
Shaper Parameter Settings [P802.1Qdq]
QoS Provisions [P802.1DC]

→ Latency

Dedicated resources & API:
Stream Reservation Protocol [802.1Qat]
Link-local Registration Protocol [802.1CS]
TSN Configuration [802.1Qcc]
Foundational Bridge YANG [802.1Qcp]
YANG for CFM [802.1Qcx]
YANG for LLDP [P802.1ABcu]
YANG for 802.1Qbv/Qbu/Qci [P802.1Qcw]
YANG & MIB for FRER [P802.1CBcv]
Extended Stream Identification [P802.1CBdb]
Resource Allocation Protocol [P802.1Qdd]
TSN Configuration Enhancements [P802.1Qdj]
LLDPv2 for Multiframe Data Units [P802.1ABdh]
Multicast and Local Address Assignment [P802.1CQ]

→ Resource Management

Zero congestion loss = Bounded latency

Note: A 'P' in front of '802.1' indicates an ongoing Project.

TSN Profiles for Various Application Areas

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An IEEE 802.1 TSN Profile specification

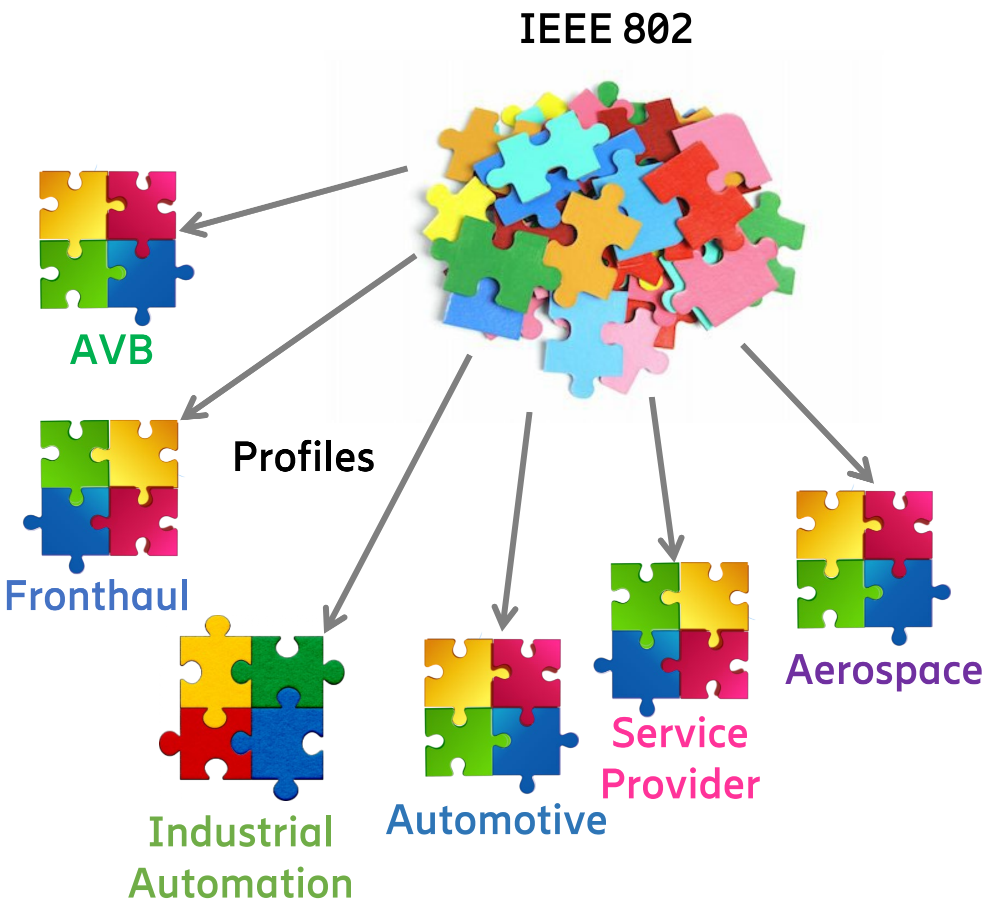
- Selects features, options, defaults, protocols, and procedures

Published IEEE 802.1 TSN profile standards:

- IEEE Std 802.1BA for Audio-Video Bridging (AVB) networks
- IEEE Std 802.1CM TSN for Fronthaul
- IEEE Std 802.1CMde Amendment on enhancements

Ongoing IEEE 802.1 TSN profile projects:

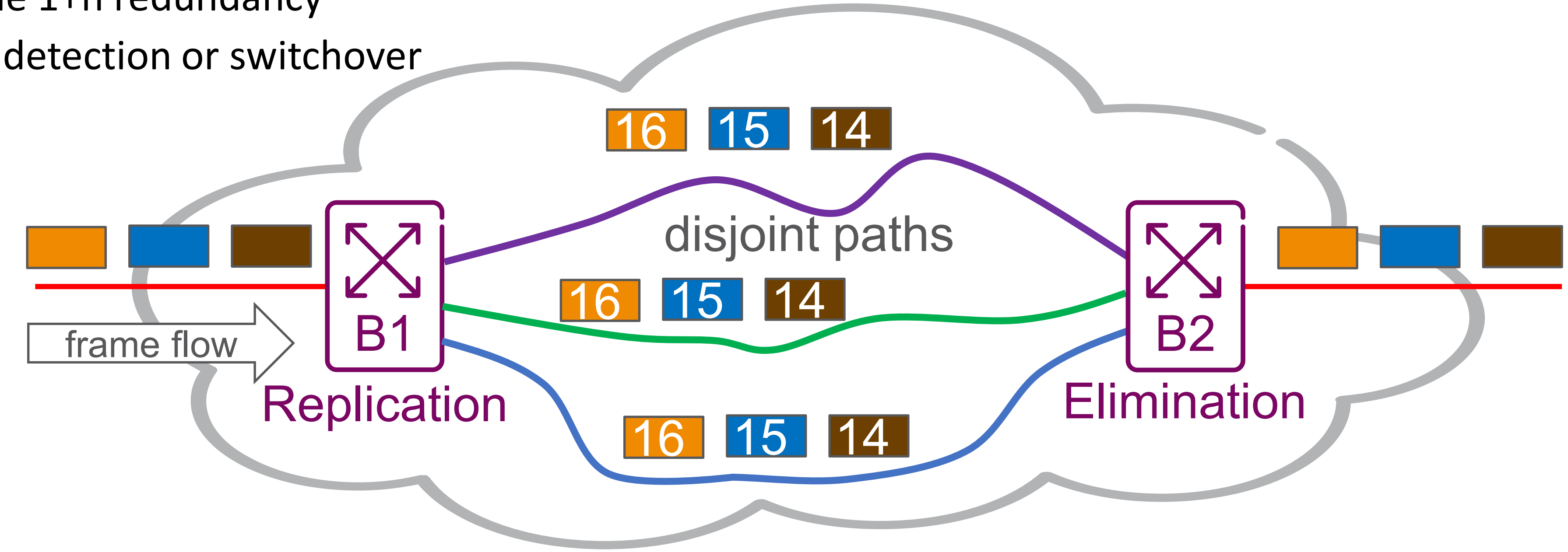
- IEC/IEEE 60802 TSN Profile for Industrial Automation
- P802.1DG TSN Profile for Automotive In-Vehicle Ethernet Communications
- P802.1DF TSN Profile for Service Provider Networks
- P802.1DP / AS6675 TSN Profile for Aerospace onboard Ethernet



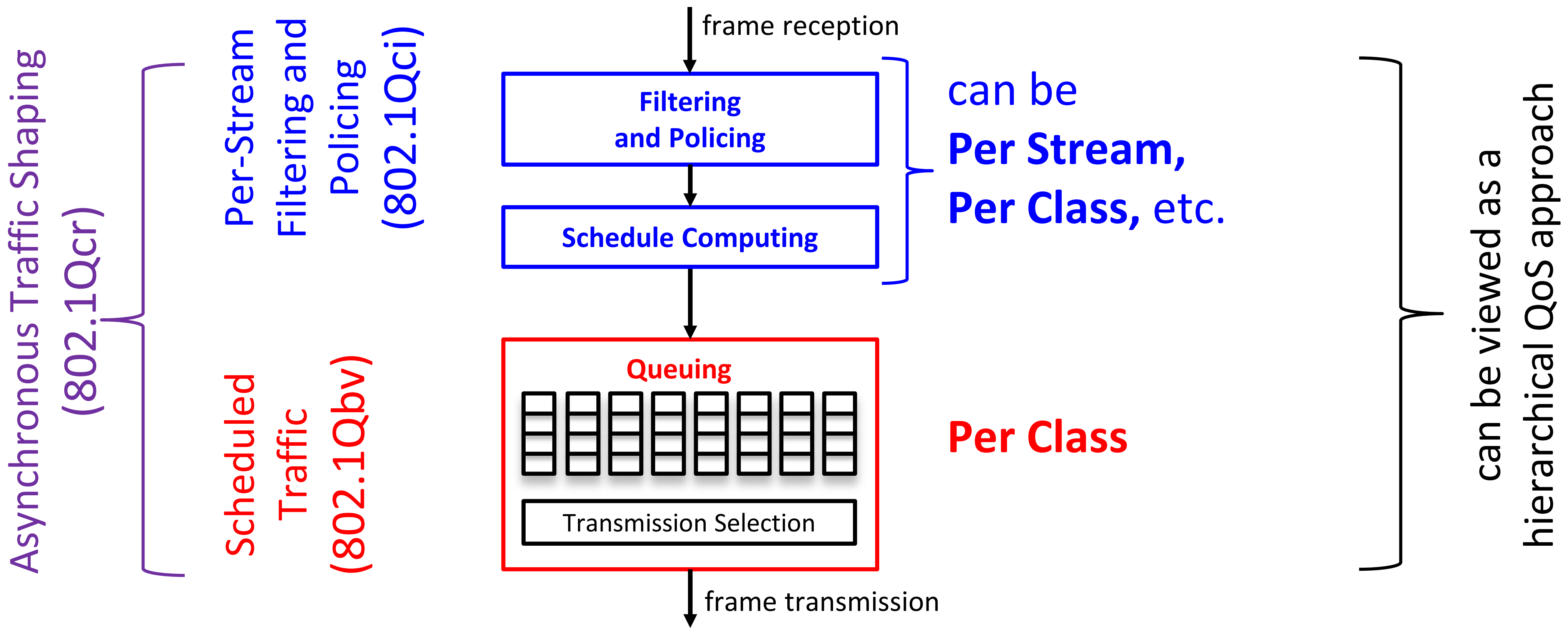
Frame Replication and Elimination for Reliability [802.1CB]

Avoids frame loss due to equipment failure

- Send frames on multiple maximally disjoint paths, then combine and delete extras
- A per-frame 1+n redundancy
- NO failure detection or switchover



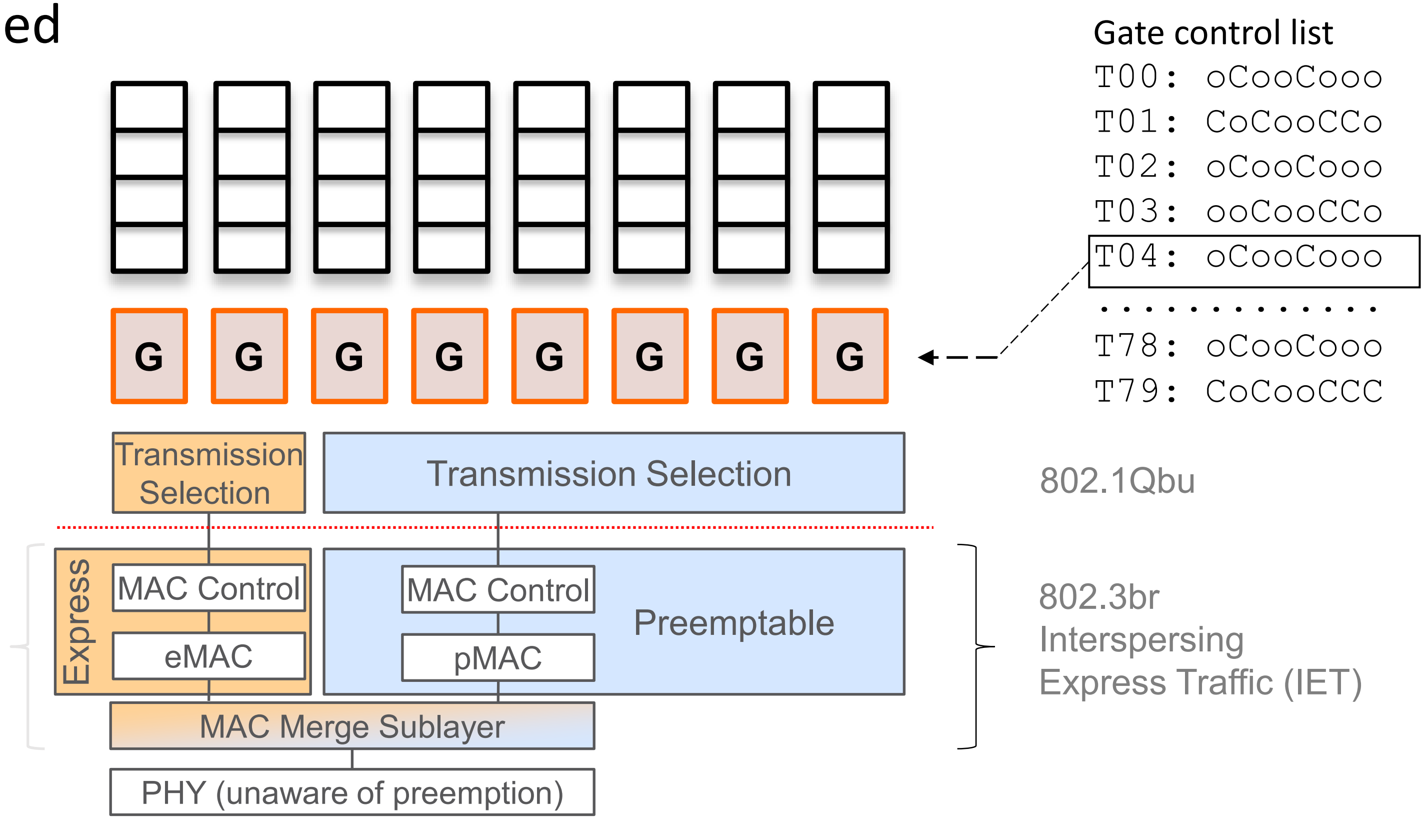
Summary of QoS Functions



note: other functions are not shown in this figure, e.g., MAC relay, reliability

Example Latency Tools: Scheduled Traffic and Frame Preemption Combined

- Scheduled Traffic [802.1Qbv]
  - Time-Gated queues: open or Closed
  - Periodically repeated time schedule (gate control list)
  - Time synchronization is needed
- Frame preemption [802.1Qbu & 802.3br]
  - Express frames can suspend the transmission of preemptable frames while one or more time-critical express frames are transmitted

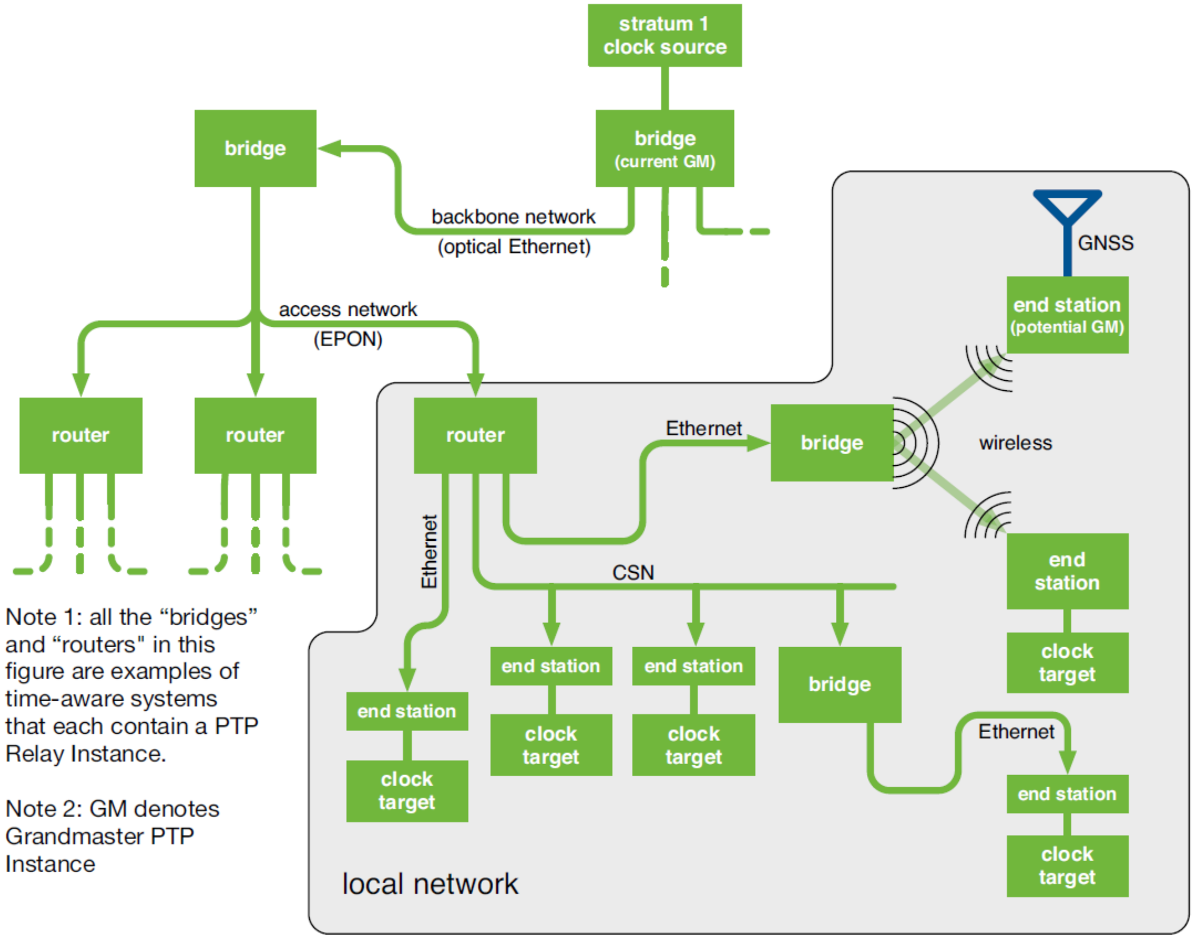


Introduction to the transport of Time Synchronization

Silvana Rodrigues

IEEE 802.1AS Transport of Time Synchronization

- IEEE Std 802.1AS is the TSN standard for the transport of time synchronization
- It includes a PTP profile and performance requirements for audio/video applications
- It specifies transport over full-duplex Ethernet, IEEE 802.11, IEEE 802.3 EPON, and Coordinated Shared Network (e.g., MoCA)
- IEEE 802.1AS-2011 includes a profile of IEEE 1588-2008
- IEEE 802.1AS-2020 includes a profile of IEEE 1588-2019

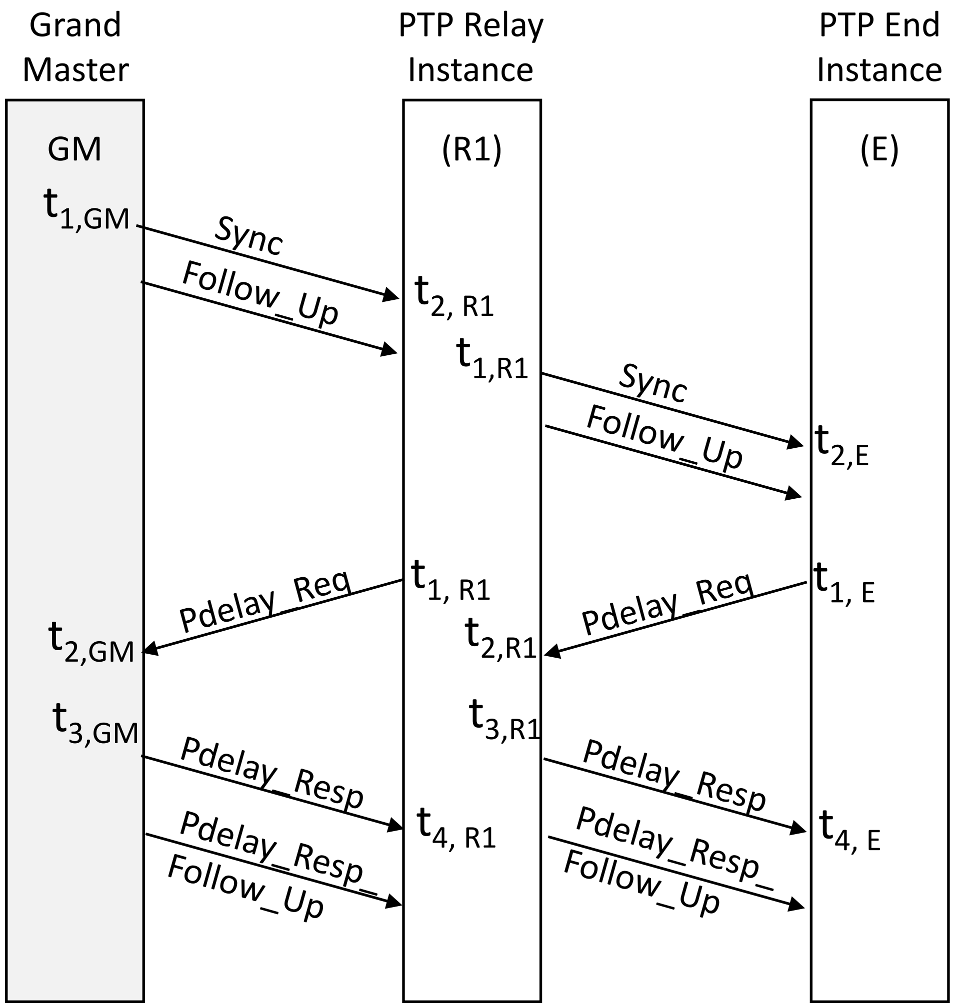


Note 1: all the "bridges" and "routers" in this figure are examples of time-aware systems that each contain a PTP Relay Instance.

Note 2: GM denotes Grandmaster PTP Instance

IEEE 802.1AS

Synchronization Mechanism for full-duplex Ethernet



- Grand Master sends Sync messages containing the GM timestamp in one-step clock. If two-step clock, then timestamp is sent in separate Follow_Up message associated with the Sync message
- PTP Relay instance R1 receives and timestamps Sync message relative to local clock
  - R1 computes the offset relative to GM and uses it to compute the time relative to GM at the reception of Sync message
- R1 sends the sync message containing the GM time to the PTP End station.
  - GM time is based on the computed GM time of the most recent Sync message received, the accumulated rate ratio relative to the GM, and the residence time ($t_{1,R1}$-$t_{2,R1}$)
- PTP End Instance may filter the GM time
- Mean Link Delay (D) is computed for each independent link, and neighborRateRatio (r) is computed at the peer delay initiator. They are both based on Pdelay mechanism

$$D = \frac{r \cdot (t_4 - t_1) - (t_3 - t_2)}{2} \qquad r = \frac{t_3(N) - t_3(0)}{t_4(N) - t_4(0)}$$

"0" refers to an initial Pdelay exchange
"N" refers to N Pdelay exchanges later

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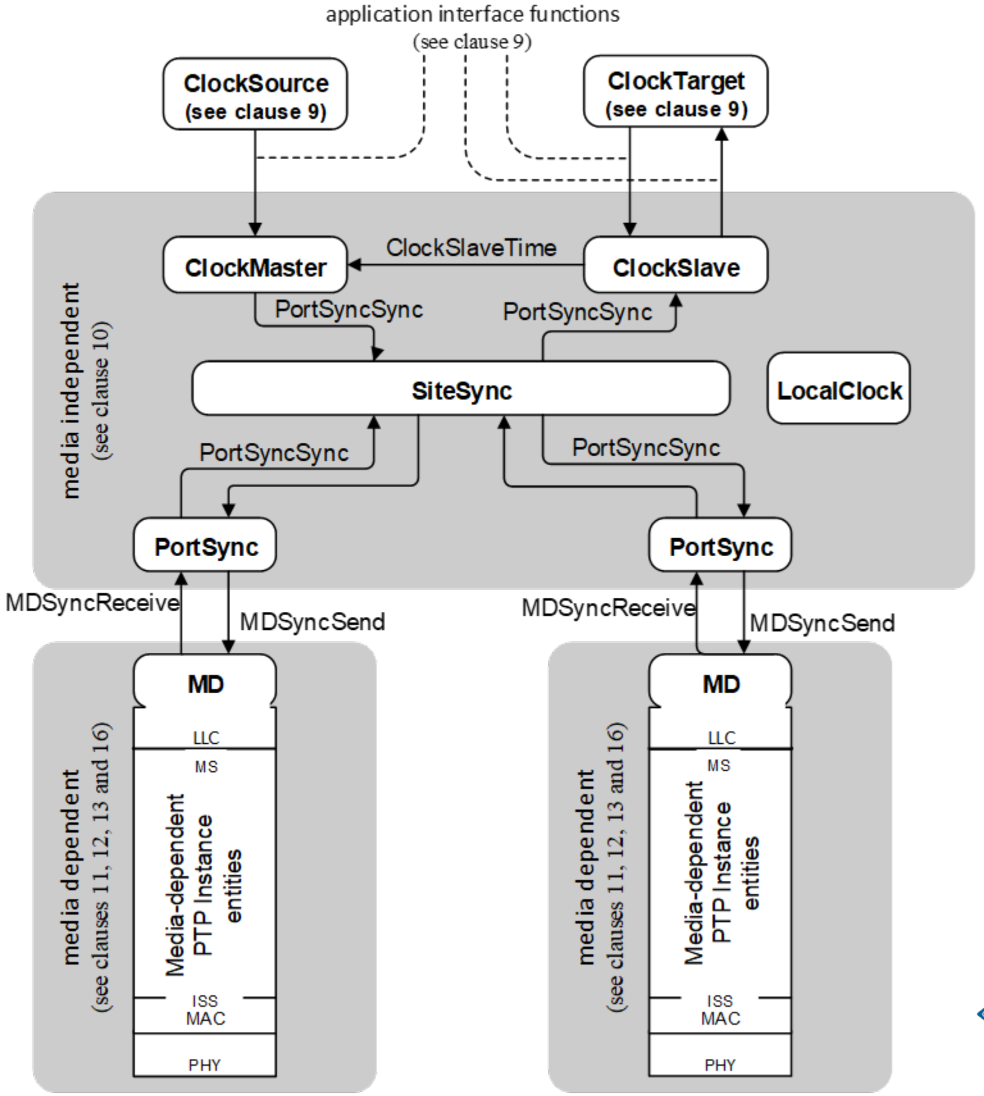
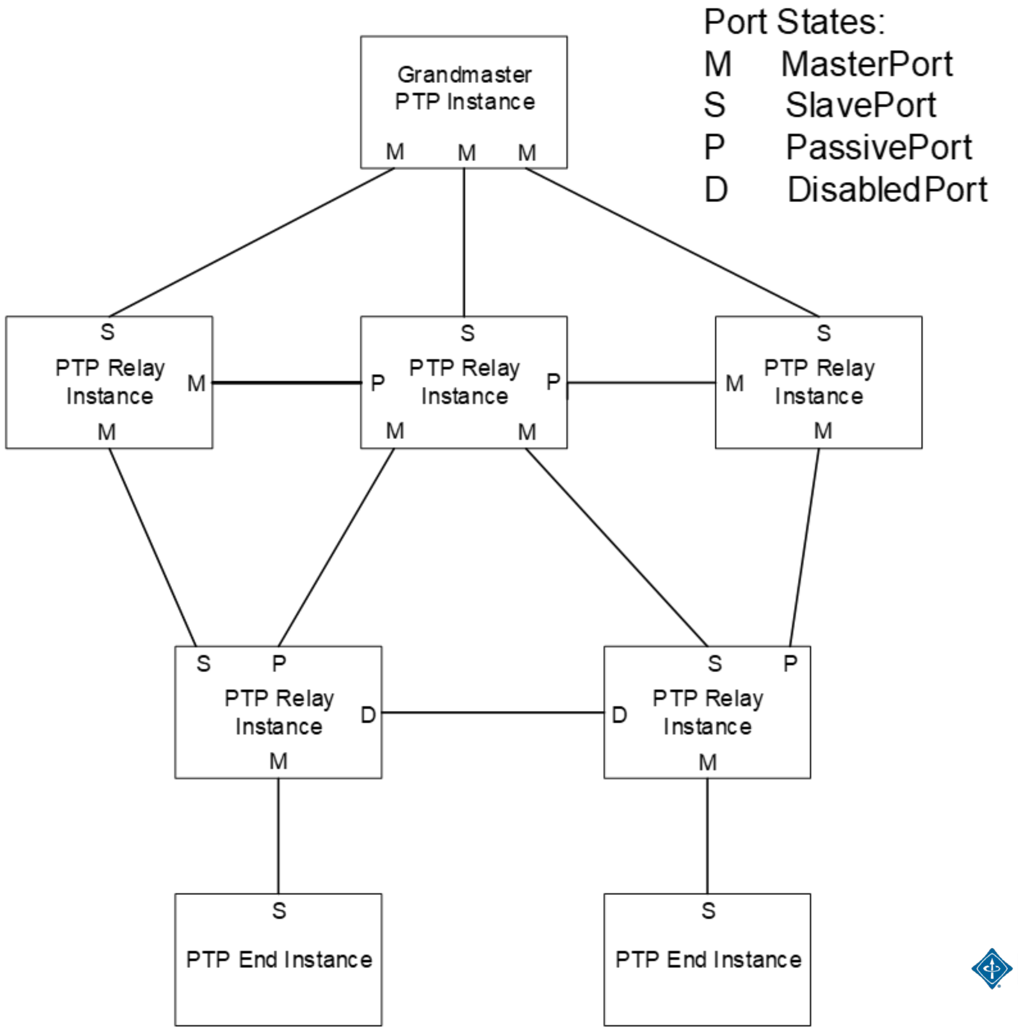
IEEE 802.1AS PTP Architecture Layering



- 802.1AS architecture is divided into media-independent and media-dependent layers
- This division was made because certain media, e.g., IEEE 802.11, IEEE 802.3 EPON, Coordinated Shared Network (e.g., MoCA), have inherent time transport mechanisms (i.e., other than IEEE 1588)
- Primitives are used to transfer media-independent information between the media-independent and media-dependent layers
  - The needed information is provided by the media-dependent layer in a common format
- The architecture also defines common (abstract) application interfaces

IEEE 802.1AS
PTP Synchronization Spanning Tree



- 802.1AS uses the 1588 Best Master Clock Algorithm (BMCA) to form the synchronization hierarchy, i.e., spanning tree
- The BMCA is functionally equivalent to the portion of 802.1Q Rapid Spanning Tree Protocol (RSTP) that sets the 802.1Q port roles (called port states in 1588 and 802.1AS)
  - Note: It is planned to replace the terms master and slave with alternate terms, which will be recommended by an amendment to IEEE 1588-2019, that are more inclusive

802.1/1588 Port States

802.1AS/1588	Corresponding 802.1Q terminology
MasterPort	Designated Port
SlavePort	Root Port
PassivePort	Alternate Port

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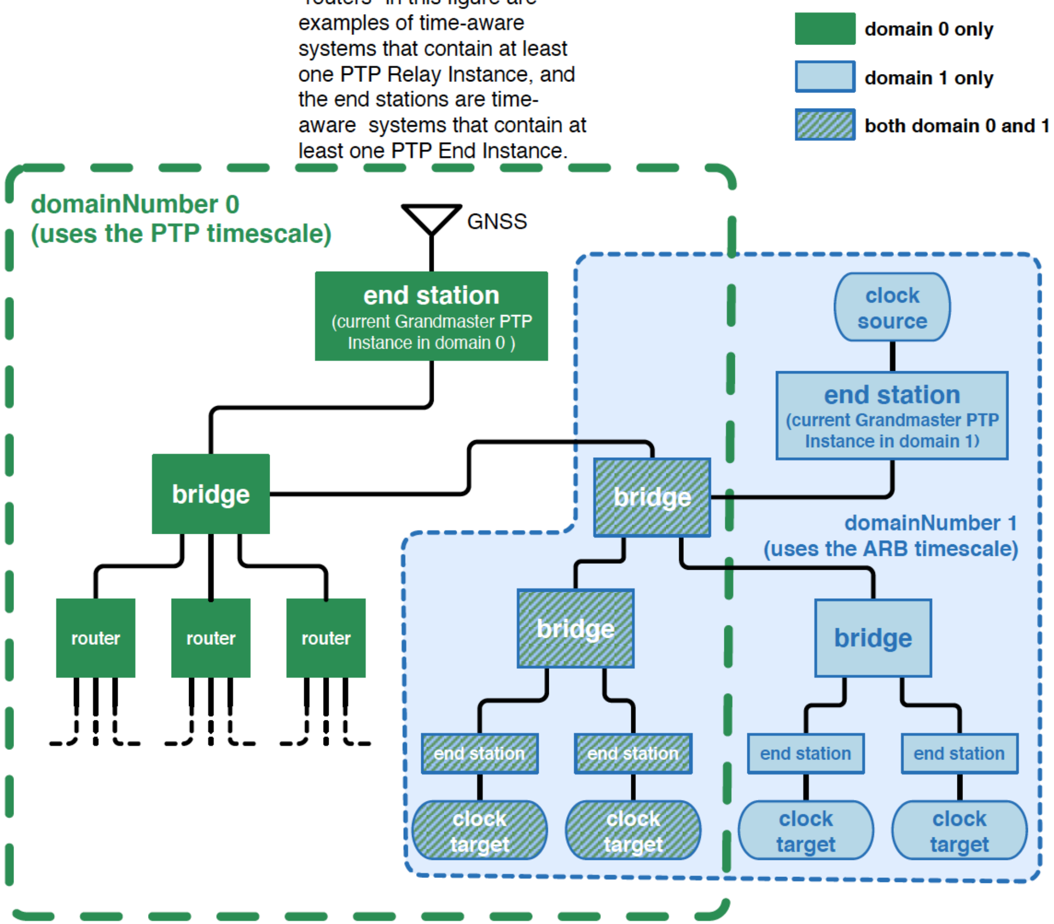
New Features of IEEE Std 802.1AS-2020

- External port configuration
  - Alternative to BMCA; can be used with external mechanism to form the synchronization spanning tree
- Fine Timing Measurement (FTM) for 802.11 transport
  - Provides improved time accuracy compared to Timing Measurement (TM) used in 802.1AS-2011
- Management support for delay asymmetry measurement (using line-swapping)
- Multiple domains (1588-2008 allowed multiple domains, but 802.1AS-2011 was limited to a single domain (domain 0))
- Common mean link delay service to make mean link delay measurements that are common across all domains
- One-step ports (1588-2008 allowed one-step clocks, but 802.1AS-2011 was limited to two-step)
- Automatic signaling of 802.1AS capability and determination of whether the port at the other end of the link is capable of executing the 802.1AS protocol

Note: all the "bridges" and "routers" in this figure are examples of time-aware systems that contain at least one PTP Relay Instance, and the end stations are time-aware systems that contain at least one PTP End Instance.

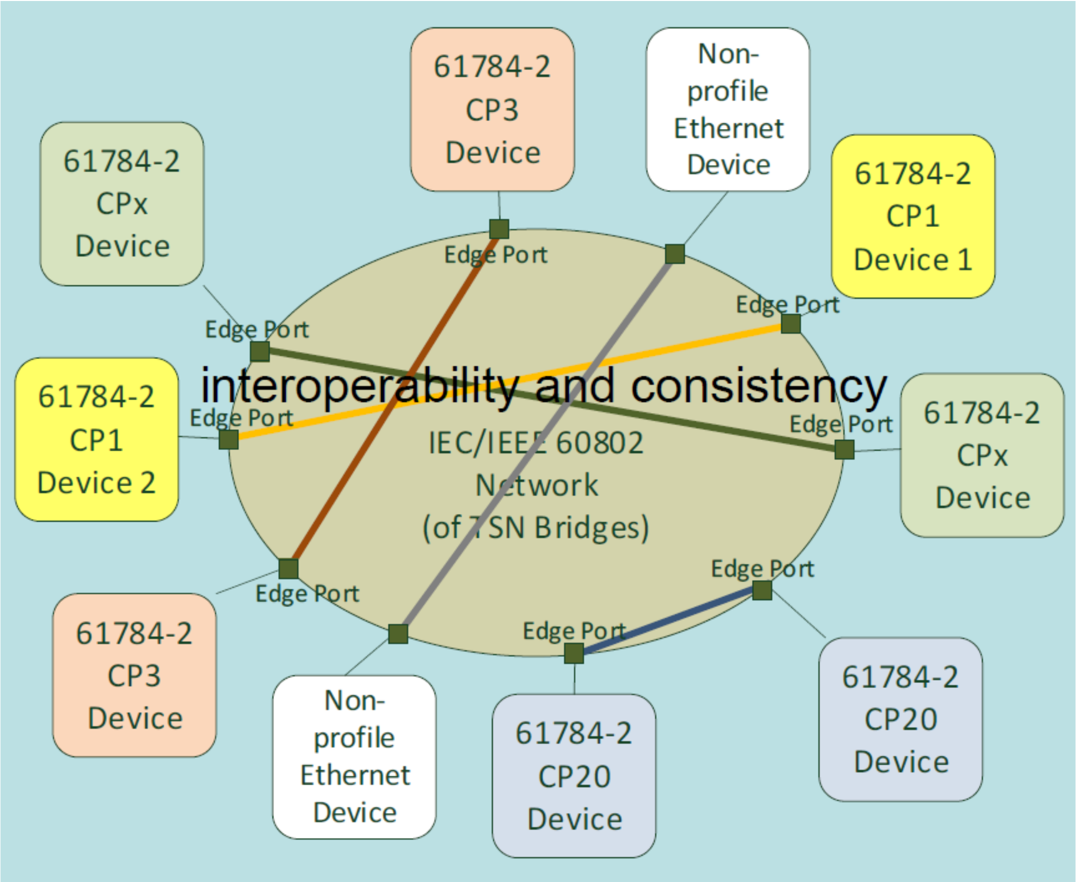


Introduction to the TSN Profile for Industrial Automation

Jordon Woods

IEC/IEEE 60802 TSN Profile for Industrial Automation

- Time-Sensitive Networking technology provides the features required for industrial networks:
  - Meeting low latency and latency variation requirements concerning data transmission.
  - Efficient exchange of data records on a frequent time period.
  - Reliable communications with calculable downtime.
  - High availability meeting application requirements
- The 60802 Profile selects "features, options, configurations, defaults, protocols, and procedures of bridges, end stations, and LANs to build industrial automation networks."



IA Networking Requirements

- **Scalability**
  - Bandwidth – 10 Mbps to 1 Gbps (2.5 / 5 / 10 Gbps for network infrastructure)
  - Network size – from tens of infrastructure devices to hundreds of infrastructure devices
- **Convergence**
  - Blending of existing non-scheduled technologies and products within a new, deterministic technologies
  - Manage low priority or interfering traffic to ensure on-time delivery of high priority traffic
- **Security**
  - Protect the integrity and availability of data
  - Tested and Validated Architectures
- **Performance**
  - Able to support from human response times to hundreds of axes of motion (drives)
- **Flexible Topologies**
  - Ring, line, star, redundant star to address physical constraints
- **Low/Bounded Latency**
  - Able to support <1ms for motion

Introduction to the TSN Profile for Automotive

Max Turner

Automotive Ethernet History

- First Ethernet series production rollout in 2008 to reduce increasing time needed to update the software on Head-Unit and Rear-Seat Entertainment
- Rudimental intra-vehicle (classic) Autosar support from R4.0 (ca. 2009)
- Development of SOME/IP as an intra-vehicle communication protocol from around 2011
- Full TCP/IP stack (classic) Autosar support from R4.1 (ca. 2012)
- ISO13400: “Diagnostic communication over Internet Protocol (DoIP)” published in 2012
- Next came IEEE1722, AVB, AVnu, OPEN Alliance, adaptive Autosar, ...
- ... and the rest is history ...

P802.1DG TSN Profile for Automotive In-Vehicle Ethernet

"This standard specifies profiles for secure, highly reliable, deterministic latency, automotive in-vehicle bridged IEEE 802.3 Ethernet networks based on IEEE 802.1 Time-Sensitive Networking (TSN) standards and IEEE 802.1 Security standards."

- Targeting Ethernet networks to support wired intra-vehicle applications for privately owned passenger vehicles (i.e. not focussed on robo-taxis, trucks, or busses and not considering backend, cellular, WiFi, smart charge, or OBD communication)
- While for any one car the network is a rather static after production, but 100's of networks are built in any one OEM's manufacturing plant daily with dependencies on options, variants and vehicle model generations
- Start-Up times (2 sec.) drive discovery and security use-cases
- Network diameters are small (<10 hops), but vary with options
- Coexistence with other systems (I^2C, FlexRay, CAN, A2B, ...)*) is very important
- Network resources are limited (buffer, compute, and line rate, i.e. 10BASE-T1S)
- Zonal-Architecture promises new options in network scaleability

*) Potential Trade-Marks apply, but not explicitly stated

Source of this picture: Don Pannell, NXP Semiconductors, dg-pannell-ChoosingTheRightTSNToolsToMeetABoundedLatency-whitePaper-0821-v01

Introduction to the TSN Profile for Aerospace

Abdul Jabbar

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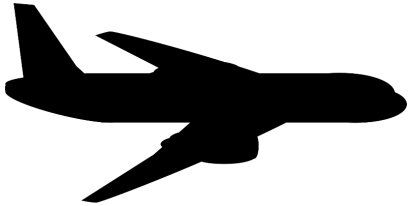
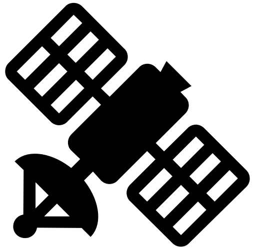
Aerospace Requirements

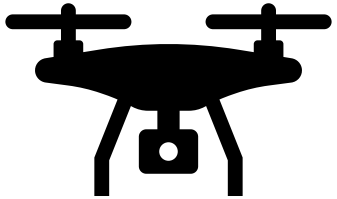


Fixed Wing Aircraft
- Control Domain Network (ACD)
- Cabin Network (AISD, PIESD)

Rotary Wing Aircraft
- Mission Network
- Flight Network



Satellite
- Platform Network
- Payload Network



Unmanned Aerial Vehicle
- Mission Network
- Flight Network

Characteristic	Requirement Bounds	
	Left Bound	*Right Bound*
Number of nodes	5	100 (500*)
Number of hops	0	5 (15*)
Data rate	10 Kbps	1 Gbps (100 Gpbs)
Synchronicity	Synchronous	Asynchronous
Periodicity	5 msec (1 msec*)	Aperiodic
Delivery guarantee mode	Deadline, Latency, Bandwidth	
Latency	1 msec (100usec*)	150 msec
Delay variation (jitter)	< 1 usec	Up to latency limit
Tolerance to loss	none	10 consecutive frames
Payload size	8 Bytes	2112 Bytes

** future requirement*

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Aerospace TSN Profile Approach

Asynchronous Profile

targets current Ethernet based use cases

- Asynchronous operation with slower cycle times (> 50 msec)
- Latency bounded with acceptable jitter up to latency bound
- Comfortable with rate constrained shaping
- Simple A/B network redundancy
- Controlled network- single criticality traffic
- Engineering, static, controlled network
- Certification burden is significant – simplicity is valuable

Synchronous Profile

targets non-ethernet and future use cases

- Synchronous operation with faster cycle times (1 msec or lower)
- Sensitive to latency (or deadline) and delay variation (jitter)
- Rate constrained and time aware shaping
- Flexible redundancy
- Convergence of mixed critical traffic
- Potential for dynamic (re)configuration
- Focused on high performance, converged, interoperable TSN backbone

Imagine the opportunities possible if networking was instant and reliable, between people and things that matter, when and where it matters most.

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Further Information

- IEEE 802.1 Working Group website - http://ieee802.org/1
- IEEE 802.1 TSN webinar series - https://engagestandards.ieee.org/TSN-Webinar-Series.html
- How Time-Sensitive Networking Benefits Fronthaul Transport: https://beyondstandards.ieee.org/how-time-sensitive-networking-benefits-fronthaul-transport/
- IEEE 802.1AS-2020 Standard Fuels Growth of Industrial Automation, Automotive Networking, and 5G Applications: https://beyondstandards.ieee.org/ieee-802-1as-2020-standard-fuels-growth-of-industrial-automation-automotive-networking-and-5g-applications/
- TSN feature topic of the June 2018 Issue of IEEE Communications Standards Magazine https://ieeexplore.ieee.org/document/8412457
- Tutorial on TSN at IETF 99 https://datatracker.ietf.org/meeting/99/materials/slides-99-edu-sessf-time-sensitive-networking-tutorial-english-language-janos-farkas-norman-finn-patricia-thaler
- Tutorial on IEEE 802 Ethernet Networks for Automotive http://www.ieee802.org/802_tutorials/2017-07/tutorial-Automotive-Ethernet-0717-v02.pdf
- “Heterogeneous Networks for Audio and Video: Using IEEE 802.1 Audio Video Bridging” http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=6595589
- Tutorial on IEEE 802.3br Interspersing Express Traffic (IET) and IEEE 802.1 Time-Sensitive Networking http://www.ieee802.org/802_tutorials/2015-03/8023-IET-TF-1501-Winkel-Tutorial-20150115_r06.pptx
- Tutorial on Deterministic Ethernet http://www.ieee802.org/802_tutorials/2012-11/8021-tutorial-final-v4.pdf
- Tutorial on IEEE 802.1Q at IETF 86 https://www6.ietf.org/meeting/86/tutorials/86-IEEE-8021-Thaler.pdf
- Paper on 802.1Q bridging https://www.ieee802.org/1/files/public/docs2014/Q-farkas-SDN-support-0314-v01.pdf