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DI PADOVA

L'evoluzione del *Time Sensitive Networking (TSN)*

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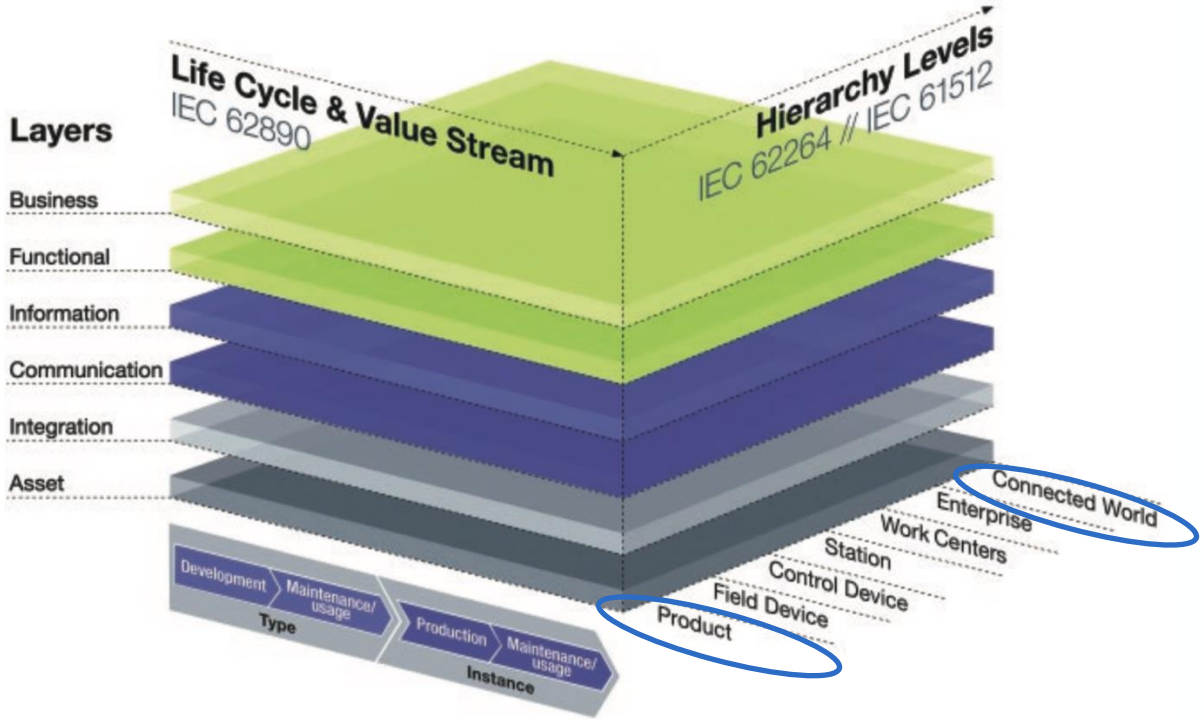
Background about Industry4.0 & IIoT

Industry 4.0 reference architecture

Industrie 4.0 is a specialization of the concept of «Internet of Things and Services»



Expansion of the hierarchy levels (IEC 62264)

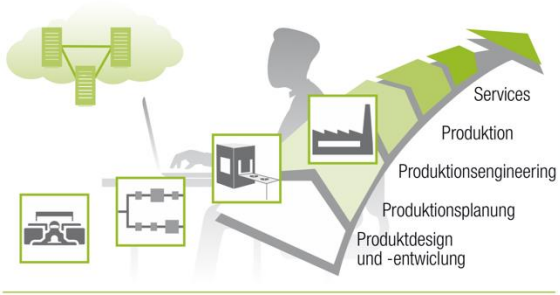
Specific «Product» or workpiece level

«Connected World» going beyond the boundaries of the individual factory

Industry 4.0 – integration

- I4.0 Aspect (1) Horizontal integration through value networks

- I4.0 Aspect (2) Vertical integration
  e. g. within a factory
  or production shop



- I4.0 Aspect (3) Life cycle management, and end–to–end engineering

- I4.0 Aspect (4) Human beings orchestrating the value stream

Common Fieldbus Technologies

Historical «Fieldbus War»

Reduced Interoperability & Internetworking

Unsuitable for the Industry 4.0 / IIoT paradigms

Real-Time (or Industrial) Ethernet

ETHERNET POWERLINK

PROFINET

SERCOS interface

EtherCAT

CC-Link IE Control

EtherNet/IP

«RTE War»?

Synergies with the ICT world → better interoperability

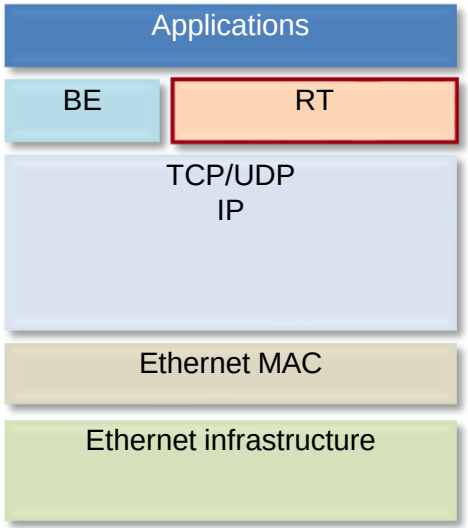
Almost suitable for the Industry 4.0 / IIoT paradigms

But not optimal!

Classification of RTE

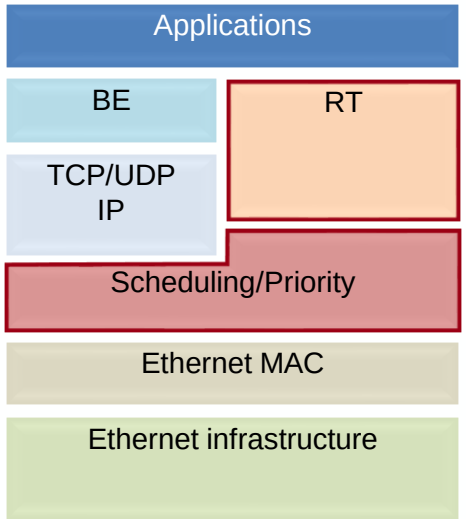
- Three conformance classes can be identified for RTE

Class 1



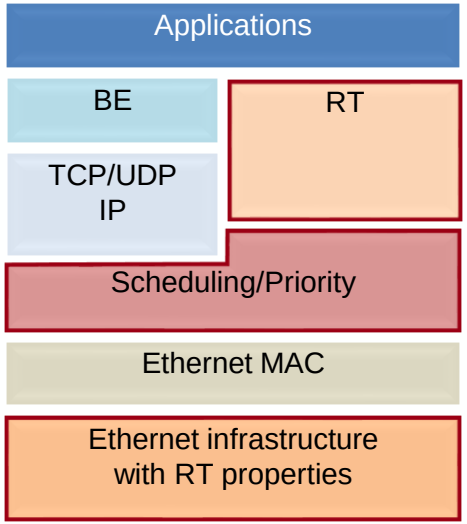
The traffic pertaining to the field level must be kept strictly under control exploiting standard traffic confinement mechanisms (IP multicast, VLANs, ecc.)

Class 2



Double protocol stack (TCP/IP + RT stack)
Communication drivers and protocol stacks are likely required to be modified

Class 3



"Reserved lane" for hard-real-time traffic. Purposely designed switches. Often, modified network topology & technology.

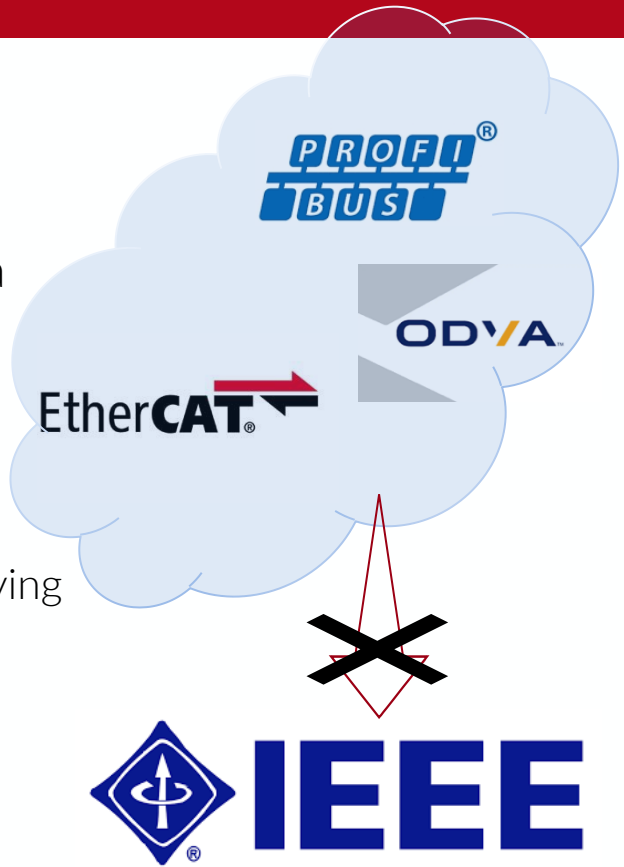
The need for a novel solution

Why developing a «new» standard?

- Industrial Ethernet are based on the use of a standardized and widespread communication protocol
  - Able to enhance fieldbus performance
- However, unless strict traffic and access controls are implemented, standard Ethernet is unable to guarantee the required network latency, reliability and determinism
- The number of different solutions quickly diverged…
  - As well as the different implementation approaches!
- This impaired interoperability, convergence, integration/implementation costs
  - *much like with old fieldbuses*

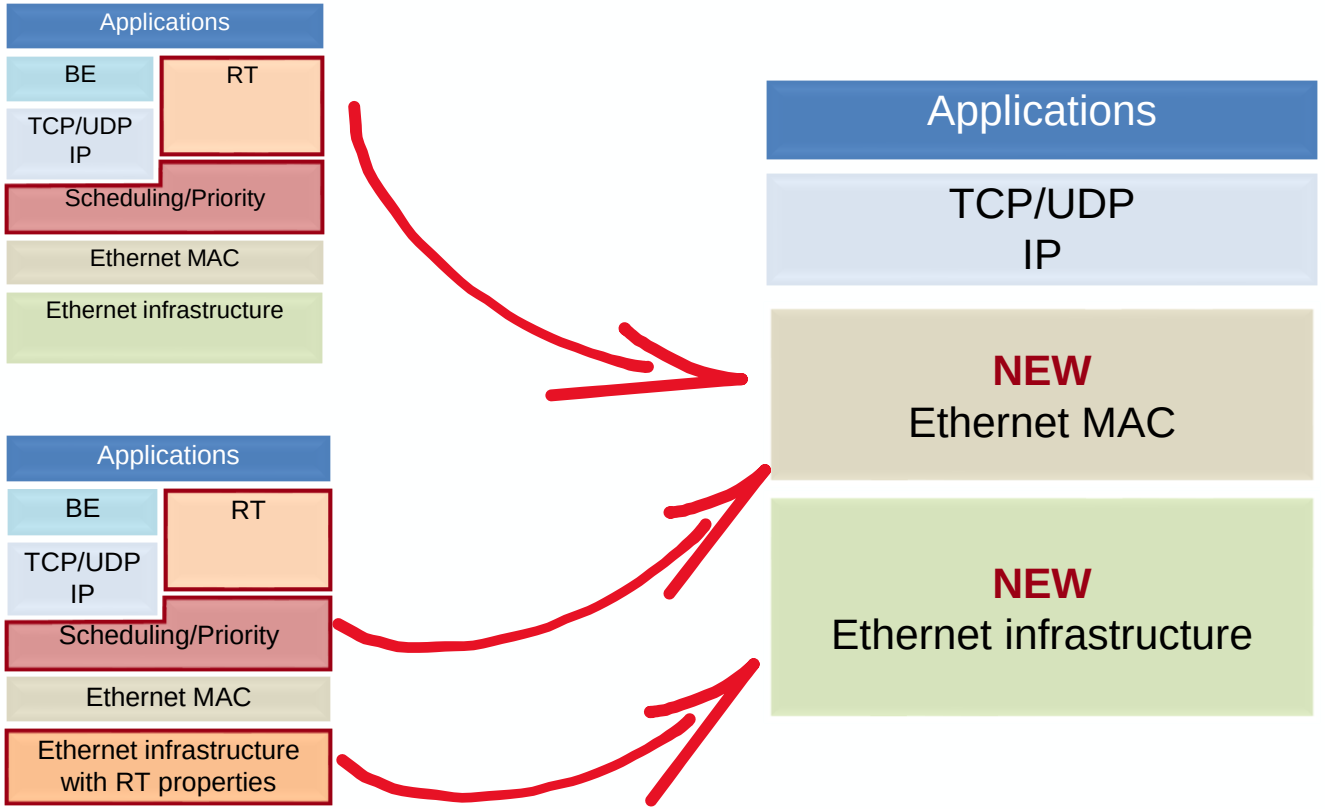
The big issue…

- Different standardization bodies involved
  - One of the major barriers to the realization of a «one fits all» solution
- The design of a new RTE protocol is often carried out by a «consortium»
  - Profibus, ODVA, etc…
- Large industrial pervasiveness and market share
  - But no control over the standardization process of the underlying Ethernet standard
  - So that RTEs are obtained as a sort of «hack» of Ethernet
- The Ethernet standard is defined by IEEE



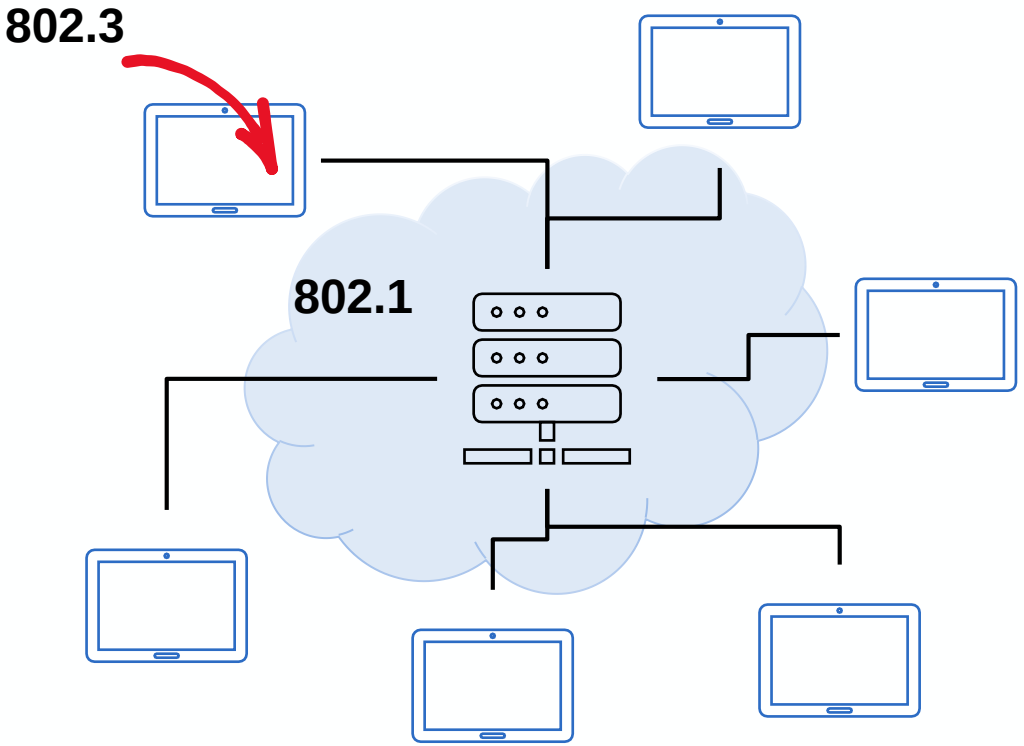
The idea…

- What if we were able to modify the intrinsic behavior of the Ethernet standard?
  - This has to be carried out by (and within) the IEEE standard development!
- IEEE took up this effort, with a strong participation by consortia and component developers



A note about Ethernet LANs

Data Link Layer	802.2 Logical Link Control [IEEE 802.2]			
	802.1 Mac Bridging [IEEE 802.1d]			
Physical Layer	802.3 CSMA/CD [Ethernet]	802.4 Token -Bus	802.5 Token -Ring	802.11 Wireless LAN



A big step forward: AVB

In 2005

- IEEE 802.1 Audio Video Bridging (AVB) Task Group (TG) – Started in 2005
  - Address professional audio, video market
  - Consumer electronics
  - Automotive infotainment
  - AVnu Alliance: associated group for compliance and marketing

Composition of the AVB standard

- IEEE Std. 802.1AS-2011 – generalized Precision Time Protocol (gPTP)
  - Time synchronizing service that is appropriate for the most stringent requirements of consumer electronics applications
  - A Layer 2 profile of the IEEE 1588 Precision Time Protocol (PTP)
  - Note the ongoing P802.1AS-REV project.

CBS + SRP to provide delays under 250 µs per bridge

- IEEE Std 802.1Qat-2010 – Stream Reservation Protocol (SRP)
  - Registration and reservation of time-sensitive streams
  - It is now part of IEEE Std 802.1Q-2018

- IEEE Std. 802.1Qav-2009 – Forwarding and Queuing Enhancements for Time-Sensitive Streams (FQTSS):
  - Specifies Credit-Based Shaper (CBS)
  - It is now part of IEEE Std 802.1Q-2018

- IEEE Std 802.1BA-2011 – Audio Video Bridging (AVB) Systems
  - Provides an overall AVB architecture and AVB profiles

From AVB to TSN

- AVB features become interesting for other use cases, e.g.
  - Industrial
  - Automotive
- AVB was not an appropriate name to cover all use cases
- AVB TG was renamed to TSN TG in 2012
- IEEE 802.1 Time-Sensitive Networking (TSN) TG

TSN Components

Synchronization

- Timing and Sync (802.1AS)
- Revision 802.1AS-Rev

Ultra Reliability

- Frame Repl & Elim (802.1CB)
- Path Control (802.1Qca)
- Per-Stream Filtering (802.1Qci)
- Time sync (P802.1AS-Rev)

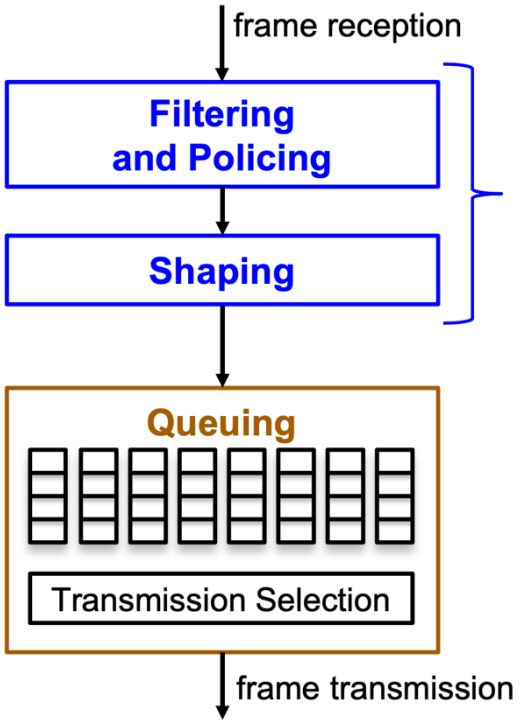
Resource Management

- Stream Resv Prot (802.1Qat)
- TSN configuration (P802.1Qcc)
- YANG (P802.1Qcp, etc.)
- Link-local Resv Prot (P802.1CS)

Bounded Low Latency

- Credit Based Shaper (802.1Qav)
- Preemption (802.3br & 802.1Qbu)
- Scheduled Traffic (802.1Qbv)
- Cyclic Q-ing & Fwd (802.1Qch)
- Async Shaping (P802.1Qcr)

Improved QoS functions



This can be
Per stream
Per class
Etc.

Per class

can be viewed as a hierarchical approach

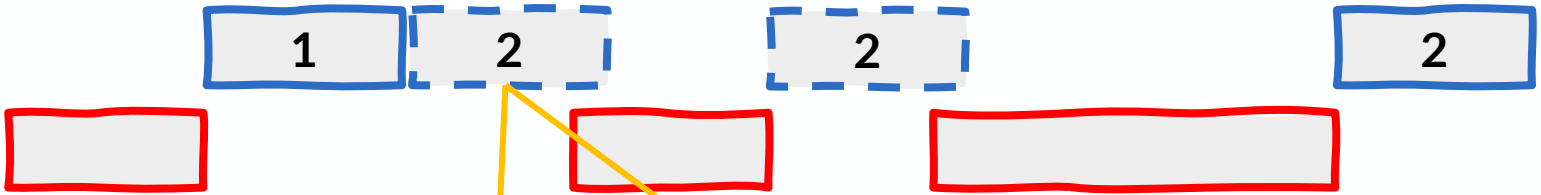
How to enable Real-Time scheduling and transmission by design

- A significant issue with standard Ethernet is the potential conflict between time-critical and non-time-critical frames
- comparing the scenario with the RT operating systems
  - Only a non-preemptive scheduling of frames is allowed
- Standard Ethernet does not support frame preemption!
- SOLUTION: rocks and sand approach
  - Introducing frame preemption capabilities

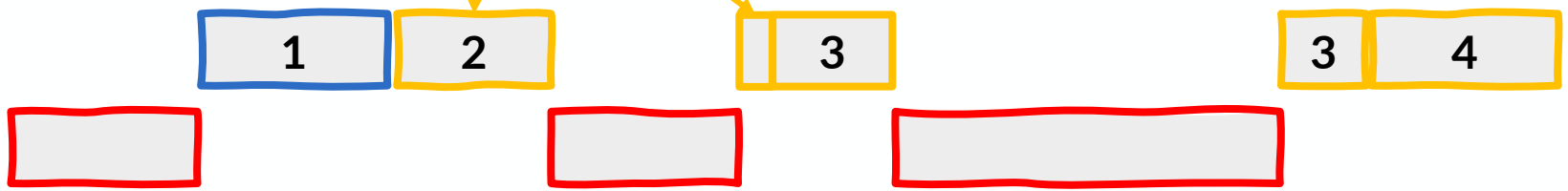
Preemptable frames

- Time-critical (Express) frames suspend the transmission of preemptable frames
- Scheduled rocks of critical packets in each cycle

- Conflict excessively with non-guaranteed packet rocks:

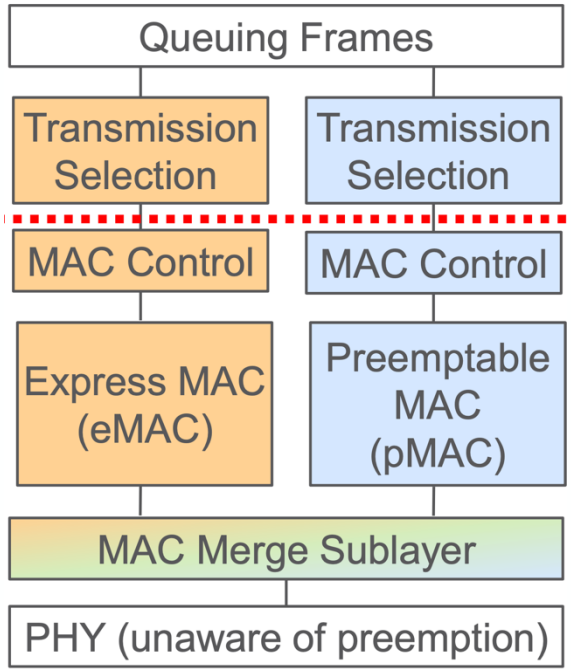


- Problem solved by preemptive sand between the rocks



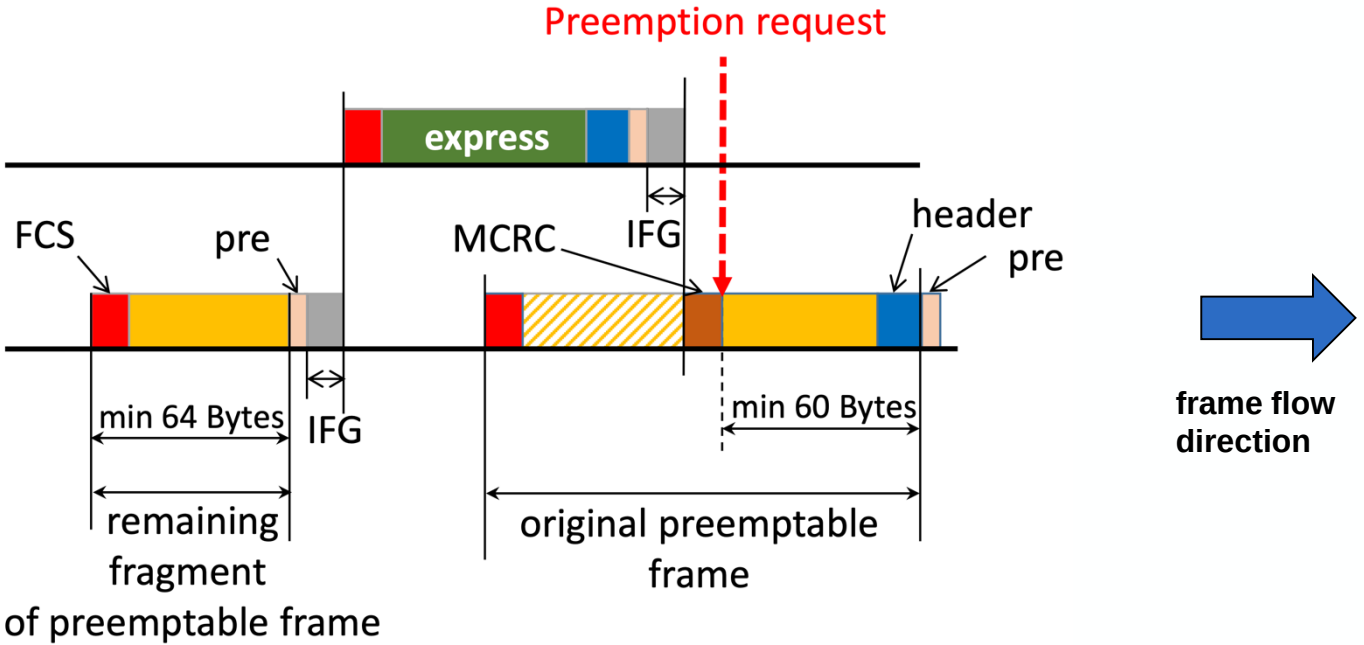
Interspersing Express Traffic & Frame Preemption

- Time-critical frames can suspend the transmission of non-time-critical frames
  - while one or more time-critical frames are transmitted
- Specified by
  - 802.1Qbu – Frame Preemption
  - 802.3br – Interspersing Express Traffic (IET)
- 802.1Qbu makes the adjustments needed in 802.1Q in order to support 802.3br
  - each traffic class queue supported by the Port is assigned a value of frame preemption status
  - the possible values of frame preemption status are express or preemptable
- Minimum fragment size is 64 bytes including CRC



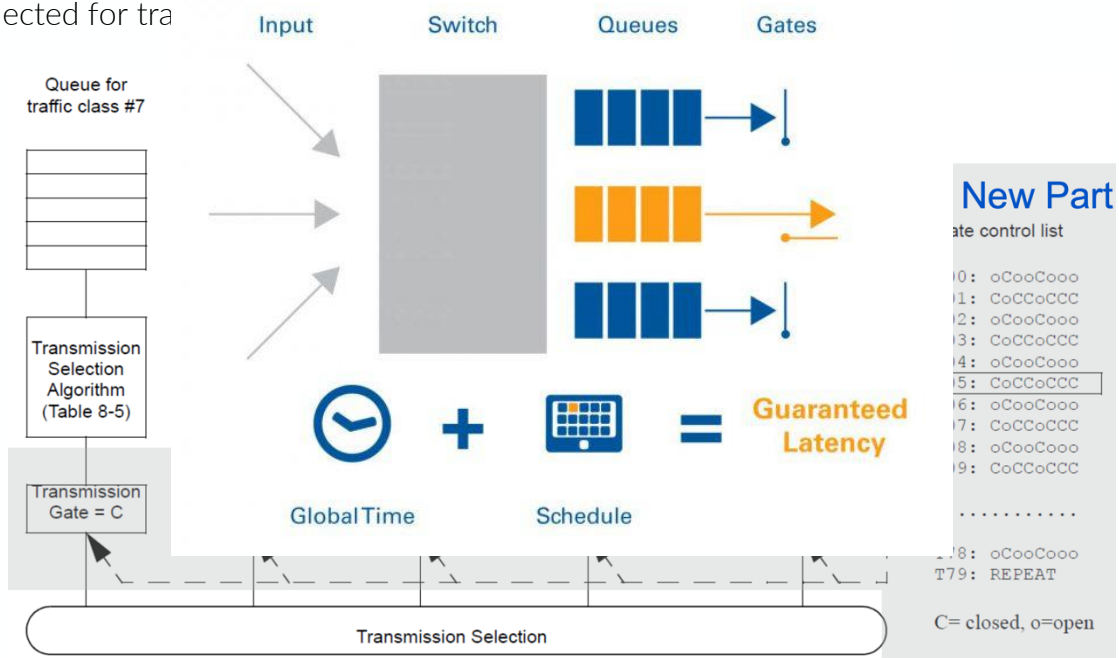
IEEE 802.3br - Interspersing Express Traffic (Frame Preemption)

- Frame preemption implementation
- Express frames can suspend the transmission of preemptable frames

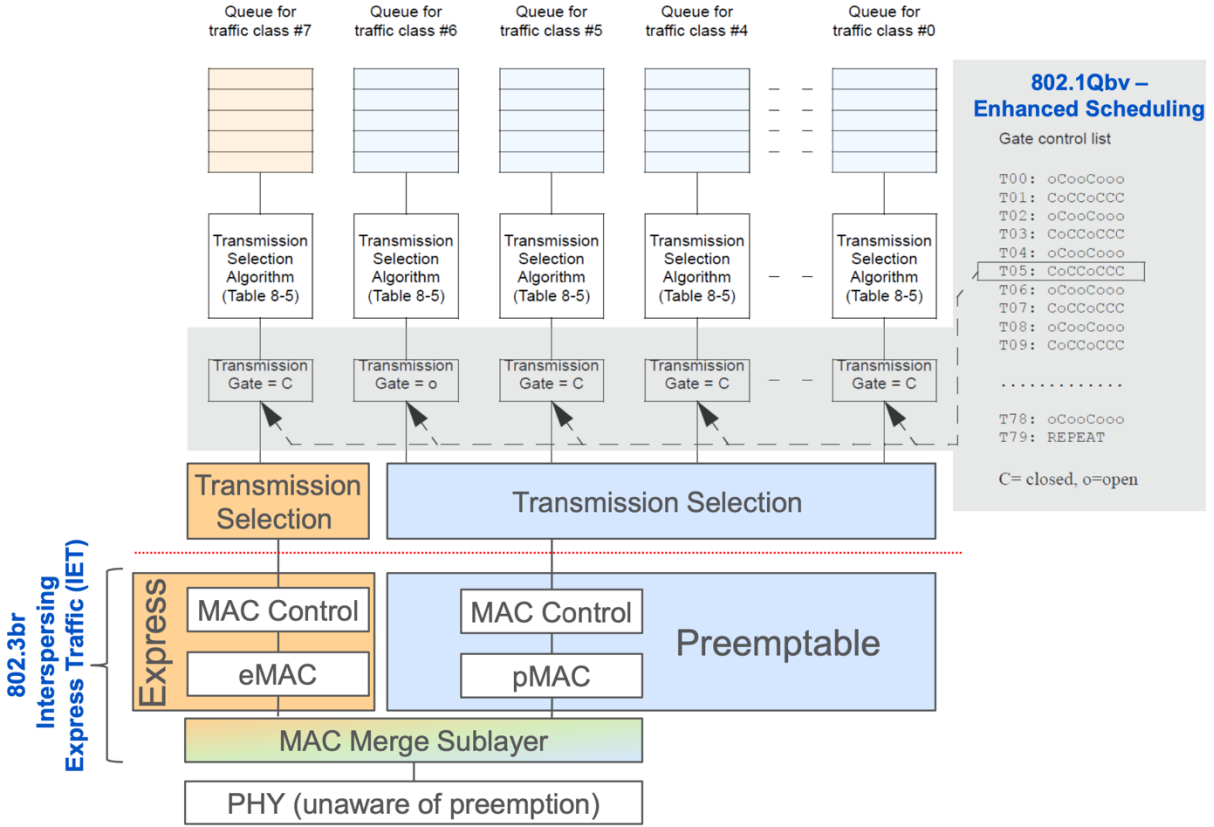


802.1Qbv – Enhancements for Scheduled Traffic

- Transmission from each queue can be scheduled (relative to a known timescale)
- For each queue, a transmissio be selected for transmission
  - Open (O): selected for transmi ssociated with the queue)
  - Closed (C): not selected for tra

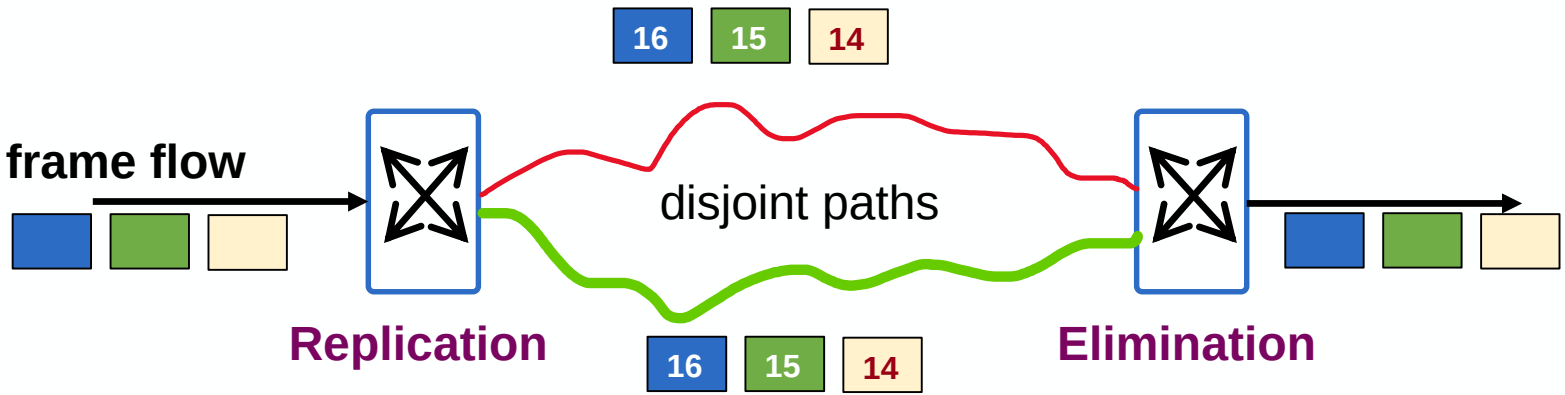


Preemption and Enhanced Scheduling together…



802.1CB – Frame Replication and Elimination for Reliability (FRER)

- Avoid frame loss due to equipment failure
- 802.1CB introduces a per-frame 1+1 (or 1+n) redundancy
  - NO failure detection / switchover
- Send frames on 2 (or more) maximally disjoint paths, then combine and delete extras



Status of the TSN standard: already published

- Most of the aforementioned ones are already published standards
  - IEEE Std 802.1 BA-2011, AX-2014, AB-2016, CB-2017, CM-2018

- Another huge part is represented by the 802.1Q standard
- The following are amendments rolled into IEEE Std 802.1Q-2018:
  - IEEE Std 802.1Qbu-2016: Frame Preemption
  - IEEE Std 802.1Qbv-2015: Enhancements for Scheduled Traffic
  - IEEE Std 802.1Qca-2015: Path Control and Reservation
  - IEEE Std 802.1Qch-2017: Cyclic Queuing and Forwarding
  - IEEE Std 802.1Qci-2017: Per-Stream Filtering and Policing
  - IEEE Std 802.1Qcc-2018: Stream Reservation Protocol (SRP)
  - IEEE Std 802.1Qcp-2018: YANG Data Model
    - This already amends IEEE Std 802.1Q-2018

Status of the TSN standard: revisions of already published standards

- Revision means that a substantial rewrite of the standard, or substantial additions are to be considered with respect to the already available version

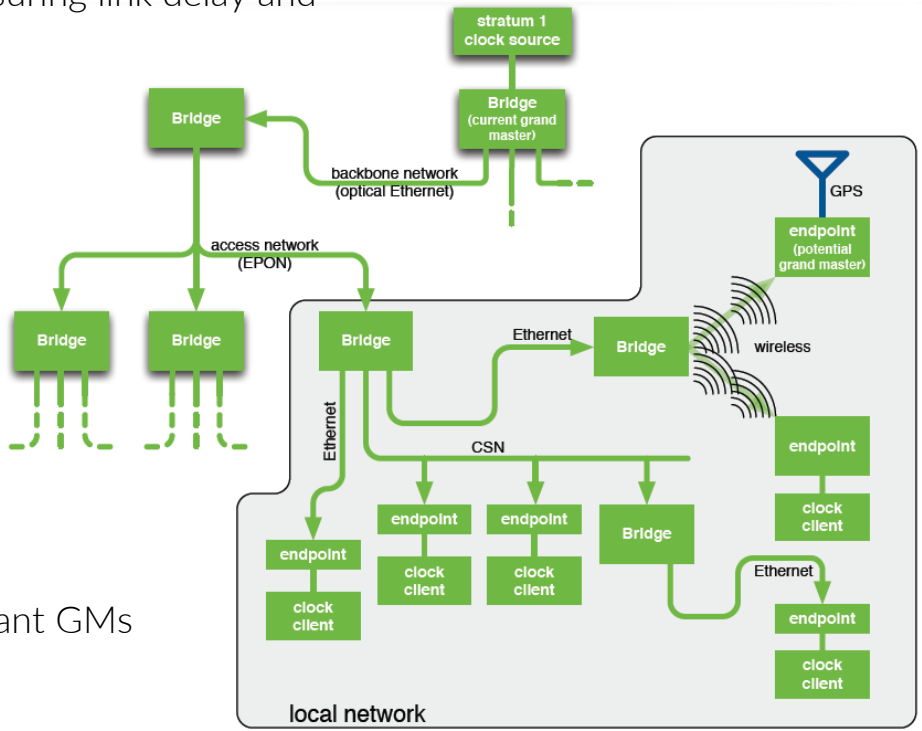
- Notably

  - P802.1AS-Rev – Timing and Synchronization for Time-Sensitive Applications
    - Now at Draft 8.1
    - Comments left to be resolved are now really few!

  - P802.1AX-Rev – Link Aggregation Revision

P802.1AS-REV – Timing and Synchronization

- A profile of 1588 for Layer 2 Ethernet
  - Common peer delay service for all domains, for measuring link delay and neighborRateRatio
  - Support of Fine Timing Measurement (FTM) for IEEE 802.11 transport
  - Support for Link Aggregation (802.1AX)
  - Improved scalability
  - One step processing
  - Improved support for long chains, rings
  - More responsive
  - Faster Grand Master change over
  - Reduce BMCA convergence time
  - Multiple domains with synchronization information
  - Redundancy: configure redundant paths and redundant GMs
  - …



TSN interest by Industry sectors

Standard / Project	Subject	Status	D#	Industry sector P	A	I	M
802.1CB	Frame Repl. & Elimin.	Published					
802.1CM	TSN for Fronthaul	Published					
802.1Qbu	Frame Preemption	Published					
802.1Qbv	Scheduled Traffic	Published					
802.1Qca	IS-IS Path Control & Rsv	Published					
802.1Qcc	SRP Enhancements	Published					
802.1Qch	Cyclic Queuing	Published					
802.1Qci	Per-Stream Filtering	Published					
802.1Qcp	YANG	Published					
P802.1AS-Rev	Time synchronization	WG	8.1				
P802.1CS	LRP (Registration)	WG	2.2				
P802.1Qcj	Auto-attach to PBB	WG	1.1				
P802.1Qcr	Asynchronous Shaping	WG	1.3				

*Updated Oct19

Status of the TSN standard

To summarize

- What we call TSN standard is actually the composition of several interplaying sub-standards
  - Which redesigned the whole Ethernet architecture (bridges, end points, LANs, etc…)
- Only a subset of them is of interest for the Industrial Automation industry
  - Other industry sectors are automotive, pro A/V, mobile and tlc…
- The strong innovation is that, with TSN the network support itself features all the needed capabilities and features to support time-critical, deterministic and safety traffic
  - No more need for protocol hacks or proprietary MAC&PHY

IEC/IEEE 60802

Motivations

- TSN defines sub-standards → not a single protocol
  - Several different application domains were driving and influencing different Amendments of IEEE 802.1, so that not all of them make sense for «Industrial Automation Applications»

- TSN allows maintaining determinism with the confidence of being able to satisfy the requirements of less demanding traffic, sharing the medium
  - The meaning of convergence in TSN is the successful convergence of critical control, non-critical control, and data streams on a single network

- The motivation for a joint IEC (TC65C) and IEEE is that IEC (IA standard developer) will have the competence of IEEE 802 on board to specify the profile
  - if gaps found → to have a short and quick relation to amend the technology!

Benefits of IEC/IEEE 60802

- IEEE 802.1 TSN gives an opportunity to converge networking for industrial automation
  - TSN is the foundation providing interoperability and connectivity
  - Simultaneously support operations technology traffic and other traffic

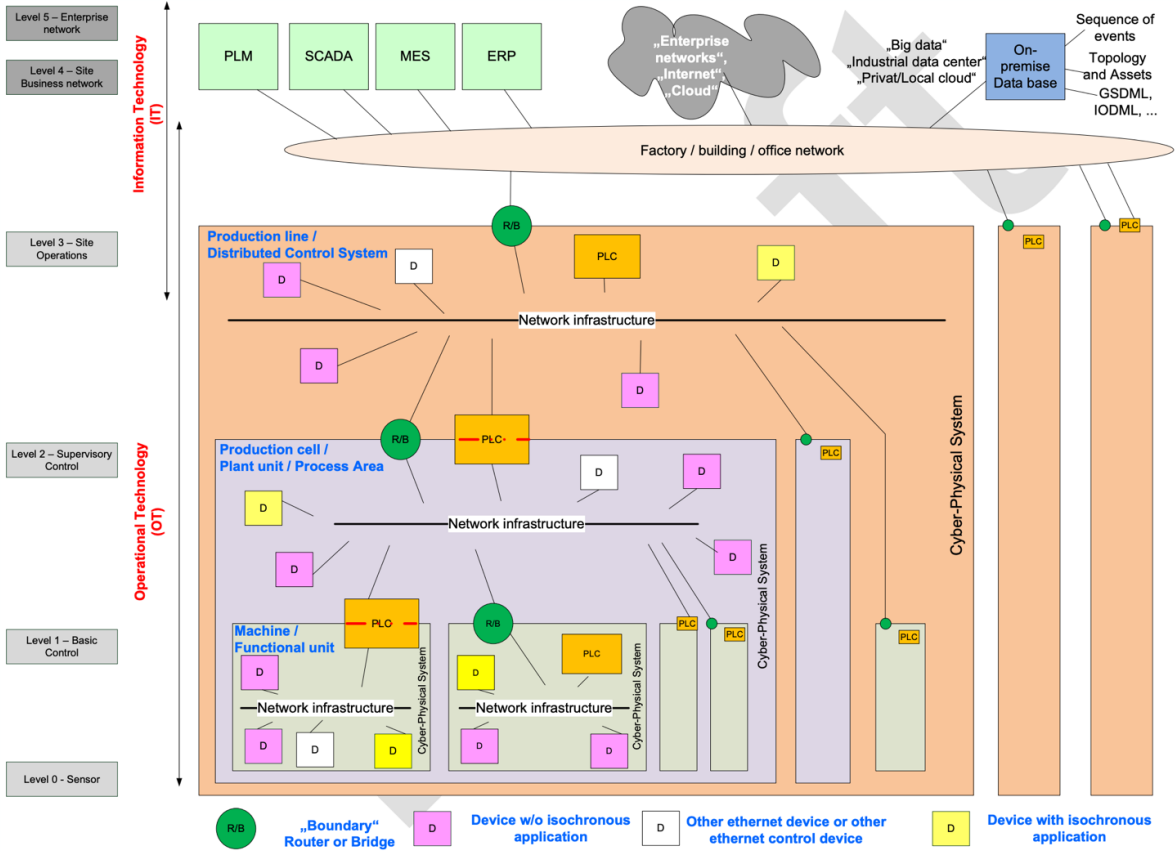
- Many industrial automation players consider TSN as the next generation networking technology in smart manufacturing

- The IEC/IEEE 60802 standard is beneficial for
  - Vendors offering and/or developing TSN products, as well as
  - The users of industrial automation technologies

http://www.ieee802.org/1/files/public/docs2018/detnet-tsn-winkel-60802-overview-1118-v01.pdf

TSN in Industrial Automation
Hierarchical structure

- Cyber-Physical Systems are the building blocks of «smart factories» and Industry4.0
- TSN provides the mechanisms for connectivity to time critical IA
  - On converged networks in operational technology control levels
- TSN can be used in IA for:
  - RT Communication within CPS
  - RT communication between CPS



From the IEC/IEEE 60802 standard draft…

INTRODUCTION

This standard defines time-sensitive networking profiles for industrial automation. The profiles select features, options, configurations, defaults, protocols, and procedures of bridges, end stations, and LANs to build industrial automation networks.

These profiles meet the industrial automation market objective of converging "Real-Time Ethernet" (RTE) networks and office networks by defining a common, standardized network infrastructure, taking advantage of the improvements of Ethernet networks in terms of deterministic transmission, bandwidth and network segmentation.

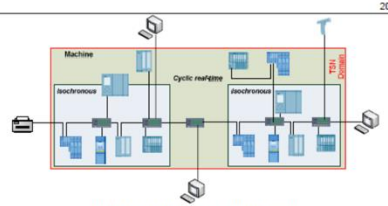
These profiles help to avoid the spreading of divergent implementations of deterministic RTE communication networks, by using only references to IEEE 802.3 and IEEE 802.1 to build the lower communication stack layers and management. Furthermore these profiles support the coexistence of different data streams between end stations, including Communication Profile Families (CPF) as defined in IEC 61784-2, each with different performance characteristics and functional capabilities, matching the diverse application requirements.

With this approach, adoption of Ethernet technology does not cause the loss of features required in the field area for industrial communication automation networks, such as:

- Support of latency and jitter requirements concerning data transmission.
- Efficient exchange of small data records on a frequent time period.
- Reliable communications with calculable downtime.
- High availability based on application requirements.

IEC/IEEE 60802 content

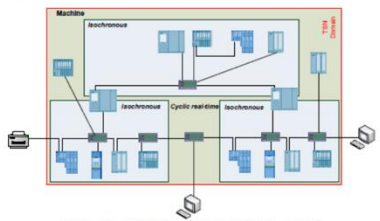
Example "Use case"



841

842 **Figure 39 – multiple isochronous domains**

843 Some kind of coupling (e.g. shared synchronization) between the isochronous domains / Working
844 Clocks may be used (see Figure 40).
845 All isochronous domains may have different network cycle times, but the cyclic real-time data
846 exchange shall still be possible for PLCs from both isochronous domains.



847

848 **Figure 40 – multiple isochronous domains - coupled**
849
850 Requirements:
851 All isochronous real-time domains may run independently, loosely coupled or tightly coupled. They
852 shall be able to share a cyclic real-time domain.
853
854 Useful 802.1 mechanisms:
855 • separate "isochronous" and "cyclic" traffic queues,
856 • Queue-based resource allocation in all bridges,
857 • ...

Relates to

Example "Requirements"

Dynamic plugging and unplugging of machines, production cells or production lines [1]

See [2] clause "Purpose"

R20	A TSN domain can be expanded dynamically at any time by attaching an additional TSN bridge to a spare port – without effect on established streams in the network.
R21*	Removal of a Bridge out of a TSN Domain which is in use will only affect streams which are using that Bridge.
R22	Streams can be established and removed at any time in ad-hoc manner without effect on other established streams in the TSN domain, i.e. particularly without re-initialization of the TSN domain.

R22.1	Adding and removing a machine/cell/production line shall not disturb existing installations.
R22.2	The traffic relying on TSN features from/to AGVs is established/removed automatically after plug/unplug events. - Different AGVs may demand different traffic layouts. - Thousands of AGVs may be used concurrently, but only a defined amount of AGVs is connected at a given time.

Energy saving [1]

R22.3	Turning off a portion of the network for energy saving reasons shall not create a process disturbance.
R22.4	Communication paths through the energy saving area between end-stations, which do not belong to the energy saving area, shall be avoided.

Multiple applications in a station using the TSN-IA profile [1]

R22.5	Stations with multiple applications using TSN traffic classes shall be supported.

Functional safety [1]

See [2] clause "Purpose"

R23	The addition of TSN functionality to an Ethernet network shall not impact proper operation of upper functional safety layers used on top of Ethernet based fieldbuses or networks (see IEC 61784-3).

R23.1	Safety applications (as black channel) and standard applications share the same TSN-IA profile based communication system at the same time.

Machine cloning [1]

R24	Support of unique TSN domain identification (e.g. using LLDP) also for cloned machines; Define handling of specific addresses (e.g. IP addresses) for global identification and how they are managed within the machine set-up procedures.

- The IEC/IEEE 60802 Joint Project is important for the success of the TSN technology
- It is the interest of all players to have only one TSN profile standard for Industrial Automation
- Current status
  - Task Group Ballot
  - Draft 1.1 (Sep 19)
- Expected publication of the final standard
  - July 2021

Industrial acceptance of TSN

- The major players in industrial automation solutions already embraced the TSN standard
  - Profinet specification 2.4
    - includes TSN capabilities at the lowest levels, retaining the Profinet Application Layer
  - CC-Link IE TSN
  - EtherCAT-TSN
    - This is more an adaptation of EtherCAT masters to include segments of TSN

- Several products are already available

MOXA® CISCO TTTech NXP SJA1105 kontron HIRSCHMANN A BELDEN BRAND

TSN & 5G

- TSN is not all about Ethernet/wired technologies
  - It is more like a huge infrastructural change!

- 3GPP (which defines 5G) has decided to embrace this new paradigm
  - From http://www.ieee802.org/1/files/public/docs2019/liaison-3gppsa2-1908630-5g-integration-with-tsn-0719.pdf
  - «3GPP is working on adding support in 5G System to integrate with IEEE Time-Sensitive Networking (TSN) networks in support of industrial automation vertical»

- 3GPP TS 22.104
  - «Technical Specification Group Services and System Aspects; Service requirements for cyber-physical control applications in vertical domains»
    - describes requirements towards 5G in order to support interconnection with TSN networks

- 3GPP has chosen to support the following (excerpt)
  - Among the three TSN configuration models defined in IEEE 802.1Qcc
    - fully centralized model is supported in this release of the specification
  - Time Sensitive Communication (TSC) traffic classes are supported with corresponding 5G QoS profiles
    - 5G System features support TSC and allow the 5G System to be integrated transparently as a logical bridge in an IEEE TSN network.
  - In Release 16 only supports interworking with TSN using IEEE 802.1Qbv based QoS scheduling.
  - In Release 16 only simplified traffic scheduling as described in IEEE 802.1Q Annex Q.2 (“Using gate operations to create protected windows”) is supported
  - Support Time Synchronisation following:
    - For TSN Synchronization, the entire E2E 5G System can be considered as an IEEE 802.1AS "time-aware system".
    - Only the TSN Translators (TTs) at the edges of the 5G System (within NW-TT and DS-TT) need to support the IEEE 802.1AS operations.
    - UE, gNB, UPF, NW-TT and DS- TTs are synchronized with the 5G GM (i.e. the 5G internal system clock) which shall serve to keep these network elements synchronized.
  - …

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Thank you!

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