TTTech

Time-Sensitive Networking

Technical Overview and the Bigger Picture

Wilfried Steiner

TTTech Computertechnik AG

7/10/2018

Outlook

- Ethernet for Real-Time Systems
  - Cost savings by harmonization of real-time standards
- General Reflections
  - General Historic Developments towards TSN
    - IEEE 802.1 Audio Video Bridging
  - TTTech-specific Developments towards TSN
    - TTP – TTEthernet – TSN
  - IEEE 802.1 TSN Standardization Introduction
    - Including special interest groups and other standardization bodies (AVnu, Open Alliance, IEC)
- TSN Technical Overview
  - Generic Queuing Model
  - Traffic policing, switching fabric, traffic shaping
  - Man with ties
  - Scheduling differences to TTEthernet/TTP
- Research Directions and their Industrial Impact
  - General configuration synthesis and verification
  - Schedule synthesis including schedule verification
  - Clock synchronization configurations
  - TSN deployment and integration in larger systems and in “brown field” installations
  - Fog Computing
  - Deterministic Internet (IETF detnet)
  - Alternative protocols and data plane modifications

* Many thanks to Marina Gutiérrez for helping out with the slides and for being TTTech’s representant at TSN.

TTTech

Ethernet for Real-Time Systems

Ethernet for Real-Time Systems

TTTech

Long-standing concepts, e.g.:

1st Intl. Workshop on Real-Time LANs in the Internet Age (2002)

http://www.hurray.isep.ipp.pt/rtlia2002/RTLIA_program.html

Session 3: An Emerging Control Network: Switched Ethernet

6 *Real-Time with Ethernet*
R. Messerschimdt
Otto-v.-Guericke-Universität, Magdeburg, Germany

7 *Utilization of Modern Switching Technology in EtherNet/IP™ Networks*
A. Moldovansky
Rockwell Automation, USA

8 *Ethernet based Realtime LAN for Automation Applications*
M. Buchwitz
Jetter AG, Germany

Ethernet for Real-Time Systems

TTTech

Long-standing concepts, e.g.:

1st Intl. Workshop on Real-Time LANs in the Internet Age (2002)

http://www.hurray.isep.ipp.pt/rtlia2002/RTLIA_program.html

Session 3: An Emerging Control Network: Switched Ethernet

6 ***Real-Time with Ethernet***
R. Messerschimdt
Otto-v.-Guericke-Universität, Magdeburg, Germany

7 ***Utilization of Modern Switching Technology in E***
A. Moldovansky
Rockwell Automation, USA

8 ***Ethernet based Realtime LAN for Automation A***
M. Buchwitz
Jetter AG, Germany

Well-Established Products

Ethernet for Real-Time Systems

TTTech

Long-standing concepts, e.g.:

1st Intl. Workshop on Real-Time LANs in the Internet Age (2002)

http://www.hurray.isep.ipp.pt/rtlia2002/RTLIA_program.html

Session 3: An Emerging Control Network: Switched Ethernet

6 *Real-Time with Ethernet*
R. Messerschimdt
Otto-v.-Guericke-Universität, Magdeburg, Germany

7 *Utilization of Modern Switching Technology in E*
A. Moldovansky
Rockwell Automation, USA

8 *Ethernet based Realtime LAN for Automation A*
M. Buchwitz
Jetter AG, Germany

Well-Established Products

Problem of Incompatibility between products from different vendors

→ TSN aims to resolve the incompatibility problem.

One Standard, or One *More* Standard?

There is a certain risk that IEEE 802.1 TSN will not become the One Standard, but just One More Standard.

Pro One Standard:

- One Standard is enables economics of scale (horizontal between application areas).
- One Standard that allows to realize converged networks, i.e., supports applications with different requirements.
- One Standard that has a defined growth path for future improvements, e.g., speed.
- One Standard that engineers (and later researchers) can be trained on.

Pro One More Standard:

- One More Standard for a foreseeable long time, as there are many “brown field” installations.
- One More Standard that will not replace highly specialized solutions in niche markets.

02

General Reflections

IEEE 802.1 Audio Video Bridging (~2006 – 2011)

TTTech

Use-case: Professional Audio / Video

Time Synchronization

IEEE 802.1AS: Time Synchronization

Latency

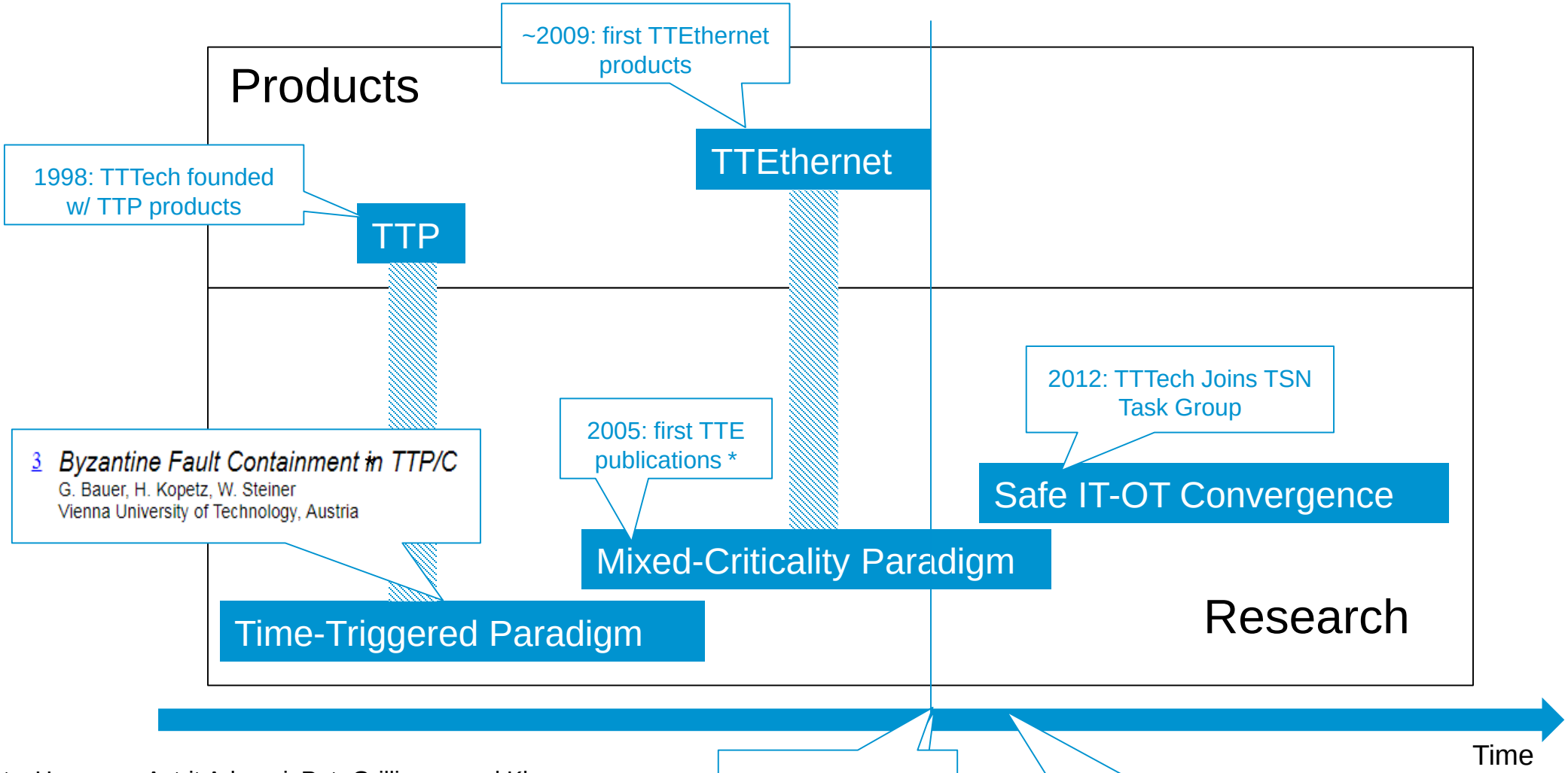
IEEE 802.1Qav: Credit Based Shaper

Reliability

Management

IEEE 802.1Qat: Stream Reservation Protocol

TTTech - Deterministic Networking History

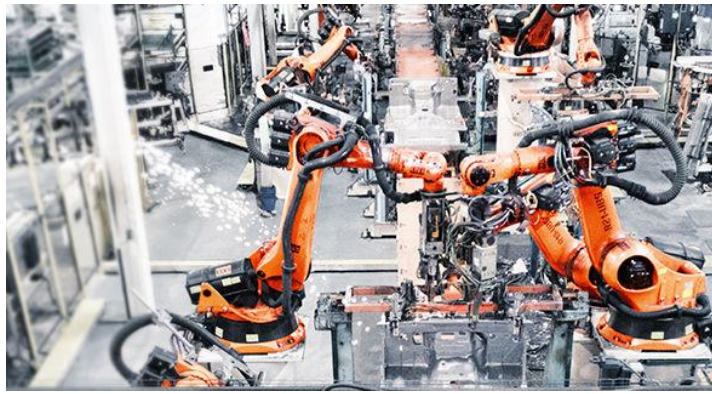


* Kopetz, Hermann, Astrit Ademaj, Petr Grillinger, and Klaus Steinhammer. "The time-triggered ethernet (TTE) design." In Object-Oriented Real-Time Distributed Computing, 2005. ISORC 2005. Eighth IEEE International Symposium on, pp. 22-33. IEEE, 2005.

IEEE 802.1 Time Sensitive Networking (TSN)

(previously IEEE 802.1 Audio Video Bridging (AVB))

- ✓ Adds real-time capabilities to switched Ethernet
- ✓ Allows convergence of multiple traffic classes on one network
- ✓ To be used in Automotive, Industrial Automation, Railway



What is TSN?

TTTech

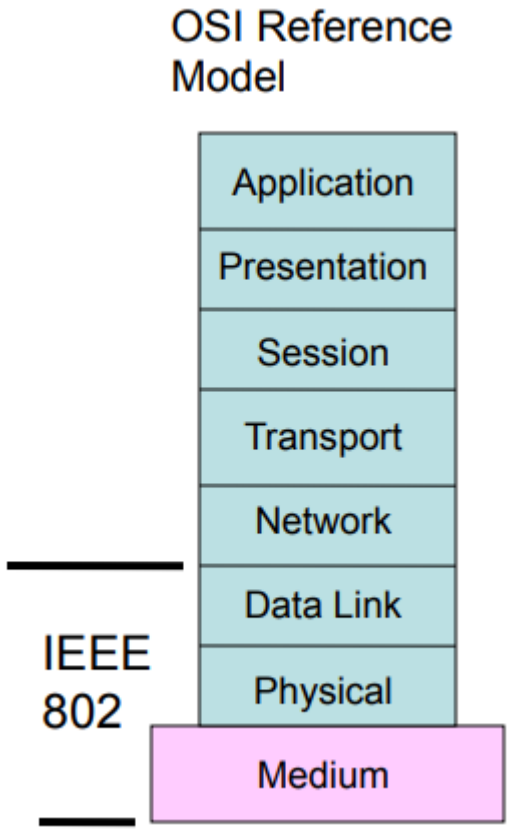
IEEE 802.1 Time-Sensitive Networking…

- ✓ … is a Task Group within 802.1
- ✓ Developing a set of standards
- ✓ To be used in different applications

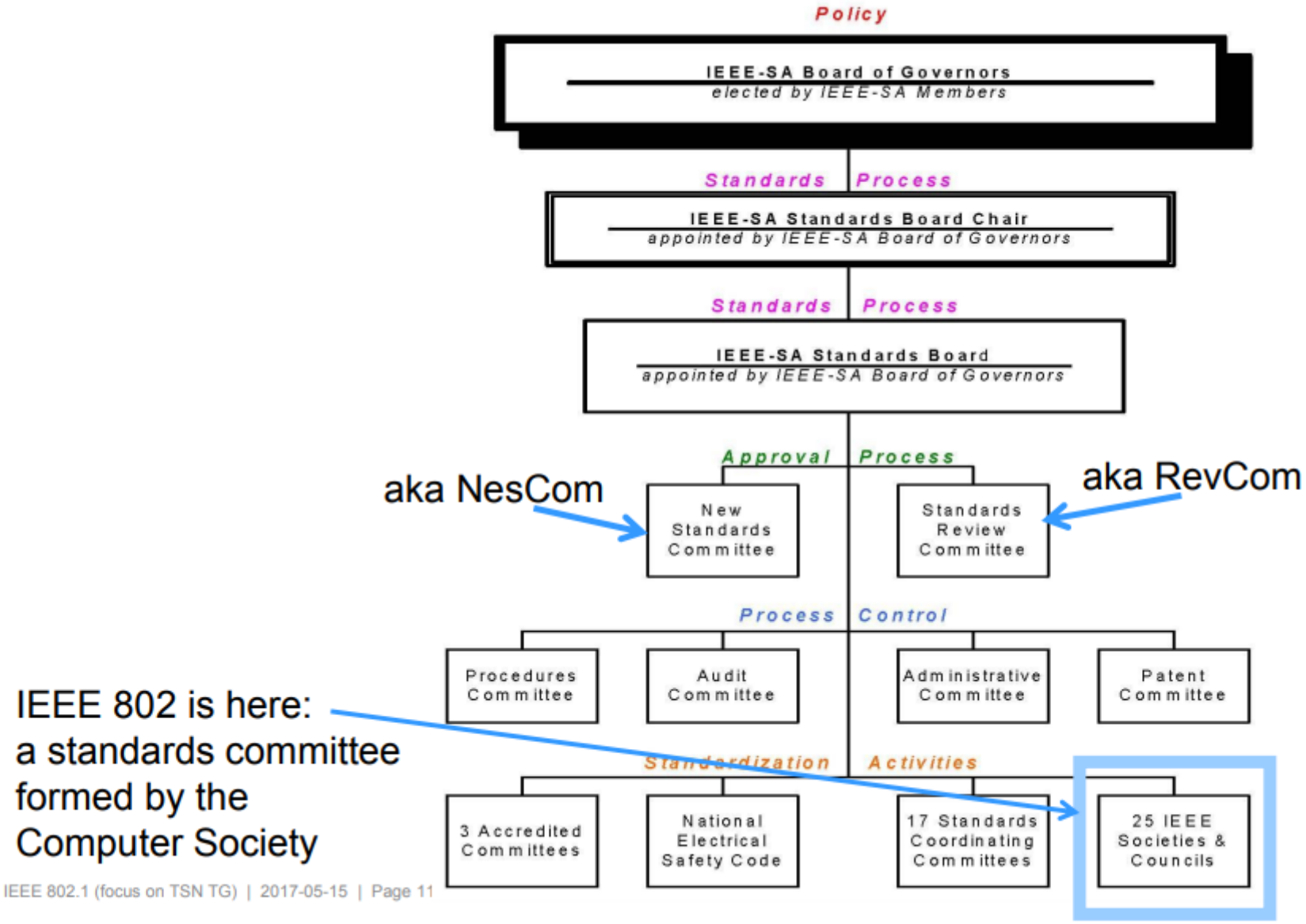
- ➢ Not a protocol!
- ➢ Not a single standard!
- ➢ Selecting the standards that fits the application is a must!

IEEE 802

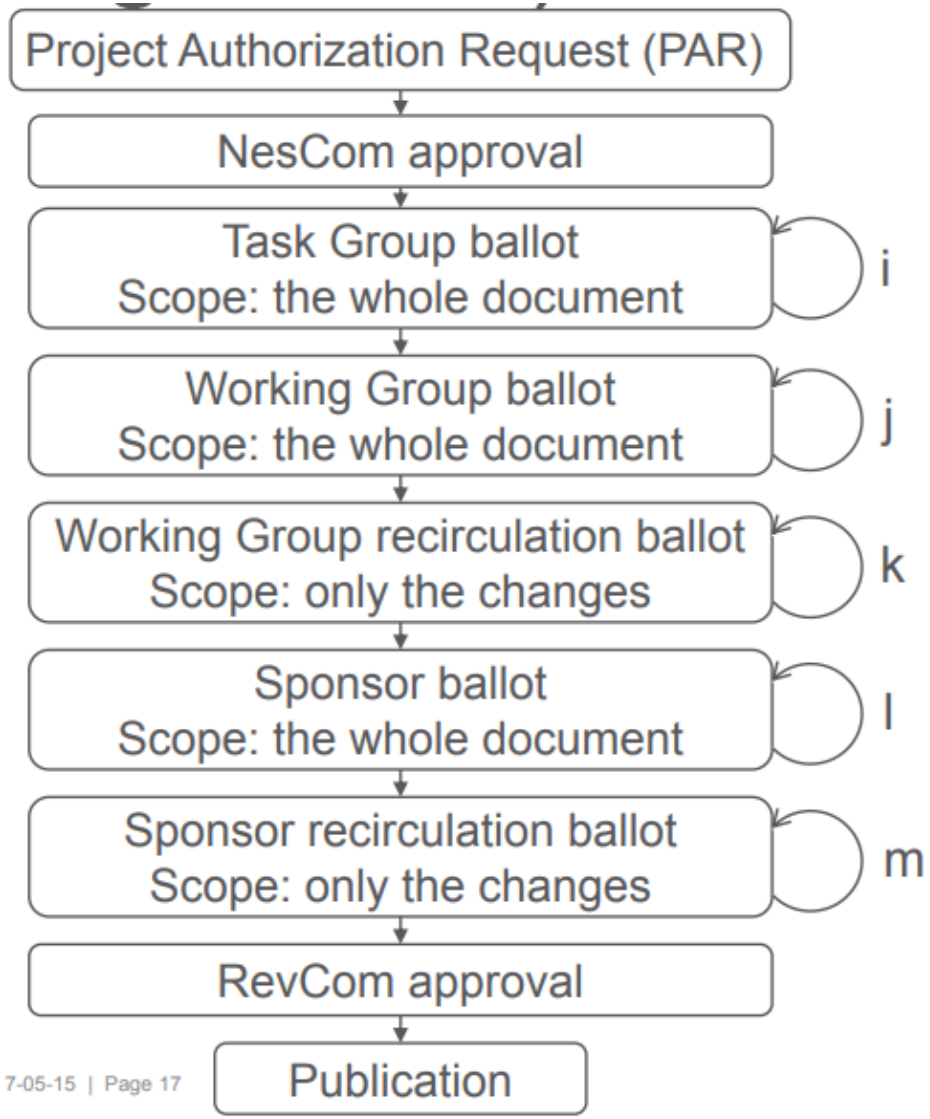
- 802.1 Bridging and Architecture
- 802.3 Ethernet
- 802.11 Wireless LAN (WLAN)
- 802.15 Wireless Personal Area Network (WPAN)
- 802.16 Broadband Wireless Access (BWA)
- 802.18 Radio Regulatory TAG
- 802.19 Coexistence TAG
- 802.21 Media Independent Handover
- 802.22 Wireless Regional Area Networks (WRAN)
- 802.24 Smart Grid TAG



IEEE Standards Organization



Standard Development Process



+ “Hallway Talks”

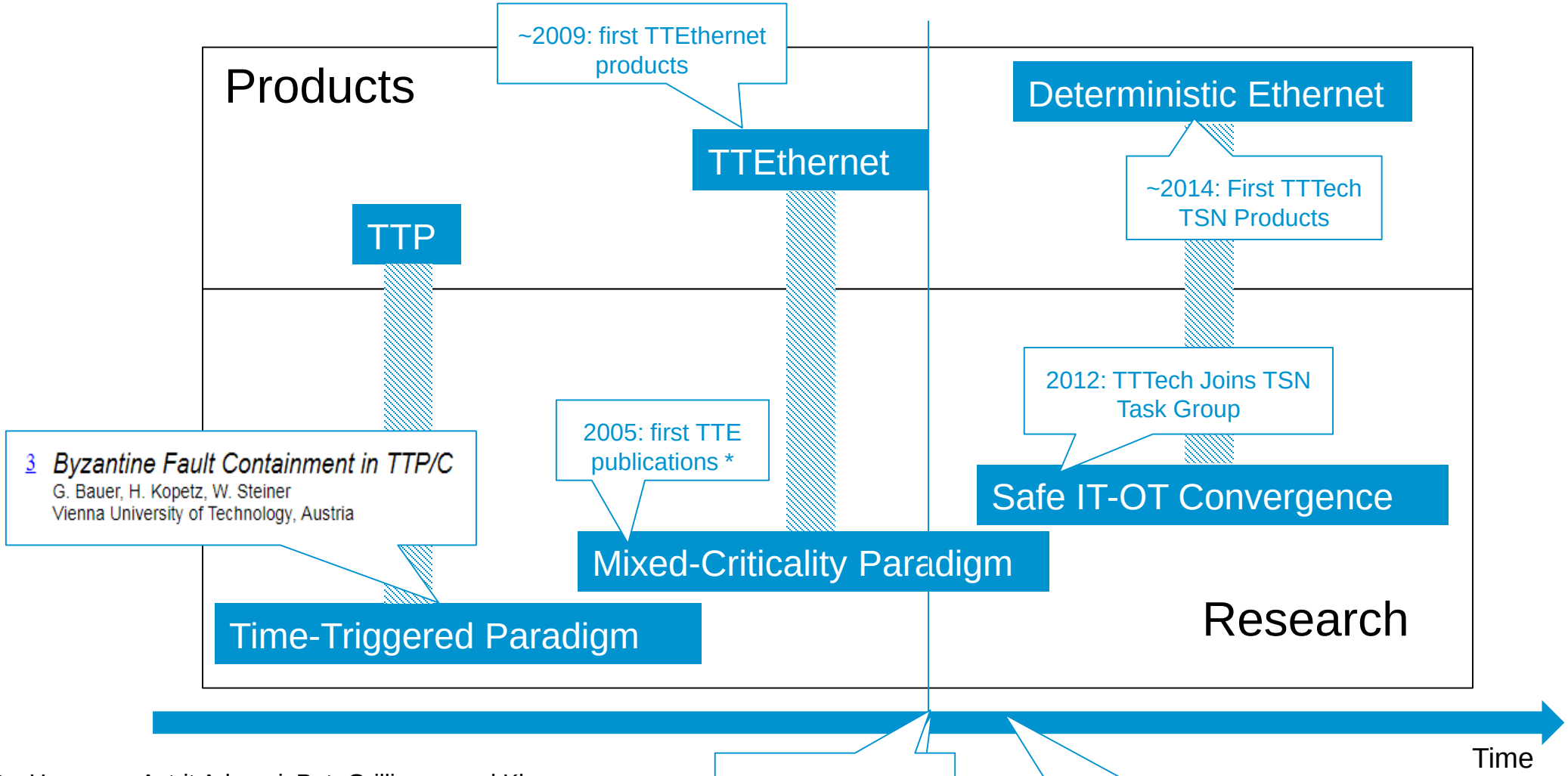
+ Maintenance

Standard Development Process / Projects Status

TTTech

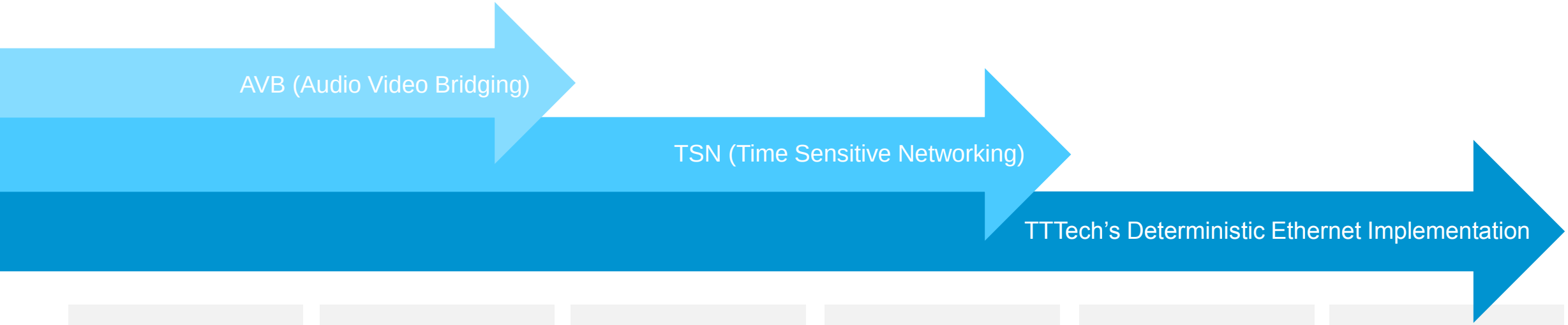
Standard	Current Version	PAR Req /Appr.	Start TG Ballot	Start WG ballot	Sponsor Ballot	RevCom
802.1Qbv	D3.1	15-May-12	02-Dec-13	04-Sep-14	17-Jul-15	18-Mar-16
802.1AS-rev	D6.0	10-Sep-11	20-May-13	16-Mar-17		
802.1CB	D2.8	01-Mar-13	03-Nov-14	17-Jul-15	28-Jul-16	16-Mar-17
802.1Qca	D2.1	05-Dec-12	09-Aug-13	05-Aug-14	12-Mar-15	11-Mar-16
802.1Qbu	D3.1	15-May-12	28-Jul-14	11-Dec-14	17-Jul-15	
802.1Qcc	D2.1	21-Oct-13	01-Dec-14	17-Mar-16	10-Nov-17	07-Mar-18
802.1Qch	D2.2	01-Nov-14	17-Mar-16	28-Jul-16	11-Nov-16	16-Mar-17
802.1Qci	D2.0	12-Mar-15	12-Nov-15	17-Mar-16	28-Jul-16	11-Nov-16
802.1Qcr	D0.3	17-Mar-16	16-Mar-17			
802.1Qcp	D2.0		before now	16-Mar-17	10-Nov-17	07-Mar-18
802.1CS	D1.2	11-Nov-16	10-Jul-17			
802.1ABcu	D0.0	10-Jul-17				
802.1Qcw		10-Jul-17				
				published standards		latest changes

TTTech - Deterministic Ethernet Development Summary



* Kopetz, Hermann, Astrit Ademaj, Petr Grillinger, and Klaus Steinhammer. "The time-triggered ethernet (TTE) design." In Object-Oriented Real-Time Distributed Computing, 2005. ISORC 2005. Eighth IEEE International Symposium on, pp. 22-33. IEEE, 2005.

TTTech's Deterministic Ethernet implementation in detail



IEEE 802.1D

- Layer 2 Switching

IEEE 802.1Q

- VLAN Aware Bridge
- Packet Priority (QoS)
- 802.1Qat Stream Reservation
- 802.1Qav Credit -Based Shaper

IEEE 802.1AS

- IEEE 802.1AS Software Stack
- Hardware Timestamping

IEEE 802.1TSN

- IEEE 802.1Qbv Time-Aware Shaper
- IEEE 802.1Qbu Preemption
- IEEE 802.1CB Redundancy
- IEEE 802.1Qci Policing
- …

Fully Scheduled Networks

- SAE AS6802 Fault-Tolerant Clock Sync.
- Time-Triggered Shaper
- Safety Extensions (Safety Master)

End-to-End Network Virtualization

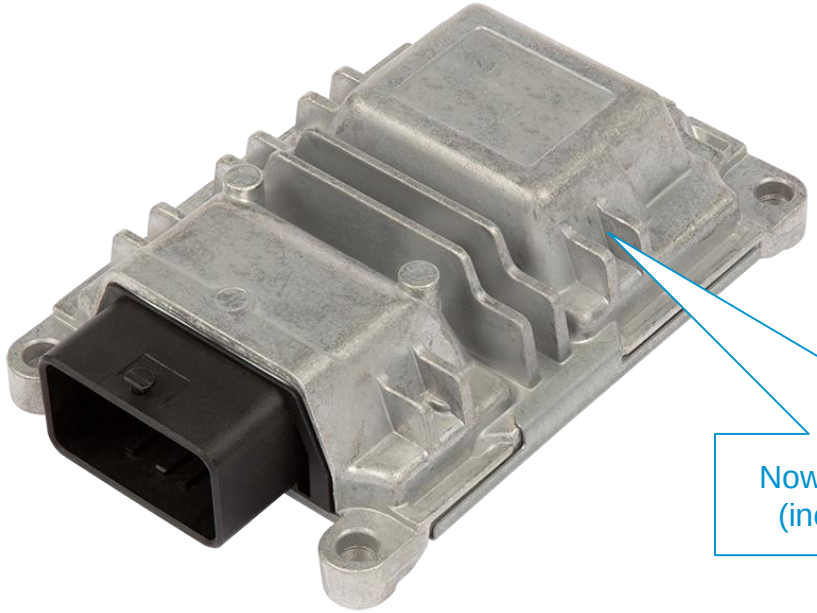
- Bandwidth Isolation through PCIe (SR-IOV)
- Flow-based Memory Partitions

High Speed Switching

- Cut-Through

The Deterministic Ethernet switch Hermes

- One Ethernet switch hardware for evaluation of different technologies including AVB, TSN and Time-Triggered Ethernet in combination with BroadR-Reach® PHY
- Platform for evaluation of NXP SJA1105T Ethernet switch chip
- Enables customized evaluation projects using the switch as an ECU with I/Os and CAN, FlexRay and Ethernet interfaces



Now the basis for Gateway ECUs (incorporate Aurix Safety CPU)

Günter Sporer,

Segment Director Ethernet,
NXP Semiconductors

> The Hermes Deterministic Ethernet Switch from TTTech serves as a platform for evaluating the functionality of our SJA1105T Ethernet switch IC, making this another stepping stone within our valuable cooperation.

https://www.kontron.com/products/systems/connectivity/network-interfaces-tsn/pcie-0400-tsn-network-interface-card.html

Other Standardization Bodies and Interest Groups (Industrial Focus)

TTTech

Testbed and Reference Architectures
- Testbeds to evaluate "full stack" and provide feedback to members and liaison organizations
- Application specific architectures to aid in market adoption
- Outbound marketing to create awareness

industrial internet CONSORTIUM

Application Layers
- Define data models for end-device communication
- Integration of TSN communications and configuration models into application tools
- Application flow for end-node configuration
- Conformance for data models and end node configuration

OPC FOUNDATION IEC 61850

TSN Transport Interoperability and Conformance
- Define network services needed by market
- Fill gaps in standards to provide interoperable network configuration services
- Conformance of transport and network services
- Establish certification services

AVNU

Network standards
- Define standard features to provide data plane and configuration plane providing TSN capabilities
- Assure proper operations and backwards compatibility with IT and OT

IEEE IETF

→ Even other groups, like Open Alliance for Automotive.

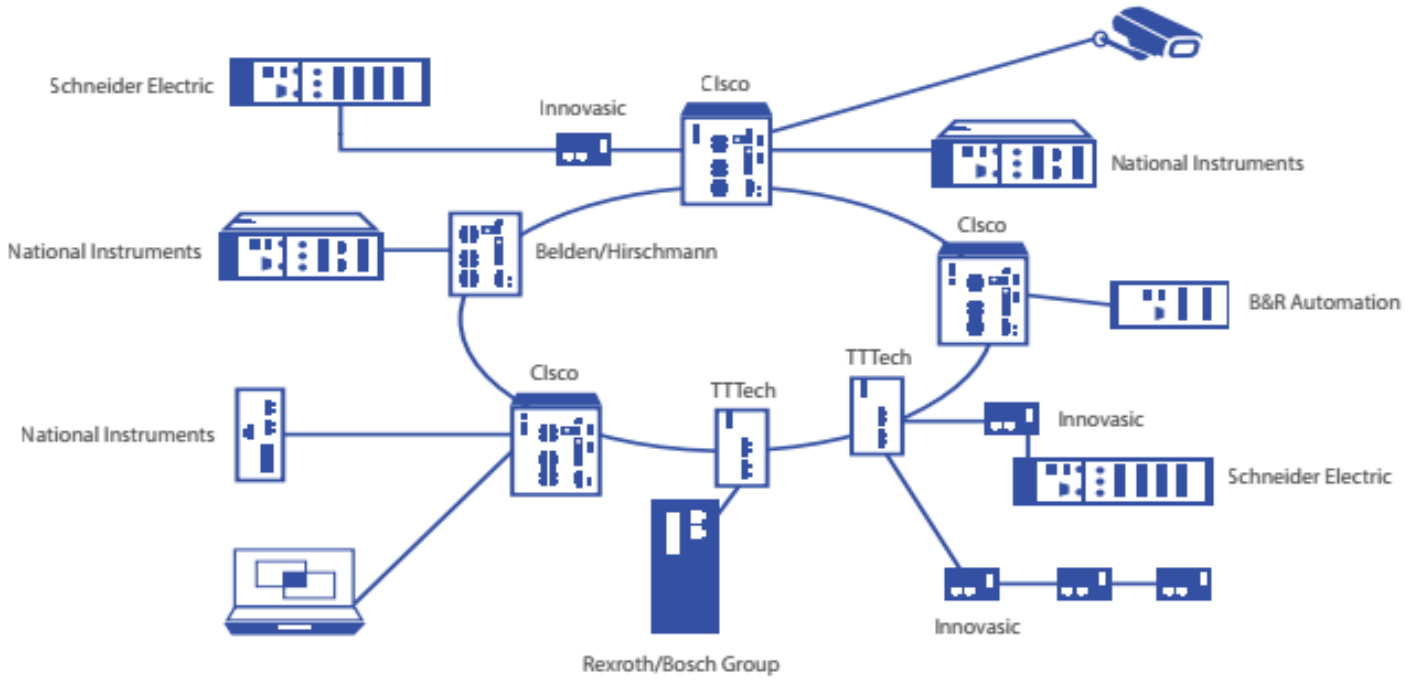
Supported by Industry Leaders: „Shapers“

Press conference in Nov 2016 announced wide industry support for the industrial networking and data management platform OPC UA TSN

Operational in IIC Testbed

TTTech

Interoperability testing for Time Synchronization, Traffic Scheduling and System Configuration functions of various vendors



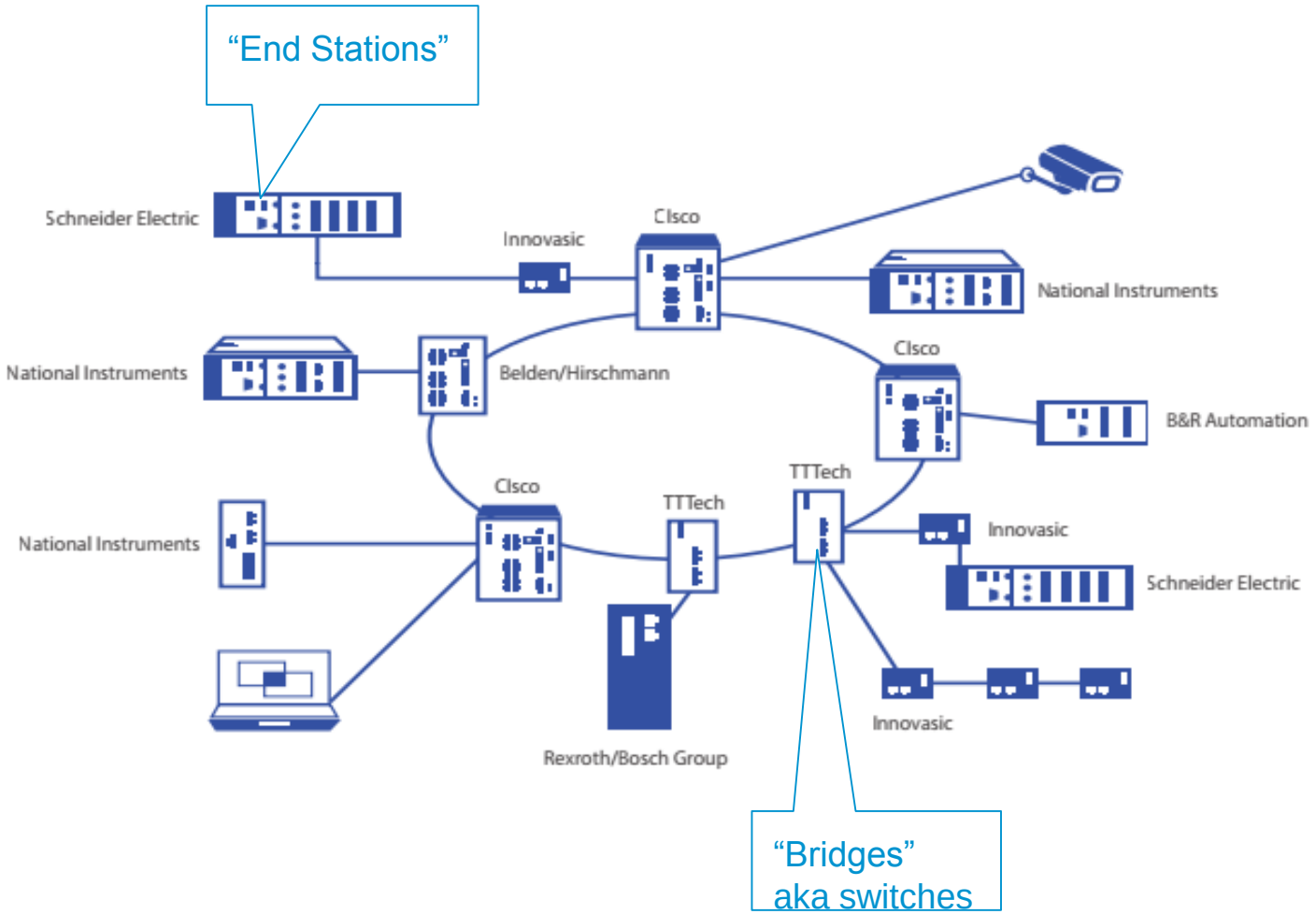
industrial internet CONSORTIUM

→ Successful Plug Feasts

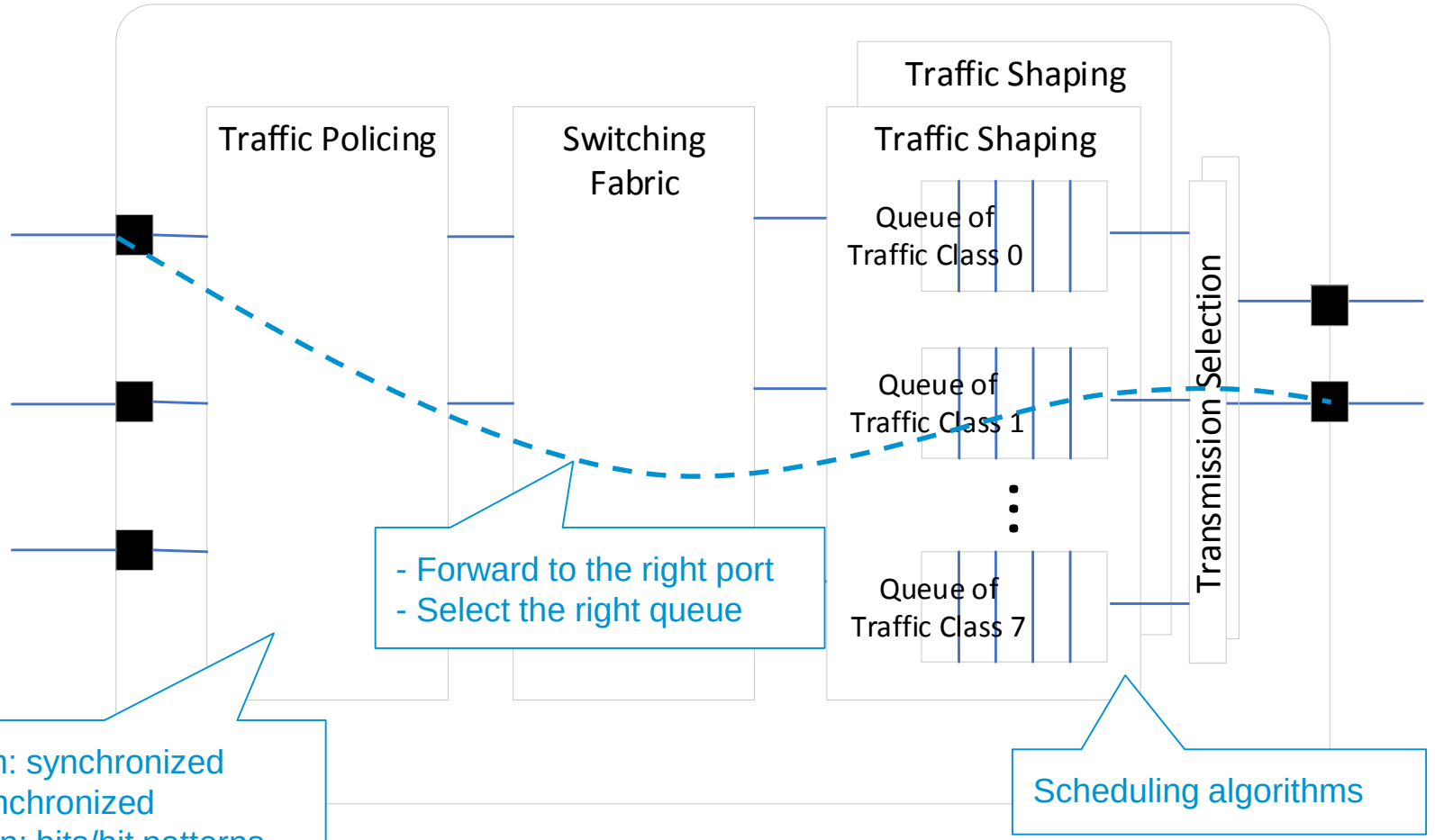
03

TSN Technical Overview

IEEE 802.1 Network



Switch (aka “bridge”) overview



Standard Development Process / Projects Status

TTTech

Standard	Current Version	PAR Req /Appr.	Start TG Ballot	Start WG ballot	Sponsor Ballot	RevCom
802.1Qbv	D3.1	15-May-12	02-Dec-13	04-Sep-14	17-Jul-15	18-Mar-16
802.1AS-rev	D6.0	10-Sep-11	20-May-13	16-Mar-17		
802.1CB	D2.8	01-Mar-13	03-Nov-14	17-Jul-15	28-Jul-16	16-Mar-17
802.1Qca	D2.1	05-Dec-12	09-Aug-13	05-Aug-14	12-Mar-15	11-Mar-16
802.1Qbu	D3.1	15-May-12	28-Jul-14	11-Dec-14	17-Jul-15	
802.1Qcc	D2.1	21-Oct-13	01-Dec-14	17-Mar-16	10-Nov-17	07-Mar-18
802.1Qch	D2.2	01-Nov-14	17-Mar-16	28-Jul-16	11-Nov-16	16-Mar-17
802.1Qci	D2.0	12-Mar-15	12-Nov-15	17-Mar-16	28-Jul-16	11-Nov-16
802.1Qcr	D0.3	17-Mar-16	16-Mar-17			
802.1Qcp	D2.0		before now	16-Mar-17	10-Nov-17	07-Mar-18
802.1CS	D1.2	11-Nov-16	10-Jul-17			
802.1ABcu	D0.0	10-Jul-17				
802.1Qcw		10-Jul-17				
				published standards		latest changes

AVB Components

Use-case: Professional Audio / Video

Time Synchronization

IEEE 802.1AS: Time Synchronization

Latency

IEEE 802.1Qav: Credit Based Shaper

Reliability

Management

IEEE 802.1Qat: Stream Reservation Protocol

TSN Components

TTTech

Use-case: Professional Audio / Video, Industrial Automation, Automotive

Time Synchronization

IEEE 802.1AS: Time Synchronization
P802.1AS-Rev: Time Synchronization Redundancy

Latency

IEEE 802.1Qav: Credit Based Shaper
IEEE 802.1Qbu: Frame Preemption
IEEE 802.1Qbv: Scheduled Traffic – Time Aware Shaper
IEEE 802.1Qch: Cyclic Queuing and Forwarding
P802.1Qcr: Asynchronous Traffic Shaper

Reliability

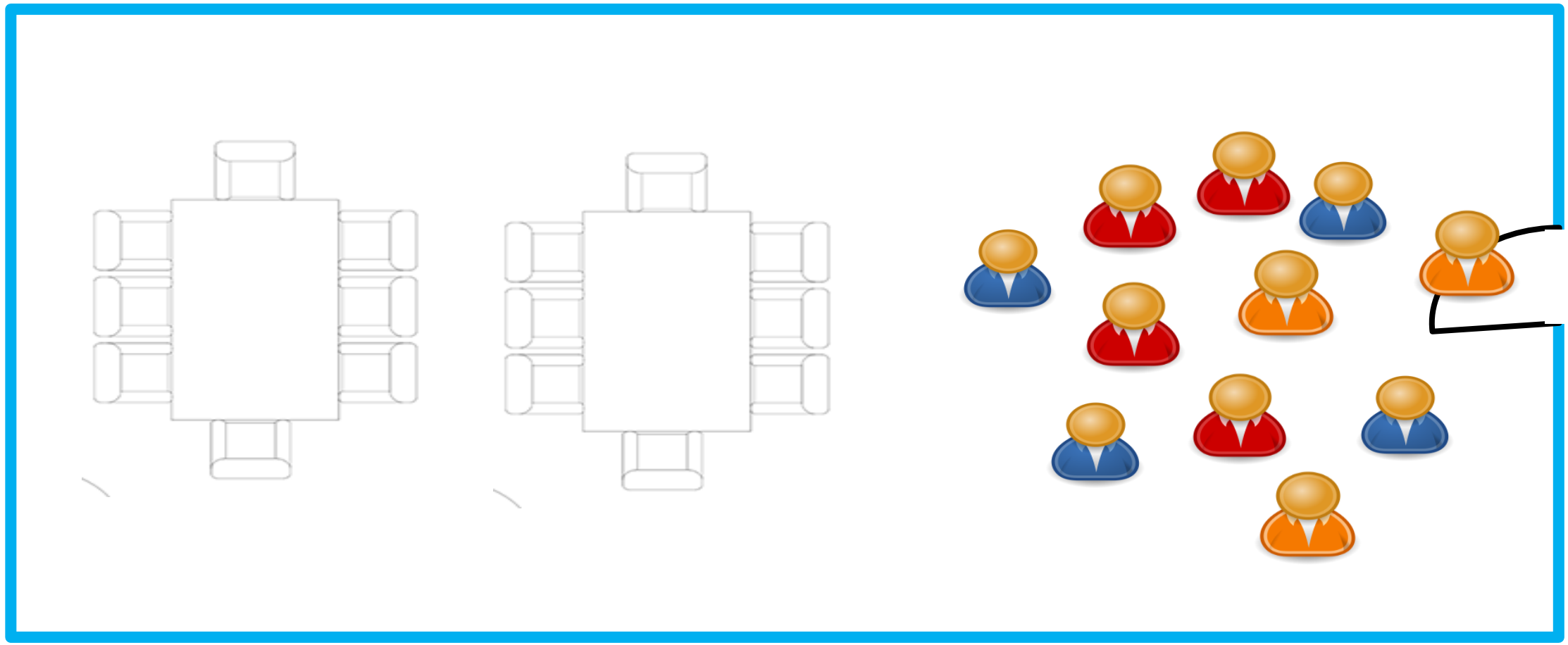
IEEE 802.1Qca: Path Control
IEEE 802.1Qci: Per-Stream Filtering and Policing
IEEE 802.1CB: Frame Replication and Elimination
+ P802.1CBdb: Extended Stream Identification
P802.1AS-Rev: Time Synchronization Redundancy

Management

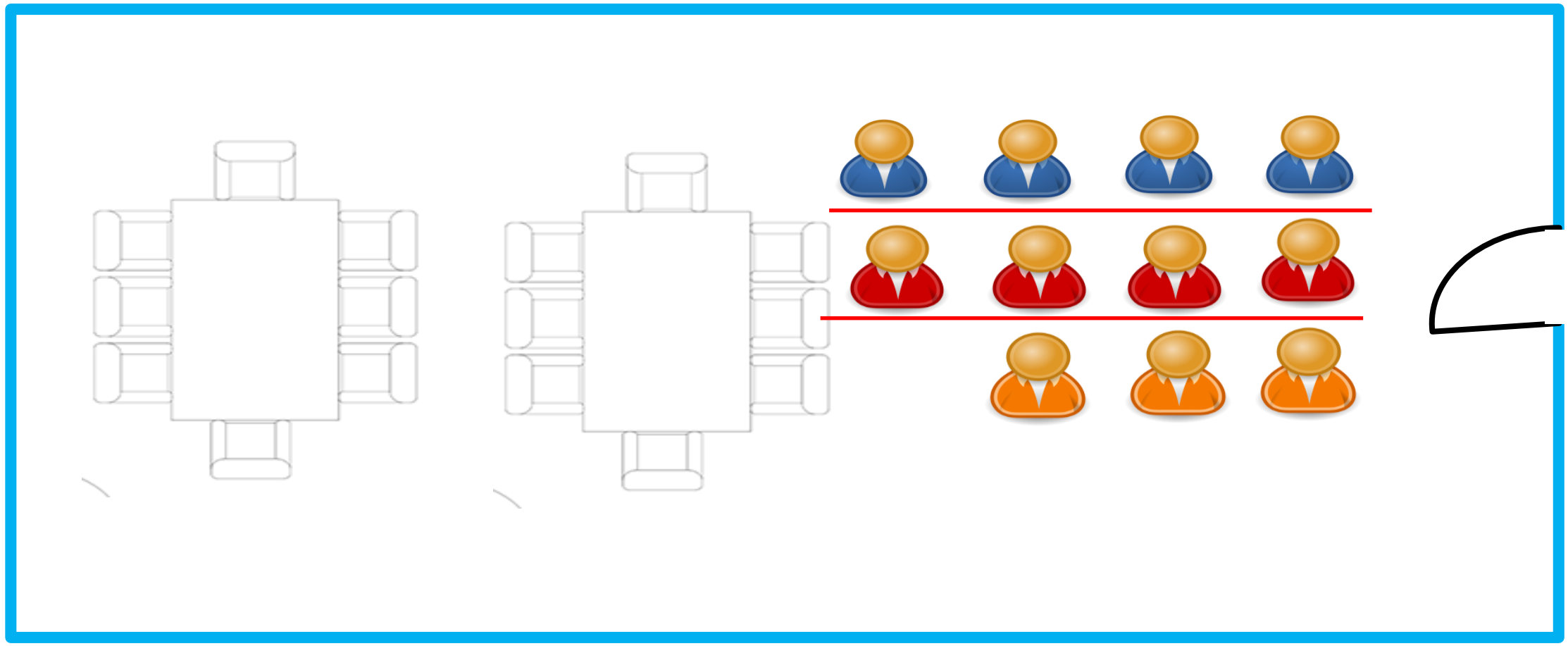
IEEE 802.1Qat: Stream Reservation Protocol
P802.1Qcc: TSN Configuration
P802.1Qcp: YANG Data Model
+ P802.1Qcw: YANG Data Models for Qbv, Qbu, Qci
+ P802.1ABcu: LLDP YANG Data Model
+ P802.1CBcv: YANG Data Model for CB
P802.1CS: Link-local Reservation Protocol

Man with Ties – Best Effort

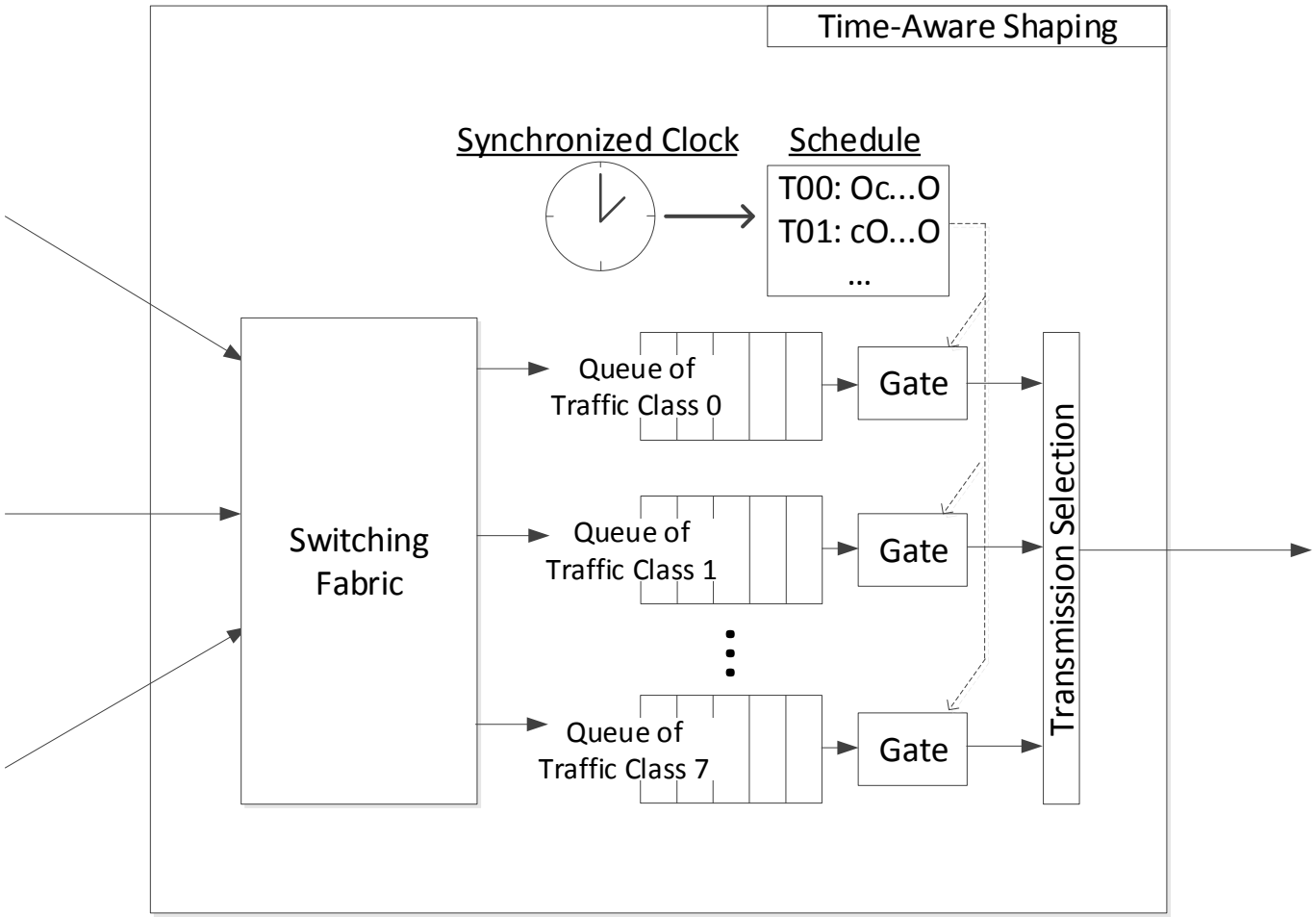
TTTech



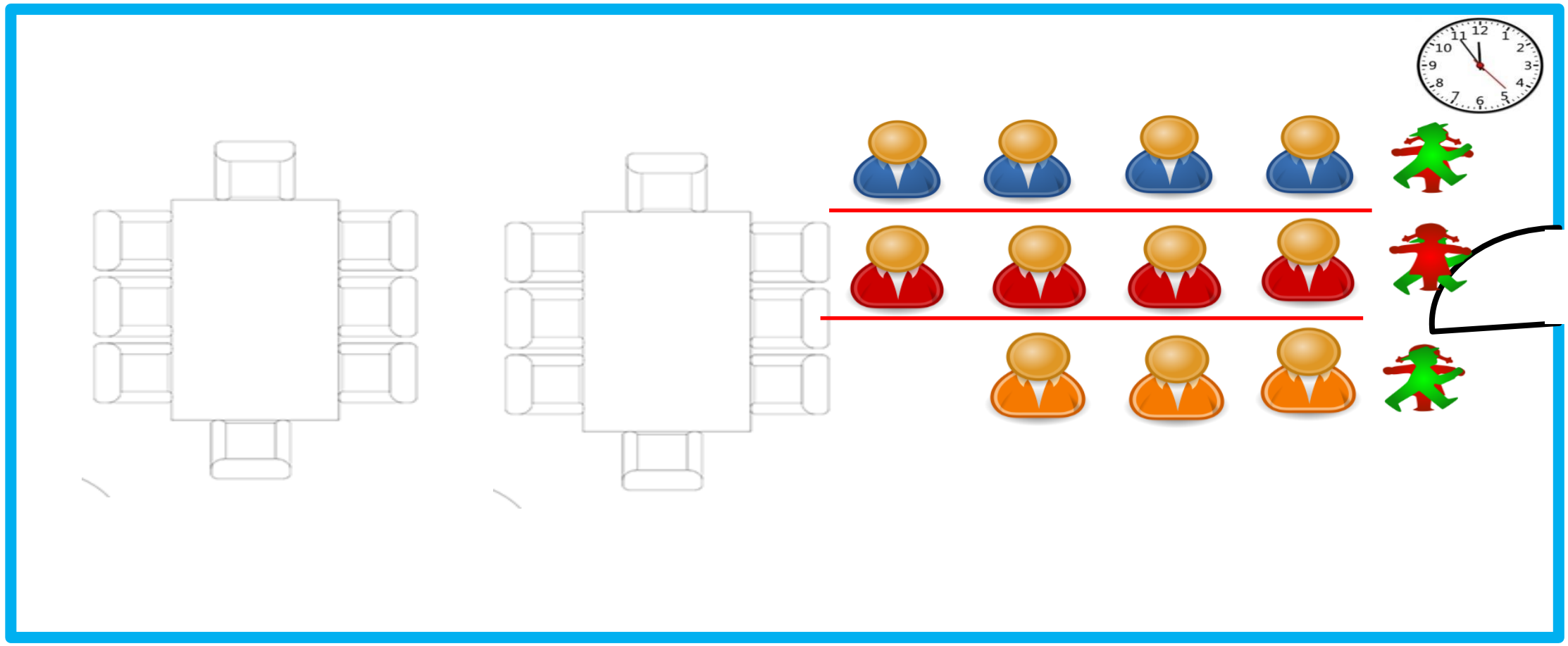
Man with Ties –
Quality of Service (Priorities only)



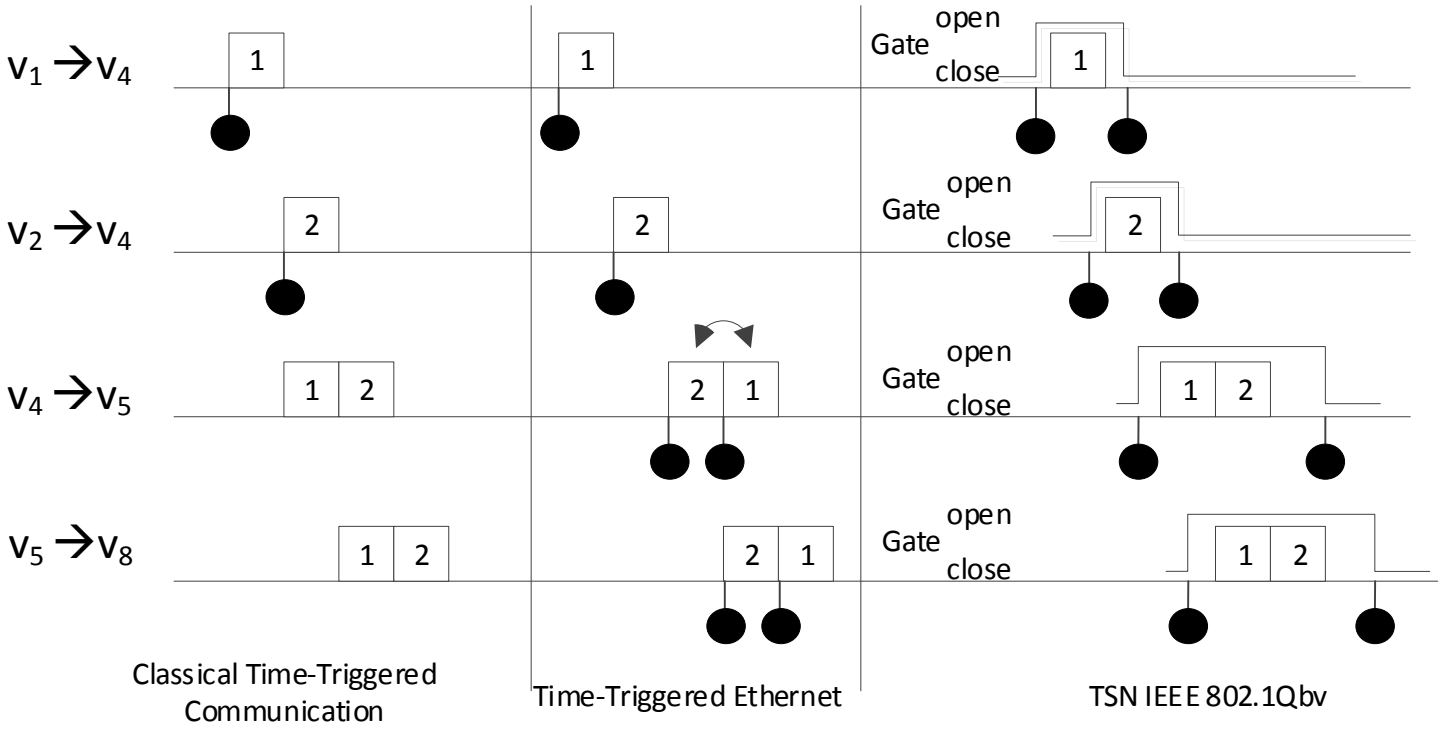
Example: IEEE 802.1Qbv

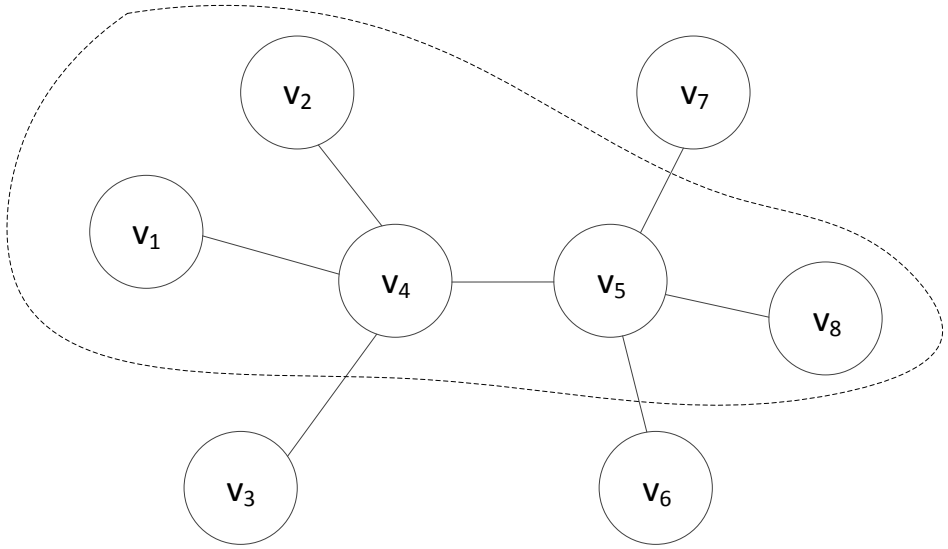


Man with Ties –
TSN IEEE 802.1Qbv



Deltas to Time-Triggered Communication in TTP/TTEthernet





- TTP/FlexRay: scheduling of transmission points in time
- TTEtherent: scheduling of transmission and forwarding points in time
- TSN: scheduling of gate open/close events per queue

04

Research Directions and their Industrial Impact

General Configuration Synthesis

The TSN protocols all in all define a huge number of configuration parameters.

Many different aspects for which a configuration can be optimized: bandwidth efficiency, real-time, safety, security.

Routing can be thrown into this “problem pot” as well (and it is).

Likely that the first question to be answered in this optimization is the selection which TSN mechanism to use for which application.

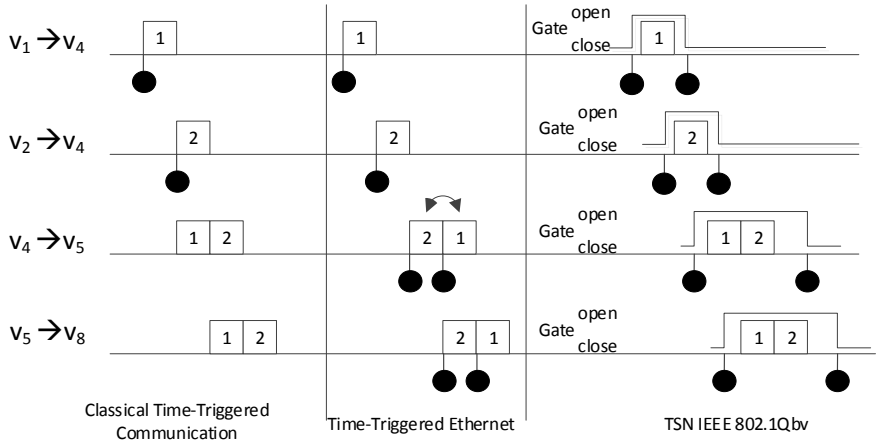
Then, also this selection process can be automatized.

There are many methods available today that need to be adjusted for TSN, e.g., network calculus.

Scalability is a big issue.

→ Finding “good” configurations is a highly relevant research direction with immediate industrial applicability.

Specifics: Schedule Synthesis



- IEEE 802.1Qbv defines Gate Control Lists (GCLs)
- The generation of the GCLs is quite challenging.
- There is already an increasing body of literature, and growing.
- We need to make sure that we address the same problem.
- We have formulated a reference set of constraints for IEEE 802.1Qbv.

Craciunas, Silviu S., Ramon Serna Oliver, and Wilfried Steiner.
"Formal Scheduling Constraints for Time-Sensitive Networks."
arXiv preprint arXiv:1712.02246 (2017).

- *Once the constraints are standardized, each vendor can produce schedules by whatever means and tricks available; a successful consistency check with the standardized constraints guarantees interoperability.*

→ The development of such means and tricks is a research direction with immediate industrial impact.

Specifics: Clock Synchronization Configurations

TTTech

How to configure IEEE 802.1AS to achieve specific requirements in one or many of the domains:

- Precision: maximum deviation of any two local clocks)

  Gutiérrez, Marina, Wilfried Steiner, Radu Dobrin, and Sasikumar Punnekkat. "Synchronization quality of ieee 802.1 as in large-scale industrial automation networks." In Real-Time and Embedded Technology and Applications Symposium (RTAS), 2017 IEEE, pp. 273-282. IEEE, 2017.

- Security: to protect the synchronized time against attacks

  Lisova, Elena, Marina Gutiérrez, Wilfried Steiner, Elisabeth Uhlemann, Johan Åkerberg, Radu Dobrin, and Mats Björkman. "Protecting clock synchronization: adversary detection through network monitoring." Journal of Electrical and Computer Engineering 2016 (2016).

- Fault-tolerance: tolerate a configurable number of faulty clocks with given failure semantics

The assessment of how the proposed configurations satisfy a given requirement or set of requirements is a key aspect, e.g., experimental evaluation of fault-tolerance is typically not sufficient.

→ Clock synchronization configurations that achieve provable performance qualities and quantities are research directions with immediate industrial impact.

Where to Compute and How to Deploy Configurations

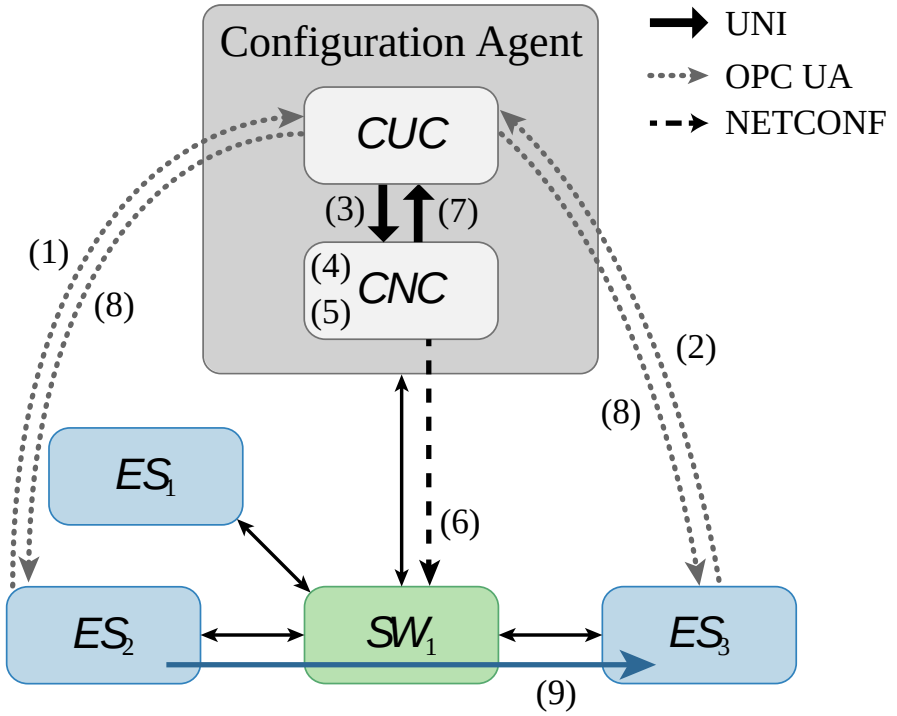
Publish-Subscribe Paradigm and Software-Defined Networking (SDN) become more and more important.

Openflow is a well-known SDN standard in various domains, e.g., telecom networks, IT networks.

In TSN we look into Netconf (and/or RESTconf) as protocol stack to deploy configurations and YANG as the data model for the TSN configuration.

OPC UA serves as the higher-layer protocol that articulates the communication requirements of applications to TSN, i.e., OPC UA replaces the manual formulation of communication requirements.

A “Central User Configuration (CUC)” registers this communication requirements and triggers a “Central Network Configuration (CNC)” to generate new TSN schedules and to deploy them in the network.



→ Demonstration of these workflows and proposals of efficiency improvements are research directions with immediate industrial impact.

Gutiérrez, Marina, Astrit Ademaj, Wilfried Steiner, Radu Dobrin, and Sasikumar Punnekkat. "Self-configuration of IEEE 802.1 TSN networks." In *Emerging Technologies and Factory Automation (ETFA), 2017 22nd IEEE International Conference on*, pp. 1-8. IEEE, 2017.

TSN Deployment and Integration in Large-Scale Systems and in “Brown-Field” Installations

TTTech

“Green-field” installations are the ones that are built entirely from scratch, e.g., a new factory.

“Brown-field” installations are TSN deployments in existing systems, i.e., upgrades to an existing infrastructure.

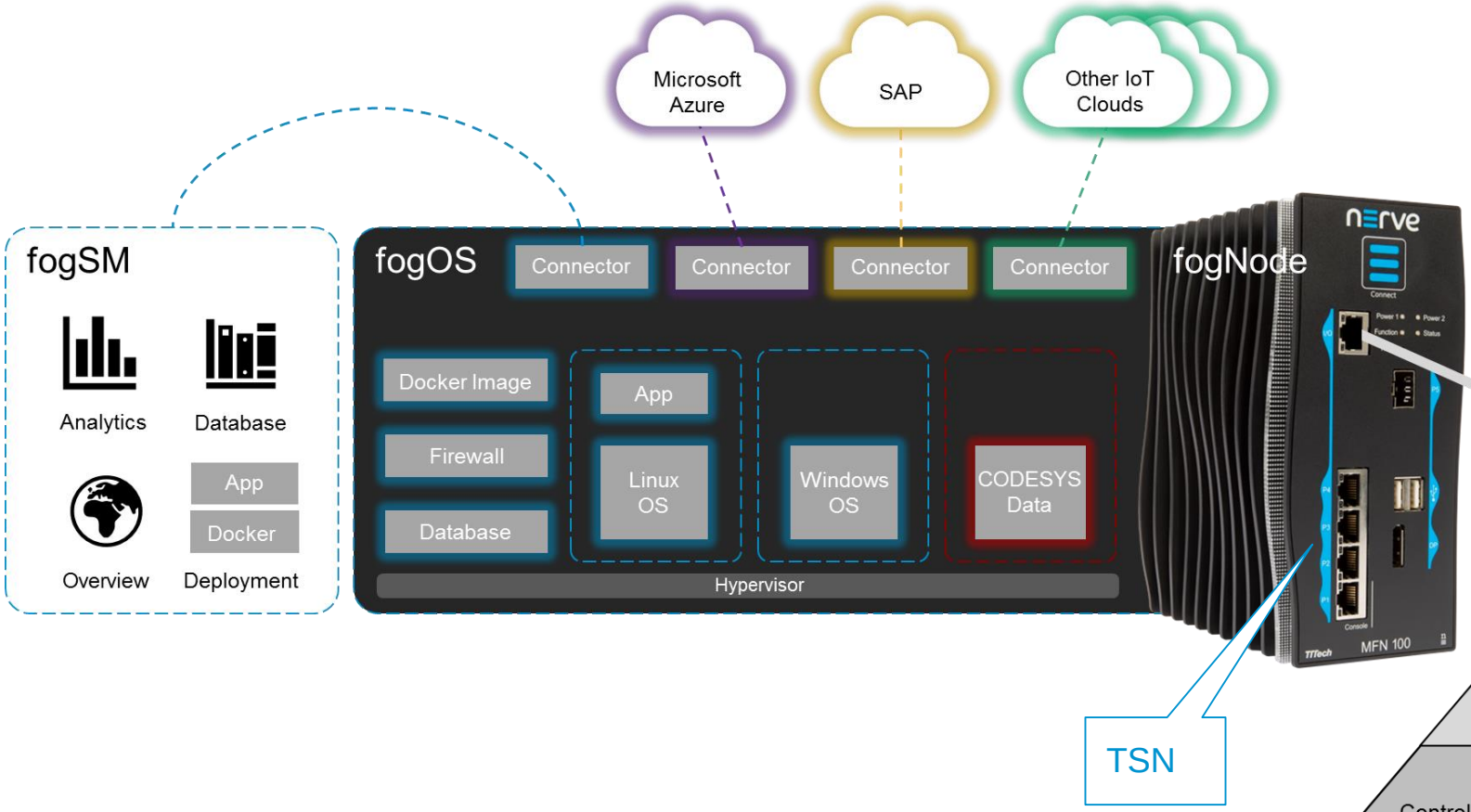
How can we still give guarantees on the network behavior if some of the participants do not play according the rules?

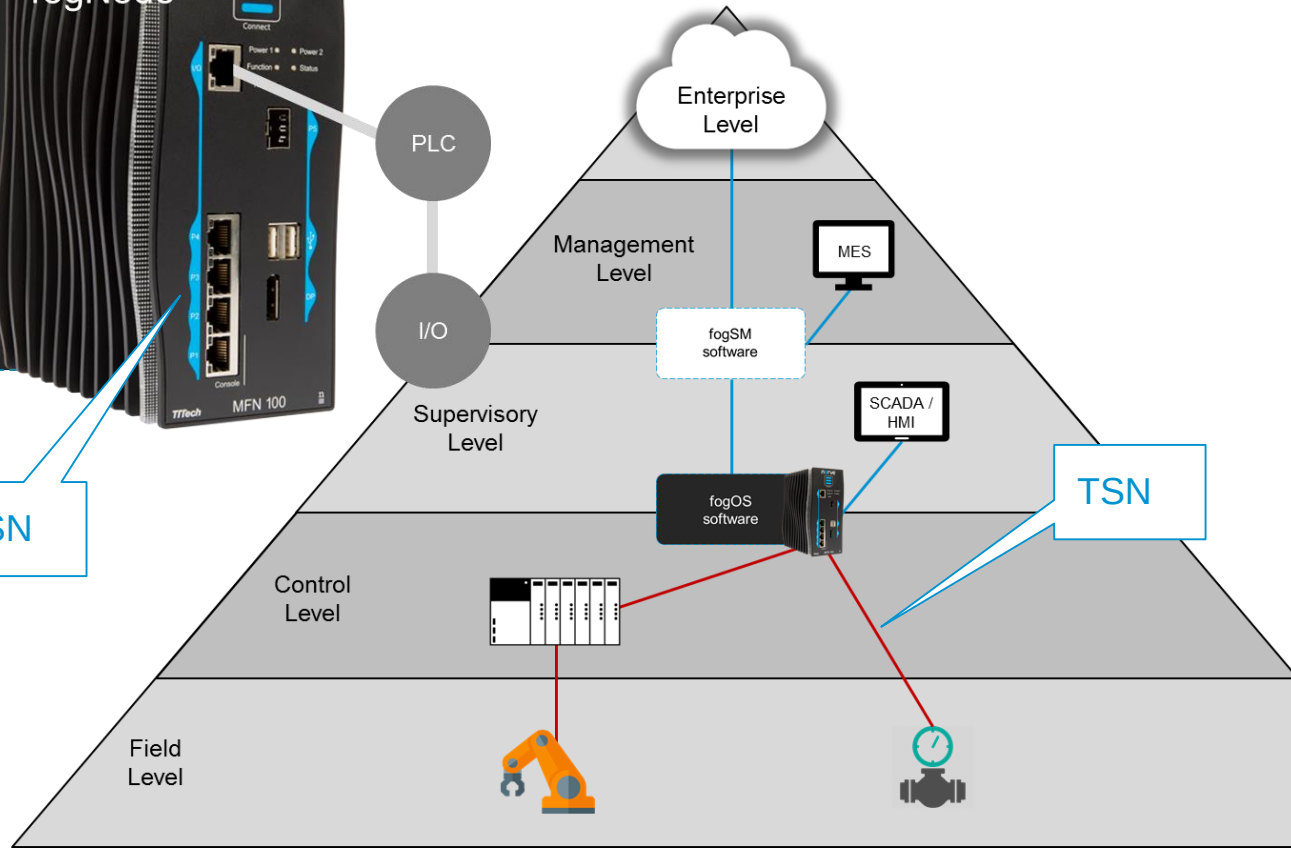
What is the minimum functionality that non-TSN components must exhibit?

→ The development of such means and tricks is a research direction with immediate industrial impact.

Fog Computing and the Automation Pyramid

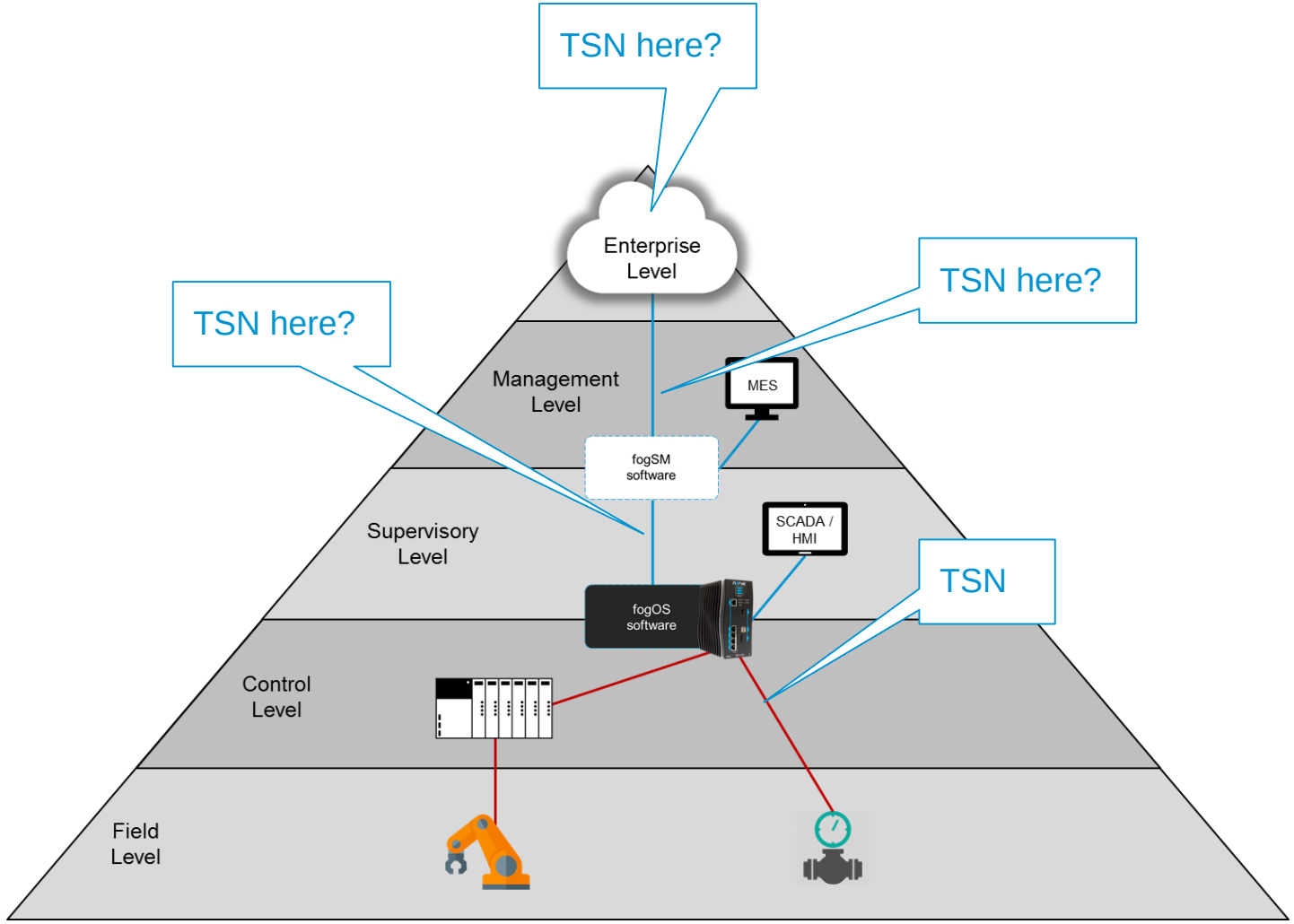
FORA Marie Curie:
www.fora-etn.eu





→ Understanding and analyzing TSN in the context of Fog Computing is a research direction with likely industrial impact.

Deterministic Internet (IETF detnet)



→ Deterministic communication beyond layer two has likely industrial impact.

→ But only when deployable on existing infrastructures.

Alternative protocols and data plane modifications

→ Research directions with the target to identify shortcomings and bugs in TSN have high industrial impact.

Alternative protocols and data plane modifications

TTTech

→ Research directions with the target to identify shortcomings and bugs in TSN have high industrial impact.

→ Research directions that put forward alternative solutions to TSN with same or similar performance will likely have little industrial impact.

05

Conclusions

Conclusions

Incompatibilities between real-time communication standards and solutions are slowing down technical advancements.

Ethernet emerges as communication standard for various industries.

In real-time critical industries, many different variants of real-time Ethernet have been developed.

IEEE 802.1 TSN has the potential to become the new baseline in real-time communication in almost all application areas.

Research that is baselined on TSN will most likely have industrial impact.

Vienna, Austria (Headquarters)	Germany	USA	Japan	China
Phone +43 1 585 65 38-5000 office@tttech-automotive.com	Phone +49 841 88 56 47-0 office@tttech-automotive.com	Phone +1 978 933 7979 usa@tttech.com	Phone +81 52 485 5898 office@tttech.jp	Phone +86 21 5015 2925-0 china@tttech.com

www.tttech-automotive.com