Use Cases – IEEE P802.1DG V0.3

Contributor group

This document is created by Don Pannell. If you wish to be a Contributor to this document, whether or not you wish your name to be listed below, please contact Don at donald.pannell@nxp.com. Feedback is welcome! Please e-mail corrections/issues with suggested text.

Dorr, Josef <josef.dorr@siemens.com> - for the source format of this document
Pannell, Don <donald.pannell@nxp.com> - this document creator
Potts, Mike <mike.potts@gm.com> - for Use Case presentations
Zinner, Helge <helge.zinner@conti.de> - for Use Case presentation

Abstract

This document summarizes use cases relevant to Automotive Time Sensitive Networking (TSN), along with their associated requirements. It will be used by the IEEE P802.1DG editor to create the standard. The IEEE P802.1DG project's title is: "TSN Profile for Automotive In-Vehicle Ethernet Communications."

The enclosed use cases are intended to guide the specification process: WHAT shall be part of the standard and WHY. Then the content of IEEE P802.1DG standard specifies the HOW to achieve these use cases.

Some use cases are on a system level of an automotive system, even if the scope of IEEE P802.1DG does not cover the overall system level. The IEEE P802.1DG should enable or at least do not prevent the features described in this use case document. Example use cases that are currently outside the scope of the P802.1DG standard are those using wireless interfaces, but these uses clearly impact the "Ethernet Communications" use in the vehicle.

This document is intended an aide to the formation of the IEEE P802.1DG standard.

THIS DOCUMENT IS NOT THE STANDARD!!

Log

V0.1	2019-May-20	First version – to show structure and flow only.
V0.2	2019-May-21	First version text with Industrial text showed in Black & the new Automotive text showed in Green so that the new Automotive text is easier to see.
V0.3	2019-July-17	Automotive text set to Black, creator's notes set to Green, & kept Industrial text set to Purple. Most Industrial use cases removed & Automotive use cases started to be added (Use Case 1 & 2 finished).
		-
		-

Content

Figures

Tables

1 Definitions and Terms

<<creator's note: The Definitions & Terms listed below are some Automotive specific definitions that have been added along with examples as listed in the Industrial Use Case document. This list will be updated & added to as needed. The intended edits for the next revision are marked. Suggestions of what should be kept or deleted is requested.>>

1.1 Definitions

ADAS	Adaptive Driver Assistance System – needed for autonomous driving
ADAS Level	Autonomous driving capability levels as defined by the Society of Automotive Engineers (SAE) Level 0: Driver controls it all, to Level 5: Fully autonomous in all environments/scenarios (no steering wheel necessary). See: https://www.techrepublic.com/article/autonomous-driving-levels-0-to-5-understanding-the-differences/
CAN(-FD)	Controller Area Network - a vehicle bus standard, '-FD' stands for the Flexible Data-rate extension
DC	Domain Controller
ECU	Electronic Control Unit
LIN	Local Interconnect Network - a vehicle bus standard
OEM	Original Equipment Manufacturer – In Automotive: The Car Maker
Tier 1	In Automotive: typically, a subsystem/ECU supplier
Tier 2	In Automotive: typically, a silicon supplier
Reconfiguration	Any intentional modification of the system structure or of the device-level content, including updates of any type
Operational state	Normal state of function of a unit
Maintenance state	Planned suspension or partial suspension of the normal state of function of a unit
Stopped state	Full non-productive mode of a unit
Convergent network concept	All LAN devices (wired or wireless) can exchange data over a common infrastructure, within defined QoS parameters <<creator's note: TSN over wireless media is outside the scope of IEEE P802.1DG (it's title specifically states Ethernet Communications), the include of wireless devices in use cases may be needed to show the system level need.>>

Device	End station, bridged end station, bridge, access point
Transmission selection algorithms	A set of algorithms for traffic selection which include Strict Priority, the Credit-based shaper and Enhanced Transmission Selection.1)
Preemption	The suspension of the transmission of a preemptable frame to allow one or more express frames to be transmitted before transmission of the preemptable frame is resumed.1)
Enhancements for scheduled traffic	A Bridge or end station may support enhancements that allow transmission from each queue to be scheduled relative to a known timescale.1)
Time-Sensitive Stream	A stream of traffic, transmitted from a single source station, destined for one or more destination stations, where the traffic is sensitive to timely delivery, and, requires transmission latency to be bounded.1)
TSN domain	A quantity of commonly managed devices; A set of devices, their Ports, and the attached individual LANs that transmit Time-Sensitive Streams using TSN standards which include Transmission Selection Algorithms, Preemption, Time Synchronization and Enhancements for Scheduled Traffic and that share a common management mechanism. It is an administrative decision to group these devices (see 4.16).
universal time domain	gPTP domain used for the synchronization of universal time
working clock domain	gPTP domain used for the synchronization of a working clock
isochronous domain	Devices of a common working clock domain with a common setup for the isochronous cyclic real-time traffic type
cyclic real-time domain	Devices with a common setup for the cyclic real-time traffic type - even from different working clock domains or synchronized to a local timescale
Network cycle	Transfer time including safety margin, and application time including safety margin; values are specific to a TSN domain and specify a repetitive behavior of the network interfaces belonging to that TSN domain;
Stream forwarding	Forwarding of stream data along the stream path including TSN domain boundary crossings

140
1.2 IEEE 802.1 Terms

Priority regeneration	See IEEE 802.1Q-2018 clause 6.9.4 Regenerating priority
Ingress rate limiting	See IEEE 802.1Q-2018 clause 8.6.5 Flow classification and metering

141

---

[1] taken from 802.1Q-2018

2 TSN in Automotive

<<creator's note: The Industrial Use Case document used this section to describe Cyber-Physical Systems and then cover generic topics such as Interoperability, TSN Domains, Synchronization, etc. These topics are now in Section 4, Saved Industrial Concepts that may be Relevant to Automotive,

I propose this section 2 can be a brief overview of non-Ethernet in-vehicle networks and where & why Ethernet came into the Automotive picture. Alternatively, this section could be a summary of the topics described in Section 3 Automotive modes of operation – the Use Cases and Section 3 will be support material for this Section 2. If people feel this is not needed, this section would just be an overview of what comes below.>>

3 Automotive modes of operation – the Use Cases

Each use case below, starts with a link to its source material (if available). The words in each use case are the interpretations of the creator of this document. It is up to the author of the source material to make sure that this interpretation is correct. Once this verification is obtained, it will be marked as ‘Reviewed by original author’.

3.1 Auto Use Case 01: Example Automotive Networks

Source material: http://www.ieee802.org/1/files/public/docs2019/dg-zinner-automotive-architecture-evolution-0319-v02.pdf <<Reviewed by original author – goes here>>

3.1.1 Traditional Model

A traditional, or present-day automotive network architectures for many can makers, are shown in Figure 1. These networks typically contain a Central Gateway ECU (top box in the left figure) with point-to-point communion between all the application specific ECUs. Most ECU’s are connected using non-Ethernet connections such as CAN, LIN, etc.

Ethernet links are limited to only those that require higher bandwidth (shown as the bold blue lines in the left figure or labeled in the right figure). The DC ECU in the right figure is a Domain Controller which will be discussed in the next section.

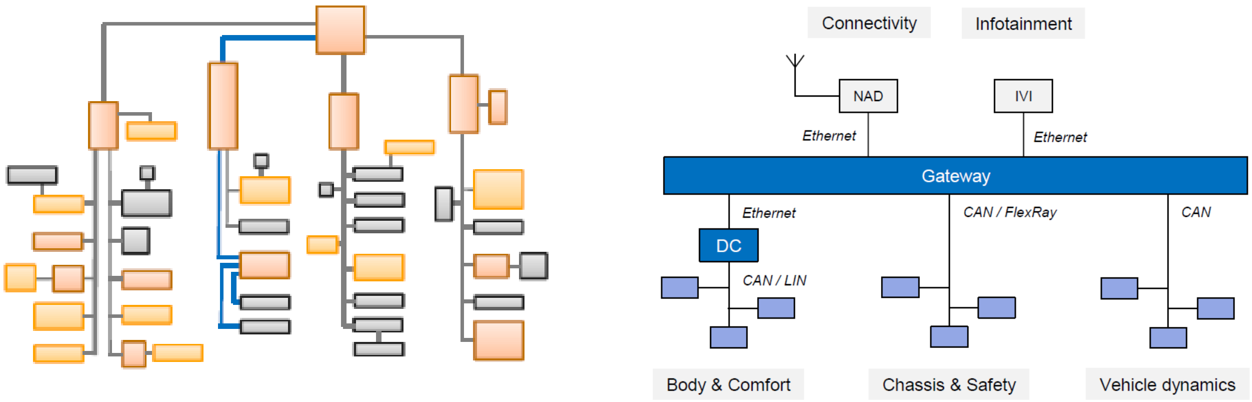

Figure 1 – Examples of Traditional or Central Gateway Automotive Networks

3.1.2 Domain Model

Examples of Domain automotive network architectures are shown in Figure 2. Domain networks are the current focus of many OEMs today. Ethernet is a clear enabler for these types of networks due to Ethernet’s speeds and its support for the OSI Layer model.

Many OEMs want their ECU applications to communicate using IP so that the underlying physical connections are abstracted from the application. This allows a fully working ECU & application in one car model to be reused in another car model even if the underlying network is of a different speed and/or topology.

Domain networks can also work modularly. This allows a common architecture to work for full feature high-end cars, mid-range cars and low-end versions of a given car model. For example, the ADAS ECU can be easily removed for those models that won’t support autonomous driving.

And/or the infotainment ECU can be scaled in quality/performance to meet the desired price point of the car (right figure).

Ethernet links can be used to connect the Domain Controllers (DC) together (depending upon the link's needed bandwidth) where the left figure shows possible redundancy support via the dotted line connection making a ring. Ethernet may be used more extensively below each Domain Controller as well (shown as the bold blue lines in the left figure or labeled in the right figure). Multiple connections to some ECU's are also shown in the left figure. These connections could be for redundancy or one set of the connections could be from an ADAS ECU so that it can autonomously drive the car.

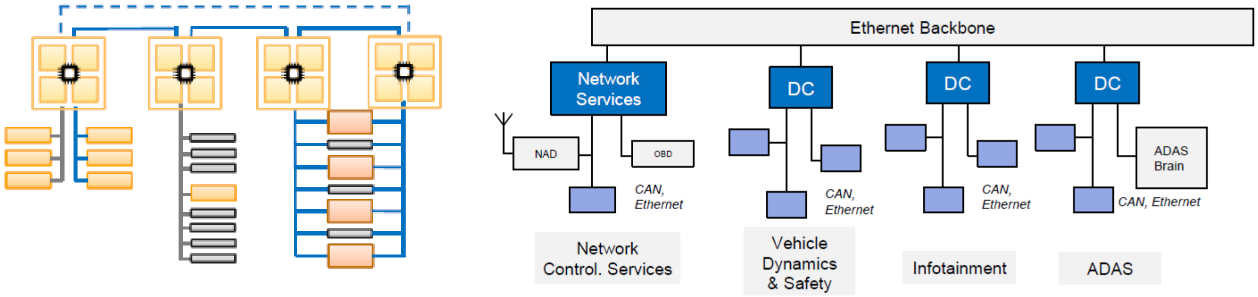

Figure 2 – Examples of Domain Automotive Networks

3.1.3 Zonal Model

Examples of Zonal automotive network architectures are shown in Figure 3. Zonal networks are sometimes called Centralized, as many implementations use centralized processing. But Zonal networks could equally well support a distributed processing implementation for physically separated processing redundancy. As this document focuses on the network only, this model is called Zonal here.

Zonal networks are seen by many as the flexible networking solution. It separates the car into topological zones where the many functions of the car, which were physically isolated in the Domain model, are now sharing the same physical wire. Ethernet's scalable bandwidth & Time Sensitive Networking's (TSN) capabilities become requirements here, on top of the OSI layering and IP requirements being used in Domain networks (section 3.1.2). Some of the driving forces for this change are:

- A large reduction in the size, weight, cost & complexity of the wiring harness
- Any data can go anywhere which saves bandwidth (i.e., no need to replicate the data), and it supports new features via over the air (OTA) updates
- The same architecture & ECUs (end nodes) can be used for both low-end, mid-range & high-end car models reducing the development overhead
- Easily made redundant using the techniques described in multiple TSN standards

This model also brings challenges:

- Requires the implementer to be familiar with IEEE 802 networking, IEEE 802.1Q and its TSN standards (as many implementers are used to the current automotive bus standards)
- Requires the implementor to trust that the TSN standards work ("I have to share my wire with Infotainment? I used to have my own wire, so I knew it always worked!")
- It must solve functional safety and security concerns.

Zonal supports a Brownfield network model. In each zone, a Zone Controller can be used to connect to existing ECUs using that ECU's native connection technology. Gateways in the Traditional model (section 3.1.1) and Domain Controllers in the Domain model (section 3.1.2) already do this.

The left figure shows limited redundancy while the right figure shows full redundancy for the TSN network. The Zonal Controllers are the boxes with leaf nodes connected to them (in both figures). The right figure shows the ADAS camera data using separate links, as today, the total bandwidth for multiple raw video streams is more than what the Ethernet TSN Backbone could handle. But history shows us that this will not always be the case.

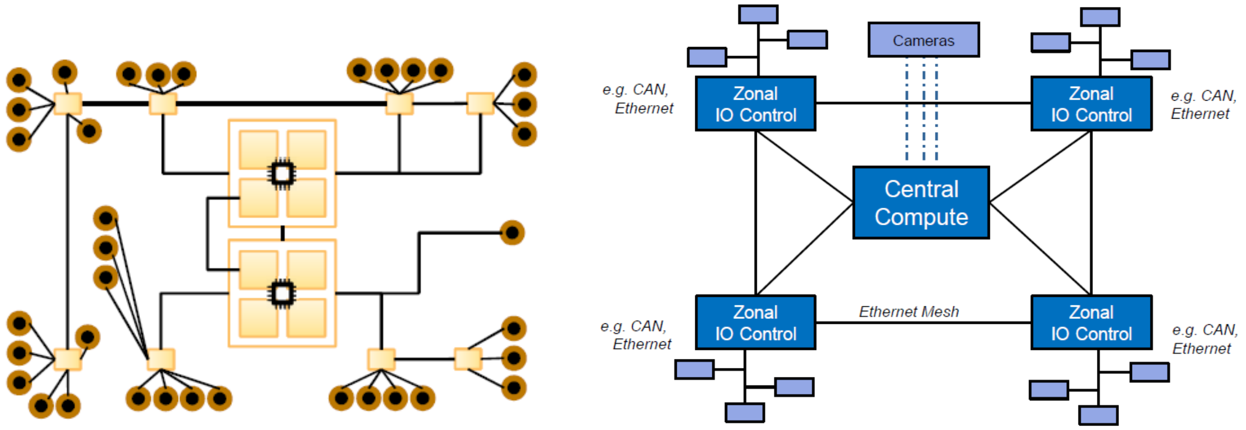

Figure 3 – Examples of Zonal Automotive Networks

3.1.4 Characteristics

Network topology	**Traditional**	**Domain**	**Zonal**
~ # hops for a stream	1-2	2-4	3-6
Link Speed	100 Mb/s	100 Mb/s to 10 Gb/s	100 Mb/s to 50 Gb/s
# of Ethernet Links	< 10	10 to 50	> 50
Stream Congestion points	0 to 1	1 to 3	2 to 5
~E2E Latency needs	10's of mSec	1s to 10's of mSec	10's to 100's of uSec
~Time Sync between any 2 nodes	1 mSec	1 mSec	10 uSec

3.1.5 Requirements from this use case

R1.1	The profile needs to be flexible as the example figures above show that every car manufacturer uses their own network architecture.
R1.2	
R1.3	

3.2 Auto Use Case 02: Example Automotive Ethernet Devices

Source material: http://www.ieee802.org/1/files/public/docs2019/dg-zinner-automotive-architecture-evolution-0319-v02.pdf <<Reviewed by original author – goes here>>

3.2.1 Classes of Ethernet Devices

TSN endpoints

1. single port talker/listener
    a. focus: safety relevant data processing e.g. server, antenna module
    b. other:
2. single port talker only (back channel data is not time critical)
    a. focus: safety relevant sensors for ADAS (Cameras, Radars, Lidars,…)
    b. other: microphone
3. single port listener only (back channel data is not time critical)
    a. focus: safety relevant actuators (steering, braking, display)
    b. other: speaker

TSN bridges

1. 3-port bridge (supports ring topology)
2. access bridge (interface to outside vehicle networks)
    a. focus: security
3. aggregation bridge (low port count)
4. aggregation bridge (high port count)

3.2.2 Requirements from this use case

R2.1	Multiple device classes for End Stations and for Bridges need to be listed and the capabilities/requirements for each need to be specified.
R2.2	The capabilities/requirements need to be specified for a single hop taking into consideration the needs of the E2E system.
R2.3	

3.3 Auto Use Case 03:

<<creator’s note: New Use Case goes here.>>

3.3.1 Requirements from this use case (or Summary?)

<<creator’s note: It is the intention that the Requirements for each Use Case will be listed at the end of each Use Case. This way it acts as a summary. This approach may need to be adjusted as this document progresses.>>

4 Saved Industrial Concepts that may be Relevant to Automotive

<<creator's note: This section contains summaries of some of the Use Case sections from the Industrial TSN Profile Use Case document. IA stands for Industrial Automation. These Use Case numbers do not line up with the Industrial Use Case document's numbers as many sections from that document were not included.

These section summaries are left in this document to act as stimulus for potential Automotive Use Cases.>>

4.1 IA Use Case 01: Isochronous Control Loops with guaranteed low latency

Control loops with guaranteed low latency implement an isochronous traffic pattern for isochronous applications, which are synchronized to the network access. It is based on application cycles, which consists of an IO data Transfer time and an Application time wherein the control loop function is executed.

4.2 IA Use Case 02: End Stations without common application cycle

The cycle time requirements of different vendors may be based on their technology, which cannot be changed with reasonable effort. These requirements may be based on hardware dependencies, independent of the capabilities of the communication part of the device.

4.3 IA Use Case 03: Non-Isochronous Control Loops with bounded latency

Control loops with bounded latency implement a cyclic traffic pattern for non-isochronous applications, which are not synchronized to the network access but are synchronized to a local timescale.

4.4 IA Use Case 04: 10 Mbit/s End-Stations (Ethernet sensors)

Simple and cheap sensor end-stations are directly attached via 10 Mbit/s links to the machine internal Ethernet and implement cyclic real-time communication with the PLC.
The support of additional physics like "IEEE 802.3cg APL support" is intended.

Requirement:

Support of 10 Mbit/s or higher link speed attached sensors (end-stations) together with POE and SPE (single pair Ethernet).

Useful 802.1Q/TSN mechanisms:

- …

4.5 IA Use Case 05: Legacy IVN Bus Gateway

Gateways are used to integrate non-Ethernet and Ethernet-based busses into TSN domains.

Many systems have at least one merging unit (e.g gateway, multiplexer) between the sensors and actuators assigned to a single machine control. The clustering is typically done with some infrastructure elements (slices) that require a backplane communication.

Requirement:

- Support of non-Ethernet and Ethernet-based bus devices via gateways either transparent or hidden;
- TSN scheduling may need configuration to meet the requirements of subordinate systems;

4.6 IA Use Case 06: Mixed link speeds

Industrial use cases refer to link speeds, as shown in Table 1, in the range from 10 Mbit/s to 10 GBit/s for Ethernet and additional Wi-Fi, Bluetooth and 5G. Thus, the TSN domains need to handle areas with different link speeds.

Table 1 – Link speeds

Link speed	Media	Comments
100 kbit/s – 3 Mbit/s	Radio Bluetooth	These devices are connected thru a Bluetooth access point. They may be battery powered.
1 Mbit/s – 1 Gbit/s	Radio Wi-Fi	These devices are connected thru a Wi-Fi access point. They may be battery powered.
1 Mbit/s – 10 Gbit/s (theoretical/expected)	Radio 5G	These devices are connected thru a 5G access point. They may be battery powered.
10 Mbit/s	Copper or fiber	May be used for end station “only” devices connected as leafs to the domain. Dedicated to low performance and lowest energy devices for e.g. process automation. These devices may use PoE as power supply.
100 MBit/s	Copper or fiber	Historical mainly used for Remote IO and PLCs. Expected to be replaced by 1 GBit/s as common link speed.
1 GBit/s	Copper or fiber	Main used link speed for all kind of devices
2,5 GBit/s	Copper or fiber	High performance devices or backbone usage
5 GBit/s	Copper or fiber	Backbone usage, mainly for network components
10 GBit/s	Fiber	Backbone usage, mainly for network components
25 GBit/s – 1 Tbit/s	tbd	Backbone usage, mainly for network components

Mixing devices with different link speeds is a non-trivial task. Figure 4 and Figure 5 show the calculation model for the communication between an IOC and an IOD connected with different link speeds.

The available bandwidth on a communication path is determined by the path segment with the minimum link speed.

The weakest link of the path defines the usable bandwidth. If a topology guideline ensures that the connection to the end-station always is the weakest link, only these links need to be checked for the usable bandwidth.

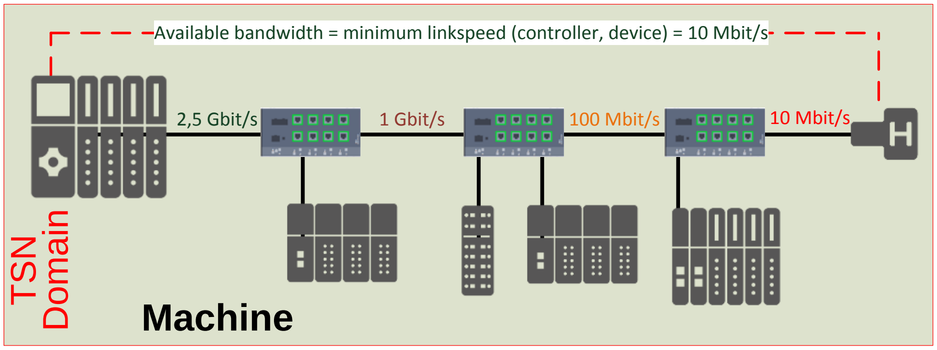

Figure 4 – mixed link speeds

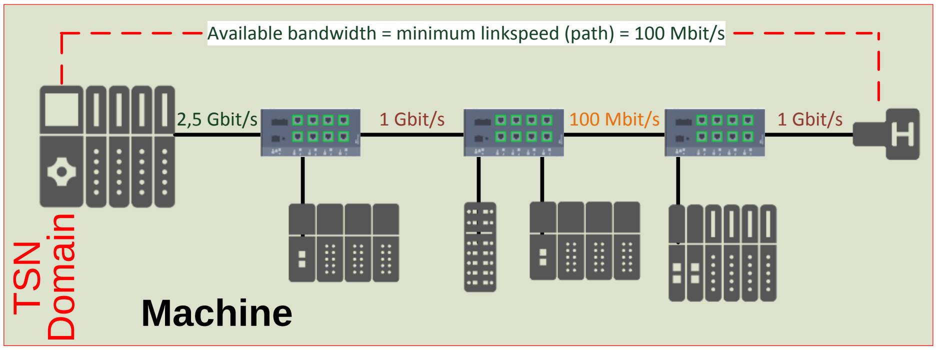

Figure 5 – mixed link speeds without topology guideline

Requirement:

Links with different link speeds as shown in Figure 4 share the same TSN-IA profile based communication system at the same time.
Links with different link speeds without topology guideline (Figure 5) may be supported.

Useful 802.1 mechanisms:

- …

4.7 IA Use Case 07: Dynamic plugging and unplugging of machines

E.g. multiple AGVs (automatic guided vehicles) access various docking stations to get access to the supervisory PLC. Thus, an AGV is temporary not available. An AGV may act as CPS or as a bunch of devices.

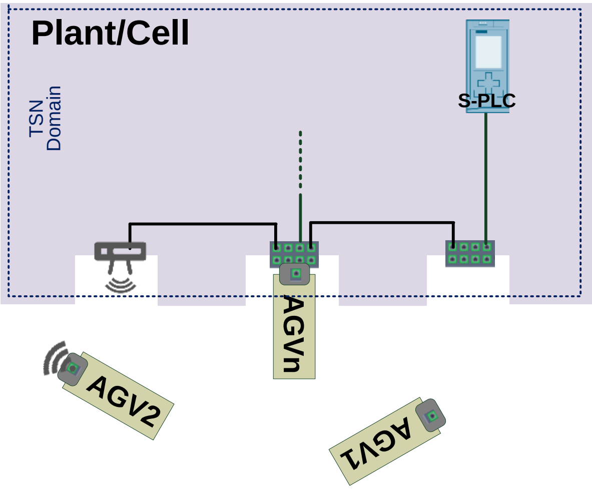

Figure 6 – AGV plug and unplug

Requirement:

The traffic relying on TSN features from/to AGVs is established/removed automatically after plug/unplug events.
Different AGVs may demand different traffic layouts.
The time till operate influences the efficiency of the plant.

Thousands of AGS may be used concurrently, but only a defined amount of AGVs is connected at a given time.

Useful 802.1Q mechanisms:

- preconfigured streams
- …

4.8 IA Use Case 08: Energy Saving

Complete or partial plant components are switched off and on as necessary to save energy. Thus, portions of the plant are temporarily not available.

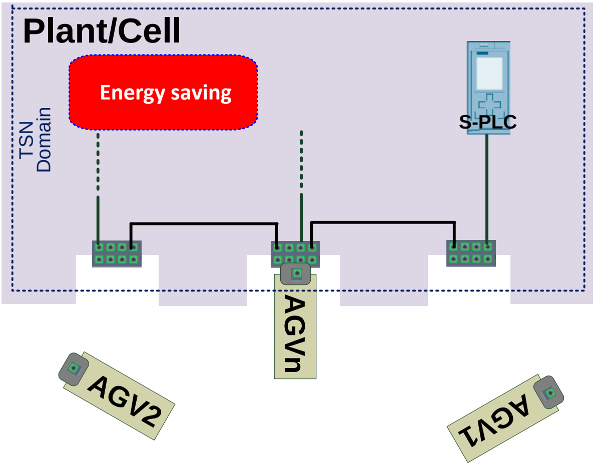

Figure 7 – energy saving

Requirement:

Energy saving region switch off/on shall not create process disturbance.

Communication paths through the energy saving area between end-stations, which do not belong to the energy saving area, shall be avoided.

Useful 802.1Q mechanisms:

- Appropriate path computation by sorting streams to avoid streams passing through energy saving region.

4.9 IA Use Case 09: Multiple applications in a station using the TSN-IA profile

Technology A and B are implemented in PLC and devices.

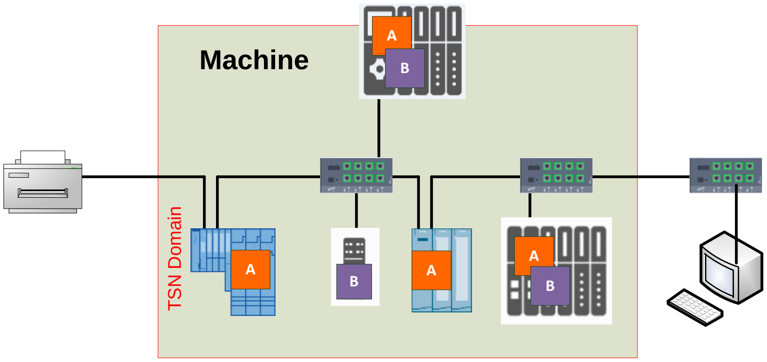

Figure 8 – two applications

Requirement:

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

Useful 802.1 mechanisms:

- …

4.10 IA Use Case 10: Functional safety

Functional safety is defined in IEC 61508 as "*part of the overall safety relating to the EUC [Equipment Under Control] and the EUC control system that depends on the correct functioning of the E/E/PE [electrical/electronic/programmable electronic] safety-related systems and other risk reduction measures*"

IEC 61784-3-3 defines a safety communication layer structure, which is performed by a standard transmission system (black channel), and an additional safety transmission protocol on top of this standard transmission system.

The standard transmission system includes the entire hardware of the transmission system and the related protocol functions (i.e. OSI layers 1, 2 and 7).

Safety applications and standard applications are sharing the same standard communication systems at the same time.

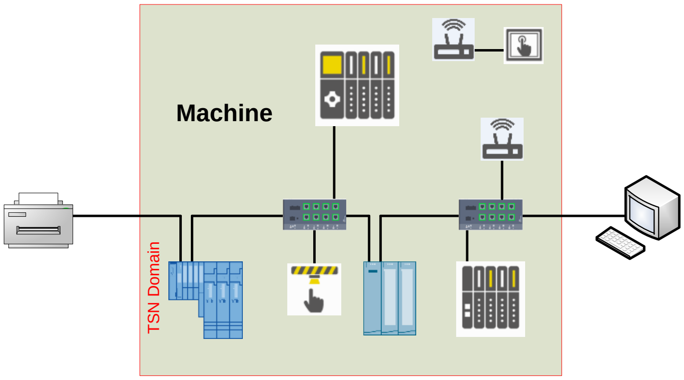

Figure 9 – Functional safety with cyclic real-time

Requirement:

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

Useful 802.1 mechanisms:

- …

4.11 IA Use Case 11: Network monitoring and diagnostics

Diagnostics plays an important role in the management of systems and of devices. Industrial automation requires a method for quick reaction to failures. The error reaction shall limit the damage caused by the error and minimize the machine downtime.

The error detection shall be done within a few cycles (exact value is depending on the application) and reaction shall be specified precisely in the case of an error. Machine stop is not always the right reaction on errors. This reaction can be located at the talker and listener.

Repairs are done by the service persons on site which have no specific communication knowledge. The indication of the components which have to be repaired shall occur within a few seconds. Machines are powered down during the repair. A typical repair time goal is below 15 min. This includes the restart of a machine and the indication that the problem is solved.

Generally speaking the mechanisms used in this context are acyclic or having large cycle times so that they could perhaps be considered, from a networking perspective as sporadic. Most of the use cases related to diagnostics will be included in this category.

- Quick identification of error locations is important to minimize downtimes in production (see also Sequence of events).
- Monitoring network performance is a means to anticipate problems so that arrangements can be planned and put into practice even before errors and downtimes occur.
- Identification of devices on an industrial Ethernet network shall be done in a common, interoperable manner for interoperability on a converged TSN network. This identification both needs to show the type of device, and the topology of the network. IEEE 802.1AB, the Link Layer Discovery Protocol (LLDP), provides one possible mechanism for this to be done at layer two, but provides a large degree of variability in implementation.

Requirement:

- Minimize downtime;
- Monitoring and diagnostics data including used TSN features shall be provided, e.g. established streams, failed streams, stream classes, bandwidth consumption, …;
- A discovery protocol such as IEEE 802.1AB shall be leveraged to meet the needs of TSN-IA;
- Reporting of detailed diagnostics information for TSN features shall be supported.

Useful 802.1 (ietf) mechanisms:

- MIBs (SNMP)
- YANG (NETCONF/RESTCONF)
- …

4.12 IA Use Case 12: Security

Industrial automation equipment can become the objective of sabotage or spying.
Therefore all aspects of information security can be found in industrial automation as well:

- Confidentiality "is the property, that information is not made available or disclosed to unauthorized individuals, entities, or processes."
- Integrity means maintaining and assuring the accuracy and completeness of data.
- Availability implies that all resources and functional units are available and functioning correctly when they are needed. Availability includes protection against denial-of-service attacks.
- Authenticity aims at the verifiability and reliability of data sources and sinks.

Requirement:

Optional support of confidentiality, integrity, availability and authenticity.
Security shall not limit real-time communication

Protection against rogue applications running on authenticated stations are out of scope.

Useful mechanisms:

- 802.1X
- IEC62443
- …

4.13 IA Use Case 13: Firmware update

Firmware update is done during normal operation to make sure that the machine e.g. with 1000 devices is able be updated with almost no down time.

With bump: separate loading (space for 2 FW versions required) and coordinated activation to minimize downtime

Bumpless: redundant stations with bumpless switchover – the single device may lose connection (bump)

Requirement:

Stations shall be capable to accept and store an additional fw version without disturbance.

Useful 802.1 mechanisms:

- …

4.14 IA Use Case 14: Virtualization

Workload consolidation is done by virtualizing the hardware interfaces. Even in such kind of environment the TSN features according to the TSN-IA profile shall be available and working.

vSwitch / vBridge

Figure 10 and Figure 11 show the two principle setups for an Ethernet communication concept allowing both, communication VM to Ethernet and VM to VM. The applications inside the VM shall not see, whether they communicate to another VM or an Ethernet node.

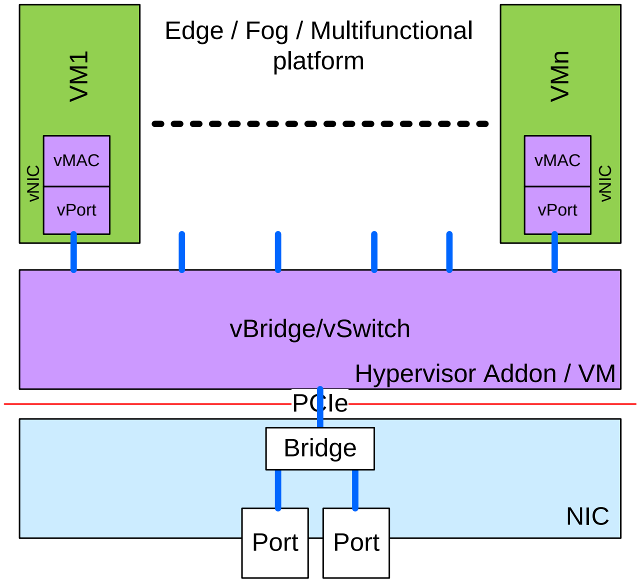

Figure 10 – Ethernet interconnect with VM based vBridge

Figure 10 scales for an almost infinite amount of VMs, because the memory bandwidth and the compute power of the vMAC/vPort and vSwitch/vBridge VM are much higher than the PCIe bandwidth to the NIC.

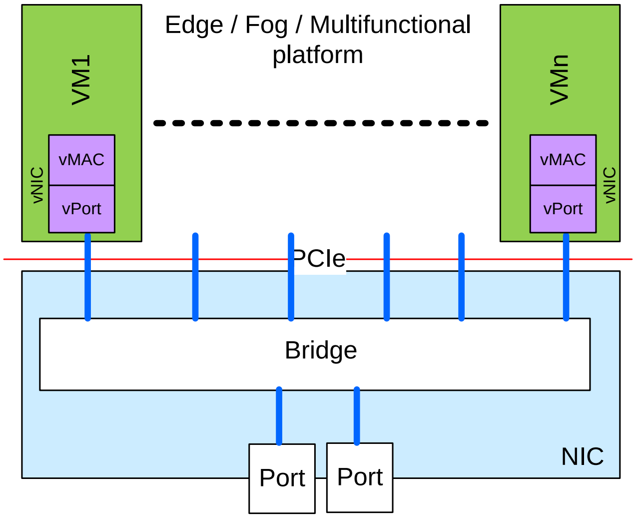

Figure 11 – Ethernet interconnect with PCIe connected Bridge

Figure 11 fits for a limited amount of VMs, because it saves the additional vSwitch/vBridge VM. For a given amount of VMs, e.g. PCIe Gen3 x4 or Gen4 x4, seems to be sufficient.

Requirement:

vBridge and vPort should behave as real Bridge and real Port: data plane, control plane, ...
vBridge and vPort can become members of TSN domains.
Should work like use case “multiple applications”

Useful 802.1 mechanisms:

- …

4.15 Interoperability

<<creator’s note: What parts of this section from the Industrial Use Case document are applicable to Automotive? Clearly there is a desire for interoperability of devices. But Automotive is historically static in its network construction, even if the flows of streams are altered by firmware updates.>>

Interoperability may be achieved on different levels. Figure 12 and Figure 13 show three areas, which need to be covered:

- network configuration (managed objects according to IEEE definitions), and
- stream configuration and establishment, and
- application configuration.

The three areas mutually affect each other (see Figure 12).

Application configuration is not expected to be part of the profile, but the two other areas are.

The selection made by the TSN-IA profile covers IEEE 802 defined layer 2 and the selected protocols to configure layer 2.

Applications make use of upper layers as well, but these are out of scope for the profile.

Stream establishment is initiated by applications to allow data exchange between applications. The applications are the source of requirements, which shall be fulfilled by network configuration and stream configuration and establishment.

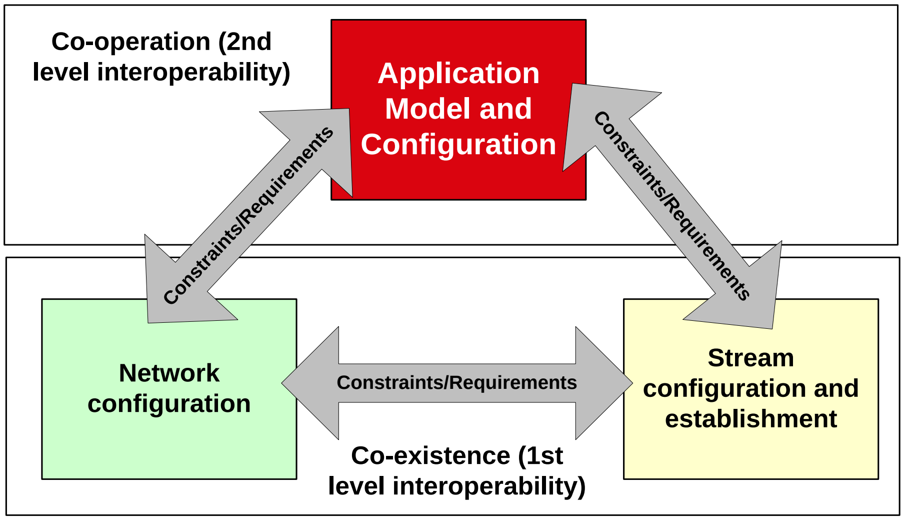

Figure 12 – Principle of interoperation

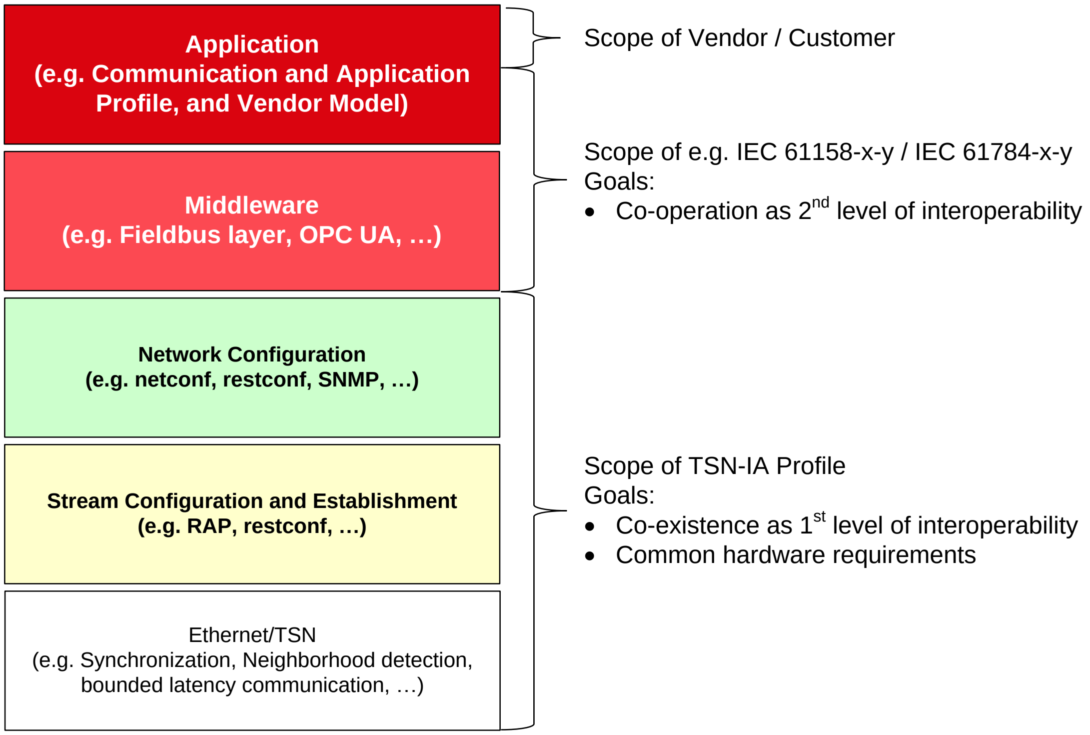

Figure 13 – Scope of work

4.16 TSN Domain

<<creator's note: What parts of this section from the Industrial Use Case document are applicable to Automotive? Is this concept needed for Automotive?>>

4.16.1 General

A TSN domain is defined as a quantity of commonly managed industrial automation devices; it is an administrative decision to group these devices.

TSN Domain Characteristics:

- One or more TSN Domains may exist within a single layer 2 broadcast domain.
- A TSN Domain may not be shared among multiple layer 2 broadcast domains.
- Multiple TSN Domains may share a common universal time domain.
- Two adjacent TSN Domains may implement the same requirements but stay separate.
- Multiple TSN domains will often be implemented in one bridge (see 4.16.2.2).
- Multiple TSN domains will often be implemented in one router (see 4.16.2.3).
- Multiple TSN domains will often be implemented in one gateway (see 4.16.2.4).

Typically machines/functional units constitute separate TSN domains. Production cells and lines may be set up as TSN domains as well. Devices may be members of multiple TSN domains in parallel.

Figure 14 shows two example TSN domains within a common broadcast domain and a common universal time domain. TSN domain 1 is a pure cyclic real-time domain, whereas TSN domain 2 additionally includes three overlapping isochronous domains.

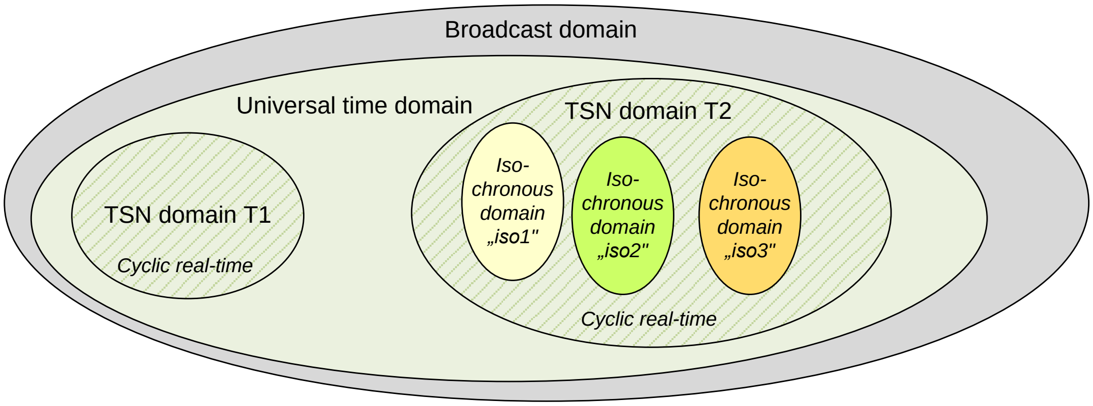

Figure 14 – Different Types of Domains

Interconnections between TSN domains are described in 4.16.2.

4.16.2 Interconnection of TSN Domains

4.16.2.1 General

TSN domains may be connected via

- Bridges (Layer 2), or
- Routers (Layer 3), or
- Application Gateways (Layer 7).

Wireless Access Points or 5G Base Stations may be used to connect TSN domains, too.

4.16.2.2 Bridges (Layer 2)

When a Bridge is member of multiple TSN domains, one bridge port must only be a member of a single TSN domain.

Figure 15 provides an example of two Bridges, which are members of two TSN domains each. Bridge B1 provides ports and connectivity in TSN domain Production Cell 1 and in TSN domain Machine 1, Bridge B2 for Production Line 1 and Production Cell 1.

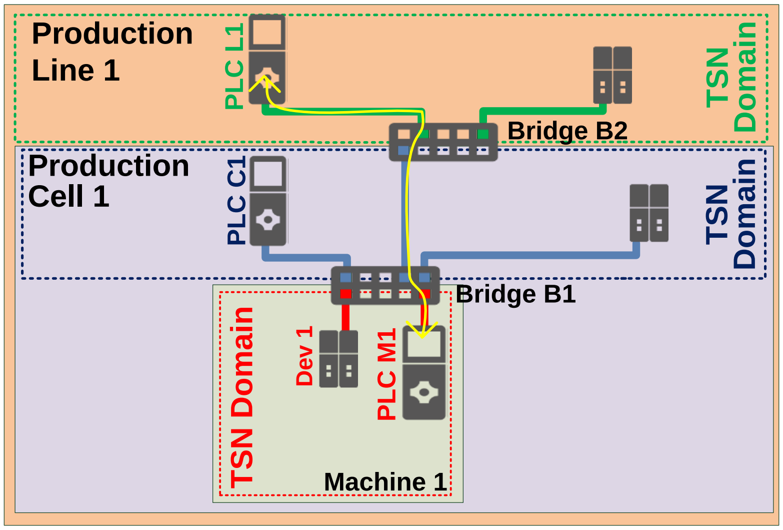

Figure 15 – Three TSN domains connected by Bridges

To support connectivity between multiple TSN domains (e.g. PLC L1 ↔ PLC M1) a method for reserving time-sensitive streams over multiple TSN domains needs to be specified, including:

- find the communication partner,
- identify the involved TSN domains,
- identify the involved management entities independent from the configuration model (centralized, hybrid, fully distributed),
- ensure the needed resources,
- parameterize the TSN domain connection points to allow stream forwarding if needed.

4.16.2.3 Routers (Layer3)

Together with routers, both intranet and internet are possible. In this sub-clause, however, only the intranet use case is addressed.

When a router is member of multiple TSN domains, one router interface/port must only be a member of a single TSN domain. Figure 16 provides an example of two routers, which are members of two TSN domains each. Router R1 provides ports and connectivity in TSN domain Production Cell 1 and in TSN domain Machine 1, Router R2 for Production Line 1 and Production Cell 1.

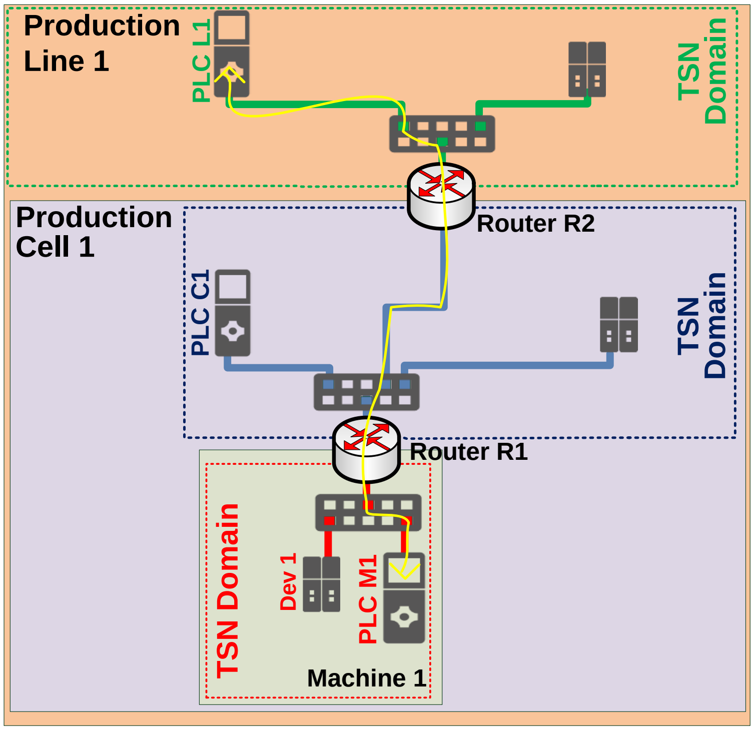

Figure 16 – Three TSN domains connected by Routers

To support connectivity between multiple TSN domains (e.g. PLC L1 ↔ PLC M1) a method for reserving time-sensitive streams over multiple TSN domains needs to be specified, including:

- find the communication partner,
- identify the involved TSN domains,
- identify the involved management entities independent from the configuration model (centralized, hybrid, fully distributed),
- ensure the needed resources,
- parameterize the TSN domain connection points to allow stream forwarding if needed.

4.16.2.4 Application Gateways (Layer7)

When an Application Gateway is member of multiple TSN domains, one gateway interface/port must only be a member of a single TSN domain.

Figure 17 provides an example of two application gateways:

- Gateway CM1 is member in the TSN domains Production Cell 1 and Machine 1;
- Gateway CF1 is member of the TSN domain Production Cell 1 and of Fieldbus 1.

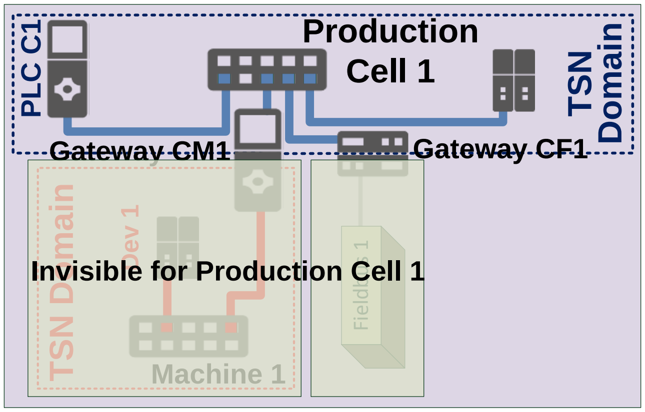

Figure 17 – Gateways with two TSN domains and an attached Fieldbus

Application level gateways do not provide direct access between devices of different TSN domains. Instead the application gateways act as end-stations for TSN domain egress and ingress communication.

An application specific translation of control and data to access adjacent TSN domains may be implemented in the application level gateway to realize TSN domain interconnections. The translation may even involve buffering, collecting and re-arranging of data and control. Thereby application level gateways decouple TSN domains, so that the internal structure and configuration of adjacent TSN domains is not visible respectively.

Application level gateways are also used to connect non-Ethernet- or Ethernet-based fieldbuses to TSN domains (see Gateway CF1 in Figure 17 and see also IA Use Case 05: Legacy IVN Bus Gateway).

4.17 Synchronization

4.17.1 General

Synchronization covering both universal time (wall clock) and working clock is needed for industrial automation systems.

Redundancy for synchronization of universal time may be solved with “cold standby”. Support of "Hot standby" for universal time synchronization is not current practice - but may optionally be supported depending on the application requirements.

Redundancy for working Clock synchronization can be solved with “cold standby” or “hot standby” depending on the application requirements. Support of "hot standby" for working clock synchronization is current practice.

More details about redundancy switchover scenarios are provided in: http://www.ieee802.org/1/files/public/docs2018/60802-Steindl-TimelinessUseCases-0718-v01.pdf.

4.17.2 Universal Time Synchronization

Universal time is used to plant wide align events and actions (e.g. for “sequence of events”). The assigned timescale is TAI, which can be converted into local date and time if necessary. Figure 18 shows the principle structure of time synchronization with the goal to establish a worldwide aligned timescale for time. Thus, often satellites are used as source of the time.

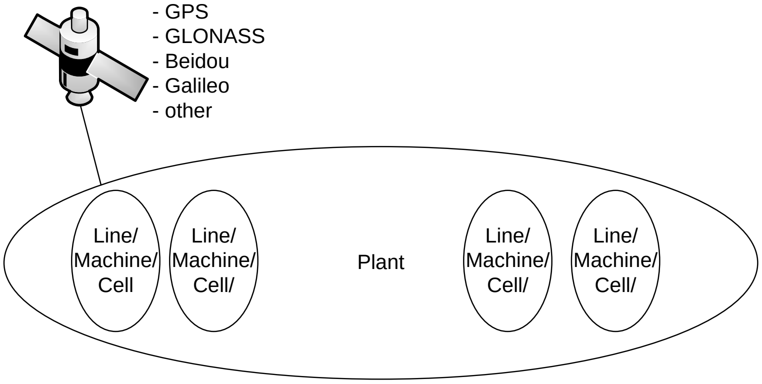

Figure 18 – plant wide time synchronization

Note: “Global Time” or “Wall Clock” are often used as synonym terms for “Universal Time”.

4.17.3 Working Clock Synchronization

Working Clock is used to align actions line, cell or machine wide. The assigned timescale is arbitrary. Robots, motion control, numeric control and any kind of clocked / isochronous application rely on this timescale to make sure that actions are precisely interwoven as needed. Figure 19 shows the principle structure of Working Clock synchronization with the goal to establish a line / cell / machine wide aligned timescale. Thus, often PLCs, Motion Controller or Numeric Controller are used as Working Clock source.

If multiple PLCs, Motion Controller or Numeric Controller need to share one Working Clock timescale (e.g. for scheduled traffic), an all-time active station shall be used as Working Clock source, also known as Grandmaster.

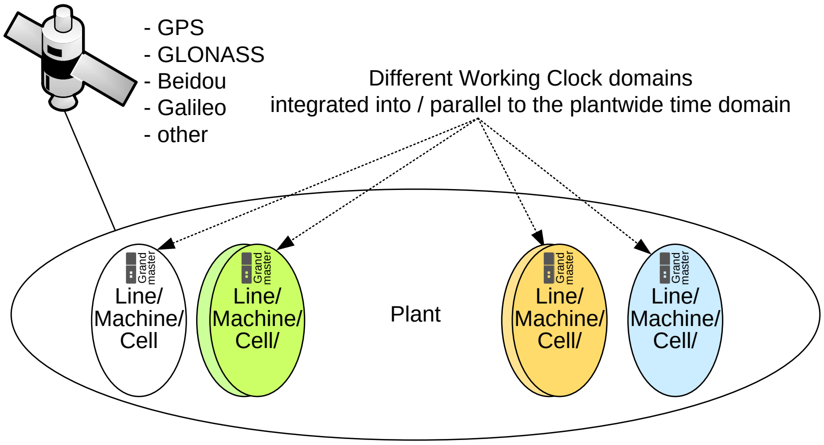

Figure 19 – line/cell/machine wide working clock synchronization overlapping with a universal time domain

Working Clock domains may be doubled to support zero failover time for synchronization.

High precision working clock synchronization is a prerequisite for control loop implementations with low latency (see 3.1).

Requirements:

- High precision working clock synchronization;
- Maximum deviation to the grandmaster time in the range from 100 ns to 1 µs;
- Support of redundant sync masters and domains;
- Zero failover time in case of redundant working clock domains;

Useful 802.1 mechanisms:

- IEEE 802.1AS-Rev

4.17.4 Sequence of events

Sequence of events (SOE) is a mechanism to record timestamped events from all over a plant in a common database.
Application defined events are e.g. changes of digital input signal values. Additional data may be provided together with the events, e.g. universal time sync state and grandmaster, working clock domain and value …

SOE enables root-cause analysis of disruptions after multiple events have occurred. Therefore SOE can be used as diagnostics mechanism to minimize plant downtime.

Plant-wide precisely synchronized time (see Figure 18) is a precondition for effective SOE application.

SOE support may even be legally demanded e.g. for power generation applications.

Requirements:

- Plant wide high precision Universal Time synchronization;
- Maximum deviation to the grandmaster time in the range from 1 µs to 100 µs;
- Optional support of redundant sync masters and domains;

- Non-zero failover time in case of redundant universal time domains;

Useful 802.1 mechanisms:

- IEEE 802.1AS-Rev

4.18 Redundancy

<<creator's note: Redundancy section was added.>>

4.19 Traffic Types

4.19.1 General

Industrial automation applications concurrently make use of different traffic types for different functionalities, e.g. parameterization, control, alarming. The various traffic types have different characteristics and thus impose different requirements on a TSN network. This applies for all use cases described in this document.

Table 2 – Industrial automation traffic types summary

Traffic type name	Periodic/ Sporadic	Guarantee	Data size	Redundancy	Details
isochronous cyclic real-time	P	deadline/ bounded latency (e.g. 20%@1 Gbit/s / 50%@100 Mbit/s network cycle)/ bandwidth	bounded	up to seamless[1]	see and 3.1
cyclic real-time	P	deadline/ bounded latency (e.g. n-times network cycle)/ bandwidth	bounded	up to seamless[1]	see and 0
network control	S	Priority	-	up to seamless[1] as required	see 4.16.2 and
audio/video	P	bounded latency/ bandwidth	bounded	up to seamless[1] as required	-
brownfield	P	bounded latency/ bandwidth	-	up to regular[2]	see
alarms/ events	S	bounded latency/ bandwidth	-	up to regular[2]	see 4.17.4
configuration/ diagnostics	S	Bandwidth	-	up to regular[2]	see 4.11
Internal / Pass-through	S	Bandwidth	-	up to regular[2]	see
best effort	S	-	-	up to regular[2]	-

[1] almost zero failover time;

[2] larger failover time because of network re-convergence

Isochronous:

→ see section 4.17.3

In addition, if an isochronous application interface is needed: Machine vision application use cases for counting, sorting, quality control, video surveillance, augmented reality, motion guidance …

Cyclic:

→ see ???

IA Use Case 02: End Stations without common application cycle

The cycle time requirements of different vendors may be based on their technology, which cannot be changed with reasonable effort. These requirements may be based on hardware dependencies, independent of the capabilities of the communication part of the device.

IA Use Case 03: Non-Isochronous Control Loops with bounded latency

In addition, if a cyclic application interface is needed: Machine vision application use cases for counting, sorting, quality control, video surveillance, augmented reality, motion guidance …

Network control:
→ see *???*

Audio/video:

→ IEEE Std 802.1BA-2011 (AVB) may be supported in industrial automation as well

Brownfield:

→ see *???*

Alarms/events:

→ see *Sequence of events*

Configuration/diagnostics:

→ see *IA Use Case 11: Network monitoring and* diagnostics

Internal:

→ see *???*

Best effort:
→ see

4.20 Other Important Concepts from Industrial

4.20.1 Isochronous Traffic Type Properties

Table 3 – Isochronous cyclic real-time and cyclic real-time traffic type properties

Property	Description
Data transmission scheme	*Periodic* (P) - e.g. every N µs, or *Sporadic* (S) - e.g. event-driven
Data transmission constraints	Indicates the traffic pattern’s data transmission constraints for proper operation. Four data transmission constraints are defined: • *deadline*: transmitted data is guaranteed to be received at the destination(s) before a specific instant of time, • *latency*: transmitted data is guaranteed to be received at the destination(s) within a specific period of time after the data is transmitted by the sending application, • *bandwidth:* transmitted data is guaranteed to be received at the destination(s) if the bandwidth usage is within the resources reserved by the transmitting applications, • *none:* no special data transmission constraint is given.
Data period	For traffic types that transmit *periodic* data this property denotes according to the *data transmission constraints*: *deadline*: application data deadline period, *latency*, *bandwidth* or *none*: data transmission period. The period is given as a *range* of time values, e.g. 1µs ... 1ms. For the *sporadic* traffic types, this property does not apply.
Network access (data transmission) synchronized to working clock (network cycle)	Indicates whether the data transmission of sender stations is synchronized to the working clock (network cycle). Available property options are: *yes, no* or *optional.*
Application synchronized to network access	Indicates whether the applications, which make use of this traffic pattern, are synchronized to the network access. Available property options are: *yes* or *no.*
Acceptable jitter	Indicates for traffic types, which apply data transmission with *latency* constraints, the amount of jitter, which can occur and must be coped with by the receiving destination(s). For traffic types with *deadline, bandwidth* or *none* data transmission constraints this property is not applicable (*n.a.*).
Acceptable frame loss	Indicates the traffic pattern’s tolerance to lost frames given e.g. as acceptable frame loss ratio range. The frame loss ratio value *0* indicates traffic types, where no single frame loss is acceptable.
Payload	Indicates the payload data *type* and *size* to be transmitted. Two payload types are defined: • *fixed:* the payload is always transmitted with exactly the same size • *bounded:* the payload is always transmitted with a size, which does not exceed a given maximum; the maximum may be the maximum Ethernet payload size (1500).

4.20.2 Bidirectional communication relations

The general behavior of field devices of process sensors and output signals is preconfigured and offers a set of services to a machine control unit. More complex field devices such as drives or machine parts have process data in both directions. If there are only outputs in a field device the stream back to the machine control is necessary for fast detection of problems in a field device. If there are only input process data the stream from the machine control to the field device is not necessary for normal operation.

The cell control communicates with the machine controls of the machines also in a bidirectional way.

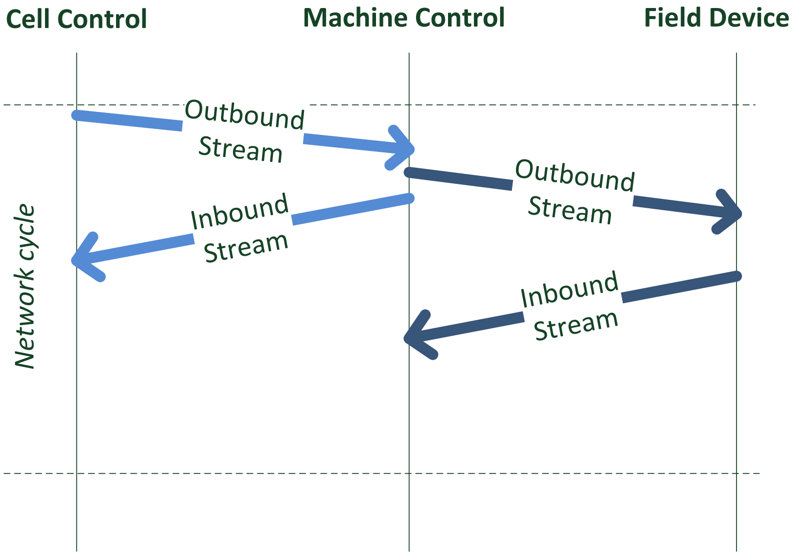

Figure 20 – Bidirectional Communication

Requirements:

- Support of bidirectional streams;
- Sequence of actions how to establish such streams;

Useful 802.1 mechanisms:

- IEEE 802.1Q (usage of streams)

4.20.3 Control Loop Basic Model

Control loops are fundamental building blocks of industrial automation systems. Control loops include: process sensors, a controller function, and output signals. Control loops may require guaranteed low latency or more relaxed bounded latency (see 0) network transfer quality.

To achieve the needed quality for Control loops the roundtrip delay (sometimes called makespan, too) of the exchanged data is essential.

There are three levels of a control loop:

- Application - within Talker/Listener,
- Network Access - within Talker/Listener,
- Network Forwarding - within Bridges.

Network Access is always synchronized to a common working clock or to a local timescale.

Application may or may not be synchronized to the synchronized Network Access depending on the application requirements. Applications which are synchronized to Network Access are called “isochronous applications”. Applications which are not synchronized to Network Access are called “non-isochronous applications”.

Network Forwarding may or may not be synchronized to a working clock depending on whether the Enhancements for Scheduled Traffic (IEEE Std 802.1Q-2018) are applied.

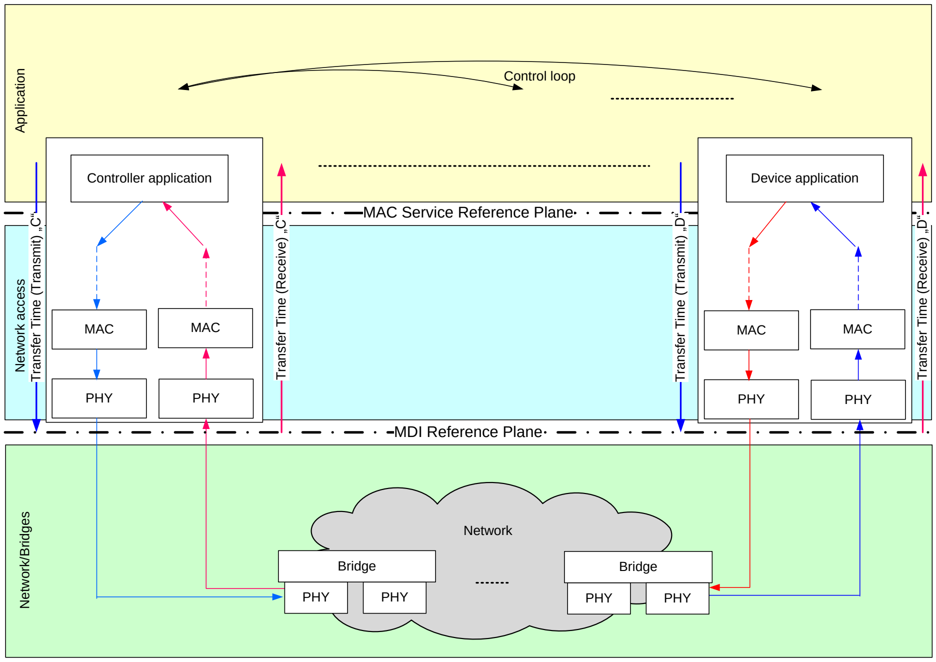

Figure 21 – Principle data flow of control loop

Transfer Times contain PHY and MAC delays. Both delays are asymmetric and vendor specific. Device vendors have to take into account these transfer times when their application cycle models are designed.

Table 4 – Application types

Level	Isochronous Application		Non-isochronous Application		
Application	Synchronized to network access		Synchronized to local timescale		
Network access	Synchronized to working clock, Stream Class based scheduling, Preemption				Synchronized to local timescale, Stream Class based scheduling, Preemption
Network/Bridges	Synchronized to working clock	Free running	Synchronized to working clock	Free running	Free running
	Scheduled traffic + Strict Priority + Preemption	Strict Priority or other Shaper + Preemption	Scheduled traffic + Strict Priority + Preemption	Strict Priority or other Shaper + Preemption	Strict Priority or other Shaper + Preemption

4.20.4 Minimum Required Quantities

The Industrial expected numbers of DA-MAC address entries used together with five VLANs (Default, High, High Redundant, Low and Low Redundant) are shown in Table 5 and Table 6.

Table 5 may be implemented as FDB table with a portion of DA-MAC address (e.g. 12 bits of Identifier and TSN-IA profile OUI) as row and the VLANs as column to ensure availability of a dedicated entry.

Table 5 – Expected number of stream FDB entries

# of VLANs	# of DA-MACs	Usage
4	4 096	Numbers of DA-MAC address entries used together with four VLANs (High, High Red, Low and Low Red)

Expected number of entries is given by the maximum device count of 1024 together with the 50% saturation due to hash usage rule. Table 6 shows the expected number of possible FDB entries.

Table 6 – Expected number of non-stream FDB entries

# of VLANs	# of entries	Usage
1	2 048	Learned and static entries for both, Unicast and Multicast

The hash based FDBs shall support a neighborhood for entries according to Table 7.

Table 7 – Neighborhood for hashed entries

Neighborhood	Usage
8	Default A neighborhood of eight entries is used to store a learned entry if the hashed entry is already used. A neighborhood of eight entries for the hashed index is check to find or update an already learned forwarding rule.

4.20.5 A representative example for data flow requirements

TSN domains in an industrial automation network for cyclic real-time traffic can span multiple Cyber-physical systems, which are connected by bridges. The following maximum quantities apply:

- Stations: 1024
- Network diameter: 64
- per PLC for Controller-to-Device (C2D) – one to one or one to many – communication:
  - 512 producer and 512 consumer data flows; 1024 producer and 1024 consumer data flows in case of seamless redundancy.
  - 64 kByte Output und 64 kByte Input data
- per Device for Device-to-Device (D2D) – one to one or one to many – communication:
  - 2 producer and 2 consumer data flows; 4 producer and 4 consumer data flows in case of seamless redundancy.
  - 1400 Byte per data flow

- per PLC for Controller-to-Controller (C2C) – one to one or one to many – communication:
  - 64 producer and 64 consumer data flows; 128 producer and 128 consumer data flows in case of seamless redundancy.
  - 1400 Byte per data flow
- Example calculation for eight PLCs
  - → 8 x 512 x 2 = 8192 data flows for C2D communication
  - → 8 x 64 x 2 = 1024 data flows for C2C communication
  - → 8 x 64 kByte x 2 = 1024 kByte data for C2D communication
  - → 8 x 64 x 1400 Byte x 2 = 1400 kByte data for C2C communication
- All above shown data flows may optionally be redundant for seamless switchover due to the need for High Availability.

Application cycle times for the 512 producer and 512 consumer data flows differ and follow the application process requirements.

E.g. 125 µs for those used for control loops and 500 µs to 512 ms for other application processes. All may be used concurrently and may have frames sizes between 1 and 1440 bytes.

4.20.6 Bridge Resources

The bridge shall provide and organize its resources in a way to ensure robustness for the traffic defined in this document as shown in Formula **[1]**.

The queuing of frames needs resources to store them at the destination port. These resources may be organized either bridge globally, port globally or queue locally.

The chosen resource organization model influences the needed amount of frame resources.

For bridge memory calculation Formula **[1]** applies.

$$\mathrm{MinimumFrameMemory} = (\mathrm{NumberOfPorts} - 1) \times \mathrm{MaxPortBlockingTime} \times \mathrm{Linkspeed} \qquad (1)$$

Where

MinimumFrameMemory	is minimum amount of frame buffer needed to avoid frame loss from non stream traffic due to streams blocking egress ports.
NumberOfPorts	is number of ports of the bridge without the management port.
MaxPortBlockingTime	is intended maximum blocking time of ports due to streams per millisecond.
Linkspeed	is intended link speed of the ports.

Formula **[1]** assumes that all ports use the same link speed and a bridge global frame resource management. Table 8, Table 9, Table 10, and Table 11 shows the resulting values for different link speeds and fully utilized links.

The traffic from the management port to the network needs a fair share of the bridge resources to ensure the required injection performance into the network. This memory (use for the real-time frames) is not covered by this calculation.

Table 8 – MinimumFrameMemory for 100 Mbit/s (50%@1 ms)

# of ports	MinimumFrameMemory [KBytes]	Comment
1	0	The memory at the management port is not covered by Formula [1]
2	6,25	All frames received during the 50%@1 ms := 500 µs at one port needed to be forwarded to the other port are stored during the allocation of this port due to stream transmission.
3	12,5	All frames received during the 50%@1 ms := 500 µs at two ports needed to be forwarded to the other port are stored during the allocation of this port due to stream transmission.
4	18,75	All frames received during the 50%@1 ms := 500 µs at three ports needed to be forwarded to the other port are stored during the allocation of this port due to stream transmission.
other	tbd	tbd

Table 9 – MinimumFrameMemory for 1 Gbit/s (20%@1 ms)

# of ports	MinimumFrameMemory [KBytes]	Comment
1	0	The memory at the management port is not covered by Formula [1]
2	25	All frames received during the 20%@1 ms := 200 µs at one port needed to be forwarded to the other port are stored during the allocation of this port due to stream transmission.
3	50	All frames received during the 20%@1 ms := 200 µs at two ports needed to be forwarded to the other port are stored during the allocation of this port due to stream transmission.
4	75	All frames received during the 20%@1 ms := 200 µs at three ports needed to be forwarded to the other port are stored during the allocation of this port due to stream transmission.
other	tbd	tbd

Table 10 – MinimumFrameMemory for 2,5 Gbit/s (10%@1 ms)

# of ports	MinimumFrameMemory [KBytes]	Comment
1	0	The memory at the management port is not covered by Formula [1]
2	31,25	All frames received during the 10%@1 ms := 100 µs at one port needed to be forwarded to the other port are stored during the allocation of this port due to stream transmission.
3	62,5	All frames received during the 10%@1 ms := 100 µs at two ports needed to be forwarded to the other port are stored during the allocation of this port due to stream transmission.
4	93,75	All frames received during the 10%@1 ms := 100 µs at three ports needed to be forwarded to the other port are stored during the allocation of this port due to stream transmission.
other	tbd	tbd

Table 11 – MinimumFrameMemory for 10 Gbit/s (5%@1 ms)

# of ports	MinimumFrameMemory [KBytes]	Comment
1	0	The memory at the management port is not covered by Formula [1]
2	62,5	All frames received during the 5%@1 ms := 50 µs at one port needed to be forwarded to the other port are stored during the allocation of this port due to stream transmission.
3	125	All frames received during the 5%@1 ms := 50 µs at two ports needed to be forwarded to the other port are stored during the allocation of this port due to stream transmission.
4	187,5	All frames received during the 5%@1 ms := 50 µs at three ports needed to be forwarded to the other port are stored during the allocation of this port due to stream transmission.
other	tbd	tbd

A per port frame resource management leads to the same values, but reduces the flexibility to use free frame resources for other ports.

A per queue per port frame resource management would increase (multiplied by the number of to be covered queues) the needed amount of frame resources dramatically almost without any benefit.

Example “per port frame resource management”:

100 Mbit/s, 2 Ports, and 6 queues
Needed memory := 6,25 KOctets * 6 := 37,5 KOctets.

No one is able to define which queue is needed during the “stream port blocking” period.

Bridged End-Stations need to ensure that their local injected traffic does not overload its local bridge resources. Local network access shall conform to the TSN-IA profile defined model with management defined limits and cycle times (see e.g. row Data period in Table 3).

4.20.7 VLAN Requirements

<<creator’s note: This section is left in as something that needs to be defined for Automotive as the use cases and needs are very different from Industrial.>>

Literature:

[1] “Cyber Physical Systems: Design Challenges”, E. A. Lee, Technical Report No. UCB/EECS-2008-8; http://www.eecs.berkeley.edu/Pubs/TechRpts/2008/EECS-2008-8.html