Use Cases IEC/IEEE 60802   V1.3

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Abstract

This document describes use cases for industrial automation, which have to be covered in the IEC/IEEE 60802 joint project for specifying the TSN Profile for Industrial Automation (TSN-IA). These use cases are intended to guide the specification process: WHAT shall be part of the dual logo International Standard IEC/IEEE 60802. The content of IEC/IEEE 60802 specifies the HOW to achieve the use cases. Some use cases are on a system level of an IA system. Even if the scope of IEC/IEEE 60802 does not cover the overall system level, the IEC/IEEE 60802 shall enable or at least do not prevent the features described in this use case document.

18   ## Log

V0.1-V0.3   working drafts
V0.4   2018-03-02   Revised after circuit meeting
V0.5   2018-03-07   Revised and presented during Chicago meeting
V0.6   2018-04-12   Elaborated additional use cases from Chicago

Added new use cases:
- Control loops with bounded latency
- Drives without common application cycle but common network cycle
- Redundant networks
- Vast number of connected stations
- Digital twin

Presented at ad-hoc meeting Munich

V0.61   2018-04-30   Revised after Munich ad-hoc review
- Added Interoperability clause (2.1)
- Reworked industrial automation traffic patterns clause (2.3.1)
- Added VLAN requirements clause (2.4.11.1)
- Added private machine domains sub-clause (2.5.2)

V0.7   2018-06-09   Comment resolution Interim Pittsburgh May 2018
V1.0   2018-07-20   Added Plenary San Diego July 2018 contributions and comments:
- TSN domain definition
- control loop clause

V1.1   2018-08-03   Added Frankfurt interim contributions and comments
V1.2   2018-09-03
- added note about the intention of the document to Abstract;
- added sub-clause 2.2.2 Interconnection of TSN Domains;
- distinguish audio/video with real-time (isochronous/ cyclic) QoS requirement from audio/video for human consumption in traffic types sub-clause;
- Enhanced Table 3: Application types;
- Added Figure 40: Add TSN machine to brownfield machine;
- Editorial changes;

V1.3   2018-09-13   Added Oslo interim contributions and comments

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208   # 1 Terms and Definitions

209   ## 1.1 Definitions

Reconfiguration	-	Any intentional modification of the system structure or of the device-level content, including updates of any type
	-	Ref: IEC 61158- Type 10, dynamic reconfiguration
	-	Document provided by PI/PNO: Guidelines for high-availability
(Process) disturbance	-	Any malfunction or stall of a process/machine, which is followed by production loss or by an unacceptable degradation of production quality
	-	Ref: IEC 61158 – Failure
	-	Ref. ODVA: Unplanned downtime
	-	Document provided by PI/PNO: Guidelines for diagnosis
Operational state of a plant (unit)/machine		Normal state of function and production of a plant(unit)/machine
Maintenance state of a plant (unit)/machine		Planned suspension or partial suspension of the normal state of function of a plant(unit)/machine
Stopped state of a plant (unit)/machine		Full non-productive mode of a plant(unit)/machine
Convergent network concept		All LAN devices (wired or wireless) are able to exchange data over a common infrastructure, within defined QoS parameters
Device		End station, bridged end station, bridge, access point
DCS		Distributed Control System
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 in particular, requires transmission latency to be bounded.[1]
TSN domain		A quantity of commonly managed industrial automation 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

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[1] taken from 802.1Q-2018

management mechanism.
It is an administrative decision to group these devices (see 2.2).

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	stations of a common working clock domain with a common setup for the isochronous cyclic real-time traffic type
cyclic real-time domain	stations 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 (see Figure 12); values are specific to a TSN domain and specify a repetitive behavior of the network interfaces belonging to that TSN domain;
Greenfield	for the context of this document: greenfield refers to TSN-IA profile conformant devices; regardless if "old" or "new";
Brownfield	for the context of this document: brownfield refers to devices, which are not conformant to the TSN-IA profile; regardless if "old" or "new";
Stream forwarding	Forwarding of stream data along the stream path including TSN domain boundary crossings

210   1.2   IEEE802 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

211

212   ## 2 TSN in Industrial Automation
213

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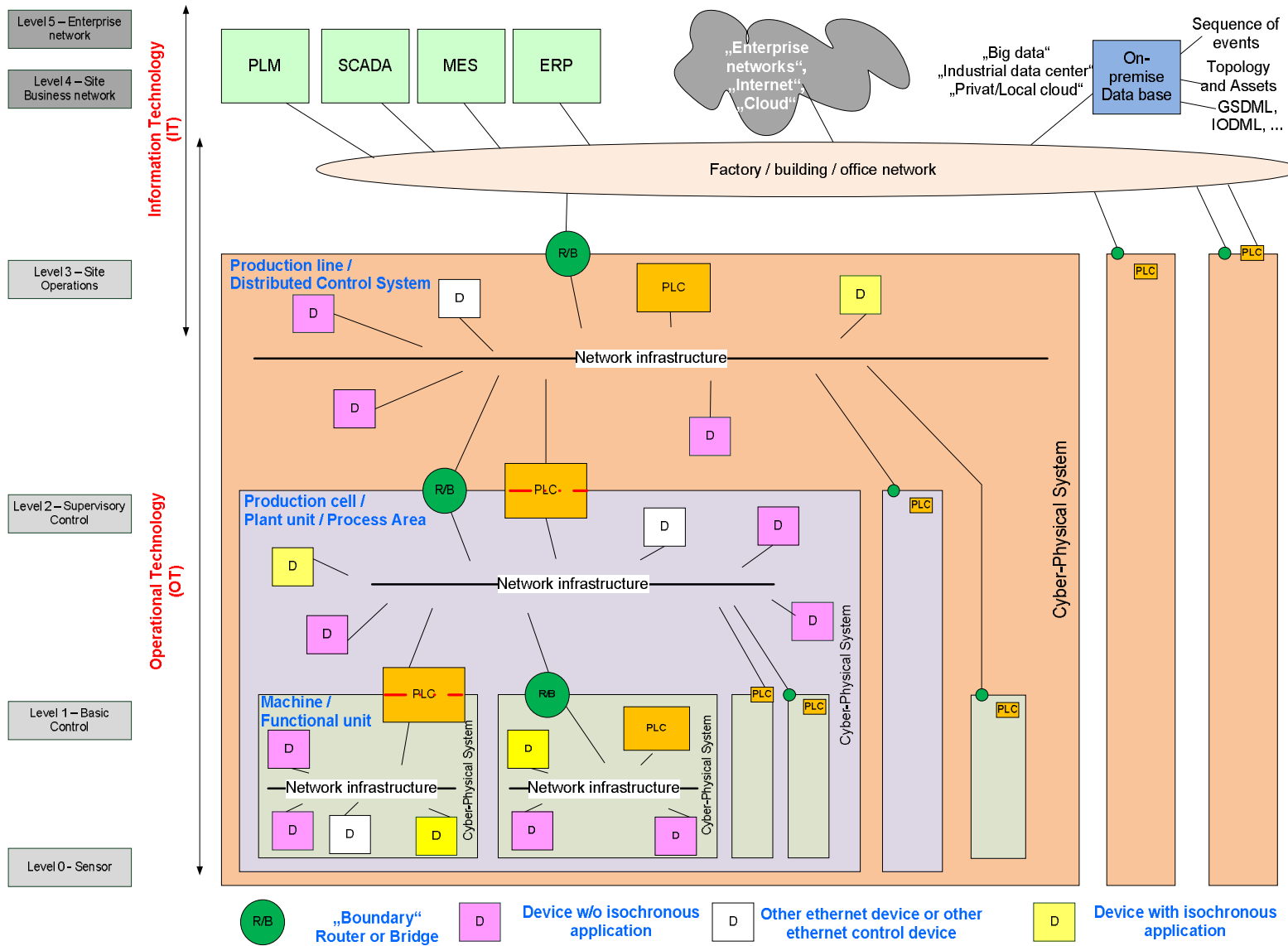
Figure 1 – Hierarchical structure of industrial automation

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216

There is no generally accepted definition of the term "Cyber-Physical System (CPS)". A report of Edward A. Lee [1] suitably introduces CPS as follows: „*Cyber-Physical Systems (CPS) are integrations of computation with physical processes. Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa.*"

Cyber-Physical Systems are the building blocks of "smart factories" and Industry 4.0. IEEE 802 LAN technologies provide the mechanisms (e.g. TSN features) for connectivity to time critical industrial applications on converged networks in operational technology control levels.

IEEE 802 LANs with TSN features can be used in Industrial Automation for:
- Real-time (RT) Communication within Cyber-Physical Systems
- Real-time (RT) Communication between Cyber-Physical Systems

A CPS consists of:
- o Controlling devices (typically 1 PLC),
- o I/O Devices (sensors, actors),
- o Drives,
- o HMI (typically 1),
- o Interface to the upper level with:
  - PLC (acting as gateway), and/or
  - Router, and/or
  - Bridge.
- o Other Ethernet devices:
  - Servers or any other computers, be it physical or virtualized,
  - Diagnostic equipment,
  - Network connectivity equipment.

2.1 Interoperability

Interoperability may be achieved on different levels. Figure 2 and Figure 3 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 2).

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.
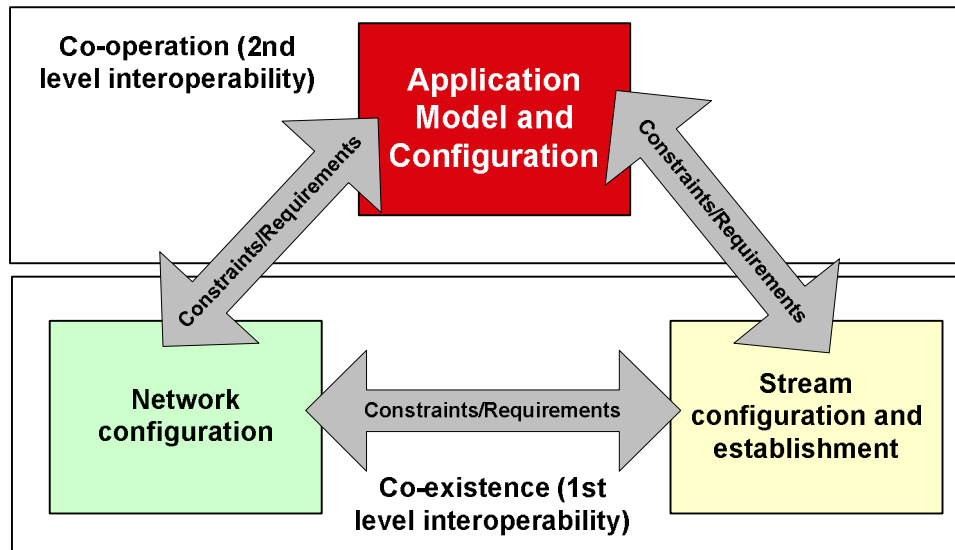
Figure 2 – Principle of interoperation
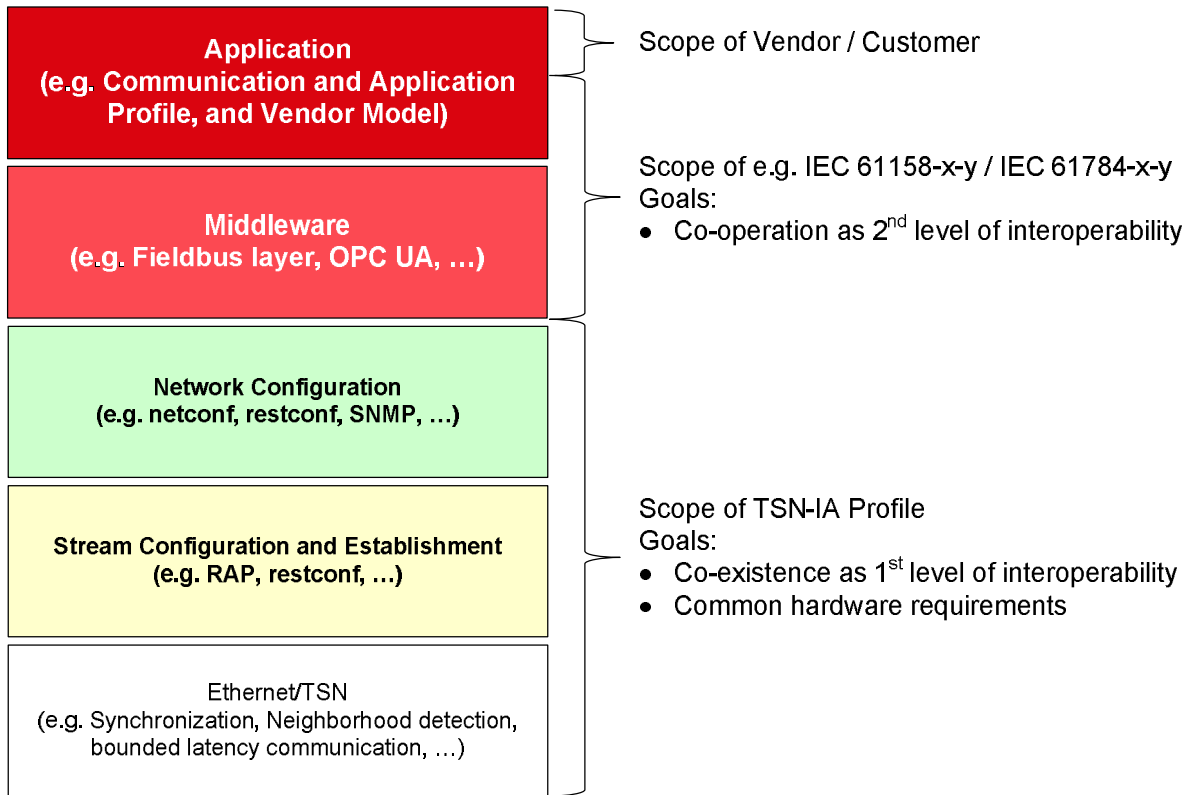
Figure 3 – Scope of work

2.2 TSN Domain

2.2.1 General

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

269   TSN Domain Characteristics:

270   • One or more TSN Domains may exist within a single layer 2 broadcast domain.
271   • A TSN Domain may not be shared among multiple layer 2 broadcast domains.
272   • Multiple TSN Domains may share a common universal time domain.
273   • Two adjacent TSN Domains may implement the same requirements but stay separate.
274   • Multiple TSN domains will often be implemented in one bridge (see 2.2.2.2).
275   • Multiple TSN domains will often be implemented in one router (see 2.2.2.3).
276   • Multiple TSN domains will often be implemented in one gateway (see 2.2.2.4).

277   Typically machines/functional units (see Figure 1) constitute separate TSN domains. Production
278   cells and lines may be set up as TSN domains as well. Devices may be members of multiple TSN
279   domains in parallel.

280   Figure 4 shows two example TSN domains within a common broadcast domain and a common
281   universal time domain. TSN domain 1 is a pure cyclic real-time domain, whereas TSN domain 2
282   additionally includes three overlapping isochronous domains.

283
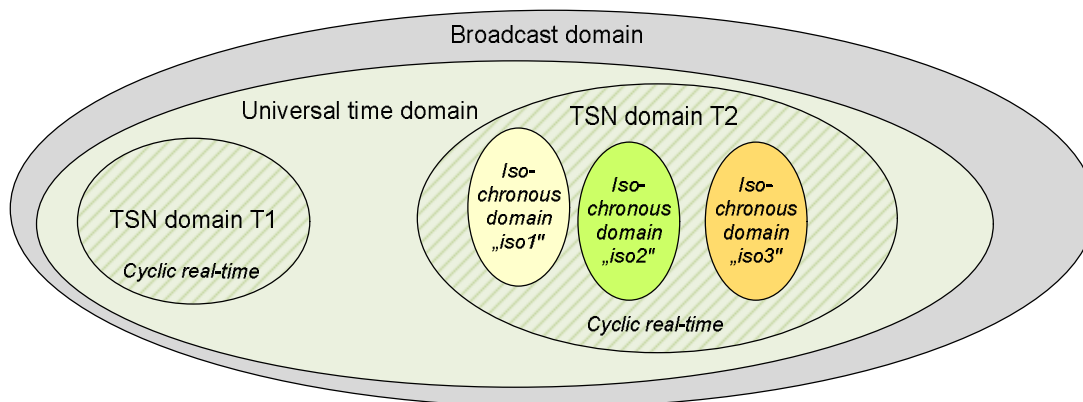
284

285   **Figure 4 – Different Types of Domains**

286   Interconnections between TSN domains are described in 2.2.2 and 2.6.1.

287   **2.2.2 Interconnection of TSN Domains**

288   *2.2.2.1 General*

289   TSN domains may be connected via

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

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

294   *2.2.2.2 Bridges (Layer 2)*

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

297   Figure 5 provides an example of two Bridges, which are members of two TSN domains each.
298   Bridge B1 provides ports and connectivity in TSN domain Production Cell 1 and in TSN domain
299   Machine 1, Bridge B2 for Production Line 1 and Production Cell 1.

300
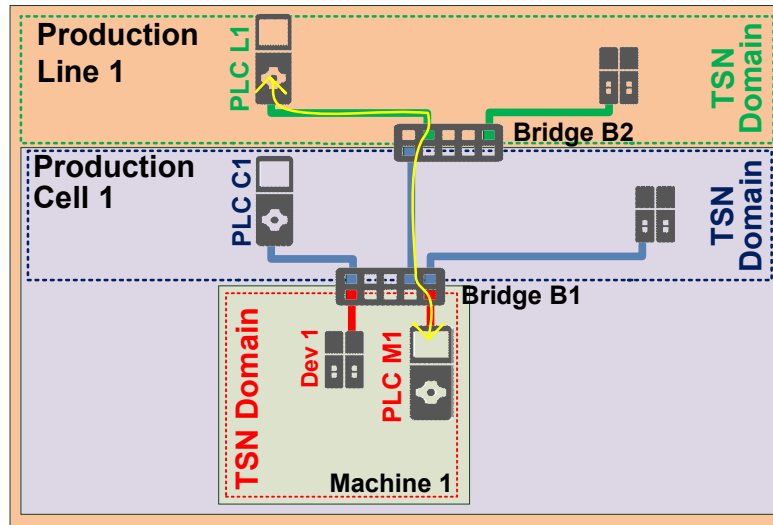
301
302   **Figure 5 – Three TSN domains connected by Bridges**

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

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

2.2.2.3 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 6 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.
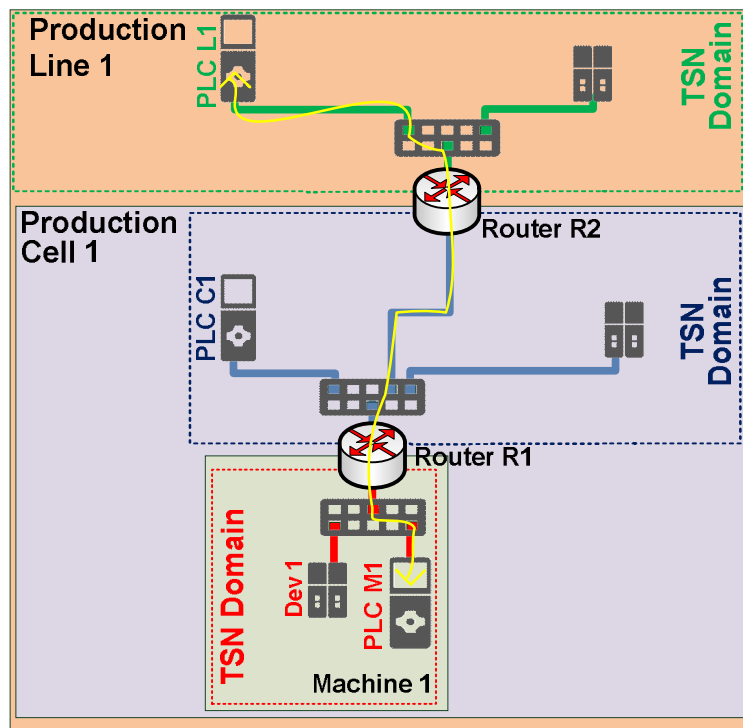
Figure 6 – Three TSN domains connected by Routers

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.

329   *2.2.2.4 Application Gateways (Layer7)*

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

332   Figure 7 provides an example of two application gateways:

333   -   Gateway CM1 is member in the TSN domains Production Cell 1 and Machine 1;
334   -   Gateway CF1 is member of the TSN domain Production Cell 1 and of Fieldbus 1.
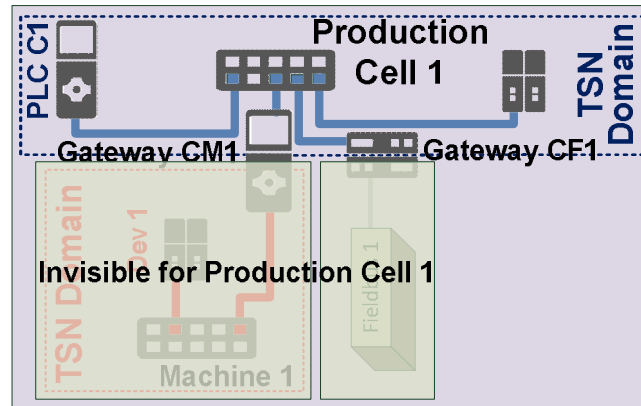
335
336   **Figure 7 – Gateways with two TSN domains and an attached Fieldbus**

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

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

345   Application level gateways are also used to connect non-Ethernet- or Ethernet-based fieldbuses to
346   TSN domains (see Gateway CF1 in Figure 7 and see also Use case 11: Fieldbus gateway).

347

2.3 Synchronization

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

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

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

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

2.3.2 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 8 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.
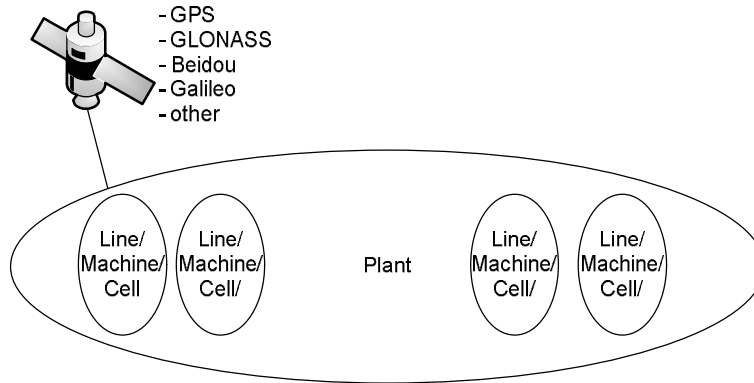
Figure 8 – plant wide time synchronization

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

2.3.3 Working Clock Synchronization

Working Clock is used to align actions line, cell or machine wide. The assigned timescale is arbitary. 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 9 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.
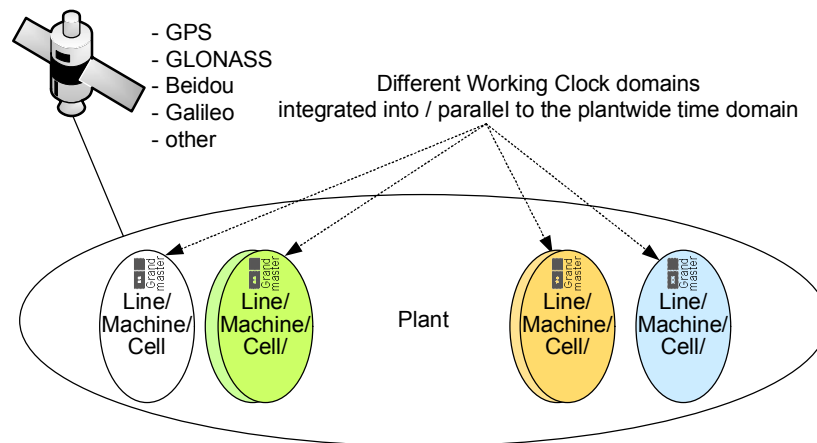
Figure 9 – line/cell/machine wide working clock synchronization overlapping with a universal time domain

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

383 High precision working clock synchronization is a prerequisite for control loop implementations with
384 low latency (see 2.4.2).

385

386 Requirements:

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

391

392 Useful 802.1 mechanisms:

393 • IEEE 802.1AS-Rev

394

2.3.4 Use case 01: Sequence of events

395
396 Sequence of events (SOE) is a mechanism to record timestamped events from all over a plant in a
397 common database (on-premise database in Figure 1).
398 Application defined events are e.g. changes of digital input signal values. Additional data may be
399 provided together with the events, e.g. universal time sync state and grandmaster, working clock
400 domain and value …
401 SOE enables root-cause analysis of disruptions after multiple events have occurred. Therefore
402 SOE can be used as diagnostics mechanism to minimize plant downtime.
403 Plant-wide precisely synchronized time (see Figure 8) is a precondition for effective SOE
404 application.

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

406 Requirements:

407 • Plant wide high precision Universal Time synchronization;
408 • Maximum deviation to the grandmaster time in the range from 1 μs to 100 μs;
409 • Optional support of redundant sync masters and domains;
410 • Non-zero failover time in case of redundant universal time domains;

411
412 Useful 802.1 mechanisms:

413 • IEEE 802.1AS-Rev

414

2.4 Industrial automation modes of operation

415

2.4.1 Industrial automation traffic types

416

2.4.1.1 General

417
418 Industrial automation applications concurrently make use of different traffic types for different
419 functionalities, e.g. parameterization, control, alarming. The various traffic types have different
420 characteristics and thus impose different requirements on a TSN network. This applies for all use
421 cases described in this document.
422 Table 1 subsumes the industrial automation relevant traffic patterns to traffic types with their
423 associated properties (see also [4]).

424   **Table 1 – 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 Table 4 and 2.4.2
cyclic real-time	P	deadline/ bounded latency (e.g. n-times network cycle)/ bandwidth	bounded	up to seamless[1]	see Table 8 and 2.4.5
network control	S	Priority	-	up to seamless[1] as required	see 2.2.2 and 2.5.1
audio/video	P	bounded latency/ bandwidth	bounded	up to seamless[1] as required	-
brownfield	P	bounded latency/ bandwidth	-	up to regular[2]	see 2.5.6
alarms/ events	S	bounded latency/ bandwidth	-	up to regular[2]	see 2.3.4
configuration/ diagnostics	S	Bandwidth	-	up to regular[2]	see 2.8.1
Internal / Pass-through	S	Bandwidth	-	up to regular[2]	see 2.6.2
best effort	S	-	-	up to regular[2]	-

425

426   [1] almost zero failover time;

427

428   [2] larger failover time because of network re-convergence

429

430   All traffic types of Table 1 are referenced by the use cases, which are described in this document:

431

432   Isochronous:

433   → see *Use case 02: Isochronous Control Loops with guaranteed low* latency

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

436

437   Cyclic:

438   → see *Use case 03: Non-Isochronous Control Loops with bounded* latency

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

441

442 Network control:
443 → see *Use case 07: Redundant networks*
444
445 Audio/video:
446 → IEEE Std 802.1BA-2011 (AVB) may be supported in industrial automation as well
447
448 Brownfield:
449 → see *Use case 12: New machine with brownfield devices*
450
451 Alarms/events:
452 → see *Use case 01: Sequence of events*
453
454 Configuration/diagnostics:
455 → see *Use case 29: Network monitoring and diagnostics*
456
457 Internal:
458 → see *Use case 18: Pass-through Traffic*

459 Best effort:
460 → see …

461 *2.4.1.2   Characterization of isochronous cyclic real-time and cyclic real-time*
462 The following properties table is used to characterize in detail the traffic types of Use case 02:
463 Isochronous Control Loops with guaranteed low latency and Use case 03: Non-Isochronous
464 Control Loops with bounded latency*.*

465   **Table 2 – 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	Indicates whether the data transmission of sender stations is synchronized to the working

Property	Description
transmission) synchronized to working clock (network cycle)	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).

2.4.2 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.
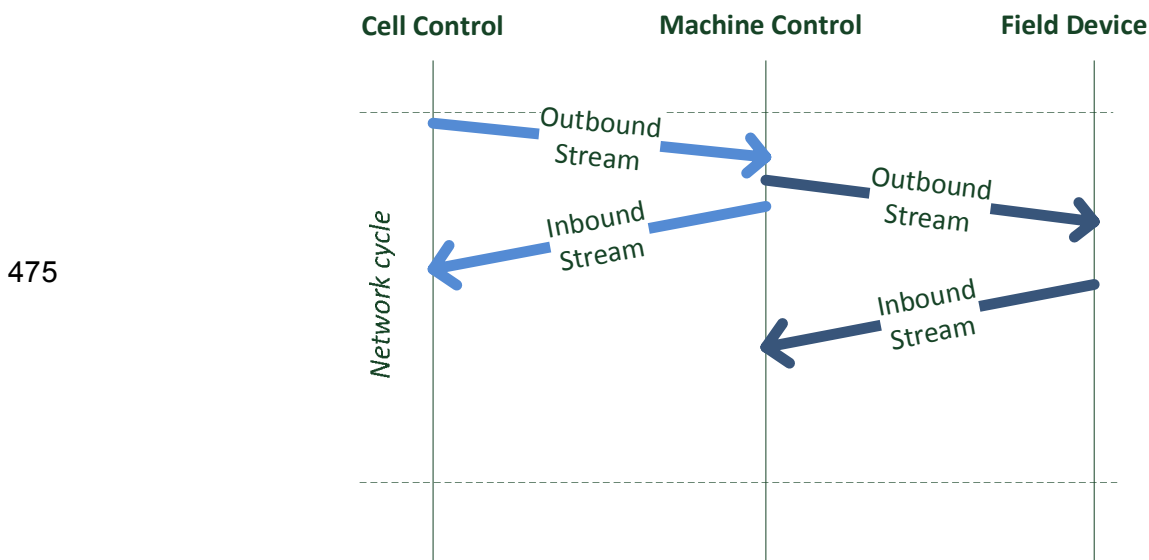
Figure 10 – Bidirectional Communication

477 Requirements:
478   • Support of bidirectional streams;
479   • Sequence of actions how to establish such streams (see Figure 10);

480 Useful 802.1 mechanisms:
481   • IEEE 802.1Q (usage of streams)

2.4.3 Control Loop Basic Model

483 **Control loops** are fundamental building blocks of industrial automation systems. Control loops include:
484 process sensors, a controller function, and output signals. Control loops may require guaranteed low
485 latency or more relaxed bounded latency (see 2.4.5) network transfer quality.

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

488 Figure 11 shows the whole transmission path from Controller application to Device application(s)
489 and back. The blue and red arrows show the contributions to the e2e (end-to-end) latency
490 respectively.
491
492 Figure 11 and Table 3 show three levels of a control loop:
493   ▪ Application   - within Talker/Listener,
494   ▪ Network Access   - within Talker/Listener,
495   ▪ Network Forwarding   - within Bridges.

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

497 Application may or may not be synchronized to the synchronized Network Access depending on
498 the application requirements. Applications which are synchronized to Network Access are called
499 "isochronous applications". Applications which are not synchronized to Network Access are called
500 "non-isochronous applications".

501 Network Forwarding may or may not be synchronized to a working clock depending on whether the
502 Enhancements for Scheduled Traffic (IEEE Std 802.1Q-2018) are applied.
503
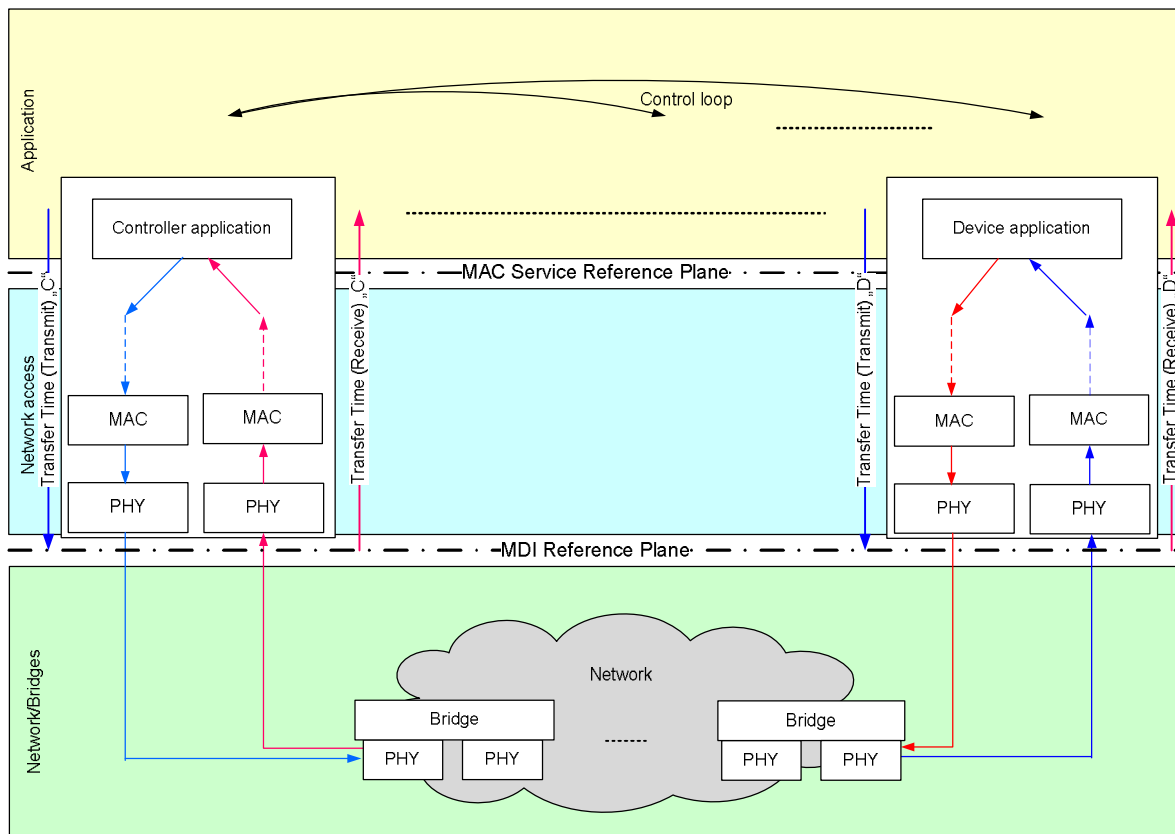
504
505 **Figure 11 – Principle data flow of control loop**

506 Transfer Times contain PHY and MAC delays. Both delays are asymmetric and vendor specific.
507 Device vendors have to take into account these transfer times when their application cycle models
508 are designed (see Figure 11 and Figure 12).
509
510 **Table 3 – 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

511

512 **2.4.4   Use case 02: Isochronous Control Loops with guaranteed low latency**

513 Control loops with guaranteed low latency implement an isochronous traffic pattern for isochronous
514 applications, which are synchronized to the network access (see Table 3). It is based on
515 application cycles, which consists of an IO data Transfer time and an Application time wherein the

516   control loop function is executed. Figure 12 shows the principle how Network cycle, Transfer time
517   and Application time interact in this use case.
518   Application cycle time and Network cycle time are identical in the example of Figure 12 (RR=1/see
519   2.4.6), whereas Figure 13 shows examples where the Application cycle time is longer than the
520   Network cycle time (RR>1/see 2.4.6).
521   The control loop function starts for controllers and devices at a fixed reference point after the
522   transfer time when all necessary buffers are available. A single execution of a control loop function
523   ends before the next transfer time period starts. Thus, all frames shall be received by the
524   addressed application within the transfer time. An optimized local transmit order at sender stations
525   is required to achieve minimal transfer time periods.
526
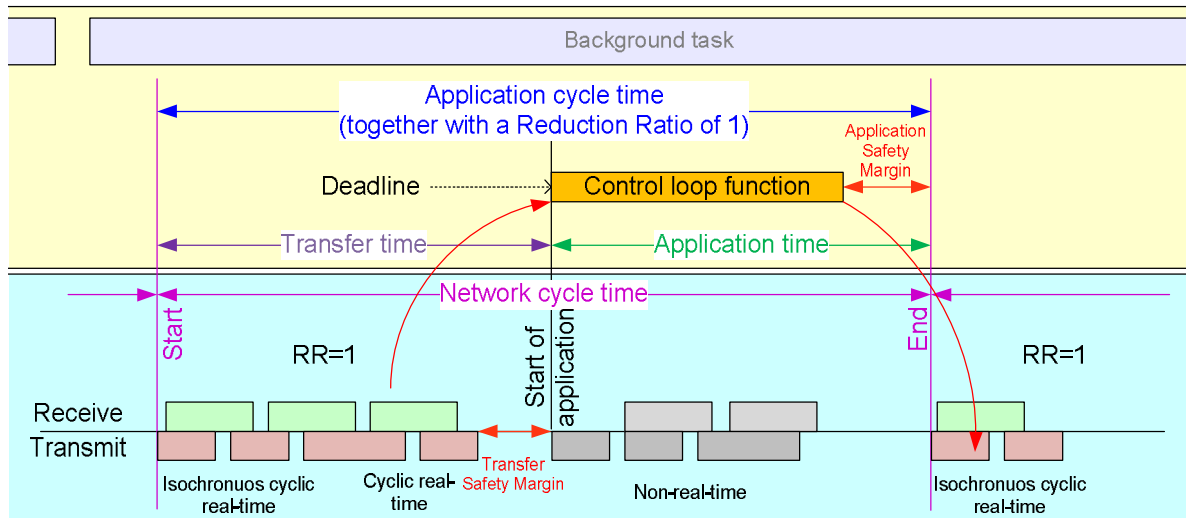
Figure 12 – network cycle and isochronous application (Basic model)

529   Transfer Safety Margin is the maximum time, which is needed to transfer received data from the
530   MDI reference plane (see Transfer Time (Receive) in Figure 11) to the application.

531   Application Safety Margin is the maximum time, which is needed to transfer the produced data from
532   the application to the MDI reference plane (see Transfer Time (Transmit) Figure 11).

533   Figure 13 shows how this principle is used for multiple concurrent applications with even extended
534   computing time requirements longer than a single application time within the network cycle time.
535   When reduction ratio >1 is applied (see 2.4.6), the control loop function can be expanded over
536   multiple network cycles (Control loop 2 with reduction ratio 2 and Control loop 3 with reduction ratio
537   16 in Figure 13).

538   Maximum available computation time for a Control loop with reduction ratio X:
539   X * network cycle time – Transfer time – Application safety margin

540   Transfer of isochronous cyclic real-time, cyclic real-time and non-real-time data is processed in
541   parallel to the various control loop functions - preserving the deadline requirement of the control
542   loops.

543   A cyclic background task can additionally run, whenever spare Transfer or Application time is
544   available.
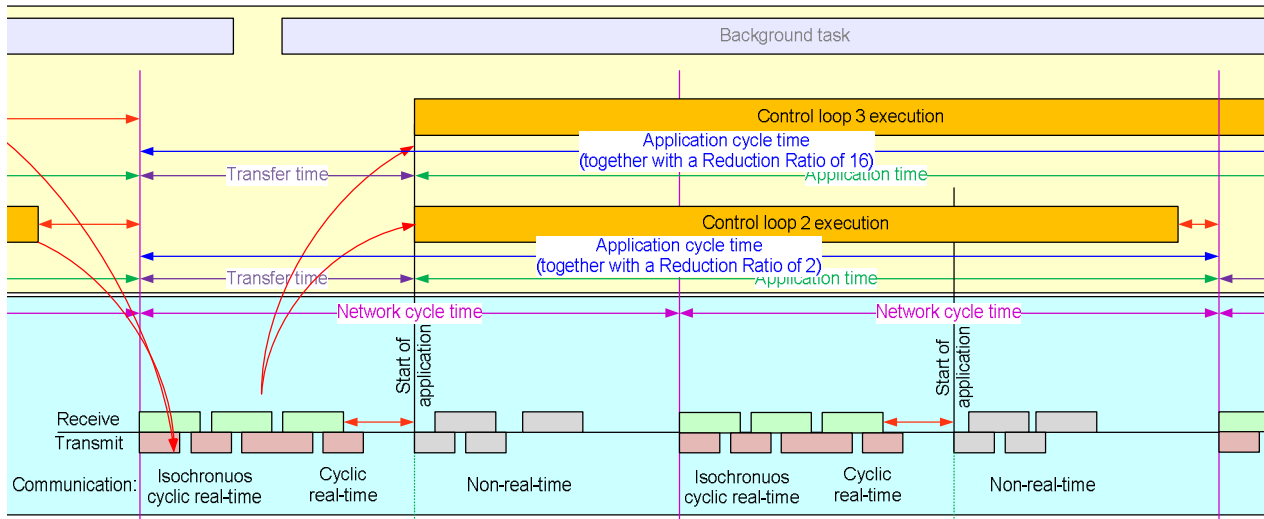
Figure 13 – Multiple concurrent isochronous control loops (Extended model)

Network cycle: transfer time (including safety margin) and application time (including safety margin)

Transfer time: period of time, wherein all necessary frames are exchanged between stations (controller, devices); the minimum transfer time is determined by the e2e latencies of the necessary frames; the e2e latency depends on: PHY-, MAC-, cable-, bridge-delays and send ordering. The transfer time is a fraction of the network cycle time.

For a given target transfer time the number of possible bridges on the path is restricted due to PHY-, MAC-, cable- and bridge-delay contributions.

Figure 14 to Figure 19 show variations of the basic model of Figure 12:

In existing technologies some of the models are used in optimized ways to reduce the network cycle time and/or the IO-reaction time (sometimes also called 'makespan' or 'roundtrip delay time').
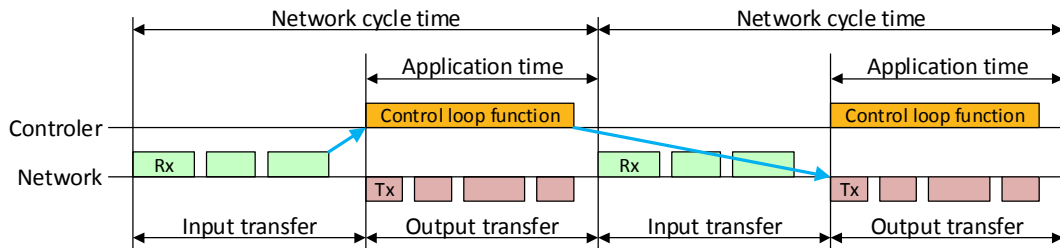
Figure 14 – Variation 1: two cycle timing model
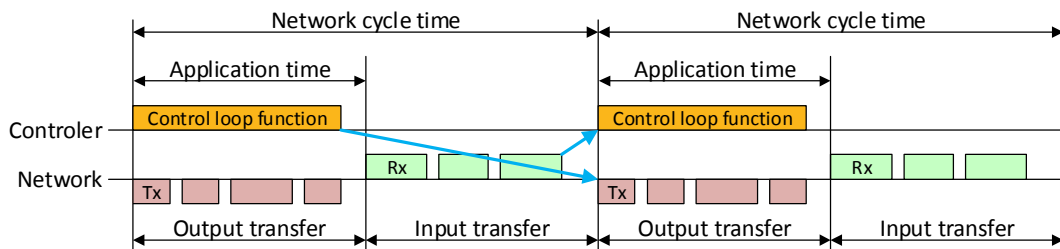
Figure 15 – Variation 2: two cycle timing model - shifted by 180°

564
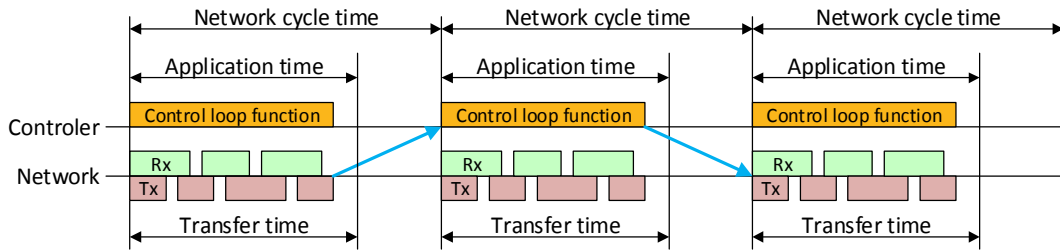
Figure 16 – Variation 3: three cycle timing model

567
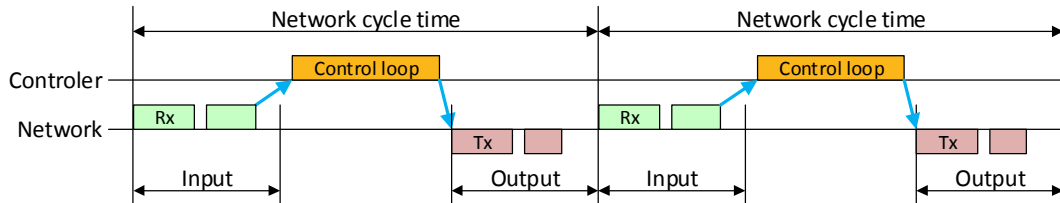
Figure 17 – Variation 4: one cycle timing model

570
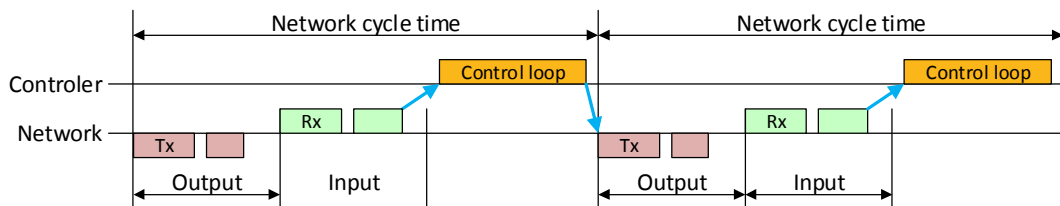
Figure 18 – Variation 5: one cycle timing model – changed sequence

573
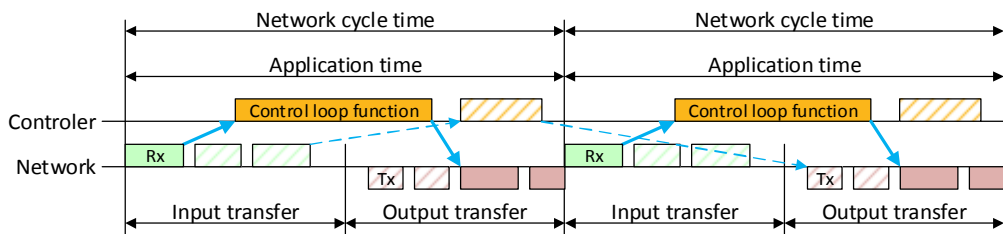
Figure 19 – Variation 6: further optimizations

The extended model of Figure 13 may be applied to these variations as well.

577

2.4.4.1 *Isochronous cyclic operation model*
Figure 20 shows the isochronous cyclic operation model for guaranteed low latency.
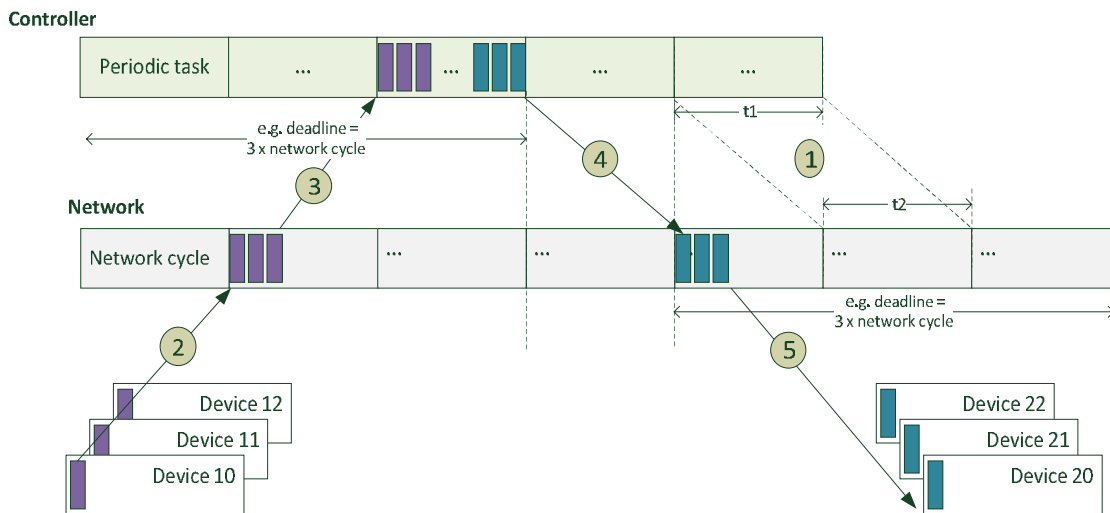
Figure 20 – isochronous cyclic operation model

Isochronous cyclic operation characteristics:

Multiple applications (periodic tasks) with different application periods are supported. Applications are synchronized to working clock:
- Devices: √
- Controller: √

Multiple application update times based on different reduction ratios are supported. Data transmission is synchronized to network cycle (WorkingClock):
- Devices: √
- Controller: √

The single steps of the isochronous cyclic operation model are:

1	Controller periodic tasks are synchronized to the working clock. Example: Periodic task_01 period (t1) == network cycle period (t2). Periodic task_02 period == 8 * network cycle period (t2). Periodic task_03 period == 32 * network cycle period (t2).
2	Device data transmission is synchronized to network cycle (Working Clock).
3	Device input data shall reach controller within an application defined deadline. Controller application may check the timeliness (by means of additional data in the payload, e.g. LifeSign model). Controller application operates on local process image data. Local process image decouples communication protocol from application. Additional: Device input data shall reach controller within a communication monitoring defined deadline (communication protocol). Communication disturbances are recognized and signaled asynchronously by communication protocol to application.
4	Controller output data transmission is synchronized to network cycle (Working Clock).

(5)	Controller output data shall reach device within an application defined deadline.
	Device application may check the timeliness (by means of additional data in the payload, e.g. PROFINET Isochronous Mode SignOfLife model – see [3]).
	Device application operates on local process image data. Local process image decouples communication protocol from application.
	Additional:
	Controller out data shall reach device within a communication monitoring defined deadline (communication protocol). Communication disturbances are recognized and signaled asynchronously by communication protocol to application.

High control loop quality is achieved by:

- Short network cycle times to minimize reaction time (dead time),
- equidistant network cycle times based on a synchronized working clock to ensure a defined reaction time,
- device signal processing and transfer coupled to synchronized working clock, and
- device and controller application (function) coupled to synchronized working clock.

isochronous mode: coupling of device and controller application (function) to the synchronized working clock

isochronous cyclic real-time: transfer time less than 20% (at link speeds > 100 Mbit/s) / 50% (at link speeds <= 100 Mbit/s) of network cycle and applications are coupled to the working clock.

Table 4 – isochronous traffic pattern properties

Characteristics		Notes
Data transmission scheme	periodic	
Data transmission constraints	deadline	End-to-end one-way latency[2] less than 20% (link speeds > 100 Mbit/s) / 50% (link speeds <= 100 Mbit/s) of network cycle
Data period	1µs .. 1ms 250µs ..4ms	
Network access (data transmission) synchronized to working clock network cycle	Yes	
Application synchronized to network access	Yes	
Acceptable jitter	n.a.	Deadline shall be kept
Acceptable frame loss	0..n frames	Media redundancy requirements according to the required tolerance; e.g. seamless redundancy for value 0
Payload	1 .. IEEE Std 802.3 maximum data payload size (i.e. 1500 bytes)	Data size negotiated during connection establishment

---

[2] The end-to-end one-way latency is measured from the arrival of the last bit at the ingress edge port of the bridged
network to the transmission of the last bit by the egress edge port of the bridged network (see, e.g., Annex L.3 in IEEE Std 802.1Q-2018).

Requirements on network cycle times:
- 1 µs to 1 ms   at link speed 1 Gbit/s (or higher)
- 250 µs to 4 ms   at link speed 100 Mbit/s
- 2 ms to 8 ms   at link speed 10 Mbit/s

2.4.4.2 Delay requirements

To make short control loop times feasible PHY, MAC and bridge delays shall meet upper limits:
- PHY delays shall meet the upper limits of Table 5.
- MAC delays shall meet the upper limits of Table 6.
- Bridge delays shall be independent from the frame size and meet the upper limits of Table 7.

Figure 21 shows the definition of PHY delay, MAC delay and Bridge delay reference points.
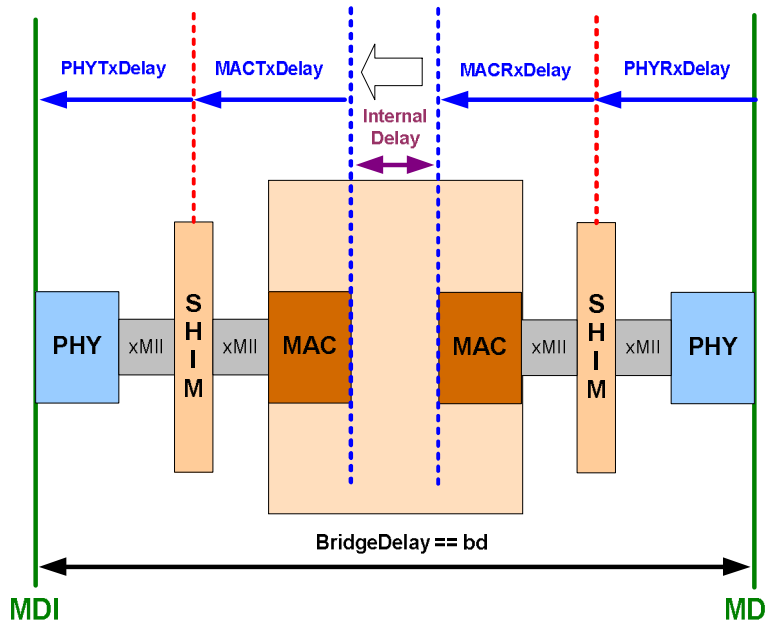
Figure 21 – delay measurement reference points

Strict numbers such as those proposed hereafter in Table 5, Table 6 and Table 7 are necessary to approach the problem of short control loop times. The numbers have to be agreed on in the profile. Specifying these numbers, however, doesn't eliminate the need to publish exact values through 802.1 standardized mechanisms as applicable.

Table 5 – Expected PHY delays

Device	RX delay [c]	TX delay [c]	Jitter
10 Mbit/s	<< 1 µs	<< 1 µs	< 4 ns
100 Mbit/s MII PHY	210 ns (Max. 340 ns) [a]	90 ns (Max. 140 ns) [a]	< 4 ns
100 Mbit/s RGMII PHY	210 ns [b]	90 ns [b]	< 4 ns
1 Gbit/s RGMII PHY	<< 500 ns [b]	<< 500 ns [b]	< 4 ns

Device	RX delay [c]	TX delay [c]	Jitter
2,5 Gbit/s RGMII PHY	<< 500 ns [b]	<< 500 ns [b]	< 4 ns
5 Gbit/s RGMII PHY	<< 500 ns [b]	<< 500 ns [b]	< 4 ns
10 Gbit/s	tdb	tdb	tdb
25 Gbit/s to 1 Tbit/s	tdb	tdb	tdb

[a] According IEEE 802.3 for 100 Mbit/s full duplex with exposed MII.

[b] Values from 100 Mbit/s PHYs (or better) are needed to allow substitution even for Gigabit or higher.

[c] Lower values mean more performance for linear topology.

613

614   **Table 6 – Expected MAC delays**

Link speed	Maximum RX delay	Maximum TX delay
10 Mbit/s	<< 1 µs	<< 1 µs
100 Mbit/s	<< 1 µs	<< 1 µs
1 Gbit/s	<< 1 µs	<< 1 µs
2,5 Gbit/s	<< 1 µs	<< 1 µs
5 Gbit/s	<< 1 µs	<< 1 µs
10 Gbit/s	<< 1 µs	<< 1 µs
25 Gbit/s – 1 Tbit/s	tdb	tdb

615

616   **Table 7 – Expected Ethernet Bridge delays**

Link speed	Value	Comment
10 Mbit/s	< 30 µs	No usage of bridging expected
100 Mbit/s	< 3 µs	Bridge delay measure from MII to MII[1)
1 Gbit/s	< 1 µs	Bridge delay measure from RGMII to RGMII[1)
2,5 Gbit/s	< 1 µs	Bridge delay measure from XGMII to XGMII[1)
5 Gbit/s	< 1 µs	Bridge delay measure from XGMII to XGMII[1)
10 Gbit/s	< 1 µs	Bridge delay measure from XGMII to XGMII[1)
25 Gbit/s – 1 Tbit/s:	tdb	Bridge delay measure from XGMII to XGMII[1)

617   [1) first bit in, first bit out

618   Useful 802.1 mechanisms:

619   • …
620

621   Example:

622   A representative example of a "Control loop with guaranteed low latency" use case is given in
623   clause 2.5.11.4 *"Fast" process applications*.

624

625   **2.4.5   Use case 03: Non-Isochronous Control Loops with bounded latency**

626   Control loops with bounded latency implement a cyclic traffic pattern for non-isochronous
627   applications, which are not synchronized to the network access but are synchronized to a local
628   timescale (see Table 3).

629   Figure 22 shows the principle how network cycle, transfer time and application time interact in this
630   use case. The control loop function starts at an application defined time, which is not synchronized
631   to the network access but to a local timescale. The network cycle, which describes the repetitive
632   behavior of the network interface, may be synchronized to a common working clock or to a local
633   timescale.
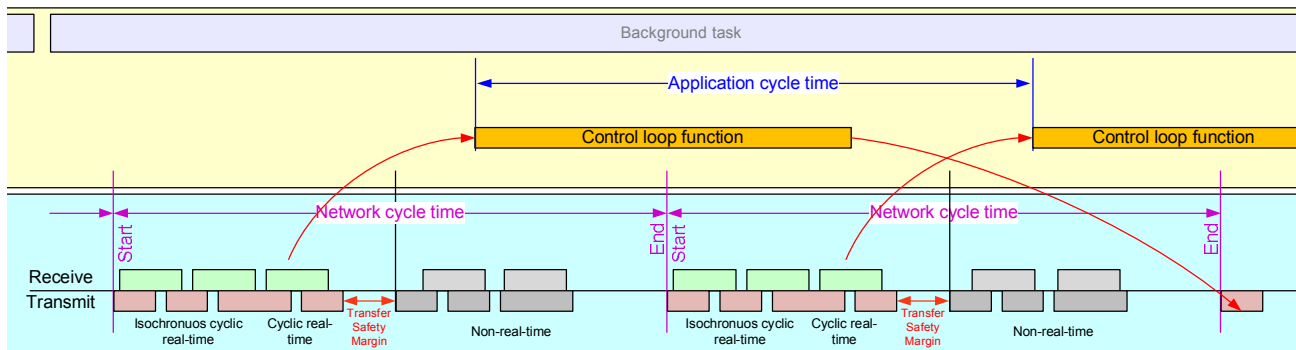
634
635

636   **Figure 22 – network cycle and non-isochronous application (Basic model)**

637   Extensions of this model analogous to Figure 13 (multiple applications with differing application
638   lengths) are also possible.

639   *2.4.5.1   Cyclic operation model*
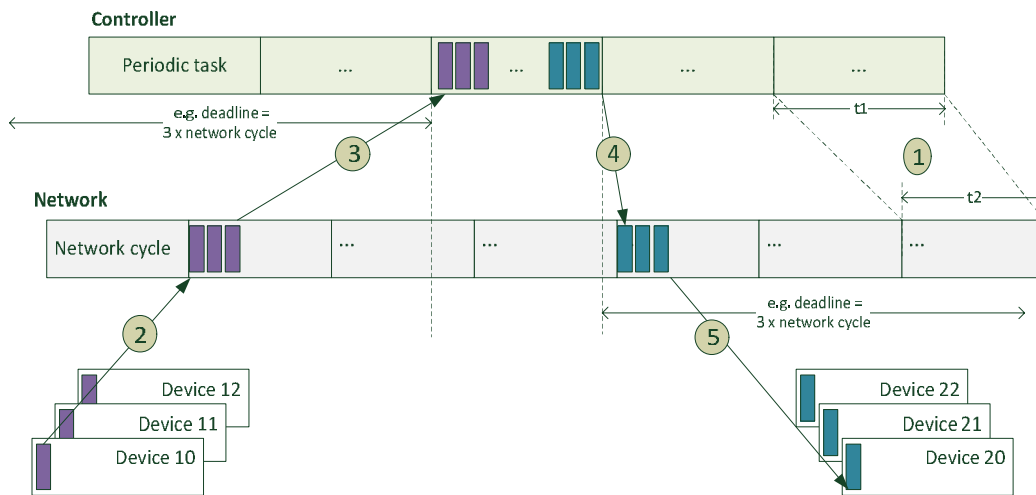
640
641
642   **Figure 23 – cyclic operation model**
643

       Cyclic operation characteristics:

              Multiple applications with different application periods are supported.
              Applications synchronized to a common working clock or a local timescale:

- Devices: √
- Controller: √

Multiple update times based on different reduction ratios are supported.
Network access is synchronized to network cycle (WorkingClock):

- Devices: √
- Controller: √

644 The single steps of the cyclic operation model are:

1	Controller periodic tasks don't need to be synchronized to working clock, but may be synchronized. Periodic task period (t1) != network cycle period (t2).
2	Data transmission is synchronized to network cycle (Working Clock)
3	Device input data shall reach controller within a communication monitoring defined deadline (communication protocol). Controller application assumes a kept update interval but doesn't know whether it is kept or not. Communication disturbances are recognized and signaled asynchronously by communication protocol to application. Controller application operates on local process image data. Local process image decouples communication protocol from application.
4	Controller output data transmission is synchronized to network cycle (Working Clock).
5	Controller output data shall reach device within a communication monitoring defined deadline (communication protocol). Device application assumes an kept update interval but doesn't know whether it is kept or not. Communication disturbances are recognized and signaled asynchronously by communication protocol to application. Device application operates on local process image data. Local process image decouples communication protocol from application.

645

2.4.5.2 Cyclic traffic pattern

647
648 Control loops with bounded latency implement a cyclic traffic pattern. More relaxed control reaction
649 time requirements (e.g. 10 ms - 10 s) allow free running applications instead of isochronous
650 applications. In consequence transfer time requirements are more relaxed as well. The transfer
time may be longer than the network cycle in this use case.

651
652 For a given target transfer time the number of possible bridges on a communication path is
653 restricted due to PHY-, MAC- and bridge-delay contributions, but can be much higher compared to
Use case 02: Isochronous Control Loops with guaranteed low latency.

654 Cyclic real-time: transfer time may be longer than network cycle and applications are decoupled
655 from the working clock.

656

Table 8 – cyclic traffic pattern properties

Characteristics		Notes
Data transmission scheme	periodic	
Data transmission constraints	deadline	End-to-end one-way latency[3] less than X * network cycle (X | 1 .. n)
Data period	X * network cycle (X | 1 .. n)	
Network access (data transmission) synchronized to working clock (network cycle)	Optional	May be synchronized to local timescale instead
Application synchronized to network access	No	synchronized to local timescale
Acceptable jitter	n.a.	Deadline shall be kept
Acceptable frame loss	0..n frames	Media redundancy requirements according to the required tolerance; e.g. seamless redundancy for value 0
Payload	1 ... IEEE Std 802.3 maximum data payload size (i.e. 1500 bytes)	Data size negotiated during connection establishment

657

658 Requirements:

659 Stations shall be able to implement Use case 02: Isochronous Control Loops with guaranteed low
660 latency and Use case 03: Non-Isochronous Control Loops with bounded latency concurrently.

661 Transmission paths shall be able to handle different

662   • working clocks, and
663   • network cycles.

664 Useful 802.1 mechanisms:

665   • …
666

667 **2.4.6 Use case 04: Reduction ratio of network cycle**
668

669 Application needs may limit the in principle flexible network cycle time to a defined granularity.
670 E.g. in case of network cycle granularity 31,25 µs the possible network cycles are:

671   >= 1Gbit/s: 31,25 µs * $2^{\wedge n}$ \| n=0 .. 5
672   < 1Gbit/s: 31,25 µs * $2^{\wedge n}$ \| n=2 .. 7
673

674 Application cycle times are the result of the used network cycle times together with reduction ratios:

675   – 31,25 µs to 512 ms
676

677 Reduction ratio: The value of "reduction ratio" defines the number of network cycles between two
678 consecutive transmits.

---

[3] The end-to-end one-way latency is measured from the arrival of the last bit at the ingress edge port of the bridged
network to the transmission of the last bit by the egress edge port of the bridged network (see, e.g., Annex
L.3 in IEEE Std 802.1Q-2018).

679 Phase: The value of "phase" in conjunction with "reduction ratio" defines the starting network cycle
680 for the consecutive transmits.
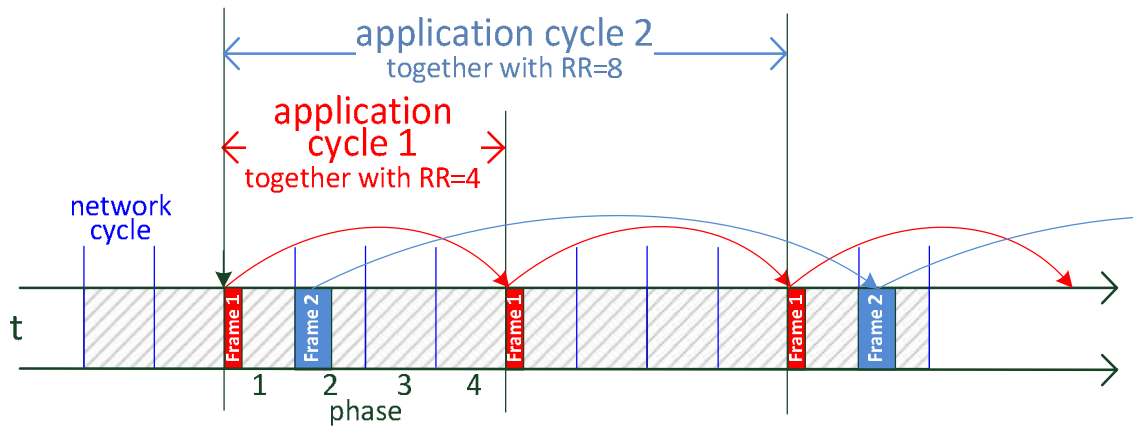
681

682 **Figure 24 – network cycle and application cycle**

683 Use case 06: Drives without common application cycle but common network cycle is an example of
684 multiple different application cycles, which are based on a common network cycle.

685 Figure 25 shows another example use case where all drives are connected in a line and every
686 drive needs direct data exchange to the Controller and additionally to its direct neighbor.
687 Some similar applications might even be more complex when the physical topology does not match
688 the logical order of drives.
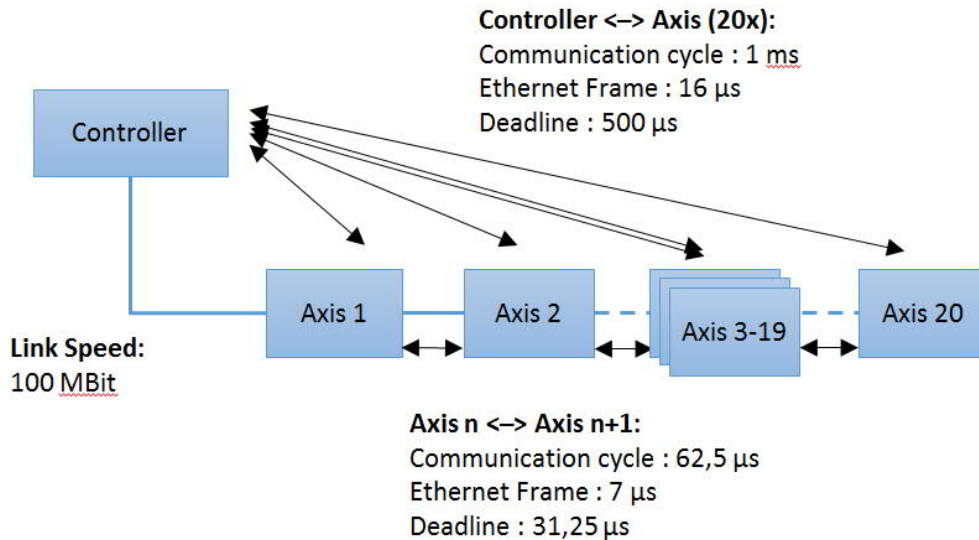
689

690 **Figure 25 – isochronous drive synchronization**

691 Requirements:

692 …

693 Useful 802.1 mechanisms:

694 • …

2.4.7 Use case 05: Drives without common application cycle

2.4.7.1 Background information

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.

Figure 26 shows an example, where Vendor A needs to communicate with 31,25 µs between its devices (A1 with A2), and Vendor B needs to communicate with 50 µs (between B1 and B2). The communication with the controller which has to coordinate both of them shall be a multiple of their local cycles. A1 needs to exchange data every 125µs with the Controller, B1 needs to exchange data every 200µs with the Controller.

Servo drives from different vendors (Vendor A and Vendor B) are working on the same network. For specific reasons the vendors are limited in the choice of the period for their control loop.
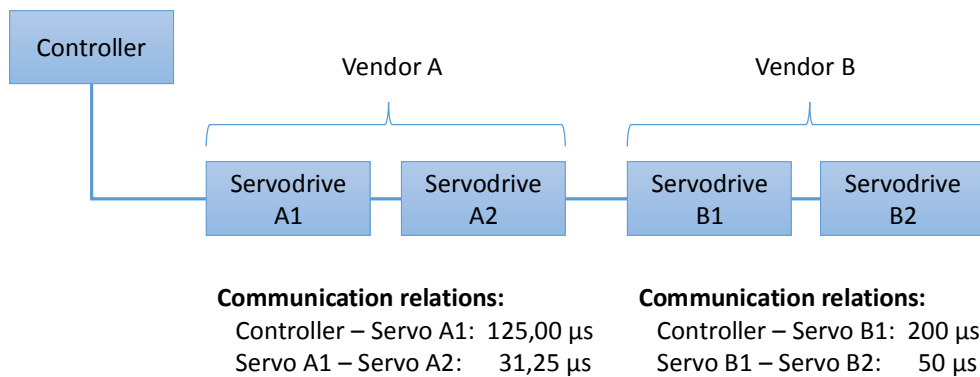
Figure 26 – network with different application cycles

The following Communication Relations are expected to be possible:

       Servodrive A1 ←→ Servodrive A2: 31,25 µs
       Servodrive B1 ←→ Servodrive B2: 50 µs

       Controller ←→ Servodrive A1: 125 µs
       Controller ←→ Servodrive B1: 200 µs

       Servodrive A1 ←→Servodrive B1: 1 ms

Requirements:
- Isochronous data exchange
- Different cycles for data exchange, which are not multiples of each other
  (cycles are not multiple of a common base, but fractions of a common base, here for instance 1 ms)

Useful 802.1Q mechanisms:
- Whatever helps
- …

727   **2.4.7.2   Controller communication**
728   The Usecase concentrates on the communication between the devices A1 and B1, and the
729   Controller as shown in Figure 27. Nevertheless the communication between A1/A2 and B1/B2 has
730   to be solved as well.

731
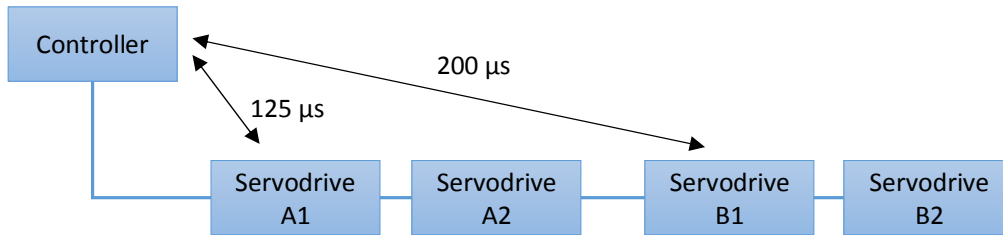
732   **Figure 27 – Multivendor Motion – Controller communication**
733

734   **2.4.7.3   Timing Requirements**

735
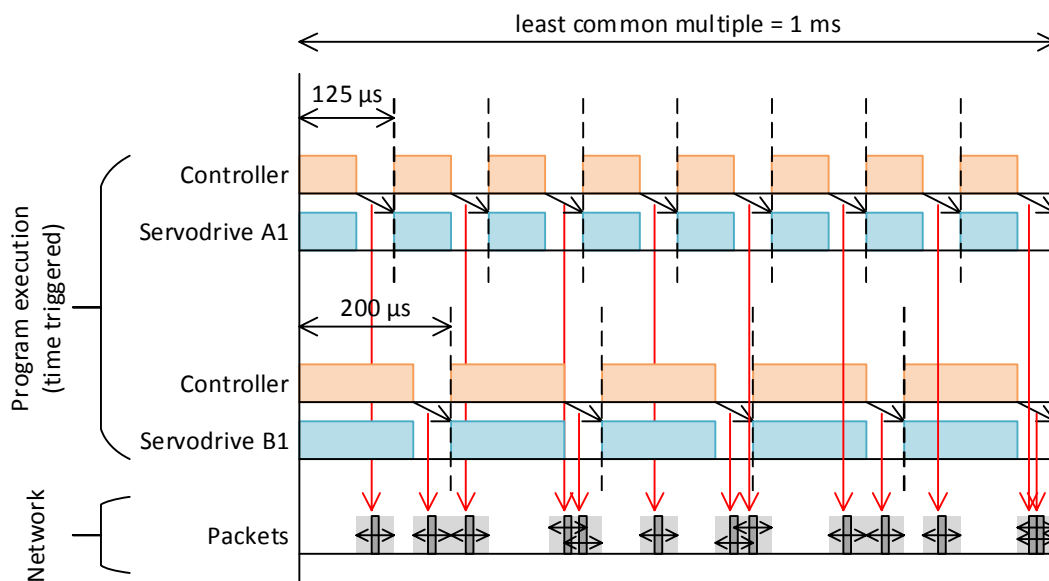
736   **Figure 28 – Multivendor Motion – Timing Requirements**
737

738   The Controller runs 2 parallel programs in multitasking, one program with 125 µs cycle, and
739   another with 200 µs cycle. Alternatively there might also be 2 independent controllers on the same
740   network, one of vendor A and one of vendor B.

741   After every program execution, data needs to be exchanged between Controller and Servodrive.
742   The time window for this exchange is application specific.

743   The actual data exchange on the wire can happen at any time in this window, the devices are not
744   dependent on any exact transmission or reception timing, as long as the packet is in the scheduled
745   window.

746   **2.4.8   Use case 06: Drives without common application cycle but common network cycle**

747   The concept of multiple different application cycles which are based on a common network cycle is
748   described in Use case 04: Reduction ratio of network cycle.

749   Examples with different application cycle times but common network cycle time 31,25 µs:

750   -   31,25 µs,   i.e. reduction ratio 1 for current control loop,

751   -   250 µs,   i.e. reduction ratio 8 for motor speed control loop,

752   -   1 ms,   i.e. reduction ratio 32 for position control loop,

753   -   16 ms,   i.e. reduction ratio 512 for remote IO.

754
755
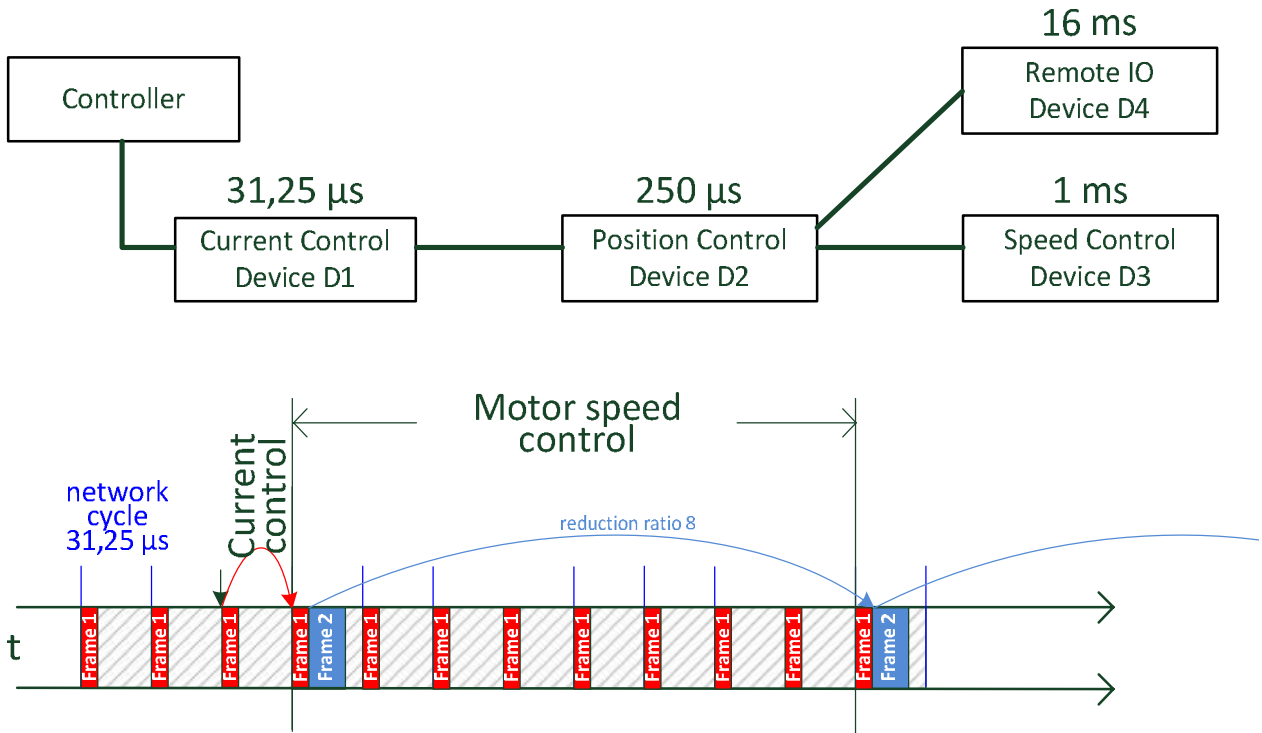
756   **Figure 29 – different application cycles but common network cycle**

757

2.5 Industrial automation networks

2.5.1 Use case 07: Redundant networks

Ring topologies are the basic industrial network architecture for switch-over or seamless redundancy.
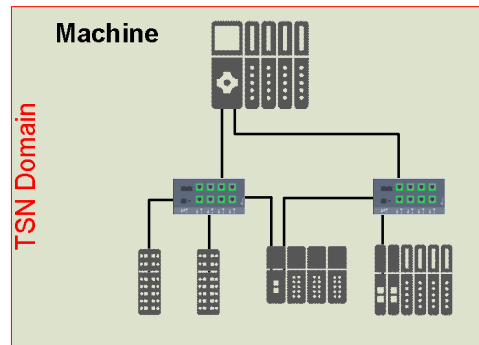
Figure 30 – ring topology

When a production cell is also arranged in a ring topology the resulting architecture of cell with attached machines is an interconnection of rings.

To even improve availability of the interconnection from the production cell into the machines this link can be arranged redundantly as well (machine 1 in Figure 31):
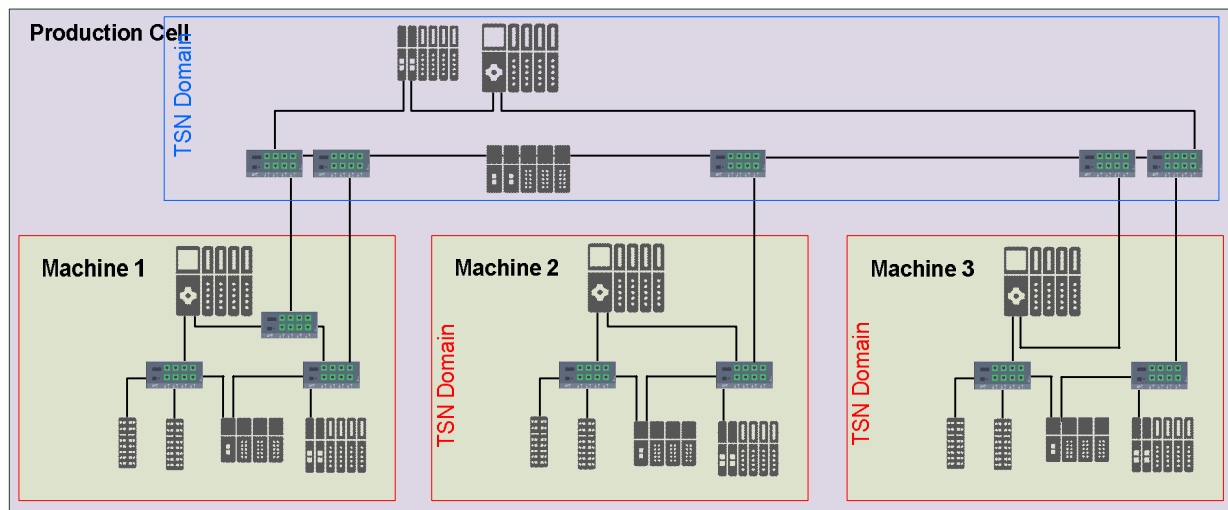
Figure 31 – connection of rings

Requirement:

Support redundant topologies with rings.

Useful 802.1 mechanisms:

- …

2.5.2 Use case 08: High Availability

High availability systems are composed of:
- Redundant networks, and
- Redundant stations.

780   E.g. tunnel control:

781   Tunnels need to be controlled by systems supporting high availability because airflow and fire
782   protection are crucial for the protection of people's lives. In this case PLC, remote IO and network
783   are installed to support availability in case of failure.

784
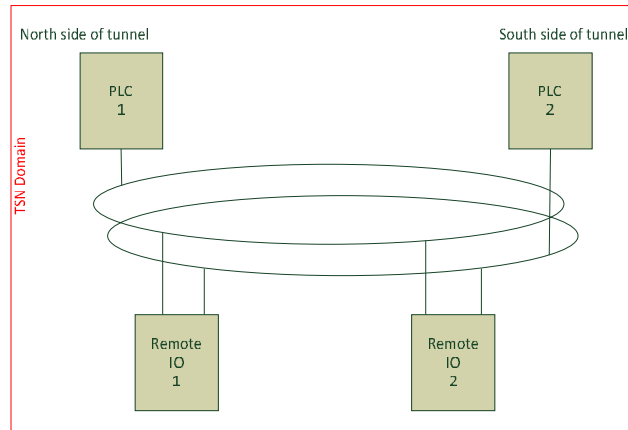
785   **Figure 32 – example topology for tunnel control**

786   Tunnel control may also include video surveillance as parallel application on the same network,
787   replacing dedicated analogue CCTV systems. This includes image processing applications like
788   speed section control, detecting lost cargo or traffic in wrong direction with minimized detection
789   time.

790   Requirement:
791   Failure shall not create process disturbance – e.g. keep air flow active / fire control active.
792   The number of concurrent active failures without process disturbance depends on the application
793   requirements and shall not be restricted by TSN profile definitions.
794   Parameter, program, topology changes need to be supported without disturbance.
795
796   Useful 802.1Q mechanisms:
797   •   Redundancy for PLCs, Remote IOs and paths through the network
798   •   …
799

800   Further high availability control applications:
801   •   Ship control
802   •   Power generation
803   •   Power distribution
804   •   …
805

806   **2.5.3   Use case 09: Wireless**
807   HMI panels, remote IOs, wireless sensors or wireless bridges are often used in industrial
808   machines. Wireless connections may be based on IEEE 802.11 (Wi-Fi), IEEE 802.15.1 (Bluetooth),
809   IEEE 802.15.4 or ITU/3GPP (5G). Even functional safety applications over wireless connections
810   are supported (see Use case 25: Functional safety).

811
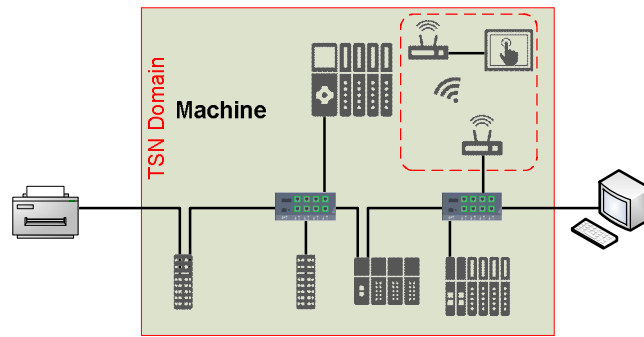
812
Figure 33 – HMI wireless connected using cyclic real-time

813
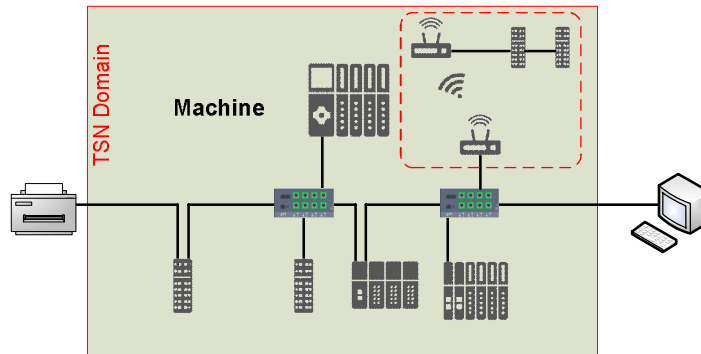
814
Figure 34 – Remote IO wireless connected using cyclic real-time

815
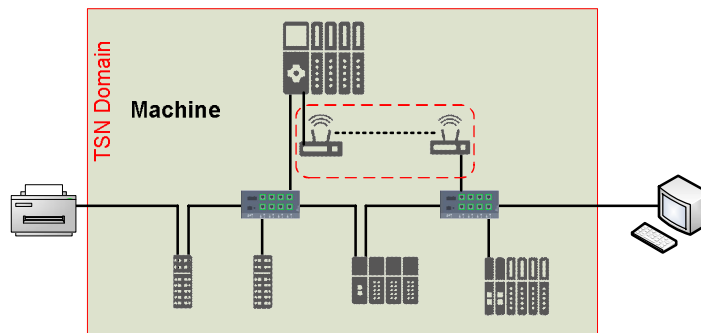
816
Figure 35 – Ring segment wireless connected for media redundancy

817
818
Requirement:

819
Support of wireless for

820
- cyclic real-time, and
821
- non-real-time communication

822
823
Useful 802.11 mechanisms:

824
- Synchronization support
825
- Extensions from .11ax
826
- …
827

828
Useful 802.15.1 mechanisms:

829 • …
830

831 Useful 802.1Q mechanisms:

832 • …
833

2.5.4 Use case 10: 10 Mbit/s end-stations (Ethernet sensors)

835 Simple and cheap sensor end-stations are directly attached via 10 Mbit/s links to the machine
836 internal Ethernet and implement cyclic real-time communication with the PLC.
837 The support of additional physics like "IEEE 802.3cg APL support" is intended.
838

839
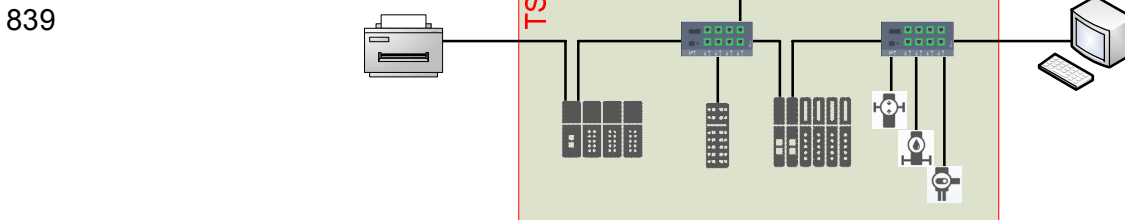
840 **Figure 36 – Ethernet sensors**

841 Requirement:

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

844
845 Useful 802.1Q mechanisms:

846 • …

2.5.5 Use case 11: Fieldbus gateway

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

849
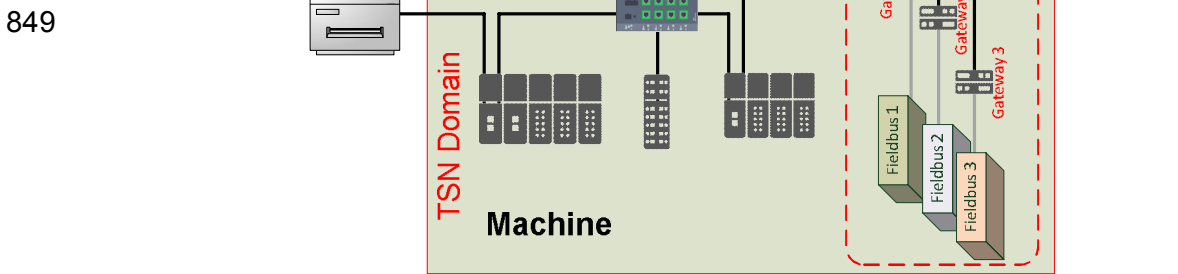
850 **Figure 37 – fieldbus gateways**

851 Many systems have at least one merging unit (e.g gateway, multiplexer) between the sensors and
852 actuators assigned to a single machine control. The clustering is typically done with some
853 infrastructure elements (slices) that require a backplane communication. The fieldbus
854 communication is in many cases the third level of communication. Thus, it is assumed that TSN is
855 not the first communication network between the sensors/actuators and a machine control unit.
856 This means that TSN should be capable to adapt an existing communication infrastructure
857 regardless of the size of those networks. The networks behind a gateway have their own timing
858 constraints. A machine level network may take into account that the lower level networks e.g.
859 behind a gateway have their own local timing. The timing of a TSN network has impact to sub-
860 ordinated structures. An optimal timing requires taking into account the gateway behavior for the
861 TSN configuration (see Figure 38).

862

Machine Control   **Gateway**

Lower level network

Outbound
Stream   Outbound

Network cycle

Inbound   Inbound
Stream
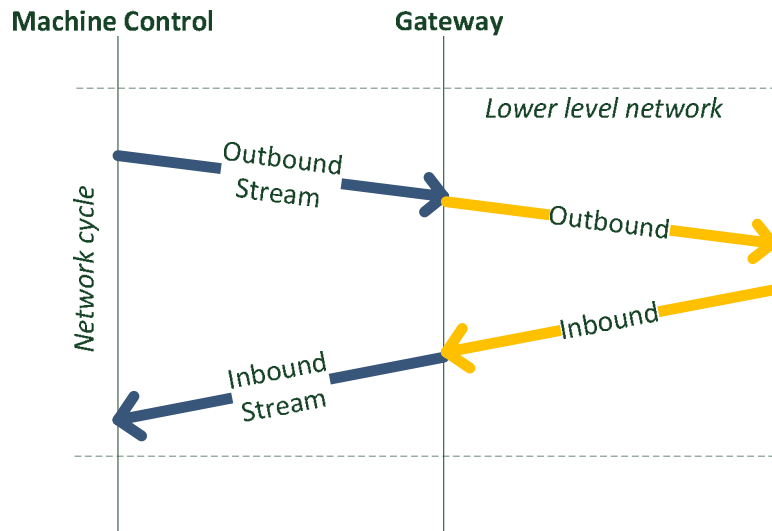
863   **Figure 38 – Embedded non TSN communication**

864 Requirement:

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

868 **2.5.6 Use case 12: New machine with brownfield devices**
869 Brownfield devices with real-time communication are attached to a PLC, which supports both
870 brownfield and greenfield, within a machine. This allows faster deployment of devices supporting
871 the TSN-IA profile into the field. Figure 39 gives an example of a machine with brownfield devices.
872

873
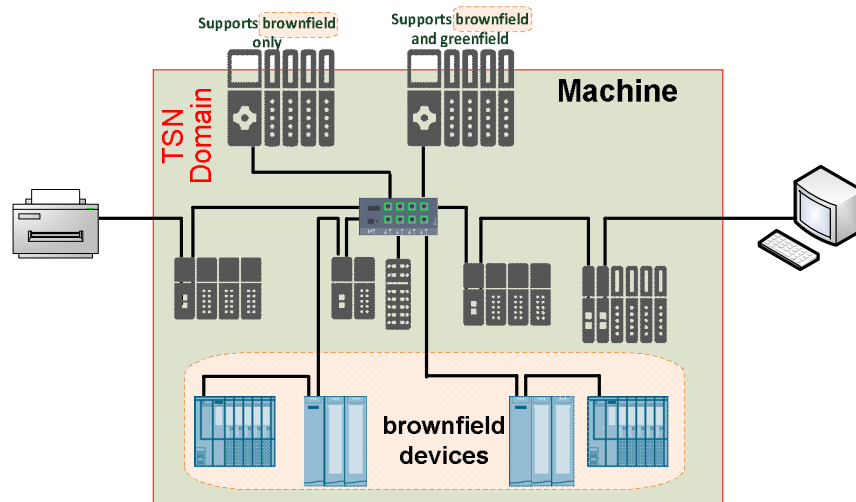
Figure 39 – New machine with brownfield devices

875 Requirement:
876 All machine internal stream traffic communication (stream traffic and non-stream traffic) is
877 decoupled from and protected against the brownfield cyclic real-time traffic.
878 Brownfield cyclic real-time traffic QoS is preserved within the TSN domain.
879
880 Useful 802.1Q mechanisms:
881 • Priority Regeneration,
882 • separate "brownfield traffic queue".
883 • Queue-based resource allocation.
884
885 Figure 40 shows a different use case where a TSN machine is attached to an existing brownfield
886 machine. In this case only non-TSN traffic is possible between the two machines.

887
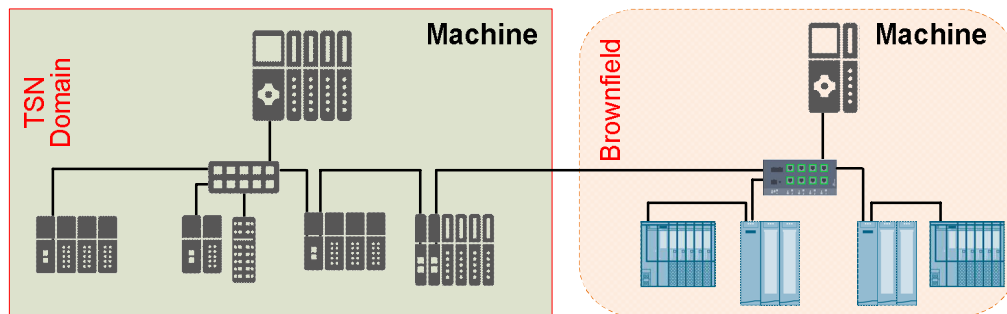
Figure 40 – Add TSN machine to brownfield machine

2.5.7 Use case 13: Mixed link speeds

890 Industrial use cases refer to link speeds, as shown in Table 9, in the range from 10 Mbit/s to
891 10 GBit/s for Ethernet and additional Wi-Fi, Bluetooth and 5G. Thus, the TSN domains need to
892 handle areas with different link speeds.

893   **Table 9 – 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

894

895   Mixing devices with different link speeds is a non-trivial task. Figure 41 and Figure 42 show the
896   calculation model for the communication between an IOC and an IOD connected with different link
897   speeds.

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

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

903
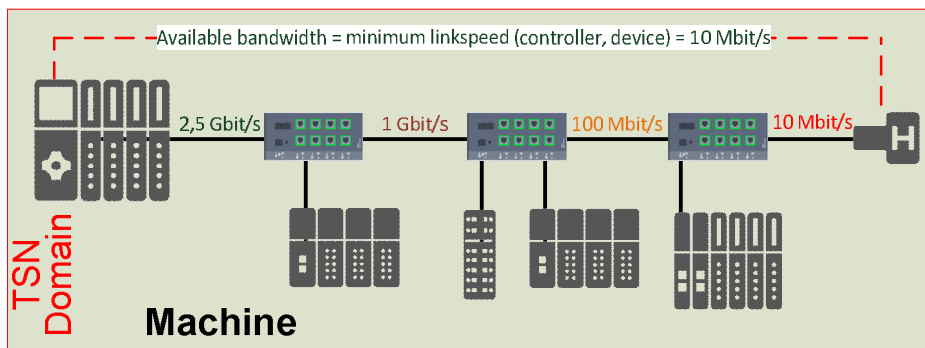
904   **Figure 41 – mixed link speeds**

905
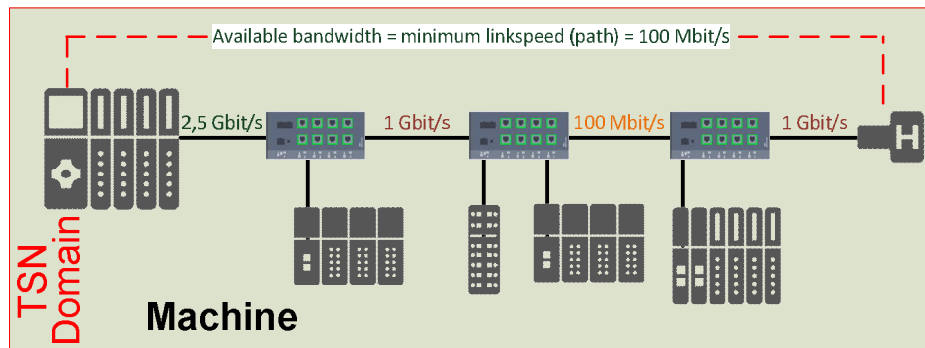
906
Figure 42 – mixed link speeds without topology guideline

907 Requirement:

908 Links with different link speeds as shown in Figure 41 share the same TSN-IA profile based
909 communication system at the same time.
910 Links with different link speeds without topology guideline (Figure 42) may be supported.
911
912 Useful 802.1 mechanisms:

913 • …

2.5.8 Use case 14: Multiple isochronous domains

915 Figure 43 shows a machine which needs due to timing constraints (network cycle time together
916 with required topology) two or more separated isochronous real-time domains but shares a
917 common cyclic real-time domain.
918 Both isochronous domains may have their own Working Clock and network cycle. The PLCs need
919 to share remote IOs using cyclic real-time traffic.

920
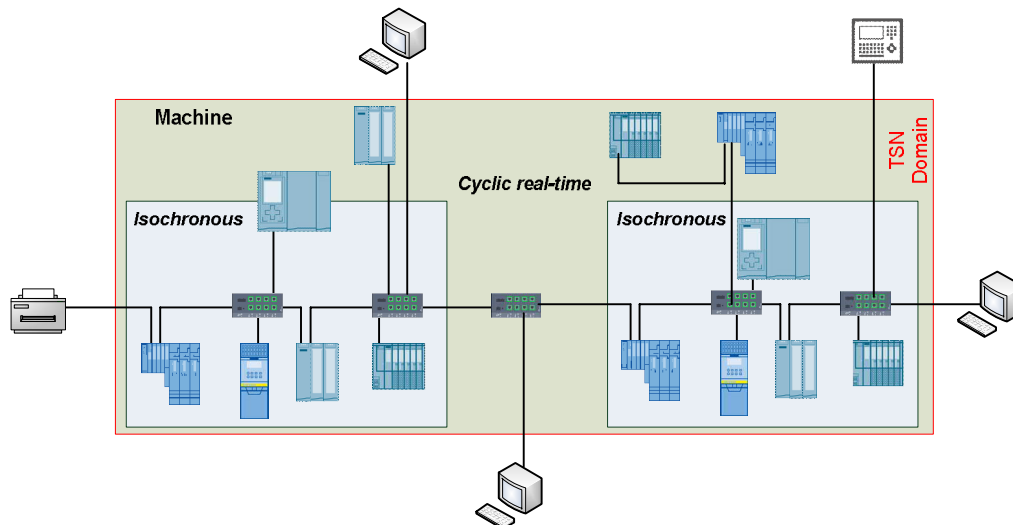
921
Figure 43 – multiple isochronous domains

922 Some kind of coupling (e.g. shared synchronization) between the isochronous domains / Working
923 Clocks may be used (see Figure 44).
924 All isochronous domains may have different network cycle times, but the cyclic real-time data
925 exchange shall still be possible for PLCs from both isochronous domains.

926

927
928
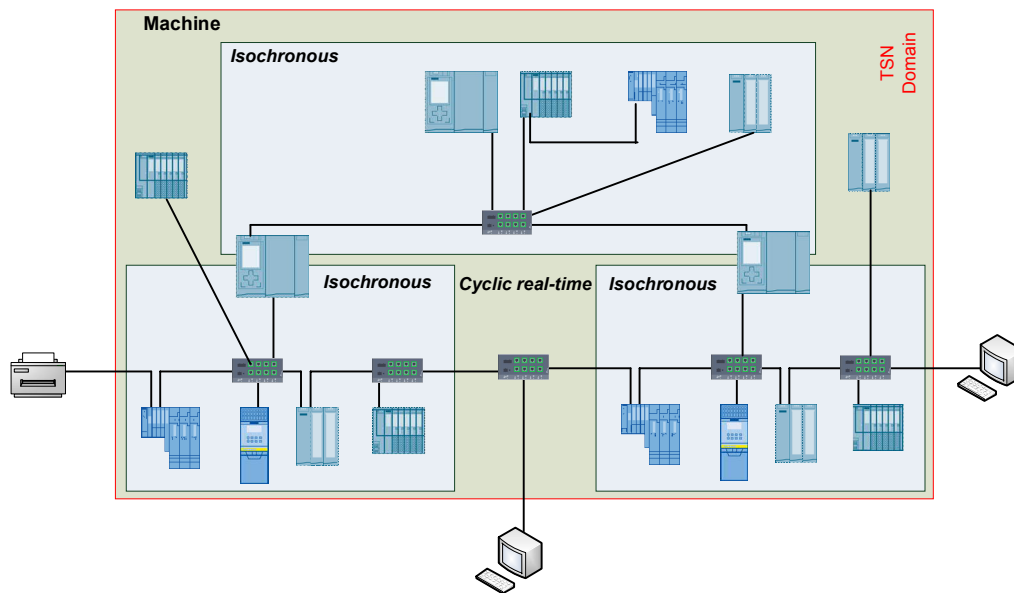
Figure 44 – multiple isochronous domains - coupled

929 Requirements:

930 Isochronous real-time domains may run independently, loosely coupled (start of network cycle is
931 synchronized) or tightly coupled (shared working clock). They shall be able to share a cyclic real-
932 time domain.

933
934 Useful 802.1 mechanisms:

935　　• separate "isochronous" and "cyclic" traffic queues,
936　　• Queue-based resource allocation in all bridges,
937　　• ...

938 **2.5.9　Use case 15: Auto domain protection**
939 Machines are built in a way that not always all devices are really attached either due to different
940 machine models/variants or repair. In this use case a TSN domain shall not expand automatically
941 when e.g. two machines get connected via an unplanned and unintended link.

942

943

944
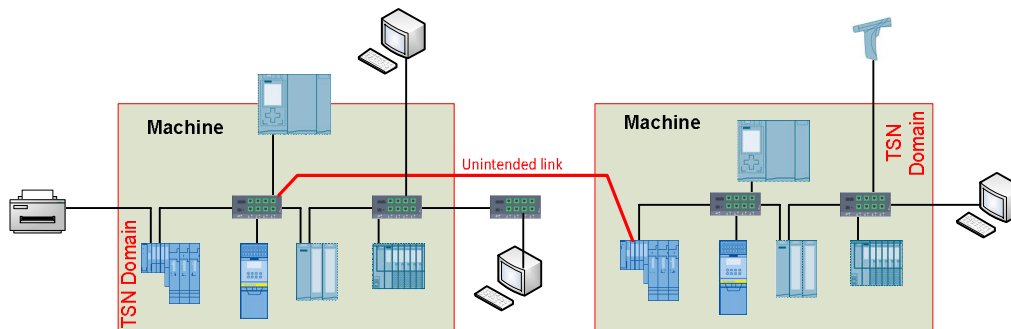
Figure 45 – Auto domain protection

945 Requirement:

946   Support of auto TSN domain protection to prevent unintended use of traffic classes
947
948   Useful 802.1Q mechanisms:

949   • Priority regeneration
950   • …

2.5.10 Use case 16: Vast number of connected stations

952   Some industrial applications need a massive amount of connected stations like
953   - Car production sites
954   - Postal, Parcel and Airport Logistics
955   - …

956   Examples for "Airport Logistics":
957   • Incheon International Airport, South Korea
958   • Guangzhou Baiyun International Airport, China
959   • London Heathrow Airport, United Kingdom
960   • Dubai International Airport, UAE
961   • …
962
963   Dubai International Airport, UAE
964   Technical Data:
965   • 100 km conveyor length
966   • 222 check-in counters
967   • car park check-in facilities
968   • Max. tray speed: 7.5 m/s
969   • 49 make-up carousels
970   • 14 baggage claim carousels
971   • 24 transfer laterals
972   • Storage for 9,800 Early Bags
973   • Employing 48 inline screening
974   • Max. 8-stories rack system
975   • 10,500 ton steel
976   • 234 PLC's
977   • 16,500 geared drives
978   • [xxxx digital IOs]
979
980   Further representative examples of required quantities are provided in 2.5.11.1 and 2.5.11.2.
981
982   Requirement:

983   Make sure that even this massive amount of stations works together with the TSN-IA profile. This
984   kind of applications may or may not require wireless support, too.
985
986   Useful 802.1 mechanisms:

987   • …

988   ## 2.5.11 Minimum required quantities

989   ### 2.5.11.1 A representative example for VLAN requirements

990   Figure 46 shows the IEEE 802.1Q based stacked physical, logical and active topology model. This
991   principle is used to build TSN domains.

992   It shows the different active topologies driven by either VID (identified by VLAN) or protocol
993   (identified by DA-MAC and/or protocol type).

994   Additionally the number of to be supported VIDs per bridge is shown. The number of protocol agent
995   defined active topologies is just an example because e.g. LLDP, RSTP or MST is missing.

996   The following topologies, trees and VLANs are shown in Figure 46.

❿	Physical network topology	all existing devices and links
❶	Logical network topology	**TSN domain**: administrative selection of elements from the physical topology
❷	Active default topology	Default VLAN: result of a spanning tree algorithm (e.g. RSTP)
❸	Cyclic RT	VLAN for cyclic real-time streams
❹	Cyclic RT „R"	VLAN for redundant cyclic real-time streams
❺	Isochronous cyclic RT 1	VLAN for isochronous cyclic real-time streams
❻	Isochronous cyclic RT 1 „R"	VLAN for redundant isochronous cyclic real-time streams
❼	Isochronous cyclic RT 2[4]	VLAN for isochronous cyclic real-time streams
❽	Working clock	gPTP sync tree used for the synchronization of a working clock
❾	Working clock „R"	Hot standby gPTP sync tree used for the synchronization of a working clock
❶ ❿	Universal time	gPTP sync tree used for the synchronization of universal time

---

[4] The isochronous cyclic RT 2 „R" is not applied in this example but can be made available additionally
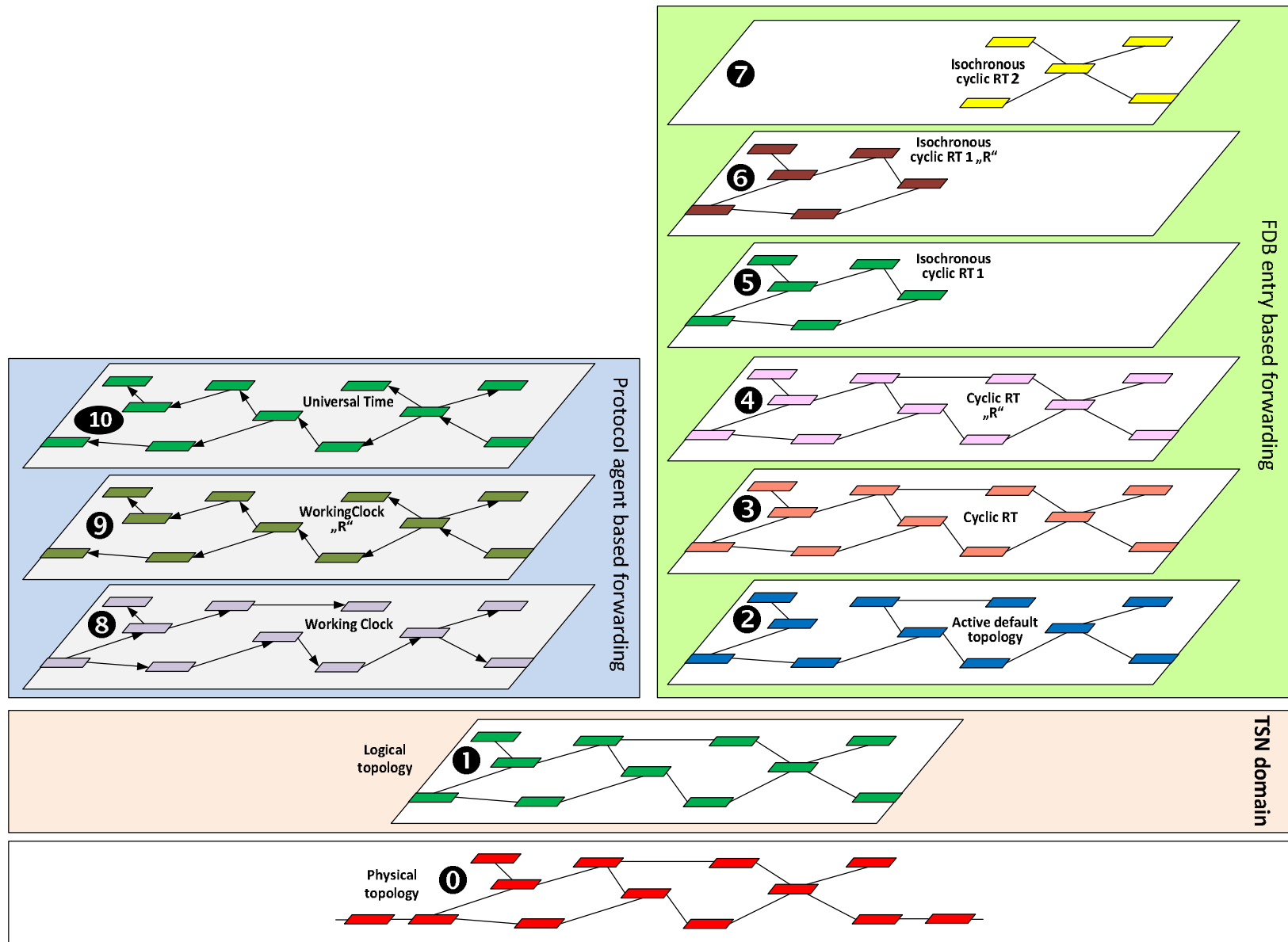
Figure 46 – Topologies, trees and VLANs

999

1000 Expected numbers of DA-MAC address entries used together with five VLANs (Default, High, High
1001 Redundant, Low and Low Redundant) are shown in Table 10 and Table 11.

1002 Table 10 may be implemented as FDB table with a portion of DA-MAC address (e.g. 12 bits of
1003 Identifier and TSN-IA profile OUI) as row and the VLANs as column to ensure availability of a
1004 dedicated entry.

1005   **Table 10 – 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)

1006

1007 Expected number of entries is given by the maximum device count of 1024 together with the 50%
1008 saturation due to hash usage rule. Table 11 shows the expected number of possible FDB entries.

1009   **Table 11 – Expected number of non-stream FDB entries**

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

1010

1011 The hash based FDBs shall support a neighborhood for entries according to Table 12.

1012   **Table 12 – 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.

1013

1014 **2.5.11.2 A representative example for data flow requirements**

1015
1016 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:

1017 – Stations: 1024

1018 – Network diameter: 64

1019 – per PLC for Controller-to-Device (C2D) – one to one or one to many – communication:
1020   o 512 producer and 512 consumer data flows; 1024 producer and 1024 consumer data
1021   flows in case of seamless redundancy.
1022   o 64 kByte Output und 64 kByte Input data

1023 – per Device for Device-to-Device (D2D) – one to one or one to many – communication:
1024   o 2 producer and 2 consumer data flows; 4 producer and 4 consumer data flows in case
1025   of seamless redundancy.
1026   o 1400 Byte per data flow

1027 – per PLC for Controller-to-Controller (C2C) – one to one or one to many – communication:

1028   o 64 producer and 64 consumer data flows; 128 producer and 128 consumer data flows in
1029   case of seamless redundancy.
1030   o 1400 Byte per data flow
1031 – Example calculation for eight PLCs
1032   → 8 x 512 x 2   = 8192 data flows for C2D communication
1033   → 8 x 64 x 2   = 1024 data flows for C2C communication
1034   → 8 x 64 kByte x 2   = 1024 kByte data for C2D communication
1035   → 8 x 64 x 1400 Byte x 2 = 1400 kByte data for C2C communication
1036 – All above shown data flows may optionally be redundant for seamless switchover due to the
1037   need for High Availability.

1038 Application cycle times for the 512 producer and 512 consumer data flows differ and follow the
1039 application process requirements.

1040 E.g. 125 µs for those used for control loops and 500 µs to 512 ms for other application processes.
1041 All may be used concurrently and may have frames sizes between 1 and 1440 bytes.

2.5.11.3 A representative example of communication use cases

1043 IO Station – Controller (input direction)
1044 – Up to 2000 published + subscribed signals (typically 100 – 500)
1045 – Scan interval time: 0,5 ..100ms (typical 10ms)
1046 Controller – Controller (inter-application)
1047 – Up to 1000 published + subscribed signals (typically 100 – 250)
1048 – Application task interval time: 10..1000ms (typical 100ms)
1049 – Resulting Scan interval time: 5 … 500 ms
1050 Closing the loop within/across the controller
1051 – Up to 2000 published + subscribed signals (typically 100 – 500)
1052 – Application task interval time: 1..1000ms (typical 100ms)
1053 – Resulting Scan interval time when spreading over controllers: 0,5 … 500 ms
1054 Controller – IO Station (output direction)
1055 – Up to 2000 published + subscribed signals (typically 100 – 500)
1056 – Application task interval time: 10..1000ms (typical 100ms
1057 – Resulting Scan interval time: 5 … 500 ms
1058

2.5.11.4 "Fast" process applications

1060 The structure shown in Figure 1 applies. Figure 47 provides a logic station view.
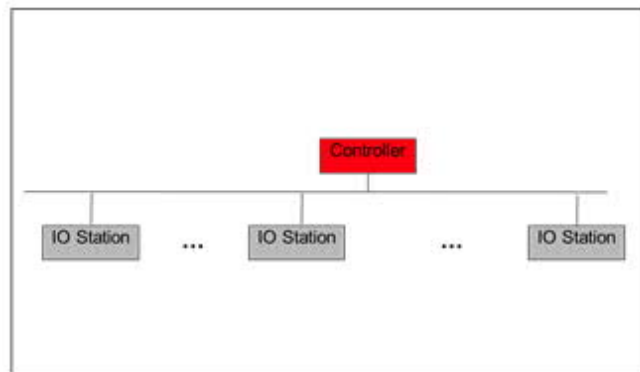
1061

1062   **Figure 47 – Logical communication concept for fast process applications**

1063   Specifics:

1064   –   Limited number of nodes communicating with one Controller (e.g. Turbine Control)

1065   –   Up to a dozen Nodes of which typically one is a controller

1066   –   Data subscriptions (horizontal):

1067   ▪   270 bytes published + subscribed per IO-station

1068   ▪   Scan Interval time 0,5 to 2 ms

1069   –   Physical Topology: Redundant (as path and as device)
1070

1071   **2.5.11.5   Server consolidation**
1072   The structure shown in Figure 1 applies. Figure 48 provides a logic station view.
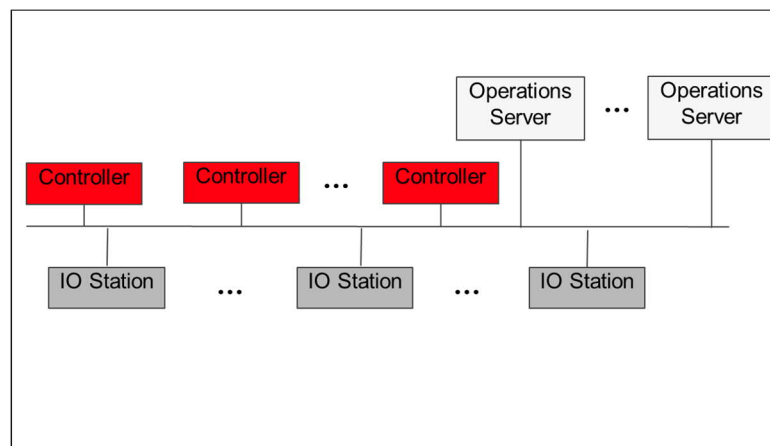
1073

1074   **Figure 48 – Server consolidated logical connectivity**
1075

1076   Data access to Operations Functionalities consolidated through Servers

1077   –   Up to 100 Nodes in total

1078   –   Out which are up to 25 Servers
1079

1080   Data subscriptions (vertical):

1081   – Each station connected to at least 1 Server

1082   – max. 20000 subscribed items per Controller/IO-station

1083   – 1s update rate

1084   – 50% analog items -> 30% change every sec

1085

1086   Different physical topologies

1087   – Rings, stars, redundancy

1088

1089   2.5.11.6 Direct client access
1090   The structure shown in Figure 1 applies. Figure 49 provides a logic station view.
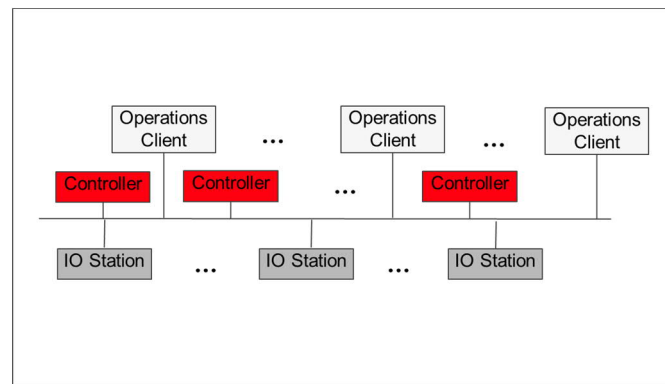
1091

1092   **Figure 49 – Clients logical connectivity view**

1093   Data access to Operations Functionalities directly by Clients

1094   – Max 20 direct access clients

1095

1096   Data subscriptions (vertical):

1097   – Up to 3000 subscribed items per client

1098   – 1s update rate

1099   – Worst case 60000 items/second per controller in classical Client/Server setup

1100   – 50% analog items -> 30% change every sec

1101

1102   Different physical topologies

1103   – Rings, stars, redundancy

1104

1105   2.5.11.7 Field devices
1106   The structure shown in Figure 1 applies. Figure 50 provides a logic station view.
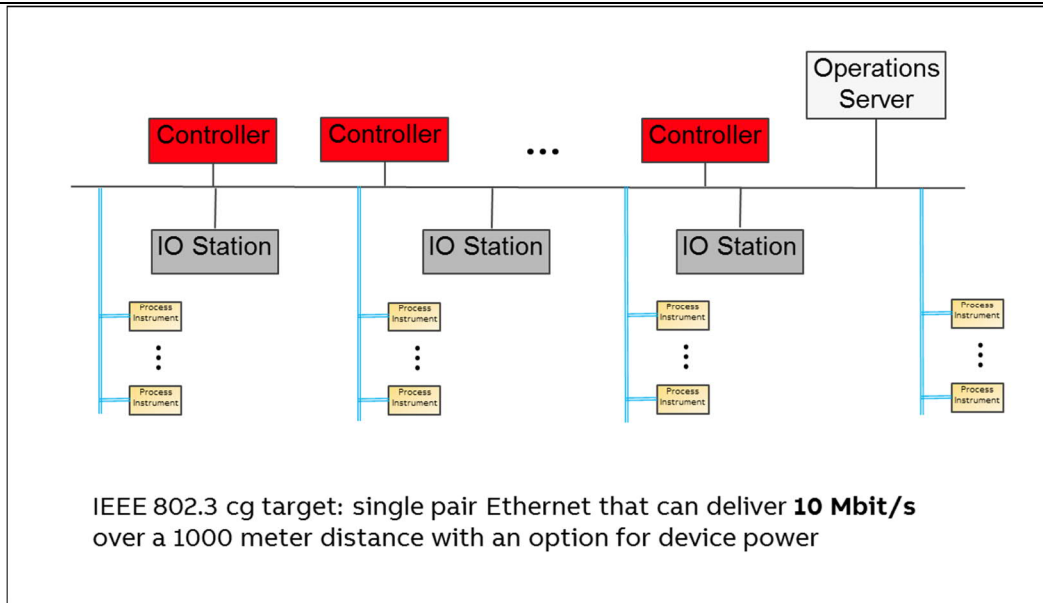
Figure 50 – Field devices with 10Mbit/s

Field Networks integrated with converged network

- Up to 50 devices per field segment

- Scan interval 50ms … 1s, typical 250ms

- Mix of different device types from different vendors

- Many changes during runtime

2.5.12 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.

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

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 13, Table 14, Table 15, and Table 16 shows the resulting values for different link speeds and fully utilized links.

1128
1129
1130
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.

1131

Table 13 – 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

1132

1133

Table 14 – 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

1134

1135

Table 15 – 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

1136

1137 **Table 16 – 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

1138

1139 A per port frame resource management leads to the same values, but reduces the flexibility to use
1140 free frame resources for other ports.

1141 A per queue per port frame resource management would increase (multiplied by the number of to
1142 be covered queues) the needed amount of frame resources dramatically almost without any
1143 benefit.

1144 Example "per port frame resource management":

1145 100 Mbit/s, 2 Ports, and 6 queues
1146 Needed memory := 6,25 KOctets * 6 := 37,5 KOctets.

1147 No one is able to define which queue is needed during the "stream port blocking" period.

1148

1149 Bridged End-Stations need to ensure that their local injected traffic does not overload its local
1150 bridge resources. Local network access shall conform to the TSN-IA profile defined model with
1151 management defined limits and cycle times (see e.g. row Data period in Table 4).

2.6 Industrial automation machines, production cells, production lines

2.6.1 Use case 17: Machine to Machine/Controller to Controller (M2M/C2C) Communication

Preconfigured machines with their own TSN domains, which include tested and approved internal communication, communicate with other preconfigured machines with their own TSN domains, with a supervisory PLC of the production cell (with its own TSN domain) or line (with its own TSN domain) or with an Operations Control HMI (with its own TSN domain).
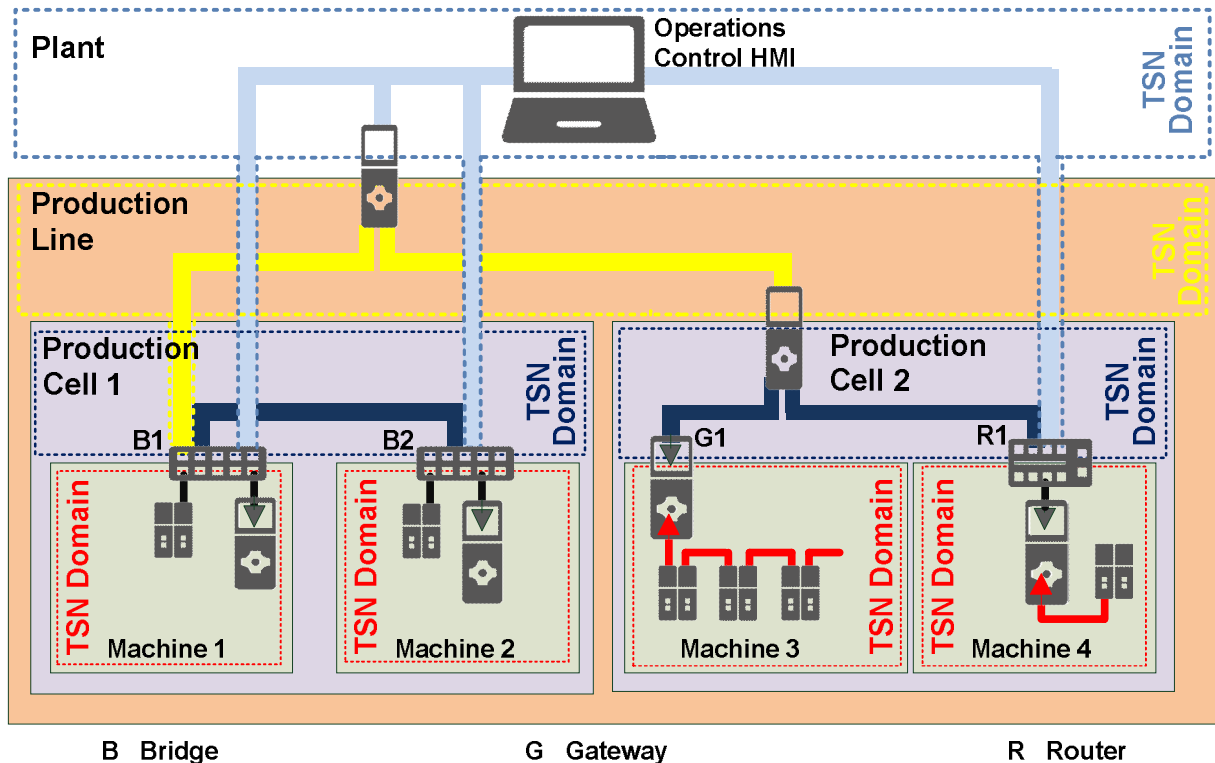
Figure 51 – M2M/C2C between TSN domains

Figure 51 shows that multiple logical overlapping TSN Domains arise, when controllers use a single interface for the M2M communication with controllers of the cell, line, plant or other machines. Decoupling of the machine internal TSN Domain can be accomplished by applying a separate controller interface for M2M communication.

Machine 1: the controller link to its connected cell bridge B1 is concurrently member of the TSN Domains of Machine 1, Production Cell 1, Production Line and Plant.

Machine 2: the controller link to its connected cell bridge B2 is concurrently member of the TSN Domains of Machine 2, Production Cell 1 and Plant.

Machine 3: the controller is directly attached to the PLC of Production Cell 2 and is therefore member of the TSN Domain of Production Cell 2. The machine internal TSN Domain is decoupled from M2M traffic by a separate interface.

Machine 4: the controller link to its connected cell bridge B3 is concurrently member of the TSN Domains of Production Cell 2 and Plant. The machine internal TSN Domain is decoupled from M2M traffic by a separate interface.

Examples:
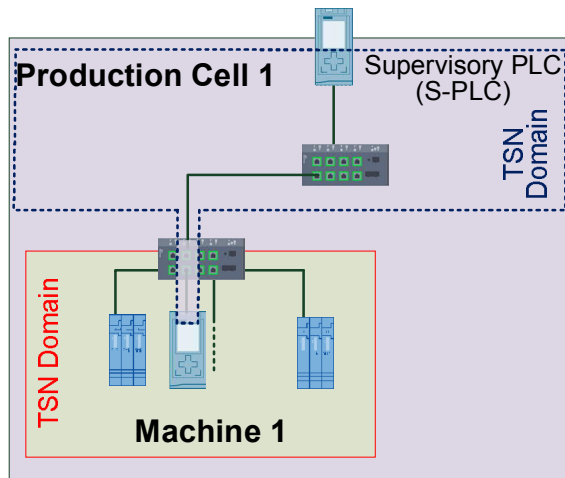
Figure 52 – M2M with supervisory PLC

Figure 52 gives an example of M2M communication to a supervisory PLC.

Figure 53 shows an example of M2M communication relations between four machines.

PLCs with one single interface lead to overlapping communication paths of M2M and machine internal traffic. In this case two TSN domains (Machine / Production cell) need to share resources due to two logical overlapping TSN domains.

There are quite a few constraints related to the machine internal networks. Each machine may run a different schedule and even the intervals may be different. It may be very complex or even impossible to find an optimal communication schedule down from the sensors and actuators to the cell control. The requirements for cascaded control loops require faster intervals for the lower control loops. The multiple machine intervals embedded in one cell interval can be mapped onto a sequence of intervals. Each step in the exchange of data between machine and cell control unit can be mapped into machine intervals:
- outbound cell communication,
- transfer outbound within machine network,
- transfer inbound within machine network,
- inbound cell communication.

Additionally Figure 54 shows an example where M2M communication is used to connect a PC for diagnostics/monitoring.

Figure 53 – M2M with four machines

Figure 54 – M2M with diagnostics/monitoring PC

1177 Figure 54 shows a M2M diagnostics related use case: communication is cyclic and shall happen
1178 within short application cycle times. An example of this use case is the verification of proper
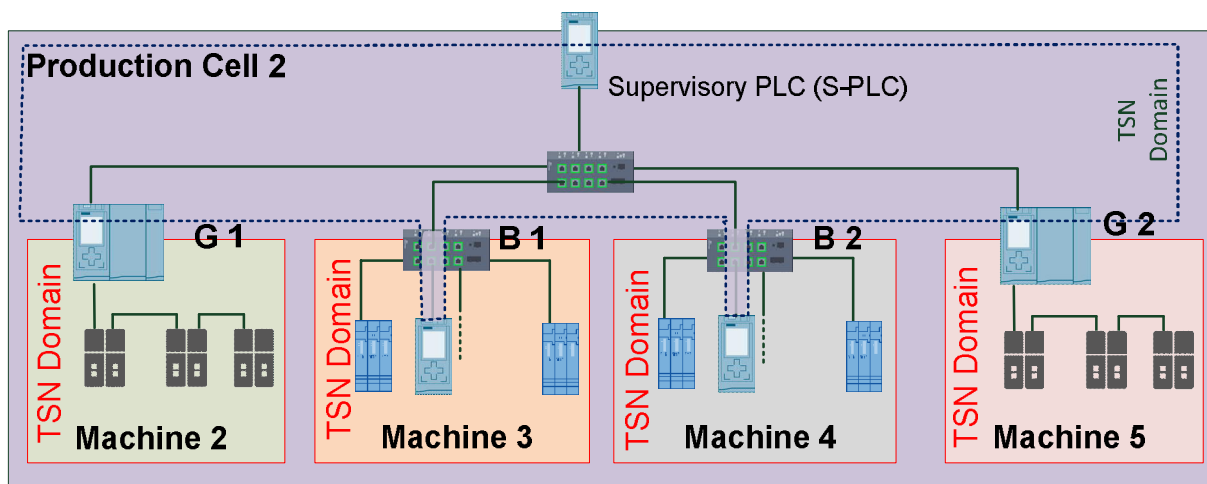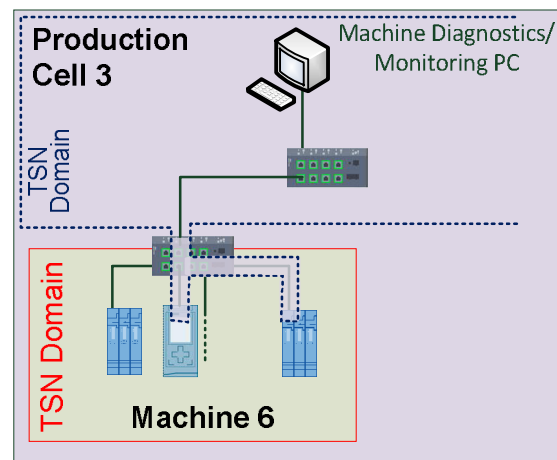1179 behavior of a follower drive, in a master-follower application. Today, the use case is covered by
1180 connecting a common PC to an interface of the follower drive. The various TSN mechanisms may
1181 now make it possible to connect such a PC network interface card anywhere in the system network
1182 and still gather the same diagnostics with the same guarantees, as the current direct connection.

1183 The required guarantees are:

1184 Each 4 ms a frame shall be sent from a follower drive and have its delivery guaranteed to the
1185 network interface of the PC used to perform the diagnostics. Of course, local PC-level processing
1186 of such frames has to be implemented such that the diagnostic application gets the required quality
1187 of service.

1188 From the communication point of view the two types of machine interface shown in Figure 53 are
1189 identical. The PLC represents the machine interface and uses either a dedicated (machine 1 and 4)
1190 or a shared interface (machine 2 and 3) for communication with other machines and/or a
1191 supervisor PLC.

1192 The communication relations between machines may or may not include or make use of a
1193 supervisory PLC.

1194 Requirement:
1195 • All machine internal communication (stream traffic and non-stream traffic) is decoupled from
1196   and protected against the additional M2M traffic and vice versa.
1197 • 1:1 and 1:many communication relations shall be possible.
1198 • Scheduling in a way that interleaved operation with machine intervals is possible.

1199 Useful 802 mechanisms:
1200 • IEEE Std 802.1Q-2018, Fixed priority, IEEE Std 802.3br
1201 • Priority Regeneration,
1202 • Queue-based resource allocation,
1203 • VLANs to separate TSN domains.

2.6.2 Use case 18: Pass-through Traffic

1204
1205 Machines are supplied by machine builders to production cell/line builders in tested and approved
1206 quality. At specific boundary ports standard devices (e.g. barcode reader) can be attached to the
1207 machines. The machines support transport of non-stream traffic through the tested/approved
1208 machine ("pass-through traffic") without influencing the operational behavior of the machine, e.g.

1209 connection of a printer or barcode reader. Figure 55, Figure 56 and Figure 57 give some examples
1210 of pass-through traffic installations in industrial automation.
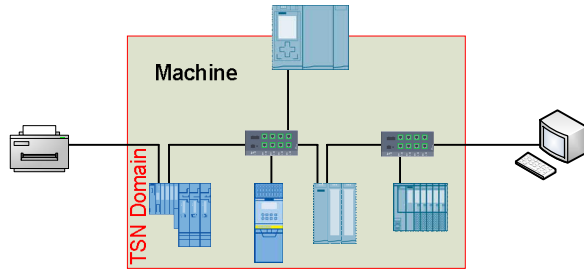
Figure 55 – pass-through one machine
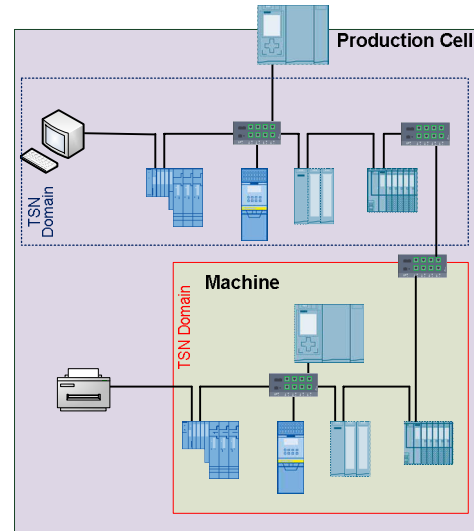
Figure 56 – pass-through one machine and production cell
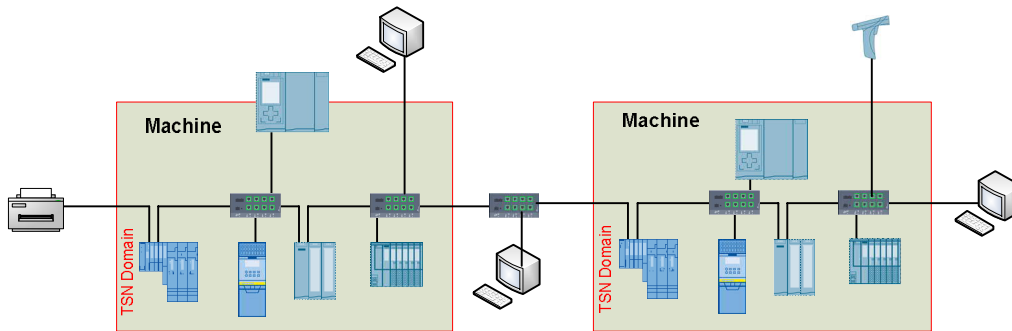
Figure 57 – pass-through two machines
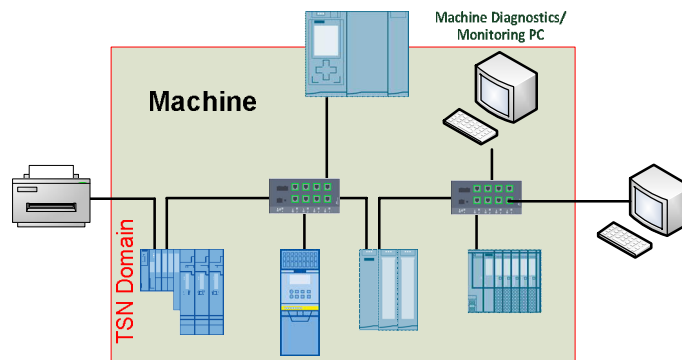
Figure 58 – machine with diagnostics / monitoring PC

1211 Requirement:

1212 All machine internal communication (stream traffic and non-stream traffic) is decoupled from and
1213 protected against the additional "pass-through" traffic.
1214 "Pass-through" traffic is treated as separate traffic pattern.
1215
1216 Useful 802.1Q mechanisms:

1217 • Priority Regeneration,

1218   • separate "pass-through traffic queue",
1219   • Queue-based resource allocation in all bridges,
1220   • Ingress rate limiting.
1221

1222   ### 2.6.3 Use case 19: Modular machine assembly
1223   In this use case machines are variable assemblies of multiple different modules. Effective
1224   assembly of a machine is executed in the plant dependent on the current stage of production, e.g.
1225   bread-machine with the modules: base module, 'Kaisersemmel' module, 'Rosensemmel' module,
1226   sesame caster, poppy-seed caster, baking oven OR advertisement feeder for newspapars.

1227   Figure 59 may have relaxed latency requirements, but the machine in Figure 60 needs to work with
1228   very high speed and thus has very demanding latency requirements.

1229

1230

1231   **Figure 59 – modular bread-machine**

1232

1233
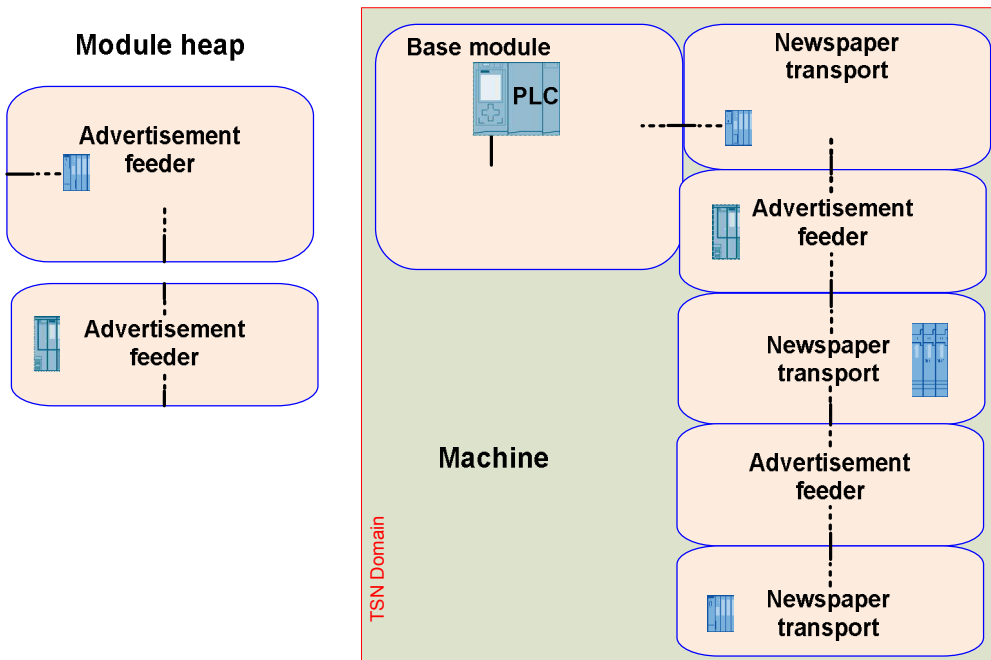
1234   **Figure 60 – modular advertisement feeder**

1235   Requirement:
1236   Modules can be assembled to a working machine variably on-site (either in run, stop or power
1237   down mode) as necessary (several times throughout a day). The machine produces the selected
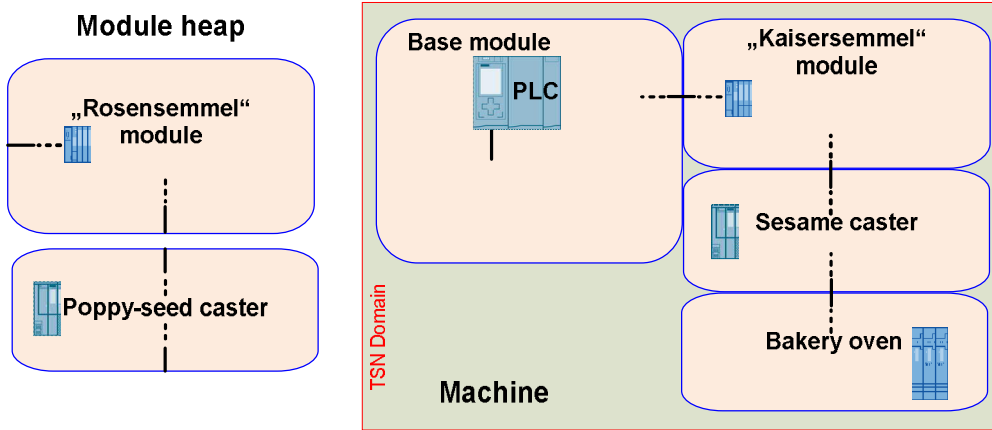1238   variety of a product. Communication relying on TSN features is established automatically after the
1239   modules are plugged without management/ configuration interaction.
1240

1241   ### 2.6.4   Use case 20: Tool changer
1242   Tools (e.g. different robot arms) are in power off mode. During production a robot changes its arms
1243   for different production steps.

1244   They get mechanically connected to a robot arm and then powered on. The time till operate
1245   influences the efficiency of the robot and thus the production capacity of the plant. Robots may
1246   share a common tool pool. Thus the "tools" are connected to different robots during different
1247   production steps.

1248
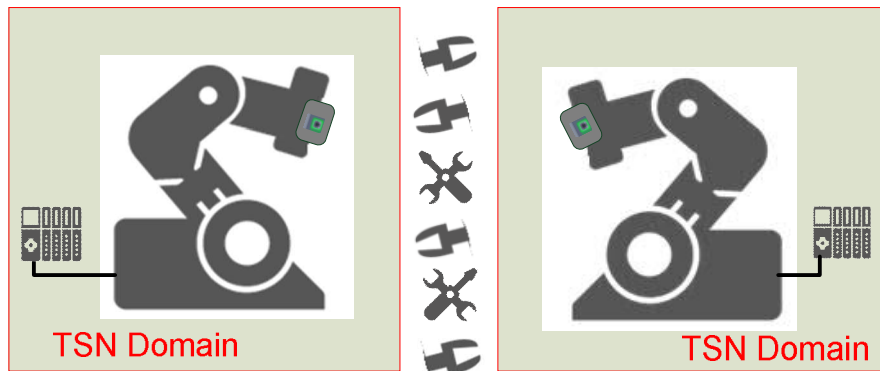
Figure 61 – tool changer

1249

1250
1251   Requirement:
1252   • Added portion of the network needs to be up and running (power on to operate) in less than
1253   500ms.
1254   • Extending and removing portions of the network (up to 16 devices) in operation
1255   ○   by one connection point (one robot using a tool)
1256   ○   by multiple connection points (multiple robots using a tool)

1257
1258
1259   Useful 802.1Q mechanisms:
1260   • preconfigured streams
1261   • …

1262 **2.6.5   Use case 21: Dynamic plugging and unplugging of machines (subnets)**
1263 E.g. multiple AGVs (automatic guided vehicles) access various docking stations to get access to
1264 the supervisory PLC. Thus, an AGV is temporary not available. An AGV may act as CPS or as a
1265 bunch of devices.

1266
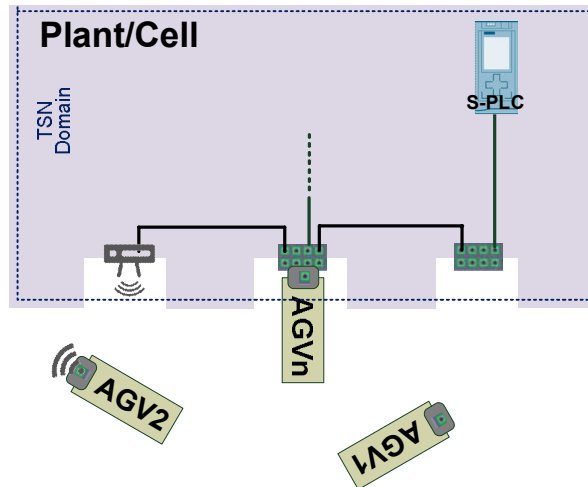
1267 **Figure 62 – AGV plug and unplug**

1268

1269 Requirement:
1270 The traffic relying on TSN features from/to AGVs is established/removed automatically after
1271 plug/unplug events.
1272 Different AGVs may demand different traffic layouts.
1273 The time till operate influences the efficiency of the plant.
1274 Thousands of AGS may be used concurrently, but only a defined amount of AGVs is connected at
1275 a given time.

1276
1277
1278 Useful 802.1Q mechanisms:
1279   • preconfigured streams
1280   • …
1281
1282

2.6.6 Use case 22: 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.
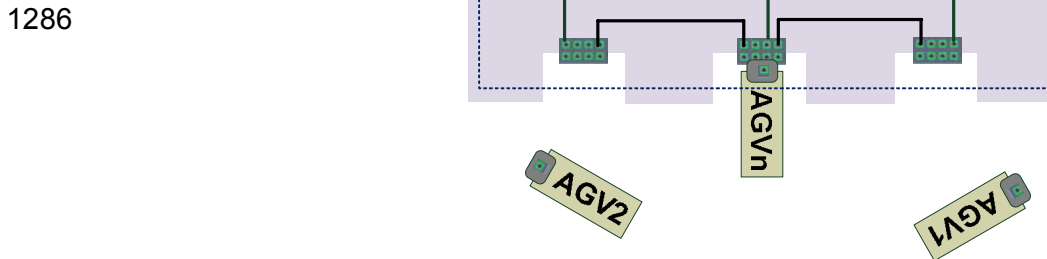
Figure 63 – energy saving

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.

2.6.7 Use case 23: Add machine, production cell or production line

When production capacity is exhausted, additional machines, production cells or even production lines are bought and integrated into a plant.
E.g. an additional welding robot is added to a production cell to increase production capacity. The additional machine has to be integrated into the production cell control with minimal disturbance of the production cell process.

Another aspect is when a machine or a group of machines is tested in a stand-alone mode first before it is used in the combination with other machines or in combination with a supervisory system.
A flexible cell communication is needed to support this. Enabling and disabling of cell communication within a machine should be possible with minimal impact on production.
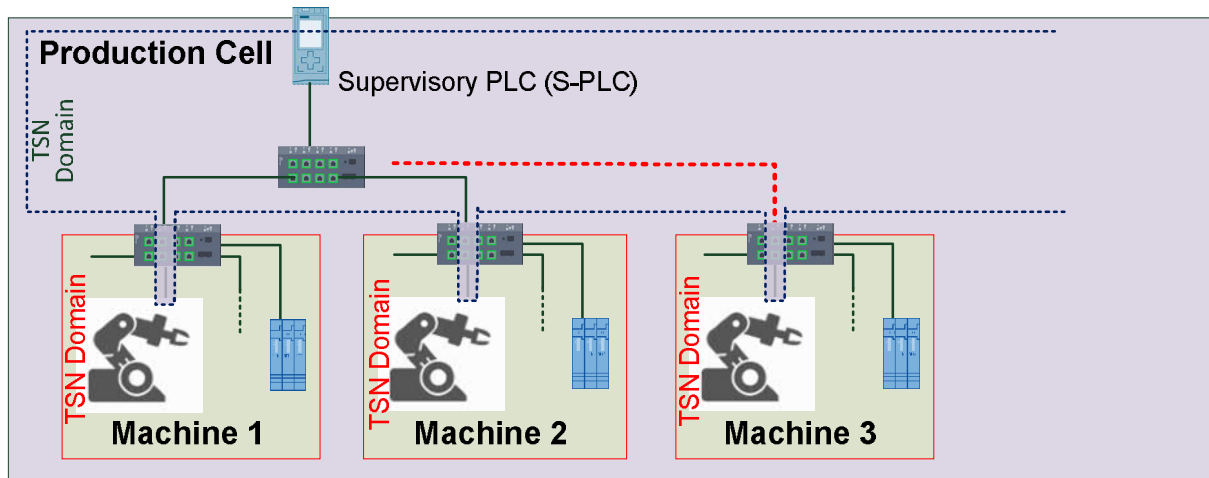
1308

1309
Figure 64 – add machine

1310
Requirement:

1311
Adding and removing a machine/cell/production line shall not disturb existing installations

1312
1313
Useful mechanisms:

1314
- …

1315

1316
2.6.8   Use case 24: Multiple applications in a station using the TSN-IA profile

1317
Technology A and B are implemented in PLC and devices.
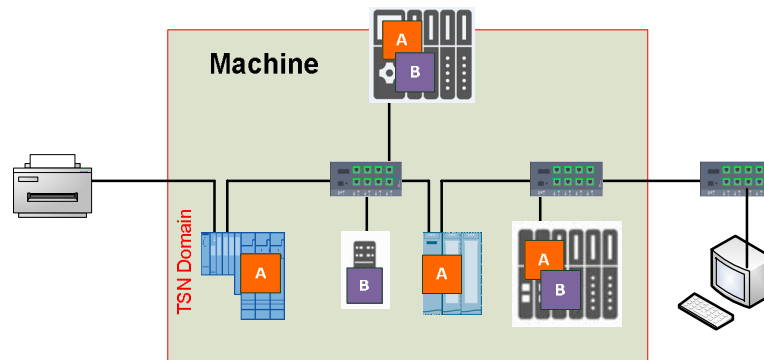
1318

1319
Figure 65 – two applications

1320

1321
Requirement:

1322
Stations with multiple applications using TSN traffic classes shall be supported.

1323
1324
Useful 802.1 mechanisms:

1325
- …

1326
2.6.9   Use case 25: Functional safety

1327
Functional safety is defined in IEC 61508 as "*part of the overall safety relating to the EUC*

1328
[Equipment Under Control] and the EUC control system that depends on the correct functioning of

1329 *the E/E/PE [electrical/electronic/programmable electronic] safety-related systems and other risk*
1330 *reduction measures*"
1331
1332 IEC 61784-3-3 defines a safety communication layer structure, which is performed by
1333 a standard transmission system (black channel), and an additional safety transmission protocol on
1334 top of this standard transmission system.
1335
1336 The standard transmission system includes the entire hardware of the transmission system and the
1337 related protocol functions (i.e. OSI layers 1, 2 and 7).
1338
1339 Safety applications and standard applications are sharing the same standard communication
1340 systems at the same time.

1341

1342 **Figure 66 – Functional safety with cyclic real-time**

1343
1344 Requirement:
1345 Safety applications (as black channel) and standard applications share the same TSN-IA profile
1346 based communication system at the same time.
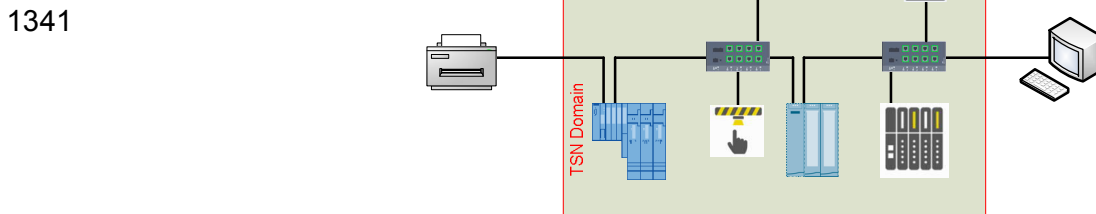1347
1348 Useful 802.1 mechanisms:

1349   • …

1350 **2.6.10 Use case 26: Machine cloning**

1351 The machines used in a cell can be identical but with a different task. Robots are a typical example
1352 of that kind of machines (see Figure 67). Thus, both machines have the same internal
1353 communication flows. The difference is just different machine identification for the external flow.
1354 The concept as of today is that the machine internal configuration has its identification and the cell
1355 system has its configuration but there is no dependency between both. The machine internal setup
1356 is done earlier and the cell identification is a result from a different configuration step and is done
1357 by a different organizational unit. Thus, it is difficult to propagate the cell level identification at the
1358 very beginning to the machine internal components. A worst case scenario is the startup of a
1359 machine and the connection to a cell in an ad hoc way with identification of the machine by the
1360 globally unique MAC address of the machine and the resolution of other addresses within the cell
1361 controller or above (e.g. for allocation of IP addresses). If there is a need to communicate with a
1362 few field device within the machine in a global way the machine subsystem has to be configured
1363 accordingly in advance. This configuration step could be done by a different organization as the
1364 stream configuration and not all machine internal elements may require a global address.
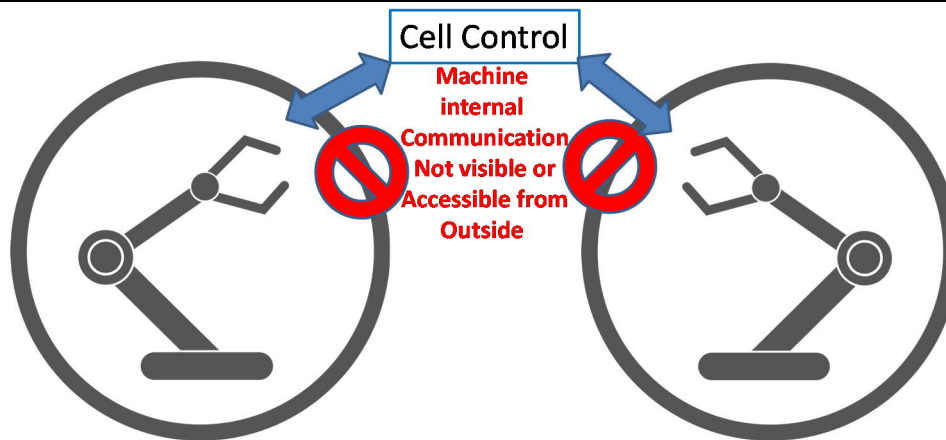
Figure 67 – Machine internal communication with isolated logical infrastructure

Requirements:

- TSN domains with unique addressing within the TSN domains;
- 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;

Useful 802.1 mechanisms:

- IEEE 802.1Q (usage of streams)
- IEEE 802.1 support for isolation is VLAN

2.7 DCS Reconfiguration

2.7.1 Challenges of DCS Reconfiguration Use Cases

The challenge these use cases bring is the influence of reconfiguration on the existing communication: all has to happen without disturbances to the production!

We consider important the use case that we can connect any number of new devices wherever in the system and they get connectivity over the existing infrastructure supporting TSN features without a change to the operational mode of the system.

2.7.2 Use case 27: DCS Device level reconfiguration

The structure shown in Figure 1 applies. Figure 68 provides a logic station view.

- SW modifications to a device

  - A change to the device's SW/SW application shall happen, which does not require changes to the SW/SW application running on other devices (incl. firmware update).

- Device Exchange/Replacement

  - The process device is replaced by another unit for maintenance reason, e.g. for off-process calibration or because of the device being defective (note: a "defective device may still be fully and properly engaged in the network and the communication, e.g. if just the sensor is not working properly anymore).

  - Use case: repair.

- Add/remove additional device(s)

1395   -   A new device is brought to an existing system or functionality, which shall be used in the
1396   application, is added to a running device, e.g. by enabling a SW function or plugging in a
1397   new HW-module. Even though the scope of change is not limited to a single device
1398   because also the other device engaged in the same application.

1399   -   For process devices, servers: BIOS, OS and applications updates, new VMs, workstations.

1400   -   Use cases: replacement with upgrade/downgrade of an existing device, simply adding new
1401   devices, removal of device, adding connections between devices.

1402 • Influencing factors relative to communication

1403   -   Communication requirements of newly added devices (in case of adding)
1404   -   Existing QoS parameters (i.e. protocol-specific parameters like TimeOuts or Retries)
1405   -   Device Redundancy
1406   -   Network/Media Redundancy
1407   -   Virtualization
1408   -   For servers: in-premise or cloud
1409   -   Clock types in the involved process devices
1410   -   Universal time and working clock domains
1411   -   Cycle time(s) needed by new devices
1412   -   Available bandwidth
1413   -   Existing security policies
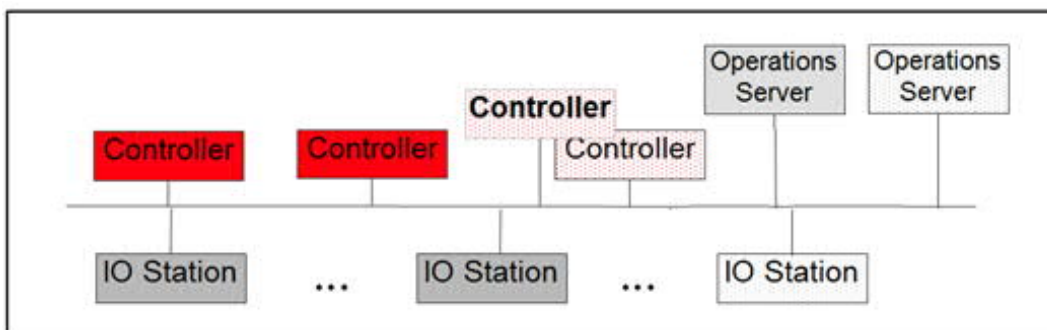
1414

1415   **Figure 68 – Device level reconfiguration use cases**

1416 **2.7.3   Use case 28: DCS System level reconfiguration**
1417 The structure shown in Figure 1 applies. Figure 69 provides a logic station view.

1418 • Extend an existing plant
1419   -   Add new network segment to existing network
1420   -   Existing non-TSN / Newly added is TSN
1421   -   Existing TSN / Newly added is TSN

1422 • Update the system security policy
1423   -   [New key lengths, new security zones, new security policy]
1424   -   To be defined how and by whom to be handled

1425 • Influencing factors
1426   -   Same as for "device-level"
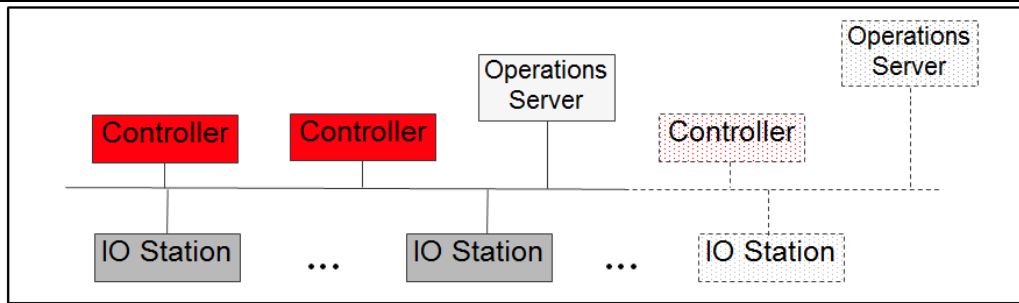
Figure 69 – System level reconfiguration use cases

2.8 Further Industrial Automation Use Cases

2.8.1 Use case 29: 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 Use case 01: 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.

1461 Useful 802.1 (ietf) mechanisms:

1462 • MIBs (SNMP)
1463 • YANG (NETCONF/RESTCONF)
1464 • …
1465

2.8.2 Use case 30: Security

1466
1467 Industrial automation equipment can become the objective of sabotage or spying.
1468 Therefore all aspects of information security can be found in industrial automation as well:

1469 • Confidentiality "is the property, that information is not made available or disclosed to
1470   unauthorized individuals, entities, or processes."
1471 • Integrity means maintaining and assuring the accuracy and completeness of data.
1472 • Availability implies that all resources and functional units are available and functioning
1473   correctly when they are needed. Availability includes protection against denial-of-service
1474   attacks.
1475 • Authenticity aims at the verifiability and reliability of data sources and sinks.
1476
1477 Requirement:
1478 Optional support of confidentiality, integrity, availability and authenticity.
1479 Security shall not limit real-time communication
1480
1481 Protection against rogue applications running on authenticated stations are out of scope.
1482
1483 Useful mechanisms:

1484 • 802.1X
1485 • IEC62443
1486 • …

2.8.3 Use case 31: Firmware update

1487
1488 Firmware update is done during normal operation to make sure that the machine e.g. with 1000
1489 devices is able be updated with almost no down time.
1490
1491 With bump: separate loading (space for 2 FW versions required) and coordinated activation to
1492 minimize downtime
1493
1494 Bumpless: redundant stations with bumpless switchover – the single device may lose connection
1495 (bump)
1496
1497 Requirement:
1498 Stations shall be capable to accept and store an additional fw version without disturbance.
1499
1500 Useful 802.1 mechanisms:

1501 • …

2.8.4 Use case 32: Virtualization

1502
1503 Workload consolidation is done by virtualizing the hardware interfaces. Even in such kind of
1504 environment the TSN features according to the TSN-IA profile shall be available and working.
1505

1506   **vSwitch / vBridge**
1507
1508   Figure 70 and Figure 71 show the two principle setups for an Ethernet communication concept
1509   allowing both, communication VM to Ethernet and VM to VM. The applications inside the VM shall
1510   not see, whether they communicate to another VM or an Ethernet node.
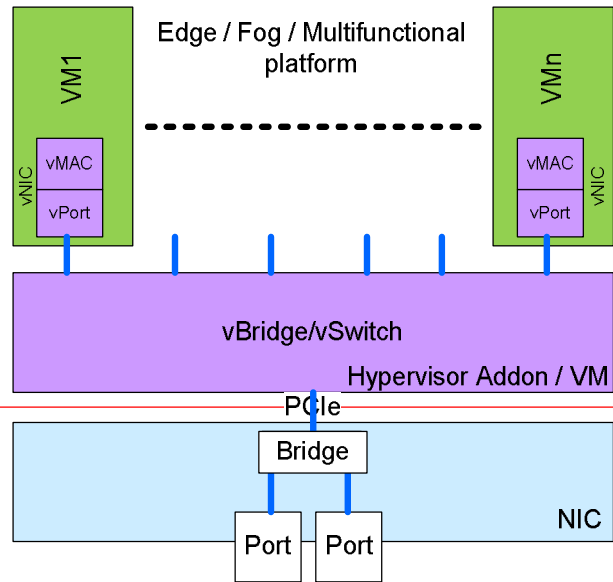
1511
1512   **Figure 70 – Ethernet interconnect with VM based vBridge**

1513
1514   Figure 70 scales for an almost infinite amount of VMs, because the memory bandwidth and the
1515   compute power of the vMAC/vPort and vSwitch/vBridge VM are much higher than the PCIe
1516   bandwidth to the NIC.
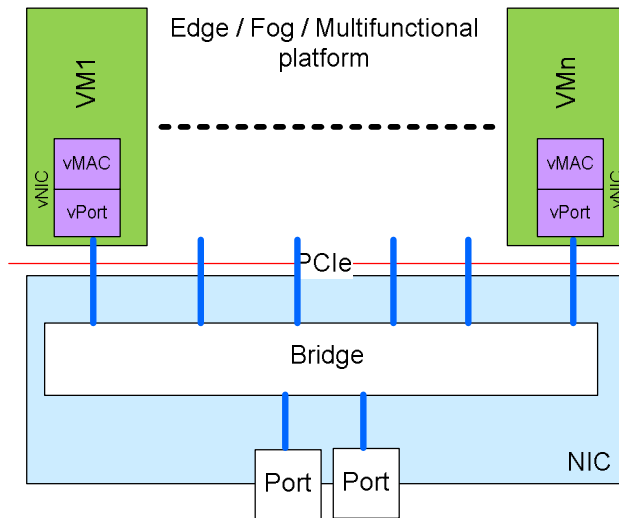
1517
1518   **Figure 71 – Ethernet interconnect with PCIe connected Bridge**

1519
1520   Figure 71 fits for a limited amount of VMs, because it saves the additional vSwitch/vBridge VM. For
1521   a given amount of VMs, e.g. PCIe Gen3 x4 or Gen4 x4, seems to be sufficient.
1522

1523 Requirement:

1524 vBridge and vPort should behave as real Bridge and real Port: data plane, control plane, ...
1525 vBridge and vPort can become members of TSN domains.
1526 Should work like use case "multiple applications"

1527
1528 Useful 802.1 mechanisms:

1529   • …
1530

2.8.5 Use case 33: Offline configuration

1531

1532 The configuration of a machine is typically done before the machine is actually built. This is
1533 necessary for checking the availability of all components and as input for the machine
1534 programming. This requires an electronic data sheet of the field devices. Bridging components and
1535 talker listener behavior shall be described in these files. The talker and listener parameters are
1536 deduced from the application configuration as well as the communication intervals. The bridge
1537 description may include the port properties and the amount of streams supported for the individual
1538 purposes. Performance parameters are also required to set up the system. XML based textual
1539 description is used currently to describe the capabilities of field devices used in machinery. The
1540 individual elements are combined and additional parameters are defined resulting in another file
1541 which describes a machine configuration. This file is given to the machine control unit after
1542 machine setup and used to verify the commissioning. Protocols are needed to compare the real
1543 machine elements with the configured ones. Topology discovery is an important feature as well as
1544 the access to bridges to read and write management data.

1545 Latency requirements restrict usable topologies and vice versa. Some applications can be handled
1546 with the description of an upper bound for latency. In this case the configuration may not use the
1547 accumulated latency from the bridge description but a limit which has to be checked during setup.

1548 Another parameter for real time communication is the quality of time synchronization which
1549 depends upon several parameters of the components used in the synchronization path. YANG
1550 models of IEEE 802 components may be suitable for that purpose as offline database for individual
1551 bridge components and for the IEEE 802 network. It is not necessary for a machine configurator to
1552 handle the YANG related protocols but use the models. YANG means a completely different
1553 language as used today and implies two databases and some transformation and consistency
1554 issues between the two descriptive units. Thus, it is recommended to provide a mapping between
1555 XML and YANG.

1556 Requirements:
1557   • Device type description of IEC/IEEE 60802 components containing all necessary managed
1558   objects needs to be defined
1559   • Means to store machine configuration offline in a textual form (e.g. XML);
1560   • Offline - Online comparison of machine configuration shall be supported;
1561

1562 Useful 802.1 mechanisms:

1563   • IEEE 802.1 YANG models;
1564

2.8.6   Use case 34: Digital twin

Virtual pre-commissioning of machines can save a lot of time and money.
Up to 30 % time-saving in the development of new machines are foreseen by an increased
engineering efficiency due to the implementation and usage of digital twins.
Faster development, delivery and commissioning of new machines at customer locations should be
possible.

A digital twin shows the real machine in as much detail as possible and allows simulation of its
operation. With the help of digital twins machines can gradually and virtually be developed – in
parallel to the real production and commissioning process of the machines at customer locations.

Requirement:

Reliable planning, development, testing, simulation and optimization results shall be possible

Useful 802.1 mechanisms:

- …

2.8.7   Use case 35: Device replacement without engineering

Any device in a plant, i.e. end-station, bridged end-station or bridge, may get broken eventually. If
this happens fast and simple replacement of a broken device is necessary to keep production
disturbance at a minimum (see also: 2.7.2 Use case 27: DCS Device level reconfiguration).
Support of "mechanical" replacement of a failed device with a new one without any engineering
effort (i.e. without the need for an engineering tool) is a prerequisite for minimal repair downtime.

Requirement:

In case of repair it shall be possible to replace end-stations, bridged end-stations or brides without
the need of an engineering tool.

Useful 802.1 mechanisms:

- …

1595   Abbreviations

AGV   Autonomous Guided Vehicle

CCTV   Closed Circuit Television

DCS   Distributed Control System

FW   Firmware

PA   Process Automation

1596
1597
1598

1599   Literature and related Contributions

1600   Literature:

1601   [1] "Cyber Physical Systems: Design Challenges", E. A. Lee, Technical Report No. UCB/EECS-
1602   2008-8; http://www.eecs.berkeley.edu/Pubs/TechRpts/2008/EECS-2008-8.html
1603

1604   [2] Beckers, K. (2015). Pattern and Security Requirements: Engineering-Based Establishment of
1605   Security Standards; Springer; ISBN 9783319166643
1606

1607   [3] PI: Isochronous Mode – Guideline for PROFINET IO; V1.0; June 2016; available at
1608   http://www.ieee802.org/1/files/private/liaisons
1609

1610   Related contributions:

1611   [4] LNI traffic patterns for TSN: http://www.ieee802.org/1/files/public/docs2018/new-Bruckner-LNI-
1612   traffic-patterns-for-TSN-0118.pdf
1613
1614   [5] Multivendor Motion Control: http://ieee802.org/1/files/public/docs2018/new-industrial-enzinger-
1615   multivendor-motion-control-0318-v01.pdf
1616
1617   [6] Hierarchical Domain based Network: http://www.ieee802.org/1/files/public/docs2018/60802-
1618   harima-industrial-use-case-0518-v04.pdf
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