

## Contributor group

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## Abstract

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

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

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

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

THIS DOCUMENT IS NOT THE STANDARD!!

23 **Log**

V0.1	2019-May-20	First version – to show structure and flow only.
V0.2	2019-May-20	First version text with Industrial text showed in Black & the new Automotive text showed in Green so that the new Automotive text is easier to see.
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## 219 1 Definitions and Terms

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

224

### 225 1.1 Definitions

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

Device	End station, bridged end station, bridge, access point
Transmission selection algorithms	A set of algorithms for traffic selection which include Strict Priority, the Credit-based shaper and Enhanced Transmission Selection. <sup>1)</sup>
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. <sup>1)</sup>
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. <sup>1)</sup>
Time-Sensitive Stream	A stream of traffic, transmitted from a single source station, destined for one or more destination stations, where the traffic is sensitive to timely delivery, and, requires transmission latency to be bounded. <sup>1)</sup>
TSN domain	A quantity of commonly managed devices; A set of devices, their Ports, and the attached individual LANs that transmit Time-Sensitive Streams using TSN standards which include Transmission Selection Algorithms, Preemption, Time Synchronization and Enhancements for Scheduled Traffic and that share a common management mechanism. It is an administrative decision to group these devices (see 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	Devices of a common working clock domain with a common setup for the isochronous cyclic real-time traffic type
cyclic real-time domain	Devices with a common setup for the cyclic real-time traffic type - even from different working clock domains or synchronized to a local timescale
Network cycle	Transfer time including safety margin, and application time including safety margin (see Figure 13); values are specific to a TSN domain and specify a repetitive behavior of the network interfaces belonging to that TSN domain;
Stream forwarding	Forwarding of stream data along the stream path including TSN domain boundary crossings

## 226 1.2 IEEE 802.1 Terms

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

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<sup>1</sup> taken from 802.1Q-2018



## 228 2 TSN in Automotive

229 <<creator's note: The Industrial Use Case document used this section to describe Cyber-Physical Systems. I  
 230 propose this section can be a brief overview of non-Ethernet in-vehicle networks and where & why  
 231 Ethernet came into the Automotive picture. If people feel this is not needed, this section would just be an  
 232 overview of what comes below.>>

### 233 2.1 Interoperability

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

237 Interoperability may be achieved on different levels. Figure 1 and Figure 2 show three areas, which  
 238 need to be covered:

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

242 The three areas mutually affect each other (see Figure 1).

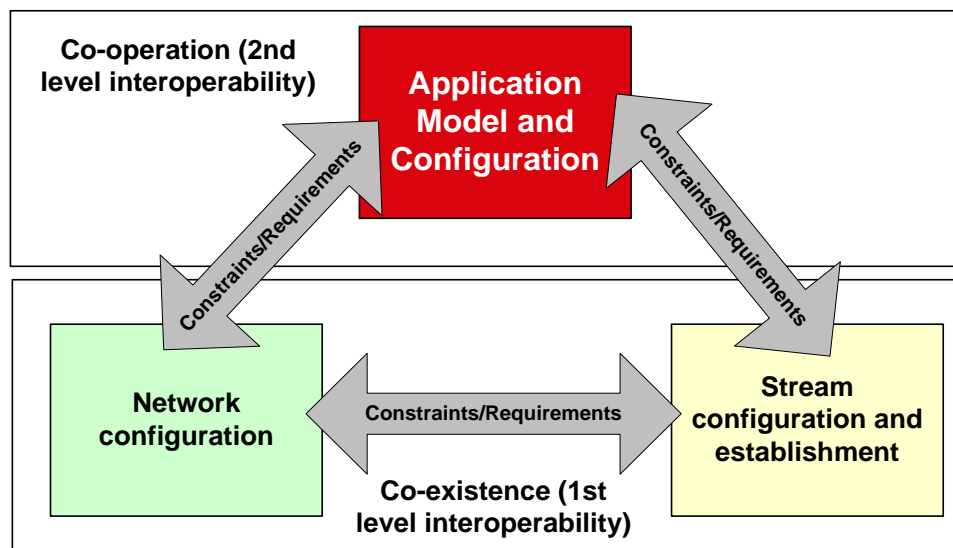
243 Application configuration is not expected to be part of the profile, but the two other areas are.

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

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

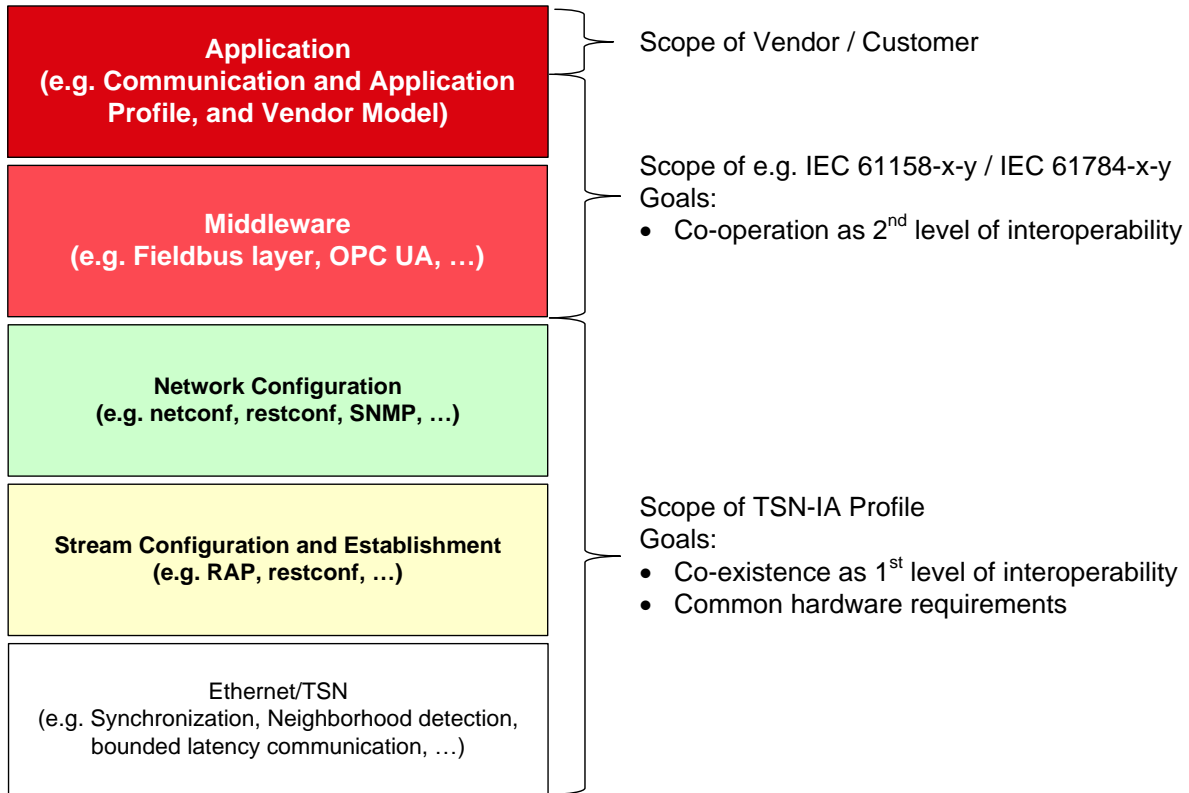
247 Stream establishment is initiated by applications to allow data exchange between applications. The  
 248 applications are the source of requirements, which shall be fulfilled by network configuration and  
 249 stream configuration and establishment.

250



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Figure 1 – Principle of interoperation



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**Figure 2 – Scope of work**

257 **2.2 TSN Domain**

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

260 **2.2.1 General**

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

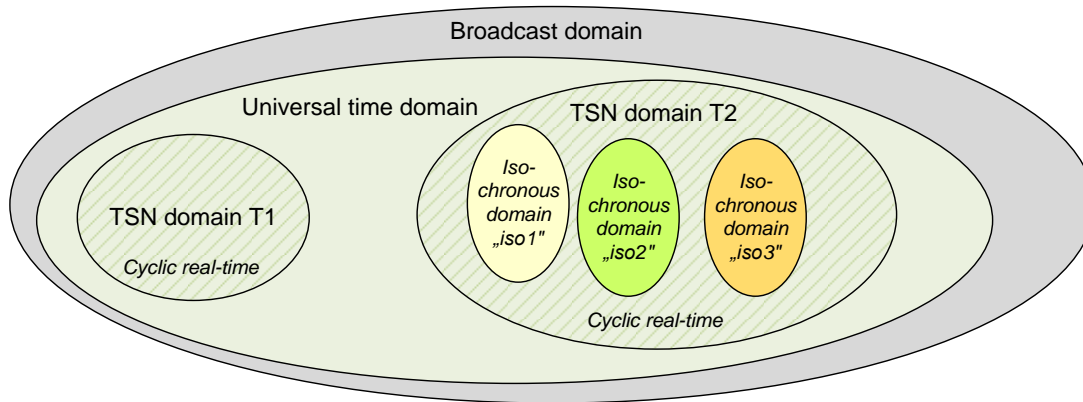
263 TSN Domain Characteristics:

- 264
- 265 • One or more TSN Domains may exist within a single layer 2 broadcast domain.
  - 266 • A TSN Domain may not be shared among multiple layer 2 broadcast domains.
  - 267 • Multiple TSN Domains may share a common universal time domain.
  - 268 • Two adjacent TSN Domains may implement the same requirements but stay separate.
  - 269 • Multiple TSN domains will often be implemented in one bridge (see 2.2.2.2).
  - 270 • Multiple TSN domains will often be implemented in one router (see 2.2.2.3).
  - Multiple TSN domains will often be implemented in one gateway (see 2.2.2.4).

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

274 Figure 3 shows two example TSN domains within a common broadcast domain and a common  
275 universal time domain. TSN domain 1 is a pure cyclic real-time domain, whereas TSN domain 2  
276 additionally includes three overlapping isochronous domains.

277



278

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**Figure 3 – Different Types of Domains**

280 Interconnections between TSN domains are described in 2.2.2 and 3.8.1.

## 281 **2.2.2 Interconnection of TSN Domains**

### 282 **2.2.2.1 General**

283 TSN domains may be connected via

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

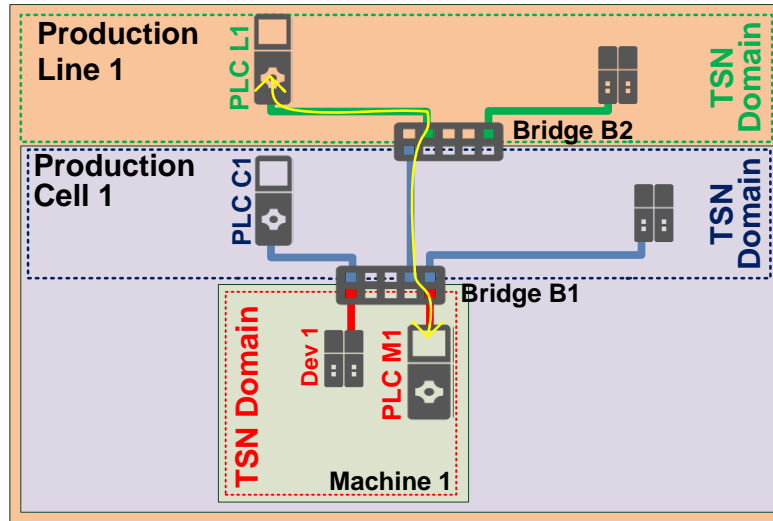
287 Wireless Access Points or 5G Base Stations may be used to connect TSN domains, too.

288 **2.2.2.2 Bridges (Layer 2)**

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

291 Figure 4 provides an example of two Bridges, which are members of two TSN domains each.  
 292 Bridge B1 provides ports and connectivity in TSN domain Production Cell 1 and in TSN domain  
 293 Machine 1, Bridge B2 for Production Line 1 and Production Cell 1.

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**Figure 4 – Three TSN domains connected by Bridges**

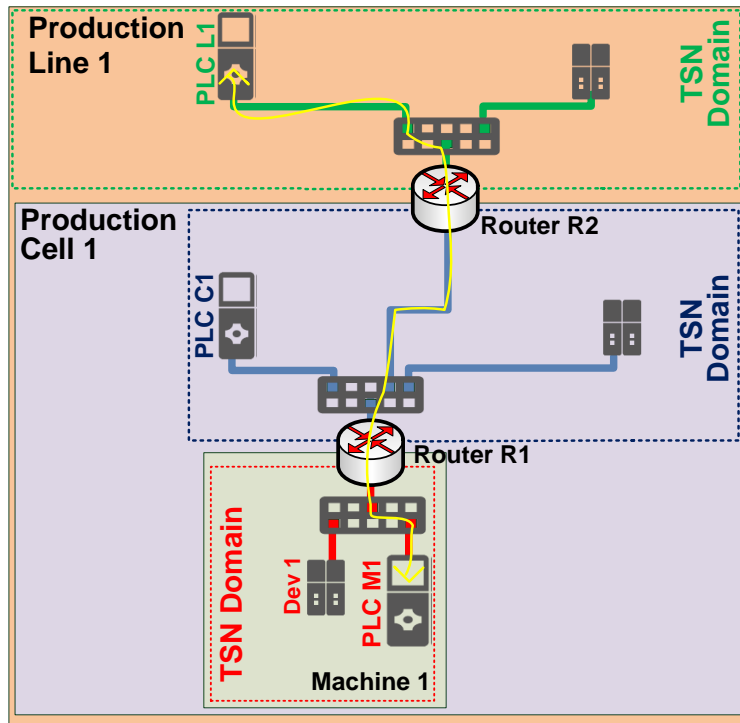
297 To support connectivity between multiple TSN domains (e.g. PLC L1 ↔ PLC M1) a method for  
 298 reserving time-sensitive streams over multiple TSN domains needs to be specified, including:

- 299
- 300 - find the communication partner,
  - 301 - identify the involved TSN domains,
  - 302 - identify the involved management entities independent from the configuration model  
 (centralized, hybrid, fully distributed),
  - 303 - ensure the needed resources,
  - 304 - parameterize the TSN domain connection points to allow stream forwarding if needed.

305 **2.2.2.3 Routers (Layer3)**

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

308 When a router is member of multiple TSN domains, one router interface/port must only be a  
 309 member of a single TSN domain. Figure 5 provides an example of two routers, which are members  
 310 of two TSN domains each. Router R1 provides ports and connectivity in TSN domain  
 311 Production Cell 1 and in TSN domain Machine 1, Router R2 for Production Line 1 and Production  
 312 Cell 1.



313

314 **Figure 5 – Three TSN domains connected by Routers**

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

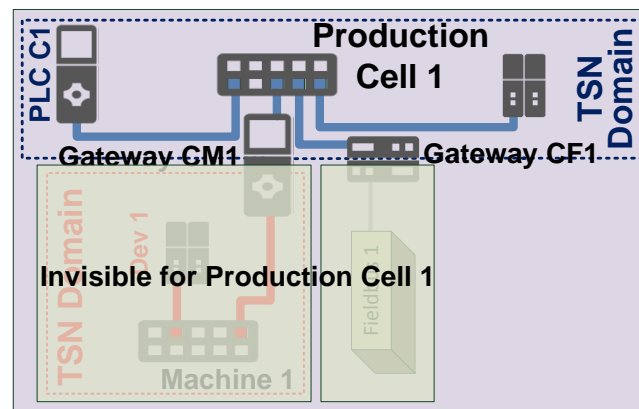
- 317
- 318 - find the communication partner,
  - 319 - identify the involved TSN domains,
  - 320 - identify the involved management entities independent from the configuration model  
(centralized, hybrid, fully distributed),
  - 321 - ensure the needed resources,
  - 322 - parameterize the TSN domain connection points to allow stream forwarding if needed.

### 323 2.2.2.4 Application Gateways (Layer7)

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

326 Figure 6 provides an example of two application gateways:

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



329  
330 **Figure 6 – Gateways with two TSN domains and an attached Fieldbus**

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

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

339 Application level gateways are also used to connect non-Ethernet- or Ethernet-based fieldbuses to  
340 TSN domains (see Gateway CF1 in Figure 6 and see also Use case 11: Fieldbus gateway).

341

## 342 2.3 Synchronization

343 <<creator's note: What parts of this section from the Industrial Use Case document are applicable to  
344 Automotive?>>

### 345 2.3.1 General

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

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

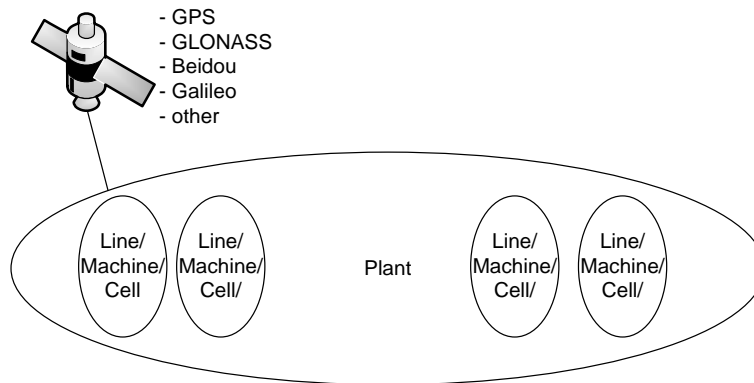
351 Redundancy for working Clock synchronization can be solved with "cold standby" or "hot standby"  
352 depending on the application requirements. Support of "hot standby" for working clock  
353 synchronization is current practice.

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

### 356 2.3.2 Universal Time Synchronization

357 Universal time is used to plant wide align events and actions (e.g. for “sequence of events”). The  
 358 assigned timescale is TAI, which can be converted into local date and time if necessary. Figure 7  
 359 shows the principle structure of time synchronization with the goal to establish a worldwide aligned  
 360 timescale for time. Thus, often satellites are used as source of the time.

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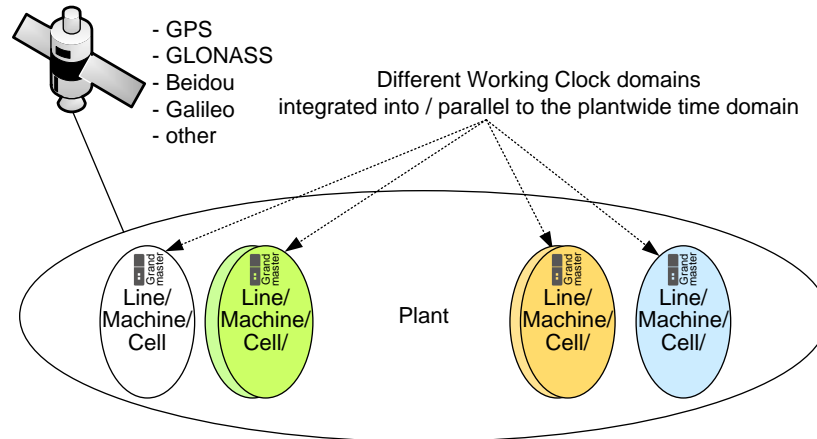
363 **Figure 7 – plant wide time synchronization**

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

### 365 2.3.3 Working Clock Synchronization

366 Working Clock is used to align actions line, cell or machine wide. The assigned timescale is  
 367 arbitrary. Robots, motion control, numeric control and any kind of clocked / isochronous application  
 368 rely on this timescale to make sure that actions are precisely interwoven as needed. Figure 8  
 369 shows the principle structure of Working Clock synchronization with the goal to establish a line /  
 370 cell / machine wide aligned timescale. Thus, often PLCs, Motion Controller or Numeric Controller  
 371 are used as Working Clock source.

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



375

376

**Figure 8 – line/cell/machine wide working clock synchronization overlapping with a universal time domain**

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

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380

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

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382

#### Requirements:

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

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#### Useful 802.1 mechanisms:

389

390

- IEEE 802.1AS-Rev

391

### 2.3.4 Sequence of events

392

393

Sequence of events (SOE) is a mechanism to record timestamped events from all over a plant in a common database.

394

395

396

Application defined events are e.g. changes of digital input signal values. Additional data may be provided together with the events, e.g. universal time sync state and grandmaster, working clock domain and value ...

397

398

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

399

400

Plant-wide precisely synchronized time (see Figure 7) is a precondition for effective SOE application.

401

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

402

#### Requirements:

403

404

405

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



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

407  
408    Useful 802.1 mechanisms:

- 409       • IEEE 802.1AS-Rev
- 410

## 411    **2.4 Redundancy**

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

413

## 414    **2.5 Security**

415    <<creator's note: Security section was added. What other sections are needed. As the Uses Cases are

416    added to, this will become clearer.>>

417

## 418    **2.6 Automotive traffic types**

419    <<creator's note: I have moved the Use Cases section (data from presentations made at meetings/calls)

420    into a separate major heading section below. And I moved the Automotive Traffic Types here. The Traffic

421    Types is a very important topic that needs to be separated out. I see these use cases as the back-up

422    material that needs to be referenced by the summary/conclusions listed here & above.>>

### 423    **2.6.1 General**

424    <<creator's note: This section has not been updated. It is unchanged from the Industrial document. This

425    information has been left here so that readers can see the kinds of information we may need to document

426    and how the Use Cases drive decisions here (as show via references to the appropriate Use Cases).>>

427

428    Industrial automation applications concurrently make use of different traffic types for different

429    functionalities, e.g. parameterization, control, alarming. The various traffic types have different

430    characteristics and thus impose different requirements on a TSN network. This applies for all use

431    cases described in this document.

432

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 <sup>1)</sup>	see Table 4 and 3.1
cyclic real-time	P	deadline/ bounded latency (e.g. n-times network cycle)/ bandwidth	bounded	up to seamless <sup>1)</sup>	see Table 8 and 3.3
network control	S	Priority	-	up to seamless <sup>1)</sup> as required	see 2.2.2 and 3.7.1
audio/video	P	bounded latency/ bandwidth	bounded	up to seamless <sup>1)</sup> as required	-
brownfield	P	bounded latency/ bandwidth	-	up to regular <sup>2)</sup>	see 3.7.6
alarms/ events	S	bounded latency/ bandwidth	-	up to regular <sup>2)</sup>	see 2.3.4
configuration/ diagnostics	S	Bandwidth	-	up to regular <sup>2)</sup>	see 3.10.1
Internal / Pass-through	S	Bandwidth	-	up to regular <sup>2)</sup>	see 3.8.2
best effort	S	-	-	up to regular <sup>2)</sup>	-

433

434

<sup>1)</sup> almost zero failover time;

435

436

<sup>2)</sup> larger failover time because of network re-convergence

437

438

439

Isochronous:

440

→ see section 2.3.3

441

442

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

444

445

Cyclic:

446

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

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

449

450 Network control:

451 → see *Use case 07: Redundant networks*

452

453 Audio/video:

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

455

456 Brownfield:

457 → see *Use case 12: New machine with brownfield devices*

458

459 Alarms/events:

460 → see *Sequence of events*

461

462 Configuration/diagnostics:

463 → see *Use case 29: Network monitoring and diagnostics*

464

465 Internal:

466 → see *Use case 18: Pass-through Traffic*

467 Best effort:

468 → see *Use case 03: Non-Isynchronous Control Loops with bounded latency.*

469

470 **Table 2 – isochronous cyclic real-time and cyclic real-time traffic type properties**

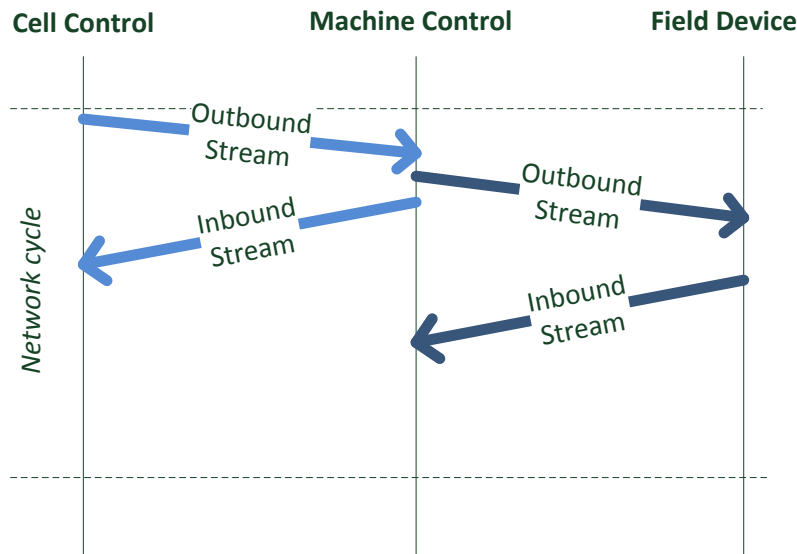
Property	Description
<b>Data transmission scheme</b>	<i>Periodic (P)</i> - e.g. every N $\mu$ s, or <i>Sporadic (S)</i> - e.g. event-driven
<b>Data transmission constraints</b>	<p>Indicates the traffic pattern's data transmission constraints for proper operation. Four data transmission constraints are defined:</p> <ul style="list-style-type: none"> <li>• <i>deadline</i>: transmitted data is guaranteed to be received at the destination(s) before a specific instant of time,</li> <li>• <i>latency</i>: 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,</li> <li>• <i>bandwidth</i>: transmitted data is guaranteed to be received at the destination(s) if the bandwidth usage is within the resources reserved by the transmitting applications,</li> <li>• <i>none</i>: no special data transmission constraint is given.</li> </ul>

Property	Description
<b>Data period</b>	For traffic types that transmit <i>periodic</i> data this property denotes according to the <i>data transmission constraints</i> : <i>deadline</i> : application data deadline period, <i>latency, bandwidth or none</i> : data transmission period. The period is given as a <i>range</i> of time values, e.g. 1 $\mu$ s ... 1ms. For the <i>sporadic</i> traffic types, this property does not apply.
<b>Network access (data transmission) synchronized to working clock (network cycle)</b>	Indicates whether the data transmission of sender stations is synchronized to the working clock (network cycle). Available property options are: <i>yes, no</i> or <i>optional</i> .
<b>Application synchronized to network access</b>	Indicates whether the applications, which make use of this traffic pattern, are synchronized to the network access. Available property options are: <i>yes</i> or <i>no</i> .
<b>Acceptable jitter</b>	Indicates for traffic types, which apply data transmission with <i>latency</i> constraints, the amount of jitter, which can occur and must be coped with by the receiving destination(s). For traffic types with <i>deadline, bandwidth or none</i> data transmission constraints this property is not applicable ( <i>n.a.</i> ).
<b>Acceptable frame loss</b>	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.
<b>Payload</b>	Indicates the payload data <i>type</i> and <i>size</i> to be transmitted. Two payload types are defined: <ul style="list-style-type: none"> <li>• <i>fixed</i>: the payload is always transmitted with exactly the same size</li> <li>• <i>bounded</i>: 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).</li> </ul>

## 471 2.6.2 Bidirectional communication relations

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

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



480

481

**Figure 9 – Bidirectional Communication**

482

Requirements:

483

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

484

485

Useful 802.1 mechanisms:

486

- IEEE 802.1Q (usage of streams)

487

### 2.6.3 Control Loop Basic Model

488

489

490

**Control loops** are fundamental building blocks of industrial automation systems. Control loops include: process sensors, a controller function, and output signals. Control loops may require guaranteed low latency or more relaxed bounded latency (see 3.3) network transfer quality.

491

492

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

493

494

There are three levels of a control loop:

495

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

496

497

498

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

499

500

501

502

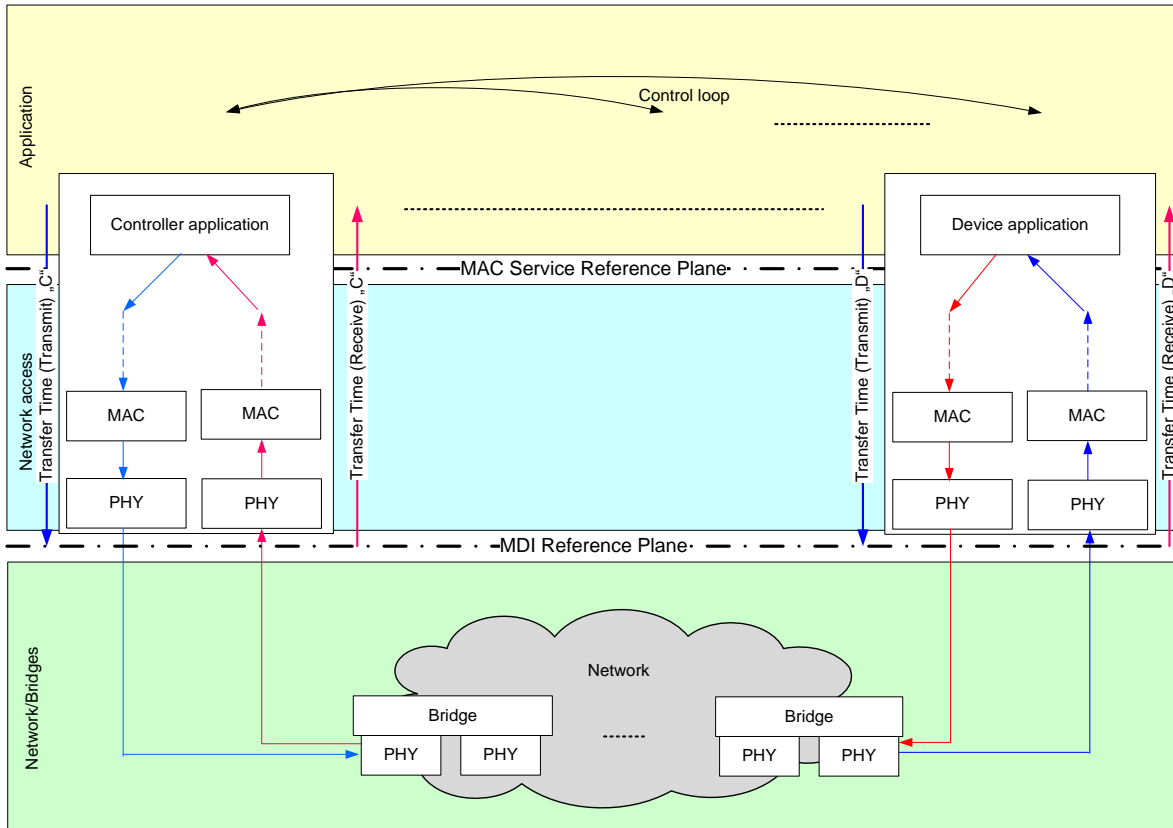
Application may or may not be synchronized to the synchronized Network Access depending on the application requirements. Applications which are synchronized to Network Access are called “isochronous applications”. Applications which are not synchronized to Network Access are called “non-isochronous applications”.

503

504

505

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



506  
507

**Figure 10 – Principle data flow of control loop**

508 Transfer Times contain PHY and MAC delays. Both delays are asymmetric and vendor specific.  
509 Device vendors have to take into account these transfer times when their application cycle models  
510 are designed (see Figure 13).  
511

512

**Table 3 – Application types**

Level	Isochronous Application		Non-isochronous Application		
<b>Application</b>	Synchronized to network access		Synchronized to local timescale		
<b>Network access</b>	Synchronized to working clock, Stream Class based scheduling, Preemption				Synchronized to local timescale, Stream Class based scheduling, Preemption
<b>Network/Bridges</b>	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

513  
514

### 515 3 Automotive modes of operation – the Use Cases

516 Each use case below, starts with a link to its source material (if available). The words in each use  
517 case are the interpretations of the creator of this document. It is up to the author of the source  
518 material to make sure that this interpretation is correct. If so, it will be marked as 'Reviewed by  
519 original author'.

520

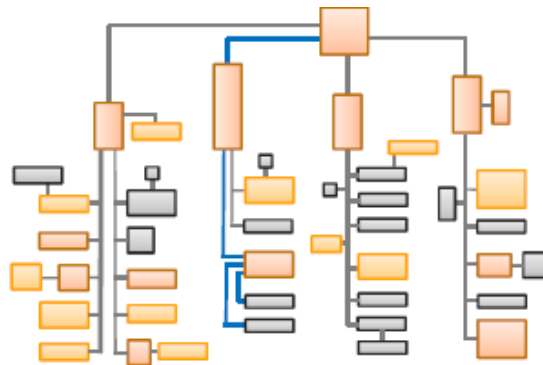
#### 521 3.1 Use case 01: Example Automotive Networks

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

##### 524 3.1.1 Traditional Model

525 A traditional, or present day automotive network architecture for many car makers, is shown in  
526 Figure 11. These networks typically contain a Central Gateway ECU (top box in the figure) with  
527 point-to-point communication between all the application specific ECUs. Most ECU's are connected  
528 using non-Ethernet connections such as CAN, LIN, etc.

529 Ethernet links are limited to only those that require higher bandwidth (shown as the bold blue lines  
530 in the figure).



531

532 *Figure 11 – Example of a Traditional or Central Gateway Automotive Network*

533

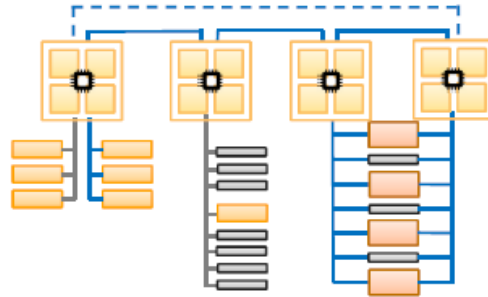
##### 534 3.1.2 Domain Model

535 An example of Domain automotive network architecture, is shown in Figure 12. Domain networks  
536 are the focus of many OEMs today. Ethernet is a clear enabler for these types of networks due to  
537 Ethernet's speeds and its support for the OSI Layer model.

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

542 Domain networks can also work modularly. This allows a common architecture to work for full  
543 feature high-end cars, mid-range cars and low-end of a given model. For example, the ADAS ECU  
544 can be easily removed for those models that won't support autonomous driving. And/or the  
545 infotainment ECU can be scaled in quality/performance to meet the desired price point of the car.

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



553  
554 *Figure 12 – Example of a Domain Automotive Network*

555 <<creator's note: This Use Case summary is not completed yet!>>

### 556 3.1.3 Requirements from this use case (or Summary?)

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

560

561 <<creator's note: From here down, this section has not been updated. It is unchanged from the Industrial  
562 Use Case document. This information has been left here so that readers can see the kinds of information  
563 we may need in the form of Use Cases.>>

564

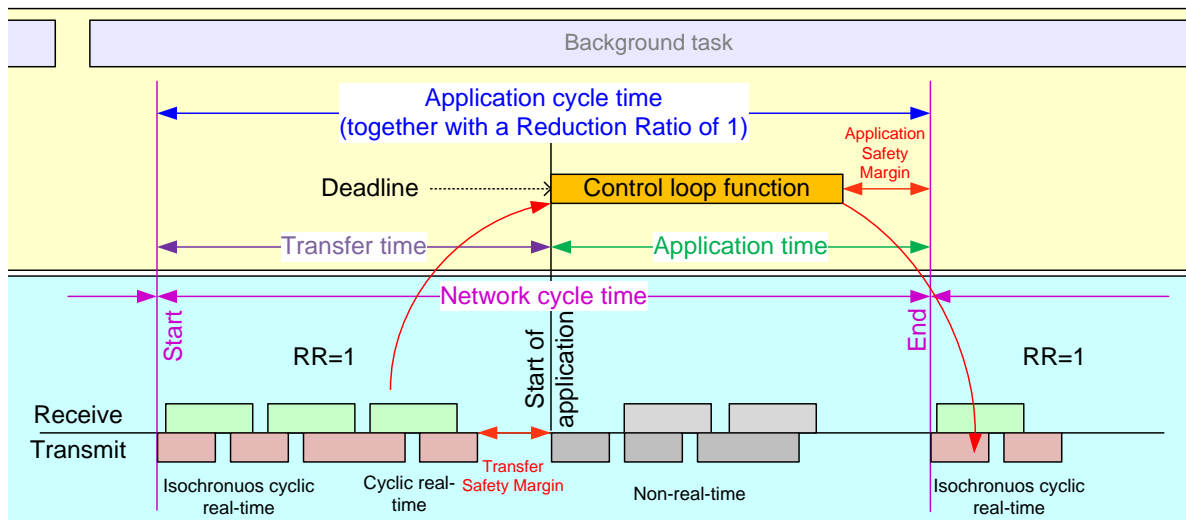


### 565 3.2 Use case 02: Isochronous Control Loops with guaranteed low latency

566 Control loops with guaranteed low latency implement an isochronous traffic pattern for isochronous  
 567 applications, which are synchronized to the network access. It is based on application cycles,  
 568 which consists of an IO data Transfer time and an Application time wherein the control loop  
 569 function is executed. Figure 13 shows the principle how Network cycle, Transfer time and  
 570 Application time interact in this use case.

571 Application cycle time and Network cycle time are identical in the example of Figure 13 (RR=1/see  
 572 3.4), whereas Figure 14 shows examples where the Application cycle time is longer than the  
 573 Network cycle time (RR>1/see 3.4).

574 The control loop function starts for controllers and devices at a fixed reference point after the  
 575 transfer time when all necessary buffers are available. A single execution of a control loop function  
 576 ends before the next transfer time period starts. Thus, all frames shall be received by the  
 577 addressed application within the transfer time. An optimized local transmit order at sender stations  
 578 is required to achieve minimal transfer time periods.  
 579



580

581

**Figure 13 – network cycle and isochronous application (Basic model)**

582 Transfer Safety Margin is the maximum time, which is needed to transfer received data from the  
 583 MDI reference plane (see Transfer Time (Receive)) to the application.

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

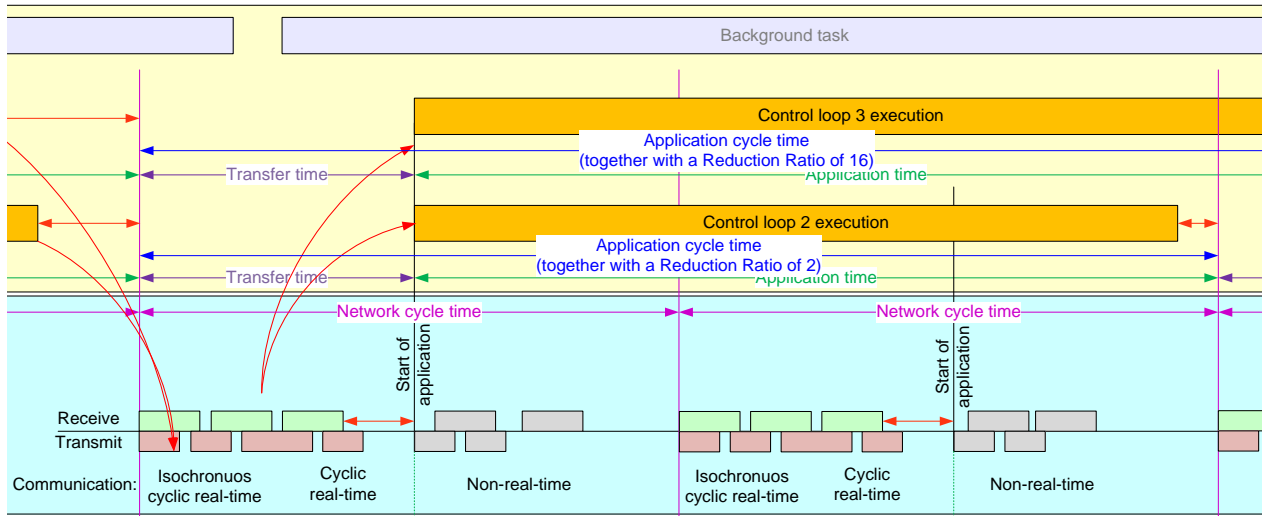
586 Figure 14 shows how this principle is used for multiple concurrent applications with even extended  
 587 computing time requirements longer than a single application time within the network cycle time.  
 588 When reduction ratio >1 is applied (see 3.4), the control loop function can be expanded over  
 589 multiple network cycles (Control loop 2 with reduction ratio 2 and Control loop 3 with reduction ratio  
 590 16 in Figure 14).

591 Maximum available computation time for a Control loop with reduction ratio X:

592  $X * \text{network cycle time} - \text{Transfer time} - \text{Application safety margin}$

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

596 A cyclic background task can additionally run, whenever spare Transfer or Application time is  
 597 available.



598

599 **Figure 14 – Multiple concurrent isochronous control loops (Extended model)**

600

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

602

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

606

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

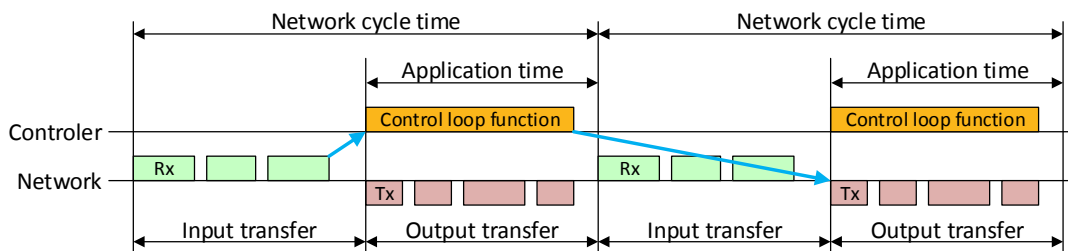
608

609 Figure 15 to Figure 20 show variations of the basic model of Figure 13:

609

610 In existing technologies some of the models are used in optimized ways to reduce the network  
 611 cycle time and/or the IO-reaction time (sometimes also called 'makespan' or 'roundtrip delay time').

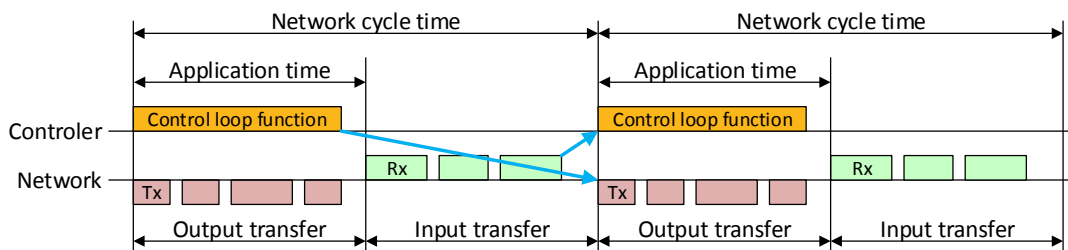
611



612

613 **Figure 15 – Variation 1: two cycle timing model**

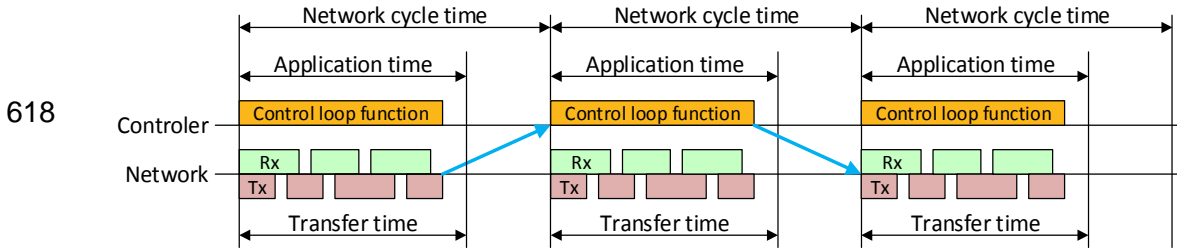
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615

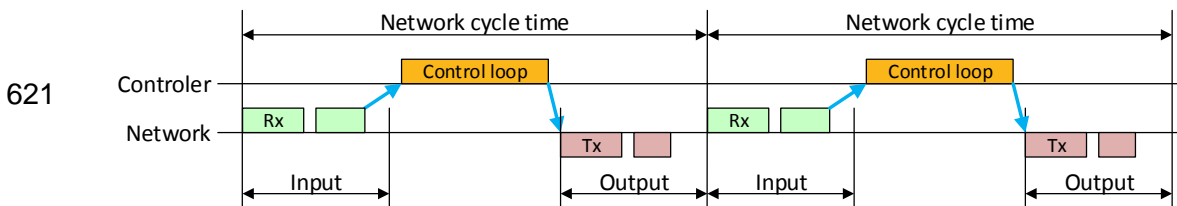
616 **Figure 16 – Variation 2: two cycle timing model - shifted by 180°**

617



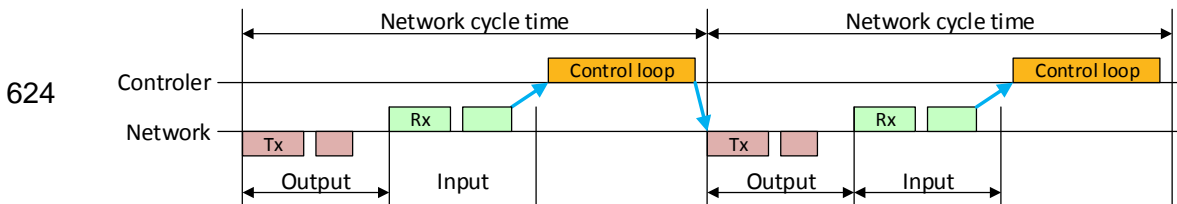
619 **Figure 17 – Variation 3: three cycle timing model**

620



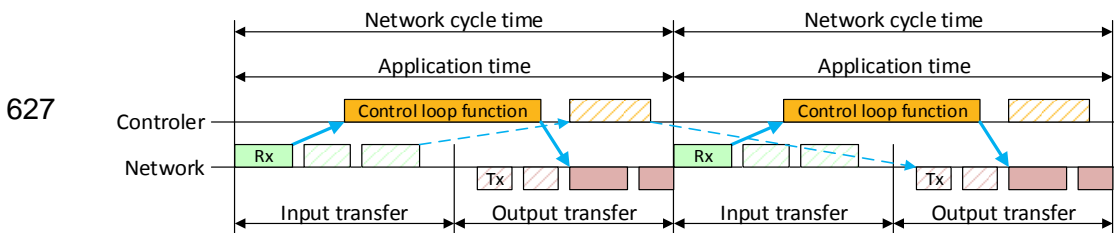
622 **Figure 18 – Variation 4: one cycle timing model**

623



625 **Figure 19 – Variation 5: one cycle timing model – changed sequence**

626



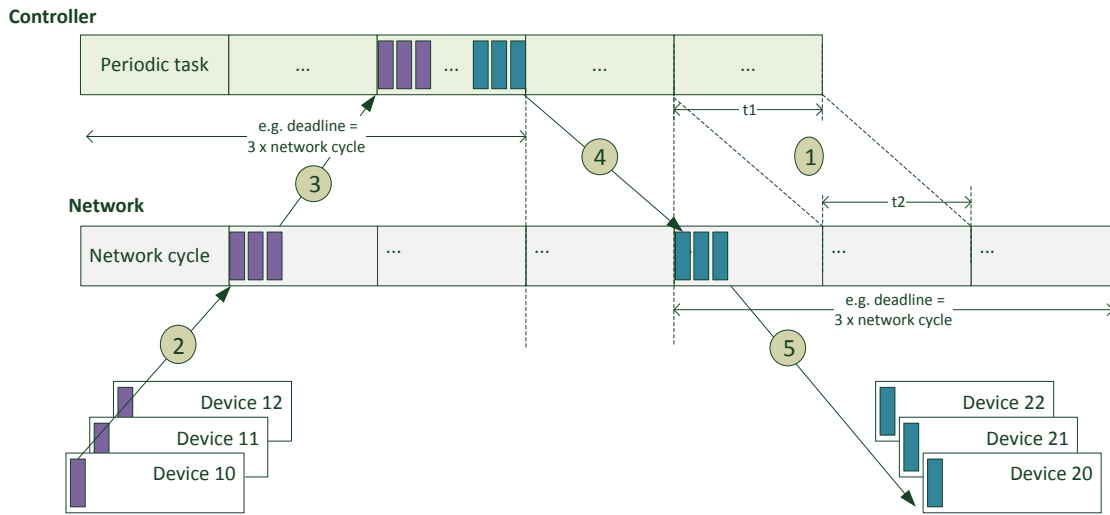
628 **Figure 20 – Variation 6: further optimizations**

629 The extended model of Figure 14 may be applied to these variations as well.

630

631 **3.2.1.1 Isochronous cyclic operation model**

632 Figure 21 shows the isochronous cyclic operation model for guaranteed low latency.



633

634

**Figure 21 – 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	<p>Controller periodic tasks are synchronized to the working clock.                  Example:                  Periodic task_01 period (<math>t_1</math>) == network cycle period (<math>t_2</math>).                  Periodic task_02 period == <math>8 \cdot</math> network cycle period (<math>t_2</math>).                  Periodic task_03 period == <math>32 \cdot</math> network cycle period (<math>t_2</math>).</p>
②	<p>Device data transmission is synchronized to network cycle (Working Clock).</p>
③	<p>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.</p> <p>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.</p>

4	Controller output data transmission is synchronized to network cycle (Working Clock).
5	<p>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]).</p> <p>Device application operates on local process image data. Local process image decouples communication protocol from application.</p> <p>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.</p>

635

636

High control loop quality is achieved by:

637

638

639

640

641

642

- 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.

643

644

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

645

646

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.

647

**Table 4 – isochronous traffic pattern properties**

Characteristics		Notes
<b>Data transmission scheme</b>	periodic	
<b>Data transmission constraints</b>	deadline	End-to-end one-way latency <sup>2</sup> less than 20% (link speeds > 100 Mbit/s) / 50% (link speeds <= 100 Mbit/s) of network cycle
<b>Data period</b>	1µs .. 1ms 250µs ..4ms	
<b>Network access (data transmission) synchronized to working clock network cycle</b>	Yes	
<b>Application synchronized to network access</b>	Yes	
<b>Acceptable jitter</b>	n.a.	Deadline shall be kept

<sup>2</sup> 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).

Characteristics		Notes
<b>Acceptable frame loss</b>	0..n frames	Media redundancy requirements according to the required tolerance; e.g. seamless redundancy for value 0
<b>Payload</b>	1 .. IEEE Std 802.3 maximum data payload size (i.e. 1500 bytes)	Data size negotiated during connection establishment

648

649

Requirements on network cycle times:

650

- 1 μs to 1 ms at link speed 1 Gbit/s (or higher)

651

- 250 μs to 4 ms at link speed 100 Mbit/s

652

- 2 ms to 8 ms at link speed 10 Mbit/s

653

*3.2.1.2 Delay requirements*

654

To make short control loop times feasible PHY, MAC and bridge delays shall meet upper limits:

655

- PHY delays shall meet the upper limits of Table 5.

656

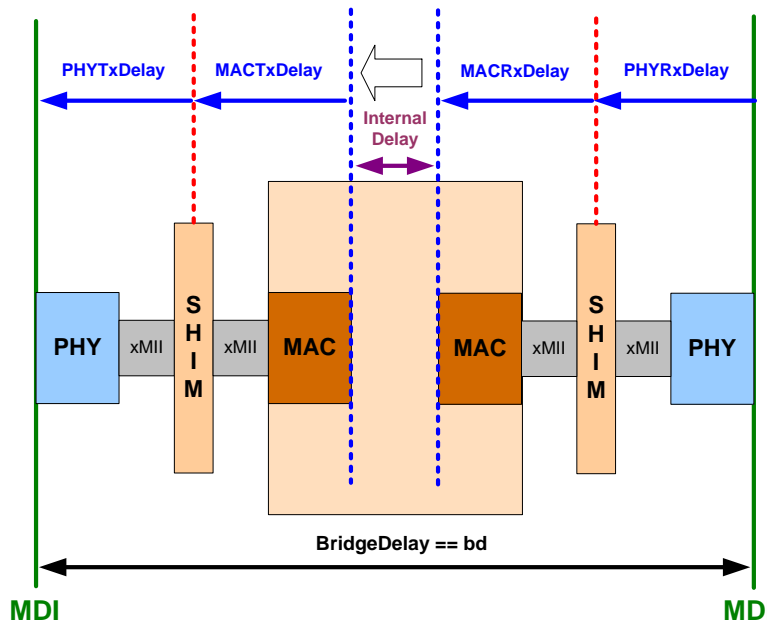
- MAC delays shall meet the upper limits of Table 6.

657

- Bridge delays shall be independent from the frame size and meet the upper limits of Table 7.

658

Figure 22 shows the definition of PHY delay, MAC delay and Bridge delay reference points.



659

660

**Figure 22 – delay measurement reference points**

661

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.

662

663

664

665

**Table 5 – Expected PHY delays**

Device	RX delay <sup>c</sup>	TX delay <sup>c</sup>	Jitter
10 Mbit/s	<< 1 $\mu$ s	<< 1 $\mu$ s	< 4 ns
100 Mbit/s MII PHY	210 ns (Max. 340 ns) <sup>a</sup>	90 ns (Max. 140 ns) <sup>a</sup>	< 4 ns
100 Mbit/s RGMII PHY	210 ns <sup>b</sup>	90 ns <sup>b</sup>	< 4 ns
1 Gbit/s RGMII PHY	<< 500 ns <sup>b</sup>	<< 500 ns <sup>b</sup>	< 4 ns
2,5 Gbit/s RGMII PHY	<< 500 ns <sup>b</sup>	<< 500 ns <sup>b</sup>	< 4 ns
5 Gbit/s RGMII PHY	<< 500 ns <sup>b</sup>	<< 500 ns <sup>b</sup>	< 4 ns
10 Gbit/s	tdb	tdb	tdb
25 Gbit/s to 1 Tbit/s	tdb	tdb	tdb

<sup>a</sup> According IEEE 802.3 for 100 Mbit/s full duplex with exposed MII.

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

<sup>c</sup> Lower values mean more performance for linear topology.

666

667

**Table 6 – Expected MAC delays**

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

668

669

**Table 7 – Expected Ethernet Bridge delays**

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

670

<sup>1)</sup> first bit in, first bit out

671 Useful 802.1 mechanisms:

- 672 • ...
- 673

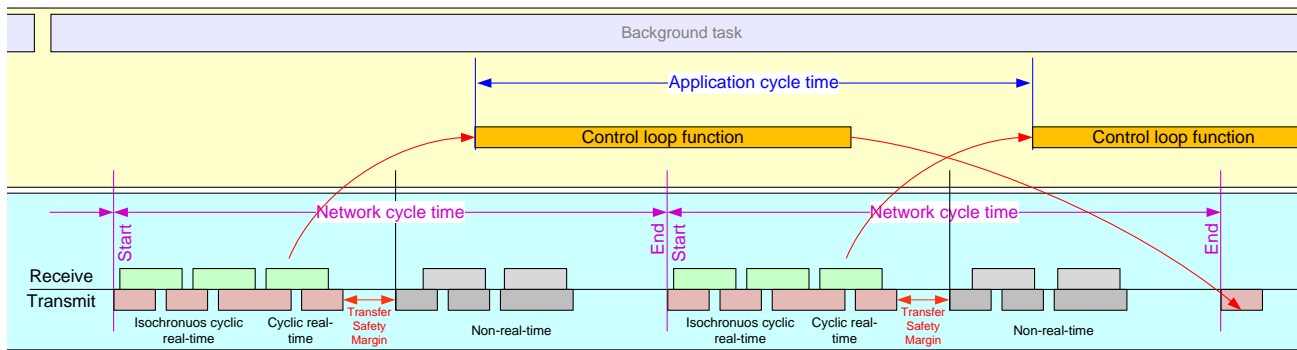
674 Example:

675 A representative example of a “Control loop with guaranteed low latency” use case is given in  
 676 clause 3.7.11.4 “Fast” process applications.  
 677

678 **3.3 Use case 03: Non-Isochronous Control Loops with bounded latency**

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

682 Figure 23 shows the principle how network cycle, transfer time and application time interact in this  
 683 use case. The control loop function starts at an application defined time, which is not synchronized  
 684 to the network access but to a local timescale. The network cycle, which describes the repetitive  
 685 behavior of the network interface, may be synchronized to a common working clock or to a local  
 686 timescale.

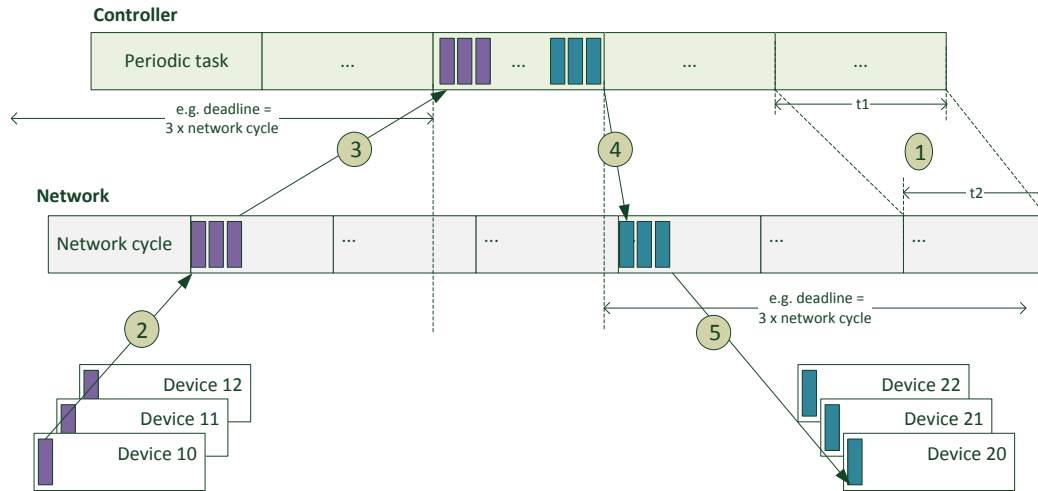


687  
 688  
 689 **Figure 23 – network cycle and non-isochronous application (Basic model)**

690 Extensions of this model analogous to Figure 14 (multiple applications with differing application  
 691 lengths) are also possible.



692 **3.3.1.1 Cyclic operation model**



**Figure 24 – cyclic operation model**

693  
694  
695  
696

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: ✓

697 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 ( $t_1$ ) $\neq$ network cycle period ( $t_2$ ).
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	<p>Controller output data shall reach device within a communication monitoring defined deadline (communication protocol).</p> <p>Device application assumes an kept update interval but doesn't know whether it is kept or not.</p> <p>Communication disturbances are recognized and signaled asynchronously by communication protocol to application.</p> <p>Device application operates on local process image data. Local process image decouples communication protocol from application.</p>
---	---

698

699 **3.3.1.2 Cyclic traffic pattern**

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

704 For a given target transfer time the number of possible bridges on a communication path is  
 705 restricted due to PHY-, MAC- and bridge-delay contributions, but can be much higher compared to  
 706 Cyclic real-time: transfer time may be longer than network cycle and applications are decoupled  
 707 from the working clock.

708 **Table 8 – cyclic traffic pattern properties**

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

709

<sup>3</sup> 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).

710 Requirements:

711 **3.4 Use case 04: Reduction ratio of network cycle**

712

713 Application needs may limit the in principle flexible network cycle time to a defined granularity.

714 E.g. in case of network cycle granularity  $31,25 \mu\text{s}$  the possible network cycles are:

715  $\geq 1\text{Gbit/s}$ :  $31,25 \mu\text{s} * 2^n \mid n=0 \dots 5$

716  $< 1\text{Gbit/s}$ :  $31,25 \mu\text{s} * 2^n \mid n=2 \dots 7$

717

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

719 -  $31,25 \mu\text{s}$  to  $512 \text{ms}$

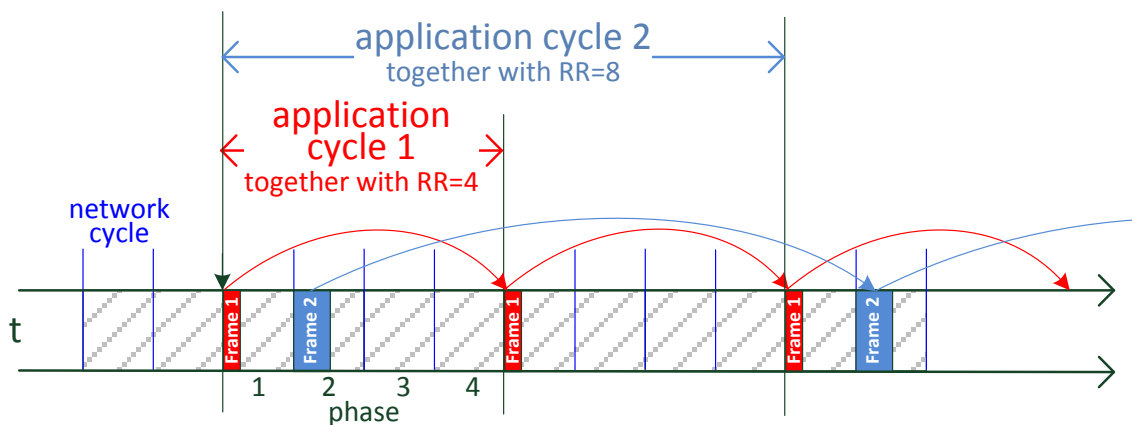
720

721 Reduction ratio: The value of “reduction ratio” defines the number of network cycles between two consecutive transmits.

722

723 Phase: The value of “phase” in conjunction with “reduction ratio” defines the starting network cycle for the consecutive transmits.

724



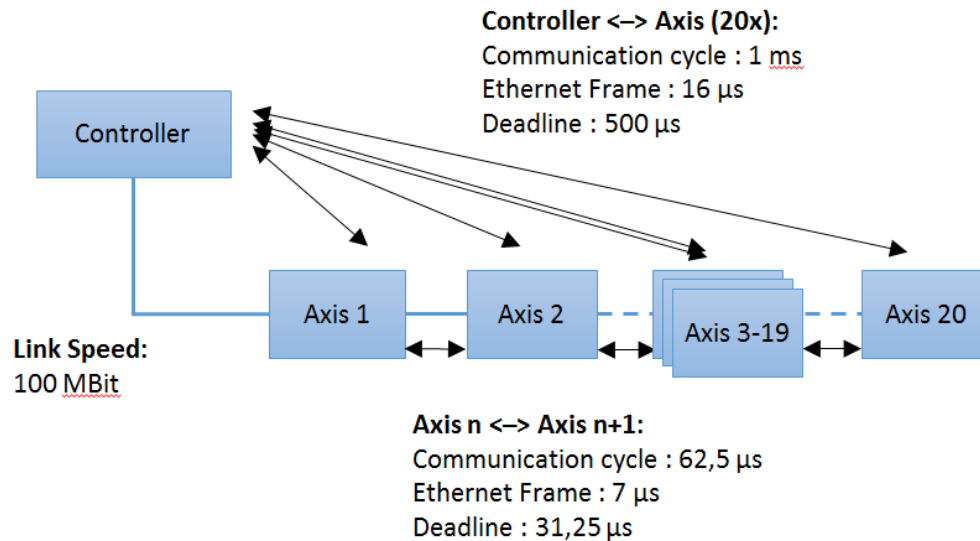
725

726 **Figure 25 – network cycle and application cycle**

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

729 Figure 26 shows another example use case where all drives are connected in a line and every  
730 drive needs direct data exchange to the Controller and additionally to its direct neighbor.

731 Some similar applications might even be more complex when the physical topology does not match  
732 the logical order of drives.



733  
 734 **Figure 26 – isochronous drive synchronization**

735 Requirements:

736 ...

737 Useful 802.1 mechanisms:

- 738 • ...

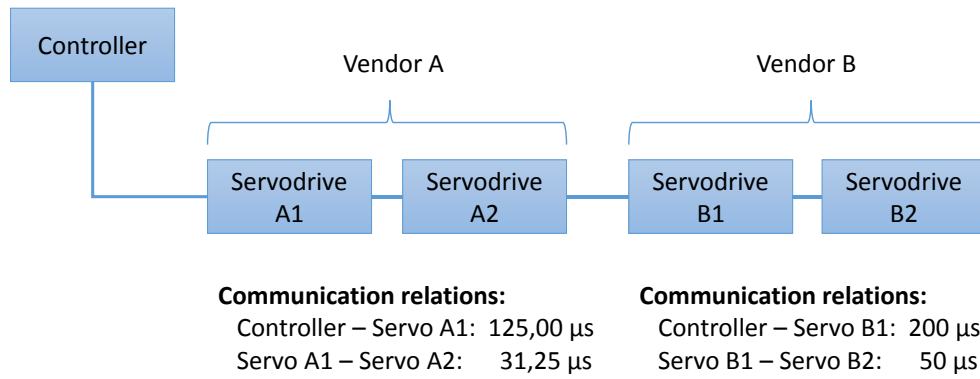
739 **3.5 Use case 05: Drives without common application cycle**

740 **3.5.1.1 Background information**

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

744 Figure 27 shows an example, where Vendor A needs to communicate with 31,25  $\mu$ s between its  
 745 devices (A1 with A2), and Vendor B needs to communicate with 50  $\mu$ s (between B1 and B2).  
 746 The communication with the controller which has to coordinate both of them shall be a multiple of  
 747 their local cycles. A1 needs to exchange data every 125 $\mu$ s with the Controller, B1 needs to  
 748 exchange data every 200 $\mu$ s with the Controller.

749 Servo drives from different vendors (Vendor A and Vendor B) are working on the same network.  
 750 For specific reasons the vendors are limited in the choice of the period for their control loop.



**Figure 27 – 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:

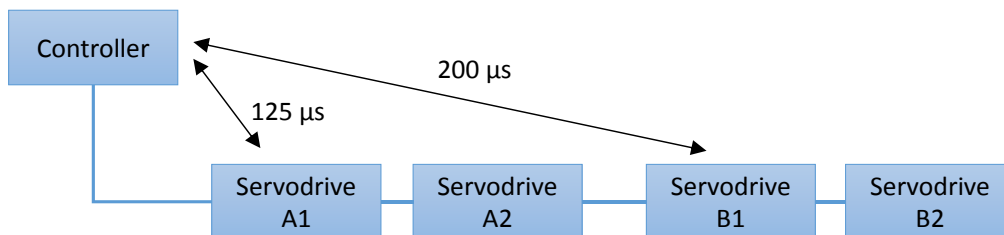
- Isochronous data exchange
- Different cycles for data exchange, which are not multiples of each other (cycles are not multiple of a common base, but fractions of a common base, here for instance 1 ms)

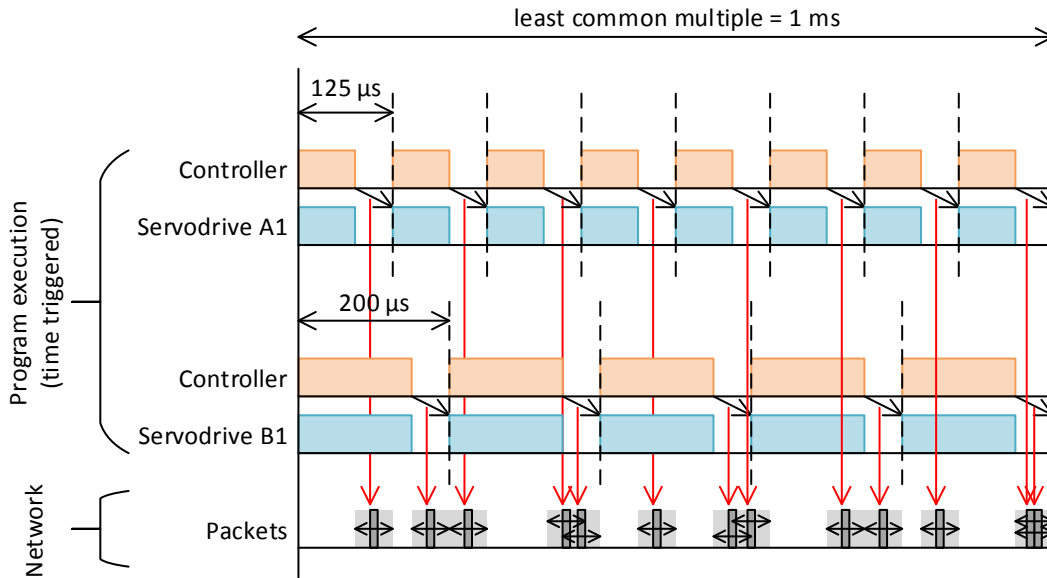
Useful 802.1Q mechanisms:

- Whatever helps
- ...

**3.5.1.2 Controller communication**

The Usecase concentrates on the communication between the devices A1 and B1, and the Controller as shown in Figure 28. Nevertheless the communication between A1/A2 and B1/B2 has to be solved as well.



776  
777**Figure 28 – Multivendor Motion – Controller communication**778 **3.5.1.3 Timing Requirements**

779

780

781

**Figure 29 – Multivendor Motion – Timing Requirements**

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

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

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

### 790 **3.6 Use case 06: Drives without common application cycle but common network** 791 **cycle**

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

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

- 795 - 31,25 µs, i.e. reduction ratio 1 for current control loop,
- 796 - 250 µs, i.e. reduction ratio 8 for motor speed control loop,
- 797 - 1 ms, i.e. reduction ratio 32 for position control loop,
- 798 - 16 ms, i.e. reduction ratio 512 for remote IO.

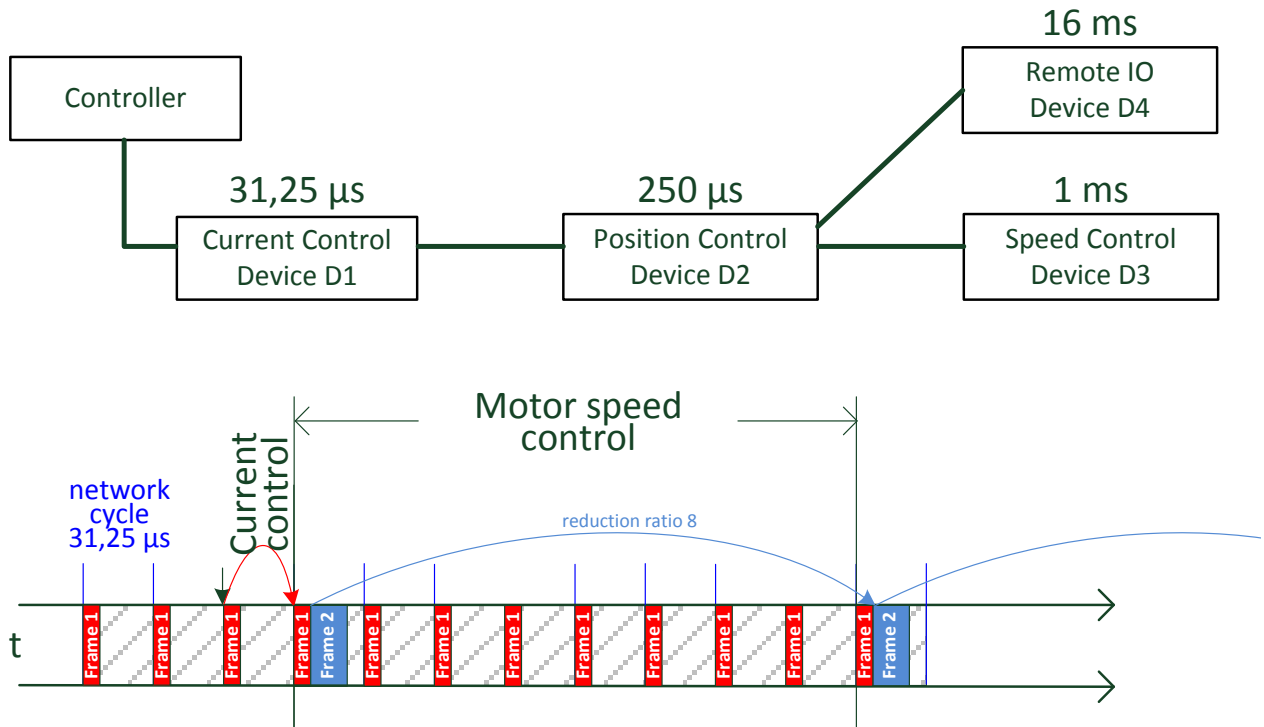


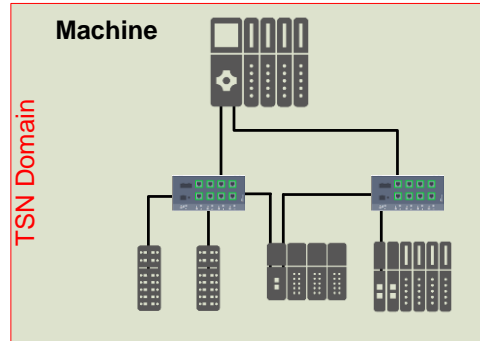
Figure 30 – different application cycles but common network cycle

799  
800  
801  
802

803 **3.7 Industrial automation networks**

804 **3.7.1 Use case 07: Redundant networks**

805 Ring topologies are the basic industrial network architecture for switch-over or seamless  
806 redundancy.



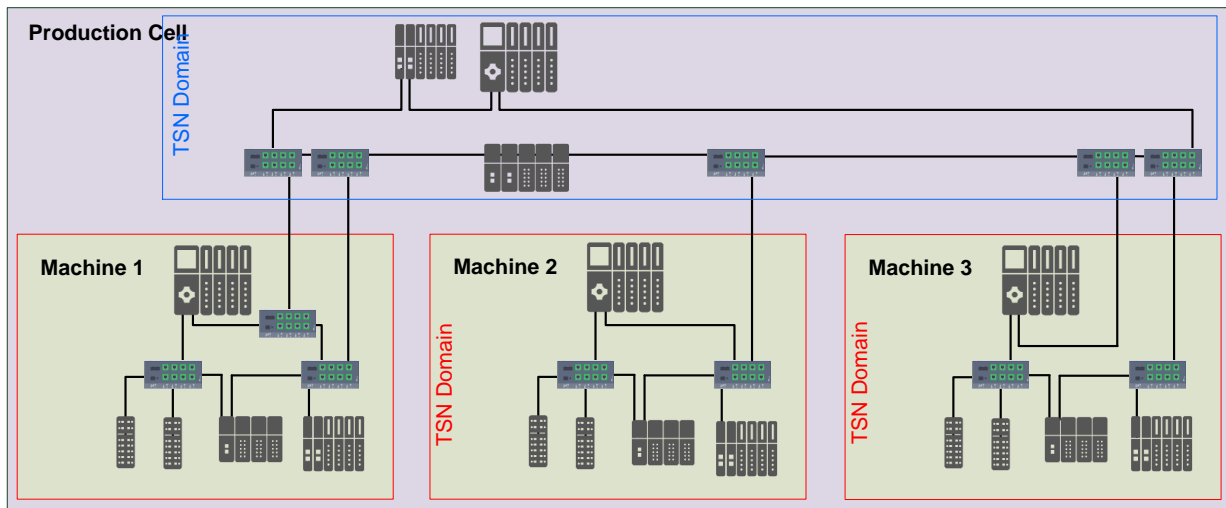
807

808

**Figure 31 – ring topology**

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

811 To even improve availability of the interconnection from the production cell into the machines this  
812 link can be arranged redundantly as well (machine 1 in Figure 32):



813

814

**Figure 32 – connection of rings**

815 Requirement:

816 Support redundant topologies with rings.

817 Useful 802.1 mechanisms:  
818

- 819 • ...

820

821 **3.7.2 Use case 08: High Availability**

822 High availability systems are composed of:

- 823 • Redundant networks, and

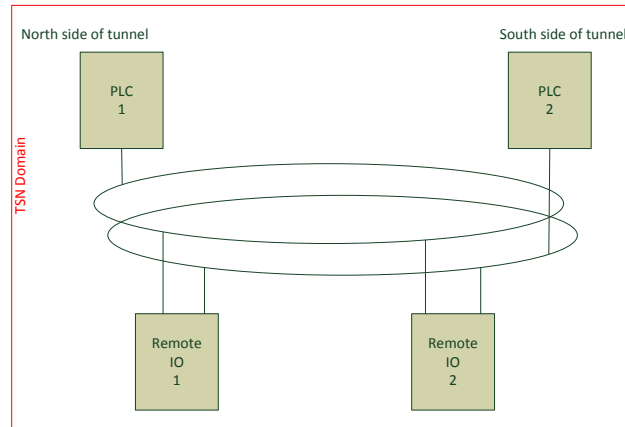


- 824 • Redundant stations.

825 E.g. tunnel control:

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

829



830

**Figure 33 – example topology for tunnel control**

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

835 Requirement:

836 Failure shall not create process disturbance – e.g. keep air flow active / fire control active.

837 The number of concurrent active failures without process disturbance depends on the application  
 838 requirements and shall not be restricted by TSN profile definitions.

839 Parameter, program, topology changes need to be supported without disturbance.

840

841 Useful 802.1Q mechanisms:

- 842 • Redundancy for PLCs, Remote IOs and paths through the network
- 843 • ...

844

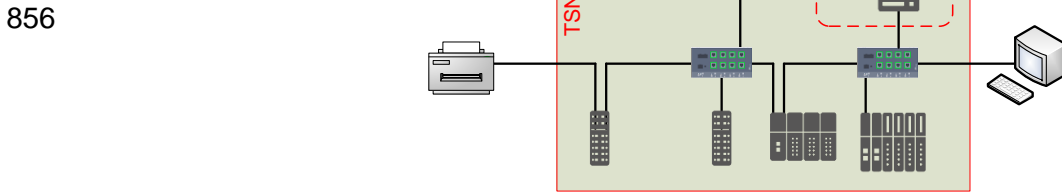
845 Further high availability control applications:

- 846 • Ship control
- 847 • Power generation
- 848 • Power distribution
- 849 • ...

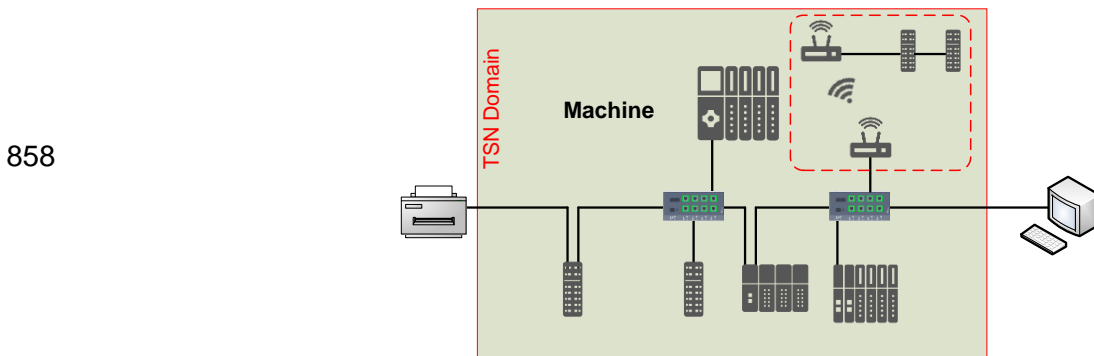
850

### 851 3.7.3 Use case 09: Wireless

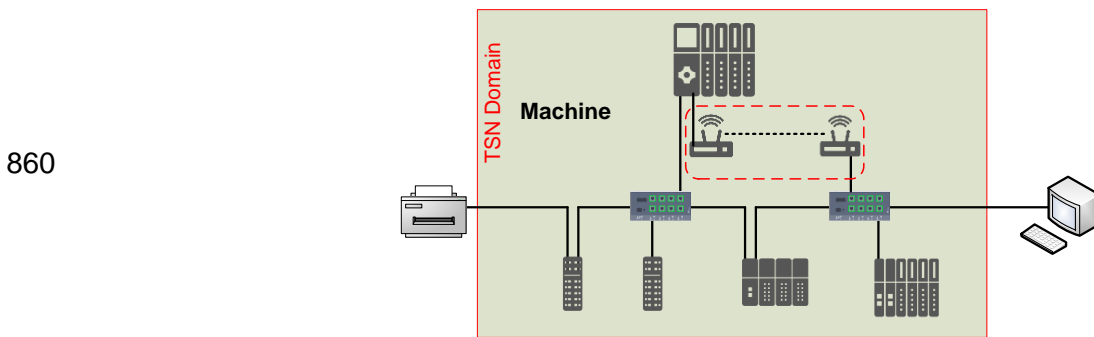
852 HMI panels, remote IOs, wireless sensors or wireless bridges are often used in industrial  
 853 machines. Wireless connections may be based on IEEE 802.11 (Wi-Fi), IEEE 802.15.1 (Bluetooth),  
 854 IEEE 802.15.4 or ITU/3GPP (5G). Even functional safety applications over wireless connections  
 855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



857 **Figure 34 – HMI wireless connected using cyclic real-time**



859 **Figure 35 – Remote IO wireless connected using cyclic real-time**



861 **Figure 36 – Ring segment wireless connected for media redundancy**

862  
863 Requirement:

- 864 Support of wireless for
- 865 • cyclic real-time, and
  - 866 • non-real-time communication

867  
868 Useful 802.11 mechanisms:

- 869 • Synchronization support
- 870 • Extensions from .11ax
- 871 • ...

872

873 Useful 802.15.1 mechanisms:

- 874 • ...

875

876 Useful 802.1Q mechanisms:

- 877 • ...

878

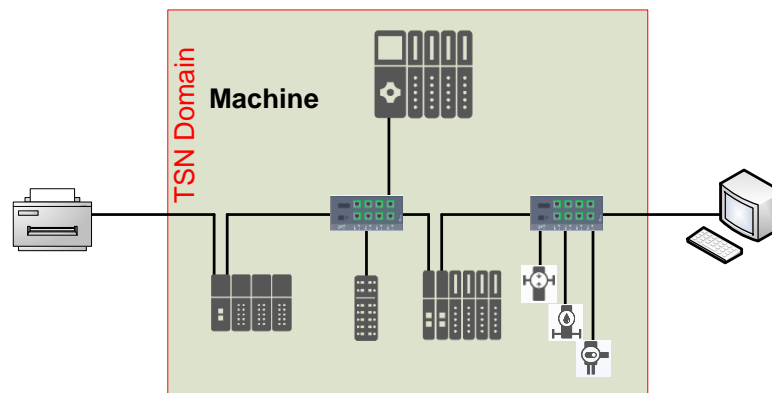
### 879 **3.7.4 Use case 10: 10 Mbit/s end-stations (Ethernet sensors)**

880 Simple and cheap sensor end-stations are directly attached via 10 Mbit/s links to the machine  
881 internal Ethernet and implement cyclic real-time communication with the PLC.

882 The support of additional physics like “IEEE 802.3cg APL support” is intended.

883

884



885

**Figure 37 – Ethernet sensors**

886 Requirement:

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

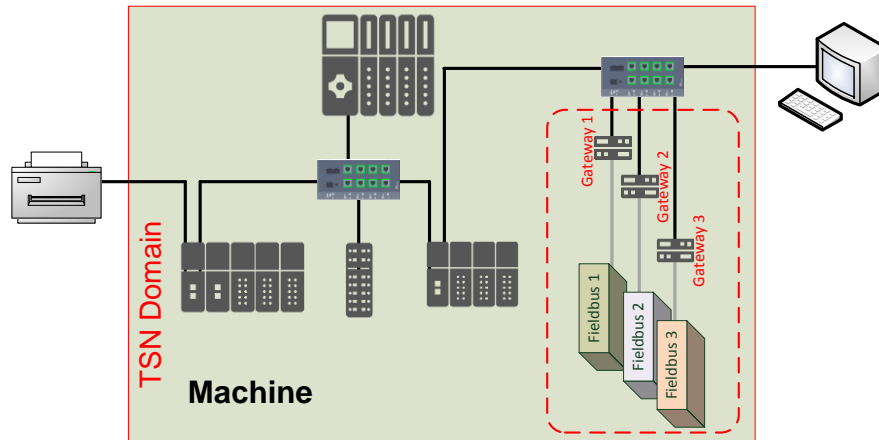
889

890 Useful 802.1Q mechanisms:

- 891 • ...

### 892 **3.7.5 Use case 11: Fieldbus gateway**

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



894

895

**Figure 38 – fieldbus gateways**

896

897

898

899

900

901

902

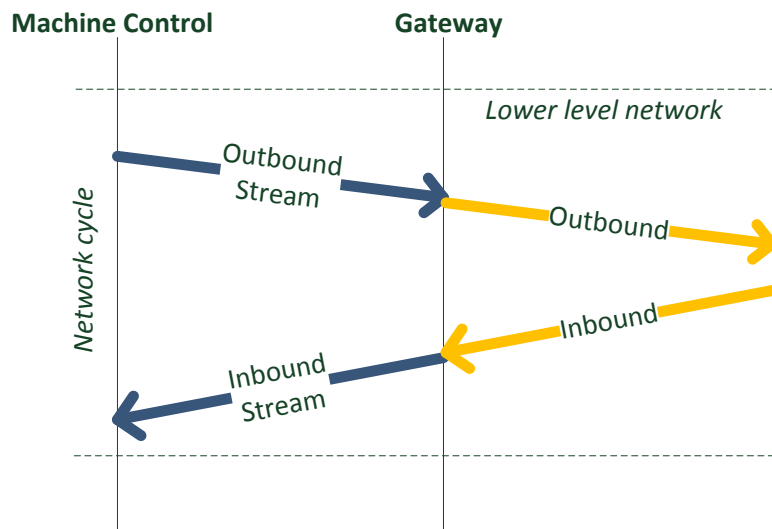
903

904

905

906

Many systems have at least one merging unit (e.g gateway, multiplexer) between the sensors and actuators assigned to a single machine control. The clustering is typically done with some infrastructure elements (slices) that require a backplane communication. The fieldbus communication is in many cases the third level of communication. Thus, it is assumed that TSN is not the first communication network between the sensors/actuators and a machine control unit. This means that TSN should be capable to adapt an existing communication infrastructure regardless of the size of those networks. The networks behind a gateway have their own timing constraints. A machine level network may take into account that the lower level networks e.g. behind a gateway have their own local timing. The timing of a TSN network has impact to subordinated structures. An optimal timing requires taking into account the gateway behavior for the TSN configuration (see Figure 39).



907

**Figure 39 – Embedded non TSN communication**

908

909

**Requirement:**

910

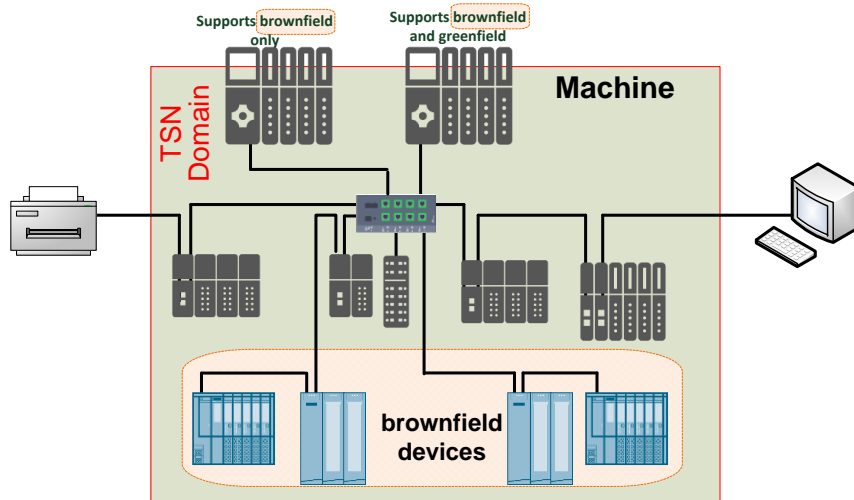
911

- Support of non-Ethernet and Ethernet-based fieldbus devices via gateways either transparent or hidden;

- TSN scheduling may need configuration to meet the requirements of subordinate systems;

**3.7.6 Use case 12: New machine with brownfield devices**

Brownfield devices with real-time communication are attached to a PLC, which supports both brownfield and greenfield, within a machine. This allows faster deployment of devices supporting the TSN-IA profile into the field. Figure 40 gives an example of a machine with brownfield devices.



**Figure 40 – New machine with brownfield devices**

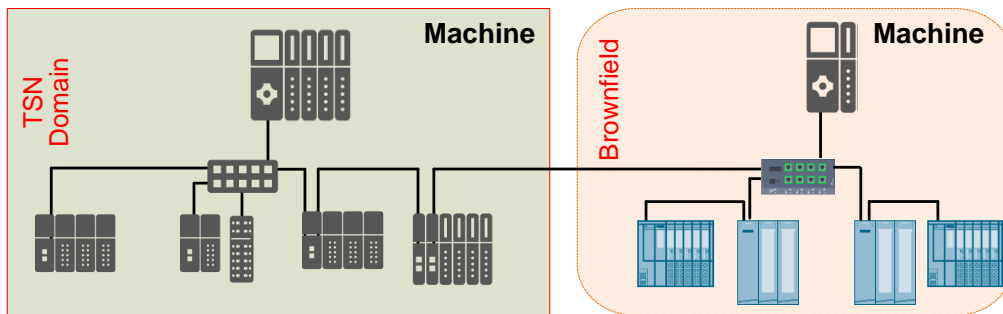
Requirement:

All machine internal stream traffic communication (stream traffic and non-stream traffic) is decoupled from and protected against the brownfield cyclic real-time traffic. Brownfield cyclic real-time traffic QoS is preserved within the TSN domain.

Useful 802.1Q mechanisms:

- Priority Regeneration,
- separate "brownfield traffic queue".
- Queue-based resource allocation.

Figure 41 shows a different use case where a TSN machine is attached to an existing brownfield machine. In this case only non-TSN traffic is possible between the two machines.



**Figure 41 – Add TSN machine to brownfield machine**

934 **3.7.7 Use case 13: Mixed link speeds**

935 Industrial use cases refer to link speeds, as shown in Table 9, in the range from 10 Mbit/s to  
 936 10 GBit/s for Ethernet and additional Wi-Fi, Bluetooth and 5G. Thus, the TSN domains need to  
 937 handle areas with different link speeds.

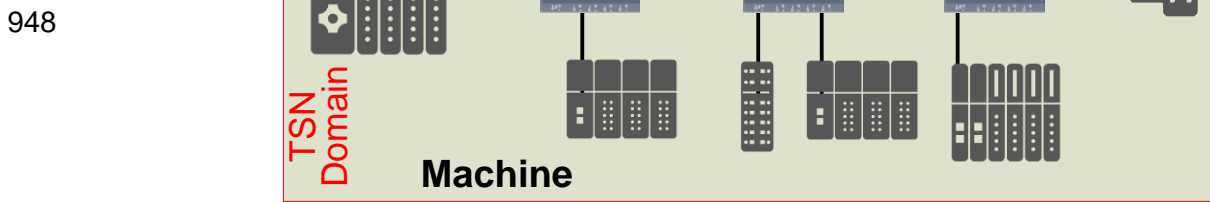
938 **Table 9 – Link speeds**

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

939  
 940 Mixing devices with different link speeds is a non-trivial task. Figure 42 and Figure 43 show the  
 941 calculation model for the communication between an IOC and an IOD connected with different link  
 942 speeds.

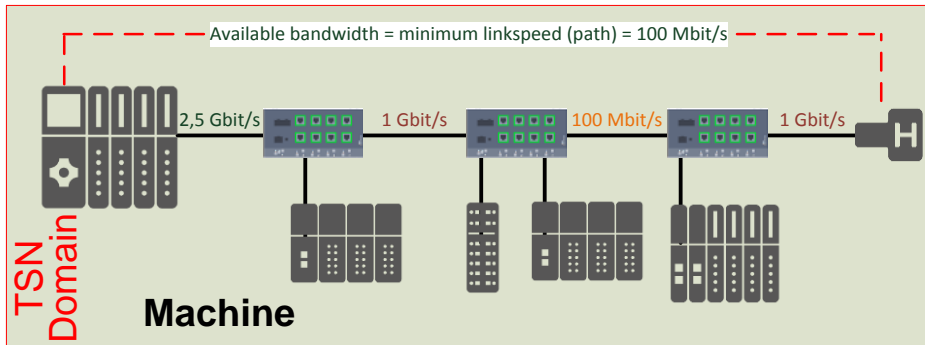
943 The available bandwidth on a communication path is determined by the path segment with the  
 944 minimum link speed.

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



949

**Figure 42 – mixed link speeds**



950

951

**Figure 43 – mixed link speeds without topology guideline**

952

Requirement:

953

Links with different link speeds as shown in Figure 42 share the same TSN-IA profile based communication system at the same time.

954

955

Links with different link speeds without topology guideline (Figure 43) may be supported.

956

957

Useful 802.1 mechanisms:

958

- ...

959

**3.7.8 Use case 14: Multiple isochronous domains**

960

Figure 44 shows a machine which needs due to timing constraints (network cycle time together with required topology) two or more separated isochronous real-time domains but shares a common cyclic real-time domain.

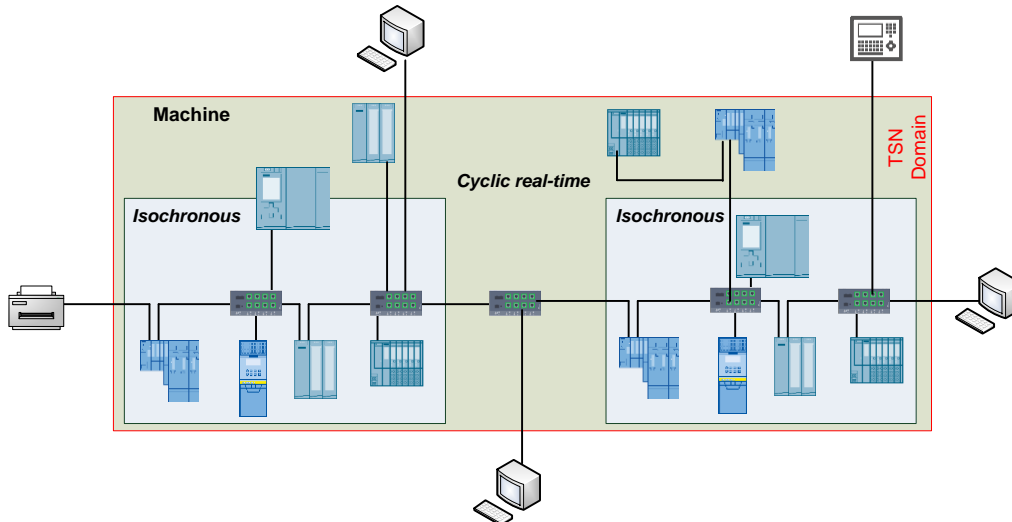
961

962

Both isochronous domains may have their own Working Clock and network cycle. The PLCs need to share remote IOs using cyclic real-time traffic.

963

964



965

966

**Figure 44 – multiple isochronous domains**

967

Some kind of coupling (e.g. shared synchronization) between the isochronous domains / Working Clocks may be used (see Figure 45).

968

969

All isochronous domains may have different network cycle times, but the cyclic real-time data exchange shall still be possible for PLCs from both isochronous domains.

970

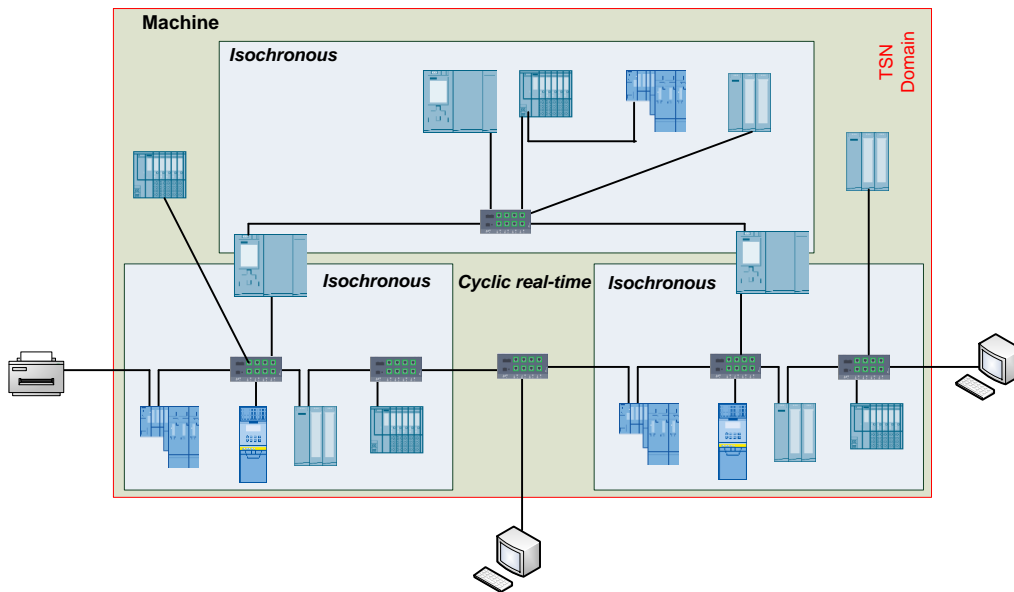


Figure 45 – multiple isochronous domains - coupled

**Requirements:**

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

**Useful 802.1 mechanisms:**

- separate “isochronous” and “cyclic” traffic queues,
- Queue-based resource allocation in all bridges,
- ...

**3.7.9 Use case 15: Auto domain protection**

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

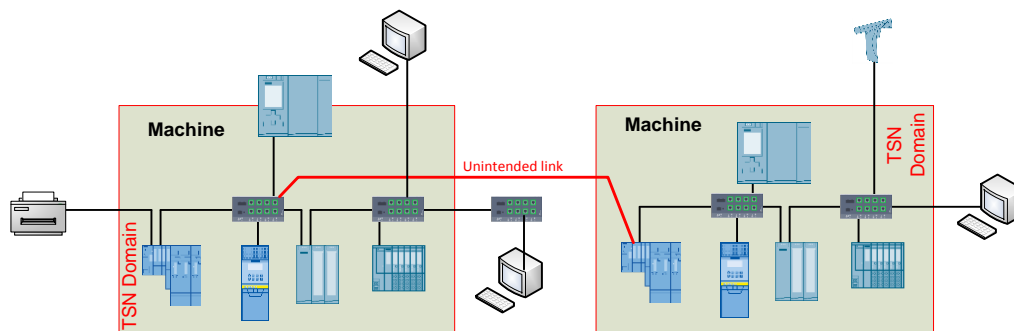


Figure 46 – Auto domain protection



990 Requirement:  
991 Support of auto TSN domain protection to prevent unintended use of traffic classes

992  
993 Useful 802.1Q mechanisms:

- 994     • Priority regeneration  
995     • ...

### 996 **3.7.10 Use case 16: Vast number of connected stations**

997 Some industrial applications need a massive amount of connected stations like  
998 - Car production sites  
999 - Postal, Parcel and Airport Logistics  
1000 - ...

1001 Examples for "Airport Logistics":

- 1002     • Incheon International Airport, South Korea  
1003     • Guangzhou Baiyun International Airport, China  
1004     • London Heathrow Airport, United Kingdom  
1005     • Dubai International Airport, UAE  
1006     • ...

1007  
1008 Dubai International Airport, UAE

1009 Technical Data:

- 1010     • 100 km conveyor length  
1011     • 222 check-in counters  
1012     • car park check-in facilities  
1013     • Max. tray speed: 7.5 m/s  
1014     • 49 make-up carousels  
1015     • 14 baggage claim carousels  
1016     • 24 transfer laterals  
1017     • Storage for 9,800 Early Bags  
1018     • Employing 48 inline screening  
1019     • Max. 8-stories rack system  
1020     • 10,500 ton steel  
1021     • 234 PLC's  
1022     • 16,500 geared drives  
1023     • [xxxx digital IOs]

1024  
1025 Further representative examples of required quantities are provided in 3.7.11.1 and 3.7.11.2.

1026  
1027 Requirement:

1028 Make sure that even this massive amount of stations works together with the TSN-IA profile. This  
1029 kind of applications may or may not require wireless support, too.

1030  
1031 Useful 802.1 mechanisms:

- 1032     • ...

1033 **3.7.11 Minimum required quantities**1034 **3.7.11.1 A representative example for VLAN requirements**

1035 Figure 47 shows the IEEE 802.1Q based stacked physical, logical and active topology model. This  
 1036 principle is used to build TSN domains.

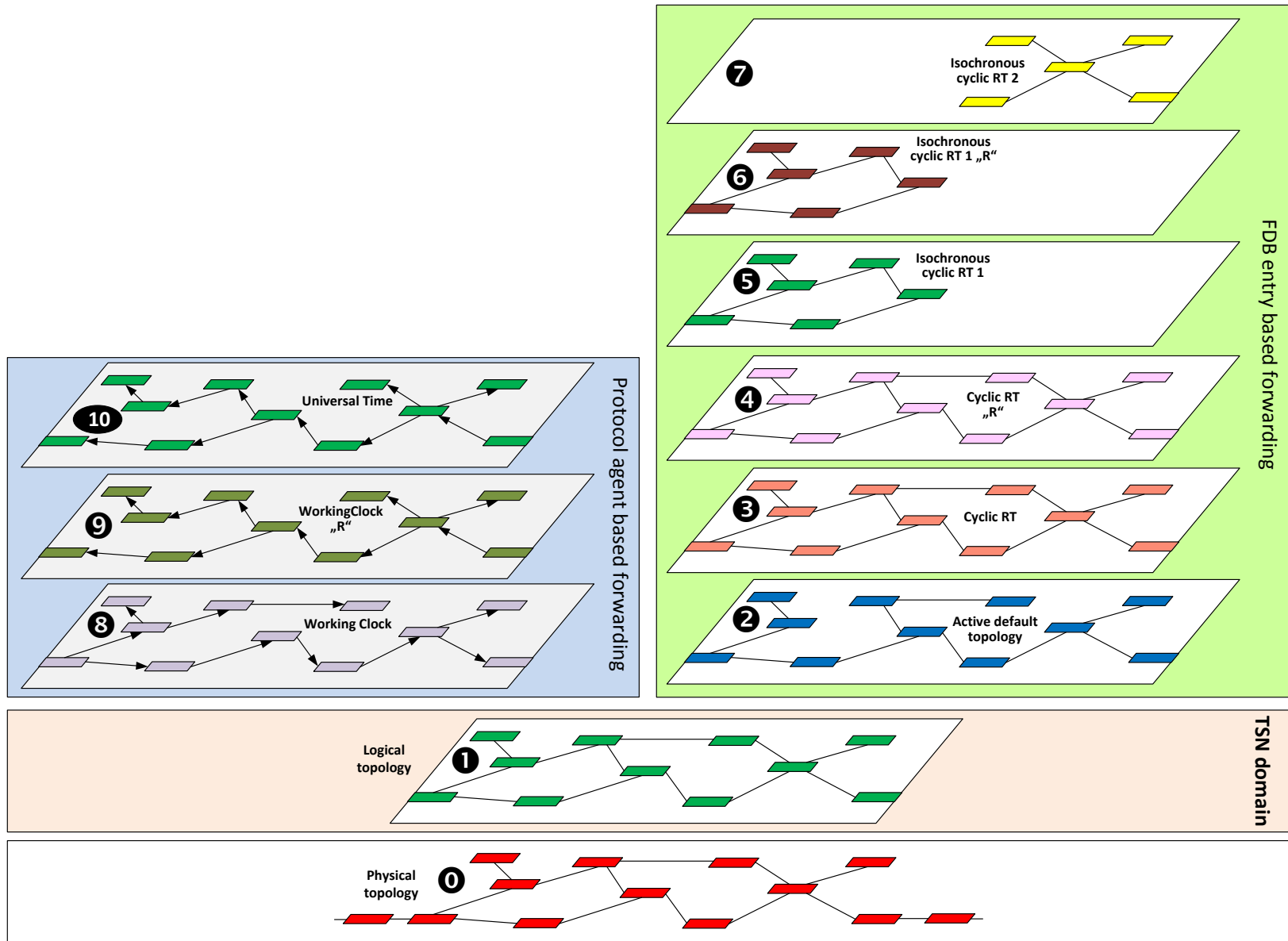
1037 It shows the different active topologies driven by either VID (identified by VLAN) or protocol  
 1038 (identified by DA-MAC and/or protocol type).

1039 Additionally the number of to be supported VIDs per bridge is shown. The number of protocol agent  
 1040 defined active topologies is just an example because e.g. LLDP, RSTP or MST is missing.

1041 The following topologies, trees and VLANs are shown in Figure 47.

①	Physical network topology	all existing devices and links
①	Logical network topology	<b>TSN domain:</b> administrative selection of elements from the physical topology
②	Active default topology	Default VLAN: result of a spanning tree algorithm (e.g. RSTP)
③	Cyclic RT	VLAN for cyclic real-time streams
④	Cyclic RT „R”	VLAN for redundant cyclic real-time streams
⑤	Isochronous cyclic RT 1	VLAN for isochronous cyclic real-time streams
⑥	Isochronous cyclic RT 1 „R”	VLAN for redundant isochronous cyclic real-time streams
⑦	Isochronous cyclic RT 2 <sup>4</sup>	VLAN for isochronous cyclic real-time streams
⑧	Working clock	gPTP sync tree used for the synchronization of a working clock
⑨	Working clock „R”	Hot standby gPTP sync tree used for the synchronization of a working clock
① ⑩	Universal time	gPTP sync tree used for the synchronization of universal time

<sup>4</sup> The isochronous cyclic RT 2 „R” is not applied in this example but can be made available additionally



1043

**Figure 47 – Topologies, trees and VLANs**

1044

1045 Expected numbers of DA-MAC address entries used together with five VLANs (Default, High, High  
1046 Redundant, Low and Low Redundant) are shown in Table 10 and Table 11.

1047 Table 10 may be implemented as FDB table with a portion of DA-MAC address (e.g. 12 bits of  
1048 Identifier and TSN-IA profile OUI) as row and the VLANs as column to ensure availability of a  
1049 dedicated entry.

1050

**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)

1051

1052 Expected number of entries is given by the maximum device count of 1024 together with the 50%  
1053 saturation due to hash usage rule. Table 11 shows the expected number of possible FDB entries.

1054

**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

1055

1056 The hash based FDBs shall support a neighborhood for entries according to Table 12.

1057

**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.

1058

### 1059 3.7.11.2 A representative example for data flow requirements

1060 TSN domains in an industrial automation network for cyclic real-time traffic can span multiple  
1061 Cyber-physical systems, which are connected by bridges. The following maximum quantities apply:

- 1062 – Stations: 1024
- 1063 – Network diameter: 64
- 1064 – per PLC for Controller-to-Device (C2D) – one to one or one to many – communication:
  - 1065 ○ 512 producer and 512 consumer data flows; 1024 producer and 1024 consumer data  
1066 flows in case of seamless redundancy.
  - 1067 ○ 64 kByte Output und 64 kByte Input data
- 1068 – per Device for Device-to-Device (D2D) – one to one or one to many – communication:
  - 1069 ○ 2 producer and 2 consumer data flows; 4 producer and 4 consumer data flows in case  
1070 of seamless redundancy.
  - 1071 ○ 1400 Byte per data flow

- 1072 – per PLC for Controller-to-Controller (C2C) – one to one or one to many – communication:
- 1073 ○ 64 producer and 64 consumer data flows; 128 producer and 128 consumer data flows in
- 1074 case of seamless redundancy.
- 1075 ○ 1400 Byte per data flow
- 1076 – Example calculation for eight PLCs
- 1077 →  $8 \times 512 \times 2 = 8192$  data flows for C2D communication
- 1078 →  $8 \times 64 \times 2 = 1024$  data flows for C2C communication
- 1079 →  $8 \times 64 \text{ kByte} \times 2 = 1024 \text{ kByte}$  data for C2D communication
- 1080 →  $8 \times 64 \times 1400 \text{ Byte} \times 2 = 1400 \text{ kByte}$  data for C2C communication
- 1081 – All above shown data flows may optionally be redundant for seamless switchover due to the
- 1082 need for High Availability.

1083 Application cycle times for the 512 producer and 512 consumer data flows differ and follow the

1084 application process requirements.

1085 E.g. 125  $\mu\text{s}$  for those used for control loops and 500  $\mu\text{s}$  to 512 ms for other application processes.

1086 All may be used concurrently and may have frames sizes between 1 and 1440 bytes.

### 1087 3.7.11.3 A representative example of communication use cases

1088 IO Station – Controller (input direction)

- 1089 – Up to 2000 published + subscribed signals (typically 100 – 500)
- 1090 – Scan interval time: 0,5 ..100ms (typical 10ms)

1091 Controller – Controller (inter-application)

- 1092 – Up to 1000 published + subscribed signals (typically 100 – 250)
- 1093 – Application task interval time: 10..1000ms (typical 100ms)
- 1094 – Resulting Scan interval time: 5 ... 500 ms

1095 Closing the loop within/across the controller

- 1096 – Up to 2000 published + subscribed signals (typically 100 – 500)
- 1097 – Application task interval time: 1..1000ms (typical 100ms)
- 1098 – Resulting Scan interval time when spreading over controllers: 0,5 ... 500 ms

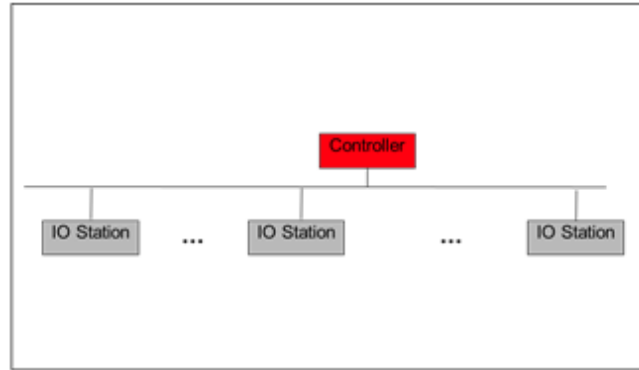
1099 Controller – IO Station (output direction)

- 1100 – Up to 2000 published + subscribed signals (typically 100 – 500)
- 1101 – Application task interval time: 10..1000ms (typical 100ms)
- 1102 – Resulting Scan interval time: 5 ... 500 ms
- 1103

### 1104 3.7.11.4 “Fast” process applications

1105 The structure shown in **Error! Reference source not found.** applies. Figure 48 provides a logic

1106 station view.



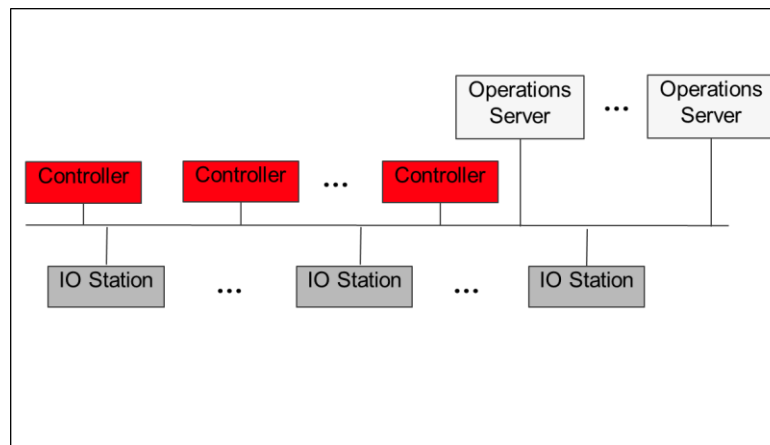
1107  
1108 **Figure 48 – Logical communication concept for fast process applications**

1109 Specifics:

- 1110 – Limited number of nodes communicating with one Controller (e.g. Turbine Control)
- 1111 – Up to a dozen Nodes of which typically one is a controller
- 1112 – Data subscriptions (horizontal):
  - 1113 ▪ 270 bytes published + subscribed per IO-station
  - 1114 ▪ Scan Interval time 0,5 to 2 ms
- 1115 – Physical Topology: Redundant (as path and as device)

1117 **3.7.11.5 Server consolidation**

1118 The structure shown in **Error! Reference source not found.** applies. Figure 49 provides a logic  
1119 station view.



1120  
1121 **Figure 49 – Server consolidated logical connectivity**

1122  
1123 Data access to Operations Functionalities consolidated through Servers

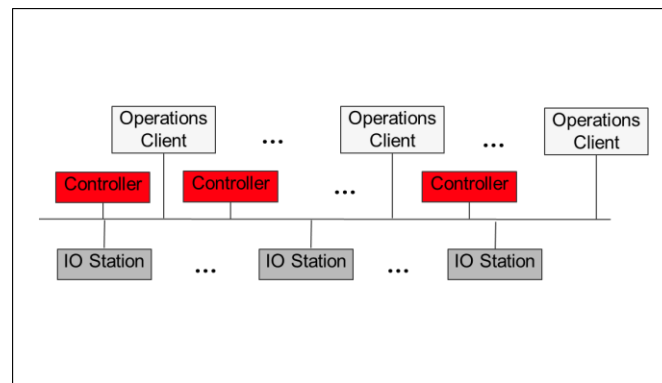
- 1124 – Up to 100 Nodes in total
- 1125 – Out which are up to 25 Servers

- 1127 Data subscriptions (vertical):
- 1128 - Each station connected to at least 1 Server
  - 1129 - max. 20000 subscribed items per Controller/IO-station
  - 1130 - 1s update rate
  - 1131 - 50% analog items -> 30% change every sec
  - 1132

- 1133 Different physical topologies
- 1134 - Rings, stars, redundancy
  - 1135

### 1136 3.7.11.6 Direct client access

- 1137 The structure shown in **Error! Reference source not found.** applies. Figure 50 provides a logic  
 1138 station view.



1139

1140 **Figure 50 – Clients logical connectivity view**

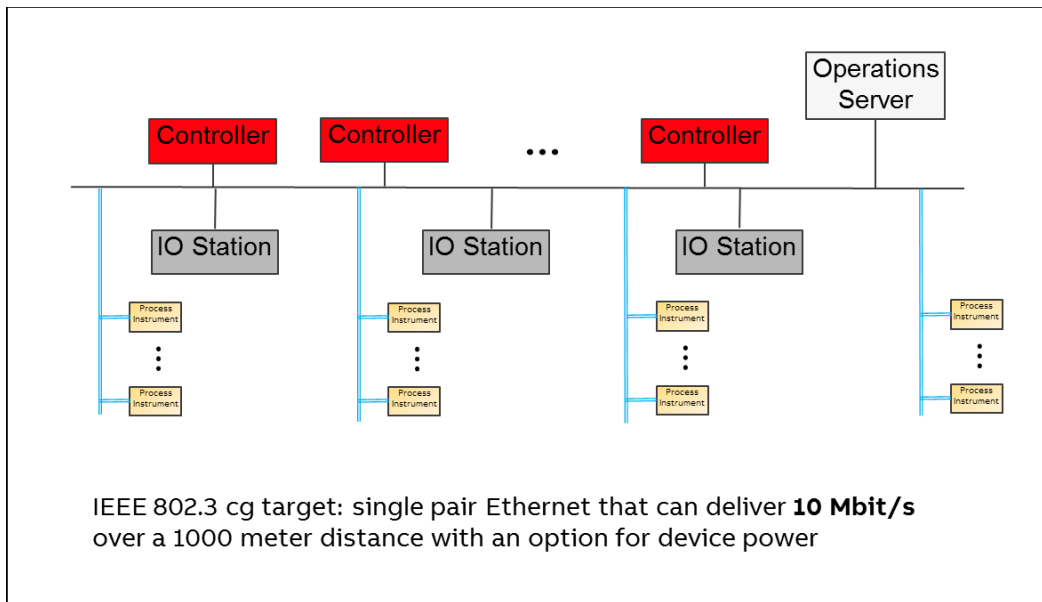
- 1141 Data access to Operations Functionalities directly by Clients
- 1142 - Max 20 direct access clients
  - 1143
- 1144 Data subscriptions (vertical):
- 1145 - Up to 3000 subscribed items per client
  - 1146 - 1s update rate
  - 1147 - Worst case 60000 items/second per controller in classical Client/Server setup
  - 1148 - 50% analog items -> 30% change every sec
  - 1149

- 1150 Different physical topologies
- 1151 - Rings, stars, redundancy
  - 1152



1153 **3.7.11.7 Field devices**

1154 The structure shown in **Error! Reference source not found.** applies. Figure 51 provides a logic  
 1155 station view.



1156 **Figure 51 – Field devices with 10Mbit/s**

1157 **Field Networks integrated with converged network**

- 1158 – Up to 50 devices per field segment
- 1159 – Scan interval 50ms ... 1s, typical 250ms
- 1160 – Mix of different device types from different vendors
- 1161 – Many changes during runtime

1162 **3.7.12 Bridge Resources**

1163 The bridge shall provide and organize its resources in a way to ensure robustness for the traffic  
 1164 defined in this document as shown in Formula [1].

1165 The queuing of frames needs resources to store them at the destination port. These resources may  
 1166 be organized either bridge globally, port globally or queue locally.

1167 The chosen resource organization model influences the needed amount of frame resources.

1171 For bridge memory calculation Formula [1] applies.

$$1172 \text{ MinimumFrameMemory} = (\text{NumberOfPorts} - 1) \times \text{MaxPortBlockingTime} \times \text{Linkspeed} \quad (1)$$

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.

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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.

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

**Table 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 $\mu$ s 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 $\mu$ s 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 $\mu$ s 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

1181  
1182

**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 $\mu$ s 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 $\mu$ s 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 $\mu$ s 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

1183  
1184

**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 $\mu$ s at one port needed to be forwarded to the other port are stored during the allocation of this port due to stream transmission.

# of ports	MinimumFrameMemory [KBytes]	Comment
3	62,5	All frames received during the 10%@1 ms := 100 $\mu$ s 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 $\mu$ s 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

1185

1186

**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 $\mu$ s 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 $\mu$ s 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 $\mu$ s 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

1187

1188

1189

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

1190

1191

1192

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

1193

Example “per port frame resource management”:

1194

100 Mbit/s, 2 Ports, and 6 queues

1195

Needed memory := 6,25 KOctets \* 6 := 37,5 KOctets.

1196

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

1197

1198

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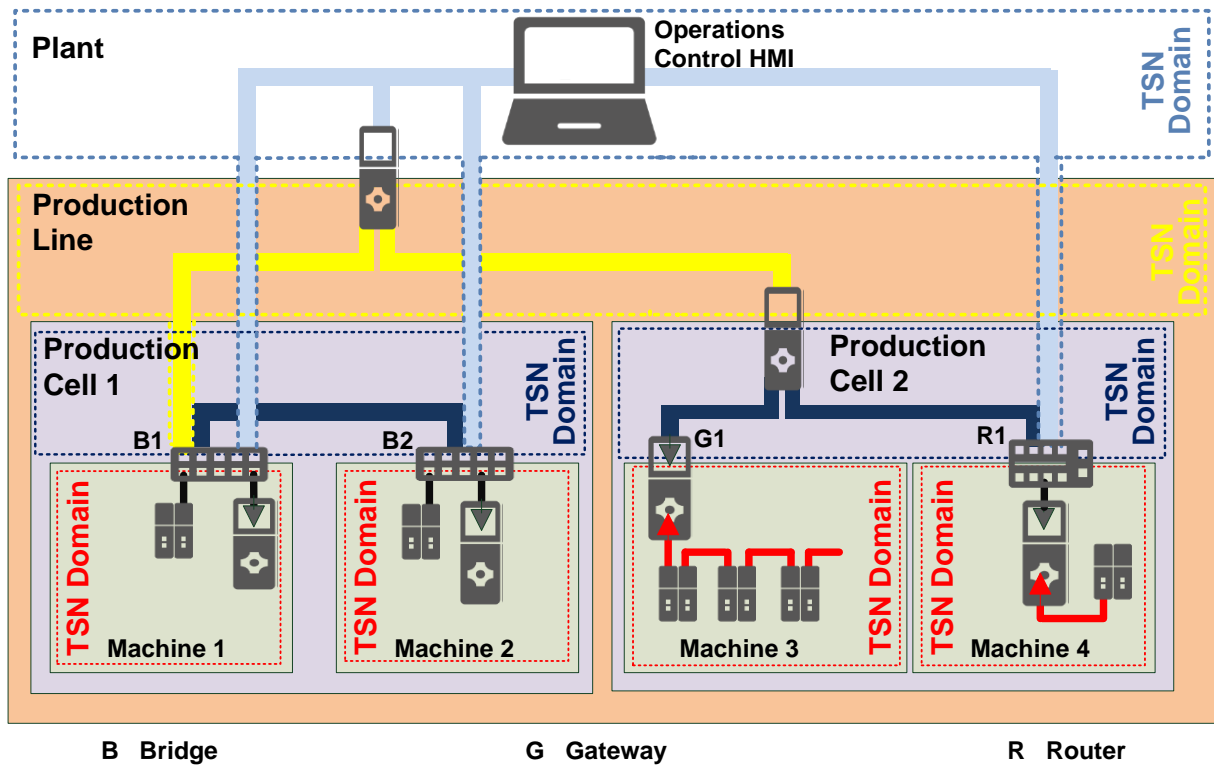
1200

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

1201 **3.8 Industrial automation machines, production cells, production lines**

1202 **3.8.1 Use case 17: Machine to Machine/Controller to Controller (M2M/C2C) Communication**

1203 Preconfigured machines with their own TSN domains, which include tested and approved internal  
 1204 communication, communicate with other preconfigured machines with their own TSN domains, with  
 1205 a supervisory PLC of the production cell (with its own TSN domain) or line (with its own TSN  
 1206 domain) or with an Operations Control HMI (with its own TSN domain).



1207  
 1208 **Figure 52 – M2M/C2C between TSN domains**

1209 Figure 52 shows that multiple logical overlapping TSN Domains arise, when controllers use a  
 1210 single interface for the M2M communication with controllers of the cell, line, plant or other  
 1211 machines. Decoupling of the machine internal TSN Domain can be accomplished by applying a  
 1212 separate controller interface for M2M communication.

1213 Machine 1: the controller link to its connected cell bridge B1 is concurrently member of the TSN  
 1214 Domains of Machine 1, Production Cell 1, Production Line and Plant.

1215 Machine 2: the controller link to its connected cell bridge B2 is concurrently member of the TSN  
 1216 Domains of Machine 2, Production Cell 1 and Plant.

1217 Machine 3: the controller is directly attached to the PLC of Production Cell 2 and is therefore  
 1218 member of the TSN Domain of Production Cell 2. The machine internal TSN Domain is  
 1219 decoupled from M2M traffic by a separate interface.

1220 Machine 4: the controller link to its connected cell bridge B3 is concurrently member of the TSN  
 1221 Domains of Production Cell 2 and Plant. The machine internal TSN Domain is  
 1222 decoupled from M2M traffic by a separate interface.

1223  
 1224 Examples:

1225

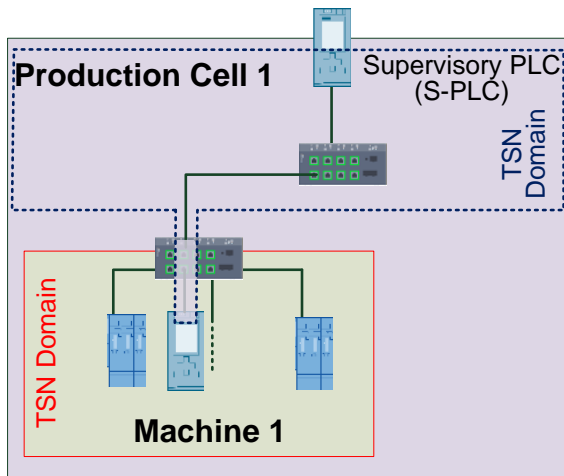


Figure 53 gives an example of M2M communication to a supervisory PLC.

Figure 54 shows an example of M2M communication relations between four machines.

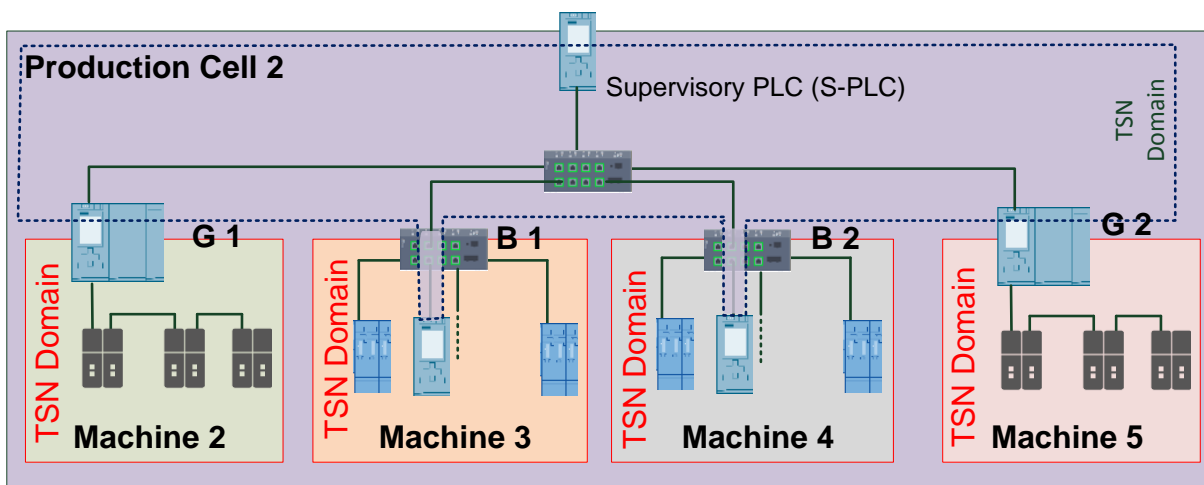
PLCs with one single interface lead to overlapping communication paths of M2M and machine internal traffic. In this case two TSN domains (Machine / Production cell) need to share resources due to two logical overlapping TSN domains.

**Figure 53 – M2M with supervisory PLC**

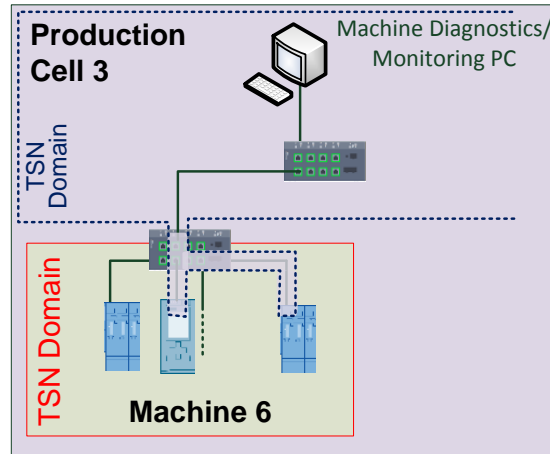
There are quite a few constraints related to the machine internal networks. Each machine may run a different schedule and even the intervals may be different. It may be very complex or even impossible to find an optimal communication schedule down from the sensors and actuators to the cell control. The 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 55 shows an example where M2M communication is used to connect a PC for diagnostics/monitoring.



**Figure 54 – M2M with four machines**



**Figure 55 – M2M with diagnostics/monitoring PC**

1226 Figure 55 shows a M2M diagnostics related use case: communication is cyclic and shall happen  
 1227 within short application cycle times. An example of this use case is the verification of proper  
 1228 behavior of a follower drive, in a master-follower application. Today, the use case is covered by  
 1229 connecting a common PC to an interface of the follower drive. The various TSN mechanisms may  
 1230 now make it possible to connect such a PC network interface card anywhere in the system network  
 1231 and still gather the same diagnostics with the same guarantees, as the current direct connection.

1232 The required guarantees are:

1233 Each 4 ms a frame shall be sent from a follower drive and have its delivery guaranteed to the  
 1234 network interface of the PC used to perform the diagnostics. Of course, local PC-level processing  
 1235 of such frames has to be implemented such that the diagnostic application gets the required quality  
 1236 of service.

1237 From the communication point of view the two types of machine interface shown in Figure 54 are  
 1238 identical. The PLC represents the machine interface and uses either a dedicated (machine 1 and 4)  
 1239 or a shared interface (machine 2 and 3) for communication with other machines and/or a  
 1240 supervisor PLC.

1241 The communication relations between machines may or may not include or make use of a  
 1242 supervisory PLC.

1243 Requirement:

- 1244 • All machine internal communication (stream traffic and non-stream traffic) is decoupled from  
 1245 and protected against the additional M2M traffic and vice versa.
- 1246 • 1:1 and 1:many communication relations shall be possible.
- 1247 • Scheduling in a way that interleaved operation with machine intervals is possible.

1248 Useful 802 mechanisms:

- 1249 • IEEE Std 802.1Q-2018, Fixed priority, IEEE Std 802.3br
- 1250 • Priority Regeneration,
- 1251 • Queue-based resource allocation,
- 1252 • VLANs to separate TSN domains.

1253 **3.8.2 Use case 18: Pass-through Traffic**

1254 Machines are supplied by machine builders to production cell/line builders in tested and approved  
 1255 quality. At specific boundary ports standard devices (e.g. barcode reader) can be attached to the

1256  
1257  
1258  
1259

machines. The machines support transport of non-stream traffic through the tested/approved machine (“pass-through traffic”) without influencing the operational behavior of the machine, e.g. connection of a printer or barcode reader. Figure 56, Figure 57 and Figure 58 give some examples of pass-through traffic installations in industrial automation.

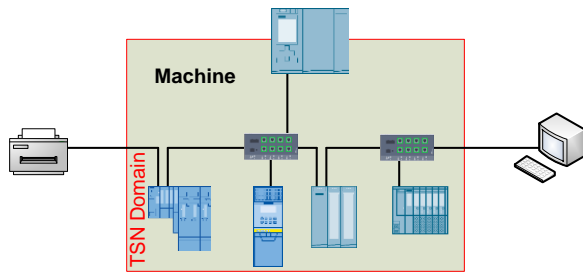


Figure 56 – pass-through one machine

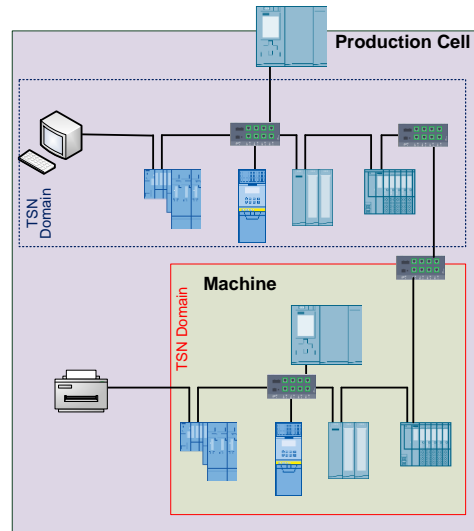


Figure 57 – pass-through one machine and production cell

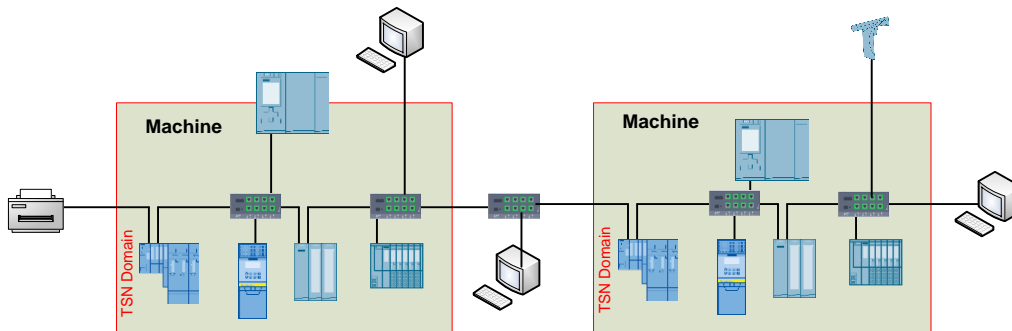


Figure 58 – pass-through two machines

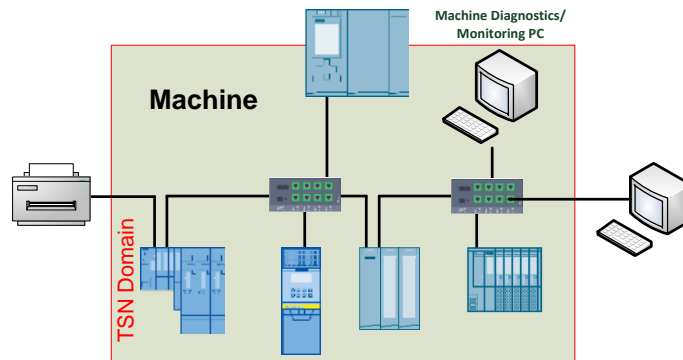


Figure 59 – machine with diagnostics / monitoring PC

1260

Requirement:

1261

All machine internal communication (stream traffic and non-stream traffic) is decoupled from and protected against the additional “pass-through” traffic.

1262

“Pass-through” traffic is treated as separate traffic pattern.

1263

1264  
1265

### Useful 802.1Q mechanisms:

- 1266
- Priority Regeneration,
  - 1267 • separate "pass-through traffic queue",
  - 1268 • Queue-based resource allocation in all bridges,
  - 1269 • Ingress rate limiting.
- 1270

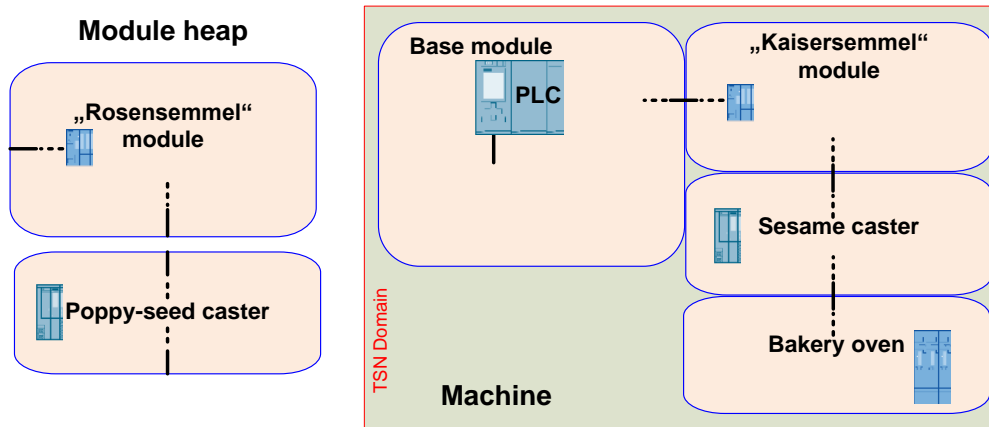
### 1271 **3.8.3 Use case 19: Modular machine assembly**

1272 In this use case machines are variable assemblies of multiple different modules. Effective  
1273 assembly of a machine is executed in the plant dependent on the current stage of production, e.g.  
1274 bread-machine with the modules: base module, 'Kaisersemmel' module, 'Rosensemmel' module,  
1275 sesame caster, poppy-seed caster, baking oven OR advertisement feeder for newspapers.

1276 Figure 60 may have relaxed latency requirements, but the machine in Figure 61 needs to work with  
1277 very high speed and thus has very demanding latency requirements.

1278

1279

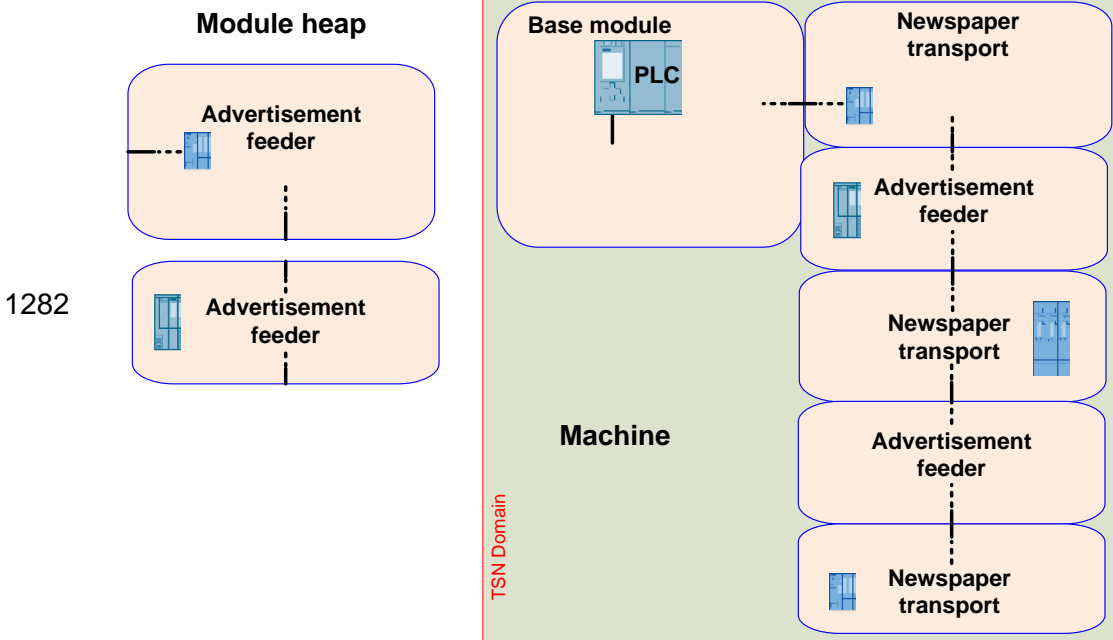


1280

**Figure 60 – modular bread-machine**

1281





1282

1283

Figure 61 – modular advertisement feeder

1284

Requirement:

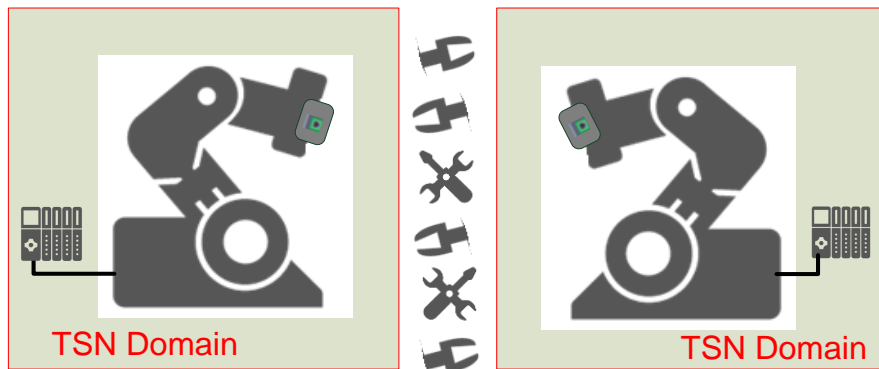
1285 Modules can be assembled to a working machine variably on-site (either in run, stop or power  
1286 down mode) as necessary (several times throughout a day). The machine produces the selected  
1287 variety of a product. Communication relying on TSN features is established automatically after the  
1288 modules are plugged without management/ configuration interaction.  
1289

1290 **3.8.4 Use case 20: Tool changer**

1291 Tools (e.g. different robot arms) are in power off mode. During production a robot changes its arms  
1292 for different production steps.

1293 They get mechanically connected to a robot arm and then powered on. The time till operate  
1294 influences the efficiency of the robot and thus the production capacity of the plant. Robots may  
1295 share a common tool pool. Thus the “tools” are connected to different robots during different  
1296 production steps.

1297



1298

Figure 62 – tool changer

1299

1300

Requirement:

1301

- Added portion of the network needs to be up and running (power on to operate) in less than 500ms.

1302

1303

- Extending and removing portions of the network (up to 16 devices) in operation

1304

- by one connection point (one robot using a tool)

1305

- by multiple connection points (multiple robots using a tool)

1306

1307

Useful 802.1Q mechanisms:

1309

- preconfigured streams

1310

- ...

1311

**3.8.5 Use case 21: Dynamic plugging and unplugging of machines (subnets)**

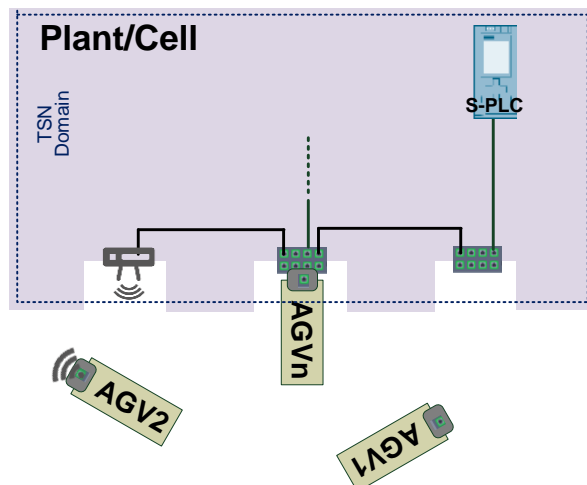
1312

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

1313

1314

1315



1316

**Figure 63 – AGV plug and unplug**

1317

Requirement:

1319

The traffic relying on TSN features from/to AGVs is established/removed automatically after plug/unplug events.

1320

1321

Different AGVs may demand different traffic layouts.

1322

The time till operate influences the efficiency of the plant.

1323

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

1324

1325

1326

Useful 802.1Q mechanisms:

1328

- preconfigured streams

1329

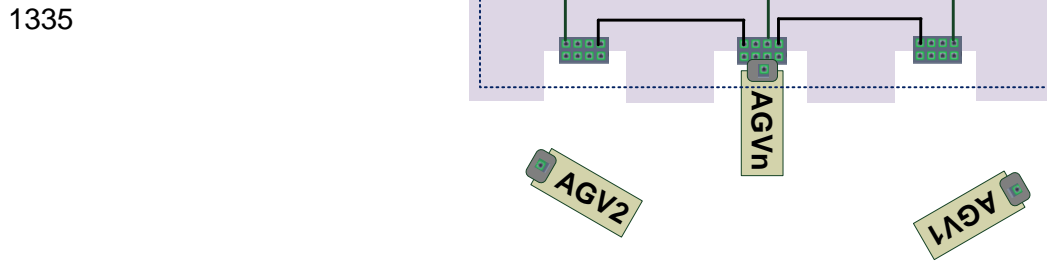
- ...

1330

1331

1332 **3.8.6 Use case 22: Energy Saving**

1333 Complete or partial plant components are switched off and on as necessary to save energy. Thus,  
1334 portions of the plant are temporarily not available.



1336 **Figure 64 – energy saving**

1337 Requirement:

1338 Energy saving region switch off/on shall not create process disturbance.

1339 Communication paths through the energy saving area between end-stations, which do not belong  
1340 to the energy saving area, shall be avoided.

1341

1342 Useful 802.1Q mechanisms:

- 1343 • Appropriate path computation by sorting streams to avoid streams passing through energy  
1344 saving region.

1345 **3.8.7 Use case 23: Add machine, production cell or production line**

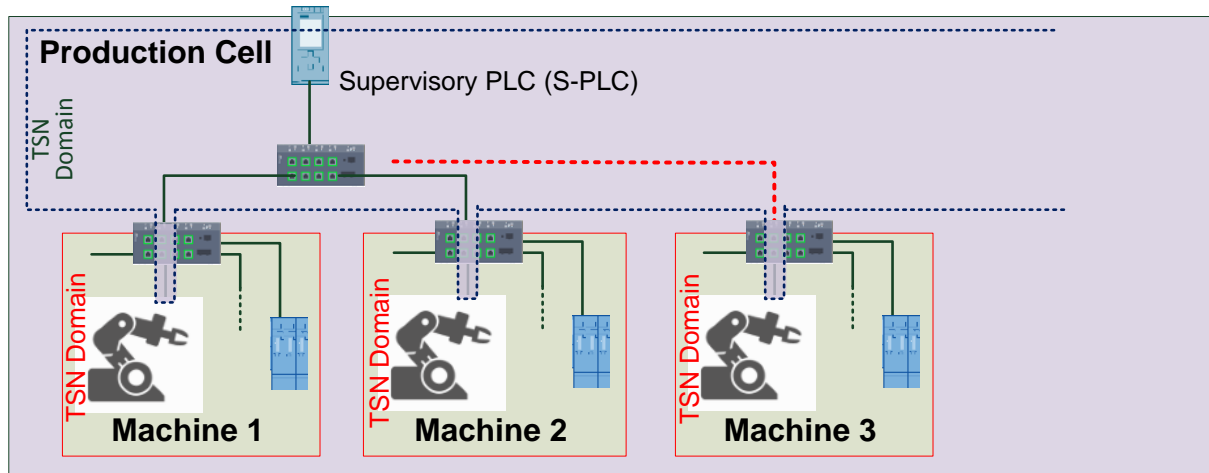
1346 When production capacity is exhausted, additional machines, production cells or even production  
1347 lines are bought and integrated into a plant.

1348 E.g. an additional welding robot is added to a production cell to increase production capacity. The  
1349 additional machine has to be integrated into the production cell control with minimal disturbance of  
1350 the production cell process.

1351

1352 Another aspect is when a machine or a group of machines is tested in a stand-alone mode first  
1353 before it is used in the combination with other machines or in combination with a supervisory  
1354 system.

1355 A flexible cell communication is needed to support this. Enabling and disabling of cell  
1356 communication within a machine should be possible with minimal impact on production.



1357

1358

Figure 65 – add machine

1359

Requirement:

1360 Adding and removing a machine/cell/production line shall not disturb existing installations

1361

1362

Useful mechanisms:

1363

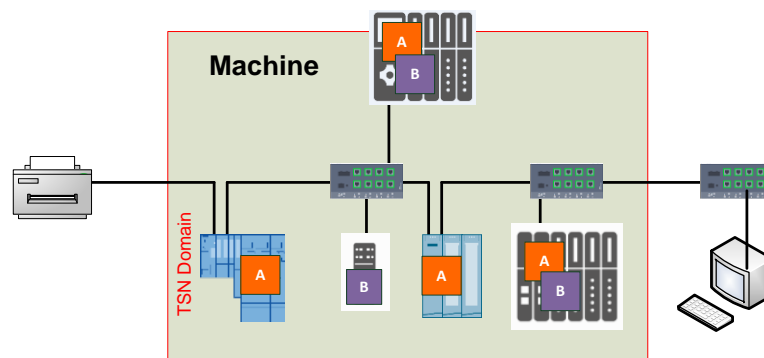
- ...

1364

1365 **3.8.8 Use case 24: Multiple applications in a station using the TSN-IA profile**

1366 Technology A and B are implemented in PLC and devices.

1367



1368

Figure 66 – two applications

1369

1370 Requirement:

1371 Stations with multiple applications using TSN traffic classes shall be supported.

1372

1373

Useful 802.1 mechanisms:

1374

- ...

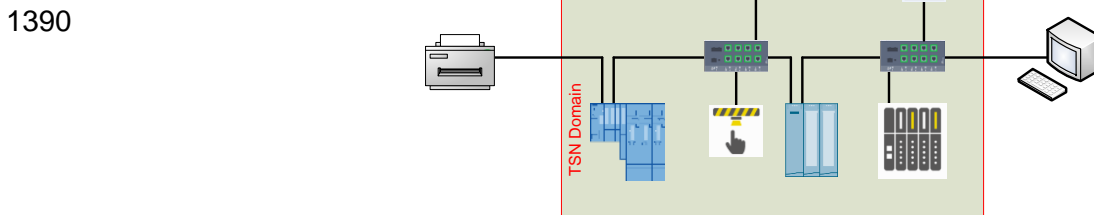
### 1375 3.8.9 Use case 25: Functional safety

1376 Functional safety is defined in IEC 61508 as “*part of the overall safety relating to the EUC*  
 1377 *[Equipment Under Control] and the EUC control system that depends on the correct functioning of*  
 1378 *the E/E/PE [electrical/electronic/programmable electronic] safety-related systems and other risk*  
 1379 *reduction measures”*

1380  
 1381 IEC 61784-3-3 defines a safety communication layer structure, which is performed by  
 1382 a standard transmission system (black channel), and an additional safety transmission protocol on  
 1383 top of this standard transmission system.

1384  
 1385 The standard transmission system includes the entire hardware of the transmission system and the  
 1386 related protocol functions (i.e. OSI layers 1, 2 and 7).

1387  
 1388 Safety applications and standard applications are sharing the same standard communication  
 1389 systems at the same time.



1391 **Figure 67 – Functional safety with cyclic real-time**

1392  
 1393 Requirement:

1394 Safety applications (as black channel) and standard applications share the same TSN-IA profile  
 1395 based communication system at the same time.

1396  
 1397 Useful 802.1 mechanisms:

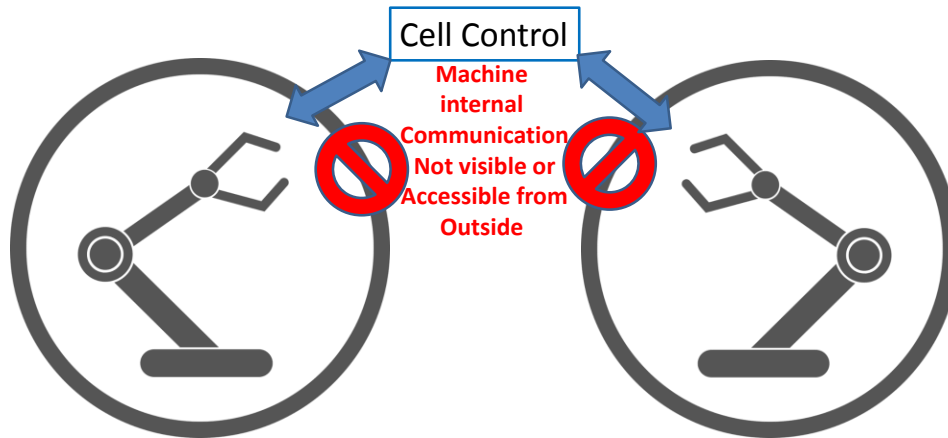
- 1398 • ...

### 1399 3.8.10 Use case 26: Machine cloning

1400 The machines used in a cell can be identical but with a different task. Robots are a typical example  
 1401 of that kind of machines (see Figure 68). Thus, both machines have the same internal  
 1402 communication flows. The difference is just different machine identification for the external flow.

1403 The concept as of today is that the machine internal configuration has its identification and the cell  
 1404 system has its configuration but there is no dependency between both. The machine internal setup  
 1405 is done earlier and the cell identification is a result from a different configuration step and is done  
 1406 by a different organizational unit. Thus, it is difficult to propagate the cell level identification at the  
 1407 very beginning to the machine internal components. A worst case scenario is the startup of a  
 1408 machine and the connection to a cell in an ad hoc way with identification of the machine by the  
 1409 globally unique MAC address of the machine and the resolution of other addresses within the cell  
 1410 controller or above (e.g. for allocation of IP addresses). If there is a need to communicate with a

1411 few field device within the machine in a global way the machine subsystem has to be configured  
 1412 accordingly in advance. This configuration step could be done by a different organization as the  
 1413 stream configuration and not all machine internal elements may require a global address.



1414

1415 **Figure 68 – Machine internal communication with isolated logical infrastructure**

1416

#### Requirements:

- 1417 • TSN domains with unique addressing within the TSN domains;
- 1418 • Unique TSN domain identification (e.g. using LLDP) also for cloned machines;
- 1419 • Define handling of specific addresses (e.g. IP addresses) for global identification and how  
 1420 they are managed within the machine set-up procedures;

1421

#### Useful 802.1 mechanisms:

- 1422 • IEEE 802.1Q (usage of streams)
- 1423 • IEEE 802.1 support for isolation is VLAN

1424

## 3.9 DCS Reconfiguration

1425

### 3.9.1 Challenges of DCS Reconfiguration Use Cases

1426 The challenge these use cases bring is the influence of reconfiguration on the existing  
 1427 communication: all has to happen without disturbances to the production!

1428

1429 We consider important the use case that we can connect any number of new devices wherever in  
 1430 the system and they get connectivity over the existing infrastructure supporting TSN features  
 1431 without a change to the operational mode of the system.

1432

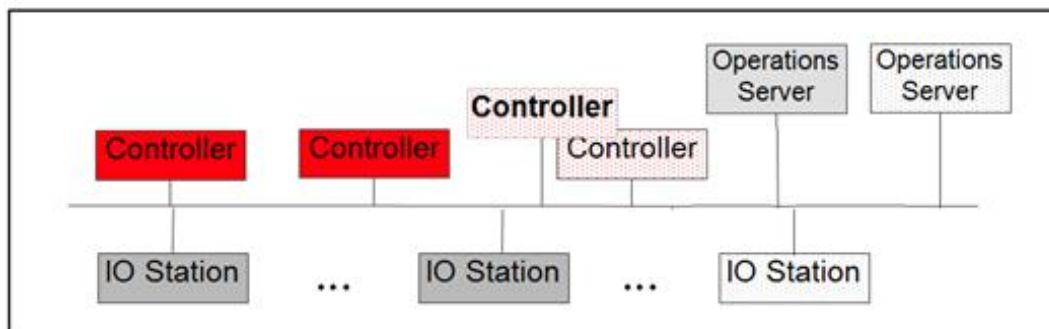
### 3.9.2 Use case 27: DCS Device level reconfiguration

1433 The structure shown in **Error! Reference source not found.** applies. Figure 69 provides a logic  
 1434 station view.

1435

- 1435 • SW modifications to a device
  - 1436 - A change to the device's SW/SW application shall happen, which does not require changes  
 1437 to the SW/SW application running on other devices (incl. firmware update).
- 1438 • Device Exchange/Replacement

- 1439 - The process device is replaced by another unit for maintenance reason, e.g. for off-process  
 1440 calibration or because of the device being defective (note: a “defective device may still be  
 1441 fully and properly engaged in the network and the communication, e.g. if just the sensor is  
 1442 not working properly anymore).
- 1443 - Use case: repair.
- 1444 • Add/remove additional device(s)
- 1445 - A new device is brought to an existing system or functionality, which shall be used in the  
 1446 application, is added to a running device, e.g. by enabling a SW function or plugging in a  
 1447 new HW-module. Even though the scope of change is not limited to a single device  
 1448 because also the other device engaged in the same application.
- 1449 - For process devices, servers: BIOS, OS and applications updates, new VMs, workstations.
- 1450 - Use cases: replacement with upgrade/downgrade of an existing device, simply adding new  
 1451 devices, removal of device, adding connections between devices.
- 1452 • Influencing factors relative to communication
- 1453 - Communication requirements of newly added devices (in case of adding)
- 1454 - Existing QoS parameters (i.e. protocol-specific parameters like TimeOuts or Retries)
- 1455 - Device Redundancy
- 1456 - Network/Media Redundancy
- 1457 - Virtualization
- 1458 - For servers: in-premise or cloud
- 1459 - Clock types in the involved process devices
- 1460 - Universal time and working clock domains
- 1461 - Cycle time(s) needed by new devices
- 1462 - Available bandwidth
- 1463 - Existing security policies



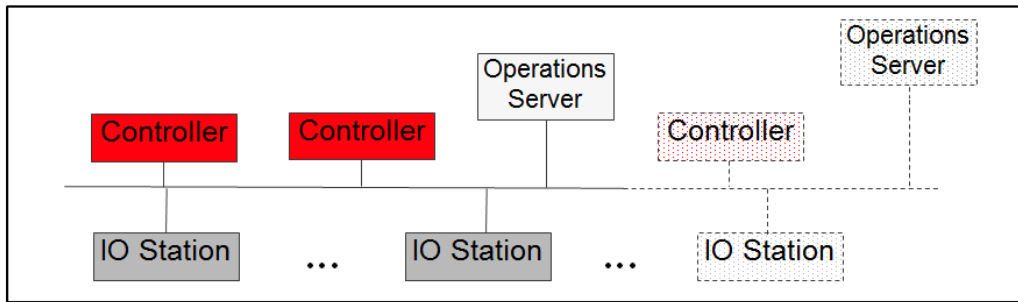
1464  
 1465 **Figure 69 – Device level reconfiguration use cases**

1466 **3.9.3 Use case 28: DCS System level reconfiguration**

1467 The structure shown in **Error! Reference source not found.** applies. Figure 70 provides a logic  
 1468 station view.

- 1469 • Extend an existing plant
- 1470 - Add new network segment to existing network
- 1471 - Existing non-TSN / Newly added is TSN
- 1472 - Existing TSN / Newly added is TSN
- 1473 • Update the system security policy
- 1474 - [New key lengths, new security zones, new security policy]

- 1475 - To be defined how and by whom to be handled
- 1476 • Influencing factors
- 1477 - Same as for “device-level”



1478  
1479 **Figure 70 – System level reconfiguration use cases**

1480 **3.10 Further Industrial Automation Use Cases**

1481 **3.10.1 Use case 29: Network monitoring and diagnostics**

1482 Diagnostics plays an important role in the management of systems and of devices. Industrial  
1483 automation requires a method for quick reaction to failures. The error reaction shall limit the  
1484 damage caused by the error and minimize the machine downtime.

1485 The error detection shall be done within a few cycles (exact value is depending on the application)  
1486 and reaction shall be specified precisely in the case of an error. Machine stop is not always the  
1487 right reaction on errors. This reaction can be located at the talker and listener.

1488 Repairs are done by the service persons on site which have no specific communication knowledge.  
1489 The indication of the components which have to be repaired shall occur within a few seconds.  
1490 Machines are powered down during the repair. A typical repair time goal is below 15 min. This  
1491 includes the restart of a machine and the indication that the problem is solved.

1492 Generally speaking the mechanisms used in this context are acyclic or having large cycle times so  
1493 that they could perhaps be considered, from a networking perspective as sporadic. Most of the use  
1494 cases related to diagnostics will be included in this category.

- 1495 - Quick identification of error locations is important to minimize downtimes in production (see  
1496 also Sequence of events).
- 1497 - Monitoring network performance is a means to anticipate problems so that arrangements can  
1498 be planned and put into practice even before errors and downtimes occur.
- 1499 - Identification of devices on an industrial Ethernet network shall be done in a common,  
1500 interoperable manner for interoperability on a converged TSN network. This identification both  
1501 needs to show the type of device, and the topology of the network. IEEE 802.1AB, the Link  
1502 Layer Discovery Protocol (LLDP), provides one possible mechanism for this to be done at layer  
1503 two, but provides a large degree of variability in implementation.

1504 Requirement:

- 1505 • Minimize downtime;
- 1506 • Monitoring and diagnostics data including used TSN features shall be provided, e.g.  
1507 established streams, failed streams, stream classes, bandwidth consumption, ...;



- 1508       • A discovery protocol such as IEEE 802.1AB shall be leveraged to meet the needs of TSN-  
1509       IA;  
1510       • Reporting of detailed diagnostics information for TSN features shall be supported.

1511  
1512   Useful 802.1 (ietf) mechanisms:

- 1513       • MIBs (SNMP)  
1514       • YANG (NETCONF/RESTCONF)  
1515       • ...  
1516

### 1517   **3.10.2 Use case 30: Security**

1518   Industrial automation equipment can become the objective of sabotage or spying.

1519   Therefore all aspects of information security can be found in industrial automation as well:

- 1520       • Confidentiality "is the property, that information is not made available or disclosed to  
1521       unauthorized individuals, entities, or processes."  
1522       • Integrity means maintaining and assuring the accuracy and completeness of data.  
1523       • Availability implies that all resources and functional units are available and functioning  
1524       correctly when they are needed. Availability includes protection against denial-of-service  
1525       attacks.  
1526       • Authenticity aims at the verifiability and reliability of data sources and sinks.

1527  
1528   Requirement:

1529   Optional support of confidentiality, integrity, availability and authenticity.

1530   Security shall not limit real-time communication

1531

1532   Protection against rogue applications running on authenticated stations are out of scope.

1533  
1534   Useful mechanisms:

- 1535       • 802.1X  
1536       • IEC62443  
1537       • ...

### 1538   **3.10.3 Use case 31: Firmware update**

1539   Firmware update is done during normal operation to make sure that the machine e.g. with 1000  
1540   devices is able be updated with almost no down time.

1541

1542   With bump: separate loading (space for 2 FW versions required) and coordinated activation to  
1543   minimize downtime

1544

1545   Bumpless: redundant stations with bumpless switchover – the single device may lose connection  
1546   (bump)

1547

1548   Requirement:

1549   Stations shall be capable to accept and store an additional fw version without disturbance.

1550

1551   Useful 802.1 mechanisms:

- 1552       • ...

1553 **3.10.4 Use case 32: Virtualization**

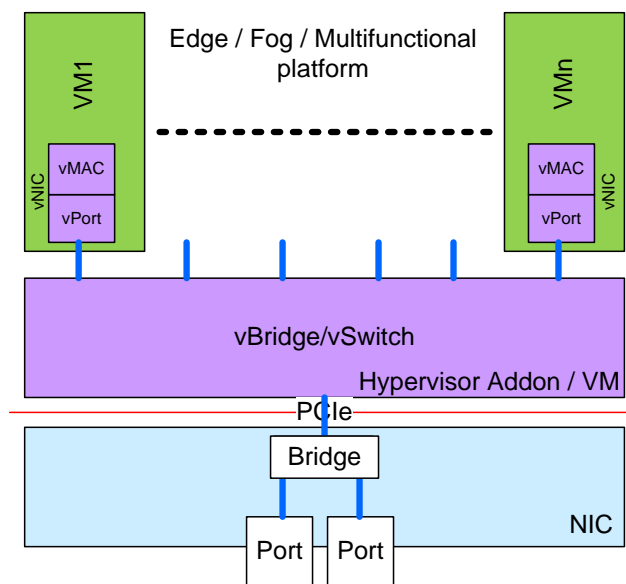
1554 Workload consolidation is done by virtualizing the hardware interfaces. Even in such kind of  
 1555 environment the TSN features according to the TSN-IA profile shall be available and working.

1556

1557 **vSwitch / vBridge**

1558

1559 Figure 71 and Figure 72 show the two principle setups for an Ethernet communication concept  
 1560 allowing both, communication VM to Ethernet and VM to VM. The applications inside the VM shall  
 1561 not see, whether they communicate to another VM or an Ethernet node.



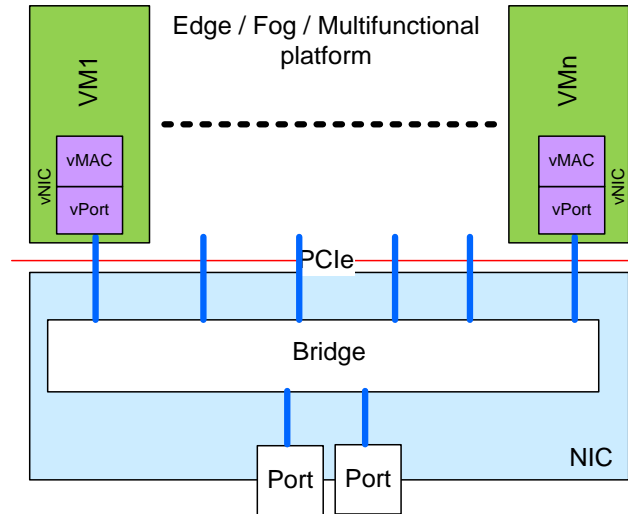
1562

1563

**Figure 71 – Ethernet interconnect with VM based vBridge**

1564

1565 Figure 71 scales for an almost infinite amount of VMs, because the memory bandwidth and the  
 1566 compute power of the vMAC/vPort and vSwitch/vBridge VM are much higher than the PCIe  
 1567 bandwidth to the NIC.



**Figure 72 – Ethernet interconnect with PCIe connected Bridge**

Figure 72 fits for a limited amount of VMs, because it saves the additional vSwitch/vBridge VM. For a given amount of VMs, e.g. PCIe Gen3 x4 or Gen4 x4, seems to be sufficient.

Requirement:

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

Useful 802.1 mechanisms:

- ...

**3.10.5 Use case 33: Offline configuration**

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

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

1599 Another parameter for real time communication is the quality of time synchronization which  
 1600 depends upon several parameters of the components used in the synchronization path. YANG  
 1601 models of IEEE 802 components may be suitable for that purpose as offline database for individual  
 1602 bridge components and for the IEEE 802 network. It is not necessary for a machine configurator to  
 1603 handle the YANG related protocols but use the models. YANG means a completely different  
 1604 language as used today and implies two databases and some transformation and consistency  
 1605 issues between the two descriptive units. Thus, it is recommended to provide a mapping between  
 1606 XML and YANG.

1607 Requirements:

- 1608 • Device type description of IEC/IEEE 60802 components containing all necessary managed
- 1609 objects needs to be defined
- 1610 • Means to store machine configuration offline in a textual form (e.g. XML);
- 1611 • Offline - Online comparison of machine configuration shall be supported;
- 1612

1613 Useful 802.1 mechanisms:

- 1614 • IEEE 802.1 YANG models;
- 1615

### 1616 **3.10.6 Use case 34: Digital twin**

1617  
 1618 Virtual pre-commissioning of machines can save a lot of time and money.  
 1619 Up to 30 % time-saving in the development of new machines are foreseen by an increased  
 1620 engineering efficiency due to the implementation and usage of digital twins.  
 1621 Faster development, delivery and commissioning of new machines at customer locations should be  
 1622 possible.

1623 A digital twin shows the real machine in as much detail as possible and allows simulation of its  
 1624 operation. With the help of digital twins machines can gradually and virtually be developed – in  
 1625 parallel to the real production and commissioning process of the machines at customer locations.

1626  
 1627 Requirement:

1628 Reliable planning, development, testing, simulation and optimization results shall be possible

1629  
 1630 Useful 802.1 mechanisms:

- 1631 • ...

### 1632 **3.10.7 Use case 35: Device replacement without engineering**

1633 Any device in a plant, i.e. end-station, bridged end-station or bridge, may get broken eventually. If  
 1634 this happens fast and simple replacement of a broken device is necessary to keep production  
 1635 disturbance at a minimum (see also: 3.9.2 Use case 27: DCS Device level reconfiguration).  
 1636 Support of “mechanical” replacement of a failed device with a new one without any engineering  
 1637 effort (i.e. without the need for an engineering tool) is a prerequisite for minimal repair downtime.

1638  
 1639 Requirement:

1640 In case of repair it shall be possible to replace end-stations, bridged end-stations or brides without  
 1641 the need of an engineering tool.

1642  
 1643 Useful 802.1 mechanisms:

- 1644 • ...

1645

1646

## Abbreviations

AGV	Autonomous Guided Vehicle
CCTV	Closed Circuit Television
DCS	Distributed Control System
FW	Firmware
PA	Process Automation

1647

1648

1649

1650

## Literature and related Contributions

1651

Literature:

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1661

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