5G-ACIA White Paper

Integration of 5G with Time-Sensitive Networking for Industrial Communications

5G Alliance for Connected Industries and Automation

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2 Executive Summary

Fifth-generation wireless communications (5G) and time-sensitive networking (TSN) technologies are key to future industrial communications: 5G for wireless connectivity and TSN for wired connectivity. Both technologies have been designed to provide converged communication for a wide range of services on a common network infrastructure, including for time-sensitive applications that require deterministic, reliable and low-latency communications. Significant benefits can be achieved for corresponding industrial use cases by introducing TSN and 5G wireless communication, e. g., increased flexibility in the deployment of industrial equipment and the network.

This paper identifies the requirements of these applications, and describes the functional capabilities needed to seamlessly integrate 5G with TSN. The paper also provides brief overviews of the 5G and TSN functions needed to support time-sensitive applications. 3GPP specified 5G support for TSN in Release 16, with further enhancements in Release 17, to allow seamless integration of a 5G system (5GS) with TSN networks. In integrated networks of this type, a 5G system will simply be perceived as IEEE-compliant virtual Ethernet-TSN bridges.

This white paper describes and examines integration of 5G with TSN for typical industrial use cases, namely controller-to-controller, controller-to-device and device-to-compute communications. The paper shows that 5G, as specified in Release 16 and 17, provides all functionality needed for integration with TSN for industrial automation.

IEEE TSN standardization is evolving, and specification of a TSN profile for industrial automation is currently under development. It is important that the 5G standard remains aligned with this evolution of TSN.

About 5G-ACIA

The 5G Alliance for Connected Industries and Automation (5G-ACIA) was established to serve as the central and global forum for addressing, discussing, and evaluating relevant technical, regulatory, and business aspects with respect to 5G for the industrial domain.

It reflects the entire ecosystem and all relevant stakeholder groups, including the operational technology (OT) industry (industrial automation companies, engineering companies, pro- duction system manufacturers, end users, etc.), the ICT industry (chip manufacturers, net- work infrastructure vendors, mobile network operators, etc.), academia, research institutes, and other relevant players.

The paramount objective of 5G-ACIA is to ensure the best pos- sible applicability of 5G technology and 5G networks to the industrial domain. 5G-ACIA's mission is to make sure the interests and needs of the industrial domain are adequately considered in 5G standardization and regulation and that ongoing 5G developments are understood by and effectively transferred to the industrial domain.

3 Introduction

This white paper looks at the standards specified for 5G by 3GPP and the standards specified for TSN by IEEE and describes how these two standardized technologies can be integrated for industrial communication.

Time-sensitive networking (TSN) [17] is a set of novel open standards that provide deterministic, reliable, high-bandwidth, low-latency communication; it is envisioned as the future-proof wired technology for convergent industrial communication, e. g., for Industry 4.0 and smart factories. Interworking of 5G with TSN is seen as a major objective in order to make 5G suitable for future Industrial Internet of Things (IIoT) solutions. 3GPP has performed significant 5G standardization work in this area, i. e., with the introduction of specifications for ultra-reliable and low-latency communication (URLLC) from Release 15, and support for TSN in Release 16; 3GPP is continuing this work in Release 17. 5G standardization work for IIoT includes understanding how TSN is applied in a smart factory environment, what kind of integration and interactions with 5G are envisioned, and what functionality is required by a 5GS. The relationship between network slicing and 5G integration with TSN is beyond the scope of this paper.

This white paper describes why and how 5G will be applied in industrial networks together with TSN and what interactions between 5G and TSN are needed. It takes as its baseline the 5G specifications in 3GPP Release 16 but also the functionality for specification of TSN support that is currently ongoing in Release 17. For TSN, the baseline is the IEEE standards up to 2020. However, the ongoing work in IEC/IEEE 60802 on an industrial automation profile for TSN is also considered to some extent.

The next section describes drivers for the introduction of TSN and 5G into industrial automation. Sections 5 and 6 present IEEE TSN standards and describe how they are applied in factory environments. 5G support for TSN is described in section 7. Section 8 explains how 5G can be integrated with TSN in an industrial deployment.

4 Digital transformation as the driver of TSN and 5G connectivity in automation

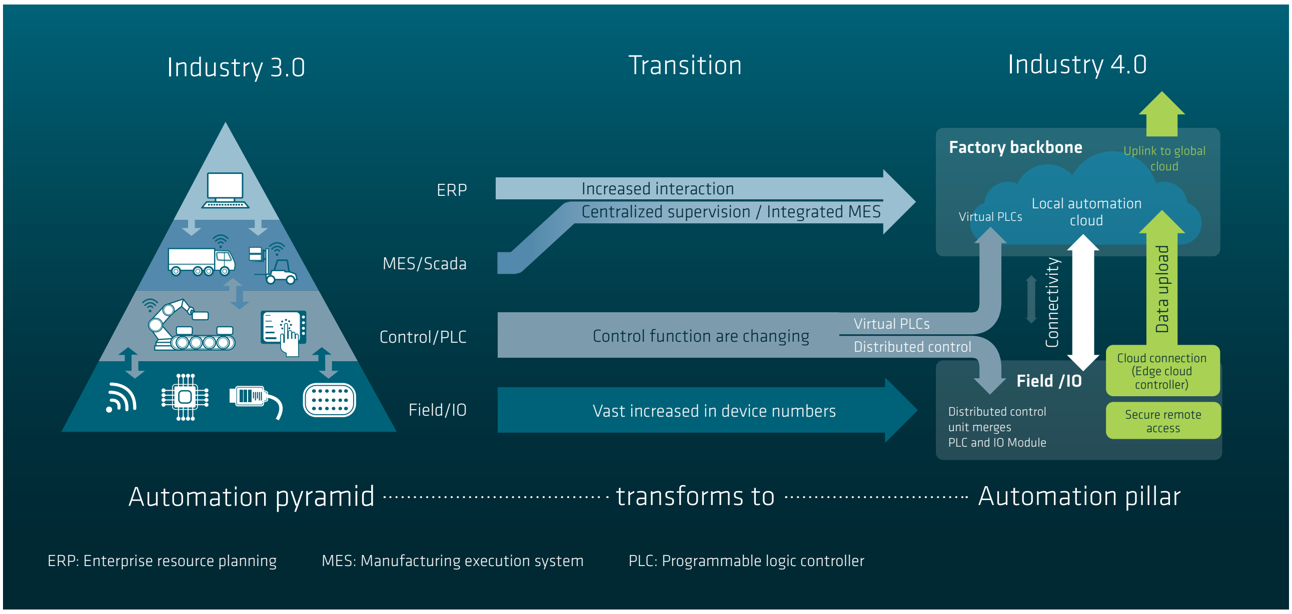
Digital transformation is creating disruptive change in all sectors [24]. By interconnecting multiple devices, information is no longer constrained locally but accessible from anywhere. The fourth industrial revolution will apply digital transformation to industrial production via enterprise-wide networks to capture data from and to exchange data between machines, devices and people [25]. By using the Internet of Things (IoT) and cyber physical systems, conventional production will be transformed into a network of smart and interconnected devices. These systems can improve flexibility, versatility, usability and efficiency of future manufacturing [26]. By using larger networks, production cells will evolve into ecosystems sharing information for enhanced decision-making and resource-efficient production. Further, rapid communication between devices, factories and suppliers will increase flexibility, enabling mass customization to meet customer requirements in terms of quantity, quality, design and configuration.

These smart production systems rely on enterprise-wide communication. For industrial use cases, these communication networks need to fulfill certain requirements [25]. In particular, they must guarantee high availability, high throughput, real-time transmission, low latency and low jitter. To meet these requirements, diverse communication technologies have been introduced, such as fieldbuses, e. g., PROFIBUS, and Ethernet-based solutions such as PROFINET or EtherCAT [8][9]. Each of these solutions addresses a particular set of requirements for specific applications. As a result, they are only mutually compatible on the physical layer. This results in a large variety of protocols and hardware on factory shop floors, making the interconnectivity needed for Industry 4.0 difficult to achieve. To overcome this issue, the IEEE 802.1 TSN Ethernet standard family has been introduced for real-time deterministic, enterprise-wide, low-latency industrial communication. In contrast to existing industrial Ethernet protocols, TSN is not only compatible with standard IEEE 802.3 Ethernet on the physical layer but also higher layers; furthermore, it is part of the IEEE 802 standards that specify Ethernet-bridged networks.

In addition to the above-mentioned requirements of industrial use cases, and the need for compatibility, a communication network for Industry 4.0 must also support wireless communication for mobile, rotating and flexible objects. Furthermore, wireless communication systems entail lower installation costs and enable upgrades and modernization of production facilities on a larger scale. The general usage of wireless communication was limited in the past to open-loop control and manufacturing execution system (MES) applications due to the lack of availability, reliability and real-time. The new 5G communication standard aims to meet these requirements for a wide range of field-level applications. Increased throughput, reliability, availability and low energy consumption will enable large-scale industrial usage. The advantages of 5G and the corresponding industrial use cases are described in more detail in [1]. As a result, TSN and 5G in combination offer wireless and wired solutions capable of creating the large real-time network needed for Industry 4.0 applications.

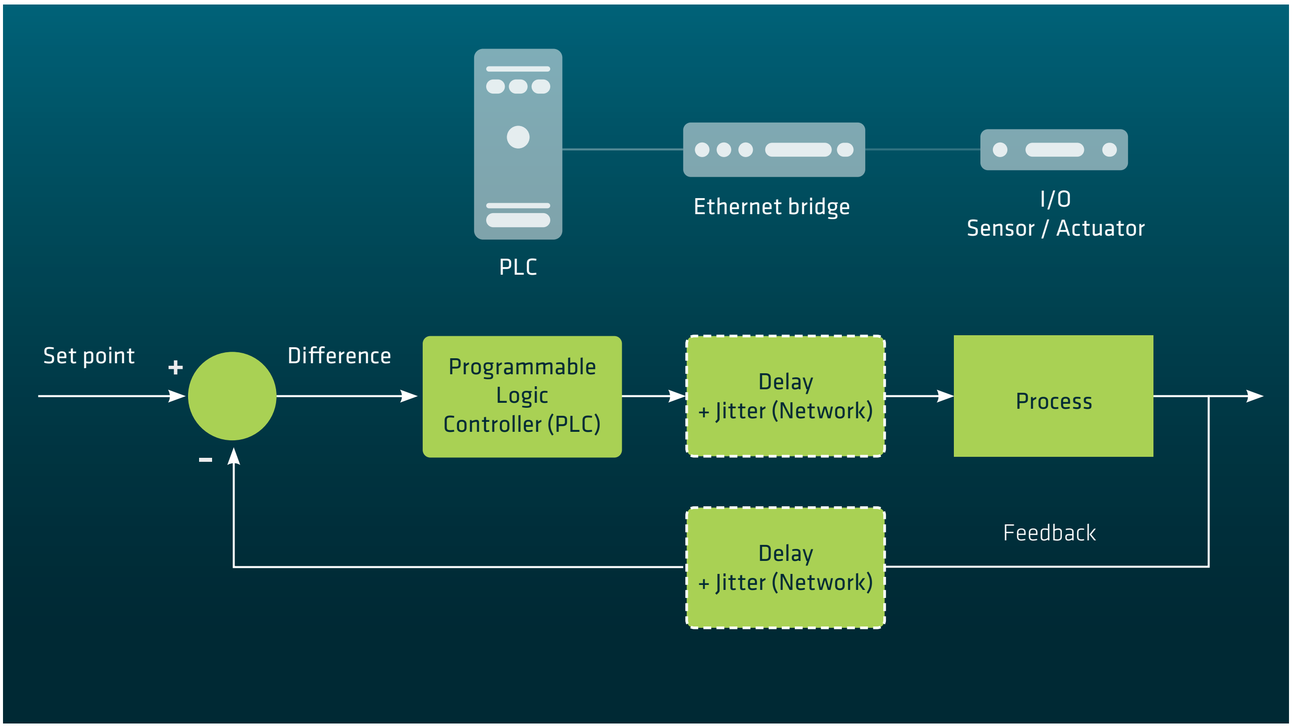
Figure 1 illustrates the transformation of industrial networks from Industry 3.0 to Industry 4.0. The Industry 3.0 automation pyramid focused on high throughput and very efficient machines, including dedicated networks. This was achieved by engineering the entire production line for very specific products with only very little communication with the outside world. This isolation meant that disruptions on one product line did not impact others. Industry 4.0 factories focus on two growing needs: mass customization and efficiency. Customization requires flexible production lines that are able to adapt dynamically using the tools and machines already available. This results in traffic patterns that differ from those of Industry 3.0, and in central storage of process descriptions. The efficiency aspect is similar to what was already required in the past. However, with greater flexibility an idle production line can adapt to execute other production orders, so no machine capacity is underutilized.

Fig. 1: Transformation of Industrial Networks



Source: Time-Sensitive Networking for Dummies [13]

Fig. 2: (Closed) control loop; dashed boxes need to be known in order to integrate them into control loop logic



Source: 5G-ACIA

Dynamic factory scenarios require the convergent usage of communication technologies. As applications vary, the network needs to be prepared for such changes. Using cables also makes dynamic arrangements of production lines difficult.

In a flexible production system, any critical process is typically based on open-loop or closed-loop controls as shown in Figure 2. In systems of this kind the most important requirement is to understand when certain measurements occur. To ensure the deterministic behavior of the control application, the network needs to comply with the corresponding quality of service (QoS) requirements of that control application. QoS in this context is defined by parameters such as jitter and latency. In addition, bandwidth in a converged network is very important. A solution in an Industry 4.0 environment is expected to use standard Ethernet (IEEE 802.3), WLAN (IEEE 802.11) and 5G (3GPP) technologies, combined with enhancements for time-sensitive communication such as the TSN standards specified by IEEE 802.1.

5 TSN standards for industrial automation

TSN is a set of standards specified by IEEE 802 to enable Ethernet networks to give QoS guarantees for time-sensitive and/or mission-critical traffic and applications. The various TSN standards provide differing QoS guarantees. As devices from multiple vendors need to offer mutually compatible functions, profiles such as IEC/IEEE 60802 for Industrial Automation are being defined. These profiles focus on a common set of functions and configurations in order to decrease the complexity which might be created by possible variations in standards.

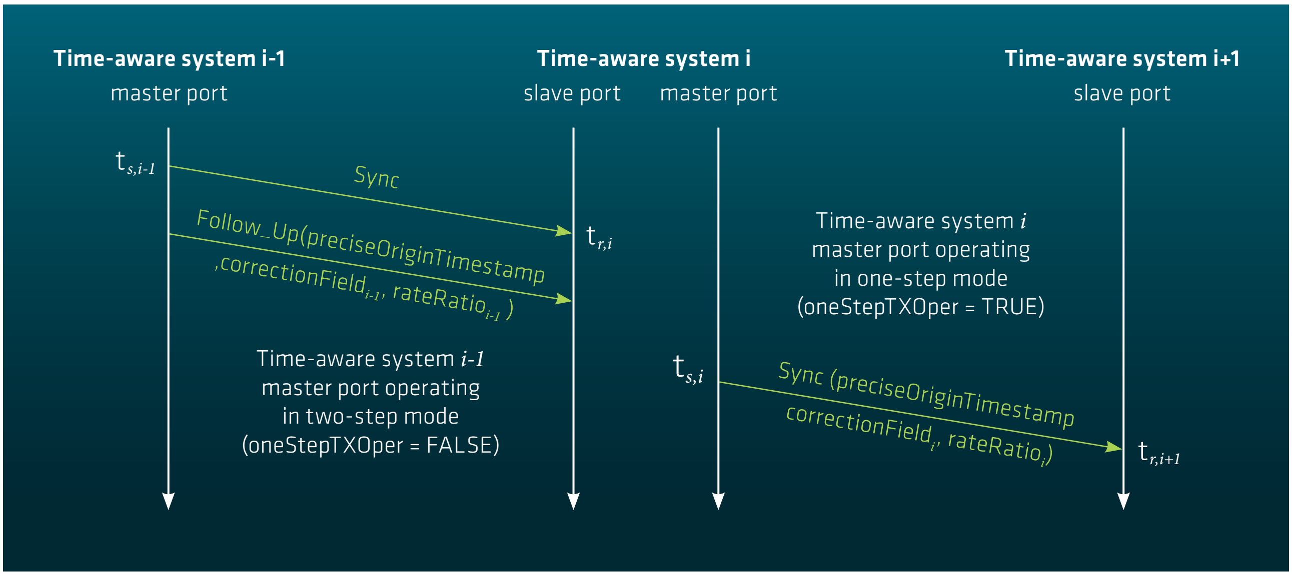
5.1 Synchronization for time-sensitive applications

Time synchronization is crucial to ensuring the deterministic behavior of end-devices. Some TSN mechanisms also require time synchronization. The TSN standard for time synchronization is the IEEE 802.1AS generalized Precision Time Protocol (gPTP) [11], which is a profile of the IEEE 1588 Precision Time Protocol (PTP) [12]; it allows time synchronization over Ethernet only. Clock synchronization is required for specific applications and to support TSN scheduled traffic (IEEE 802.1Qbv) – and may be needed for per-stream filtering and policing (IEEE 802.1Qci), described in section 5.4, ensuring that the bridges and end-stations can operate on a schedule based on a shared understanding of time.

gPTP synchronization is defined in IEEE 1588 [12]: a grandmaster PTP instance sends information, including the current synchronized time, to all directly connected (g)PTP instances, e.g., using Ethernet multicast. Each of these PTP instances must correct the received synchronized time by adding the propagation time needed for the information to transit the gPTP communication path from the grandmaster PTP instance. If the PTP instance is a PTP relay instance, then it must forward the corrected time information (including additional corrections for delays in the forwarding process) to all the other connected PTP instances [11].

Figure 3 shows an example of transmission of time synchronization information for three adjacent time-aware systems. The master port of the first node (i-1) sends "Sync" and "Follow_Up" messages to the PTP instance at time-aware system i at local clock time "ts,i-1". The time-aware system i

Fig. 3: Transmission of time synchronization information



Source: IEEE Standard 802.1AS-2020 [11]

receives the "Sync" message from the first node, and then timestamps the receipt of the message, and the timestamp value is "tr,i". After receiving a "Follow_Up" message, the time-aware system i computes the "correctionField(i)" which includes the residence time of the time-aware system i, and the propagation delay between time-aware system i-1 and i. Finally, the time-aware system i sends a new "Sync" message at time "ts,i", with the recalculated "correctionField(i)".

5.2 Scheduled traffic

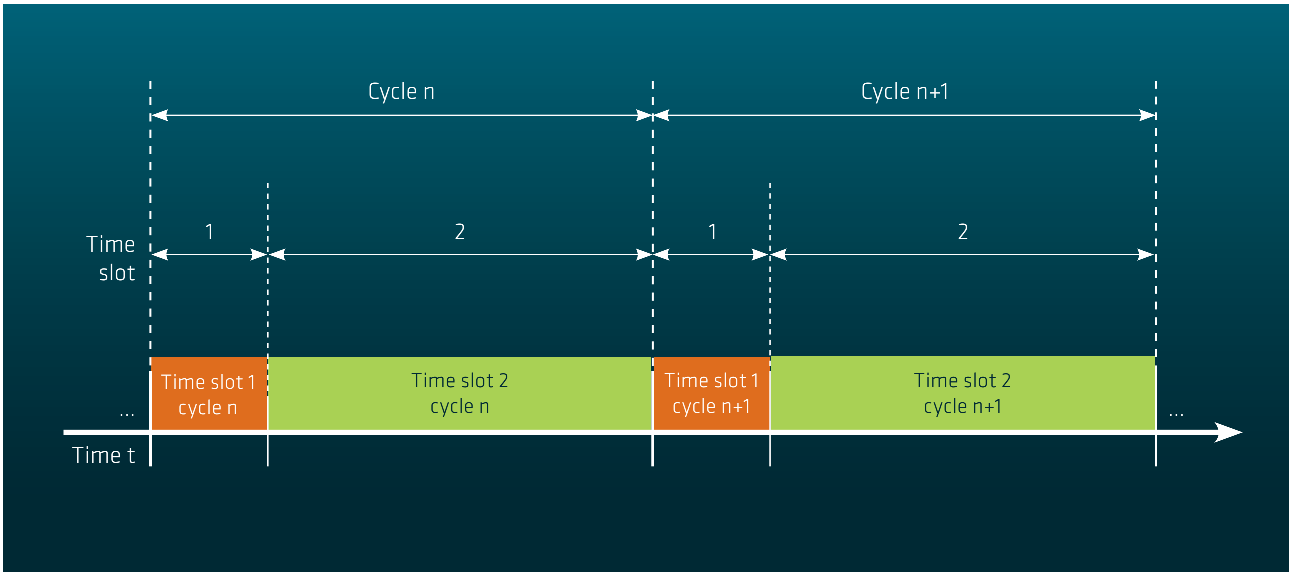
Scheduled traffic provides time-division-based resource allocation for the various traffic classes identified by the priority code point (PCP) field in the VLAN tag of an Ethernet header. Scheduled traffic has been standardized in IEEE 802.1Qbv and has been already included in IEEE 802.1Q [18].

Figure 4 visualizes how time is divided into multiple time slots which repeat cyclically. Within each of these time slots a set of traffic classes can be selected so that this slot is only for transmission of these traffic classes. Packets belonging to other traffic classes remain in their buffers until their traffic class is allowed to be transmitted. This gating mechanism is applied on the egress side of a bridge. If multiple traffic classes are allowed to transmit at the same time, then further transmission selection is applied to them, e. g., strict prioritization. The mechanism of blocking queues in a time-based manner with a gate for each queue is shown in Figure 5.

Figure 6 shows how traffic scheduling is applied throughout the bridged network by coordinating the schedules of the bridges along the paths of the TSN streams. A packet that enters the network can be transmitted in a single flow, without being impeded at any point by another packet.

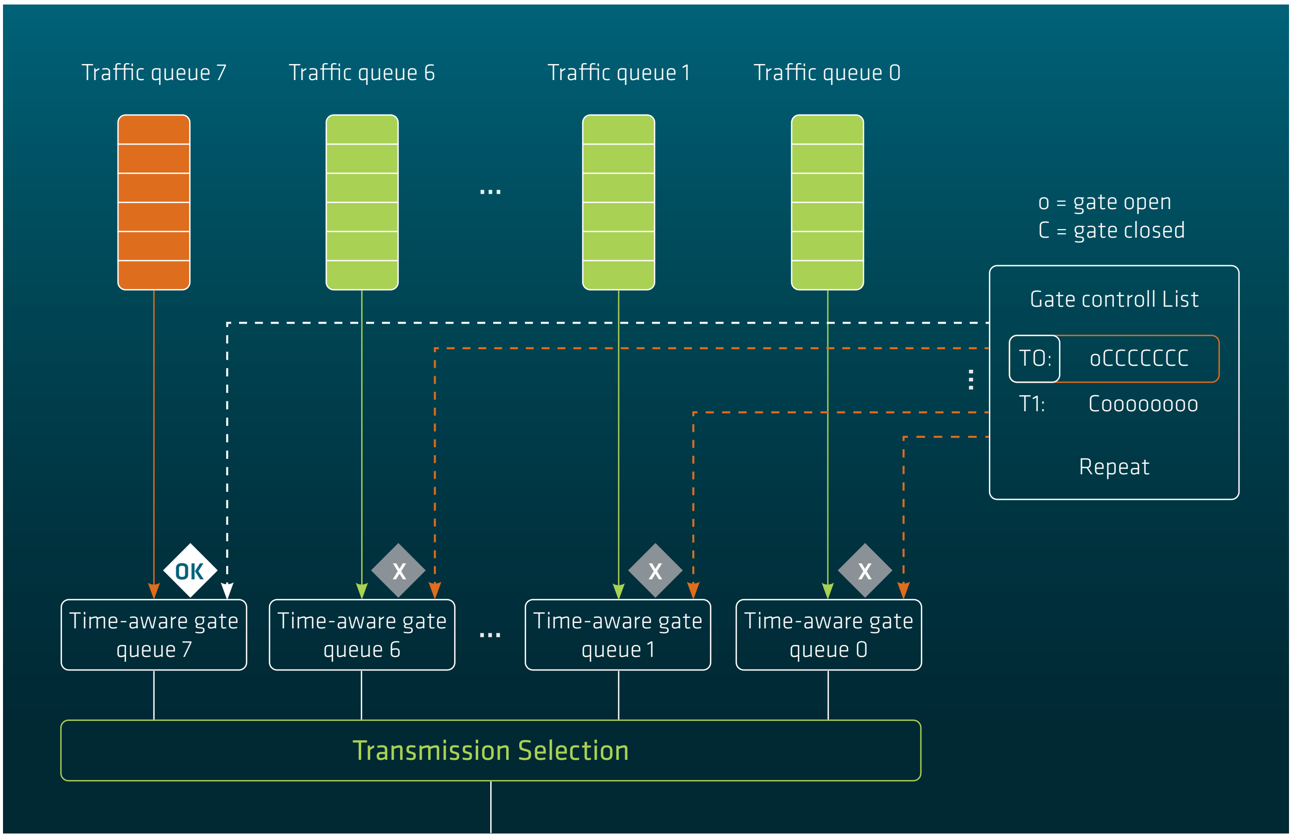
The various packets in Figure 6 are indicated by colors. Blue boxes represent bridges; the egress queues are shown in green with a white arrow pointing to the next hop. Colored bars represent packets of a certain priority and visualize when the corresponding gate is open for the given priority in accordance with the gate control list. For example, as a packet travels along multiple bridges, it will be transmitted later within the cycle. For each direction there is an egress queue, which will only allow the traffic class that is scheduled to transmit at the indicated time slots. The white arrows show

Fig. 4: Cyclical time division with scheduled traffic



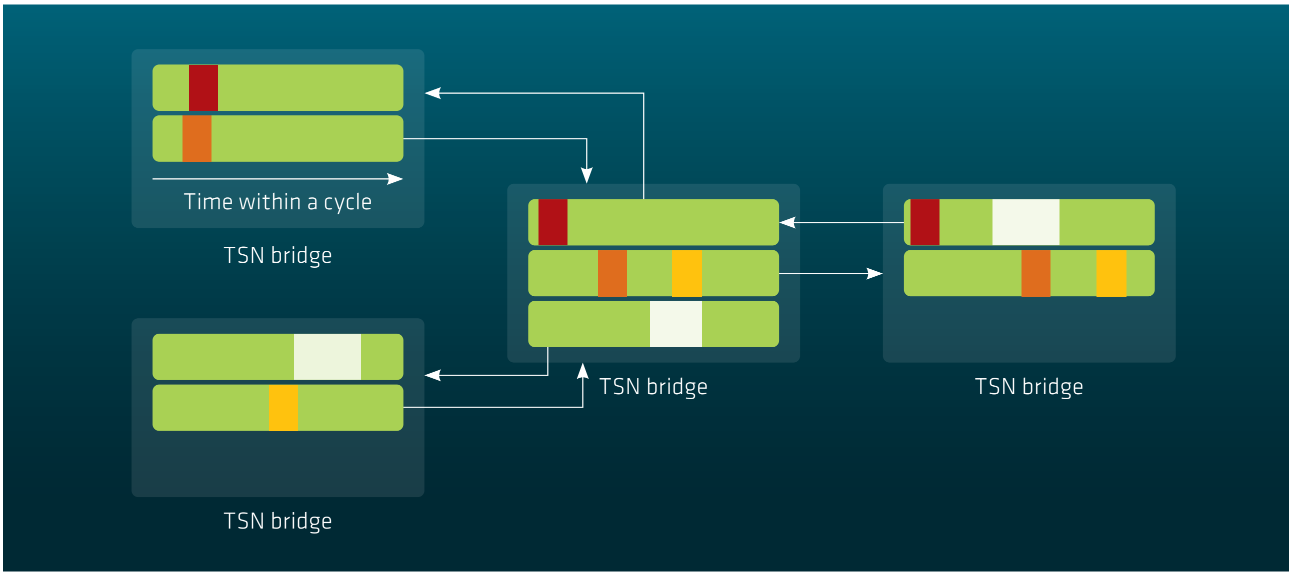
Source: Time Sensitive Networking white paper [16]

Fig. 5: Gate control list that allows transmission of traffic queue 7 only in T0 and all other traffic queues in T1



Source: Time Sensitive Networking white paper [16]

Fig. 6: Schematic network with scheduled traffic



Source: 5G-ACIA

the connection between an egress queue and the next hop. Any other traffic is allowed to be transmitted when there are no marked packets.

5.3 Frame preemption

Certain traffic needs to pass through the network with only minimal interference. Frame preemption specifies how packets of such high-priority traffic can preempt lower-priority traffic in order to decrease interference. Frame preemption can be used in combination with scheduled traffic to decrease interference further. Frame preemption has been standardized in IEEE 802.3br (already incorporated into IEEE 802.3-2018 [19]) and in IEEE 802.1Qbv (already included in IEEE 802.1Q [18]).

5.4 Per-stream filtering and policing

As time-sensitive applications are very susceptible to interfering traffic, these networks have in the past been kept completely isolated from the outside. Converged networks erode this isolation. In order to comply with QoS guarantees, per-stream filtering and policing (PSFP) was standardized in IEEE 802.1Qci (included in IEEE 802.1Q [18]). These mecha- nisms allow the identification and management of non-compliant traffic, such as intentional or unintentional excess bandwidth usage or incorrect prioritization within a given time interval.

IEEE-defined PSFP includes several policing actions, e. g., flow meters can provide data- rate-based policing and stream gates can provide time-based policing [14]. Rate-based policing uses flow meter instances that apply to one or more TSN streams. It specifies parameters such as committed information rate and excess information rate, and these enable the policing of streams that exceed the permitted rate.

Time-based policing is provided by stream gates and requires time synchronization, i. e., bridges, end-stations and the applications need to have a common understanding of time. A stream gate is set to open only for frames during a scheduled arrival time slot. Frames arriving outside a time slot are considered interferences or unwanted frames, and are therefore "dropped", as the gate is already closed. PSFP requires the implementation of stream identification as specified by IEEE 802.1CB.

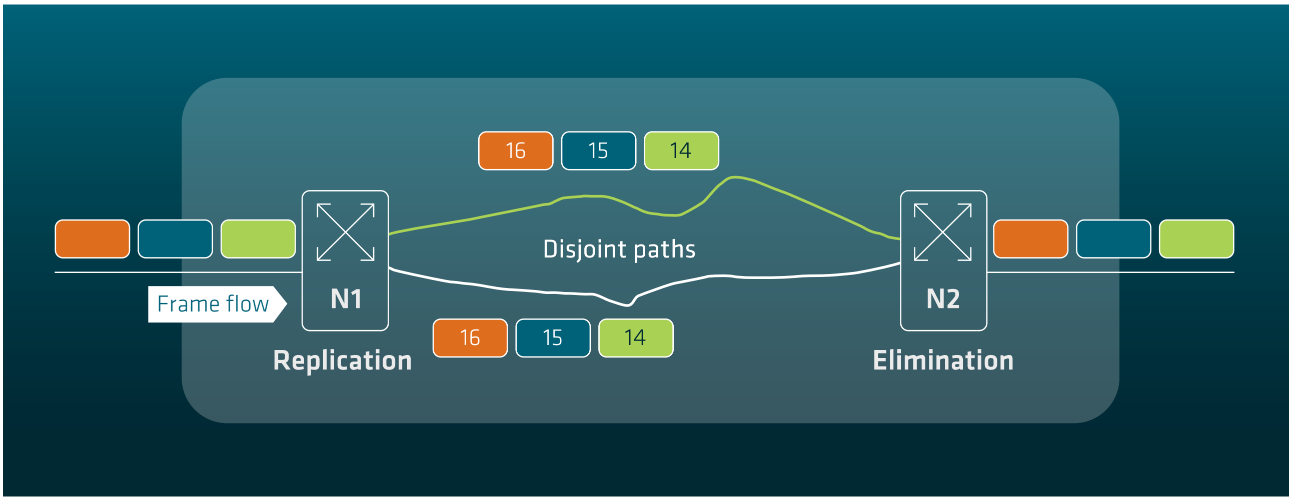
5.5 Frame replication and elimination for reliability

Redundancy is important for critical applications. The IEEE 802.1CB Frame Replication and Elimination for Reliability (FRER) standard [22] defines a mechanism for multiplying packets belonging to a given stream. This mechanism ensures the network will not be overloaded unnecessarily by the duplication of all frames. Also, the detection of duplicates and merging of streams is possible, making redundancy transparent for the application and ensuring redundancy is only within the network. Figure 7 illustrates the concept of FRER. The replication function sends copies of a frame/packet on two (or more) disjoint-routed paths, and the copies are assigned the same sequence number. The elimination function, when receiving the packets, deletes extra frames/packets (based on the sequence number carried in the packet). The replication and elimination function can be either at the end- stations or at various bridges of the network.

5.6 TSN for industrial automation

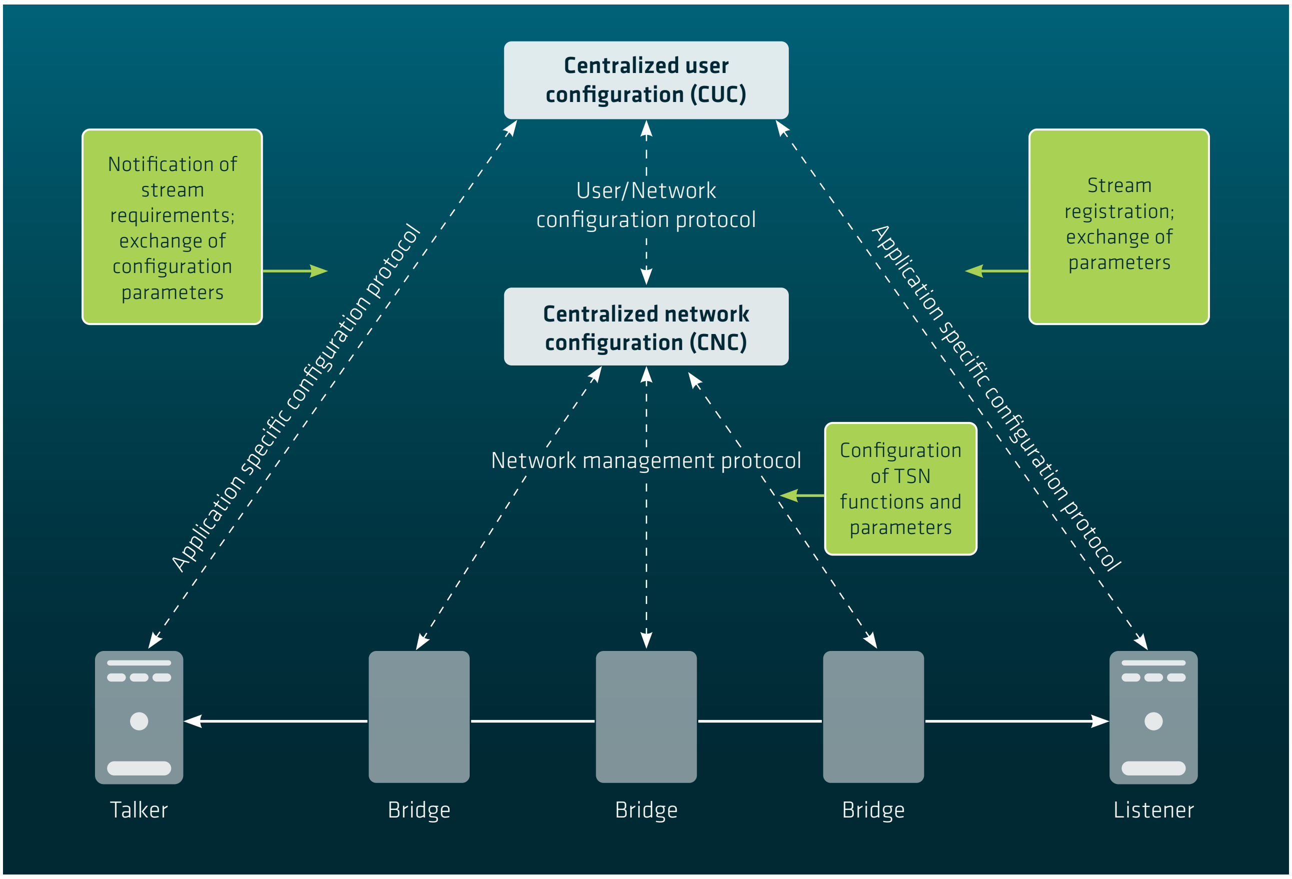
The IEC/IEEE 60802 joint project [10] is currently defining a TSN profile specification for the TSN features to be supported for industrial automation. This will enable interoperability, testing and certifications. The Open Platform Communications (OPC) Foundation's Field Level Communications (FLC) initiative also aims to provide specifications based on IEC/IEEE 60802 to achieve a single common multi-vendor converged TSN network infrastructure [7]. However, the work in both groups is still ongoing.

Fig. 7: Frame replication and elimination for reliability (FRER)



Source: 5G-ACIA

Fig. 8: Centralized TSN network configuration



Source: Time-Sensitive Networking for Dummies [13]

5.7 TSN configuration

For the external configuration of a network bridge, IEEE 802.1 specifies either management information base (MIB) files for configuration via the Simple Network Management Protocol (SNMP) or YANG modules for configuration via NetConf or RESTconf. The external centralized TSN configuration between the centralized network configuration (CNC) and the bridges is visualized in Figure 8. The task of centralized user configuration (CUC) is to collect the requirements of the various applications in the network and forward them in collections per stream ("one talker, multiple listeners") to the CNC. After configuration by the CNC, the CUC forwards the final configurations to the end-devices. The CNC either knows the capabilities and boundaries of a bridge in the network in advance, via file descriptors, or can read them at runtime.

The IEEE 802.1Qcc-2018 standard [23] defines data structures for the requirements per talker and listener, and all necessary information for talkers and listeners, for the final configuration. Enhancements to the centralized configuration will be provided by the ongoing IEEE P802.1Qdj project. The IEEE P802.1Qdj Project Authorization Request (PAR) is expected to be completed in October 2022. Various organizations, such as the OPC Foundation, are currently defining communication between their end-devices and the CUC. Other TSN configuration models – in addition to the fully centralized configuration model described above – are the centralized network and distributed user model and the fully distributed model. These two models rely on the Stream Reservation Protocol (SRP), which uses the Multiple Stream Registration Protocol (MSRP), the Multiple VLAN Registration Protocol (MVRP), and the Multiple MAC Registration Protocol (MMRP). However, it has been demonstrated that SRP cannot fulfill the needs of industrial automation networks. Therefore, completely new protocols are being developed to perform distributed resource reservation. The IEEE P802.1CS Link-local Registration Protocol (LRP) will provide a new base protocol, in a similar way to the role of the Multiple Registration Protocol (MRP) as a base protocol for MSRP, MVRP, and MMRP. The IEEE P802.1Qdd Resource Allocation Protocol (RAP), which builds upon LRP, will be the actual resource reservation protocol suitable for industrial automation. However, standardization of RAP is at an early stage and the draft is still incomplete. The IEEE P802.1Qdd Project Authorization Request (PAR) indicates completion in October 2022. It is expected to take some time until RAP can be considered for 5G networks.

6 TSN in a factory

6.1 Typical use cases

Industrial automation comprises the automated control, monitoring and optimization of processes and workflows. It includes aspects such as closed-loop control applications and robotics, as well as aspects of computer-integrated manufacturing [4].

3GPP TS 22.104 [3] and IEC/IEEE 60802 [15] [33] have described many important indus- trial automation use cases. This white paper focuses on the following high-level industrial automation control use cases as described in [2]:

A Controller-to-controller (C2C) and line controller-to-controller (L2C) communication
C2C is communication between controllers/masters (C/M). L2C is communication between production line C/M and machine C/M

B Controller-to-device (C2D) communication
Communication between controllers (C/M) and field devices (sensor/actuator, S/A), C2D can be further divided into:
- C2D distributed control: both controller, e.g., programmable logic controller (PLC), and field devices are distributed in local machines or production cells.
- C2D centralized control: virtualized PLCs are located at a centralized location in, e.g., an edge cloud, and they control field devices at local machines or production cells.

C Device-to-compute (D2Cmp) communication
Non-control-relevant communication (not handled by C/M) between device and com- puter, for example, applications used in process automation (monitoring, data collection and analytics, inventories). These functions are typically implemented across the entire production facility or are cloud-based.

Concrete industrial automation applications have been described in [29], and include safety light curtains to protect defined areas from intrusion by objects, control of autonomous guided vehicles (AGVs) and mobile robots, closed-loop control in discrete manufacturing or process automation, and coordination of multiple controllers for joint performance of tasks. Applications of this type can be mapped to the above high-level use cases.

A more advanced example is a camera-assisted production cell, where a robot arm performs sorting or palletizing operations. A set of image sensors with wireless and/or wired connectivity can be placed around a production cell or be integrated into machines and robots. Image analysis allows 3D image reconstruction, or scene analysis, and can be utilized for the control of industrial machines, AGVs or robots. Based on the image analysis results, a controller unit controls the robot arm position to pick up and place items into the correct package or onto a pallet. Camera-assisted control of this kind entails both C2C and C2D. When 3D image analysis is performed centrally in a control/server room, centralized control can be applied. This would be the case, for instance, if the controlling devices on the shop floor do not have the necessary hardware and processing power to perform complex 3D imaging processing in a bounded time. If, on the other hand, the distributed control devices have the necessary hardware and processing capacity to perform the 3D image analysis locally, distributed control can be applied. Recorded images can also be used for offline quality inspection; the related communication corresponds to D2Cmp.

6.2 Industrial communication requirements

A TSN-based industrial communication network is a converged network that allows a mix of various traffic types. Service requirements range from best-effort traffic to critical real-time traffic. Several organizations (e.g., 3GPP [3], IEC/IEEE [33] , IEEE [18], IIC [14]) have defined traffic types and corresponding requirements of relevance to industrial automation, and these are summarized in Table 1.

Table 1: Industrial automation traffic types, service requirement and related TSN features [33] [14]

Traffic types	Periodic / Sporadic	Typical period	Data delivery guarantee	Tolerance to Jitter	Tolerance to loss	Typical data size (Byte)	Criticality
Isochronous	P	100 µs ~ 2 ms	Deadline	0	None	Fixed: 30 ~ 100	High
Cyclic -Synchronous	P	500 µs ~ 1 ms	latency bound (τ)	≤ τ	None	Fixed: 50 ~ 1000	High
Cyclic -Asynchronous	P	2 ms ~ 20 ms	latency bound (τ)	≤ τ	1 ~ 4 Frames	Fixed: 50 ~ 1000	High
Events: control	S	10 ms ~ 50 ms	latency bound (τ)	n.a.	Yes	Variable: 100 ~ 200	High
Events: alarm & operator commands	S	2 s	latency bound (τ)	n.a.	Yes	Variable: 100 ~1500	Medium
Network control	P	50 ms ~ 1 s	throughput	Yes	Yes	Variable: 50 ~ 500	High
Configuration & diagnostics	S	n.a.	throughput	n.a.	Yes	Variable: 500 ~ 1500	Medium
Video	P	Frame Rate	throughput	n.a.	Yes	Variable: 1000 ~ 1500	Low
Audio/Voice	P	Sample Rate	throughput	n.a.	Yes	Variable: 1000 ~1500	Low
Best effort	S	n.a.	None	n.a.	Yes	Variable: 30 ~ 1500	Low

Note 1: M: mandatory, (T): time-based policing, (R): rate-based policing, O: optional, R: recommended. Various organizations have proposed diverse traffic priority values that differ from those given here

Note 2: Time synchronization refers to synchronization of data transmission time to the network cycle for synchronized TSN operation. In addition, some applications may require time synchronization via the network.

Note 3: For camera-assisted control applications, camera traffic can be cyclic-asynchronous. Cameras are synchronized at application level with a required synchronicity in the range of 1µs-10µs. Camera traffic may produce higher data throughputs (e. g., 1080p / 30Hz / 8-bit pixel video corresponds to 500 Mbit/s).

Traffic priorities (VLAN PCP)	Strict priority IEEE 802.1Q	Redund-ancy IEEE 802.1CB	Time synchroni-zation IEEE 802.1AS	Scheduled traffic IEEE 802.1Qbv	Frame preemp-tion IEEE 802.1Qbu	PSFP IEEE 802.1Qci	TSN confi-guration IEEE 802.1Qcc
6	M	O	Yes	M		M(T)	M
5	M	O	Yes	M		M(T)	M
5	M	O	No		R	M(R)	M
4	M	O	No		O	M(R)	M
3	M	O	No		O	M(R)	M
7	M	O	No				
2	M				O	M(R)	M
1	M	O	No		O	M(R)	M
1	M	O	No		O	M(R)	M
0	M				O		

The traffic may be sporadic, i.e., a message may be transmitted by an application at any time, or periodic, where messages are transmitted regularly in a cyclic pattern. The typical period denotes the interval commonly experienced between successive messages of the application.

Data delivery guarantee [14] serves as a guide to the selection of appropriate Ethernet QoS mechanisms for the application's data transmission. If a packet cannot meet its guaranteed requirement, the packet may be considered lost or discarded by the application. Three types of data delivery guarantees are defined:

- Deadline: packet delivery is guaranteed to arrive at the receivers by a specified time. A deadline describes the upper latency bound which is usually one transmission period. This type of delivery guarantee is applicable to isochronous traffic types with periodic data transmission.
- Latency: packet delivery is guaranteed to arrive at receivers within a predictable timespan. The timespan varies depending on the traffic type.
- Throughput: packet delivery is guaranteed to arrive at receivers within the reserved throughput bound.

Tolerance to jitter [14]: the application's tolerance to jitter. This parameter is applicable to most types of periodic traffic. In the case of cyclic traffic type, the jitter must be less than the guaranteed latency.

Tolerance to loss [14]: application's tolerance to a certain degree of consecutive packet loss (or packets which do not meet the data delivery guarantee).

Typical data size [14]: the size of application message (e.g., encapsulated in the payload of an Ethernet frame). According to IEEE 802.3 [19], the payload size of an Ethernet frame ranges from 46 bytes to 1500 bytes.

Priority code point (PCP): a field of the VLAN tag that indicates the priority of the frame. There are eight traffic priorities values, where "0" denotes the lowest priority and "7" denotes the highest priority. Different traffic types are assigned PCPs according to their QoS requirements and criticality, as shown in Table 1.

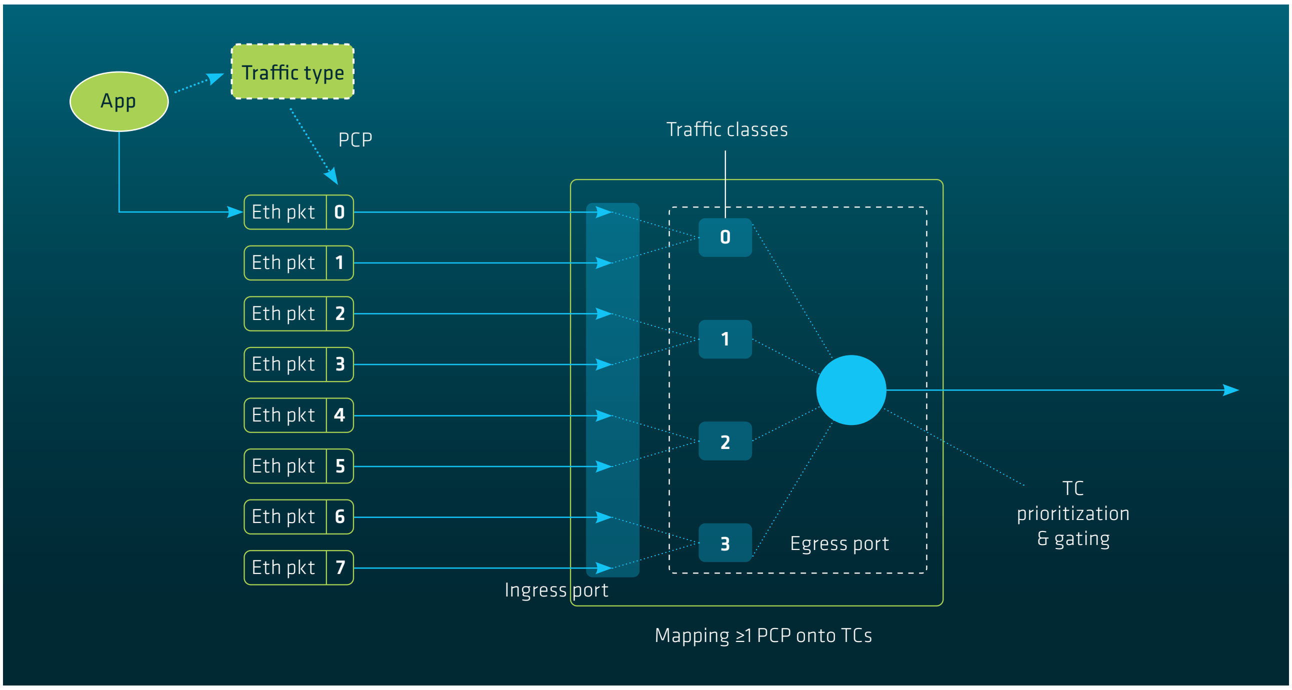
Criticality in Table 1 refers to the criticality of the data for the operation of the critical parts of the system [14]. This application criticality is used as a criterion for the selection of the appropriate QoS/TSN mechanisms and bandwidth reservations in case of conflicting requirements.

- High (e.g., PCP 4 to 7 in Table 1): for traffic types used either by applications or net- work services that are highly critical to the operation of the system. Data loss of this traffic type may cause critical system malfunction and cannot be repeated or retransmitted by the application,
- Medium (e.g., PCP 2 and 3 in Table 1): for traffic types used either by applications or network services that are relevant to but not continuously needed for the operation of critical parts of the system. Data loss may cause degraded operation but not a system malfunction. Data loss can be rectified by repeating/retransmitting the same data.
- Low (e.g., PCP 0 and 1 in Table 1): for traffic types used either by applications or network services that are not relevant to the operation of the critical parts of the system. Data loss can be rectified by repeating/retransmitting the same data.

Table 1 lists the TSN features recommended for the different traffic types.

IEEE 802.1Q strict priority is the default transmission selection algorithm using PCP values. Traffic class priority is one of the main mechanisms for addressing criticality in industrial automation. IEEE 802.1Q [18] provides an example of mapping between traffic class and PCP values according to the number of traffic classes supported by the bridge port. For example, if eight traffic classes are supported by the bridge port, each PCP is mapped to a separate traffic class with its own specific queue at the bridge port; if fewer traffic classes are supported by the bridge (as shown in Figure 9), multiple PCPs need to be merged into a single traffic class and port queue. The traffic class value indicates which QoS mecha-

Fig. 9: Packet prioritization in TSN based on IEEE 802.1Q



Source: 5G-ACIA

nisms the network queuing and forwarding functions should apply to the packet.

According to [14][33], the isochronous, cyclic and events traffic types are classified as critical for industrial automation. Both isochronous and cyclic traffic types entail periodic data transmission. The isochronous type has more stringent service performance requirements than other types. Therefore, a set of TSN features, such as strict priority control, time synchronization according to IEEE 802.1AS, and scheduled traffic according to IEEE 802.1Qbv, are required.

The cyclic traffic type also has high performance requirements; however, it differs from the isochronous traffic type in that some jitter and a limited degree of packet loss may be acceptable. Cyclic can be divided into synchronous cyclic and asynchronous cyclic. Synchronous cyclic has similar service requirements to isochronous. They both require IEEE 802.1AS time synchronization and IEEE 802.1Qbv scheduled traffic. For the asynchronous cyclic traffic type, time synchronization and scheduled traffic features are not required.

Events traffic for “alarms and operator commands” requires time synchronization via the network [14] because it is necessary for the application to timestamp or track the sequence of events, e. g., alarms on devices. However, it does not have to be synchronized to the network cycle.

IEEE 802.1Qci per-stream filtering and policing is an important TSN feature that can be applied to protect the devices from unexpected traffic or interference. In some cases, PSFP is only applied at end-stations; in other cases, it is also applied at network bridges. In the ongoing IEC/IEEE 60802 [10], PSFP is currently an optional function for TSN bridges and end-stations.

Network control traffic has the highest priority of all. Dropped packets due to ingress policing are unacceptable. Due to its high criticality, it is advisable to reserve some bandwidth for network control even if transmission gates are used, e. g., by assigning some portion of the transmission gate time to network control, potentially in combination with other critical traffic types.

6.3 Introduction and use of TSN in industrial scenarios

6.3.1 TSN deployments

There can be three connectivity segments in an industrial automation network, as shown in Figure 10:

- a central room / edge cloud,
- local machines, and
- an industrial backbone.

The central room is a centralized management segment where centralized control and management functions are located, such as centralized PLCs, CNC and automation data collection. These functions typically have interactions with other devices across the entire industrial automation network. The central room can host the enterprise edge cloud, for example a local automation cloud as indicated in Figure 1.

The local machine segment consists of multiple machines. Each machine is equipped with field devices (e. g., sensors, actuators) and may have a local PLC.

The industrial backbone provides transport services for the central management segment and local machine segments. The connectivity service can be either between multiple local machines or between the central management level and local machines.

A likely scenario is that the brownfield introduction of TSN would probably begin with providing backbone connectivity for interconnecting machines. These machines in turn use existing fieldbus solutions [8][9]. The machine controller (PLC) is connected to a TSN edge bridge or bridges in the industrial backbone network. The TSN backbone network provides transport services for machines with TSN features (e. g., C2C and L2C communication). As a result, all ecosystems benefit from the technical advancements of the IEEE 802 standards, such as higher throughput and support for new media types [17][34]. In addition, field level devices generate non-time-sensitive traffic (i. e., D2Cmp communication) which is transmitted to the local automation cloud via both the industrial Ethernet and/or fieldbus inside each machine and in the backbone via the TSN connectivity layer.

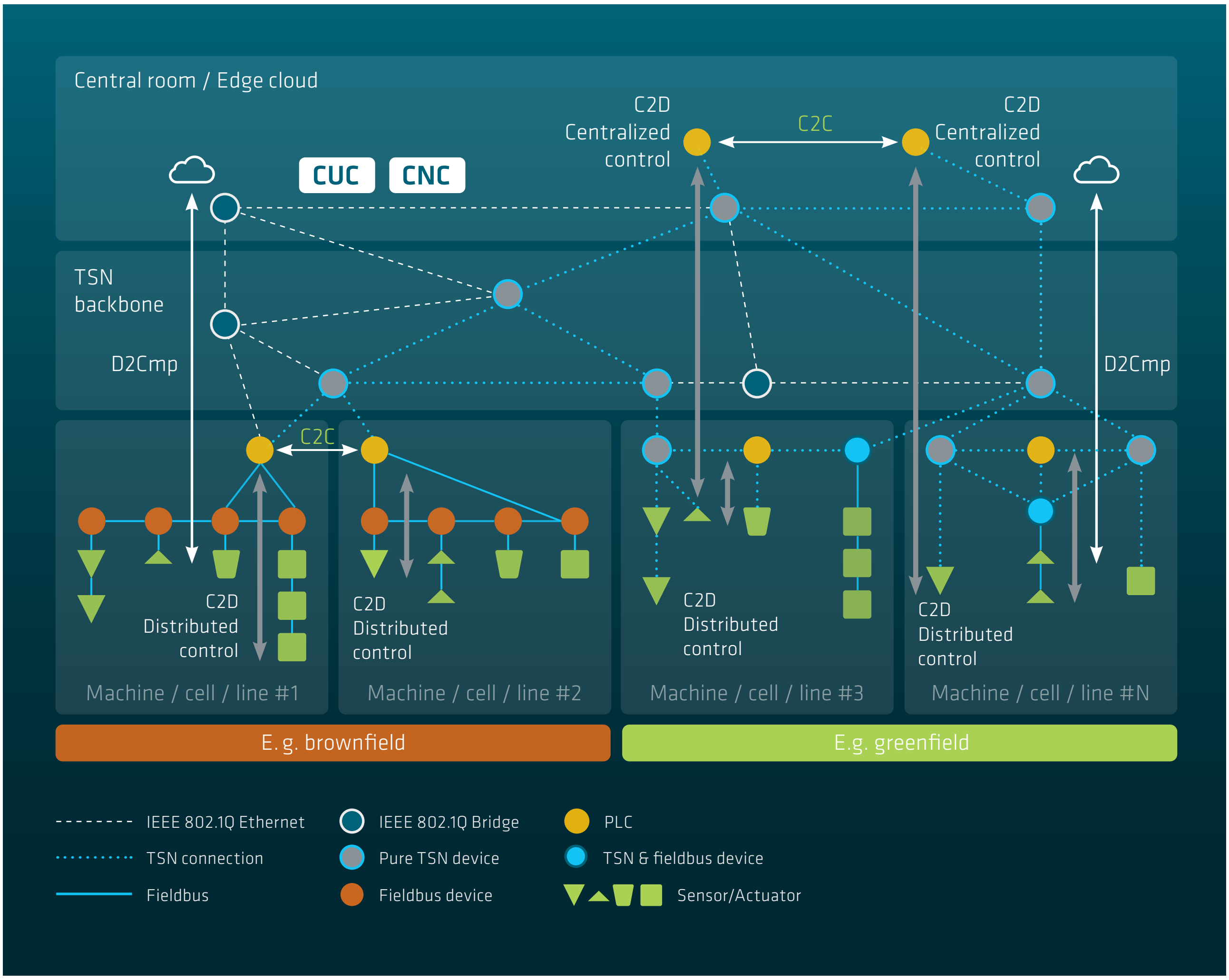
TSN is fully backward compatible with legacy Ethernet bridging. Both TSN bridges and legacy Ethernet bridges (i. e., up to IEEE 802.1Q-2014 compliant) can co-exist in the same network with some limitations. For example, with a brownfield deployment, TSN can be partly introduced in the backbone segment, and TSN-capable devices can be connected to legacy Ethernet devices, and vice versa, without the need for protocol translators or gateways.

As shown on the left in Figure 10, existing vendor-specific industrial Ethernet solutions (brown circles) are typically used inside a machine. The green blocks denote various types of field-level devices, e. g., sensors, actuators, i. e., input and output (I/O) devices. Brown circles denote industrial Ethernet or fieldbus devices, e. g., Profinet bridges. The PLC is located inside a machine (yellow circles), production cell or production line, and it controls field-level devices (i. e., C2D communication) through existing industrial Ethernet or fieldbus solutions. Field-level devices react to the control data received from the PLCs, and subsequently send their feedback to the PLCs via the same link.

The relationship between traffic types (as described in Table 1) and use cases is shown in Table 2. The C2D and C2C use cases mainly comprise cyclic, events, and configuration and diagnostics traffic types. C2D may in addition include isochronous communication. D2Cmp comprises the traffic types: events, configuration and diagnostics, audio/voice and video, and best-effort traffic services.

Full adoption of TSN on the shop floor is shown on the right-hand side of Figure 10 (grey arrows). Full adoption will be possible in future (greenfield) factory deployments based on the latest, future-proof wired TSN technology. This can also be achieved with existing networks provided all legacy wired connectivity infrastructure is migrated to TSN. In this scenario, all devices in the network must be TSN-compatible, i. e., TSN not only enables communication for the backbone segment of the network, but also inside local machines and production cells. As a result, the entire industrial automation network can be interconnected by a single communication

Fig. 10: Example of the introduction of TSN for industrial automation



Source: 5G-ACIA

solution. PLCs and I/O devices inside an individual machine are also then connected via TSN. Bridges in the TSN network will support TSN functionality, while some bridges may use other industrial protocols (such as a PROFINET 2.4 compliant bridge [20], which expands the existing PROFINET portfolio to include TSN).

In an Industry 4.0 production environment with a converged network infrastructure enabled by TSN, applications can be located anywhere and do not need to be physically close to the field-level applications. This offers far greater flexibility, and allows some control functions to be moved from field level to centralized management level [2][13]. It also allows the exploitation of technological advances, for instance in edge cloud computing. Centralized controllers and PLCs are enabled by a TSN deployment as shown on the righthand side of Figure 10 where TSN connectivity reaches down to the field devices. In this figure, virtualized PLCs are located centrally, e. g., in an edge cloud, and they control field devices at Machine #3 and Machine #N respectively (C2D centralized control). At the same time, Machine #3 and #N could also have local PLCs for C2D distributed control, e. g., for safety functions.

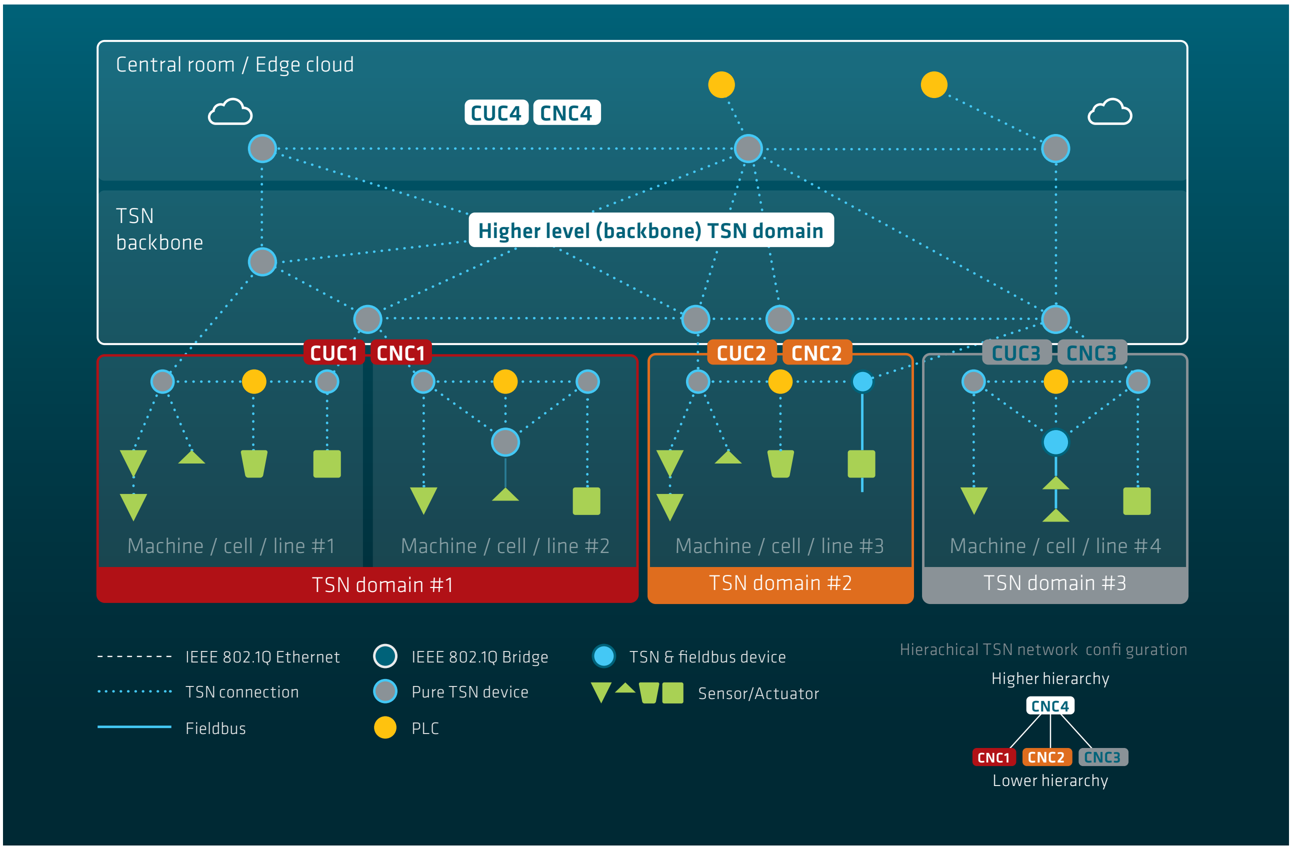
Table 2: Summary of traffic types, requirements and TSN functionality

Adoption steps towards wired TSN in industrial automation	C2C / L2C	C2D (distributed control)	C2D (centralized control)	D2Cmp
Traffic types options	• Isochronous • Cyclic synchronous & asynchronous • Events • Config & diagnostics	• Isochronous • Cyclic, synchronous & asynchronous • Events • Config & diagnostics	• Isochronous • Cyclic, synchronous & asynchronous • Events • Config & diagnostics	• Events • Config & diagnostics, • Audio/voice, • Video, • Best effort
Connectivity domains	Backbone	Local connectivity (intra-cell/machine)	Device to central location via local and backbone domains	Device to central location via local and back-bone domains
A Legacy pre-TSN communication	Legacy (fieldbus)	Legacy (fieldbus)	Legacy (normally not used)	(partially available)
B1 Mixed legacy Ethernet and TSN in the backbone	Legacy Ethernet and TSN (+5G)	Legacy (fieldbus)	Legacy fieldbus (local) Legacy Ethernet + TSN (backbone)	(partially available)
B2 backbone	TSN (+5G)	Legacy (fieldbus)	Legacy fieldbus (local) TSN (backbone)	(partially available)
C Full TSN adoption (in the backbone and the machines / production cells)	IEEE 802.1Q + TSN (+5G)	IEEE 802.1Q + TSN (+5G)	IEEE 802.1Q + TSN (+5G)	IEEE 802.1Q (+5G)
Features required when TSN is used (from Table 1)	• Needed: IEEE 802.1Q strict priority, Qci, Qcc • Optional: IEEE 802.1CB FRER, Qbu			
	• IEEE 802.1AS + Qbv (in case of isochronous and synchronous cyclic traffic type)			
Additional features	• Synchronization of applications via the network is optional in line with the application's requirements, e. g., for events/alarms traffic type. Synchronization of this type can be with multiple clocks and can be, e. g., via IEEE 802.1AS.			

Note 1: Network control traffic is generic for the entire industrial network, not specific to the use case.

Note 2: The table lists traffic type options for C2C, C2D and D2Cmp. The choice of suitable traffic types is up to implementation.

Fig. 11: An example scenario with multiple TSN domains



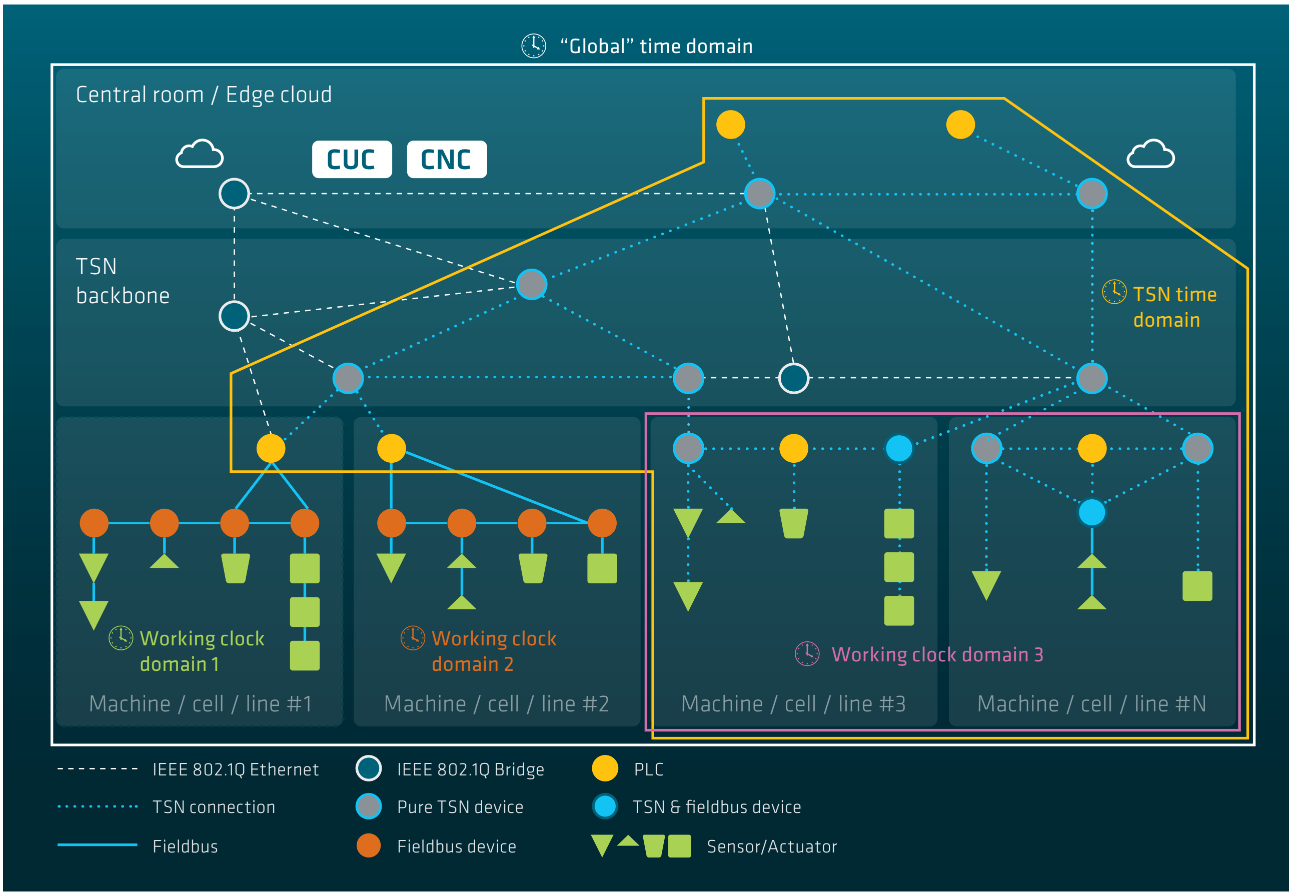
Source: 5G-ACIA

With regard to network configuration and deployment, a factory can be divided into one or multiple TSN domains. Each TSN domain is characterized by its own CUC/CNC in the case of centralized configuration. See Figure 11, where the TSN network is divided into four TSN domains.

A TSN domain is defined as two or more industrial automation devices that are jointly managed [33][15]. A TSN domain is generally different from the time synchronization domains described in section 6.3.2, Figure 12. A TSN domain can have its own dedicated TSN working clock domain, or multiple TSN domains can share a working clock domain. Figure 11 only depicts a multiple TSN domain configuration: This differs from the one with multiple clock domains depicted in Figure 12 and should be considered separately.

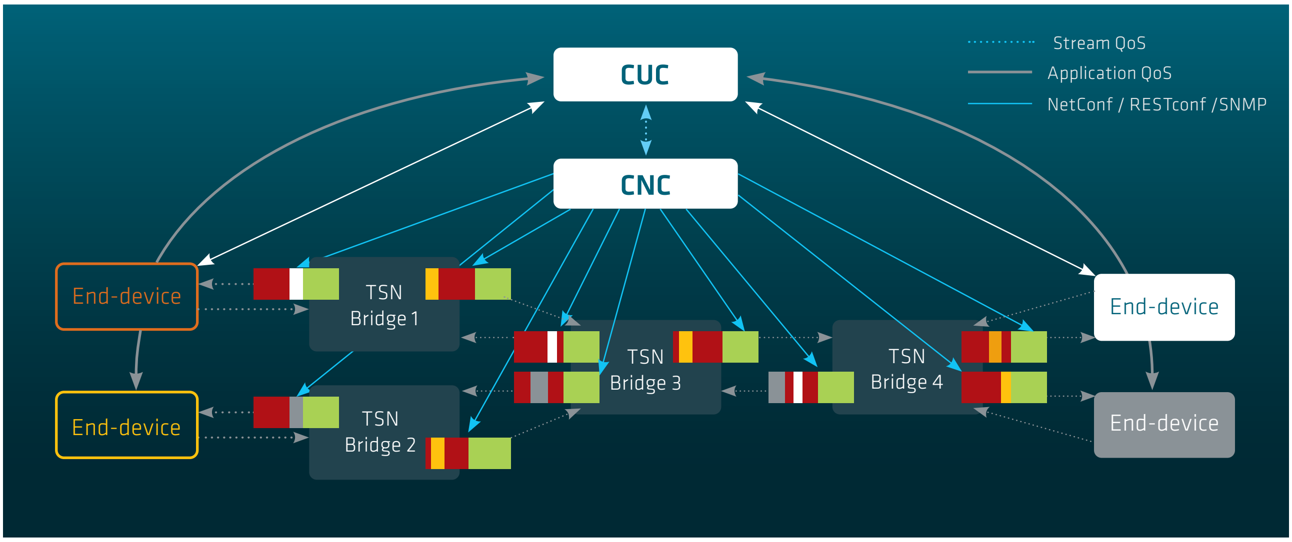
The definition of and relationship between TSN domains is ongoing work for IEEE 802.1 and IEC/IEEE 60802. However, Figure 11 shows an example of how various CNCs can be structured, e. g., in a hierarchy. In Figure 11 certain machines or production cells could potentially have their own dedicated TSN domains, each domain with its own CNC. When there is a need to create TSN streams across TSN domain boundaries, also known as inter- TSN domain communication, a lower hierarchy CNC can escalate TSN stream requests bet- ween TSN domains to the CNC higher in the hierarchy. The higher-level CNC can then configure these TSN stream paths between the TSN domains at the lower hierarchy level.

Fig. 12: Time synchronization domains within a factory



Source: 5G-ACIA

Fig. 13: IEEE 802.1Qbv centrally managed network with traffic-class-based scheduling



Source: 5G-ACIA

6.3.2 Use of TSN features

Time synchronization

Time synchronization in a TSN network is achieved by distributing time information within a time domain. A device can be in two differing types of time domains simultaneously:

- A global/universal clock domain, typically one for the whole plant/factory, providing date and time
- A working clock domain, typically one for each single (or set of) machine/cell/line, providing a highly precise time

In the example given in Figure 12 there is a single global time domain spanning the entire factory, and three working clock domains. Of these, domains 1 and 2 are used in the production cells 1 and 2, respectively, and working clock domain 3 spans the two production cells 3 and 4. For redundancy, a device may also be assigned a second global time domain and a second working clock domain (not shown in the figure).

For some industrial applications, e. g., isochronous or cyclic synchronous applications, the application and network access can be synchronized with the working clock. This means that TSN bridges in the network (at least those that make use of IEEE 802.1Qbv and time-based PSFP) need to have a common understanding of time across the application data cycle, the network cycle and the scheduling cycle [33]. In this case, the working clock used to synchronize the application is also used to synchronize network access [33]. In Figure 12 this is shown as a TSN time domain (yellow dotted line), which may in practice be identical to one of the working clock domains.

Scheduled traffic

For critical communication streams, the CNC can manage the entire path of time-sensitive streams from end to end via scheduled traffic according to IEEE 802.1Qbv. The end-devices and TSN bridges are synchronized with a shared time, and the CNC receives the transmis- sion schedule of TSN talkers via the CUC. The CNC can define traffic schedules for each traffic class at the egress port of TSN bridges, as depicted in Figure 13. In this example, all time-critical traffic streams are mapped to the same priority code point used for real-time traffic. Other traffic is mapped to other PCPs. The CNC configures the transmission gates for each bridge to create a time slot for transmission of the traffic of all TSN streams mapped to the time-sensitive PCP (marked as red in Figure 13) and another time slot for other PCPs (marked as green in Figure 13). In this example, the gate control list for each bridge egress port has only two entries.

7 5G support for TSN

5G, the next generation of 3GPP technologies, offers capabilities specifically designed to meet industrial needs. These include URLLC in 5G-NR, support for TSN, and the network deployment scenarios for non-public network (NPN) operation, ranging from standalone NPNs to public network integrated NPNs [6]. In Release 16 [5], 3GPP adopted 5G-TSN integration for time-sensitive communication. Some 5GS features for 5G-TSN integration are described below.

7.1 5G-TSN bridge model

For integration with TSN, it was proposed by 3GPP that the 5GS interoperate in a transparent manner to minimize impact on other TSN entities. The 5GS acts as one or more virtual or logical TSN bridge(s) of the TSN network, providing control plane connectivity and TSN ports at the user plane (see Figure 14). This bridge model includes TSN translator (TT) functionality that is available

(i) at the control plane by means of a TSN application function (AF),
(ii) on the UE side by means of a device-side TT (DS-TT), and
(iii) on the user plane function (UPF) side by means of a network-side TT (NW-TT).

A UPF and all UEs connected to that UPF act as a 5GS virtual bridge, as shown in Figure 14. The 5GS may have more than one UPF and may therefore have multiple 5GS bridges. Each DS-TT port is assigned to a specific protocol data unit (PDU) session in the 5GS, and every NW-TT port is assigned to a physical port at the UPF. All PDU sessions connected to a specific UPF form a group and belong to a single virtual bridge. The NW-TT ports support connectivity to the TSN network; the ports on DS-TT side are assigned to the PDU session providing connectivity to the TSN network.

Multiple PDU sessions from a single UE to differing UPFs may be established for redundant transmission or for traffic isolation. In this scenario, a UE configured with multiple PDU sessions to differing UPFs is shared by multiple virtual bridges. Each DS-TT port (assigned to a PDU session) belongs to one virtual bridge. Time-sensitive UE-to-UE communication for TSN via UPF will be improved in 5G Release 17 [32].

Table 3 lists the individual IEEE 802 standards that are being considered by 3GPP for the specification of the 5GS bridge. The 5GS bridge must support all features but does not necessarily need to use all of them for transmitting TSN streams; it can also operate as an IEEE 802.1Q bridge without specific TSN capabilities. However, the 5GS bridge is able to make use of this information in order to optimize its operation, e. g., to optimize radio access resource allocation.

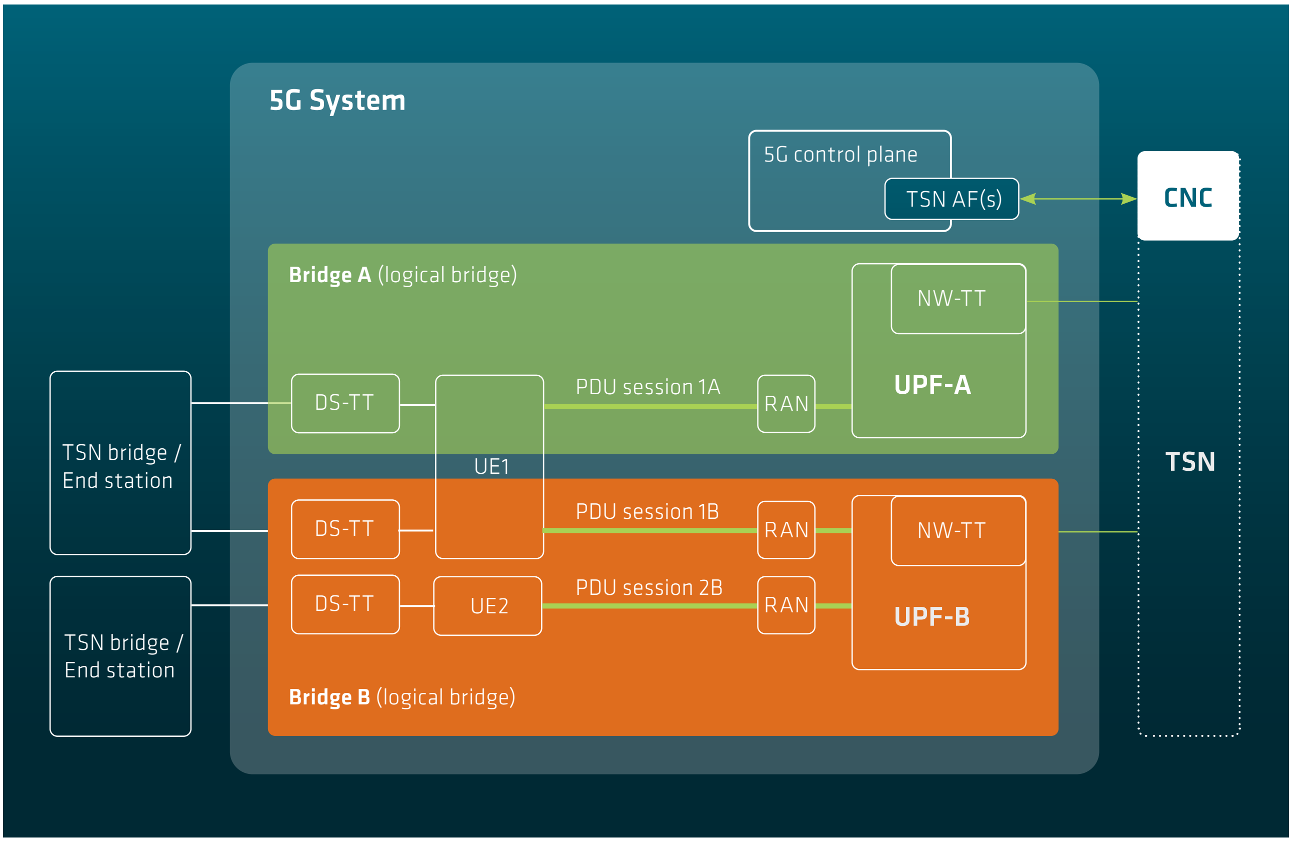
In addition to integration on the user plane, the 5GS bridge model supports integration with existing network management systems (NMSs), typically using protocols such as SNMP/ MIB. Via TSN AF, the 5GS bridge would expose its capabilities, including individual ports and topology information, and the NMS would be able to provide configuration information to the 5GS, particularly information related to IEEE 802.1Q. All information relevant to establishing an end-to-end connection can be controlled by the NMS through existing interfaces with the 5GS (which needs to be correctly pre-configured with all necessary information). To this end, the TSN-enabled 5GS bridge exposes the relevant interfaces to a CNC via the aforementioned TSN AF. Further details of exposure of 5G network capabilities for TSN support are addressed in [31] and by ongoing work on Release 17 [32].

The 5GS bridge contains bridge information used by the TSN network to make appropriate configurations for the 5GS bridge. A list of bridge capabilities that are supported by the 5GS bridge is given in Table 3.

Table 3: List of 5G bridge capabilities [5]

Bridge capability	Reference
Bridge ID, Chassis ID, etc.	IEEE 802.1Q
Traffic forwarding information	IEEE 802.1Q clause 8.8.1
Bridge delay, propagation delay related information	IEEE 802.1Qcc clause 12.32.1, 12.32.2
5GS bridge topology and neighbor discovery	IEEE 802.1AB
Traffic class related information	IEEE 802.1Q clause 12.6.3 and clause 8.6.6.
Bridge enhancements for support of scheduled traffic	IEEE 802.1Q clause 8.6.8.4, 12.9, Annex Q.2 (Qbv) (optional)
Per-Stream filtering and policing information	IEEE 802.1Q clause 8.6.5.1 (Qci)
Time synchronization as a time-aware system	IEEE 802.1AS

Fig. 14: The 5GS acts as one or more virtual TSN bridge(s) (per UPF-based 5G virtual bridge) [5]



Source: 3GPP technical specification 23.501

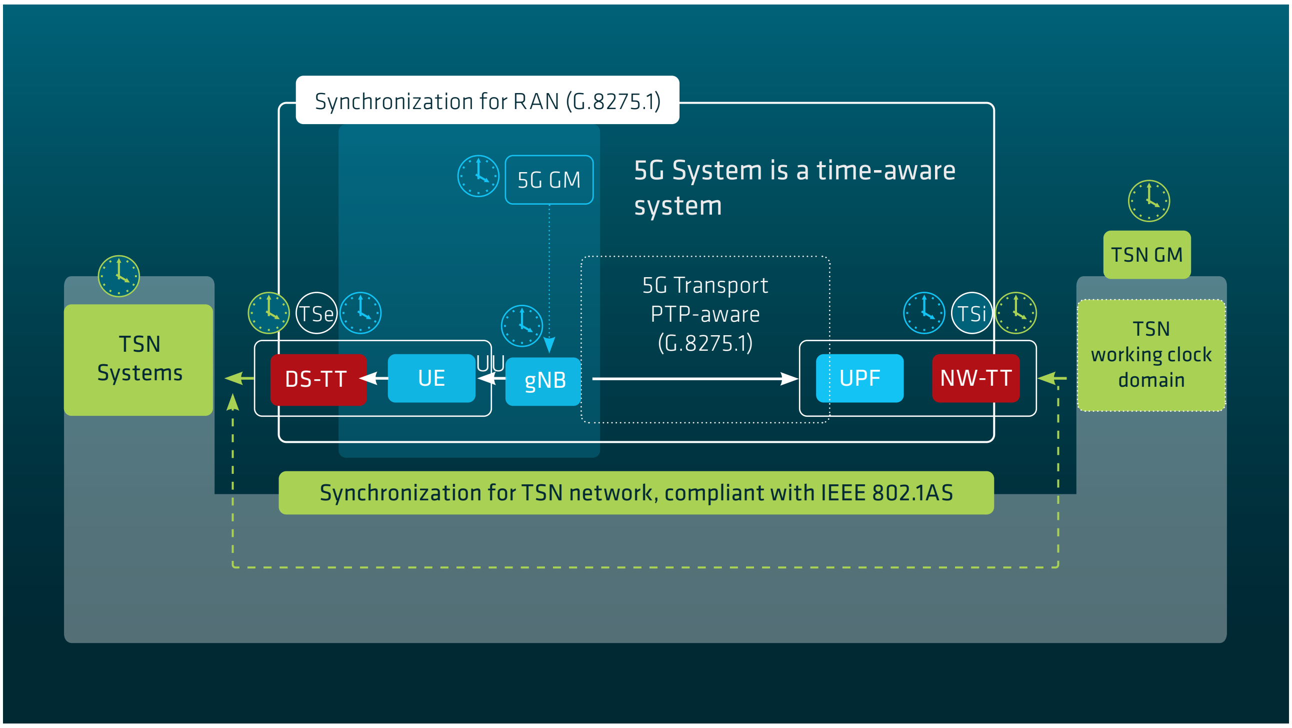
For 5G standardization work on Release 16 [5], it is assumed that all VLAN settings are pre-configured by the 5GS operation and maintenance (OAM) entity. The VLAN configuration information is located at the TSN AF and UPF/NW-TT without the need to exchange any information via the port management information container. The TSN AF and UPF/NW-TT have the same 5GS bridge VLAN configuration. This can be applied to both network- and device-side ports. VLAN information is part of 5GS bridge capabilities. The CNC obtains the 5GS bridge VLAN configuration from the TSN AF as per IEEE 802.1Q [18] clause 12.10.1.1. 5GS support for dynamic VLAN configuration (i. e., CNC-controlled VLAN configuration) is being improved in Release 17.

7.2 5G support for TSN time synchronization

5G supports TSN time synchronization (as defined by IEEE 802.1AS) across 5G-based Ethernet links with PDU-session type Ethernet. The 5GS is a time-aware system [5] as per IEEE 802.1AS as depicted in Figure 15. The time error introduced by the 5GS is limited to 900ns [3].

There are two concurrent synchronization processes in an integrated 5G-TSN system: 5GS synchronization and TSN synchronization. TSN synchronization provides the synchronization service to devices in the TSN network. 5GS provides an internal system clock for 5GS internal synchronization where the gNB, the NW-TT at UPF side and the DS-TT at UE side are all synchronized to the 5G internal system clock.

Fig. 15: 5G support for TSN synchronization (IEEE 802.1AS)

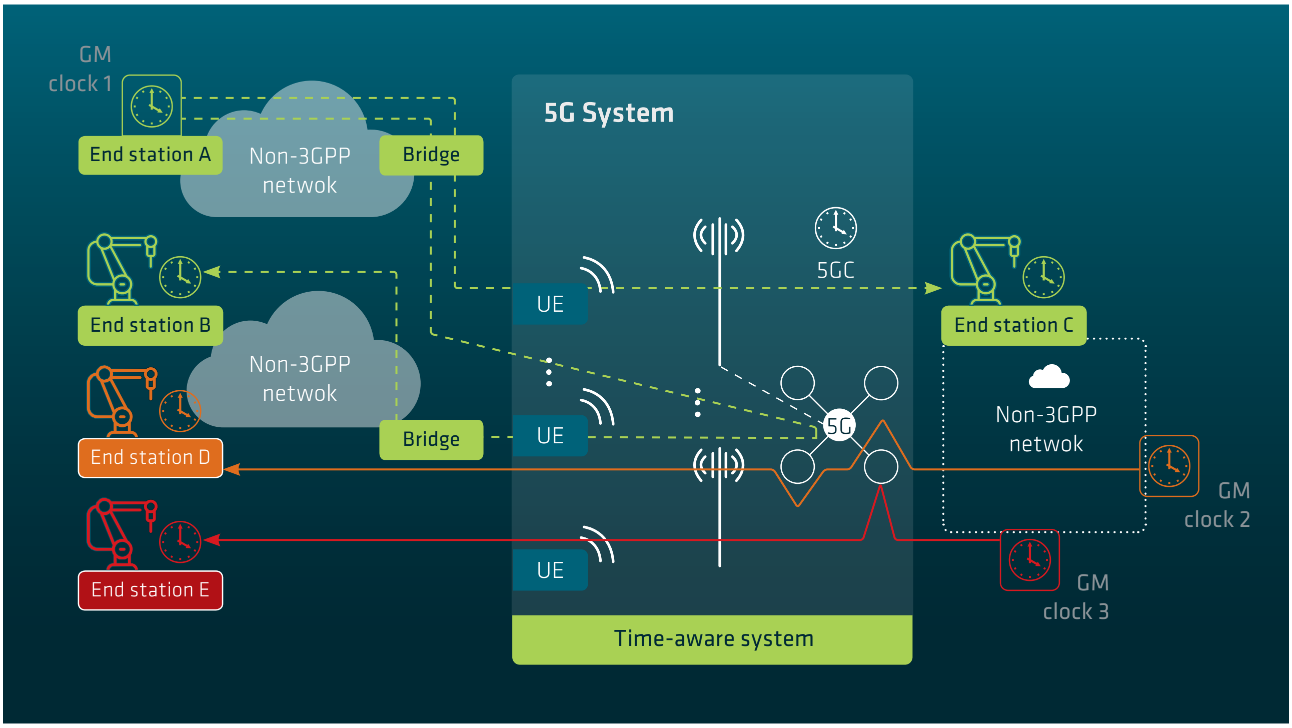


Source: "A Look Inside 5G Standards to Support Time Synchronization for Smart Manufacturing", IEEE communications standards Magazine, 2020 [27]

With regard to TSN synchronization, the NW-TT entity generates an ingress timestamp (TSi) based on the 5GS reference time for every gPTP message entering the 5GS at the UPF and embeds the timestamp within that gPTP message. Furthermore, the UPF forwards the gPTP message to the UE via the user plane (i. e., via a PDU session). Once a UE receives the gPTP message, the UE forwards it to the DS-TT. The DS-TT then creates an egress timestamp (TSe) for the gPTP message of the external gPTP working domain. This timestamp is also based on the 5GS reference time which was provided to the UE by the 5GS internal synchronization process. The difference between TSi and TSe is the residence time this gPTP message has spent within the 5GS. The DS-TT modifies the TSN timing information received from gPTP messages based on the calculated 5GS residence time and sends it to the next time-aware TSN system connected to the UE/DS-TT. The 5GS can also support multiple time domains, including both global time and working clock domains (up to 128 working clock domains [3]) as shown in Figure 16. Each time domain is identified by a specific domain number in the gPTP message. An end-station can select timing information of interest based on the domain number in the gPTP message.

To further facilitate deployment in industrial automation scenarios, 3GPP is currently developing uplink TSN time synchronization and UE-to-UE time synchronization for the upco- ming Release 17. This is shown in Figure 16. In these two cases, the TSN grandmaster can come from the UE side, whereby the DS-TT at UE side can also act as the ingress interface for gPTP messages while the NW-TT can act as the egress interface.

Fig. 16: 5G support for multiple time synchronization domains and uplink synchronization via the network



Source: 5G-ACIA

7.3 5G support for highly reliable communication

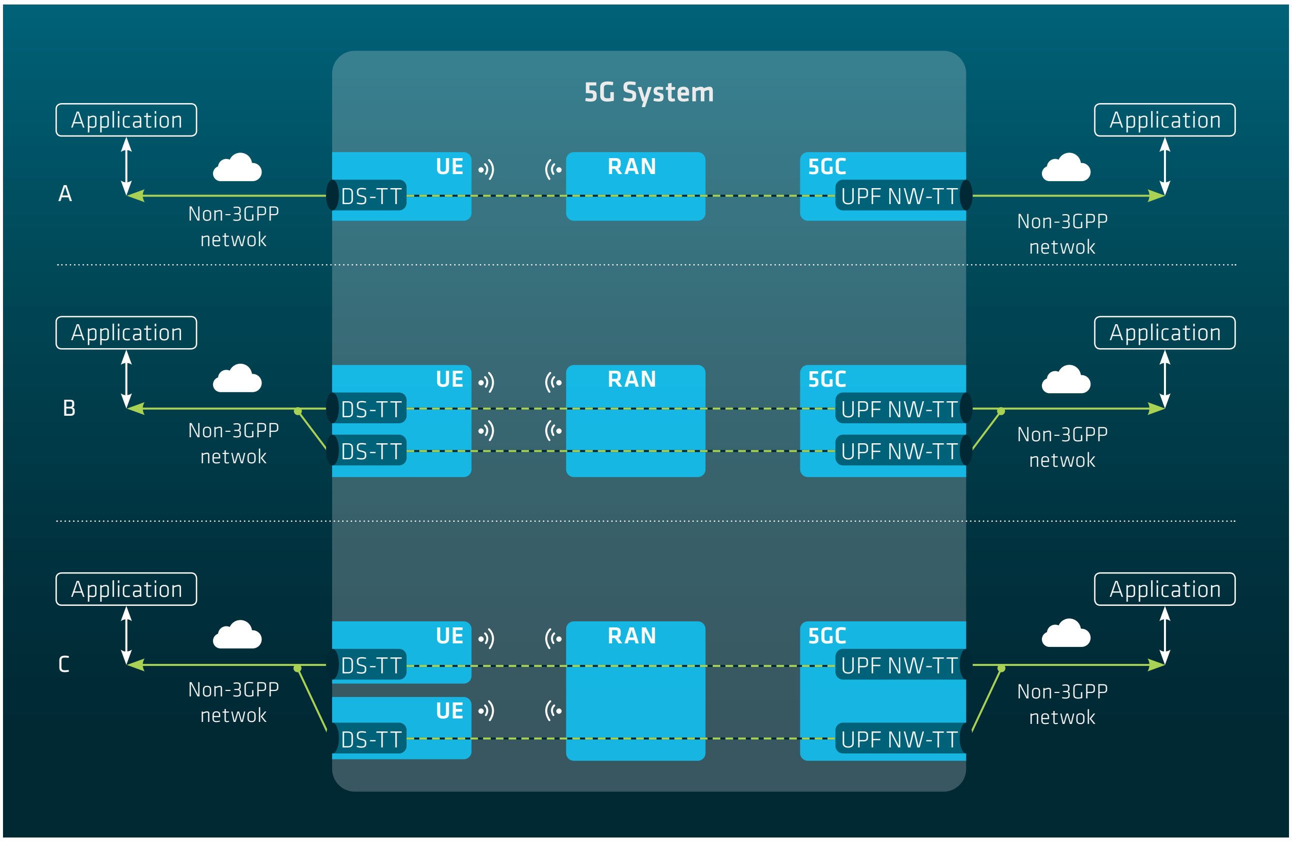
5G enables extra-robust transmission modes for increased reliability for both data and control radio channels. Reliability can be further improved by various techniques, such as multi-antenna transmission, the use of multiple carriers, and packet duplication over independent radio links.

Figure 17 (a) shows an example of reliable transmission between nodes. A single PDU session is transmitted through the 5GS. Various mechanisms can be applied to the multiple segments of the transmission to increase transmission reliability. For example, for transmission between RAN and UPF, two redundant and independent transport network paths can be configured. Also, between UE and RAN, techniques such as multi-antenna trans- mission, multiple carriers and data duplication can be used via independent radio links. Figure 17 (b) shows how RAN dual connectivity is employed to create redundant paths via

independent RAN nodes and UPF nodes to achieve both link redundancy and node redundancy. Figure 17 (c) further extends reliability with the use of redundant UEs.

IEEE 802.1CB for frame replication and elimination for reliability (FRER) can be used in combination with 3GPP redundancy features. A 5GS can be deployed as separate virtual bridges (as shown in Figure 14). When this is exposed to the CNC, the CNC can configure the traffic flow in the TSN network to use the redundant virtual bridges and paths. The FRER functions can be located outside 3GPP nodes (e. g., at TSN end-stations); the redundant PDU sessions provided by 5GS are part of two separate virtual bridges (Figure 17 (b) and (c)).

Fig. 17: 5G support for highly reliable communication



Source: 5G-ACIA

A 5G core network (CN) also provides control plane redundancy through a service-based architecture (SBA). The SBA can be independent of user plane redundancy solutions. The combination of control-plane and user-plane redundancy maximizes 5G reliability. The 5G CN control plane supports the network function (NF) set, which provides distributed, redundant and load-balancing NFs. Equivalent control plane NFs may be grouped into NF sets, e. g., several access and mobility management function (AMF) instances are grouped into an AMF set. NF instances within an NF set are interchangeable; they have the same functionality and share the same context. They can be deployed in multiple locations, e. g., multiple data centers or edges. The NFs in a CN can be deployed with 1:1 or 1:N hot or cold backup

.

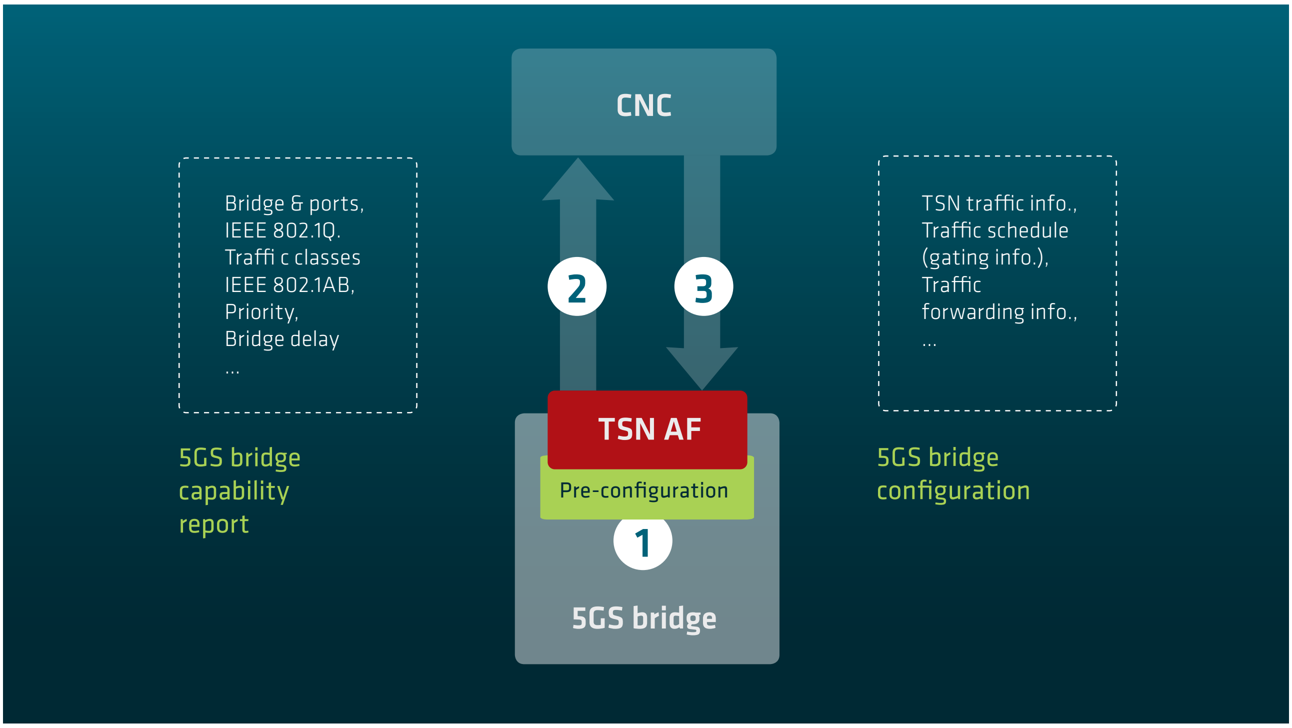
7.4 TSN traffic handling in a 5GS

For configuration of TSN traffic handling in the 5GS bridge, the TSN application function (AF) interacts on the basis of IEEE 802.1Qcc (see, e. g., [28][21]) with a CNC as specified in 3GPP TS 23.501 [5] and TS 23.502 [30].

Figure 18 describes the interaction between a CNC and the TSN AF in three phases, where the TSN AF acts as a "proxy" between a CNC using standardized network management interfaces, and the 5GS. This avoids the exposure of 5G-specific configuration details and it allows the use of established network management systems.

Phase 1 (pre-configuration)
Pre-configuring the bridge information in a 5GS. The bridge ID of the 5GS bridge, and port numbers of the NW-TT ports, can be pre-configured on the UPF. The TSN AF needs to be pre-configured with a QoS mapping table. The mapping table

Fig. 18: Control plane interaction between TSN and 5GS



Source: 5G-ACIA

lists the traffic classes and their relationship to the preconfigured 5G QoS profiles, such as the 5GS bridge delay (i. e., the delay between UE/DS-TT and UPF/NW-TT), and priority levels. The pre-configured 5GS bridge delay can be adjusted during the second phase (e. g., taking into consideration the reported UE/DS-TT residence time).

Phase 2 (5GS bridge capability report)
In addition to the pre-configured information, some items of 5GS bridge and port manage- ment information are also reported to TSN AF during PDU session establishment, as descri- bed in TS 23.502 [30]. The SMF provides PDU session-related information to the TSN AF via the policy control function (PCF). The TSN AF takes the information described above to generate a 5GS bridge report for the TSN controller (i. e., CNC) to use.

A 5GS can be exposed to a CNC via the TSN AF in the form of multiple virtual bridges. The information to be reported includes bridge-specific information, such as bridge name, address, number of ports, and port-specific information, such as port number and port address. These ports are located either at a DS-TT or the NW-TT. 5G-specific information with respect to the mobility of these ports is not exposed.

The TSN AF further exposes topology information based on the IEEE 802.1AB Link Layer Discovery Protocol (LLDP). This allows the capture of information on devices and bridges connected to the 5GS via a standardized interface. It should be noted that information is captured via a standardized management interface as defined in IEEE 802.1AB. This facilitates fast and seamless integration with IT management systems already in use.

The TSN AF further exposes capabilities, such as guaranteed maximum delays between multiple ports in the system. This enables the CNC to schedule end-to-end traffic accordingly (in the case of a TSN centralized configuration model). Furthermore, 5G supports various traffic classes and IEEE 802.1Q-based priority code points (PCPs) for traffic prioritization. The supported traffic classes are also exposed through the interface standardized in IEEE 802.1Q between the TSN AF and the corresponding network management system (CNC).

Phase 3 (bridge configuration)
Similarly, the 5GS receives the TSN configuration via the TSN AF and configures the 5GS bridge as described in TS 23.502 [30]. The configuration can include scheduling informa- tion as specified in IEEE 802.1Qbv, PSFP information as specified in IEEE 802.1Qci, and traffic forwarding information.

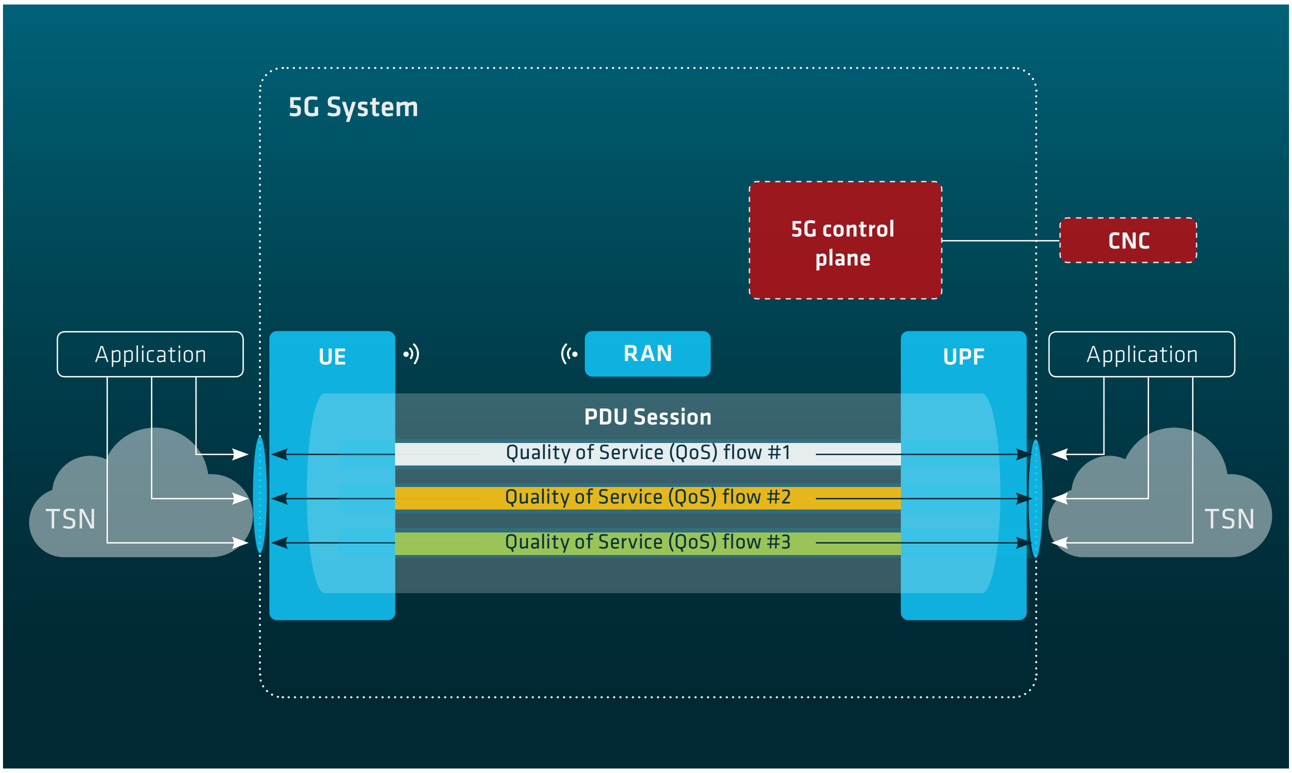
Based on the PSFP and traffic forwarding information, the TSN AF identifies the ingress port and egress port for a given stream. From the TSN AF point of view, a 5GS TSN bridge has a single NW-TT entity within a UPF whereas the NW-TT may have multiple ports for traffic for- warding. The UPF/NW-TT forwards traffic to the appropriate egress port based on the recei- ved traffic forwarding information. For UE-side forwarding, the DS-TT MAC address used by the PDU session is determined by the AF to identify the UE whose traffic is to be routed.

When TSN traffic arrives at the 5GS bridge it must be mapped to 5G QoS flows in a corres- ponding PDU session, together with the appropriate QoS configuration, as shown in Figure 19. A 5GS can receive TSN traffic QoS information from the CNC via the interface standardized in IEEE 802.1Q. The mapping table pre-configured in Phase 1 is used to identify a suitable 5GS QoS profile. The 5GS uses this profile to establish 5G QoS flows to deliver TSN traffic between the ingress and egress ports of the 5G bridge. The filters on the UE and UPF sides can be used to map various TSN streams to corresponding 5G QoS flows.

A 5G QoS flow can be characterized by several parameters. In general, it can be divided into either guaranteed bit rate (GBR) or Non-GBR, depending on its QoS profile. A 5G QoS profile consists of multiple parameters, such as allocation and retention priority (ARP), guaranteed flow bit rate (GFBR) and maximum flow bit rate (MFBR), and a 5G QoS identi- fier (5QI). ARP is set to a pre-configured value for TSN communication services. MFBR and GFBR can be derived by the 5GS from the PSFP information received via the AF [5].

A 5QI itself also contains a set of QoS characteristics, e. g., resource type, packet delay bud- get (PDB), packet error rate (PER) and priority level. 3GPP has produced a list of defined, standardized 5QI values [5]. Some of them can be used for

Fig. 19: QoS mapping between TSN traffic and 5G QoS flow



Source: 5G-ACIA

industrial automation applications, for example, 5QIs numbered 82 to 85 with resource type delay-critical GBR (see table 5.7.4-1 in [5]). However, the operator-defined 5QI values can be used to define 5QI values that specify exactly the QoS requirements of certain industrial applications, such as for isochronous or cyclic traffic types. For example, the priority level of the 5QI can be mapped to a specific PCP value given in IEEE 802.1Q. The packet delay budget of a 5G QoS flow describes the latency of a packet within the 5GS during transmission, and this can be used to determine and report the 5GS bridge delay.

The AF can calculate time-sensitive communication assistance information (TSCAI) from the PSFP information received from the CNC. This TSCAI can then be provided to the 5G RAN. There it can be used to configure RAN connectivity to provide efficient support for the TSN streams.

7.5 5G support for bounded latency

5G RAN with its New Radio (NR) interface possesses several functions designed to achieve low latency for selected data flows. NR includes the flexible configuration of the orthogo- nal frequency division multiplexing (OFDM) signal. This enables shorter slots for a radio subframe, which benefits low-latency applications. NR also introduces mini-slots, where prioritized transmissions can be started sooner, further reducing latency.

To help grant priority to, and faster radio access to URLLC traffic, NR introduces the concept of preemption – where URLLC data transmission can preempt ongoing non-URLLC transmis- sions. Additionally, NR enables very fast data processing, permitting retransmissions even within short latency bounds.

8 5G-TSN integration options and validation

8.1 Integrated 5G-TSN architecture

Section 6.3.1 Figure 10, describes a number of TSN deployment options where TSN is used in three connectivity segments of the industrial network:

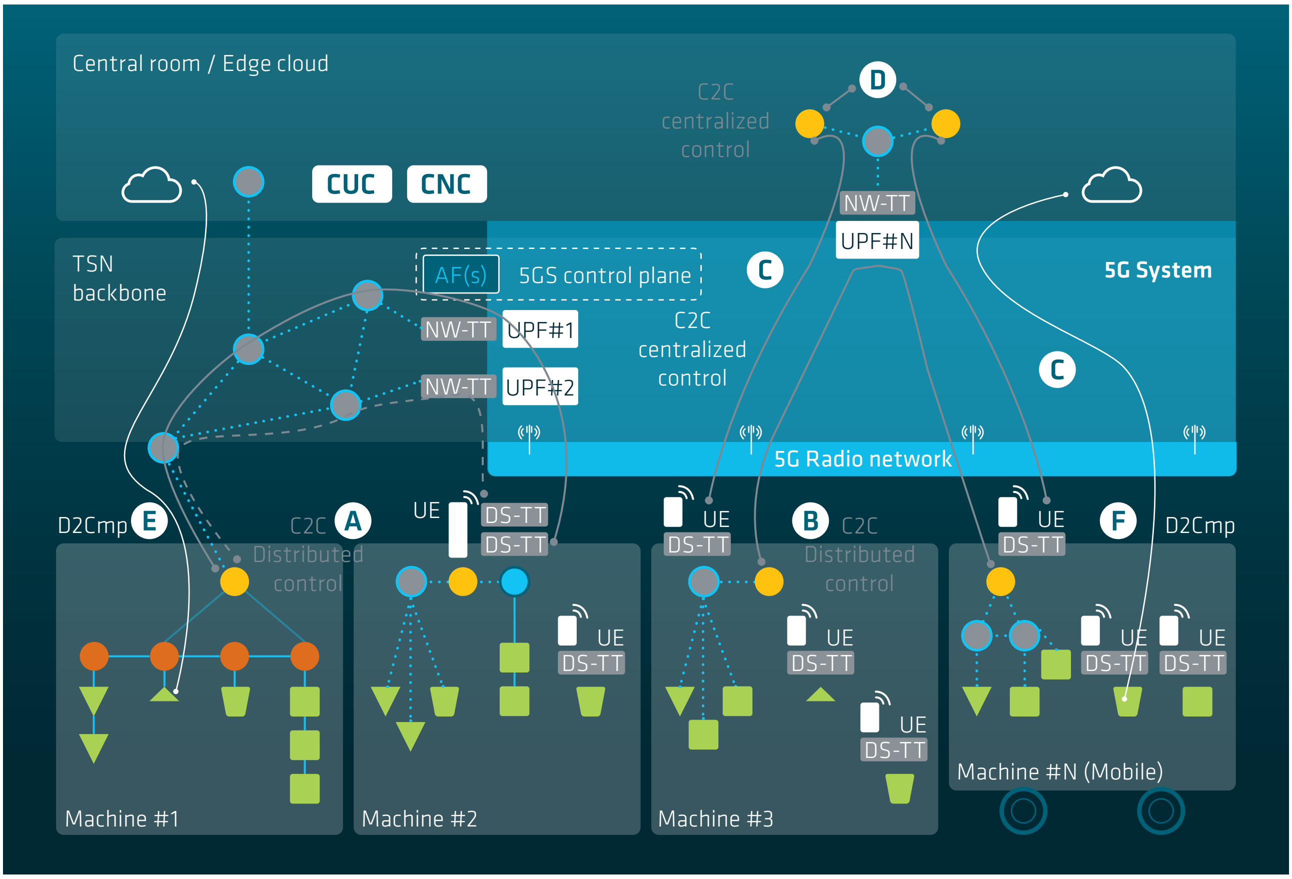
- the central management segment,
- the backbone segment, and
- local machines / production cells / line segments.

When a 5GS is integrated with the industrial network, the 5GS can support various indus- trial use cases by providing communication services in the three segments as shown in Figure 20 and Figure 21. In the backbone segment, the 5GS provides transport services between various machines and/ or cells.

The 5GS is directly connected to the central management level and edge cloud, therefore providing connectivity between the machines/cells and the central management segment. In the machine/cell segment, field level devices and distributed PLCs can also be connected via 5G connections.

The roles of 5GS bridges in the industrial network are shown in Figure 22. When 5GS virtual bridges are used in industrial backbone networks as shown in Figure 22 (a), the machine/ cell #1 can use a 5G UE instead of a cable to connect to the backbone. The backbone network bridges interconnect machines/cells. Inside the local segments of machines/cells, I/O devices are connected to the PLC via an existing wired network; both TSN and existing fieldbus or Industrial Ethernet protocols can be used within the machine/cell.

Fig. 20: Adoption of 5GS in industrial automation (C2C and D2Cmp use cases)



Source: 5G-ACIA

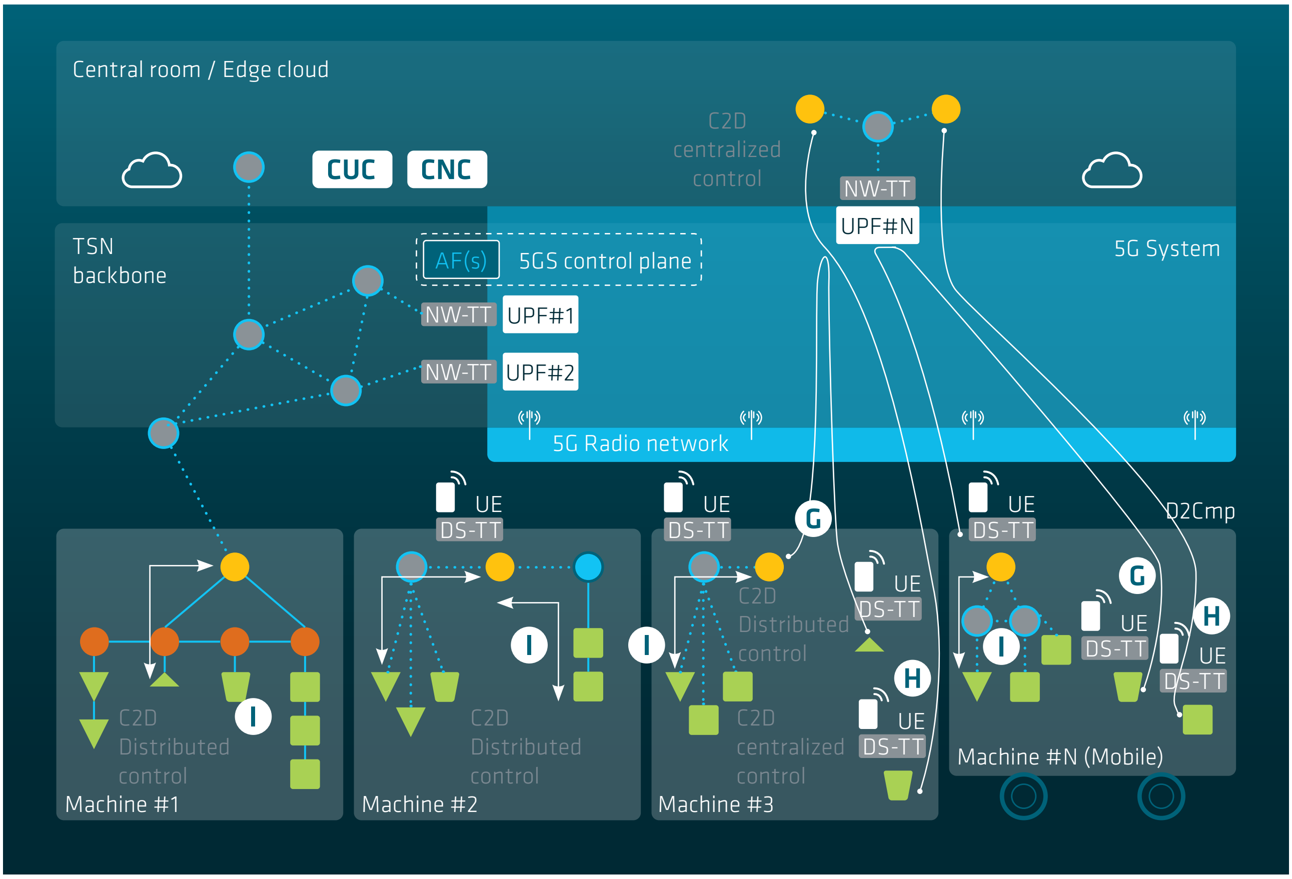
Figure 22 (b) depicts an example where the 5GS bridge extends from the backbone into the machine/cell segments. In this case, 5G also provides wireless connectivity for the devices inside a local machine/cell, e. g., the PLC and I/O devices can communicate via 5G wireless connections. This means that 5G plays a role in supporting the communication within a machine/cell.

Figure 22 (c) shows a variant of the scenario given in Figure 22 (b), where the 5GS has a direct connection to the centralized management/edge cloud segment. In this scenario, the 5GS can provide connectivity across all three segments. Field-level devices at local machine/cell segments can communicate with a central management segment entirely via the 5GS. The 5GS virtual bridges can be established through interaction of the 5G control plane with the TSN control plane.

The same 5GS can expose multiple TSN bridges where each bridge is assigned uniquely to a 5G UPF providing connectivity to the TSN backbone. Using the TSN AF, a 5GS is able to report information on the capabilities of each 5GS bridge, and is able to receive TSN configuration data.

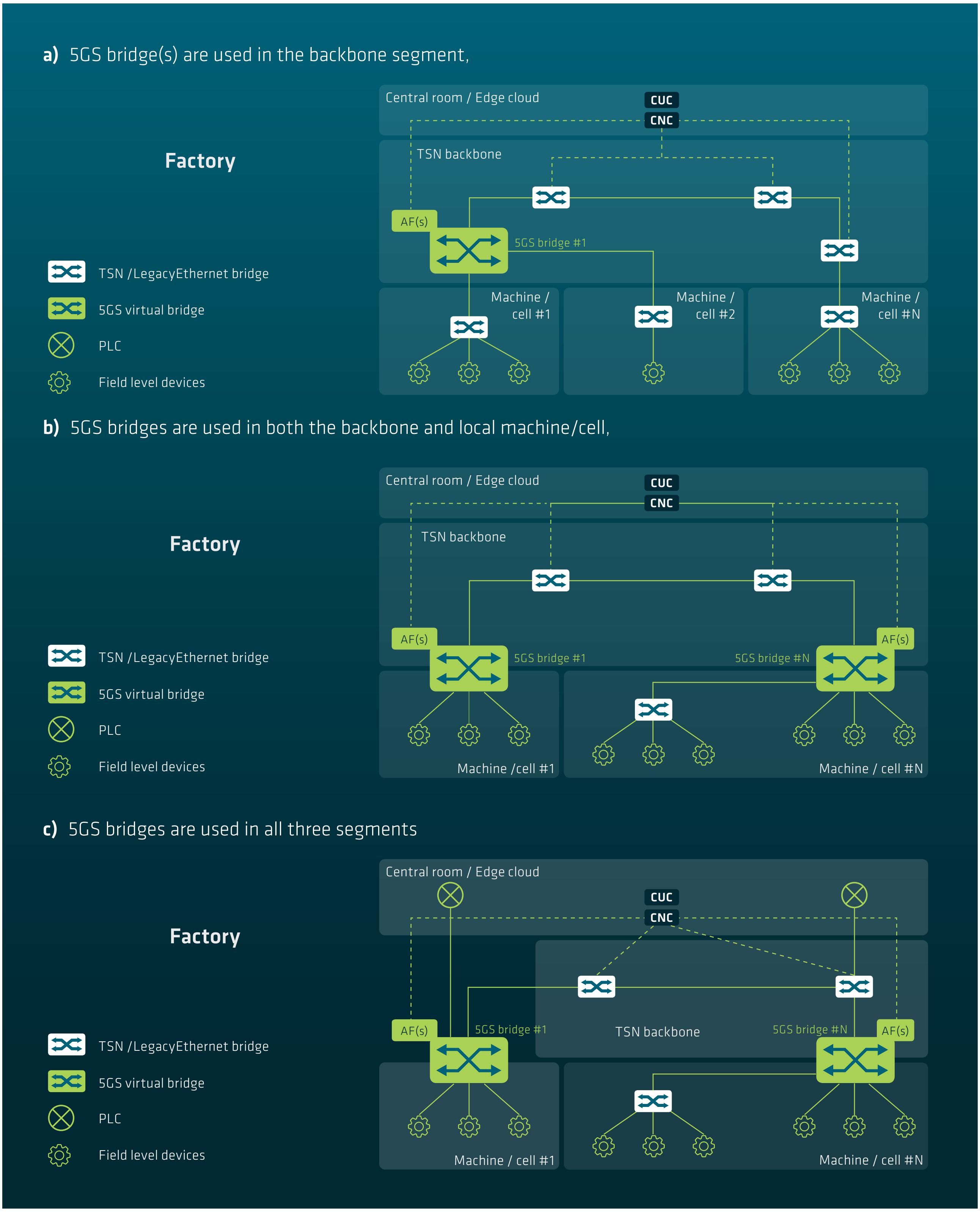
In general, the 5GS and IEEE TSN need to be integrated on both the user and control planes. In the text above, this paper introduced the options for establishing user plane connectivity in conjunction with 5GS. In addition to these user plane options, 5GS Release 16 introduced the ability to interact with a centralized network configuration (CNC) via standardized interfaces. To this end, a TSN application function (AF) has been specified in 3GPP TS 23.501 [5]. This allows interaction with a CNC based on IEEE 802.1Qcc. The details of how the 5G control plane supports TSN can be found in section 7.4.

Fig. 21: Adoption of 5GS in industrial automation (C2D)



Source: 5G-ACIA

Fig. 22: The role of 5GS bridges in industrial automation:



Source: 5G-ACIA

As described in section 6.3.1, the definition of and interworking between multiple TSN domains is ongoing work on IEC/IEEE 60802. Interaction of the 5GS with TSN has been specified by 3GPP (see section 7.4) and does not preclude support for multiple TSN domains. This would need further validation when specification work on IEC/IEEE 60802 has advan- ced further.

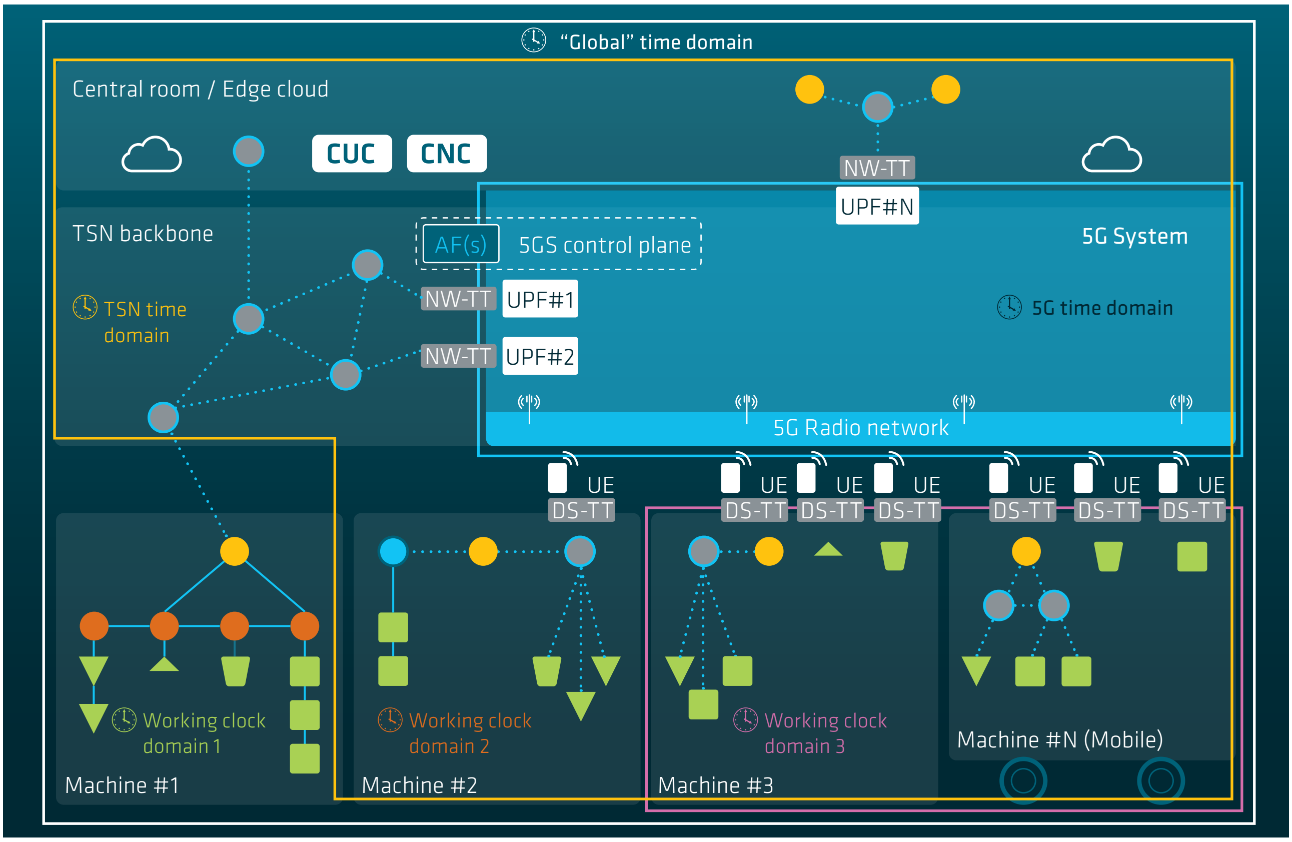
8.2 Time synchronization in an integrated 5G-TSN architecture

Section 6.3.2, Figure 12, depicts an example of time synchronization in a factory. In this section, where 5G is integrated with TSN infrastructures, Figure 23 shows how time synchronization is applied in the 5G-TSN network. The 5GS, which acts as an IEEE 802.1AS compatible time-aware system, can support time synchronization across multiple time domains or within a single time domain.

For the global time domain that spans the entire factory, 5G can distribute the global timing information to any machine / cell / line or device via a UE. For the three working clock domains, the timing information can either be distributed inside a machine / cell / line using the existing wired network, e. g., as shown in working domains 1 and 2 in Figure 23, or by means of 5G wireless connectivity between a sync master and sync devices, e. g., as shown in working clock domain 3.

With regard to the TSN time domain, when there is a need for TSN scheduled traffic (IEEE 802.1Qbv), e. g., for isochronous applications, the application and TSN bridges and 5GS virtual bridges need to be synchronized to a common working

Fig. 23: Time synchronization in a 5G-TSN integrated network



Source: 5G-ACIA

clock. In Figure 23, this is indicated as a TSN time domain, which may in practice be identical to one of the working clock domains [33].

8.3 5G-TSN integration for industrial automation use cases

Section 6 describes various use cases for TSN communication in a factory. Figure 20 and Figure 21 show how these industrial automation control use cases are implemented when 5G is introduced into the industrial network. The following sections describe those use cases by highlighting the interactions with the 5GS.

8.3.1 Controller-to-controller

Controller-to-controller (C2C) communication is the communication that takes place bet- ween a control entity for a machine, production cell or line with another control entity, as introduced in section 6. C2C communication in an example integrated 5G-TSN factory network is depicted in Figure 20. The example TSN stream (A) shows C2C communication between distributed controllers. The controller in machine #1 uses legacy industrial networking based on, e. g., fieldbus technology. It is also connected via a wired TSN connection to the backbone network. The second controller is connected to the TSN backbone network via a 5GS bridge, where the Ethernet-TSN port connecting the second controller is provided via a 5G UE. The TSN connection via the 5GS is therefore between a network-side TSN port (at the UPF) of the 5GS bridge and a device-side TSN port (at the UE) of the 5GS bridge. The connectivity corresponds to the connectivity between two controllers in machine 1 and machine N, as shown in Figure 22 (a).

The TSN capabilities for C2C communication are listed in Table 2. These include support for IEEE 802.1Q priorities, IEEE 802.1AS time synchronization, IEEE 802.1CB FRER, IEEE 802.1Qbv transmission gate scheduling, IEEE 802.1Qci per-stream filtering and policing, and configuration of the 5GS TSN bridge according to IEEE 802.1Qcc.

Whether all or just a subset of these features are used depends upon the actual application and its requirements, as shown in Table 1 and Table 2. However, as described in section 7, the 5GS is capable of supporting all these features.

For time synchronization, the grandmaster clock is typically directly connected to the TSN backbone, and connects to the 5GS via the UPF. TSN nodes connected to the TSN backbone via a 5G UE are synchronized to this grandmaster clock via 5G wireless connectivity. This is supported by Release 16 of the 5G standard. Where a grandmaster clock is connected via a 5G UE to the TSN backbone and to any other TSN sync receiver, time synchronization would need to be provided via the 5G uplink. This is supported as of Release 17 of the 5G standard.

Another example of C2C communication with distributed controllers is depicted as TSN stream (B) in Figure 20. In contrast to TSN stream (A), both controllers are connected to the TSN backbone via a 5G wireless link. This means the 5GS assumes the role of the TSN backbone in its entirety. In this case, TSN communication via the 5GS bridge takes place between two device-side TSN ports (at differing UEs) of the 5GS bridge. This entails two wireless transmission hops. These two wireless hops introduce a larger bridge delay, and also increased synchronization inaccuracy for TSN stream (B) between two device-side ports, compared to TSN stream (A). However, apart from this larger bridge delay that is reported by the 5GS to the CNC as part of the bridge capability information, no additional TSN capabilities are required from the 5GS compared to TSN stream (A). This example of TSN stream (B) corresponds to the logical bridge shown in Figure 22 (a) where two machines/cells are connected to the same 5GS bridge. TSN communication between two UEs via the 5G network as in TSN stream (B), i. e., between two device-side Ethernet ports located at differing UEs and connected via the 5G network, will be enhanced in Release 17 of the 5G standard by improving TSN stream forwarding within the 5GS.

The introduction of advanced networking capabilities based on TSN and 5G, in conjunction with advances in small-scale cloud computing platforms that enable on-premises computing in an edge cloud, is driving the relocation of industrial controllers from the shop floor to a central point. In other words, control based on a large number of industrial controllers distributed across the shop floor can be transformed to central control with many diverse industrial controllers moving to a central room in the factory. The controllers may also be virtualized and operated on the edge cloud platform. C2C communication between two centralized controllers in a central room or edge cloud is depicted by TSN stream (D) in Figure 20. Communication takes place locally via the backplane of the edge cloud platform or via the TSN backbone connecting multiple controllers within the central room. In this case, no communication over the 5G network is required. If one of the controllers is on the shop floor in the machine/cell, and the other controller is in the central room or edge cloud, C2C communication takes place as shown as TSN stream (C) in Figure 20. The central controller is directly connected to the 5GS bridge via a network-side port at the UPF and a distributed controller is connected to the 5GS bridge via a device-side port at the UE. In the simplest case, the two controllers are directly connected via a single TSN bridge, which is the 5GS bridge as shown in Figure 22 (c). 5G-TSN communication requirements for TSN stream (C) are identical to those of TSN stream (A), as described above.

8.3.2 Device-to-compute

Device-to-compute (D2Cmp) communication is used, e. g., by applications that monitor the production process, capture maintenance information and capture data for analytics. The communication path is in most cases from a large number of sensors, machines and controllers to a central computing platform located, e. g., in an edge cloud. Traffic is typically asymmetric to the central location, and it includes configuration data transmitted to devices and equipment. The type of traffic can vary from low data volumes for sensor reports to high-data-rate video imaging. D2Cmp communication is characterized by low and medium criticality and is not delay-bounded, as displayed in Table 1 and Table 2. D2Cmp communication is shown in Figure 20 with TSN streams (E) and (F). For TSN stream (E), a data source is connected to the edge cloud via the TSN backbone, and 5G does not play any role in communication. For D2Cmp, the number of data sources that provide infor- mation can be very large. The number of sources is increasing significantly with the introduction of the IIoT, which entails, e. g., large-scale monitoring of processes and assets. Many new types of sensors are being introduced, and/or existing equipment is being retrofitted with data collectors. For many information sources, wired connectivity to a TSN backbone is not easily available. 5G introduces significant flexibility when connecting data collectors and equipment to the edge cloud for D2Cmp communication. This is shown in TSN stream in Figure 20. A device can be connected to a device-side TSN port of the 5GS bridge at the 5G UE to provide TSN connectivity to the edge cloud, which itself is connected to a network-side port of the 5GS bridge. The required TSN capabilities, as given in Table 2, are IEEE 802.1Q prioritization and IEEE 802.1Qci per-stream filtering and policing. As D2Cmp traffic has lower criticality than most C2C and C2D traffic, traffic prioritization and policing are essential to ensure that large volumes of D2Cmp traffic do not interfere with transmission of other, more critical traffic. Redundant transmission according to IEEE 802.1CB FRER may optionally be provided. Time synchronization can be provided to D2Cmp devices if synchronization is needed by the applications.

8.3.3 Controller-to-device

Controller-to-device (C2D) communication takes place between controllers and field devices. C2D traffic is typically cyclic or isochronous with low data rates and strict delay bounds as given in Table 1. C2D communication is highly critical. In some cases, C2D communication may include time-sensitive high-rate data transmission to the controller, e. g., when imaging and machine vision data is utilized in the controller, as described in the example in section 6.1. C2D communication is shown in Figure 21. Traffic flows (I) correspond to C2D communication based on local legacy fieldbus networks. Control is de- centralized, i. e., the controllers are in close proximity to the field devices.

With the introduction of TSN and 5G, critical latency-bounded communication is achievable over a converged network with a large mixture of traffic types and over larger distances. This lessens the need to install the controller locally on the shop floor, and enables it to be moved to a more convenient location, such as a central room. Controllers may even be virtualized and operated on an edge cloud platform. This entails the transition from a distributed C2D control architecture towards a centralized C2D architecture, as shown in Figure 21. TSN stream (H) depicts communication between a centralized controller in the edge cloud and a field device on the shop floor. The device is connected to the 5GS via the device-side TSN port of the 5GS bridge at a 5G UE, and the controller is connected to the network-side TSN port of the 5GS bridge at a UPF. Additionally, for certain extremely critical applications (e. g., for safety), distributed C2D can still remain at the local machine/ cell, as shown for machine #3.

Table 2 lists the TSN features needed for C2D communication. These include support for IEEE 802.1Q prioritization and IEEE 802.1Qci per-stream filtering and policing. Optionally redundant transmission via IEEE 802.1CB FRER may also be desired. Synchronous cyclic traffic types and isochronous traffic types also require scheduled TSN traffic according to IEEE 802.1Qbv. This requires time synchronization of end-stations and bridges according to IEEE 802.1AS. The bridges are configured by a CNC according to IEEE 802.1Qcc. For IEEE 802.1Qci per-stream filtering and policing, and for IEEE 802.1Qbv traffic scheduling, the corresponding configuration data is received from the CNC by the 5GS as described in section 7.4. It is important that the 5GS can provide the CNC with precise information on latencies between the port pairs of the 5GS bridge in the bridge capability report to enable CNC TSN time scheduling along the path of the critical TSN streams. The 5G standard speci- fies how IEEE 802.1Qbv and IEEE 802.1Qci information is distributed via internal signaling from the TSN AF within the 5GS to the ports at NW-side and device-side TSN translators. The implementation details of specific IEEE 802.1Qci per-stream filtering and policing, as well as the IEEE 802.1Qbv traffic scheduling are not specified by the 3GPP standard; these are specified in IEEE 802.1Q and it is the responsibility of UE and UPF equipment suppliers to provide them.

5G wireless connectivity can also be utilized in a distributed control architecture, where a controller is placed locally in the machine or cell. It may be challenging to connect devices via cables, e. g., due to the complexity of machine movements or due to devices being added to an existing installation; such devices can instead be connected via 5G. C2D communication in this case is shown as TSN stream (G) in Figure 21. From the external perspective of the 5GS bridge, as depicted in Figure 22 (c), there is no difference between TSN streams (G) and (H). From the 5GS internal view, a difference is that for TSN stream both the ingress and egress ports are device-side ports provided by 5G UEs. Commu- nication between these port pairs within the 5GS passes from one UE via the 5G network back to the other UE, and is twice transmitted over the 5G wireless link; in the context of 5G, this type of communication is referred to as UE-to-UE. For UE-to-UE communication, corresponding 5GS-internal forwarding capability is needed, as well as the capability to accurately determine the port-to-port latency which comprises two in-sequence QoS flows over the two radio links. Functionality for time-sensitive UE-to-UE communication for TSN will be improved in Release 17. From the perspective of the CNC and the external TSN network, there is no difference between TSN communication over the 5GS bridge via two UEs as shown for TSN stream (G), or between a UE and the network as shown for TSN stream (H). However, port-to-port latency for communication between two device-side ports of the 5GS bridge is greater, due to the two wireless links, compared to port-to-port latency between a device-side port and a network-side port.

8.3.4 Summary of 5G TSN validation

A 5GS can be regarded by an external TSN network as a set of virtual TSN-capable 5GS bridges. A 5GS bridge interfaces with the external TSN network via TSN translator functions, and the internal functionality of the 5GS for time-sensitive communication is not exposed to the external network. A 5GS bridge provides Ethernet-TSN connectivity via ports in the same way a wired TSN bridge does. Some of the ports of a 5GS bridge are on the network side, i. e., provided by the UPF gateway of the 5GS. Other ports of the 5GS are on the device side, i. e., are provided by wireless 5G devices (UEs). TSN communication is possible via any of the port pairs of the 5GS bridge.

A 5GS bridge provides a management function (the 5G TSN AF) that interacts with a CNC of the TSN network (or network domain). Via this interface a 5GS bridge reports its capabilities to the CNC and receives 5GS bridge configuration data from the CNC. This interaction between the 5GS bridge and the CNC is according to IEEE 802.1Qcc as is the case for inter- actions between TSN bridges and a CNC. The CNC configures frame forwarding for the 5GS bridge, as well as the supported TSN features, e. g., per-stream filtering and policing (IEEE 802.1Qci) and time scheduling for traffic classes (IEEE 802.1Qbv).

The 5GS provides the features and capabilities needed to support TSN traffic, as summarized below.

5G introduces functionality for ultra-reliable and low-latency communication. In general, 5G supports retransmissions to provide very reliable data delivery over the wireless link. However, retransmissions can introduce increased latencies and jitter. Ultra-reliable communication for 5G means that robust transmission modes and configurations have been specified to increase the probability of successful transmissions within a specified delay bound. In addition, 5G introduces very low transmission latencies. Support for QoS is an inbuilt function of the 5GS. Different traffic flows can be separated into differing QoS flows. This allows prioritization of specific traffic types. In addition, various transmission modes can be configured to match the QoS requirements of the traffic. For time-sensitive traffic types, a 5GS can provide delay-bounded low-latency transmission, i. e., it prioritizes resource allocation for those types over less critical traffic. Traffic separation and prioritization can be configured on the basis of the PCP of Ethernet/TSN traffic defined in IEEE 802.1Q.

5G supports time synchronization via gPTP according to IEEE 802.1AS. This means that end-stations and/or TSN bridges can be synchronized via a 5GS bridge to a grandmaster clock with a time error that can be limited to 900ns. For industrial automation, a TSN network is expected to support time synchronization for at least four clock domains [33]. A 5GS can go beyond this to support synchronization for up to 128 separate gPTP time domains simultaneously [3]. This is possible irrespective of whether the grandmaster clock is connected to the 5GS on the network side or via a 5G mobile device.

TSN bridges can apply per-stream filtering and policing (IEEE 802.1Qci) to protect the network from anomalous traffic. The 5GS receives the PSFP configuration from the CNC. 5G procedures have been standardized to provide the PSFP configuration to the ports at the 5G UPF and 5G UE. When PSFP is configured by the CNC for the 5GS bridge, the filtering and policing needs to be performed in accordance with IEEE 802.1Qci. Execution of PSFP at the user plane is currently not mandated by 3GPP specifications.

An optional TSN feature to increase reliability in TSN transmission is seamless redundancy by means of FRER according to IEEE 802.1CB, where frames of selected TSN streams are replicated and transmitted over two or more maximally divergent paths; duplicate messages are discarded at the receiving end of the redundant paths. FRER can be applied via the 5GS, where the redundant streams are transmitted over divergent paths within the 5GS, by using, e. g., different UPFs, and possibly different base stations and UEs.

For isochronous or synchronous cyclic traffic types, TSN scheduled traffic according to IEEE 802.1Qbv is applied, where the schedules for all bridges on the path are configured by the CNC. The 5GS bridge receives the transmission gate schedules from the CNC. 5G internal signaling has been standardized to forward the transmission gate configuration to the egress ports at the UPF and UE. Outbound data transmission at the egress port is defined upon implementation to ensure compliance with the transmission gate schedules for the various traffic classes specified by IEEE 802.1Qbv.

5G supports all TSN features identified thus far as relevant to industrial automation as given in Table 1 and Table 2. In section 8.3, this paper described how various TSN features are applied to different industrial automation use cases, and has described interaction between 5G and the TSN network in practical deployments. By carefully analyzing the TSN use cases, this paper was able to demonstrate that 5G has all essential capabilities requi- red to interwork with TSN for industrial automation. This enables the benefits of wireless 5G connectivity to be harnessed in industrial 5G-TSN deployments, and is only limited by achievable 5G performance, e. g., extremely low latencies.

9 Conclusion

TSN is recognized as the primary networking technology for industrial automation in the future, as specified in the open standards of IEEE 802.1. In this paper, the main TSN features are described in section 5, including TSN traffic scheduling (IEEE 802.1Qbv), per-stream filtering and policing (IEEE 802.1Qci), time synchronization (IEEE 802.1AS), frame replication and elimination for reliability (IEEE 802.1CB), and TSN network configuration (IEEE 802.1Qcc). Section 5 also addresses the work-in-progress in IEC/IEEE 60802 on defi- ning a TSN profile for industrial automation. Section 6 describes typical use cases for TSN in industrial automation. It also identifies different traffic types and the corresponding communication requirements.

This paper shows that significant benefits can be achieved for industrial use cases with the introduction of TSN and 5G wireless communication, e. g., due to increased flexibility in the deployment of industrial equipment and the network. This requires 5G to provide robust support for Ethernet-TSN communication services and interworking with wired TSN networks. The standardized capabilities of 5G required to support TSN services are described in section 7, based on 3GPP Release 16 and the enhancements of Release 17. An integra- ted 5G and TSN network design is presented in section 8. The integration of 5G and TSN connectivity is investigated for various use case categories, i. e., controller-to-controller, controller-to-device and device-to-compute communication.

The main finding of this paper is that 5G has been standardized with all the necessary support to seamlessly integrate with industrial TSN networks. However, the future evolution of TSN will have to be matched by 5G enhancements in coming releases.

In particular, the 5G standard must remain aligned with the development of the industrial automation profile for TSN, which is taking place within the scope of IEC/IEEE 60802, to ensure adequate support for interworking in seamlessly integrated 5G-TSN networks of the future.

10 Key terms and definitions

3GPP
The 3rd Generation Partnership Project (3GPP) is a collaborative project that brings together standardization organizations from around the world to create globally accepted specifications for mobile networks. As its name implies, it was first created to establish such specifications for the third generation (3G) of mobile communication systems. It has continued its work for subsequent generations, including the one considered here, the fifth generation (5G).

5G-ACIA
5G-ACIA is the leading global organization for shaping and promoting Industrial 5G.

IEEE
The Institute of Electrical and Electronics Engineers Standards Association (IEEE-SA) is a leading consensus building organization that nurtures, develops, and advances global technologies. IEEE SA develops standards in various areas, including Ethernet, bridged networks and TSN.

5G system
A 5G system consists of a 5G core network (5GC), a next-generation radio access network (NG-RAN) and 5G user equipment (UE), such as mobile devices. The 5GC includes user plane functions (UPF) and control plane network functions, such as an access and mobility management function (AMF), a session management function (SMF) and a policy control function (PCF).

Protocol data unit (PDU) session
Communication association in a 5G network for communication between a UE and a data network.

TSN translator (TT)
A 5G system function defined in 3GPP [5], located at the edge of the 5G network, to inter- act with external TSN nodes. It includes both control plane TTs and user plane TTs. On the control plane, the TT is a 5G core network application function (TSN AF) which is used to interact with TSN control and management, e. g., the CNC. On the user plane, there is a device-side TT (DS-TT) and network-side TT (NW-TT). These are located on the UE side and on the UPF side respectively.

Clock synchronicity
The maximum permissible time offset within a synchronization domain between the clocks of a sync master and any sync device [3].

Legacy Ethernet bridge
A bridge that is compliant to IEEE 802.1Q-2014 or earlier. It is a basic Ethernet bridge without TSN features such as those defined in IEEE 802.1 Qbv, Qci, Qbu.

TSN terms and definitions can be found at IEEE 802.1 [17] and IEC/IEEE 60802 [10][33].

11 Acronyms and abbreviations

3GPP	3rd Generation Partnership Project
5G	5th generation of cellular networks
5GC	5G core network
5GS	5G system
5QI	5G QoS identifier
AMF	Access and mobility management function
C2C	Controller-to-controller
C2D	Controller-to-device
C/M	Controller / master
CN	Core network
CNC	Central network configuration
CUC	Central user configuration
D2Cmp	Device to compute
DS-TT	Device-side TSN translator
ERP	Enterprise resource planning
FLC	Field-Level Communications
FRER	Frame replication and elimination for reliability
gNB	Next-generation node B (5G NR base station)
gPTP	Generalized Precision Time Protocol
GM	Grandmaster
GW	Gateway
ICT	Information and communications technology
IIoT	Industrial Internet of Things
L2C	Line controller-to-controller
LAN	Local area network
LRP	Link-local Registration Protocol
MES	Manufacturing execution system
MIB	Management information base
MRP	Multiple Registration Protocol
MMRP	Multiple MAC Registration Protocol
MVRP	Multiple VLAN Registration Protocol
MSRP	Multiple Stream Registration Protocol
NF	Network function
NG-RAN	Next generation – radio access network
NMS	Network management system
NPN	Non-public network
NR	New radio
NW-TT	Network-side TSN translator
OPC	Open Platform Communication
OT	Operational technology
PAR	Project authorization request
PCF	Policy control function
PCP	Priority code point
PDU	Protocol data unit
PLC	Programmable logic controller
PSFP	Per-stream filtering and policing
PTP	Precision Time Protocol
QoS	Quality of service
RAN	Radio access network
RAP	Resource Allocation Protocol
S/A	Sensor / actuator
SBA	Service-based architecture
SMF	Session management function
SNMP	Simple Network Management Protocol
SRP	Stream Reservation Protocol
TR	Technical report
TS	Technical specification
TSCAI	Time-sensitive communication assistance information
TSN	Time-sensitive networking
TSN AF	TSN application function
TT	TSN translator
UE	User equipment
UPF	User plane function
URLLC	Ultra-reliable and low-latency communication
VLAN	Virtual LAN
YANG	Yet Another Next Generation (data modelling language)
5G-ACIA	5G Alliance for Connected Industries and Automation

12 References

[1] 5G-ACIA White Paper, "5G for connected Industries and Automation", published February 2019. https://www.5g-acia.org/publications/5g-for-connected-industries-and-automation-white-paper/

[2] 5G ACIA White Paper, "Integration of Industrial Ethernet Networks with 5G networks", published November 2019. https://www.5g-acia.org/publications/integration-of-industrial-ethernet-networks-with-5g-networks/

[3] 3GPP Technical Specification 22.104, "Service requirements for cyber-physical control applications in vertical domains", v17.3.0, published July 2020. https://www.3gpp.org/ftp/Specs/archive/22_series/22.104/

[4] 3GPP Technical Report 22.804, "Study on Communication for Automation in Vertical Domains", v16.3.0, published July 2020. https://www.3gpp.org/ftp/Specs/archive/22_series/22.804/

[5] 3GPP Technical Specification 23.501, "System Architecture for the 5G System", v16.5.1, published August 2020. https://www.3gpp. org/ftp/Specs/archive/23_series/23.501/

[6] 5G-ACIA White Paper, "5G Non-Public Networks for Industrial Scenarios", published July 2019. https://www.5g-acia.org/publications/5g-non-public-networks-for-industrial-scenarios-white-paper/

[7] Bruckner, D., Stănică M., Blair, R., Schriegel, S., Kehrer, S., Seewald, M., and Sauter, T., "An Introduction to OPC UA TSN for Industrial Communication Systems", in Proceedings of the IEEE, vol. 107, no. 6, pp. 1121–1131, published June 2019. https://ieeexplore.ieee.org/document/8610105

[8] IEC 61158 series, "Industrial Communication Networks – Fieldbus specifications".

[9] IEC 61784-2, "Industrial Communication Networks – Profiles – Part 2: Additional fieldbus profiles for real-time networks based on ISO/IEC/IEEE 8802-3", published April 2019.

[10] IEC/IEEE 60802, "Time-Sensitive Networking Profile for Industrial Automation". https://1.ieee802.org/tsn/iec-ieee-60802/

[11] IEEE Standard 802.1AS-2020, "IEEE Standard for Local and Metropolitan Area Networks – Timing and Synchronization for Time-Sensitive Applications", published June 2020.

[12] IEEE Standard 1588–2019, "IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems"", published November 2019.

[13] Kleineberg, O., and Schneider, A., "Time-Sensitive Networking for Dummies", Belden/Hirschmann Special Edition, published by John Wiley & Sons, Inc., 2018.

[14] Industrial Internet Consortium (IIC): "Time Sensitive Networks for Flexible Manufacturing Testbed – Characterization and Mapping of Converged Traffic Types", v1.0, published March 2019. https://www.iiconsortium.org/pdf/IIC_TSN_Testbed_Char_Mapping_of_Converged_Traffic_Types_Whitepaper_20180328.pdf

[15] IEC/IEEE 60802, "Industrial Use Cases", V1.3, published September 13, 2018. https://www.ieee802.org/1/files/public/docs2018/60802-industrial-use-cases-0918-v13.pdf

[16] Belden white paper, "Time Sensitive Networking", published March 2020. https://www.belden.com/dfsmedia/f1e38517e0cd4caa8b1acb6619890f5e/7897-source

[17] IEEE Time-Sensitive Networking (TSN) Task Group, http://www.ieee802.org/1/tsn

[18] IEEE Standard 802.1Q-2018, "IEEE Standard for Local and metropolitan area networks: Bridges and Bridged Networks", published July 2018.

[19] IEEE Standard 802.3-2018, "IEEE Standard for Ethernet", published August 2018.

[20] PROFIBUS & PROFINET International press release: "Specification of PROFINET with TSN complete", published July, 2019. https://profibusgroup.com/2019/07/15/specification-of-profinet-with-tsn-complete/

[21] J. Farkas, B. Varga, G. Miklós, and J. Sachs. "5G-TSN integration meets networking requirements for industrial automation" Ericsson Technology Review, vol. 96, no 7, published 2019. https://www.ericsson.com/en/reports-and-papers/ericsson-technology-review/articles/5g-tsn-integration-for-industrial-automation

[22] IEEE 802.1CB-2017, "IEEE Standard for Local and metropolitan area networks-Frame Replication and Elimination for Reliability", published October 2017.

[23] IEEE P802.1Qcc-2018, "Standard for Local and metropolitan area networks – Bridges and Bridged Networks – Amendment: Stream Reservation Protocol (SRP) Enhancements and Performance Improvements", published October 2018.

[24] Kagermann, H., "Change through digitization – Value creation in the age of Industry 4.0". Management of permanent change. Springer Gabler, Wiesbaden, pp 23–45, published 2015.

[25] Wollschlaeger, M., Sauter, T., and Jasperneite, J., "The Future of Industrial Communication: Automation Networks in the Era of the Internet of Things and Industry 4.0" in IEEE Industrial Electronics Magazine, vol. 11, no. 1, pp. 17–27, published March 2017. https://ieeexplore.ieee.org/abstract/document/7883994/

[26] Kagermann, H., Wahlster, W., and Helbig, J., "Recommendations for implementing the strategic initiative industrie 4.0 – final report of the industrie 4.0 working group", Munich, published April 2013.

[27] Gódor. I., Luvisotto, M., Ruffini, S., et al., "A Look Inside 5G Standards to Support Time Synchronization for Smart Manufacturing", IEEE communications standards Magazine, published September 2020. https://ieeexplore.ieee.org/document/9204594

[28] Rost, P. M., Chandramouli, D., Kolding, T., "How the 3GPP 5G System facilitates Industrial Ethernet deployments to fuel-Industry 4.0 applications", Nokia white paper, published 2020. https://onestore.nokia.com/asset/207281

[29] 5G-ACIA White Paper, "Key 5G Use Cases and Requirements – From the Viewpoint of Operational Technology Providers", published May 2020. https://www.5g-acia.org/publications/key-5g-use-cases-and-requirements/

[30] 3GPP Technical Specification 23. 502, "Procedures for the 5G System", v16.5.1, published August 2020. https://www.3gpp.org/ftp/Specs/archive/23_series/23.502/

[31] 5G-ACIA white paper, "5G-ACIA white paper, "Exposure of 5G Capabilities for Connected Industries and Automation Applications", published May 2020. https://www.5g-acia.org/publications/exposure-of-5g-capabilities-for-connected-industries-and-automation-applications/

[32] 3GPP Technical Report 23.700-20, "Study on enhanced support of Industrial Internet of Things (IIoT) in the 5G System", v0.4.0, published June 2020. https://www.3gpp.org/ftp/Specs/archive/23_series/23.700-20/

[33] IEC/IEEE 60802, "Time-Sensitive Networking Profile for Industrial Automation", draft v1.2, published June, 2020. https://www.ieee802.org/1/files/private/60802-d1-2.pdf

[34] IEEE 802.3 Ethernet Working Group. https://www.ieee802.org/3/index.html

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