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5G plug-and-produce

How the 3GPP 5G System facilitates Industrial Ethernet deployments to fuel Industry 4.0 applications

White paper

Peter M. Rost, Devaki Chandramouli, Troels Kolding

Mobile communication will be a key enabler in achieving the objectives of the Fourth Industrial Revolution. This goes along with the need for coherent integration and migration strategies to transform existing industrial production, which is mostly based on fixed-line networks, toward the next level of industrial production, which will make use of ubiquitous, highly reliable and ultra-low-latency communication networks.

This paper provides a comprehensive overview of the tools and features standardized by 3GPP 5G Release 16 (Rel-16), which enable a seamless integration of mobile and wireless communication in industrial networks. It shows specifically how existing industrial networking standards based on IEEE 802.1 (bridged networks) are utilized by the 3GPP 5G System in order to integrate seamlessly into “brownfield” deployments and to offer novel disruptive services to industrial production. Furthermore, the paper provides an overview of technologies standardized in 3GPP Rel-16 that enable Time-Sensitive Communication (TSC) with latencies far below 1ms and synchronization precision below 1µs.

Both the ability to integrate with existing industrial networks and the extraordinary performance of 3GPP TSC enables a true 5G “plug-and-produce” experience.

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Introduction

5G networks are expected to create more than $1 trillion in new value by 2028 by enabling the modernization of industries and the Industrial Internet of Things (IIoT). One critical enabler for Industry 4.0 is scalable and pervasive connectivity between machines, people and objects, for which wireless connectivity will play a pivotal role. Currently, within industrial communications, wireless networks are still primarily used for special applications and IT-originated scenarios. Enabling mobile and wireless communications also for critical applications with stringent requirements provides added value to industrial communications in several ways. The most significant advantage is the provisioning of reliable connectivity to moving objects such as mobile robots, automated guided vehicles (AGVs), drones and humans. Mobile and wireless communication systems also offer benefits in removing cables from stationary, rotating or other objects with limited mobility. Ubiquitous connectivity is a key characteristic of mobile communication systems, which enables flexible manufacturing setups and reconfiguration not constrained by available cabling. In many scenarios, reliable and guaranteed wireless connectivity in the given service area may be more important than the support of mobility.

With Ultra-Reliable Low-Latency Communication (URLLC), 5G offers sub-ms latency transport at five-nines reliability and beyond. In Release 16 (Rel-16) of 5G, 3GPP has introduced TSC, which enables strictly deterministic traffic, including Isochronous Real-Time (IRT), to be carried over 5G wireless.

In order to enable novel use cases and make use of the potential offered by 5G networks, an efficient and seamless integration of Industrial Ethernet technologies and the 3GPP 5G System (5GS) is essential. Today, most communication technologies used in the manufacturing industry are wire-bound, including dedicated fieldbus technologies, some of which use IEEE 802.3 Ethernet as a baseline (e.g., SERCOS, PROFINET and EtherCAT), while others use non-standard transmission technologies (e. g., PROFIBUS, CC-Link and CAN). In a push to provide a standard and inter-operable fieldbus technology for Industry 4.0, IEEE is standardizing Time-Sensitive Networking (TSN), which adds determinism to Ethernet, specifying features such as synchronization, stream reservation, pre-emption, scheduling and seamless redundancy. TSN provides an openly standardized Layer 2 solution that allows many different critical industrial applications and protocols to coexist using the same physical infrastructure. In this context, IEEE TSN is of particular interest, as it defines building blocks to be supported by a 5GS. The seamless integration happens in four areas: (1) the user plane, including the enforcement of Quality of Service (QoS) policies, (2) the control plane, including QoS control, bridge management and network discovery, (3) the management plane, including standardized northbound interfaces and (4) the synchronization plane.

This white paper specifically focuses on how to facilitate the integration of 3GPP 5GS and Industrial Ethernet in order to enable a 5G “plug-and-produce” experience.

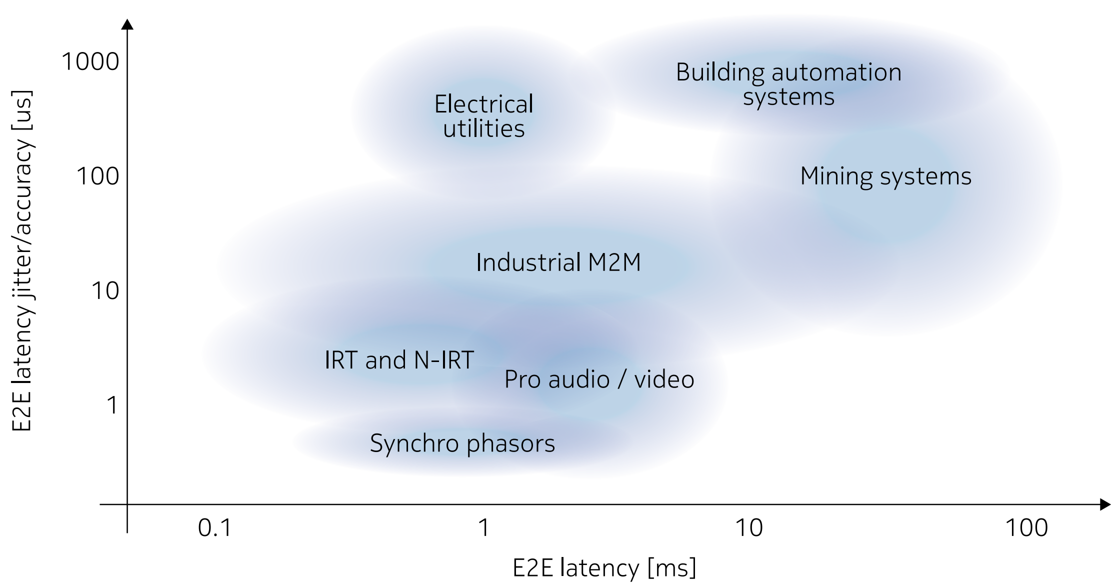
Time-Sensitive Communication (TSC)

TSC can support many applications, as shown in Figure 1. The applications are typically categorized in relation to both the latency and latency accuracy that they require. As shown, application latency tolerance ranges from the sub-ms up to the 10ms range. For sub-ms latency applications, most likely dedicated private L2 LAN deployments are needed, while performance-optimized LAN slices deployed from a public network infrastructure become possible for applications with more relaxed latency requirements (e.g., beyond 1ms). For larger latency tolerances (e.g., 10ms or beyond), any 5G public infrastructure can be used to deliver the service.

The other domain of importance is how accurate the latency must be, either in terms of tolerated latency jitter for the case when messages are executed immediately, or in terms of synchronization of the application endpoints so that timestamped or cyclic messages can be aligned with an absolute required timeline locally. Here, typical requirements range from the sub-μs area, as found for many critical factory applications, or the pro audio/video area up to the ms range, as seen for example in electrical utilities, building automation and mining. Sub-μs accuracy may require more confined low-mobility deployments, while tens of ms synchronization accuracy can be achieved for all wide area high-speed applications.

Figure 1: Example application areas and associated deployment types targeted by 5G TSC. Release 16 TSC focuses mainly on factory LAN deployments, while Release 17 TSC extends focus toward, for example, Video, Imaging and Audio for Professional Applications (VIAPA)

Deployment	Dedicated LAN	+ Private LAN slice	+ Private WAN slice
App. integration	L2 Eth	+ Converged IP	+ L3 IP



The network carrying time-sensitive applications is synchronized to a global clock used across the full network or to a local own timescale, for example a working clock. Applications may or may not be synchronized to this network clock. Deterministic applications that are synchronized to the network clock are called “Isochronous Real-Time” (IRT) applications. Applications that are not synchronized to the network clock are called “Non-Isochronous Real-Time” (N-IRT) or just “real-time” applications.

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Industrial bridged Ethernet technologies

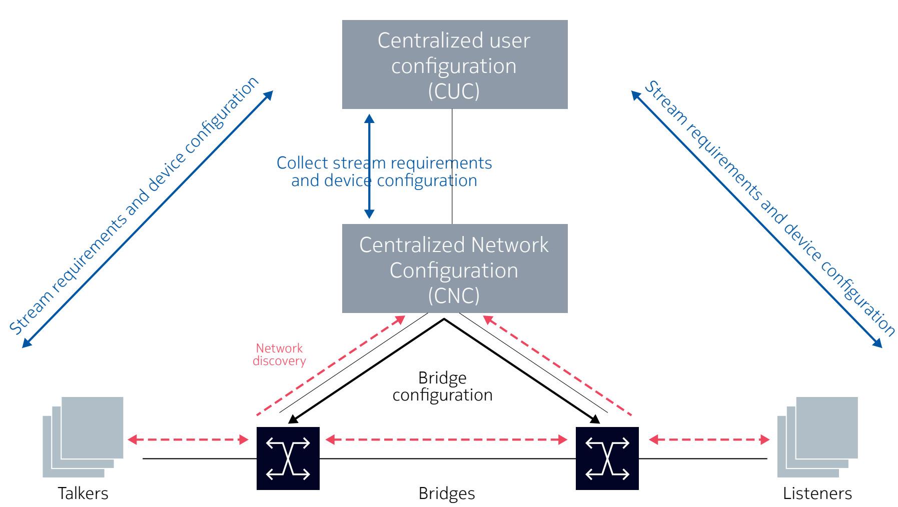
To show how integration of a 5GS into an Industrial Ethernet environment is accomplished, we provide an overview of the IEEE technologies that must be supported.

IEEE Time-Sensitive Networking (TSN) Ethernet

TSN is a collection of IEEE 802.1 standards including 802.1AS, 802.1CB and multiple 802.1Q amendments, which, when combined and configured appropriately, result in end-to-end communication over Ethernet with a deterministic delay. This set of standards provides many ways of operating a TSN system, although only a subset would be found in a single deployment. TSN implements three different configuration models: (1) fully centralized, (2) fully distributed and (3) centralized network/distributed user configuration model. This white paper focuses on the fully centralized model, which is the baseline for the 5G TSC solution in Rel-16. However, the described integration architecture applies similarly to all configuration models.

Figure 2 shows the fully centralized TSN configuration model. The talker end stations are devices such as sensors providing information to listener end stations that consume the information (e.g., controllers or monitoring devices). The end stations provide their communication requirements to the Centralized User Configuration (CUC), which translates them into corresponding communication requests. In one TSN system, multiple CUCs may coexist. Each TSN system has a single Centralized Network Configuration (CNC) entity. The CNC receives the end-to-end stream requirements from the CUCs through the so-called User/Network Configuration Information interface, which is standardized in TSN. A CNC has a complete view of the network in order to compute the transmission schedule and configure each of the bridges. Although a TSN system, in general, does not necessarily require time synchronization, industrial deployments are likely to require end-to-end synchronization for deterministic industrial applications. For those applications, the network would consist of a set of bridges and devices that are synchronized using IEEE 802.1AS (generalized Precision Time Protocol or gPTP). These bridges and end stations are synchronized to a master clock in the system and are therefore aware of the global and local working clocks in the system. In this case, all communication partners should be part of the same gPTP domain, which is also the underlying assumption of the centralized TSN model.

Figure 2: Centralized TSN configuration model

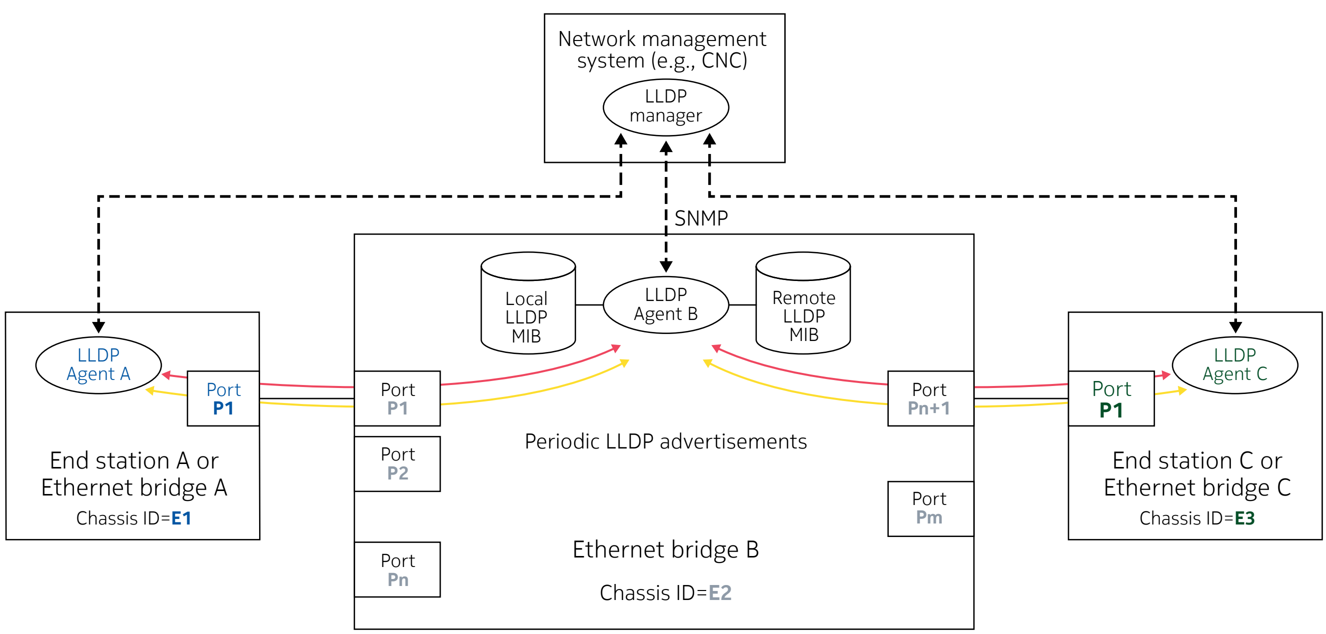


Link Layer Discovery Protocol (LLDP)

As explained, the CNC must understand the full network topology including all bridges and end stations in order to plan and optimize end-to-end communication paths. The LLDP, standardized in IEEE 802.1AB, is used to discover the link relations between Ethernet bridges and end stations in an Ethernet network. Beside topology discovery, LLDP identifies not only where individual sensors or actuators are connected but also if those devices are available.

Figure 3 shows the basic handling of LLDP information exchange. Each end station and each Ethernet bridge provides a set of LLDP agents (e.g., one per interface) that are responsible for handling the LLDP information exchange within their neighborhood. In general, each LLDP agent in the network is configured to receive and process LLDP frames of neighbors and to transmit LLDP frames toward its neighbors. Each LLDP frame is port-specific in order to identify the network topology. The end station or Ethernet bridge with an LLDP agent that acts as receiver receives LLDP advertisements, checks them and stores the information in the LLDP remote Message Information Base (MIB). This information can be retrieved from each bridge using management interfaces such as ones based on Simple Network Management Protocol (SNMP) or MIB.

Figure 3: Link Layer Discovery Protocol (LLDP) information exchange (simplified)



Simple Network Management Protocol (SNMP)

SNMP is an IP-based protocol for monitoring and managing network bridges and end stations. On each bridge or end station, an SNMP agent provides information about the current status and configuration using an MIB. Most of these MIBs are standardized by IETF and IEEE, for example for bridged networks, in order to allow for wide compatibility between SNMP agents and SNMP-based network management systems. Besides providing the current configuration of a network element, SNMP also allows for manipulating the state of network elements, and SNMP agents can trigger notifications (so-called "traps") toward the network management system in order to inform about events.

Along these lines, the management of a centralized TSN network also utilizes SNMP/MIB – which is to say, IEEE 802.1Qcc defines a management interface between bridges and the CNC. The configuration of bridges for TSN streams is performed by the CNC using either SNMP/MIB, or in the future NETCONF (IETF RFC 6241) and RESTCONF (IETF RFC 8040). While SNMP uses MIBs, RESTCONF uses the YANG modeling language.

Some of the most important MIBs when considering integration of 5G wireless devices include "Bridge Delay," "Propagation Delay," "LLDP-MIB," "Schedule Configuration," etc.; see relevant IEEE and IETF standards.

Precision Time Protocol (PTP)

TSN key features rely on strict time synchronization among listeners, talkers and bridges in order to align transmission schedules across the system. IEEE 802.1AS defines a specific profile of the IEEE 1588 PTP with additional timing features denoted gPTP that is used in TSN. Fundamentally, the synchronization procedure enables a clock master (M) to synchronize a clock slave (S) by exchanging a series of messages, allowing the slave to inherit the absolute time of the clock master, including accurate compensation for propagation delay between the two nodes as well as internal processing delays. The following basic messages are required:

- M>S: Sync packet that contains a timestamp of the time when the packet left the grandmaster clock. If the master cannot exactly control the transmission of its Sync packets (e.g., due to queuing delays) it may also send a Follow-Up packet that contains the timestamp for the Sync packet. This allows the slave to adjust its time to the clock with an error only for the propagation delay.
- S>M>S: To estimate the propagation delay, the slave sends a Delay Request packet that is timestamped upon departure. The master receives the message and timestamps the message and sends it back to the slave in a Delay Response packet. The slave may now estimate the propagation delay and compensate its clock, either assuming that the link between master and slave is symmetrical or offset by a known and configured value.

To ensure accuracy over time and compensate for any clock drift, synchronization messages are sent periodically.

The role of each bridge in the network is to forward gPTP messages between its ports. In IEEE802.1AS, the bridge acts a gPTP relay instance in a transparent mode – for example, it adds its own delay contribution (residence time) to the correction field of gPTP messages in the Follow-Up packet to compensate for any delay jitter caused by the bridge.

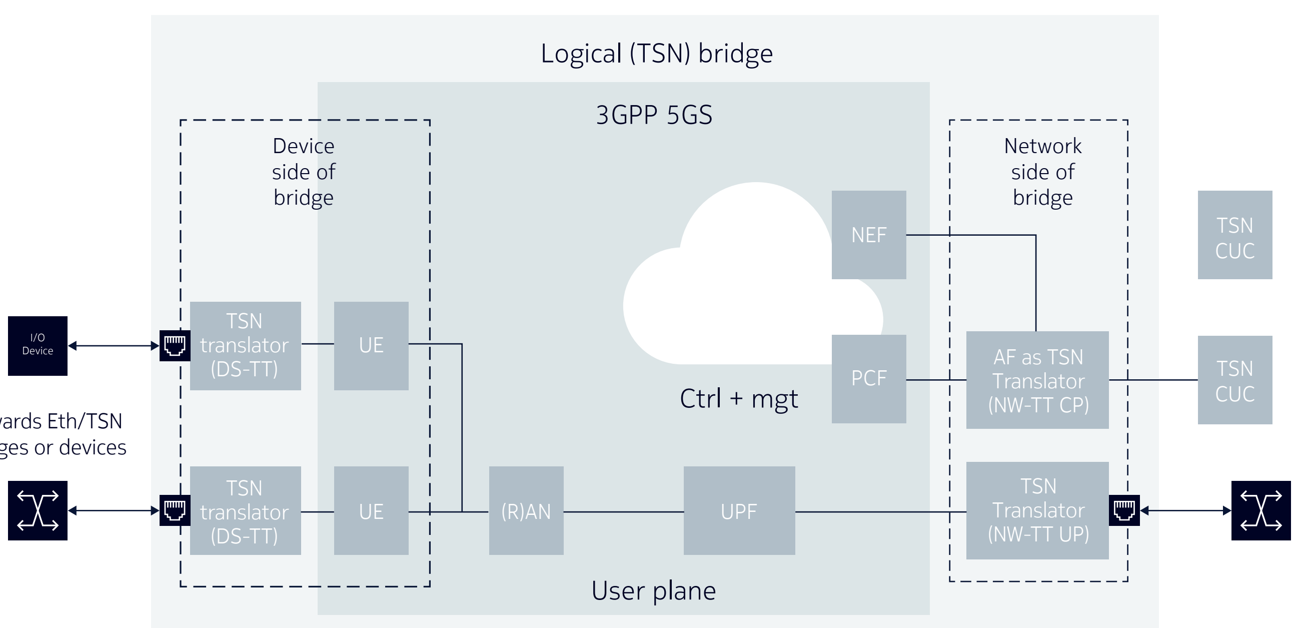
Industrial Ethernet and 5G System integration

The main challenge of integrating a 3GPP 5GS and existing Industrial Ethernet networks ("brownfield deployments") is finding common interfaces for exchanging data (user/data plane integration) for controlling the behavior of the 3GPP 5GS (control plane integration) and for managing the 3GPP 5GS (management plane integration). Solving this challenge is key to an end-to-end integration. In this section, we provide an outline of how 3GPP 5G Rel-16 allows for integrating mobile communications into brownfield deployments utilizing existing protocols and interfaces in the Industrial Ethernet domain – mainly standards from the IEEE 802.1 Working Group, which builds the basis for many Industrial Ethernet protocols, such as PROFINET, EtherCAT and TSN.

5G System integration as a "bridge"

3GPP Rel-16 allows for encapsulating the 5GS such that it appears as a TSN bridge, and hence the presence of the 5GS is not known to the fixed-line TSN system. A simplified representation is shown in Figure 4, where each user equipment (UE) and core network element represents a port of the virtual bridge. To achieve this transparency, translator functions are introduced in the architecture: the DS-TT (Device-side TSN Translator), which provides an Ethernet port on the UE side; the NW-TT UP (Network-side TSN Translator UP), co-located with the user plane function (UPF), which provides an Ethernet port toward the data network; and the NW-TT control plane, located in the TSN application function (AF), which provides a control/management plane interface toward the CNC. In Rel-16, 3GPP specifies the integration of the 5GS as a bridge with the IEEE TSN fully centralized model. Particularly, capabilities have been defined for interacting with the TSN CNC, including reporting 5GS QoS capabilities and receiving TSN stream scheduling information to be used for establishment and optimization of QoS flows inside the 5GS.

Figure 4: 5G System integration as a "bridge" (simplified illustration)



The “TSN Translators” in fact represent a multitude of sub-functions. On the one hand, each of them must implement the specific interface (protocol and information/data models) toward other TSN entities. On the other hand, it is necessary to exchange TSN-related information between the UE-side and the network-side TSN Translator and with other 5GS functions.

Integration of Quality of Service (QoS) frameworks

A key for the integration of a 3GPP mobile network and a TSN/Ethernet network is a common framework to characterize the traffic – that is to say, the QoS of individual traffic flows. 3GPP needs to map end-to-end QoS parameters in the 3GPP mobile network to TSN-specific management attributes. Such parameters include the 5G Packet Delay Budget, which must match the corresponding Bridge Delay attributes of the logical 3GPP/TSN bridge. As baseline, one 5G-defined connectivity service (e.g., Protocol Data Unit (PDU) Session) that is tasked with carrying TSN traffic is mapped to a port tuple (ingress, egress) of the bridge. Each established PDU Session is then linked to multiple QoS flows with associated 5G Quality Indicators (5QIs) mapped to different TSN streams. One of these QoS flows must be configured to handle the Ethernet best-effort traffic.

In scheduled TSN networks, TSN frames are transmitted in time cycles, where part of such a cycle (with specific length) is assigned to a specific traffic class. In this way, according to the traffic class priority, the traffic receives an exclusive right for a defined time to use the transmission medium. Thus, a Time Division Multiple Access (TDMA) approach with high granularity is used in TSN networks to separate in the time domain time-critical communications from best-effort traffic. In contrast to TSN networks, 3GPP 5G applies Orthogonal Frequency Division Multiplexing (OFDM), where data is encoded in the frequency domain, and therefore the mapping of delay parameters between TSN and 3GPP networks is not straightforward.

The delay that frames experience while being forwarded through the TSN bridge is expressed by the Bridge Delay Managed Object (BMO). The BMO contains four attributes that refer to frame length dependent (minimum and maximum) and independent (minimum and maximum) delay to forward a frame from one port to another. According to the definition of the TSN BMO, it has three indices: (1) ingress port, (2) egress port and (3) traffic (QoS) class, for which the dependent and independent delays need to be provided. Similarly, in 5G the PDU Session is defined by source and destination address, and the QoS flow is characterized by the selected resource type and 5QI class.

For TSN-relevant QoS flows, TSN BMO attributes are derived for a logical 3GPP/TSN bridge, taking into account the Packet Delay Budget (packet corresponds to a frame/PDU) values and the Maximum Data Burst Value (MDBV) indicated in the 3GPP 5G QoS profile. Following the notion of TSN Bridge Delay, packet size dependent and packet size independent delay is determined considering the guaranteed throughput, the MDBV, the packet processing time at the user terminal and base station, and the communication latency in the RAN and core network. The exact mapping between the 3GPP parameters and BMO is up to the implementation and not specified by 3GPP.

A logical 3GPP/TSN bridge further employs a hold-and-forward buffer at TSN Translators that compensates for potential jitter within the 3GPP network – that is to say, in the case where a frame has been delivered faster than the minimum reported delay, it is held back for queuing. This is an essential function for simplifying scheduling over the wireless air interface so that jitter does not need to be considered, only maximum scheduling delay.

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Integration of forwarding and topology information

Retrieving topology information from the 3GPP network is an essential feature in enabling industrial applications. In a logical 3GPP/TSN bridge, each DS-TT uses a unique Media Access Control address for LLDP processes. LLDP results are provided to the 3GPP control plane, which then compiles the corresponding BMO for the CNC. This allows for exposing the topology of all connected mobile devices toward any standard network management tool, including a TSN CNC.

IEEE 802.1Q further introduces the concept of Virtual LAN (VLAN), which allows for separating a network into smaller logical networks. Each TSN stream is assigned a VLAN and Priority Code Point (PCP) tag. With flexible mapping options between PCP tags and 5QI priority, the 5GS can perform the same traffic differentiation as found in IEEE 802.1Q, or it is free to aggregate multiple TSN streams into a single QoS flow. The PDU Session is chosen based on the port where the Ethernet frame is sent or received.

Furthermore, IEEE TSN uses locally managed unicast and multicast Media Access Control addresses that are configured for individual TSN streams. Hence, each logical 3GPP/TSN bridge needs to be configured with a set of filtering/forwarding rules for each VLAN – that is to say, defining a tuple of destination address and set of egress ports where a frame is forwarded. In the 5GS, the 3GPP control plane would receive the filtering database and would properly configure the 3GPP user plane including the terminal and TSN Translators.

Integration with industrial network management

The SNMP is currently the most widely used network management protocol. Therefore, in order to guarantee a seamless and fast integration of the 5GS with industrial networks, integration with existing network management systems is also necessary to guarantee a “plug-and-produce” experience. In order to manage the 3GPP network, the logical 3GPP/TSN bridge provides the SNMP agent functionality expected by a network bridge. Within this bridge, the Ethernet port of each UE and UPF is represented as an interface. This allows for collecting all relevant information about connected devices and Ethernet ports offered by the logical 3GPP/TSN bridge. It further allows for managing the state of each Ethernet port, which is tightly coupled with the status of the UE within the 5GS – for example, a port can only be operational if a PDU Session has been established.

Furthermore, information on the network topology and the network status is collected by the 3GPP bridge on the existing interfaces – that is to say, ports of a 3GPP bridge. This information needs to be maintained in the form of BMOs describing the bridge ports. Any change in the state of bridge ports or the connectivity between ports needs to be signaled to the network management (e.g., CNC) so that potential bridge reconfigurations can be made.

Integration with the synchronization framework

Acting as a bridge, the 5GS must behave like a gPTP relay instance, adding its residence time to the correction field of gPTP messages and thereby compensating for any delay jitter experienced inside the 5GS, including air interface. The accuracy achieved via the gPTP protocol depends significantly on the accuracy with which residence time is compensated (e.g., resulting delay jitter), and hence a key element is an internal 5GS mechanism in order to wirelessly synchronize the UE to the network timing so that a reliable assessment of the internal delays can be conducted. The 5G bridge acts in transparent mode – for example, the bridge port (e.g., UE) will estimate the residence time spent through the 5GS (via timestamps provided both in the core network and the UE) and then will modify the timestamp of the Follow-Up packet to account for this delay. To ensure full integration, the translator components (DS-TT and NW-TT) facing the external Industrial Ethernet need to provide several functionalities as part of an IEEE802.1AS system.

5G System enhancements for TSC

In order to optimally support TSC applications, the 5GS has adopted several features and mechanisms in Rel-16 that go beyond the support of the IEEE TSN standard. The RAN is generally the bottleneck inside the bridge, and thus new enhancements have been tailored to the requirements and traits of TSC traffic flows. As described earlier, the 5G network establishes key end-to-end QoS parameters for each of the UE-UPF TSC connection pairs linked to the committed bridge object attributes (e.g. TSN Bridge Delay and packet size dependent/independent delay). In addition to using the configuration received from the CNC relating to, for example, gate schedules, priority information about the supported traffic flows can be acquired that can help optimize the wireless resource utilization and efficiency.

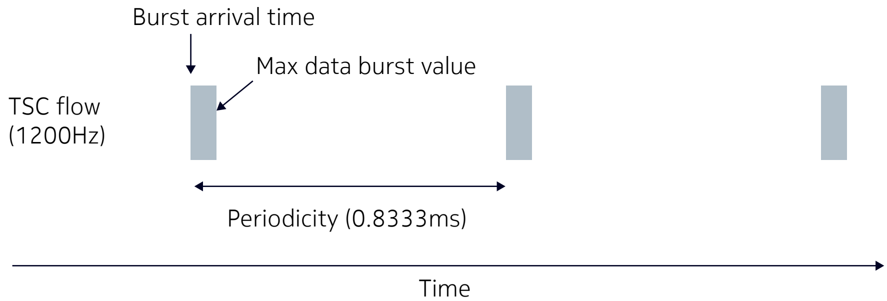
Configuring the RAN for TSC traffic

TSC applications are often characterized by being strictly periodic and with well-defined behavior. Furthermore, absolute time of arrival of messages can often be configured and is known within the network. In order to improve both the delay performance as well as TSC traffic capacity that can be provided, a key feature of the 5GS is to configure the RAN with detailed a priori information of the deterministic TSC traffic flows. Knowing the behavior of the application flow, the system can pre-reserve resources, not only for TSC traffic but also to free up resources for other non-TSC traffic. This is a key philosophy in all deterministic networking in order to increase the possible offered load for critical flows with strict requirements.

TSC flows are mapped to the Delay Critical Guaranteed Bitrate QoS category, which informs the RAN about expected packet burst size etc. However, for the base station (gNB) to have extended information regarding deterministic and periodic flows, 3GPP has introduced TSC Assistance Information (TSCAI), which comprises Burst Arrival Time and Periodicity for uplink and downlink flows. The 5GS may derive the TSCAI parameters from the IEEE TSN parameters provided by the CNC. The arrival time and periodicity of a TSN stream may be mapped to specific TSCAI to be used to tune radio, transport and core network resources inside the 5GS.

As shown in Figure 5, the TSCAI represents some of the key service flow characteristics. The Burst Arrival Time is defined either at the UE for uplink flows or the gNB for downlink flows. It should be noted that the periodicity of vertical services may not always fit well with the 3GPP 5G numerology and the periodicity of transmitting radio frames. Knowing the exact timing of the incoming bursts, the base station scheduler can prepare its resources to reduce the latency in both uplink and downlink, and it can reduce the time of the scheduling process and thus also reduce the experienced delays.

Figure 5: Simple example of TSC flow defined by TSC Assistance Information (TSCAI) parameters



Optimized scheduling of TSC traffic

Being strictly periodic with very low periodicity down to 0.5ms and delay requirements for the air interface lower than 0.5ms, semi-persistent scheduling (SPS) methods are very attractive compared to dynamic scheduling methods. Beside lower scheduling complexity, SPS provides other notable benefits for TSC, including less reliance on control channel reliability. This benefit often outweighs the drawback of fixing resources semi-statically compared to using optimal parameters per transmission with dynamic grants. Notably, because for the shortest delay requirements, there is no time for retransmissions. With 3GPP Rel-16, semi-persistent allocations can now support very fast periodic allocations, for example down to 250μs for a 60kHz subcarrier spacing. Furthermore, for uplink and downlink, multiple configured grant (in uplink) or SPS configurations (in downlink) are supported per UE in order to support multiple TSC flows effectively.

For dynamic scheduling, the available TSCAI can also be used to effectively pre-reserve uplink resources, for example avoiding the traditional uplink scheduling delays when a UE requests a scheduling grant only after data has arrived for transmission.

Time synchronization of end devices

The 5GS enables support of synchronization of end devices to TSN clock Grand Master (GM) using IEEE 802.1AS. Thus, in order for the 5GS to support the transmission of gPTP messages and perform residence time compensation, the UPF as well as DS-TT behind each UE must share a common time reference to be used for timestamping messages at the ports of the logical 3GPP/TSN bridge. Furthermore, to adjust the scheduler and allocated resources to the packets of the traffic flows, the RAN also needs to know the absolute time for which traffic is defined. Internally, in the 5GS the 5G clock is used as common reference among the UE, RAN and UPF. When traffic characteristics (i.e., relevant parameters) are defined in another clock domain (e.g., the clock domain used by a vertical), conversion of the parameters to be based on the 5G clock needs to be done as part of setting up the TSC QoS flows.

Phase synchronization to the RAN clock is something 3GPP terminals have always done for the purpose of frame alignment. In Rel-16, additional capability has been added for the network to inform the terminal about what was the absolute time at predefined boundaries, allowing the terminal to set its internal real-time clock with high accuracy compared to the clock of the 5GS; typically Universal Time Coordinated (UTC). To deliver the reference time, Rel-16 includes two different methods based on System Information Block messages that can be broadcasted to all UEs, and Radio Resource Control messages for unicast transmission of absolute time to a single UE, respectively. The achievable accuracy of the UE time synchronization with a 5G GM depends on several factors, including channel environment, cell size, mobility and implementation. An evaluation of the achievable time synchronization performance was performed by 3GPP (see 3GPP TR 38.825), assuming that timing errors within the operator's network (e.g., between the UPF and gNBs) and toward the vertical network (in the case where the vertical provides the GM) do not exceed the inherent time synchronization errors over the air interface. The study concluded that an absolute time synchronization accuracy better than the requirement of 1μs can be achieved for the IIoT use cases currently considered for wireless TSC.

5G bridge performance

Given the enhancements provided in Rel-16 and using the 3GPP IIoT reference scenarios (3GPP TR 38.901), Nokia has numerically evaluated the expected performance for a logical 3GPP/TSN bridge for an open space scenario with 12 ceiling-mounted cells with 20m inter-site distance and 20MHz spectrum deployed (30kHz subcarrier configuration, 2-symbol mini-slot). An SPS method was applied where allocations are tuned to the traffic flow (e.g., known from TSCAI) or delayed to the next transmission time interval if the system is fully loaded. User locations were randomized, and so were the arrival time of their traffic flows.

Table 1: Example performance results of 5G TSN bridge, from core network port to any device port

Characteristic	Performance
One-way latency (99.999% reliability)	<60μs*
Synchronization inaccuracy	<1μs (5G air interface <50ns)**
Number of supported TSN listeners/talkers	>360***

* Frequency Division Duplex (FDD) arrangement. Assuming local optimized core network connection with <10μs contributed latency (obtained based on measurements).
** Assuming that timing errors between gNBs and the UPF as well as drift errors between vertical and 5G clock domains do not exceed those of the 5G air interface.
*** Each having traffic with random time offset, 0.5ms periodicity and up to 50B payload.

Deployment

Planning a deployment of the 5G bridge within an existing factory environment calls for several considerations, some of which are listed in Table 2.

Table 2: Planning 5G TSN bridge deployment in an existing factory environment (brownfield)

Area	Considerations
IEEE 802.1Q vs. full TSN support in 5G bridge	For many real-time applications, already today IEEE 802.1Q provides sufficient QoS guarantees. A logical 3GPP/TSN bridge also supports IEEE 802.1Q and as such does not rely on the availability of TSN. However, as networks are upgrading and TSN is also deployed in factories, 5G deployment is future-proof and would be capable of making use of TSN.
Number of bridges/ access points toward the fixed-line network	The logical 3GPP/TSN bridge is dependent on a fixed number of ports on both the terminal side and fixed-line network side. Hence, it is possible to instantiate a flexible number of bridges using the same 5G installation. Furthermore, the fixed-line network access can be localized in order to guarantee low latencies and localize traffic. Localized and campus-wide 5G bridges can coexist.
Synchronization	The deployment of end-to-end synchronization features and their quality can be localized as well, whether for a static machine, a mobile automated guided vehicle or a wide area process automation deployment. The 5G clock can be used as a grandmaster also outside of the logical 3GPP/TSN bridge.
Public/private deployments	The logical 3GPP/TSN bridge is usable with purely private deployments as well as operator-based public deployments, for example where it may be offered in a specific network slice managed by a mobile network operator.
Performance and scalability	In quantitative analyses based on the 5G-ACIA use case models, Nokia has shown that the end-to-end system latency for highly critical traffic based on IEEE 802.1Q (typical “PCP 7” traffic) can be as low as 60µs (in uplink and downlink) using 5G New Radio technologies with 15kHz subcarrier spacing. 3GPP 5G is also capable of making use of IEEE 802.1Q traffic differentiation methods (PCP) to significantly reduce the experienced end-to-end latency, and of IEEE 802.1Qbv (TSN scheduled traffic) to eliminate jitter and further reduce latency. Wireless performance depends, however, on detailed planning against both reliability and availability targets.
Spectrum	Generally, licensed spectrum offers guaranteed resource allocation according to specific periodic schedules and is more robust compared to unlicensed technologies for cases where an external interface cannot be fully controlled. With multi-connectivity methods, robust solutions can be built combining licensed and unlicensed spectrum. Spectrum may be licensed through an operator or acquired directly via license. Paired spectrum (FDD) generally offers better delay performance compared to unpaired (TDD) spectrum.

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Summary and outlook

Creating full support for factory automation and other critical IIoT applications requires effort spanning multiple 3GPP Releases. 3GPP Rel-16 was the first main Release introducing significant new features for IIoT applications. Support for integration with IEEE TSN is extremely critical to addressing use cases (especially factories) where TSN deployment is expected.

Leveraging the 5GS enablers specified for IEEE TSN integration also for other use cases will increase the value-add of the enablers specified for TSN in Rel-16. In Rel-17, enhancements to support TSC natively (without dependency on IEEE TSN) within the 5GS are expected. Native support of TSC increases the value-add of the 5GS by enabling various deployments (e.g., audio-video production, music festivals, smart grids, etc.).

Furthermore, enablers introduced for TSC could be offered as a service independently by the network based on application needs. These enablers may also be leveraged by internet and gaming applications to obtain support for necessary QoS, reliability and synchronization. The aim is to capture mass market when and where possible with low incremental cost but with high reward. This also allows newer business models to be enabled between an operator and application provider.

Further reading

Bell Labs Report: “Industrial IoT Networks: 5G transforming industry verticals”, https://onestore.nokia.com/asset/202286

Use cases, IEC/IEEE 60802: http://www.ieee802.org/1/files/public/docs2018/60802-industrial-use-cases-0918-v13.pdf

3GPP TS 23.501 “System architecture for the 5G System (5GS)”

3GPP TS 23.502 “Procedures for the 5G System (5GS)”

3GPP TS 23.503 “Policy and charging control framework for the 5G System (5GS)”

3GPP TS 38.30 “New Radio; Overall description”

3GPP TS 38.401 “5G; NG-RAN; Architecture description”

3GPP TS 38.410 “NG-RAN; NG general aspects and principles”

3GPP TR 38.825 “Study on NR industrial Internet of Things (IoT)”

3GPP TR 38.901 “Study on channel model for frequencies from 0.5 to 10 GHz”

IEEE 802.1Q-2018 “IEEE standard for local and metropolitan area networks – Bridges and bridged networks”

IEEE 802.1AB-2016 “IEEE standard for local and metropolitan area networks – Station and Media Access Control connectivity discovery”

IEEE 802.1AS-2011 “IEEE standard for local and metropolitan area networks – Timing and synchronization for time-sensitive applications”

IETF RFC 3410 “Introduction and applicability statements for internet standard management framework”

About Nokia

We create the technology to connect the world. Only Nokia offers a comprehensive portfolio of network equipment, software, services and licensing opportunities across the globe. With our commitment to innovation, driven by the award-winning Nokia Bell Labs, we are a leader in the development and deployment of 5G networks.

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Nokia OYJ
Karakaari 7
02610 Espoo
Finland
Tel. +358 (0) 10 44 88 000

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