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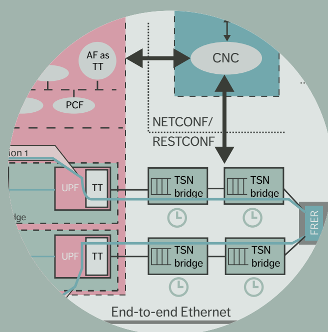
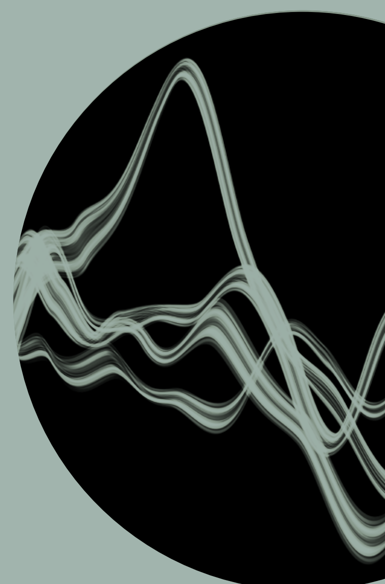
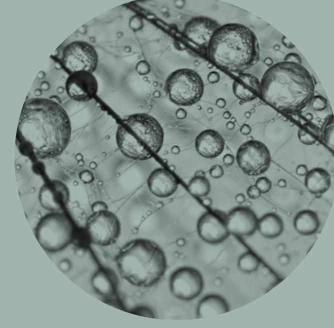
ERICSSON TECHNOLOGY Review





5G-TSN INTEGRATION FOR INDUSTRIAL AUTOMATION



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5G-TSN integration meets networking requirements

FOR INDUSTRIAL AUTOMATION

The move toward smart manufacturing creates extra demands on networking technologies – namely ubiquitous and seamless connectivity while meeting the real-time requirements. Today, 5G is good for factories; nevertheless, its integration with Time-Sensitive Networking (TSN) would make smart factories fully connected and empower them to meet all key requirements on industrial communication technology.

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Industrial automation is one of the industry verticals that can benefit substantially from 5G, including, for example, increased flexibility, the reduction of cables and support of new use cases [1]. At the same time, factory automation is going through a transformation due to the fourth industrial revolution (also known as Industry 4.0), and this requires converged networks that support various types of traffic in a single network infrastructure.

As it stands, IEEE (Institute of Electrical and Electronics Engineers) 802.1 Time-Sensitive Networking (TSN) is becoming the standard Ethernet-based technology for converged networks of Industry 4.0. It is possible for 5G and TSN to coexist in a factory deployment and address their primary requirements, such as 5G for flexibility and TSN for extremely low latency. Beyond that, 5G and TSN can be integrated to provide solutions to the aforementioned demands of ubiquitous and seamless connectivity with the deterministic QoS required by control applications end to end. Ultimately, integrating these key technologies provides what is needed for smart factories.

5G: adding ultra-reliable low-latency communication

5G has been designed to address enhanced mobile broadband services for consumer devices such as smartphones or tablets, but it has also been tailored for Internet of Things (IoT) communication and connected cyber-physical systems. To this end, two requirement categories have been defined: massive machine-type communication for a large number of connected devices/sensors, and ultra-reliable low-latency communication (URLLC) for connected control systems and critical communication [1] [2]. It is the capabilities of URLLC that make 5G a suitable candidate for wireless deterministic and time-sensitive communication. This is essential for industrial automation, as it can enable the creation of real-time interactive systems, and also for the integration with TSN.

Several features have been introduced to 5G in phase 1 (3GPP Release 15) and phase 2 (3GPP Release 16, to be finalized by March 2020) that reduce the one-way latency and enable the transmission of messages over the radio interface with reliability of up to 99.999 percent, achievable in a controlled environment such as a factory.

> “ULTIMATELY, INTEGRATING THESE KEY TECHNOLOGIES PROVIDES WHAT IS NEEDED FOR SMART FACTORIES”

5G RAN features

5G RAN [3] with its New Radio (NR) interface includes several functionalities to achieve low latency for selected data flows. NR enables shorter slots in a radio subframe, which benefits low-latency applications. NR also introduces mini-slots, where prioritized transmissions can be started without waiting for slot boundaries, further reducing latency. As part of giving priority and faster radio access to URLLC traffic, NR introduces preemption – where URLLC data transmission can preempt ongoing non-URLLC transmissions. Additionally, NR applies very fast processing, enabling retransmissions even within short latency bounds.

Definition of key terms

Smart factories are being developed as part of the fourth industrial revolution. They require ubiquitous connectivity among and from the devices to the cloud through a fully converged network, supporting various types of traffic in a single network infrastructure, which also includes mobile network segments integrated into the network.

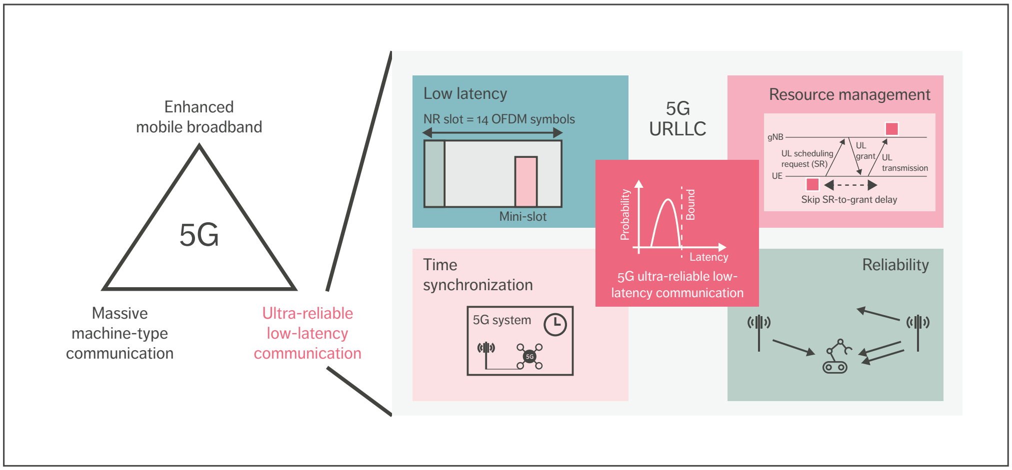

Figure 1 5G URLLC overview

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

Time synchronization is embedded into the 5G cellular radio systems as an essential part of their operation, which has already been common practice for earlier cellular network generations. The radio network components themselves are also time synchronized, for instance, through the precision time protocol telecom profile [4]. This is a good basis to provide synchronization for time-critical applications.

Figure 1 illustrates URLLC features. It shows that 5G uses time synchronization for its own operations, as well as the multiple antennas and radio channels that provide reliability. 5G brings in redefined schemes for low latency and resource management, which can be combined to provide ultra-reliability and low latency.

Besides the 5G RAN features, the 5G system (5GS) also provides solutions in the core network (CN) for Ethernet networking and URLLC. The 5G CN supports native Ethernet protocol data unit (PDU) sessions. 5G assists the establishment of redundant user plane paths through the 5GS, including RAN, the CN and the transport network. The 5GS also allows for a redundant user plane separately between the RAN and CN nodes, as well as between the UE and the RAN nodes.

Time-Sensitive Networking for converged networks

TSN provides guaranteed data delivery in a guaranteed time window; that is, bounded low latency, low-delay variation and extremely low data loss, as illustrated in Figure 2. TSN supports various kinds of applications having different QoS requirements: from time- and/or mission-critical data traffic, for example, closed-loop control, to best-effort traffic over a single standard Ethernet network infrastructure; in other words, through a converged network. As a result, TSN is an enabler of Industry 4.0 by providing flexible data access and full connectivity for a smart factory.

Time-Sensitive Networking standards

TSN is a set of open standards specified by IEEE 802.1 [5]. TSN standards are primarily for IEEE Std 802.3 Ethernet, which means they utilize all the benefits of standard Ethernet, such as flexibility, ubiquity and cost savings.

TSN standards can be seen as a toolbox that includes several valuable tools, which can be categorized into four groups: traffic shaping, resource management, time synchronization and reliability, as shown in *Figure 2*. Here, we focus only on the TSN tools that are strong candidates for early TSN deployments in industrial automation.

TSN guarantees the worst-case latency for critical data by various queuing and shaping techniques and by reserving resources for critical traffic. The Scheduled Traffic standard (802.1Qbv) provides time-based traffic shaping. Ethernet frame preemption (802.3br and 802.1Qbu), which can suspend the transmission of a non-critical Ethernet frame, is also beneficial to decrease latency and latency variation of critical traffic.

Resource management basics are defined by the TSN configuration models (802.1Qcc). Centralized Network Configuration (CNC) can be applied to the network devices (bridges), whereas, Centralized User Configuration (CUC) can be applied to user devices (end stations). The fully centralized configuration model follows a software-defined networking (SDN) approach; in other words, the CNC and CUC provide the control plane instead of distributed protocols. In contrast, distributed control protocols are applied in the fully distributed model, where there is no CNC or CUC.

High availability, as a result of ultra-reliability, is provided by Frame Replication and Elimination for Reliability (FRER) (802.1CB) for data flows through a per-packet-level reliability mechanism. This provides reliability by transmitting multiple copies of the same data packets over disjoint paths in the network. Per-Stream Filtering and Policing (802.1Qci) improves reliability by protecting against bandwidth violation, malfunctioning and malicious behavior.

The TSN tool for time synchronization is the

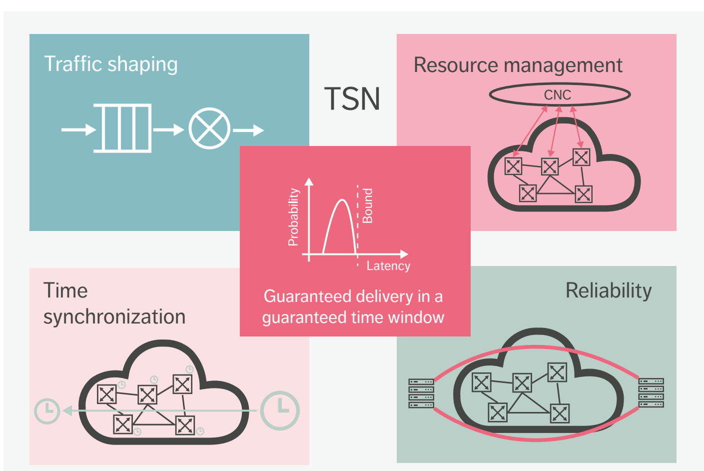

Figure 2 Valuable tools within the TSN toolbox that enable deployments in industrial automation

generalized Precision Time Protocol (gPTP) (802.1AS), which is a profile of the Precision Time Protocol standard (IEEE 1588). The gPTP provides reliable time synchronization, which can be used by other TSN tools, such as Scheduled Traffic (802.1Qbv).

It is important to note that TSN standards are built upon the base IEEE 802.1 bridging standards, some of which have to be supported in TSN deployments as well – including industrial automation.

A special set of TSN standards are the TSN profiles because a profile selects TSN tools and describes their use for a particular use case or vertical.

Time-Sensitive Networking for industrial automation

The IEC/IEEE 60802 profile [6] specifies the application of TSN for industrial automation, and also gives guidelines to what 5G needs to support. IEC/IEEE 60802 provides basis for other standards targeting interoperability in industrial automation. For instance, Open Platform Communications (OPC) Foundation's Field Level Communications [7] initiative aims for one common multi-vendor converged TSN network infrastructure.

The IEC/IEEE 60802 profile will specify multiple classes of devices. There will be at least two classes of devices for both device types – bridges and end stations. One class is feature rich (currently called Class A), and the other class is constrained (currently called Class B), meaning that it supports a smaller set of features. Bridges and end stations belonging to the same class have the same mandatory and optional TSN capabilities.

The Link Layer Discovery Protocol (LLDP) (802.1AB) is mandatory for all device types and classes for the discovery of the network topology and neighbor information.

Time synchronization is also mandatory for all device types and classes. The current target is to support a minimum of three time domains for Class A and a minimum of two time domains for Class B.

Class A devices must support a wide range of TSN functions (such as Scheduled Traffic, Frame Preemption, Per-Stream Filtering and Policing, FRER and TSN configuration), which are optional for Class B devices.

Integrated 5G and Time-Sensitive Networking

5G URLLC capabilities provide a good match to TSN features (as illustrated in Figures 1 and 2). The two key technologies can be combined and integrated to provide deterministic connectivity end to end, such as between input/output (I/O) devices and their controller potentially residing in an edge cloud for industrial automation. The integration includes support for both the necessary base-bridging features and the TSN add-ons.

Terms and abbreviations

5GS – 5G System | **5QI** – 5G QoS Indicator | **AF** – Application Function | **CN** – Core Network | **CNC** – Centralized Network Configuration | **CUC** – Centralized User Configuration | **FRER** – Frame Replication and Elimination for Reliability | **gNB** – Next generation Node B (5G base station) | **gPTP** – Generalized Precision Time Protocol | **I/O** – Input/Output | **IEC** – International Electrotechnical Commission | **IEEE** – Institute of Electrical and Electronics Engineers | **IoT** – Internet of Things | **LLDP** – Link Layer Discovery Protocol | **NR** – New Radio | **OFDM** – Orthogonal Frequency Division Multiplexing | **OPC** – Open Platform Communications | **PCF** – Policy Control Function | **PDU** – Protocol Data Unit | **SDN** – Software-Defined Networking | **TSN** – Time-Sensitive Networking | **TT** – TSN Translator | **UE** – User Equipment | **UL** – Uplink | **UPF** – User Plane Function | **URLLC** – Ultra-Reliable Low-Latency Communication

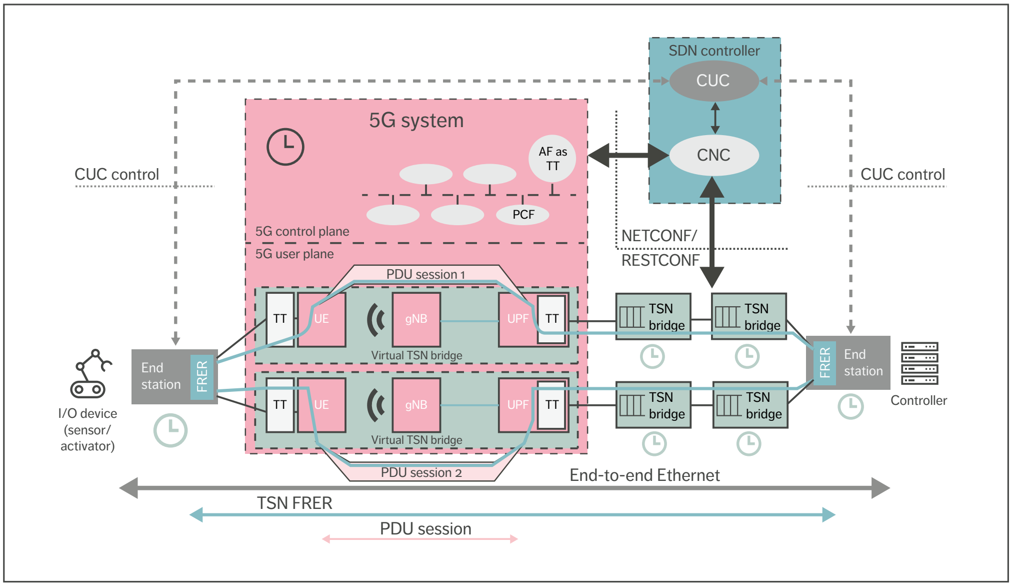

Figure 3 5GS integrated with TSN providing end-to-end deterministic connectivity

Figure 3 illustrates the 5G-TSN integration, including each TSN component shown in Figure 2. It shows the fully centralized configuration model, which is the only configuration model supported in 5G phase 2 (3GPP Release 16).

The 5GS appears from the rest of the network as a set of TSN bridges – one virtual bridge per User Plane Function (UPF) as shown in the figure. The 5GS includes TSN Translator (TT) functionality for the adaptation of the 5GS to the TSN domain, both for the user plane and the control plane, hiding the 5GS internal procedures from the TSN bridged network.

The 5GS provides TSN bridge ingress and egress port operations through the TT functionality. For instance, the TTs support hold and forward functionality for de-jittering. The figure illustrates functionalities using an example of two user equipments (UEs) with two PDU sessions supporting two correlated TSN streams for redundancy. But a deployment may only include one physical UE with two PDU sessions using dual-connectivity in RAN. The figure illustrates the case when the 5GS connects an end station to a bridged network; however, the 5GS may also interconnect bridges.

The support for base bridging features described here is applicable whether the 5G virtual bridges are Class A or Class B capable. The 5GS has to support the LLDP features needed for the control and management of an industrial network, such as for the discovery of the topology and the features of the 5G virtual bridges. The 5GS also needs to adapt to the loop prevention method applied in the bridged network, which may be fully SDN controlled without any distributed protocol other than LLDP.

5G supporting Time-Sensitive Networking

Ultra-reliability can be provided end to end by the application of FRER over both the TSN and 5G domains. This requires disjoint paths between the FRER end points over both domains, as illustrated in Figure 3.

> THE 5G-TSN INTEGRATION IS A KEY TOPIC OF IMPORTANCE AT ERICSSON

A 5G UE can be configured to establish two PDU sessions that are redundant in the user plane over the 5G network [2]. The 3GPP mechanism involves the appropriate selection of CN and RAN nodes (UPFs and 5G base stations (gNBs)), so that the user plane paths of the two PDU sessions are disjoint. The RAN can provide the disjoint user plane paths based on the use of the dual-connectivity feature, where a single UE can send and receive data over the air interface through two RAN nodes.

The additional redundancy – including UE redundancy – is possible for devices that are equipped with multiple UEs. The FRER end points are outside of the 5GS, which means that 5G does not need to specify FRER functionality itself. Also, the logical architecture does not limit the implementation options, which include the same physical device implementing end station and UE.

Requirements of a TSN stream can be fulfilled only when resource management allocates the network resources for each hop along the whole path. In line with TSN configuration (802.1Qcc), this is achieved through interactions between the 5GS and CNC (see Figure 3). The interface between the 5GS and the CNC allows for the CNC to learn the characteristics of the 5G virtual bridge, and for the 5GS to establish connections with specific parameters based on the information received from the CNC.

Bounded latency requires deterministic delay from 5G as well as QoS alignment between the TSN and 5G domains. Note that 5G can provide a direct wireless hop between components that would otherwise be connected via several hops in a traditional industrial wireline network. Ultimately, the most important factor is that 5G can provide deterministic latency, which the CNC can discover together with TSN features supported by the 5GS.

For instance, if a 5G virtual bridge acts as a Class A TSN bridge, then the 5GS emulates time-controlled packet transmission in line with Scheduled Traffic (802.1Qbv). For the 5G control plane, the TT in the application function (AF) of the 5GS receives the transmission time information of the TSN traffic classes from the CNC. In the 5G user plane, the TT at the UE and the TT at the UPF can regulate the time-based packet transmission accordingly. TT internal details are not specified by 3GPP and are left for implementation. For example, a play-out (de-jitter) buffer per traffic class is a possible solution. The different TSN traffic classes are mapped to different 5G QoS Indicators (5QIs) in the AF and the Policy Control Function (PCF) as part of the QoS alignment between the two domains, and the different 5QIs are treated according to their QoS requirements.

Time synchronization

Time synchronization is a key component in all cellular networks (illustrated by the black 5GS clock in Figure 3). Providing time synchronization in a 5G-TSN combined industrial deployment brings in new aspects. In most cases, end devices need time reference regardless of whether it is used by TSN bridges for their internal operations. Bridges also require time reference if they use a TSN feature that is based on time, such as Scheduled Traffic (802.1Qbv). The green clocks in Figure 3 illustrate a case when both bridges and end stations are time synchronized.

As gPTP is the default time synchronization solution for TSN-based industrial automation, the 5GS needs to interwork with the gPTP of the connected TSN network. The 5GS may act as a virtual gPTP time-aware system and support the forwarding of gPTP time synchronization information between end stations and bridges through the 5G user plane TTs. These account for the residence time of the 5GS in the time synchronization procedure. One special option is when the 5GS clock acts as a grandmaster and provides the time reference not only within the 5GS, but also to the rest of the devices in the deployment, including connected TSN bridges and end stations.

Overall, 5G standardization has addressed the key aspects needed for 5G-TSN integration.

Conclusion

Together, 5G and Time-Sensitive Networking (TSN) can meet the demanding networking requirements of Industry 4.0. The 5G-TSN integration is a key topic of importance at Ericsson, and we see that the combination of 5G and TSN is perfect for smart factories, given the features provided for ultra-reliability and low latency. That said, a certain level of integration of the two technologies is needed to provide an end-to-end Ethernet connectivity to meet the industrial requirements.

Integrated time synchronization via wireless 5G and wired TSN domains provides a common reference time for industrial end points. 5G is also integrated with the given TSN tool used in a particular deployment to provide bounded low latency. The disjoint forwarding paths of the 5G and TSN segments are aligned to provide end-to-end ultra-reliability and high availability.

The first step of control plane integration is being carried out for a software-defined networking-based approach (the fully centralized model of TSN). Fundamentally, 5G and TSN include the key technology components required for combined deployment in industrial automation and high availability.

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Further reading

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