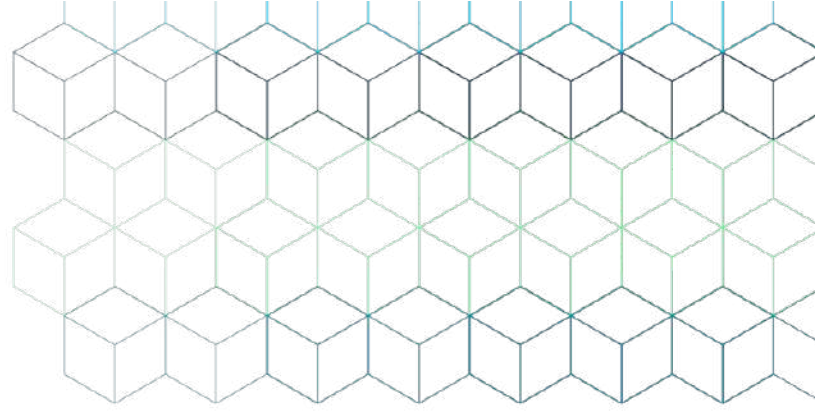


A 5G AMERICAS WHITE PAPER

UNDERSTANDING 5G & TIME CRITICAL SERVICES

AUG 2022



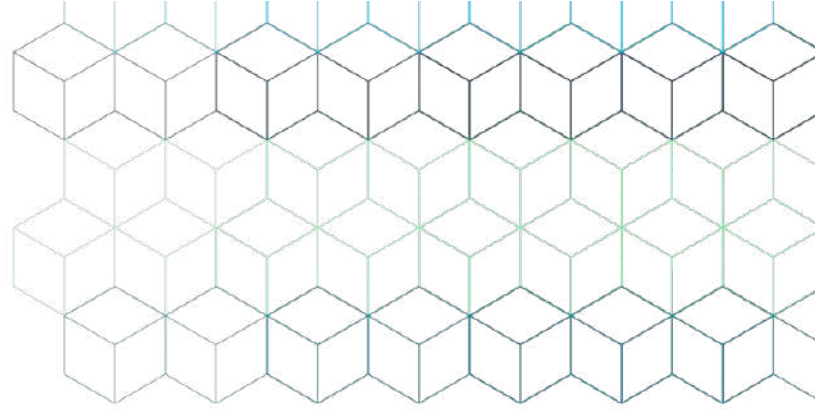


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1. Introduction

Starting with 3GPP Release 16, 5G is enhanced to address many new verticals including industrial, mission critical use cases, and precise time delivery. 5G introduced technologies such as Ultra Reliable Low Latency Communication (URLLC) and Time Sensitive Networking (TSN) support to address these verticals. This report highlights how these technologies operate and come together to address the diverse use cases and new applications required by these verticals.



2. Key use cases and requirements

2.1 Overview

5G has been designed to fulfill a vision to help digitally transform various enterprises and industries. Digitalization improves agility, increases production efficiency, and unlocks intelligence. The connectivity requirements for enterprise and industrial use cases can be very different from those of consumer use cases. While data rate and throughput serve as the main benchmarks for consumer use cases like internet browsing and video streaming, the requirements for many use cases in enterprises and industrial sectors go much beyond these. In this section, we describe use cases in various industrial sectors that require data delivery within a specified time duration, and with guaranteed reliability. Such bounded-latency requirements and use cases that require bounded latency can generally be referred to as time-critical service (TCS) use cases. TCS use cases can be served by the URLLC and TSN features in 5G, which will be described in Section 3.

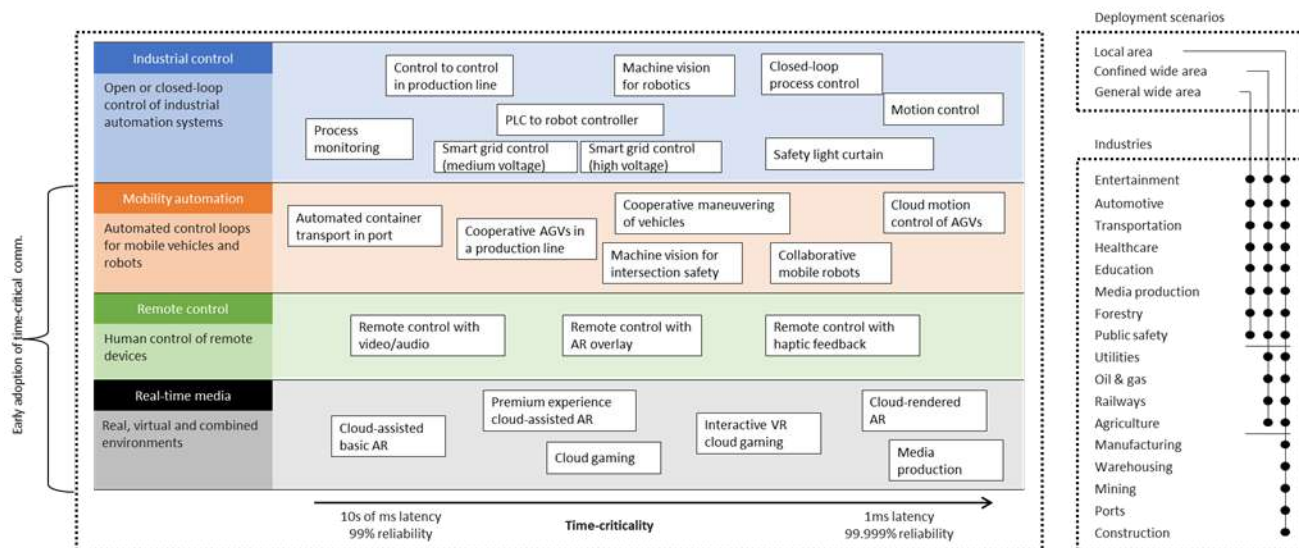
As part of the development of this white paper, we surveyed industrial sectors such as entertainment, automotive, transportation, healthcare, education, media production, forestry, public safety, utilities, oil and gas, railways, agriculture, manufacturing, warehousing, mining, ports, and construction. The TCS use cases in these industrial sectors can be classified into four use case families: Industrial Control, Mobility Automation, Remote Control, and Real-Time Media. Within each use case family, the use cases can be further classified into several categories according to different levels of time-criticality requirements as shown in Figure 2-1.

These industrial sectors also have different coverage needs and therefore call for different deployment scenarios. While we have found that all these industrial sectors have use cases that require local area coverage, most sectors also have use cases that require wide-area coverage, either general wide-area for serving devices virtually anywhere or a confined wide area, e.g., along a highway, between certain electrical substations, or within a city center.

Although the exact time-criticality of each of the use-case categories shown in Figure 2-1 can be further debated and refined, key take-aways from the summary in Figure 2-1 are:

- *Many industrial sectors have TCS use cases that require bounded latency and a guaranteed level of reliability.*
- *The TCS use cases in a specific industrial sector can have a wide-range of time-criticality requirements.*
- *The coverage consideration of one industrial sector can go much beyond local-area and would therefore require network deployment in wide area.*

Figure 2-1 TCS use cases in various industrial sectors (Contributed by a 5G Americas member company)



2.2 IEEE Time Sensitive Networking over 5G

The IEEE 802.1 TSN standard is becoming the converged networking technology for factories to enable deterministic and low-latency communication in delay-sensitive industrial applications, due to its ability to provide flexible data access and full connectivity for a smart factory. To enable factory automation, different connectivity technologies need to coexist and be possible to be integrated in a TSN network used for factory automation - whether they are wired or wireless, 3GPP-based or non-3GPP.

The integrated network needs to be able to provide end-to-end ubiquitous and seamless connectivity with the deterministic quality of service (QoS) required by factory control applications. 5G-TSN integration is made possible with the new features introduced in 3GPP Release 16, including the support of IEEE 802.1AS [1] based TSN clock synchronization distribution over 5G, IEEE 802.1Q [2] based TSN bridge operation (specifically Qbv, Qcc and Qci), and IEEE 802.1AB [3] based TSN bridge neighboring discovery. Release 17 work further defined enhanced integration with IEEE TSN including support for uplink synchronization via 5G System (5GS), End-to-End QoS with multiple clock domains and UE-to-UE communication within 5GS.

2.3 Timing as a Service (TaaS) over 5G

2.3.1 Introduction and prominent use cases

Several systems require precision timing to ensure consistent operation. The timing accuracy requirement for such systems is typically about 1usec (microsecond). Such systems historically relied on Global Navigation Satellite

Systems (GNSS) to provide the required timing accuracy. 5G technology, starting in Release 16 and further enhanced in Release 17, provides similar level of timing service to such use cases. Typical use cases requiring precision timing are:

- *Commercial banking, asset exchanges and high frequency trading. These use cases typically require 1usec to 1msec of timing accuracy depending on regulatory standards and other factors. They are also a challenging use cases for existing precision timing solutions, such as GNSS, as they are indoor deployments.*
- *Electrical grip applications: Electrical grid systems with multiple generators require the generated power to be phase synchronized to each other, requiring precision timing at each station. While these systems typically utilize GNSS systems because they are outdoor deployments, 5G can provide a second source of timing as a backup solution.*
- *Industrial applications: Modern factories operate many types of machinery that are required to work in complete coordination with the rest of the factory system. To achieve high degree of coordination, precise time synchronization (usually about 1usec) between the machines is needed. Currently Precision Time Protocol (PTP) or its variants, such as IEEE 802.1AS, are used for time synchronization which requires wired ethernet connectivity.*

2.3.2 How to typically deliver accurate time

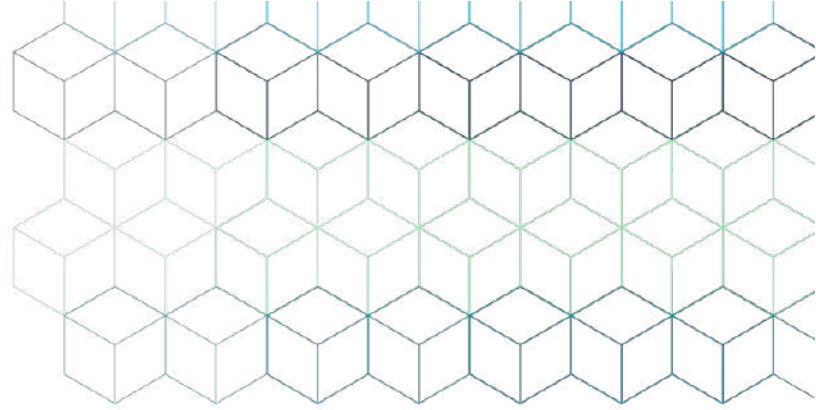
There are several technologies for generating and delivering timing information over a network connection. The table below summarizes the typical timing generation, delivery, and synchronization mechanisms.

Time delivery over 5G is unique compared to all the others in the sense that it can provide indoor coverage, microsecond level precision and wireless timing delivery.

Table 2-1 Typical timing generation, delivery, and synchronization mechanisms

Source	Typical Precision	Description
Atomic Clock	1 part per 10^{15}	An extremely expensive method of generating very high precision time. The root time reference for all other systems is typically an atomic clock.
NTP	<20 ms	Network Time Protocol: Dominant protocol for distributing time over internet. Not suitable for precision time delivery.
PTP	<1 us	Precision Time Protocol: Requires end-to-end support at all switches. Used in controlled deployments (e.g., factory, radio access network).
GPS	<50 ns	Global Positioning System: Over the air, free and very accurate. Requires outdoor unobstructed antenna.
GLONASS	<200 ns	Same as GPS
5GS	<1us	5G system may provide timing based on several referenes; Universal Time Coordinated (UTC), GNSS or Local Time.

3. Technology Enablers in 5G Releases 16 and 17



3.1 5G Architecture Supporting Time Synchronization

In order to support TSN over 5G, 3GPP Release 16 introduced IEEE 802.1AS [1] compliant time-aware system PTP-based time synchronization over. Release 17 supports other types of PTP instance compliant to IEEE Std 1588 [4], including boundary clock, peer-to-peer transparent clock and end-to-end transparent clock. As shown in Figure 31, the 5G solution supporting multiple modes of PTP time synchronization over 5G consists of two interworking synchronization systems.

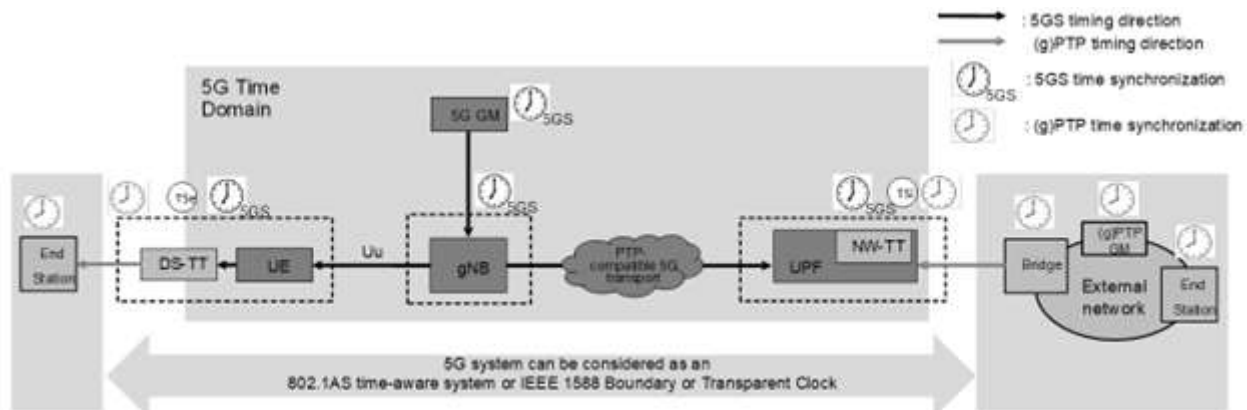
1.) **5G Access Stratum Timing Distribution System:** Used for 5G Radio Access Network (RAN) synchronization, including over the air with the UEs for time/frequency synchronization. Release 16 introduces distributing additional time-of-day absolute time to the UEs over the air. The User Equipment (UE), gNodeB (gNB), User Plane Function (UPF), Network-side TSN Translator (NW-TT) and Device side TSN Translator (DS- TT) are synchronized with the 5G Grandmaster (GM) clock, i.e., the 5G access stratum time.

2.) **(g)PTP domain synchronization:** To distribute PTP domain synchronization of the external network over 5G system.

These two synchronization processes can be considered independent from each other. For instance, gNB only needs to be synchronized to the 5G GM clock and provide 5G RAN synchronization process independent to the external network PTP. The DS-TTs and NW-TTs located at the edge of 5G system fulfill the functionalities (like PTP time stamping) to provide (g)PTP support from the end-to-end network perspective. From the end-to-end perspective, the 5G system can be considered as a bridge (as a time aware network) or act as a clock for the PTP system (reference/ boundary clock or transparent clock).

NW-TT and DS-TT handles PTP events and messages for distribution and updates time stamps at the ingress (ingress timestamping [TSi]) and at the egress (egress timestamping [TSe]) of the 5G network, respectively. These entities ensure that 5G networks comply with the externally observable behavior of the PTP instance as defined in the IEEE Std 1588 [4].

Figure 3-1 PTP Time Synchronization over 5G [5]



3.2 5G Architecture Supporting IEEE TSN

The support of TSN over 5G has been specified in 3GPP Release 16. As illustrated in Figure 32, 5GS acts as a virtual Layer 2 Ethernet bridge supporting the TSN functions that are compliant to IEEE 802.1Q [2], IEEE 802.1AS [1] and IEEE 802.1AB [3]. The 5G virtual bridge carries TSN traffic in 5G downlink (DL) and uplink (UL) directions via the ingress-egress port pair between the DS-TT of each UE and the NW-TT of the UPF.

The key functions to enable the support of TSN over 5G include TSN synchronization over 5G bridge, 5G bridge and port TSN capability reporting and configuration, 5G bridge TSN neighboring topology discovery, reporting and management, and 5G data path handling to map the TSN traffic streams to the proper 5G QoS flows of the UE's Protocol Data Unit (PDU) session via 5G session binding and QoS flow binding mechanisms.

In Release 17, the 5G system is expanded to support all bridge synchronization types defined in IEEE Std 1588 [4] (versus one type supported in Release 16), more accurate clock distribution over 5G with round-trip-time (RTT) based propagation delay compensation (including application survival time in QoS configuration), and deterministic QoS requested by 3rd party application functions outside of 5GS for both IP-based and ethernet-based traffic (vs only IEEE 802.1Q [2] specified QoS for Ethernet-based traffic). TSN over 5G deployment can take advantage of this Release 17 enhancement in synchronization and QoS handling to support broader deployment scenarios and use cases.

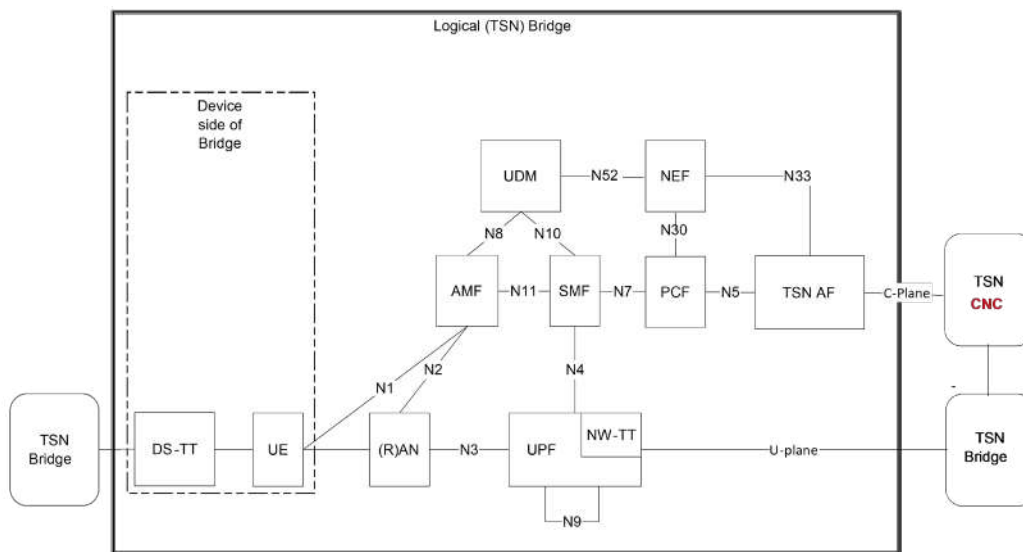
3.2.1 User Plane Support

In Release 16, NW-TT and DS-TT are introduced in the 5G user plane to support 5G bridge user plane integration with other TSN bridges. The main functions supported by NW-TT and DS-TT are:

- Synchronizing to TSN grandmaster clock and distributing grandmaster clock over 5G bridge to downstream TSN bridges. Please refer to Section 3.1 for details.
- Supporting hold-and-forward mechanisms compliant to IEEE 802.1Q [2]'s Qbv protocol to transmit the packets at the egress ports during the gate open interval.
- Supporting IEEE 802.1AB [3] Link Layer Discovery Protocol (LLDP) to discover 5G bridge's neighboring topology outside of its DS-TT ports and NW-TT ports.
- NW-TT and UPF to detect and report clock drift, in term of time offset and cumulative rate ratio exceeding certain thresholds, between 5G system time and external TSN grandmaster time.

The operation of NW-TT and DS-TT is managed by TSN Application Function (TSN-AF) via Bridge Management Information Container (BMIC) (as is called in Release 16 or User Plane Node Management Information Container (UMIC) as is called in Release 17), and Port Management Information Container (PMIC) as specified in 3GPP TS24.519 [6] in Release 16 and in 3GPP TS 24.539 [7] in Release 17. The detailed operation management is explained in Section 3.2.2.2.

Figure 3-2 Release 16 5G System as TSN Bridge [5]



3.2.2 Control Plane Support

In Release 16, a new network function is introduced in the 5G core network's control plane to allow an external TSN control node—Central Network Controller (CNC)—to manage 5G virtual bridge the same way as other conventional TSN-compliant bridge. Through TSN-AF, CNC manages the 5G virtual bridge the same way as it does towards a conventional TSN-compliant bridge. TSN-AF, NW-TT and DS-TT together enable the integration of the 5G virtual bridge with the TSN network completely transparent to CNC, TSN bridges, and TSN end points in control plane and user plane. Within 5GS, new signaling and procedures are specified in Release 16 to support information exchange between TSN-AF and 5G UE/DS-TT, Session Management Function (SMF), Policy Control Function (PCF) and UPF/NW-TT to support 5G virtual bridge detection, 5G bridge/port capability reporting, 5G bridge neighboring topology discovery and update, and 5G bridge/port operation configurations.

3.2.2.1 Interaction Between TSN-AF and CNC

In the north bound, TSN-AF and CNC exchange the following information to manage the 5G bridge in compliance with IEEE 802.1AB [3] and IEEE 802.1Q (Qbv, Qcc and Qci) [2] specs:

- *Information provided from TSN-AF to CNC:*
 - » *5G bridge and ingress-egress port pair capability update, e.g., bridge delay per port pair and txPropagationDelay per port*
 - » *5G bridge and ingress-egress port pair status update, e.g., a new pair detected*
 - » *5G bridge neighboring discovery results*
- *Information provided from CNC to TSN-AF:*
 - » *5G bridge and port egressing configuration*
 - *TSN traffic transmission configuration per traffic class at the egress port, e.g., IEEE 802.1Qbv's gate control information*
 - *TSN traffic forwarding info, i.e., static filtering entry containing the mapping between the destination mac address and the 5G bridge's egress port*
 - » *5G bridge neighboring discovery configuration*
 - » *Service data flow's QoS requirements and the scheduling assistant information per TSN stream*
 - *TSN stream characteristics per port pair, e.g., burst size, burst periodicity, burst arrival time, max bit rate and traffic class*

In Release 16 and Release 17 there are limitations on how TSN-AF can derive sufficient information based on the information that CNC can provide with current IEEE 802.1Q [2] specs with respect to the per TSN stream QoS and scheduling assistant information. For example, a lack of ingress port information of a TSN stream provided by CNC via IEEE 802.1Q's Per-Stream Filtering and Policing (PSFP) protocol prevents TSN-AF from associating UL stream's QoS requirement to a particular PDU session because TSN-AF relies on DS-TT port number (the ingress port for UL TSN streams) to determine which UE's PDU session should be configured with a QoS flow that supports the stream's UL QoS requirements.

3.2.2.2 5GC Control Plane Update

In the south bound, TSN-AF interacts with PCF via the Npcf_PolicyAuthorization service to support 5G bridge detection, 5G bridge information reporting, and 5G bridge traffic scheduling configuration as specified in 3GPP TS29.514 [8].

5G Bridge Detection

The 5G bridge does not register with CNC until the DS-TT of a 5G UE establishes an ingress-egress port pair with the NW-TT of a UPF in the 5GS. 5GS supports such ingress-egress port pair via an Ethernet Type PDU session between the corresponding UE and UPF.

A TSN-capable UE with DS-TT function initiates a PDU session establishment procedure to request an Ethernet type PDU session. It includes the following parameters: UE-DS-TT residence delay, DS-TT MAC address and the support of PMIC transport, i.e., in compliance with 3GPP TS24.519 [6] in Release 16 and 3GPP TS24.539 [7] in Release 17 by setting TPMIC bit to TRUE.

Once the SMF receives such PDU session establishment request, the SMF selects a proper TSN-capable UPF with NW-TT function before setting up a Packet Forwarding Control Protocol (PFCP) session with the UPF as specified in 3GPP TS29.224 [9]. The SMF also initiates the Npcf_SMPolicyControl_Create service as specified in 3GPP TS29.512 [10] to establish a SM Policy Association with PCF for this Ethernet type PDU session. Based on the Data Network Name (DNN) and/or Single Network Slice Selection Assistance Information (S-NSSAI) provided by SMF, PCF can detect that the PDU session is for a TSN service and will provide the "TSN_BRIDGE_INFO" policy control request trigger within the "policyCtrlReqTriggers" attribute within

the SmPolicyDecision data structure to instruct the SMF to trigger a PCF interaction when the trigger is met, such as when the new TSC bridge information is available.

During the PFCP session setup, SMF requests the UPF to allocate the port number for DS-TT and to provide the related 5G Bridge ID (as in Release 16) or User Plane Node ID (as in Release 17) by including the “Create Bridge Info for TSC” information element with the Bridge Information Indication bit set to “1” in the PFCP Session Establishment Request. The UPF allocates a port number for the UE’s DS-TT and reports it with Bridge ID or User Plane Node ID and NW-TT port number back to SMF. While SMF continues to complete PDU session establishment procedure with the signaling exchange towards UE, gNB, Access and Mobility Management Function (AMF) and UPF, SMF also initiates Npcf_SMPolicyControl_Update service to report to PCF about the detection of the new 5G bridge information with “tsnBridgeInfo” and NW-TT PMIC containing bridge ID, NW-TT and DS-TT port number, DS-TT MAC addresses and UE-DS-TT residence time.

The PCF then notifies TSN-AF about the detected 5G TSN bridge with “tsnBridgeInfo” and BMIC/UMIC information included in “PduSessionTsnBridge” of Npcf_PolicyAuthorization_Notify (specified in 3GPP TS29.514 [8]) over an existing pre-configured application function (AF) session. The TSN-AF then requests the creation of a new AF session associated with the DS-TT MAC address with PCF using the Npcf_PolicyAuthorization_Create and subscribes for TSN events over the newly created AF session using the Npcf_PolicyAuthorization_Subscribe. PCF binds the new AF session with an existing Ethernet Type PDU session based on the DS-TT MAC address.

5G Bridge Information Reporting

After a 5G bridge is detected and the binding between TSN-AF session and the 5G PDU session is completed, TSN-AF provides further TSN bridge configurations to manage the 5G bridge neighboring topology discovery and additional information reporting. TSN-AF initiates the Npcf_PolicyAuthorization_Update service with BMIC/UMIC and PMICs included in AppSessionContextUpdateData to:

- 1.) *provide DS-TT with LLDP configurations to discover DS-TT port’s neighboring TSN nodes, if DS-TT support the neighboring discovery;*
- 2.) *provide NW-TT with LLDP configurations to discover NW-TT port’s neighboring TSN nodes and potentially also DS-TT port’s neighboring TSN nodes if DS-TT does not support the neighboring discovery;*

3.) *and request NW-TT port and DS-TT port to report its txPropagationDelay and supported traffic classes.*

The BMIC/UMIC and PMIC information is encoded/decoded as specified in 3GPP TS24.519 [6] in Release 16 and 3GPP TS 24.539 [7] in Release 17 between TSN-AF and NW-TT/DS-TT. The message container is relayed by PCF and SMF to UE and UPF transparently via Npcf_SMPolicyControl_UpdateNotify/Update over N7 interface, PDU Session Modification procedure over N1 interface and Session Modification procedure over N4 interface. Based on the TSN-AF’s subscriptions established after 5G bridge detection, once PCF receives the PMIC and BMIC/UMIC from NW-TT and DS-TT, PCF will update TSN-AF using the data type of “EventsNotification” in Npcf_PolicyAuthorization_Notify over N5 interface with 5G bridge’s neighboring discovery information and ports’ capability information. N1, N4, N5 and N7 interfaces are shown in Figure 32.

TSN-AF constructs 5G bridge information to be provided to CNC based on the information provided by PCF and with certain bridge information provisioned at TSN-AF by Operations, Administration and Maintenance (OAM) during the initiation of the 5GS (such as bridge’s VLAN capability).

5G Bridge Traffic Scheduling Configuration

With the 5G bridge topology information and capability information provided by TSN-AF, CNC can determine which TSN traffic streams to be scheduled over 5G bridge and the corresponding egress port gate control information per egress port per traffic class.

TSN-AF sends the gate control information to the corresponding egress port, either a DS-TT port or a NW-TT port, with the same mechanism as described in Section 3.2.2.2.2. The egress port performs a hold-and-forward function based on the gate control information to ensure that the data packets of a TSN stream are transmitted at egress port only during the gate open window as scheduled by CNC.

In order to facilitate a 5G system that meets its QoS requirements (in terms of latency, the packet loss rate and the required data rate), TSN-AF needs to determine the proper 5G QoS flow mapping for the TSN stream. This includes 5G QoS Identifier (5QI), Guaranteed Flow Bit Rate (GFBR) and packet filter, based on the TSN stream’s traffic characteristics provided by CNC. In that case, the selection of 5QI should consider packet delay budget, packet error rate and max data burst volume of the stream’s

QoS requirements. To further improve 5G air interface scheduling efficiency, it is preferable for the TSN-AF to derive a set of scheduling assistant information, including the traffic stream's burst periodicity, burst size and burst arrival time as specified in Release 16, as well as the survival time as introduced in Release 17.

3.3 5G Architecture Supporting AF Requested Time Sensitive Communication and Time Synchronization Services

Release 17 introduces further enhancement to expand 5G system's support of time synchronization services from supporting IEEE 802.1AS [1] with Ethernet type PDU session only to supporting the full scope of IEEE Std 1588 [4] with both Ethernet type and IP type PDU session. A new network entity Time Sensitive Communication and Time Synchronization Function (TSCTSF) is introduced to enable such time synchronization enhancement and to support an AF to request 5G to provide the time synchronization services and/or to support non-TSN time sensitive communications. TSCTSF interacts with AF directly when AF is trusted, or indirectly via NEF when AF is non-trusted, depending on the network operator's deployment situation.

The main functionality of TSCTSF is to provide the following services to AF directly or indirectly via NEF as defined in 3GPP TS29.565 [11] and TS29.522 [12]:

- *Exposing AF with 5GS synchronization capability and availability to provide time synchronization service, using the following Application Programming Interface (API):*
 - » *Ntsctsf_TimeSynchronization_CapsSubscribe/CapsUnsubscribe/CapsNotify APIs;*
 - » *Nnef_TimeSyncExposure API's resources of "Time Synchronization Exposure Subscriptions" and "Individual Time Synchronization Exposure Subscriptions", as well as the API's "Time Synchronization Capability Notification";*
- *Enabling AF to configure the DS-TT and NW-TT of the 5GS to operate on an AF-selected synchronization method (e.g., one of the PTP instances compliant to either IEEE Std 1588 or IEEE 802.1AS) to support the time synchronization service using the following APIs:*
 - » *Ntsctsf_TimeSynchronization_ConfigCreate/ConfigUpdate/ConfigUpdateNotify/ConfigDelete APIs;*
 - » *Nnef_TimeSyncExposure API's resources of "Time Synchronization Exposure Configurations"*

and "Individual Time Synchronization Exposure Configurations", as well as the API's "Time Synchronization Configuration Notification";

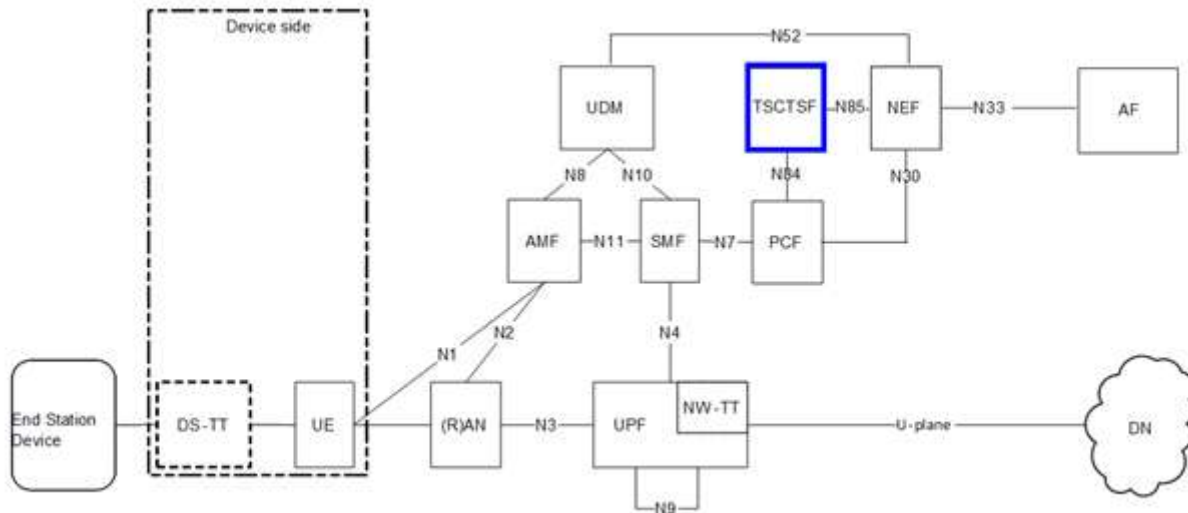
- *Enabling an AF to configure 5GS to distribute the 5G access stratum time clock to outside of 5GS, using the following APIs:*
 - » *Ntsctsf_ASTI_Create/Update/Delete/Get APIs;*
 - » *Nnef_TimeSyncExposure API's resources of "ASTI Configurations" and "Individual ASTI Configurations";*
- *Enabling an AF to provide 5GS with the proper QoS requirement, in term of packet delay budget (PDB), maximum data burst volume (MDBV) and priority level, so that the 5G system can determine and perform a proper end-to-end QoS treatment to the corresponding service data flow. In addition, for a deterministic periodic traffic, the traffic characteristics (including periodicity, burst arrival time, and service survival time) should be provided by AF to the 5G system to facilitate sufficient scheduling.*
 - » *Ntsctsf_QoSandTSCAssistance_Create/Update/Delete/Notify/Subscribe/Unsubscribe APIs;*
 - » *Nnef_AFSessionWithQoS API's resources of "AS Session with Required QoS subscriptions" and "Individual AS Session with Required QoS subscriptions";*

The network architecture showing the 5GS supporting TSCTSF function in Figure 3-3.

Within a 5G system, TSCTSF interacts with PCF via Npcf_PolicyAuthorization service to:

- *Collect the time synchronization capabilities supported by the 5G bridge, such as PTP instance type, transport protocol, PTP profiles, grandmaster mode, access stratum timing source, etc.;*
- *Provide the time synchronization configurations requested by AF to the 5G bridge (such as PTP instance type, PTP profile, a 5G system acting as grandmaster clock and its GM priority, clock domain(s), 5G air interface time synchronization error budget, synchronization service temporal and validity) so that the 5G system either transports external grandmaster clock PTP synchronization packets or distributes 5G access stratum time as grandmaster clock to external nodes;*

Figure 3-3 5G Network and TSCTSF architecture [5]



- Provide the 5G system with the proper QoS configurations to the time synchronization data flows and time sensitive communication service data flows;

The time sensitive communication services, especially when the traffic includes deterministic periodicity, should be supported by a delay-critical Guaranteed Bit Rate (GBR) QoS flow, whose QoS parameters (including GBR, PDB and MDBV) satisfy the traffic’s requirements. This is very similar to the TSN traffic QoS handling described on page 8 under **5G Bridge Traffic Scheduling Configuration**. The main difference is that the AF for the time sensitive communication service should determine the QoS parameters and the deterministic periodic traffic’s assistance data—time sensitive communication assistance container (TSCAC)—directly from its knowledge of the service requirements and the traffic characteristics.

3.4 TaaS Timing Distribution over 5G

There are three main types of precision timing information that can be delivered over 5G:

- 5GS transferring the time advertised by a TSN 802.1AS GM clock
- 5GS transferring the time generated at the 5G Core (NW-TT)
- 5G UE/DS-TT transferring the UTC time received from the 5GS

3.4.1 Time from TSN 802.1AS GM Clock

Figure 3-4 shows the architecture of a 5GS that carries the precision timing from the TSN 802.1AS master clock to the end devices. This configuration is typically used in industrial settings and factory automation.

The time delivery system consists of the following major components:

- A TSN 802.1AS Master Clock provides timing information the devices in the factory. It uses IEEE 802.1AS (gPTP) [1] protocol to advertise its time, which is represented by the blue clock-face.
- NW-TT (Network TSN Translator) acts as recipient of the IEEE 802.1AS [1] messages from the TSN Master Clock. It forwards these messages to the 5G Core, in addition it captures and forwards the “ingress timestamp” of the message
- NW-TT, 5G Core, gNB, UE and the DS-TT are all synchronized to the 5G clock (represented by the white clock-face). Note that the 5G time can be different than the TSN Master Clock time. UE is synchronized to the 5G clock using System Information Block 9 (SIB9) message.
- 5G Core forwards the 802.1AS messages to the UE via the gNB. In turn, the UE forwards the IEEE 802.1AS messages to the DS-TT.

- *The DS-TT runs an IEEE 802.1AS protocol stack in Relay Mode. It forwards the IEEE 802.1AS messages to downstream devices via Ethernet port. At the same time, the DS-TT captures the egress time of the message and calculates the residence time of the message over 5GS using the ingress time provided by the NW-TT. The DS-TT updates the correction field of the IEEE 802.1AS message using the calculated residence time, precisely accounting for the delay the message has experienced over 5GS.*

The DS-TT then forwards the time to the downstream devices using the same IEEE 802.1AS [1] protocol. The system transfers the TSN time to the end devices with a time precision of 1 microsecond.

3.4.2 Time Generated at the 5G Core (NW-TT)

The 5G standard allows time generation at the NW-TT rather than a TSN Master clock. The architecture of this system is shown in Figure 3-5. The operation of this system is similar to the one described in Section 3.4.1, with the exception of NW-TT advertising the time of the 5G system (UTC time) rather than a different factory time. This is typically used in large deployments, such as electric grid type of applications. The operation of the UE and the DS-TT are identical to the previous scenario.

3.4.3 Time Generated at the DS-TT

The architecture of this system is shown in Figure 3-6. In this time delivery system, the UE synchronizes to the 5G clock using SIB9, transferring this time to the DS-TT. The DS-TT operates as an IEEE 802.1AS [1] Master Clock and transfers the 5G time to the downstream nodes using IEEE 802.1AS [1] protocol. Note that the residence time calculation is not needed in this mode. The operation of the DS-TT is different in this mode than the previous two scenarios. The DS-TT is configured by the network to properly operate in this mode.

3.5 Timing Service resiliency

Several industries (both public and vertical) depend on accurate clock synchronization. Many of these currently use GNSS to achieve clock synchronization. Industries are looking for secure and reliable timing service with concerns for threats of spoofing and interference of GNSS provided timing.

When 5G is deployed and combined with 3GPP TSN functionality from Release 16, a IEEE TSN network can act as a gPTP relay in transparent mode to provide resilient time synchronization.

Most of current day 5G networks use GNSS as the 5G system time (5G system internal clock) synchronization. To address any potential degradation or unavailability of GNSS timing source, 3GPP Release 18 is standardizing mechanisms to provide 5G Timing Resiliency. This will help to detect primary GNSS reference timing signal degradation or loss and enables 5G systems to also receive accurate timing signals from an independent timing source. These enhancements enable use of the 5G system for time critical services in collaboration with or as a backup to other timing solutions.

3.6 Ultra-Reliable Low-Latency Communication

Ultra-reliable low-latency communication was first introduced in 5G new radio (NR) to support new applications, such as augmented and virtual reality, industrial automation, and autonomous vehicles. These applications require stringent reliability and latency for one transmission of a packet (10^{-5} for 32 bytes with a user plane latency of 1ms).

The Release 15 of 5G NR provided a foundation for URLLC functionality with features such as flexible sub-carrier spacing, a sub-slot-based transmission scheme, new channel quality indicator, low spectrum efficiency modulation and coding scheme table, and configured-grant transmission with automatic repetitions.

Release 16 of 5G NR further enhanced URLLC functionality and improved the latency and reliability of the system, with a target of 10^{-6} reliability and latency ranging from 0.5ms to 1ms to support industrial IoT applications. The improvements included enhanced physical downlink control channel monitoring capability, new DL control information format, sub-slot physical uplink control channel transmission, sub-slot-based physical UL shared channel repetition, enhanced mobile broadband, and URLLC inter-UE multiplexing with cancellation indication and enhanced power control.

Release 17 of 5G NR targeted further enhanced URLLC operation by improving mechanisms such as feedback, intra-UE multiplexing and prioritization of traffic with different priority, support of time-sensitive communication, new QoS parameters, and operation in unlicensed spectrum [13].

Figure 3-4 Time from TSN 802.1AS Grand Master Clock

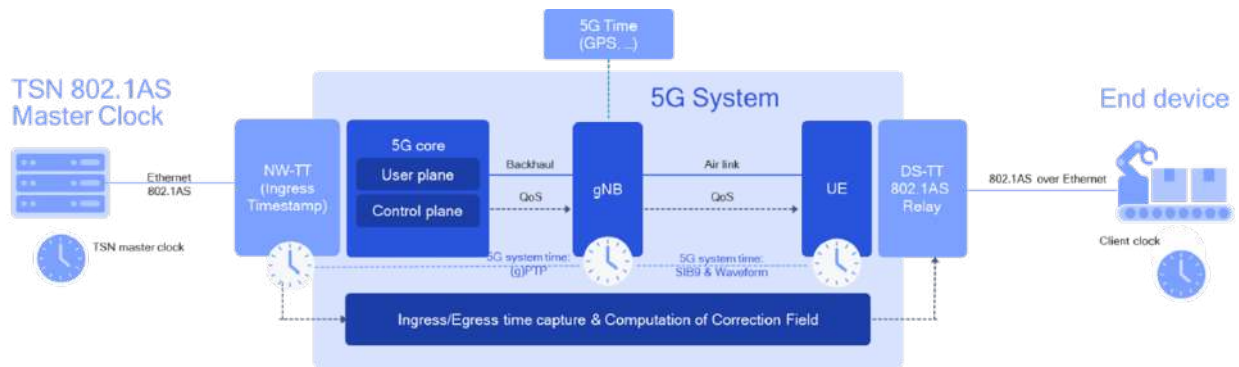


Figure 3-5 Time generated at the NW-TT

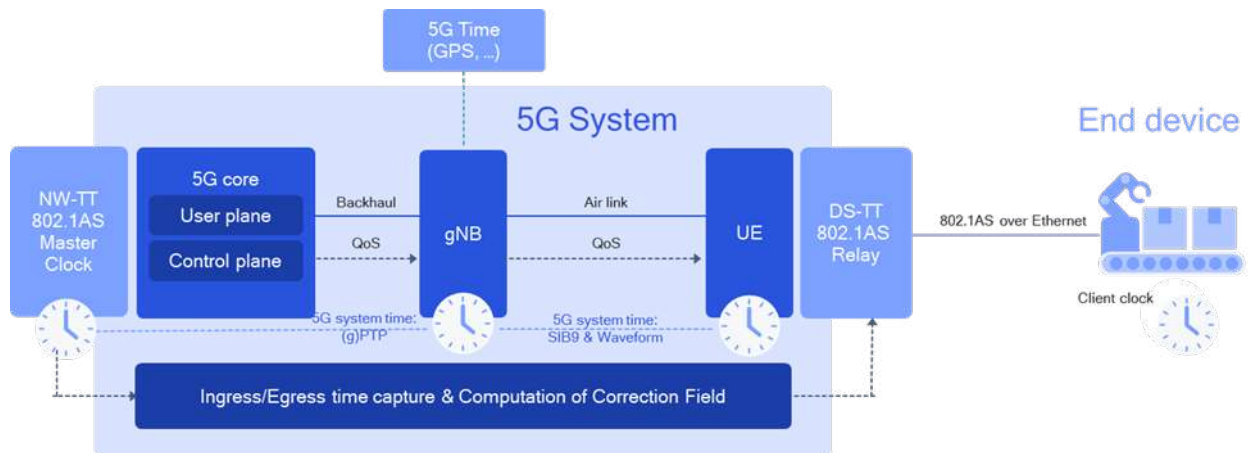
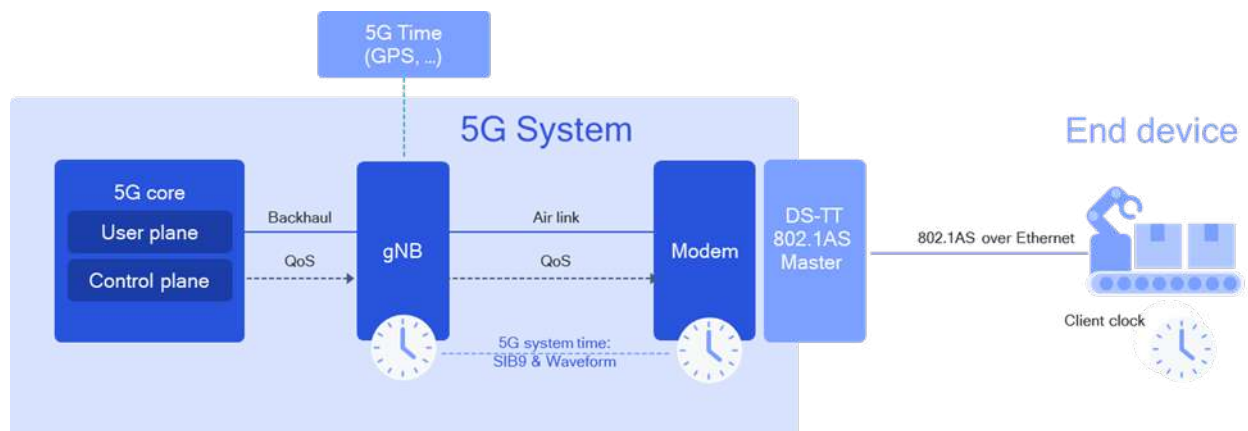


Figure 3-6 Time Generated at the UE/DS-TT



3.6.1 URLLC Support in 3GPP 5G New Radio Release 15

A key feature of the 5G physical layer was the introduction of flexible sub-carrier spacing (SCS). In 5G NR, the SCS can exist at 15, 30, 60, 120 and 240 kHz. This was meant to reduce the transmission latency by decreasing the Orthogonal Frequency Division Multiplex (OFDM) symbol duration. Furthermore, new Channel Quality Indicator (CQI) and Modulation and Coding Scheme (MCS) tables were specified to support the Physical Downlink Shared Channel (PDSCH) and Physical Uplink Shared Channel (PUSCH) transmission with the URLLC requirement of 10^{-5} block error rate (BLER). Multiple MCS tables allow the transmission to adapt the code rate and modulation scheme for URLLC or enhanced Mobile Broadband (eMBB) transmissions [14].

In 5G NR, slot-based transmission of PDSCH or PUSCH is based on mapping Type A, where one slot is a transmission time interval. In this type, the transmission can only start at the beginning of a slot, so a packet arriving after the starting point in a slot must wait until the next slot to be transmitted. In order to reduce latency by shortening transmission time interval, sub-slot-based transmission of PDSCH or PUSCH based on mapping Type B was introduced. In this case, a packet can be scheduled for transmission over 2, 4 or 7 OFDM symbols. A transmission can start at the beginning of the sub-slot transmission time interval and reduce the waiting time of the packets.

When a 5G base station (gNB) attempts to schedule a URLLC transmission with resources that are already allocated to an eMBB transmission, it can preempt the eMBB transmission by puncturing the eMBB resources to schedule the URLLC transmission. This results in faster transmission of the URLLC packets and reduction of the latency. After puncturing a part of the eMBB transmission, the gNB transmits a preemption indication to the eMBB user to inform them of punctured resources. Thus, the eMBB UE does not decode the data of the punctured resources.

In regular transmissions, an uplink transmission typically starts with a scheduling request from the UE and an uplink grant from the gNB, which would take a few milliseconds. In addition to dynamic scheduling, configured grant (CG) in UL and semi-persistent scheduling (SPS) in DL was standardized to support time sensitive transmissions and reduce transmission latency. The resources for a configured grant are allocated to the UE by the gNB so that the UE uses these resources to transmit data on PUSCH directly to the gNB without scheduling request.

There are two types of CG PUSCH transmission. In Type 1, an RRC signaling configures the time and frequency domain resource allocation including periodicity of CG resources, offset, start symbol and length of PUSCH, MCS, the number of repetitions, redundancy version, power level, and more. In Type 2, only periodicity and the number of repetitions is configured by radio resource control (RRC) signaling. The other parameters are configured through an activation downlink control information (DCI). To reduce the latency and increase the reliability of the uplink transmission, the UE is configured to automatically transmit a number of repetitions in consecutive slots without waiting for feedback from the gNB [14].

3.6.2 Release 16 Improvements for URLLC Applications

As mentioned earlier, sub-slot-based transmission was one of the features introduced in Release 15 to enable URLLC transmissions. In the downlink this feature requires the UE to monitor downlink data including Physical Downlink Control Channel (PDCCH) and PDSCH at the sub-slot level. The location of PDSCH is indicated by PDCCH, so the UE must decode PDCCH before decoding PDSCH. However, the UE does not know the exact location of the PDCCH and will perform blind decoding in a search space. Each possible location of PDCCH in the search space is called the “PDCCH candidate”. However, in Release 15, the number of PDCCH candidates that the UE can monitor in a slot is limited.

Furthermore, the allocated resources for PDCCH in a slot are limited by the number of control channel elements (CCEs). A CCE consists of 6 resource element groups. A resource element group is equal to one resource block over one OFDM symbol that contains 12 resource elements. The number of CCEs that a PDCCH may contain is defined as the aggregation level (AL). While the transmission may occur at sub-slot level, PDCCH monitoring interval is defined at slot level. This limitation degrades the ability of the UE to operate in sub-slot-based transmission when not all PDCCHs can be transmitted from the gNB and monitored by the UE.

Release 16 solves this problem by enhancing PDCCH monitoring capability by defining the maximum number of monitored PDCCH candidates and non-overlapping CCEs over 2, 4 or 7 symbols instead of per slot. When monitoring capability is defined per span for sub-slot level transmission, the UE has more PDCCH candidates and non-overlapping CCEs that it can monitor in a sub-slot because the capability is not divided by the number of sub-slots in a slot as in the conventional scheme. Therefore, PDCCH with a high AL

value can be used to guarantee reliability. Additionally, more PDCCHs can be transmitted in a slot, reducing the latency caused by the PDCCH monitoring limitation. The UE can be configured by the gNB to monitor PDCCH for the maximum number of PDCCH candidates and non-overlapping CCEs defined per slot as in Release 15 or per span as in Release 16 [14].

In Release 15, DCI formats have a fixed number of bits in the information fields. However, with the introduction of new RRC parameters in Release 16, new DCI formats are introduced to schedule downlink/uplink URLLC transmissions, where the number of bits in several fields are configurable based on time and frequency resources of data, frequency hopping, or antenna ports. The information content of some fields can be null and signaled using new RRC parameters. For example, the redundancy version field of Release 16 DCI is configurable from 0 to 2 bits compared to a fixed 2 bits in Release 15. Similarly, hybrid automatic repeat request (HARQ) process field is configurable from 0 bit to 4 bits compared to a fixed 4 bits in Release 15. Therefore, Release 16 DCI can be configured to use fewer bits than Release 15, which helps improve DCI transmission performance for URLLC. Using a Release 16 DCI with 24 bits increases the reliability of DCI transmission because this DCI with a smaller payload achieves higher reliability than a Release 15 DCI with 40 bits encoded with the same codeword length.

In Release 16, new DCI fields were added to support new features. As an example, priority indicator field with 0 or 1 bit was added to indicate the priority of a scheduled PDSCH or PUSCH. Open-loop power control set indication field with 0 to 2 bits was added to control PUSCH transmission power level when eMBB and URLLC data are multiplexed and invalid symbol pattern indicator field with 0 or 1 bit was added to indicate the invalid symbols for PUSCH repetition.

The gNB can configure SPS resources with a specific periodicity for the UEs in the downlink. When these SPS resources are activated by the gNB, the UEs will expect to receive their corresponding PDSCH in these resources. In this case, the gNB can transmit PDSCH without an associated PDCCH to schedule SPS transmissions. The transmission of SPS PDSCH without PDCCH reduces control overhead and makes it more suitable for URLLC applications. The periodicity of SPS resources can be configured to support URLLC transmissions with low latency requirements.

To accommodate different types of traffic, the gNB can configure multiple configurations of SPS resources with

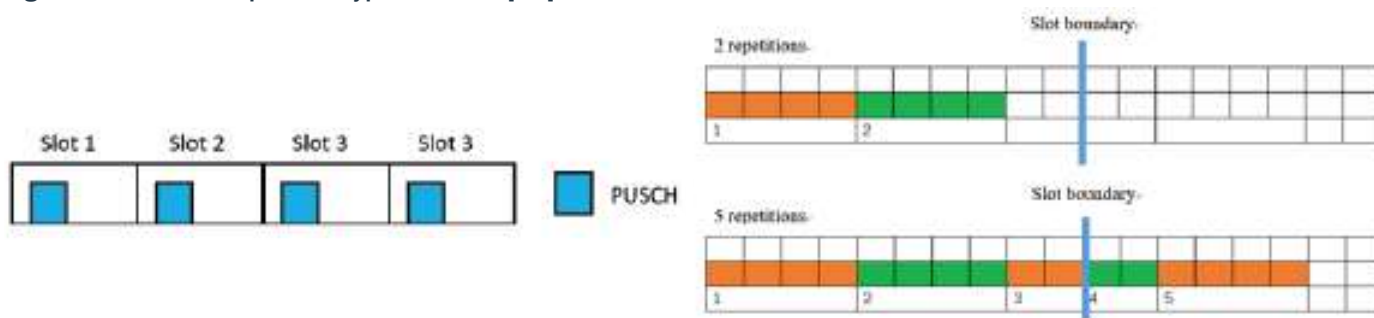
different periodicities, resource allocations, or MCS. For a given operating bandwidth, the maximum number of SPS configurations is eight and each configuration can be separately activated by a DCI. The SPS resources in different configurations may overlap in time. If the UE receives multiple SPS PDSCH transmissions overlapped in time, it starts decoding the SPS PDSCH with the lowest SPS configuration index followed by any SPS PDSCH burst in the received group that overlaps with the initially selected SPS PDSCH. A maximum of four physical uplink control channel resources are configured for all SPS configurations per HARQ-ACK codebook. The HARQ feedback for SPS PDSCH can burst in multiple SPS configurations is multiplexed with HARQ feedback for a dynamically scheduled PDSCH. In this case, the HARQ bit location for SPS PDSCHs is based on the time-domain resource assignment (TDRA) table row index and the time interval from the end of PDSCH transmission to the beginning Physical Uplink Control Channel (PUCCH) for HARQ feedback indicated in the activation DCI [14].

In Release 15, a UE could transmit only one PUCCH with HARQ-ACK information in a slot. If the UE could finish decoding of a packet after the PUCCH resource for HARQ feedback in a slot, it must wait until the next slot to transmit feedback which would cause a delay in HARQ feedback transmission and a subsequent retransmission, if necessary. Moreover, if HARQ-ACK for URLLC PDSCH occurs in the same slot as HARQ-ACK for other eMBB/ URLLC PDSCHs, all the HARQ-ACK information will be multiplexed together and transmitted over the PUCCH resource indicated in the latest downlink assignment. The multiplexing degrades the reliability of HARQ feedback.

In Release 16, the sub-slot-based HARQ-ACK feedback is supported, where PUCCH resources are configured per sub-slot of 2 or 7 symbols, so multiple PUCCH occasions for HARQ-ACK can be transmitted within a slot.

In Release 15, the number of PUCCH occasions transmitted by a UE in a slot was limited to 2. Consequently, when a UE has multiple overlapping PUCCH or PUCCH and PUSCH occasions in a slot, it multiplexes different Uplink Control Information (UCI) types in one PUCCH/PUSCH. In URLLC transmission, low latency requires immediate transmission which causes overlapping of URLLC UCI with PUCCH/PUSCH of a different service type of lower priority, resulting in degradation of URLLC transmission. Furthermore, if the last symbol of the multiplexed PUCCH/PUSCH follows the last symbol of URLLC UCI, it causes an additional delay to URLLC transmission.

Figure 3-7: PUSCH Repetition Types A and B [15]



In Release 16, this problem is addressed by UCI prioritization based on two-level priority. If there is overlap between two low-priority and high-priority uplink transmissions, the low-priority transmission is cancelled instead of being multiplexed with the high-priority transmission. In the event that the UE encounters simultaneous transmission of more than two PUSCH/PUCCH, the UE resolves contention between uplink transmissions with the same priority by UCI multiplexing and resolves contention between uplink transmissions of different priorities via UCI prioritization.

In Release 15, dynamic and configured grant PUSCH transmissions cannot straddle slot boundaries. The UE can transmit several small PUSCH bursts in consecutive instances to avoid a long PUSCH transmission without feedback scheduled by an uplink grant or RRC signaling referred to as PUSCH repetition Type A (shown on the left side of Figure 37). Each slot contains one repetition and the time duration for the repetitions of a transport block is the same in those slots. This scheme causes a time gap between the repetitions which could render the system unable to achieve the URLLC latency requirement.

In Release 16, PUSCH repetition Type B (shown on the right side of Figure 37) was developed to eliminate the time gap between repetitions and to ensure the configured number of repetitions in certain time duration. For PUSCH repetition Type B, the time domain resource is indicated by the gNB for the first repetition while the resources for the remaining repetitions are derived based on the resources for the first repetition and UL/DL direction of the symbols. The dynamic indication of the number of nominal repetitions for the dynamic grant is jointly coded with start and length indicator of PUSCH in time domain resource assignment by adding an additional column for the number of repetitions [14].

To increase spectrum efficiency, time-sensitive and delay tolerant transmissions of different UEs are multiplexed in the uplink. As a result, the gNB requires a mechanism to manage potential collisions and multiplexing of uplink

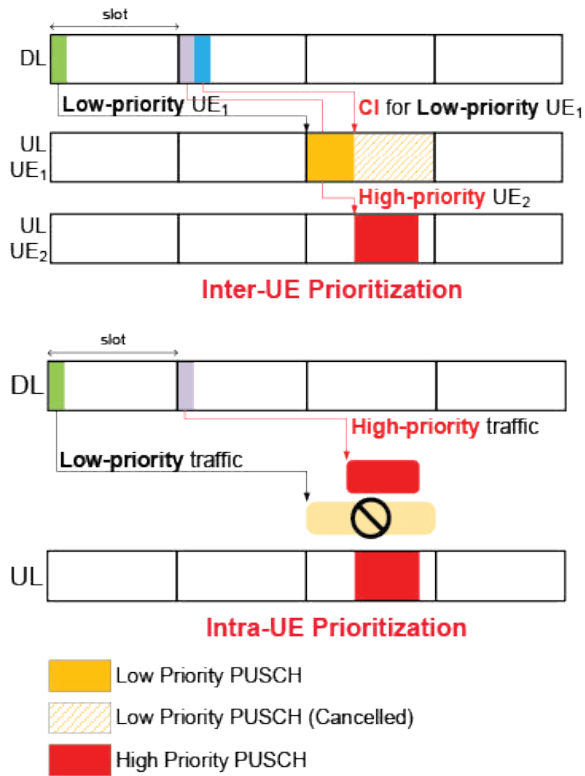
transmissions with different priorities. After receiving a scheduling request (SR) from an eMBB UE, the gNB schedules uplink resources for its data transmission. Once a URLLC UE sends an SR, the gNB must schedule the URLLC resources over those of the eMBB transmission that causes a collision between the transmission of two UEs. While there is no mechanism in Release 15 to handle this situation, 5G NR supported uplink cancellation indication (CI) and enhanced power control in Release 16 to mitigate this problem (shown in Figure 38).

When the gNB reallocates resources that have been scheduled for an eMBB traffic to a URLLC UE, it transmits an uplink CI as a group common DCI (DCI format 2_4) to the eMBB UEs in the group to cancel their transmissions. However, only the sounding reference signal and PUSCH can be cancelled by uplink CI. In case of PUSCH repetitions, uplink CI is applied individually to each repetition overlapping the resource indicated by uplink CI. The gNB can further instruct the URLLC UE to increase PUSCH transmit power to improve decoding of its data despite overlapping with the eMBB transmission of another UE. For dynamic grant PUSCH transmission, an open-loop power control set indication field of uplink grant is supported to control transmission power.

Figure 38: UL Cancellation Operation for Inter and Intra-UE Prioritization [16]

In Release 15, the UE blindly transmits CG repetitions without any feedback from the gNB. However, the UE is only allowed to transmit the repetitions in one HARQ process interval to avoid any confusion between the initial transmission and the retransmissions. If the gNB misses the first UE transmission and only detects the retransmissions in a different HARQ process corresponding to that transmission, it may use an incorrect UE HARQ identity in the uplink grant to schedule retransmissions. The UE must stop transmitting the repetitions if it reaches the boundary of a HARQ process.

Figure 3-8: UL Cancellation Operation for Inter and Intra-UE Prioritization [16]



To solve this problem, multiple active CG configurations for a given bandwidth part of a serving cell are supported in Release 16. The number of CG configurations of a UE is configured by RRC signaling related to logical channel configuration with maximum of 12 configurations per bandwidth part. The UE selects the configuration with the earliest starting point to transmit data so it is always transmitted at the beginning of a HARQ process, and all configured repetitions are transmitted before reaching the HARQ process boundary. A UE can have multiple configurations and one configuration might be shared among several UEs. Multiple CG configurations are also used to serve different traffic types in the UE. The RRC or DCI signaling is used to notify the UE to activate or release the configurations.

In Release 15 and 16, the URLLC services are carried out in licensed spectrum. However, the unlicensed spectrum can provide a complement to URLLC services because of availability and lower cost. One important use case is the industrial automation in controlled environments with restricted access.

The PUSCH repetition scheme in unlicensed spectrum was specified in Release 16 with a difference between the two schemes (similar to PUSCH repetition Type B). Downlink or invalid symbols are not supported in unlicensed spectrum

with segmentation of PUSCH repetition at the slot boundary. This causes a gap between PUSCH repetitions in unlicensed spectrum versus PUSCH repetition Type B which supports back-to-back repetitions. Instead, a PUSCH repetition scheme in unlicensed spectrum has an advantage when resources for PUSCH repetitions can be repeated in several consecutive slots (indicated by an RRC parameter). This gives the UE more opportunities to schedule multiple transport blocks by a single DCI.

3.6.3 Release 17 Improvements for URLLC Applications

In Release 16 a CG PUSCH transmission corresponding to URLLC traffic supports timer-based feedback. If the gNB decodes PUSCH correctly, it does not send acknowledgement (ACK) feedback to reduce overhead. The UE waits until the end of timer and assumes a successful transmission if no feedback is received. If the gNB fails to decode PUSCH, then it sends an uplink grant to schedule a retransmission.

However, feedback for CG PUSCH transmissions in unlicensed spectrum follows explicit-ACK feedback to overcome the uncertainty of the channel access in unlicensed spectrum. If the gNB decodes PUSCH correctly, it sends ACK and if it fails to decode PUSCH, it sends an uplink grant or NACK to schedule a retransmission. If the gNB cannot gain access to the channel to transmit ACK, NACK or an uplink grant, the UE does not receive any signal from the gNB and waits until the expiration of the timer to retransmit data over the CG resources.

The gNB instructs the UE to use timer-based feedback for URLLC transmissions in unlicensed spectrum. Otherwise, the UE uses explicit-ACK feedback in unlicensed spectrum for other types of transmissions. The enhancements in Release 17 aim to improve spectral efficiency and system capacity, support URLLC in unlicensed spectrum environments, and improve the framework to support TSC. They include HARQ-ACK enhancements, CSI enhancements, intra-UE multiplexing, time-synchronization enhancements, and service survival time as an extension to TSC assistance information.

In unlicensed spectrum, a transmitter is required to support listen-before-talk (LBT) to access the channel and transmit data during channel occupancy time (COT). One of the channel access mechanisms is frame-based equipment (FBE) where the transmitter performs LBT in certain instances. The periodicity between two consecutive LBT instances is a fixed frame period (FFP) from 1 to 10ms. In

Release 16, only the gNB can initiate a COT by performing LBT at fixed occasions. After gaining access to the channel, the gNB may share the COT with the UE so that it can transmit its uplink transmission. This may cause long delay in uplink transmission due to the following reasons: (1) if LBT fails, the gNB must wait from 1 to 10ms to retry LBT, thus the UE cannot start its uplink transmission, and (2) if the gNB has no downlink data to transmit it does not initiate a COT. If the UE has UL data at that time, it also cannot transmit because of the absence of the gNB-initiated a COT. To reduce latency and support URLLC in unlicensed spectrum in Release 17, the UE is allowed to initiate its own COT to transmit uplink data. The configuration of the UE's FFP should avoid blocking the gNB to initiate its own COT [14].

In Release 17, a gNB can transmit PDSCH to the UE in pre-configured resources without an associated PDCCH. The time from the end of PDSCH transmission to the beginning of HARQ feedback is set, since the SPS resources are activated. However, in TDD configuration, the configured time may coincide with a downlink symbol and the feedback is dropped. The UE is configured to transmit HARQ feedback three slots after an SPS PDSCH transmission. This value is used from the activation to the suspension of an SPS configuration. The gNB cannot predict slot format of all slots in advance, so HARQ feedback coinciding with a downlink symbol is cancelled. Ultimately, this results in degradation of URLLC transmission because the gNB does not have prior information to trigger a retransmission if necessary. In addition to the possibility of dropped feedback—even without PDSCH transmission over the SPS resources—the UE is required to send a NACK which results in inefficient use of resources, and potential interference with other UEs.

Channel state information (CSI) feedback helps the gNB make optimal scheduling decisions and is further helpful for URLLC traffic types with infrequent traffic bursts. The latency of CSI feedback is considered in the new URLLC features of Release 17. The new schemes are required to trigger periodic CSI feedback with lower latency. Simplified CSI calculations allow more accurate channel fading and interference information.

In Release 16, specified UCI prioritization based on a two-level priority scheme where the low-priority UCI was cancelled by the high-priority UCI transmission if they overlap. Release 17 supports multiplexing of UCI such as HARQ-ACK and SR on PUCCH with different priorities. In multiplexing, the target code rate and latency of the high-priority UCI is guaranteed using separate coding scheme

based on their original PUCCH resources. The high-priority UCI is mapped to the multiplexing PUCCH before the low-priority UCI to guarantee the resource for the high-priority UCI. With separate coding, latency of the high-priority UCI decoding is also reduced because the gNB can start the decoding process after receiving the symbols in the high-priority UCI resources. Release 17 also supports UCI multiplexing on PUSCH with different priorities. Separate coding rates are used in UCI multiplexing on PUSCH (similar to PUCCH) to guarantee target code rate and latency of the high-priority UCI on PUSCH. The last symbol of the low-priority PUSCH is no later than the ending symbol of PUCCH carrying the high-priority HARQ-ACK [14].

3.7 Time synchronization accuracy

As explained in Section 3.1 and Section 3.4, the sync master's clock synchronization message is distributed to the sync devices over the 5G system data path. The time error contributed by the 5G system between ingress and egress of the 5G system on the data path of the clock synchronization message will degrade the overall clock synchronization performance. It's required that the 5G system's time error should not exceed 900ns as specified in 3GPP TS 22.104 v18.3.0 [17]. The overall end-to-end requirement supported by the 5G system for various industrial use cases and scenarios are specified by 3GPP as shown in Table 3-1.

Time error can be broken into three parts within a 5G system: Uu interface synchronization error, network synchronization error and device synchronization error. The synchronization error in Uu interface includes the aspects of gNB antenna alignment errors, ReferenceTimeInfo delivery uncertainty, and system frame number (SFN) estimation error due to propagation delay estimation error. In Release 17, 3GPP concluded that in order to support the most challenging scenario (scenario #2 in Table 3-1) where the clock synchronization messages traverse the 5G system twice, the 5G Uu interface error should not exceed 145ns to 235ns [18]. In a wireless and mobile environment, especially for a deployment scenario where a large gNB-to-UE distance is expected, the propagation delay estimation error must be compensated in order to achieve 145ns accuracy. In Release 17 3GPP introduced a round-trip-time (RTT) based propagation delay compensation procedure to improve the synchronization accuracy performance to meet +/-145ns requirement [19].

Please also note that the propagation delay compensation based on 5G Release 15 and Release 16 timing advance (TA) procedure and associated granularity with no enhancements in NR physical layer is sufficient for meeting the Uu interface synchronicity error budget for the smart grid scenario ($\pm 795\text{ns}$ to $\pm 845\text{ns}$) [20].

Table 3-1 Clock Synchronization Service Performance Requirements for 5G System [17]

User-specific clock synchronicity accuracy level	Number of devices in one communication group for clock synchronisation	5GS synchronicity budget requirement (note 1)	Service area	Scenario
1	up to 300 UEs	$\leq 900 \text{ ns}$	$\leq 100 \text{ m} \times 100 \text{ m}$	Motion control Control-to-control communication for industrial controller
2	up to 300 UEs	$\leq 900 \text{ ns}$	$\leq 1,000 \text{ m} \times 100 \text{ m}$	Control-to-control communication for industrial controller
3	up to 10 UEs	$< 10 \mu\text{s}$	$\leq 2,500 \text{ m}^2$	High data rate video streaming
3a	up to 100 UEs	$< 1 \mu\text{s}$	$\leq 10 \text{ km}^2$	AVPROD synchronisation and packet timing
4	up to 100 UEs	$< 1 \mu\text{s}$	$< 20 \text{ km}^2$	Smart Grid: synchronicity between PMUs
4a	up to 100 UEs	$< 250 \text{ ns}$ to $1 \mu\text{s}$	$< 20 \text{ km}^2$	Smart Grid: IEC 61850-9-2 Sampled Values
4b	up to 100 UEs	$< 10\text{-}20 \mu\text{s}$	$< 20 \text{ km}^2$	Smart Grid: IEC 61850-9-2 Sampled Values – Power system protection in digital substation
4c	54/km ² (note 2) 78/km ² (note 3)	$< 10 \mu\text{s}$	several km ²	Smart Grid: Intelligent Distributed Feeder Automation
4d	up to 100 UEs	$< 1 \text{ ms}$	$< 20 \text{ km}^2$	Smart Grid: IEC 61850-9-2 Sampled Values – Event reporting and Disturbance recording
5	up to 10 UEs	$< 50 \mu\text{s}$	400 km	Telesurgery and telediagnosis

NOTE 1: The clock synchronicity requirement refers to the clock synchronicity budget for the 5G system, as described in Clause 5.6.1.

NOTE 2: When the distributed terminals are deployed along overhead line, about 54 terminals will be distributed along overhead lines in one square kilometre. The resulting power load density is 20 MW/km².

NOTE 3: When the distributed terminals are deployed in power distribution cabinets, there are about 78 terminals in one square kilometre. The resulting power load density is 20 MW/km²

4. Security of TaaS over 5G

The current precision time delivery systems (GPS/GNSS) are subject to spoofing attacks as the time information is carried without security or encryption. When a 5G system is operated as a time source it benefits from the full security infrastructure provided by 5G system. 5G standard allows time delivery over SIB9 in one of two modes:

- *As a broadcast SIB9: The SIB9 timing message is not encrypted and could be subject to spoofing attacks.*
- *As a unicast SIB9: The SIB9 is sent using unicast channels, and benefits fully from the security and encryption provided by the 5G system. Timing for sensitive applications should use unicast SIB9 messages to enhance security of time delivery.*

Regardless of the method of delivery for SIB9, the IEEE 802.1AS messages carrying the timing information is always sent using unicast channels, therefore always benefit from the security provided by the 5G System.

5. Conclusion

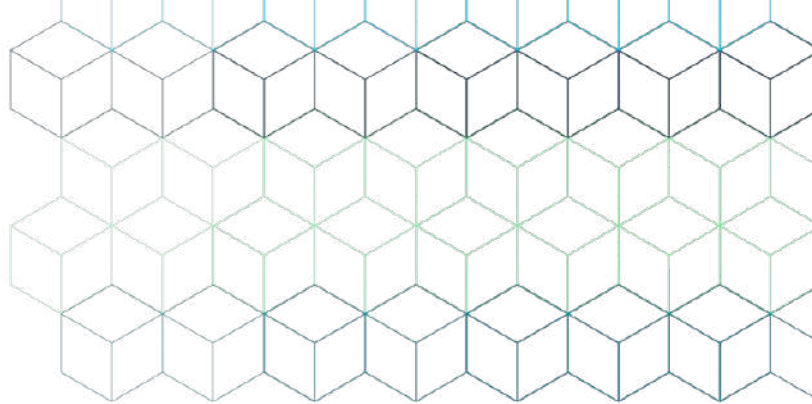
5G is an essential technology and provides a foundation for a new era of innovation. This white paper provides a valuable resource in the understanding, planning and implementation of time-critical services for 5G networks.

As advances in technology continue in 5G cellular network operations, innovative spectrum allocation methods, and support for network sharing models, new challenges and opportunities emerge in the delivery of time-critical services. With the deployment of 5G networks around the world, these kinds of opportunities and challenges can be found in many industrial sectors, each with very diverse quality of service requirements in terms of latency, coverage, and bandwidth.

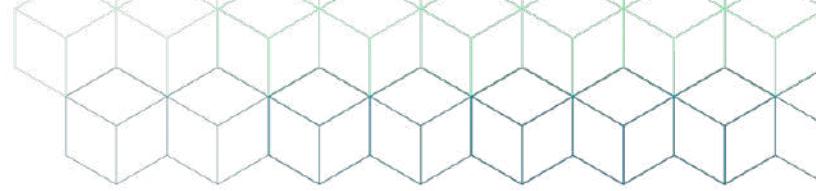
As explained in Section 2, time-critical services require the services' clients and servers across the network to be strictly synchronized, and its underlying communication network to be ultra-reliable and strictly latency-bounded. To support Time Critical Services over 5G networks, 5G technology has incorporated various enhancements in Release 16 and Release 17. In Section 3, Two types of TCS (IEEE TSN operation and TaaS) are discussed in detail regarding how the services can be supported by 5G network with Release 16 and Release 17 5G enhancements in 5G core network architecture aspects and 5G NR air interface aspects. Section 4 discusses security supporting TaaS over 5G.

Network operators and their vendor partners could benefit from adopting standardized 5G NR technology due to the economies of scale leveraged by sophisticated 5G ecosystems as they pursue the development of time-critical services on 5G networks. Taking advantage of the scale provided by standardized technology could help operators gain momentum in vertical business segments previously dominated by proprietary communication technologies.

5G technical capabilities continue to improve. The features standardized at 3GPP can address many new verticals including industrial, mission critical use cases, and precise time delivery. 5G technologies such as Ultra Reliable Low Latency Communication (URLLC) and Time Sensitive Networking (TSN) together provide a large opportunity for the 5G ecosystem to support new applications.



Acronyms



5GS: 5G System

5QI: 5G QoS Identifier

ACK: Acknowledgement

AF: Application Function

AL: Aggregation Level

AMF: Access and Mobility Management Function

API: Application Programming Interface

BLER: Block Error Rate

BMIC: Bridge Management Information Container

CCE: Control Channel Element

CG: Configured Grant

CI: Cancellation Indication

CNC: Central Network Controller

COT: Channel Occupancy Time

CQI: Channel Quality Indicator

CSI: Channel-State Information

DCI: Downlink Control Information

DL: Downlink

DNN: Data Network Name

DS-TT: Device side TSN Translator

eMBB: enhanced Mobile Broadband

FBE: Frame-Based Equipment

FFP: Fixed Frame Period

GBR: Guaranteed Bit Rate

GFBR: Guaranteed Flow Bit Rate

GM: Grandmaster

gNB: gNodeB

GPS: Global Positioning System

GNSS: Global Navigation Satellite System

HARQ: Hybrid Automatic Repeat Request

LBT: Listen-Before-Talk

LLDP: Link Layer Discovery Protocol

MCS: Modulation and Coding Scheme

NEF: Network Exposure Function

NR: New Radio

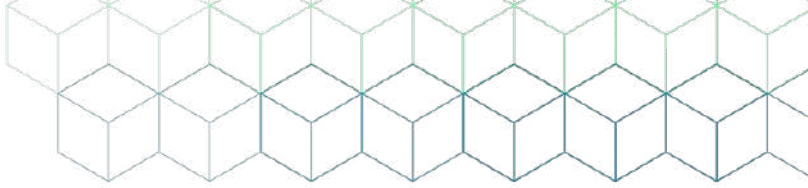
NTP: Network Time Protocol

NW-TT: Network side TSN Translator

MDBV: Maximum Data Burst Volume

OAM: Operations, Administration and Maintenance

OFDM: Orthogonal Frequency Division Multiplex



PCF: Policy Control Function

PDB: Packet Delay Budget

PDU: Protocol Data Unit

PDCCH: Physical Downlink Control Channel

PDSCH: Physical Downlink Shared Channel

PCFP: Packet Forwarding Control Protocol

PMIC: Port Management Information Container

PSFP: Per-Stream Filtering and Policing

PTP: Precision Time Protocol

PUCCH: Physical Uplink Control Channel

PUSCH: Physical Uplink Shared Channel

QoS: Quality of Service

RAN: Radio Access Network

RRC: Radio Resource Control

RTT: Round-Trip-Time

SCS: Sub-Carrier Spacing

SFN: System Frame Number

SIB: System Information Block

SMF: Session Management Function

S-NSSAI: Single Network Slice Selection Assistance Information

SPS: Semi-Persistent Scheduling

SR: Scheduling Request

TA: Timing Advance

TaaS: Timing As A Service

TCS: Time-Critical Service

TDRA: Time-Domain Resource Assignment

TSCTS: Time Sensitive Communication and Time Synchronization Function

TSe: Egressing Time Stamping

TSi: Ingressing Time Stamping

TSN: Time Sensitive Networking

TSN-AF: TSN Application Function

UCI: Uplink Control Information

UE: User Equipment

UL: Uplink

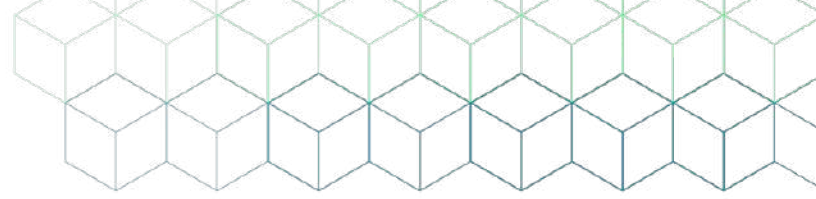
UMIC: User Plane Node Management Information Container

UPF: User Plane Function

URLLC: Ultra-Reliable Low Latency Communication

UTC: Universal Time Coordinated

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Acknowledgments

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5G Americas would like to recognize the significant project leadership and important contributions of group leader Pingping Zong of Intel, and Fatih Ulupinar of Qualcomm, along with many representatives from member companies on 5G Americas' Board of Governors who participated in the development of this white paper.

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