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JOINT WHITE PAPER

Empowering 5G Data Path for Time Sensitive Networking

(时间敏感网络技术　赋能 5G 确定性数据传输)

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Foreword

The deterministic network is the core technology to support digital transformation, and it is also one of the most important roadmaps for the future wireless communication networks. 5G technology, as the most cutting-edge communication technology, should be integrated with the Time-Sensitive Networking (TSN) technology to be deterministic. With the continuous advancement of deterministic characteristics in the 5G standards and specifications, as well as the continuous popularization of 5G network coverage and vertical industry applications, the integration of 5G technology and TSN technology has become particularly important. Applied Science and Technology Research Institute (ASTRI) and Peng Cheng Laboratory (PCL) are two of the largest R&D centers in the Greater Bay Area (GBA), with the strongest R&D background in networking and communications technologies. In this white paper, ASTRI and PCL have jointly developed and showcased the end-to-end 5G data plane integrating with TSN technology and have achieved high-precision time synchronization with minimized jitter. The research results are positive and instructive to explore 5G vertical application scenarios, leading industrial evolution in smart manufacturing, power, and mining industries.

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1. Introduction

1.1 Background & Market Needs

In *"Industrial Internet Innovation and Development Plan (2021-2023)"*, it has clearly mentioned the technology "Time Sensitive Network (TSN) over the Fifth Generation (5G) telecommunication technology" being one of the key innovative technologies. Previously, the TSN has been a wireline technology commonly used in factories for deterministic services. However, being a wireline technology, the wire has limited the usage scope as well as its application because of different considerations, such as space and connections needed between different devices. Industrial Internet, also known as the fourth industrial evolution (Industry 4.0), is well agreed to be the cornerstone for the revolution of the industry. Mobilized TSN becomes a way to go and 5G has been selected as the mobile technology which will be merging with the TSN to interconnect people, machines, things, systems, etc., to form a new ecology. TSN-enabled 5G system does not only digitalize people's living, but also creates a new era for the connected and digitalized industrial industry.

In a recent report from the China Academy of Information and Communication Technology, it has shown that, from only the first quarter of 2022, China's Industrial Internet industry has made over trillion yuan, an enticing result from the digital transformation of the industrial enterprises. On the other hand, the 5G network is well known for its support of ultra-low latency communications and large bandwidth. The Industrial Internet is expected to be the killer application for 5G. It has been projected that the 5G vertical applications penetration rate will reach 35% in 2023 for mainland China alone. The integration of 5G and the Industrial Internet is accelerating China's new industrialization process and serving as a breeding ground for China's economic development.

1.2 5G and TSN: IT/OT Convergence

1.2.1 5G Roadmap in 3GPP

The fifth-generation mobile communication technology (referred to as 5G or 5G technology) is the latest generation of mobile communication technology. It is a telecommunication and information technology (IT) defined by the 3rd generation partnership project (3GPP), evolving from the 4G, 3G, and 2G systems. In 5G New Radio, or 5G NR, the enhancements of the multi-antenna enhancement technologies improve the spectrum diversity and efficiency, modulation and coding techniques for better cell coverage, and slot time operations for system flexibility. As a result, 5G provides a higher data transmission rate and yet ultra-low latency services as comparing to 4G.

There are three major deployment scenarios for 5G networks:

- **Enhanced Mobile Broadband (eMBB)**: large bandwidth and moderate latency for use cases, such as emerging AR/VR media and applications, low bandwidth transmissions for machine-to-machine communication.
- **Massive Machine Type Communications (mMTC)**: low cost, low power wide area for latency-sensitive applications, such as the Internet of Things (IoT) that connect all physical things (people to people, people to things, things to things, etc.)
- **Ultra-Reliable Low Latency Communications (URLLC)**: extremely low latency applications, such as for vehicle-to-vehicle and vehicle-to-infrastructure communications.

3GPP Release 15 marks the beginning of the 5G era, the architecture has revolutionary change from the previous generation. The 3 major changes in the architecture include the Control and User Plane Separation (CUPS), Service-based Architecture (SBA) infrastructure, and network slicing. In CUPS, the separation of control and user plane delocalizes the need of placing all the network entities nearby in the network, allowing a more flexible and expandible deployment. For instance, placing the user plane entity closer to the base station allows edge computing with lower latency for application. The SBA infrastructure has modulated the network core into network functions (NFs), where the NFs are interconnected by HTTP2 protocols. The service-based interface has simplified the protocols between different NFs, allowing the deployment, upgrades, and scaling to be more efficient, which in turn realizing faster time-to-market for new functions and features. The network slicing aims to create separation of the network into slices for different markets and needs. With each slice being isolated from the other slices, the resources can be shared but resource in each slice meeting different requirements.

Evolving from Release 15, the 3GPP standards continue to evolve to connect virtually everything and everyone together, delivering higher data rates with lower latency, becoming more reliable have offering a better experience. With these performance enhancements and efficiency improvements, new user experiences and new industries are being enabled. Release 15 is known to be the 5G Phase 1, Release 16 being 5G Phase 2 and Release 17 being the 5G enhancements. Release 15 lays the foundation of the new architecture and security, and Release 16 adds more features for additional use cases, for example enabling the applications for new verticals of deployment scenario which includes the Non-Public Networks (NPN), positioning services, NR Cellular IoT, URLLC, and TSN. Release 17 protocol freeze was in June 2022, supporting new use cases and verticals such as coverage and positioning enhancements, enhanced support of NPNs, supporting unmanned aerial systems, support for edge computing in 5G Core (5GC) and network automation for 5G (Phase 2). Release 18 has been named 5G Advanced as it introduces intelligence (machine learning techniques) into the wireless networks at different levels of the network.

1.2.2 IEEE-Standardized TSN

IEEE Time Sensitive Networking Task Group is part of the IEEE 802.1 working group. It is an Operation Technology (OT) to provide deterministic services through IEEE 802 networks, in time synchronization, bounded latency, reliability, and resource management. Some of the standards in the IEEE 802.1 are listed in Table 1.

Table 1 Examples of IEEE TSN Task group standards

IEEE Standards	Description	Information
IEEE 802.1AS	Timing and Synchronization	Protocol and procedures used to ensure that the synchronization requirements are met for time sensitive applications.
IEEE 802.1Qbv	Enhancements for Scheduled Traffic	Time-aware queue-draining procedures, managed objects and extensions to existing protocols that enable bridges and end stations to schedule the transmission of frames based on timing derived from IEEE 802.1AS.
IEEE 802.1Qbu	Frame Pre-emption	Provide reduced latency transmission for scheduled time-critical frames in a bridged local area network.
IEEE 802.1CB	Frame Replication and Elimination for Reliability	Procedures, managed objects and protocols for bridges and end stations to create and eliminate duplicate frames.

One of the most important TSN task group standards is IEEE 802.1AS (time synchronization) which is based on the IEEE 1588 protocol. The IEEE 802.1AS precise clock synchronization protocol is commonly known as the generalized Precision Time Protocol (gPTP) generalized clock synchronization protocol to distribute time across the network domain. The port in this time-aware system utilizes a master slave paradigm in which the master sends the time synchronization information to the slave port of a time-aware system, while the slave receives that information from the master port. The one with all its ports in the master state is known as the Grandmaster (GM) and it is the time source of the network. In a network environment with a maximum of 7 hops, gPTP can theoretically ensure that the clock synchronization error is in units of nanoseconds.

Bounded latency or deterministic end-to-end latency is defined in IEEE 802.1Qbv for traffic scheduling and management of time. It defines the queuing management, gating, and traffic shaping to ensure the time-critical flows are scheduled based on service level, thus avoiding mutual interference between traffic of different priorities.

1.2.3 TSN-enabled 5G System

Starting from 3GPP Release 16, the 5G system's role has becoming like an industry-grade communication fabric. In Release 16, it has introduced the integration of the 5G system (5GS) with the Time-Sensitive Networking task group of the IEEE 802.1 working group in support of the industrial automation vertical, converging the IT and OT.

In the liaison statement S2-1908630 from the 3GPP SA WG2 (SA2) to the IEEE 802 workgroup, 3GPP has integrated transparently as the 5G System as a logical TSN bridge to support time-sensitive communication. In Release 16, it will support:

- IEEE 802.1Qcc: three TSN configuration models
- IEEE 802.1Qbv based QoS scheduling for interworking with TSN
- IEEE 802.1Q Annex Q.2 ("Using gate operations to create protected windows") for simplified traffic scheduling
- IEEE 802.1AS for the entire end-to-end 5G System as a "time-aware system" for TSN synchronization.

In TSN-enabled 5G system, the 5G System is acting as a virtual gPTP time-aware system (IEEE 802.1AS) where the 5GC is acting as a TSN bridge port with time synchronization between the TSN system clock and the 5G clock.

The 5GS is perceived as an IEEE-compliant virtual Ethernet TSN bridge. At the edges of the 5GS, Network-Side TSN Translator (NW-TT) and Device-Side TSN Translator (DS-TT) are synchronized with the 5G GM clock (i.e., the 5G internal system clock) to keep these network elements synchronized, see Figure 1 for illustration.

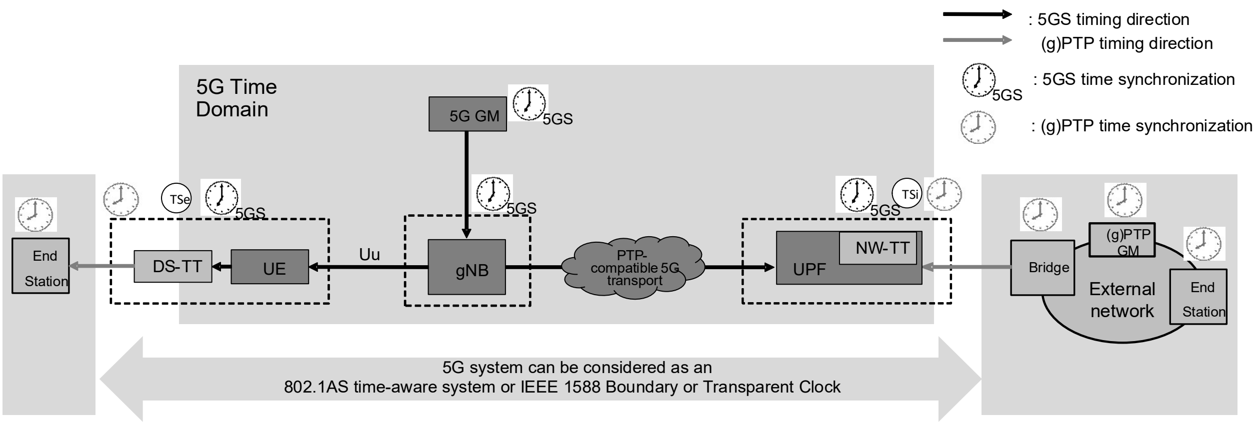

Figure 1 5G System as a time-aware system [Source: TS23.501 Figure 5.27.1-1]

In 3GPP, the data session is known as Packet Data Unit (PDU) Session between the user equipment (UE) and the data network (DN) via the User Plane Function (UPF) acting as a PDU Session Anchor (PSA). In the schematic diagram of the 5G bridge system, each 5G bridge consists of port on the UE/DS-TT sides, user plane tunnels (PDU session) between the UE and UPF, and ports on the UPF/NW-TT side. The port on the UE/DS-TT side is bound to a PDU session, and the port on the UPF/NW-TT side supports connection with the external TSN network, as shown in Figure 2. In the 5GS, from NW-TT to DS-TT, is considered as a single bridge while there could be more than one UPFs involved in the end-to-end connection. Each bridge will be assigned a unique bridge identifier for use in the TSN domain, e.g., the configurations in CNC and TSN AF.

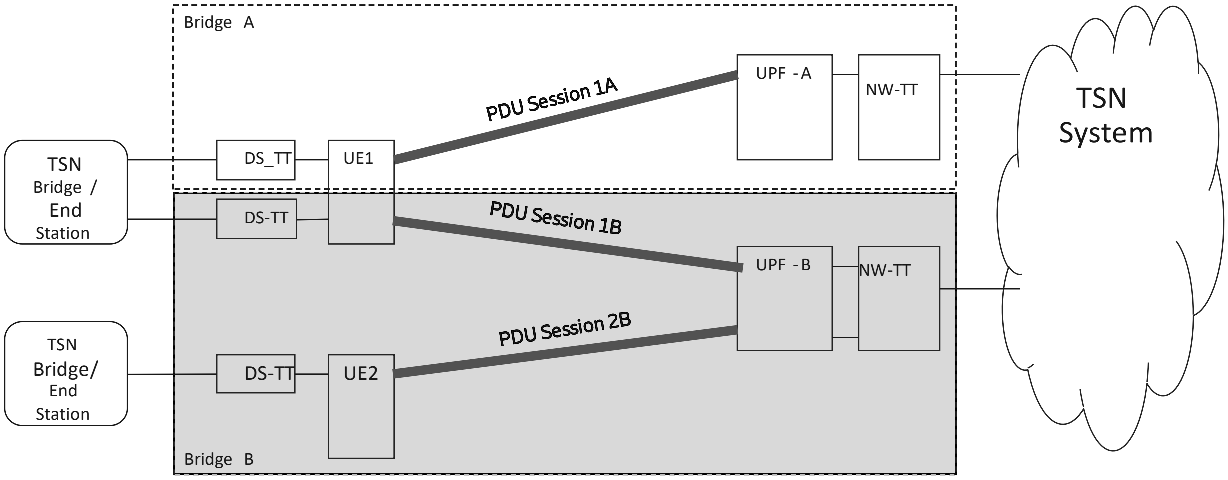

Figure 2 5GS as a TSN bridge [Source: TS23.501 Figure 5.28.1-1]

1.3 Collaborations

1.3.1 Peng Cheng Laboratory

Peng Cheng Laboratory (PCL) is an advanced and innovative research institution in the field of network communications and artificial intelligence in China. It is focusing in solving strategic, forward looking, fundamental yet critical scientific problems. It is a major contributor to this field, supporting national strategic science and technology efforts.

PCL is a laboratory with a team of talented researchers and engineers to develop network communication projects to fully enable large-scale industrial use cases, such as smart manufacturing, smart city, Industrial Internet, and artificial intelligence (AI). One of the research focuses of PCL is to facilitate the deterministic transmission requirements of the Industrial Internet and high-end equipment scenarios. PCL has been researching and developing TSN chips and platform equipment to achieve the deterministic network service capabilities with controllable bandwidth and delay. Through collaboration of innovative wired and wireless communication technologies, a fully connected "5G + Industrial Internet" factory could be achieved by integrating the key technologies of 5G and TSN.

1.3.2 Hong Kong Applied Science and Technology Research Institute

Hong Kong Applied Science and Technology Research Institute (ASTRI) was founded by the Government of the Hong Kong Special Administrative Region in year 2000 with the mission of enhancing Hong Kong's competitiveness through applied research. The Communications Technologies (CT) Division of ASTRI delivers cutting-edge 5G network technologies and applications, and other next-generation network solutions. Its applications are helping manufacturers, operators, and solution providers to introduce faster and more intelligent services for network users, benefiting both industries and the community.

ASTRI is supporting Hong Kong's digital transformation, re-industrialization, and Industry 4.0 upgrade in terms of standards, solutions, and infrastructure, especially in 5G-related transformations with TSN technologies. ASTRI is developing open broadband wireless networks and applications, including 5G base stations and core networks, and focusing on creating new technology infrastructure and platforms for a wide range of sectors and applications. ASTRI also offers end-to-end system solutions (Easy 5G) with TSN-enabled for various players at different levels of the value chain in the industry ecosystem.

1.3.3 White Paper Highlight

The vision of this white paper is to support the mainland China Government's *Action Plan for Industrial Internet Innovation* and *Development and The Guidelines for the Construction of 5G Fully Connected Factories* and to support the Hong Kong Government's re-industrialization plan which emphasizes the requirements for TSN-enabled 5G infrastructure to support digital transformation and re-industrialization for smart manufacturing, power, and transportation industries locally in China and worldwide. The integration of 5G and smart manufacturing with TSN-related technologies to provide high-precision time synchronization, ultra-reliable network, high throughput, and low latency is undoubtedly the trend of future development.

In this white paper, we have demonstrated the capabilities of ASTRI together with PCL on this new solution of the TSN-enabled 5G network. ASTRI will further leverage the TSN-enabled 5G network and other cutting-edge networking technologies with the OT related industries and other innovations such as smart manufacturing and Cellular Vehicle-To-Everything (C-V2X) for more tests and demonstrations in the near future.

2. Key Challenges

2.1 Requirements of Vertical Industries

In this section, several technical problems and challenges will be described for TSN-enabled 5G system architecture. It has been anticipated that the TSN-enabled 5G system technology is mainly used in vertical industry, where the vertical industry as defined by the 3GPP covers factory of the future, eHealth, smart city and so on. Different fields of the vertical industry have their own requirements, thus posing different challenges in terms of latency, numbers of connection, quality of service, precision, speed, and degree of determinism.

Taking the field of industrial automation as an example, it typically involves flexible manufacturing, remote equipment control, equipment collaboration, field auxiliary assembly, warehousing, logistics, different kinds of quality control and safety monitoring, many of which require clock synchronization accuracy, delay control ability and transmission reliability of the communication network. TSN-enabled 5G system is committed in solving the challenges of such deterministic and low-latency communication with requirement in end-to-end time/frequency synchronization, reliability, delay, and jitter.

Some business requirements of industrial automation in typical application scenarios of TSN-enabled 5G system are given in Table 2:

Table 2 Examples of industrial automation in typical application scenarios of TSN-enabled 5G system [Source: 5G ACIA White Paper, "Integration of 5G with Time-Sensitive Networking for Industrial Communications"]

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

2.2 End-to-End Time Synchronization Challenges

In the 3GPP specifications, the 5GS has been modeled as a TSN virtual switch. It takes the role of realizing the time synchronization of the 5G system itself, the time synchronization of the TSN system and the time synchronization signaling in the TSN system. Therefore, the 5G virtual TSN switch needs to maintain the clock synchronization of the 5GS and TSN domains simultaneously, signaling of the TSN time synchronization information across the 5GS time domain, and ensures that the TSN time deviation after cross-domain shall not exceed 900 nanoseconds. In Table 3, it describes the clock synchronization service performance requirements for the 5GS.

Table 3 Clock synchronization service performance requirements for 5G System [Source: TS22.104 v17.7.0 Table 5.6.2-1]

User-specific clock synchronicity accuracy level	Number of devices in one Communication group for clock synchronisation	5GS synchronicity budget requirements	Service area	Scenario
1	up to 300 UEs	≤ 900 ns	≤ 100 m x 100 m	- Motion control - Control-to-control communication for industrial controller
2	up to 300 UEs	≤ 900 ns	≤ 1,000 m x 100 m	- Control-to-control communication for industrial controller
3	up to 10 UEs	< 10 μs	≤ 2,500 m2	- High data rate video streaming
3a	up to 100 UEs	< 1 μs	≤ 10 km2	- AVPROD synchronization and packet timing
4	up to 100 UEs	< 1 μs	< 20 km2	- Smart Grid: synchronicity between PMUs
5	up to 10 UEs	< 50 μs	400 km	- Telesurgery and telediagnosis

The underlying condition for achieving deterministic communication is to have end-to-end synchronization in place. The working clock domains require a precision of ≤ 1 μs between the sync master and any device of the clock domain as defined in 3GPP TS 22.104. In Table 3, it is shown that the most stringent 5GS synchronicity budget requirement within a working clock domain shall not exceed 900 nanoseconds. The requirement on the synchronicity budget for the 5G system is the time error contribution between ingress and egress of the 5G system on the path of clock synchronization messages.

There are two time-domains in the TSN-enabled 5G system architecture, namely the 5GS time domain and the end-to-end TSN time domain. Therefore, the end-to-end synchronization includes the synchronization of these two time-domains.

1. TSN time-domain: Follow the IEEE 802.1AS or IEEE 1588 protocols.
2. 5GS time-domain: Require all the 5G components involving the data path, i.e., the UE, next generation NodeB (gNB) and UPF to be time synchronized to the 5G internal system clock, also known as the 5G GM.

For instance, the synchronization of the 5GS time domain can be further divided into wired and wireless domains:

1. Wired Network: The time synchronization of the gNB, UPF and 5G GM can be carried out through the wired network using the standard PTP IEEE 1588 or gPTP IEEE 802.1AS mechanism.
2. Wireless Network: The time synchronization between UE and 5G GM is realized through the air interface between the UE and the gNB. The

accuracy of the time synchronization over the air interface is dependent on various factors, such as the multipath effect, UE movement, radio condition asymmetry, and frequency synchronization. Therefore, it is especially challenging to take all these into considerations and to achieve the synchronization accuracy in end-to-end 5GS.

In short, from the system-model perspective, the end-to-end synchronization of TSN-enabled 5G system utilizes the 5G system as a TSN virtual switch. It realizes not only the time synchronization of the 5GS time domain, but also the synchronization with the TSN domain, while providing the time information across the two domains with accuracy across the two domains meeting the requirement in end-to-end time/frequency synchronization of deterministic communications.

2.3 End-to-End Low Latency and Determinism

In TSN-enabled 5G system, the end-to-end low latency challenge includes the delay control in the 5G system and the TSN system.

The 5GS can be divided into 3 components: the core network, the transport network, and the access network. There are different mechanisms for reducing the latency in the 5GS, for example, (1) network slicing support for combinations of these 3 components, (2) Multi-Access Edge Computing (MEC) network with collocated UPF with gNB for traffic splitting/offloading, (3) low-latency optimization in the air interface, etc. Among these approaches, the delay control poses the biggest challenge. The challenge includes how to design an efficient scheduling strategy in reducing the delay introduced by the scheduling sequence, how to balance the reliability with the delay, how to handle a huge number of simultaneous UEs accessing the network, how to reduce the uncertainty of the wireless environment introduced by the joint wireless optimization of the Physical (PHY) layer and the Media Access Control (MAC) layer of the access network.

In TSN-enabled 5G system, it is expected that the network to be deterministic (i.e., lower jitter) where the network translators (Traffic Translator, TT) support the hold and forward mechanism and service shaping for time-based traffic. The IEEE 802.1Qbv protocol defines a Time Aware Shaper (TAS), based on Gate Control List (GCL), dynamically enables/disables the gates of egress queues of the TSN switches and TSN end devices via the Hold-and-Forward mechanism. When the GCL-controlled gates of queues are closed, the packets are buffered in the queue until gates (currently in Hold) are opened (Forward). Typically, TSN devices will be in the Hold state (GCL closed) until the maximum delay of upstream packets arriving the node is reached, then the gates of queues will be opened and switched to the Forward state for forwarding the traffic. By doing so, the mechanism reduces the fluctuation of the delay, eliminating the jitter and achieving determinism. As the mechanism suggests, the degree of controlling end-to-end time-based traffic shaping in the TSN-enabled 5G system network depends on the time accuracy of the GCL, which is the end-to-end time synchronization accuracy. Therefore, the higher the time synchronization precision, the smaller the jitter values will become.

Although IEEE and 3GPP have defined relevant deterministic forwarding mechanisms, however, there are still practical challenges to be resolved:

1. **TAS Hold-Forward time control:**
   The states (Open/Close) of GCL-controlled time-aware gates are determined by the modeling accuracy between the traffic flow and the traffic model (packet arriving time, maximum packet length, burst number and offset time in the cycle) of the service data flow in the queue, as well as the modeling accuracy between the traffic flow and the delay/jitter model. In the model, since the delay and jitter of the 5G virtual switches are relatively large, it is possible to use the TSN TAS adaption to achieve lower jitter to some extent by estimating the worst delay of 5GS. Unfortunately, this approach will result in higher end-to-end latency and larger buffer sizes in the 5GS switches. Therefore, in practical implementation, it is important to minimize the delay of the 5GS and thus the jitter, and at the same time, have accurate measurements or predictions on the 5GS delay and the jitter introduced, such that the Hold time in 5GS can be managed for specific service data flow by TSN Centralized Network Function (CNC). By doing so, the delay and jitter characteristics could be adapted for the service flow model and thereby, the end-to-end traffic achieves low jitter while ensuring the lowest possible delay.

2. **Mapping between the queue and service flows:**
   As mentioned earlier, the control of the TAS GCL is based on queues. In most cases, the number of queues should be no more than 8. If one service flow is mapped on to one queue, then the control will be relatively simple, but the number of service flows that can be supported will be small and limited by the number of queues supported. In fact, the numbers of service data flow are much larger on one service port of 5GS, and the 5GS needs to aggregate multiple service data flows into one egress port/queue for time control. In IEEE 802.1Qch (Cyclic Queuing and Forwarding, CQF), it has described the aggregation of multiple flows into one queue by applying the CQF mechanism for a small network with small delay. In the TSN-enabled 5G system network, the delay of the 5GS is relatively large (in the order of milliseconds). As a result, the CQF mechanism is not suitable, thus a new time control mechanism is needed to support such aggregation.

2.4 QoS Mapping for TSN Flows

For 5G, in 3GPP, a user equipment (UE) can have up to 15 PDU sessions. Each PDU session is identified by a unique PDU Session Identifier per UE, Data Network Name (DNN), and PDU Session Type (IP, Ethernet and Non-Structured) in a network slice. Each PDU session can support up to 63 flows and each flow is identified with a unique

5G QoS Flow Identifier (QFI). All the data flows with the same QFI will be treated the same as they have the identical QoS profile, thus the same overall performance of the service/application experience can be expected. The main QoS profile includes the 5G QoS Identifier (5QI), Allocation and Retention Priority (ARP) and the flow type. The 5QI is defined as shown in Table 4. The ARP indicates the information about priority level, pre-emption capability (whether pre-empt resources can be assigned to other QoS flows), and the pre-emption vulnerability (whether pre-empted allowed by other QoS flows). There are three types of flows: Guaranteed Bit Rate (GBR) QoS Flows, Non-GBR QoS Flows and Delay Critical GBR QoS Flows. The standardized 5QI to QoS characteristics mapping is also given in Table 4.

The QoS parameters and data/service profile for a PDU session are authorized by the Policy Control Function (PCF). The PCF receives policies from Application Function (AF) or static configuration and converts them into Policy Control and Charging (PCC) rules. This information will be provided to Session Management Function (SMF) during UE-initiated session establishment/modification/termination or when triggered by Application Function (AF) to the SMF.

In TSN-enabled 5G system, there are several network functions being involved for the QoS mapping in both the TSN domain and the 5GS domain. In the TSN network, both bridges and end stations need to be time synchronized. The time reference is needed by the end stations for their internal operations. The mechanisms for service classification and management configuration between TSN and 5GS are very different. Therefore, in order to realize different end-to-end QoS profiles to have end-to-end low latency and determinism, we need to be able to perform QoS mapping between 5G Flow and TSN stream/traffic class.

The time reference is realized by the QoS parameter mapping from the TSN service flow to the 5GS QoS. The TSN CNC will update the TSN AF for dynamic flow configurations. The PCF in the 5GC will convert the policy provided by the TSN AF with the user subscription information on the TSN service flow to PCC Rules and authorized that via the SMF. The SMF will provision the PCC rules into packet handling/forwarding rules for enforcement in the UPF and the TSC Assistant Information (TSCAI) via the Access and Mobility Management Function (AMF) to the Radio Access Network (RAN). Comparing with non-TSN signaling, the processing of these parameters mappings, decision making, and processing of these dynamic information pose high volume of control signaling between all the involved network elements, which in turn put stringent requirements for the 5GS network functions, including the AMF, SMF, PCF, and UPF.

Table 4 Standardized 5QI to QoS characteristics mapping [Source: TS23.501 Table 5.7.4-1]

5QI Value	Resource Type	Default Priority Level	Packet Delay Budget	Packet Error Rate	Default Maximum Data Burst Volume	Default Averaging Window	Example Services
1	GBR	20	100 ms	10^{-2}	N/A	2000 ms	Conversational Voice
2		40	150 ms	10^{-3}	N/A	2000 ms	Conversational Video (Live Streaming)
3		30	50 ms	10^{-3}	N/A	2000 ms	Real Time Gaming, V2X messages. Electricity distribution – medium voltage, Process automation monitoring
4		50	300 ms	10^{-6}	N/A	2000 ms	Non-Conversational Video (Buffered Streaming)
65		7	75 ms	10^{-2}	N/A	2000 ms	Mission Critical user plane Push To Talk voice (e.g., MCPTT)
66		20	100 ms	10^{-2}	N/A	2000 ms	Non-Mission-Critical user plane Push To Talk voice
67		15	100 ms	10^{-3}	N/A	2000 ms	Mission Critical Video user plane
71		56	150 ms	10^{-6}	N/A	2000 ms	"Live" Uplink Streaming
72		56	300 ms	10^{-4}	N/A	2000 ms	"Live" Uplink Streaming
73		56	300 ms	10^{-8}	N/A	2000 ms	"Live" Uplink Streaming
74		56	500 ms	10^{-8}	N/A	2000 ms	"Live" Uplink Streaming
76		56	500 ms	10^{-4}	N/A	2000 ms	"Live" Uplink Streaming
5	Non-GBR	10	100 ms	10^{-6}	N/A	N/A	IMS Signalling
6		60	300 ms	10^{-6}	N/A	N/A	Video (Buffered Streaming) TCP-based (e.g., www, e-mail, chat, ftp, p2p file sharing, progressive video, etc.)
7		70	100 ms	10^{-3}	N/A	N/A	Voice, Video (Live Streaming) Interactive Gaming
8		80	300 ms	10^{-6}	N/A	N/A	Video (Buffered Streaming) TCP-based (e.g., www, e-mail, chat, ftp, p2p file sharing, progressive video, etc)
9		90					
69		5	60 ms	10^{-6}	N/A	N/A	Mission Critical delay sensitive signalling (e.g., MC-PTT signalling)
70		55	200 ms	10^{-6}	N/A	N/A	Mission Critical Data (e.g., example services are the same as 5QI 6/8/9)
79		65	50 ms	10^{-2}	N/A	N/A	V2X messages
80		68	10 ms	10^{-6}	N/A	N/A	Low Latency eMBB applications Augmented Reality
82	Delay Critical GBR	19	10 ms	10^{-4}	255 bytes	2000 ms	Discrete Automation
83		22	10 ms	10^{-4}	1354 bytes	2000 ms	Discrete Automation; V2X messages (UE - RSU Platooning, Advanced Driving: Cooperative Lane Change with low LoA.)
84		24	30 ms	10^{-5}	1354 bytes	2000 ms	Intelligent transport systems
85		21	5 ms	10^{-5}	255 bytes	2000 ms	Electricity Distribution-high voltage, V2X messages
86		18	5 ms	10^{-4}	1354 bytes	2000 ms	V2X messages (Advanced Driving: Collision Avoidance, Platooning with high LoA.)

3. 3GPP Specification for TSN-enabled 5G system

3.1 Packet Data Unit Session

In 5G system, a PDU Session refers to an end-to-end user data connectivity between the UE and a specific Data Network (DN) through the UPF(s). A UE can have up to 15 PDU Sessions and each PDU Session can have up to 63 QoS Flow, where each QoS flow has a unique QoS profile, thus the same 5QI.

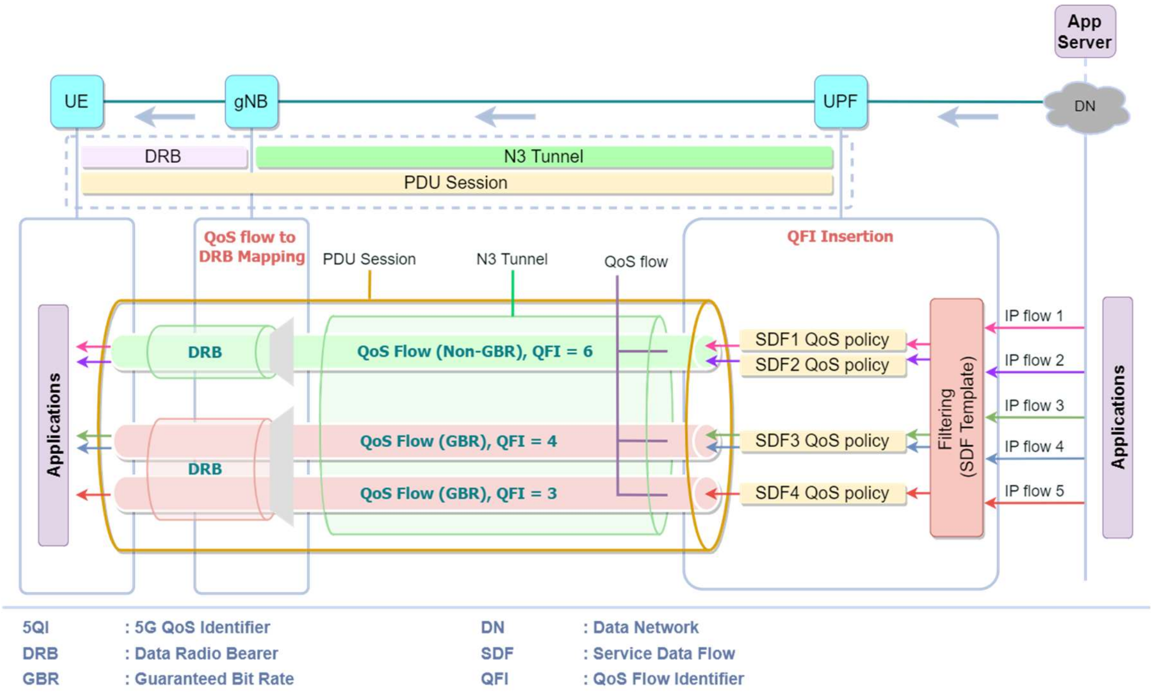

Figure 3 QoS differentiation within a PDU Session [source: www.netmanias.com]

The flow binding is performed by the SMF upon receiving the PCC rules from the PCF. The PCC rules will then be mapped to QoS Rule and sent to the RAN and UE for uplink QoS enforcement and to the UPF for downlink QoS enforcement.

A PCC rule received from the PCF indicates how the user data should be handled in the data plane. It provides the QoS measure, traffic control, usage monitoring, handling action, and application filter. Upon receiving this information, SMF will carry out not only the QoS flow binding but also select the UPF(s) to form the topology of the data path. For each session, there is typically one GPRS Tunnelling Protocol User Plane (GTPU) tunnel between the RAN and the UPF as well as between the intermediate UPFs. The PSA UPF will filter downlink packet from the DN according to the filtering information and create a GTPU outer header with the QFI and tunnel identifier. All the data flows in a session, even with different QFIs, will be forwarded in the same GTPU tunnel. The QoS Flow will then be mapped into different Data Radio Bearer at the RAN.

3.2 5GS Acting as a Bridge in TSN

The 3GPP standards define the 5GS as one or more virtual TSN switches and thus 5GC will be regarded as such in TSN-enabled 5G system architecture. Similar to ordinary TSN switches, 5GS virtual switches need to implement IEEE 802.1Qbv TAS mechanism on TSN egress ports, namely NW-TT and DS-TT, to achieve deterministic forwarding, and each egress port of the TT can support up to 8 queues. The major network elements of achieving end-to-end synchronization for 5G virtual switches are NW-TT and DS-TT, where both TSN and 5GS time-domain synchronizations are supported to accomplish the mapping and calibration among these time domains. Furthermore, NW-TT is also necessary to implement the Best Master Clock Algorithm (BMCA) from 3GPP Release 17 onwards to determine the PTP port states.

Noted that each PDU session will be corresponding to a single DS-TT port for a given UPF. 5GS bridges are grouped per UPF basis, that is, all PDU sessions connect to a common TSN system via a specific UPF (UPF-A/UPF-B in Figure 2) belonging to a 5GS bridge.

3.3 Time Synchronization

As shown in Figure 1, there are two concurrent processes involved in end-to-end synchronization in the TSN-enabled 5G system, which are the synchronization of the 5GS time-domain and TSN time-domain respectively. 5GS will provide its own internal GM clock for the 5G network elements to maintain their synchronization where the UE, gNB, UPF, NW-TT, and DS-TT should remain synchronized with the 5G GM clock while NW-TT and DS-TT(s) have to be additionally synchronized with TSN GM clock.

End-to-End synchronization cannot be fulfilled without proper 5G system time-domain synchronization. UE/DS-TT and UPF/NW-TT need to be synchronized with the 5G GM.

3.3.1 5GS Time Synchronization

From standard perspectives, time synchronization of 5GS in NW-TT at UPF side can be achieved using non-3GPP compliant procedures through the underlying PTP transmission network between UPF and NG RAN, that is, according to IEEE 802.1AS or IEEE 1588 PTP clock information transfer processes.

On the other hand, the time synchronization of 5GS in DS-TT at UE side is not determined by the mechanism defined in IEEE 1588/802.1AS. However, DS-TT at UE side obtains synchronization information from gNB through the radio interface, which is called 5G Access Stratum timing distribution as described in 3GPP Radio Resource Control (RRC) processes. The details of high-level signaling of RRC processes are illustrated in 3GPP TS 38.331.

3.3.2 End-to-End Time Synchronization

In order to realize the end-to-end synchronization of 5GS and TSN, on the basis of realizing the synchronization of the time domain of the 5GS, it is also necessary to have the transmission of the synchronization information of the TSN time across the 5GS domain. Figure 1 also suggests the mechanism of distributing timing information: for every downlink PTP message received at NW-TT port sent by an external TSN node, the NW-TT of UPF will mark the ingress timestamp (TSi) following by forwarding PTP message to the gNB through a PTP-aware transport network. Similarly, an egress timestamp (TSe) will be generated upon receiving the PTP message at the DS-TT. Throughout the process described above, the time difference between TSi and TSe is defined as the residence time within the 5GS for this particular PTP message and it will be further used by DS-TT to modify the timing information prior sending it to the next TSN node. It is also necessary to implement the Best Master Clock Algorithm (BMCA) from 3GPP release 17 onwards.

3.4 Enhancements for QoS Mappings

As mentioned in Section 2.4, there are 2 sets of QoS parameters in the 5G and TSN networks: the TSN QoS profile and the 5GS QoS profile. The TSN AF is responsible to have the TSN QoS profile configured locally or dynamically from the TSN CNC for parameters such as the Per-Stream Filtering and Policing (PSFP) information and gating parameters. The TSN QoS profile includes the TSN flow descriptions, Time Synchronization Communication Assistance Information (TSCAI) burst time, periodicity, flow direction, priority, delay, and bandwidth parameters. The PCF converts the policy received from the TSN AF and provides the mapping to the 5GS

QoS Profile. The QoS profile includes the Authorized 5QI, Authorized Allocation and Retention Priority (ARP) and Authorized Maximum/Guaranteed Data Rate UL/DL. And such process also includes the derivation of the QoS Notification Control (QNC), Reflective QoS Indication (RQI), Priority Level (PL), Averaging Window (AW) and Maximum Data Burst Volume (MDBV). The PCF can dynamically trigger the Network-initiated PDU session modification procedures to update the 5GS QoS profile for the data flow.

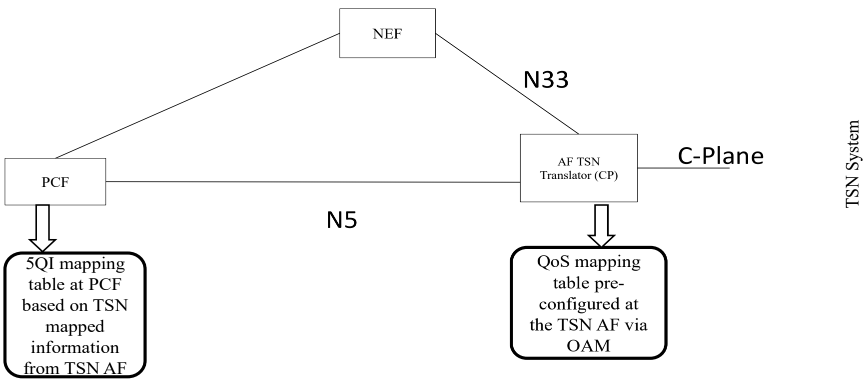

Figure 4 QoS Mapping in TSN AF and PCF architecture [Source: TS23.501 Figure 5.28.4-1]

In order to support TSN flows in the 5G System, the TSN QoS parameters need to be mapped to the 5G QoS parameters as shown in Figure 4. The PDU session type for TSN flows could be either Ethernet or IP data traffic. The NEF supports external exposure of capabilities of network functions. Therefore, if TSN AF is part of the network, the NEF is not needed and the TSN AF will be connected to the PCF directly.

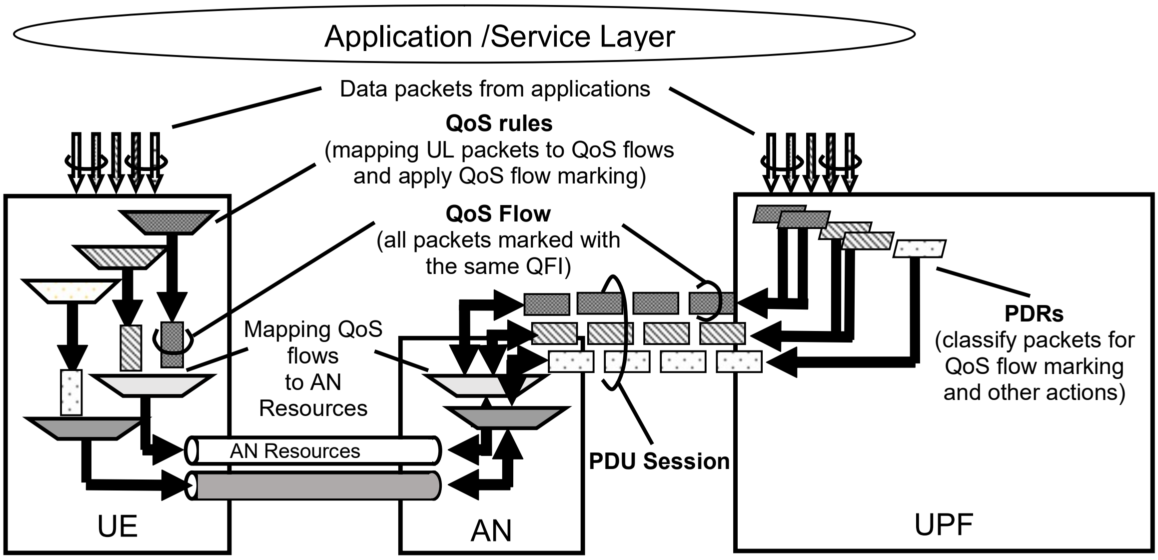

Figure 5 User data handling in the UPF [Source: TS23.501 Figure 5.7.1.5-1]

The PCF is responsible for translating the policy received from the TSN Application Function (AF) and combines that with the user subscription information and the service flow requirement to provide a mapping function from the TSN QoS information to the 5GS QoS profile into the PCC rules. Upon receiving the PCC rules, SMF will perform the flow binding and convert the PCC rules into Packet Data Rules (PDRs), Forwarding Action Rules (FARs), QoS Enforcement Rules (QERs), Usage Reporting Rules (URRs), Buffering Action Rules (BARs) and Multi-Access Rules (MAR) to be enforced in the UPF for packet forwarding and filtering. The TSN QoS requirement needs to be decided by the PCF for establishing a 5G QoS Flow with desired TSN service flow characteristics, TSCAI burst time, period, flow direction, priority, delay, bandwidth, etc., to realize the low-latency and deterministic transmission of TSN service flow in the 5G system. For instance, TSN service flows and TSN clock synchronization message flows will be assigned a specific QoS flow profile that meets their respective transmission requirements. The handling of the user data at the UPF is shown in Figure 5, where the TSN service flows will be classified according to the PDRs and forwarded according to associated FAR in the PDR, where the outer header of the data flow is labeled with the QFI.

For each QFI, the SMF will also decide on the TSCAI to be enforced in the gNB. The gNB will take the TSCAI, including the flow direction, periodicity, burst arrival time and survival time, for more efficient radio resource scheduling for periodic ethernet and IP traffic. The AMF will communicate these parameters with the gNB.

As the TSN AF continuously receiving information from the TSN CNC on the time synchronization information, it will consistently update the PCF, and thus the SMF, UPF and gNB on the QoS parameters. The frequent dynamic updating across all these network elements pose additional processing, computational and handling pressure in the control signaling in a timely manner, and thus higher requirement on the processing power for AMF, SMF, PCF and UPF.

4. Data Service Solution

4.1 Architecture of End-to-End Synchronization Solution

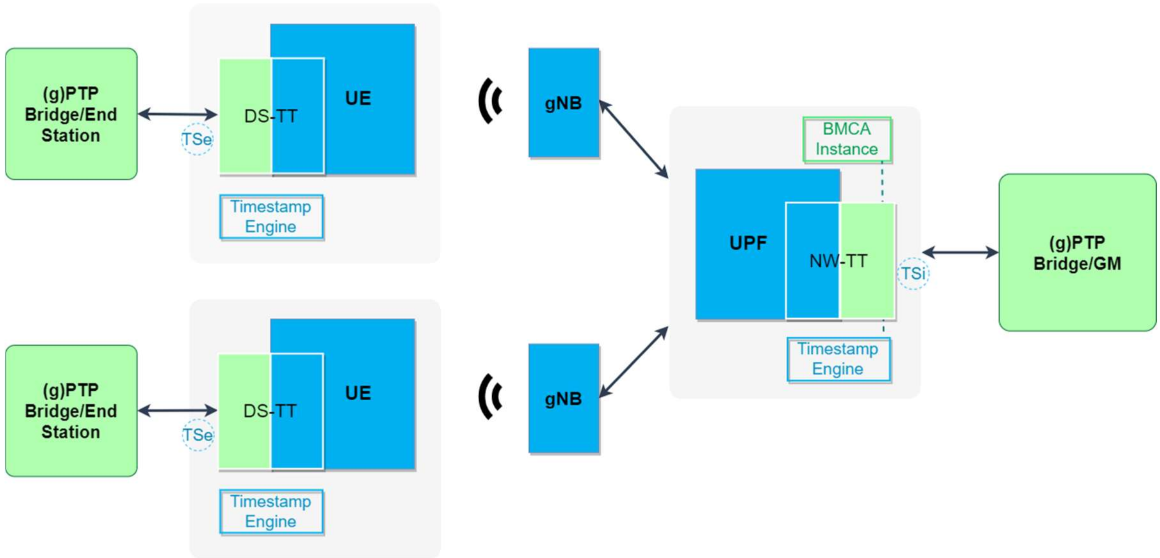

Figure 6 End-to-End Synchronization Solution

The end-to-end synchronization solution can be visualized as shown in Figure 6. The 5GS time-domain has been representing in blue and several TSN time domains representing in green, and it should be aware that both domains can coexist in NW-TT and DS-TT.

4.1.1 Timestamp Modelling

There are at least two time-domains involved in 5G integrated TSN system: 5GS time-domain and TSN time-domain. The TSN time domain will be synchronized across the 5GS time domain.

The 5GS time domain is synchronized with the 5GS GM. Specifically, the Rate Estimation and Control (RC) model in the protocol can be used or combined with the Phase-locked Loop (PLL) to implement the Real Time Clock (RTC) timing algorithm. In the lower right of Figure 7, it shows that the local time tracks the 5GS GM clock and the local time through a closed-loop control, and it serves as the reference clock for the TSN time domain.

The TSN time domain shall be synchronized with the TSN GM, and it will be used to provide timestamps which are used in IEEE 802.1Qci and 802.1Qbv procedure. The implementations of TSN time domain RTC timing algorithm utilize combining Rate Estimation (RE) and RC modeling described in IEEE 1588 and IEEE 802.1AS protocol.

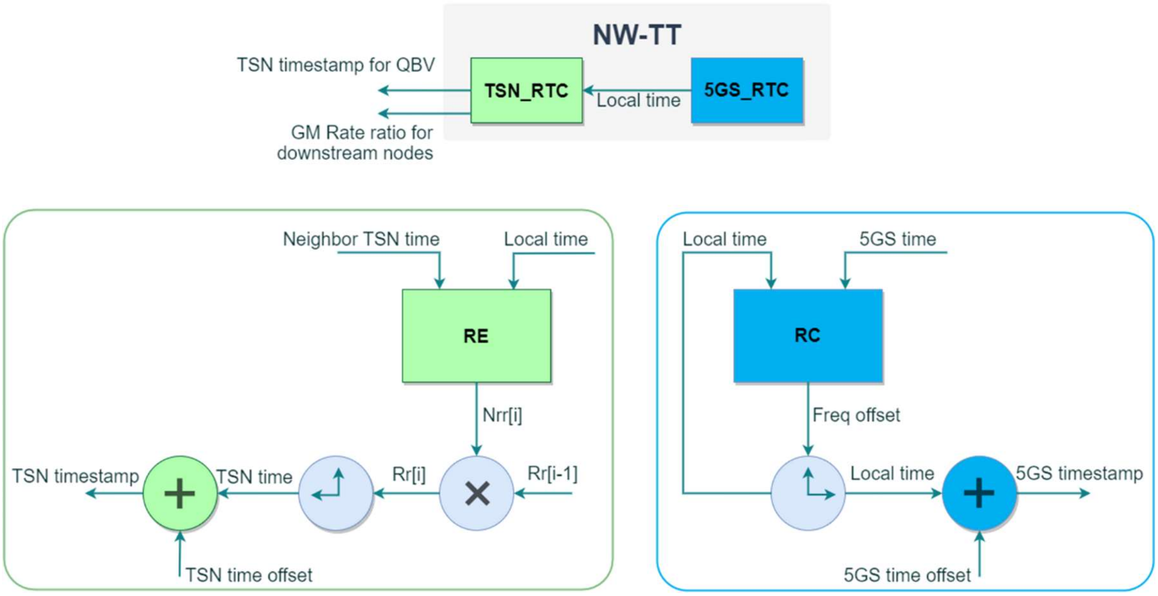

Figure 7 NW-TT Timing Algorithm

4.1.2 Solution of 5GS Time-Domain Synchronization

End-to-end synchronization cannot be fulfilled without proper 5GS time-domain synchronization. Hence, the synchronization of the 5GS time domain can be divided into the following perspectives:

In order to have end-to-end time synchronization, it is critical to have time synchronization in the 5GS time domain. The time synchronization in the 5GS time domain can be further divided into three parts:

1. The NW-TT/UPF and the gNB are synchronized by standard PTP protocol.

2. The UE obtains the 5GS absolute time from the gNB through radio signaling.

3. The DS-TT retrieves 5G time directly from UE.

4.1.3 TSN-enabled 5G End-to-End Synchronization Solution

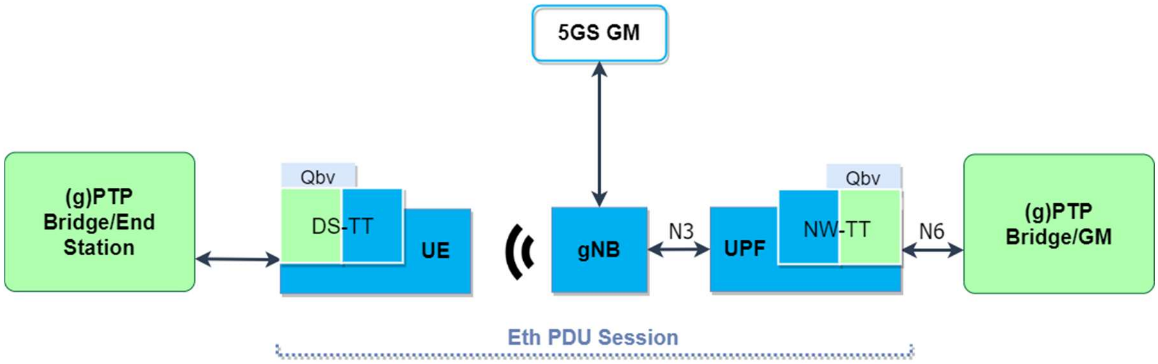

Figure 8 TSN-enabled 5G system End-to-End synchronization demo solution

In Figure 8, it shows the TSN-enabled 5G system end-to-end synchronization solution jointly developed by PCL and ASTRI. The NW-TT resides in the UPF and it uses the TSN network card running on x86 server, whereas the DS-TT uses a TSN switch with a build-in TT port.

The figure has been color-coded. The blue rectangular boxes illustrate the domain being synchronized by the standard PTP protocol between the 5GS GM, the gNB and TSN network cards. The gNB sends time information to the UE through radio signaling. The standard PTP protocol is used for synchronization between the UE and the TSN switch. The external end-to-end green time region is being time synchronized as follows: 5GS configures NW-TT, DS-TT to support all synchronization models defined in IEEE802.1AS, including PTP Boundary Clock, PTP End-to-End Transparent Clock, PTP Peer-to-Peer Transparent Clock, and gPTP Relay instance respectively.

The synchronization model of gPTP relay instance is shown in figure 9 below. The 5G system is considered as a TSN virtual switch, and the egress port is named as TSN translator (TT) port. There are several other synchronization models' mechanisms such as PTP Boundary Clock, PTP End-to-End Transparent Clock and PTP Peer-to-Peer Transparent Clock and they will not be discussed in this paper.

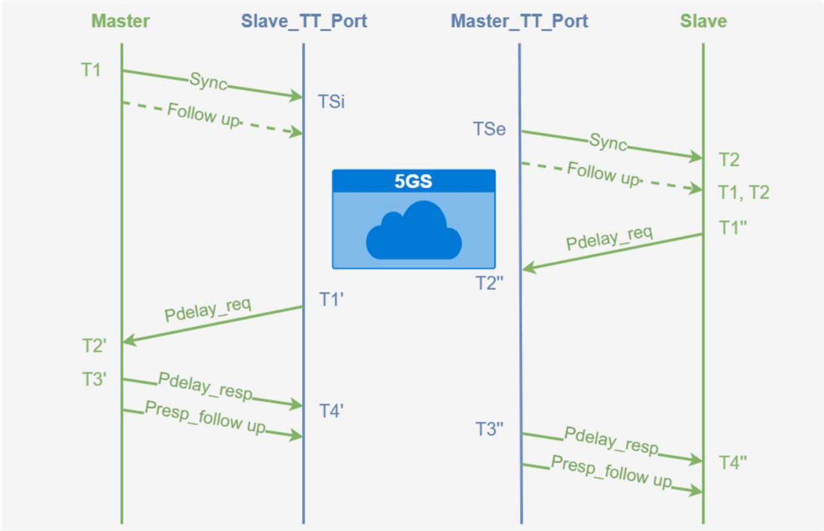

Figure 9 gPTP relay instance model

The details of synchronization mechanism of gPTP Relay instance model are described as follow:

1. The Master port (in green), outside the 5G system, sends Sync/Sync, Follow-up packets to the salve port TT at timestamp T1.
2. Upon 5GS Slave TT port receiving the packet sent by Master port in step 1, it will (1) add the link delay from Master port to Slave TT port in the CF (Correction Field) within Sync/ Sync, Follow-up packet header, and (2) record the arrival time (TSi) of Sync packet using 5G system timestamp. TSi will then be encoded in the 3GPP Type-length-value (TLV) field and the cumulative rate ratio field in Sync/Follow-up message is updated according to Neighbor Rate Ratio (NRR).
3. The Sync/ Sync, Follow-up packet will be forwarded to Master TT port via 5GS, and the outgoing ports are determined by relative forwarding configurations in 5GS.
4. The Master_TT port records the egress timestamp TSe and calculates with the entry timestamp TSi to obtain the residence time of the packet in the 5G system (the residence time in the 5G system needs to be converted to the PTP GM clock domain). After accumulating the residence time in the CF domain, removing the TSi TLV field, the Sync/ Sync, Follow-up packet will be forwarded to the downstream node.
5. The downstream slave port retrieves timestamps T1 and T2 from the Sync/Sync, Follow-up) message.
6. Downstream slave node performs the time synchronization based on timestamps T1 and T2, CF domain and the link delay.

For instance, for the link delay, the NRR is computed on the Slave TT port node as follows:

1. The Slave TT port sends the Pdelay_req message, and the egress timestamp T1' is recorded when sending.
2. The Pdelay_req packet is forwarded to the upstream master port, and the upstream master port records the ingress timestamp T2', generates a Pdelay_resp packet with the T2' timestamp.
3. When the Pdelay_resp message is sent from the master port, the egress timestamp T3' is recorded, and stored in the Pdelay_resp_follow_up message.
4. The Pdelay_resp and Pdelay_resp_follow_up packets are forwarded to the downstream Slave TT port. When the downstream Slave TT port receives the Pdelay_resp packet, it records the ingress timestamp T4', and then decodes the Pdelay_resp_follow_up packet to obtain the T3' timestamp.
5. After the Slave TT port obtains a set of T1', T2', T3', T4', it can compute the link delay.
6. The Slave TT port periodically sends the Pdelay_req message and receives corresponding sets of T1' to T4'. By using any two groups, e.g. (T1', T2') and (T3', T4'), the NRR can be obtained.

4.2 End-to-end Deterministic Scheduling Scheme

4.2.1 5G and TSN QoS Mapping

In the control plane, the Time Synchronization Communication Assistance Information (TSCAI) has been introduced for the purpose of allowing the gNB to adjust the scheduling of the TSC packets. The TSCAI related parameters are provided to PCF from TSN AF. During the flow establishment, the SMF will include this information when configuration the QoS profile in the signaling. The TSN QoS parameters, namely the maximum burst size and the maximum flow bitrate of the TSN flows, are eventually mapped to the Maximum Data Burst Volume (MDBV) and QoS Flow-level Guaranteed Flow Bit Rate (GFBR) in the 5G System. Upon receiving these parameters, the gNB will adjust and adapt the scheduling of the TSC packets accordingly to achieve a more efficient periodic scheduling of the TSN service flows.

In this TSN-enabled 5G system evaluation, jointly developed by PCL and ASTI, the focus has been on the realization of the data path. Therefore, the base station (gNB) as well as the control plane network elements, such as the AMF, SMF, PCF and TSN AF, have been simulated. The 5G QoS profile and the mapping to TSN QoS profile have been pre-configured in the system according to the scenario under study. Among them, the guaranteed bit rate (GBR) and maximum bit rate (MBR) of the uplink and downlink data are configured to be 2Gbps, meeting the QoS requirements of service flows and the QoS requirements of interference background flows. On the

TSN side, the TSN QoS has been configured and tuned by adjusting the GCL.

4.2.2 End-to-End Deterministic Traffic Scheduling

The deterministic traffic scheduling mechanism of a 5G virtual TSN switch remains unchanged with a common TSN switch. The general mechanism can be described as the following steps:

1. Reports forwarding delay of switch and port link propagation delay.
2. Receives traffic flow identification, priority mapping and forwarding rules from CNC and configures the above information to UPF/NW-TT and UE/DS-TT.
3. Receive GCL configurations for TSN port (DS-TT, NW-TT) from CNC.

However, considering the nature of relatively large latency, jitter introduced by 5GS bridge and TSN's time scheduling based on queues , the TSN traffic scheduling of CNC should consider using the following mechanism:

1. Enhancing multi-queue scheduling

Enhancing multi-queue scheduling mechanism is considered to solve the complexity and low resource utilization problems of the scheduling of the aggregated TSN streams. In the extreme case, the impact of jitter can be completely eliminated if each TSN stream is assigned to an exclusive queue.

2. Enhancing cyclic queuing forwarding

Frames are kept within a certain delay range and sent within their allotted time through the cyclic queuing forwarding (CQF) mechanism combining the IEEE 802.1Qci entry policy and IEEE 802.1Qbv Time-Aware Shaper (TAS). The CQF solution integrated with TAS is developed to shape and regulate the transmission selection for providing the protected transmission window for time-triggered flows at the egress port, as shown in Figure 10. Further enhancement of cyclic queuing forwarding mechanism including multi CQF and multi-queue CQF is considered to solve the scheduling problems of the aggregated TSN streams caused by the large latency and jitter of 5GS bridge.

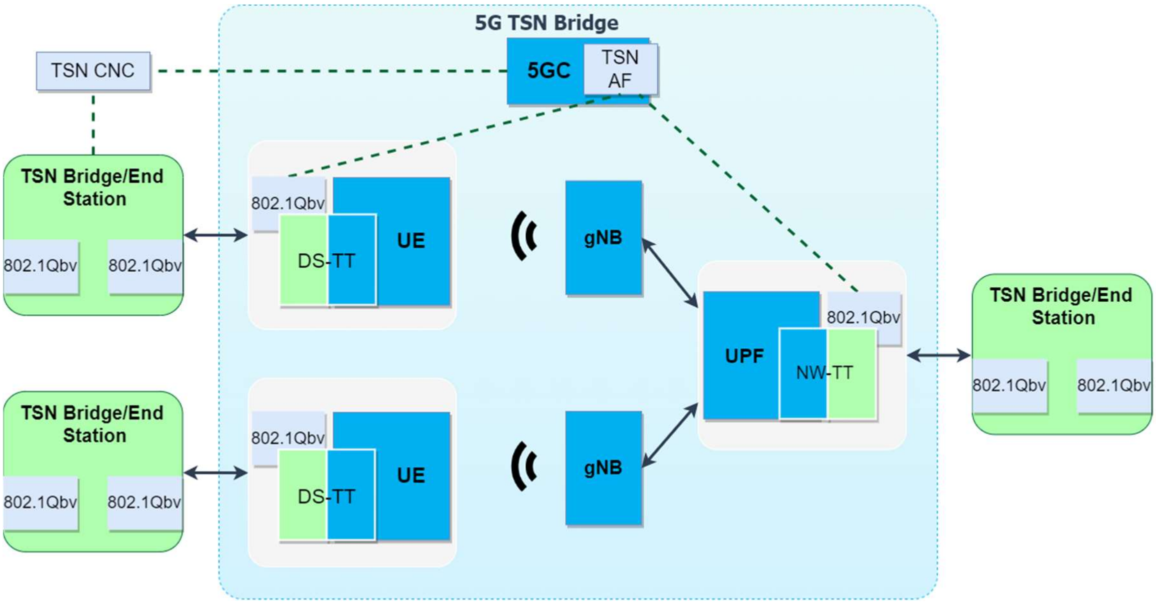

Figure 10 Traffic Scheduling

4.2.3 Supporting hold and forward buffering mechanism (DS-TT/NW-TT)

The 3GPP standards define the 5G system as a virtual TSN switch. Similarly, to a common TSN switch, 5G TSN switch needs to implement IEEE 802.1Qbv TAS mechanism on TSN egress port (i.e., NW-TT and DS-TT) to fulfill deterministic forwarding, moreover, each egress port of the TT should support a maximum of 8 queues.

According to the definition of IEEE 802.1Qcc, the 5GS virtual switch needs to report the switch forwarding delay (Bridge Delay) and the link propagation delay (txPropagationDelay) for the TSN CNC to configure the Hold-Forward time scheduling of the GCL on the service path (GCL switch gate) accordingly.

1. Link propagation delay: Propagation delay per port (txPropagationDelay), the link propagation delay between the egress port of the 5GS switch and the downstream TSN device. The NW-TT and DS-TT report the txPropagationDelay of each port to the 5GC TSN AF, and the TSN AF reports it to the TSN CNC.

2. Switch forwarding delay: A.k.a. Bridge Delay, is the forwarding delay inside the 5GS virtual switch. It is defined to be the delay per port pair per traffic class, e.g., between 1 DS-TT port and 1 UPF/NW-TT (N6) port, or 2 DS-TT ports form a port pair (port pair) where the port pair can carry services of multiple service levels (traffic class). The 5GS gives 1 switch delay parameter for each service class on each port pair. The switch delay consists of two parts: the delay between the UE and the UPF/NW-TT(N6) and the UE-DS-TT

residence time, the switch delay is the sum of these two parts. The switch delay is captured as follow: UE-DS-TT residence time is reported to 5GC TSN AF by DS-TT in the form of device capability and the delay between UE and UPF/NW-TT(N6) is pre-configured in TSN AF. Upon the UE-UPF PDU session has been successfully established, the 5G TSN AF sums up the two and reports it to the TSN CNC with the Bridge Delay parameter. For instance, if it is DS-TT to DS-TT forwarding, it is the sum of 2 DS-TT to UPF/NW-TT delays.

5. Evaluation

5.1 Solution Architecture of TSN-enabled 5G Core Proof of Concept (PoC)

Figure 11 illustrates the overall architecture supported by ASTRI and PCL in TSN-enabled 5G system. The 5GS is provided by ASTRI and it is connected to the TSN network as a TSN Bridge. The ASTRI 5GS is connected to the external TSN network through the NW-TT at the network side in the UPF and the DS-TT at the user equipment side. The configurations from the TSN network are provisioned from the CNC via the TSN-AF to the 5G System. The NW-TT and DS-TT are responsible for the PTP synchronization with the 5G GM inside the 5G System, thus these two are time synchronized in the 5GS domain.

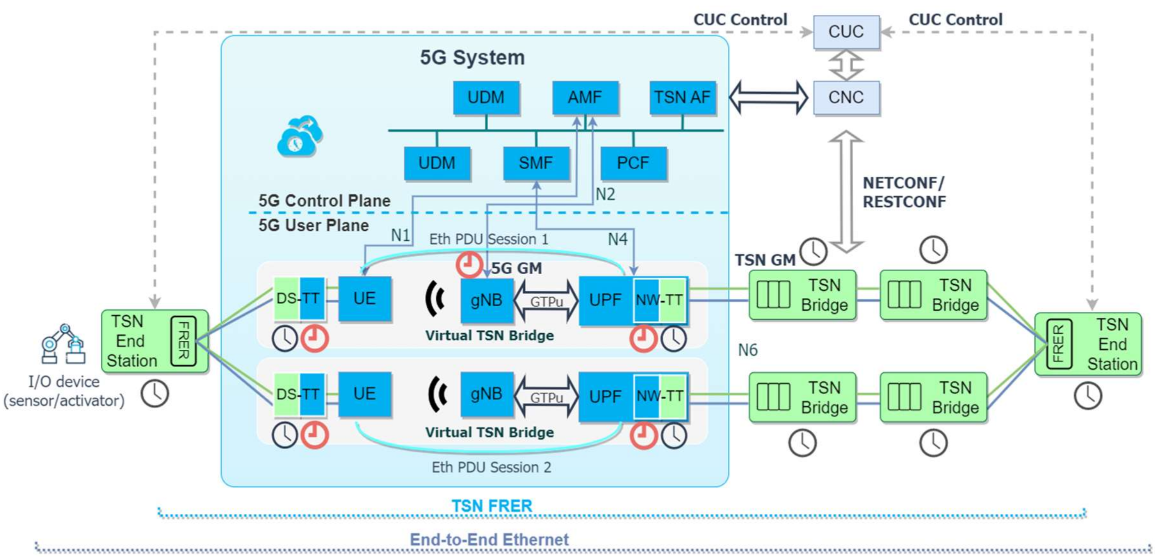

Figure 11 Complete PCL and ASTRI solution architecture with 5G Network Functions

For gPTP synchronization packets received by NW-TT, an ingress timestamp will be added based on the clock synchronized from the 5G GM. Similarly, when DS-TT sends gPTP synchronization packets, it will mark the egress timestamp based on the clock synchronized from the 5G GM. Because the NW-TT and the DS-TT are in a time synchronization state, the DS-TT can obtain the residence time of the entire 5G system according to the incoming timestamp and outgoing timestamp from the synchronization packets. In addition to calculating residence time, the NW-TT and the DS-TT also need to support other features of a TSN Bridge, such as IEEE 802.1Qbv and IEEE 802.1Qbu.

ASTRI and PCL have different focuses in this research. ASTRI focuses on 5G protocol research and the realization of TSN features in the 5G network, while PCL's specialty lies in the TSN, thus integrating the 5G into the TSN environments. The design and implementation of ASTRI comply with the 3GPP specifications for supporting the TSN feature in the 5G, including the Ethernet PDU session management, the TSN AF for interfacing with the TSN CNC, the enhanced PCF, SMF, UPF and AMF, and more importantly the development of the NW-TT residing in the UPF. PCL conducts research in 5G protocol and IEEE TSN protocol, and develops NW-TT and DS-TT, as well as providing the other components in the TSN network, such as the CNC for interfacing with the TSN AF. PCL also takes lead in the formulation of the TSN integration.

5.2 Collaboration Results from Actual Deployment Evaluation Setup

The goal of this demonstration is to integrate TSN technology with existing 5G network, empowering it with determinism. Figure 12 describes overall architecture of the demonstration, consisting of several major components including 5G and TSN Network, where 5G system will act as a single TSN switch within the whole TSN-enabled 5G network, interconnected with various end devices such as cameras and synchronous mechanical arms. Video streams with large bandwidths will be transmitted by cameras while jitter/latency-sensitive controlling streams will be transmitted to two synchronous mechanical arms. With background traffic, these two types of different streams will be transmitted through TSN-enabled 5G network containing both 5G systems and TSN switches. The oscilloscope is used to observe the offset of the accuracy of the two TSN translators with the TSN Grandmaster in the network.

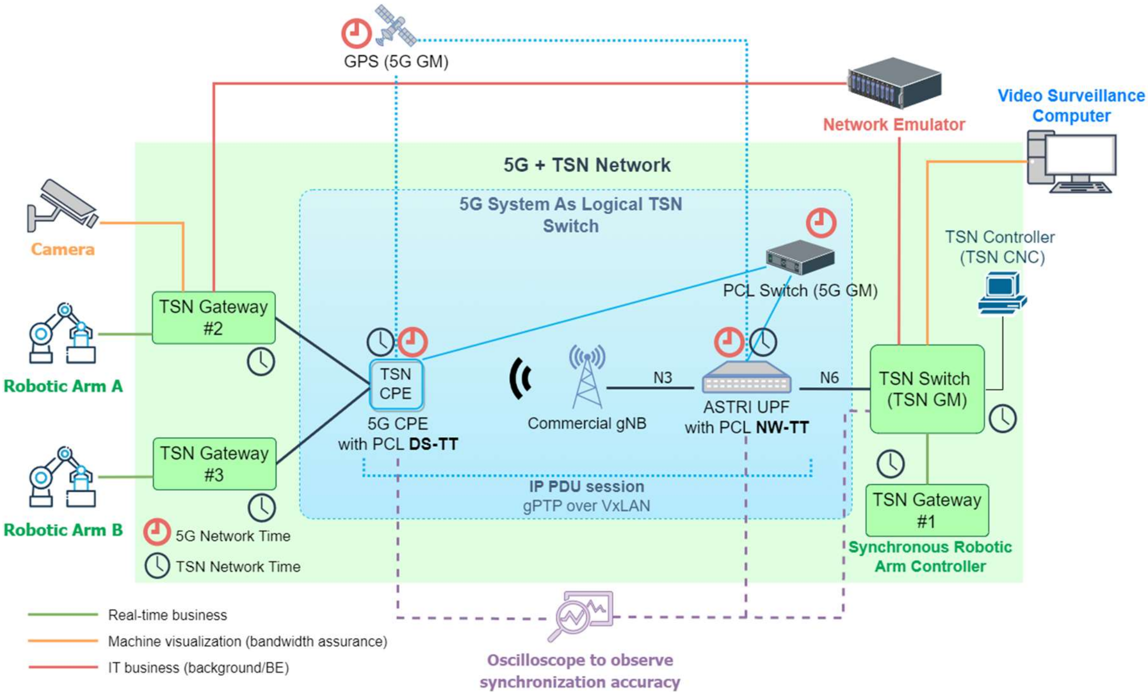

Figure 12 Actual Architecture of TSN-enabled 5G system Demo Architecture Setup

Taking into consideration that both commercialized 5G base stations and Customer Premises Equipment (CPE) within 5G system on the market have the limitations to fully enable TSN technology since they support common IP-type PDU session instead of ethernet PDU session type required. Hence, VxLAN has been implemented to mitigate this situation so that an ethernet network can be constructed between NW-TT and DS-TT by establishing IP-type PDU sessions. TSN traffic flows and gPTP synchronization packets are transmitted across Ethernet network built by the VxLAN tunnel, enabling the characteristics of TSN-enabled 5G network with accurate synchronization and jitter.

On the other hand, the synchronization accuracy of commercialized 5G base stations in the market and CPEs cannot fulfil the requirements of TSN networks. In order to emulate the result of the 5GS time synchronization, the GPS is used directly for illustration. Therefore, it is necessary to integrate GPS time synchronization mechanism to enhance the accuracy, by communicating with GPS, DS-TT and NW-TT achieve synchronization.

5.3 Evaluation, Discussion & Results

5.3.1 End-to-end time synchronization test

Considering the TSN-enabled 5G system, the end-to-end time synchronization refers to the end-to-end time synchronization of the TSN domains across the 5GS time domain. In this test, the time offset between DS-TT/NW-TT and TSN GM are computed for identifying the TSN time domain offset. It compares the TSN 1 PPS second pulse offset output by DS-TT/NW-TT and TSN GM respectively to obtain the end-to-end synchronization accuracy of TSN.

End-to-end time synchronization depends on the synchronization accuracy inside the 5G system. Currently, commercial UEs do not support high accuracy time synchronization through the air interface, therefore, in the evaluation, the 5G system has adopted two simplified synchronization methods here: (1) synchronization via direct connection via Ethernet and (2) synchronization via Global Positioning System (GPS). The details are in the subsection below.

5.3.1.1 5GS Synchronization via direct connection

In the direct connection approach, the topology setup is shown in Figure 13. The PCL switch is being used as a 5G GM, whereas the DS-TT and NW-TT are directly connected to the 5G GM through the wired Ethernet. In order to simulate a more realistic environment, background traffic of 300Mbps in the downlink direction with data packet size of 512 bytes are added. The setup with IEEE 802.1AS synchronization enabled was evaluated for more than 14 hours.

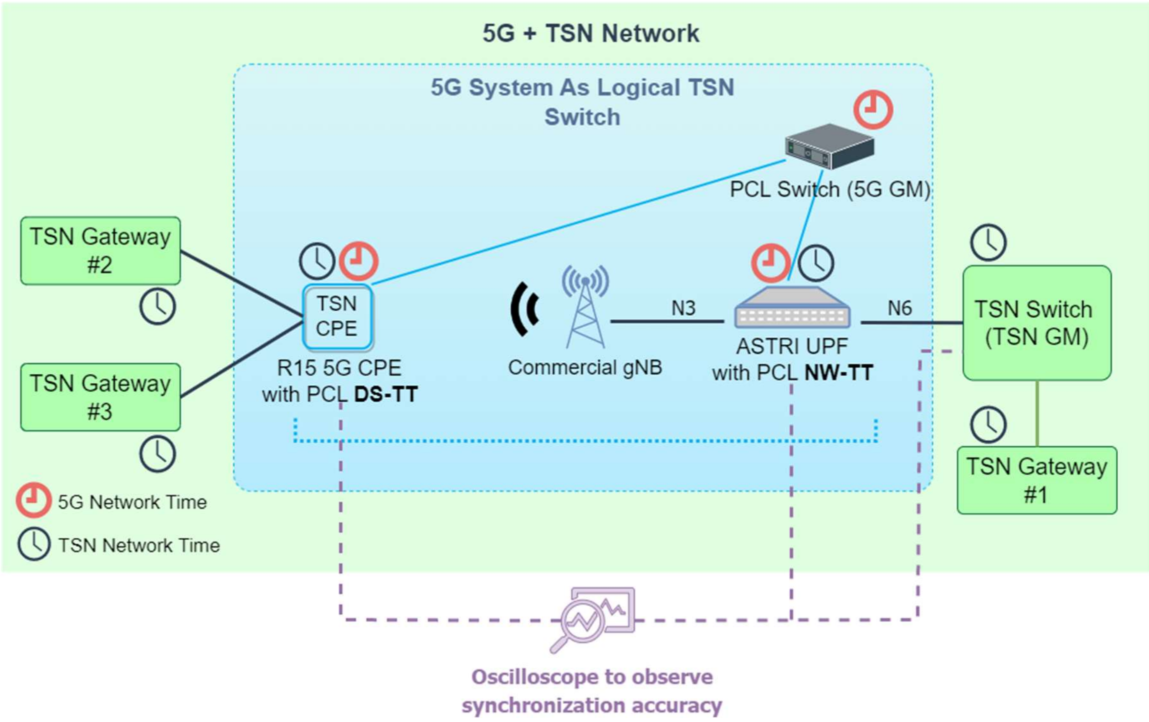

Figure 13 5G System synchronization via direct connection

In the evaluation, the time offset between the two TSN translators (DS-TT and NW-TT) and the TSN GM in the TSN time domain have been maintained under 30 nanoseconds on the oscilloscope (Figure 13). The time offset between the DS-TT and the 5G GM is under 10 nanoseconds, while the value between the NW-TT and the 5G GM is under 26 nanoseconds in 5GS time domain. In 3GPP TS22.104 (Table 3), the synchronicity budget for the 5G system within a working clock domain is 900 nanoseconds. The evaluation shows our result meets this requirement.

5.3.1.2 5GS Synchronization via GPS

In the GPS approach, the topology setup is shown in Figure 14. The GPS is being used as a 5G GM, whereas the DS-TT and NW-TT are synchronized to GPS through its build-in GPS receiver. The background traffic of 300Mbps in the downlink direction with data packet size of 512 bytes are added. The setup with IEEE 802.1AS synchronization enabled was evaluated for more than 18 hours.

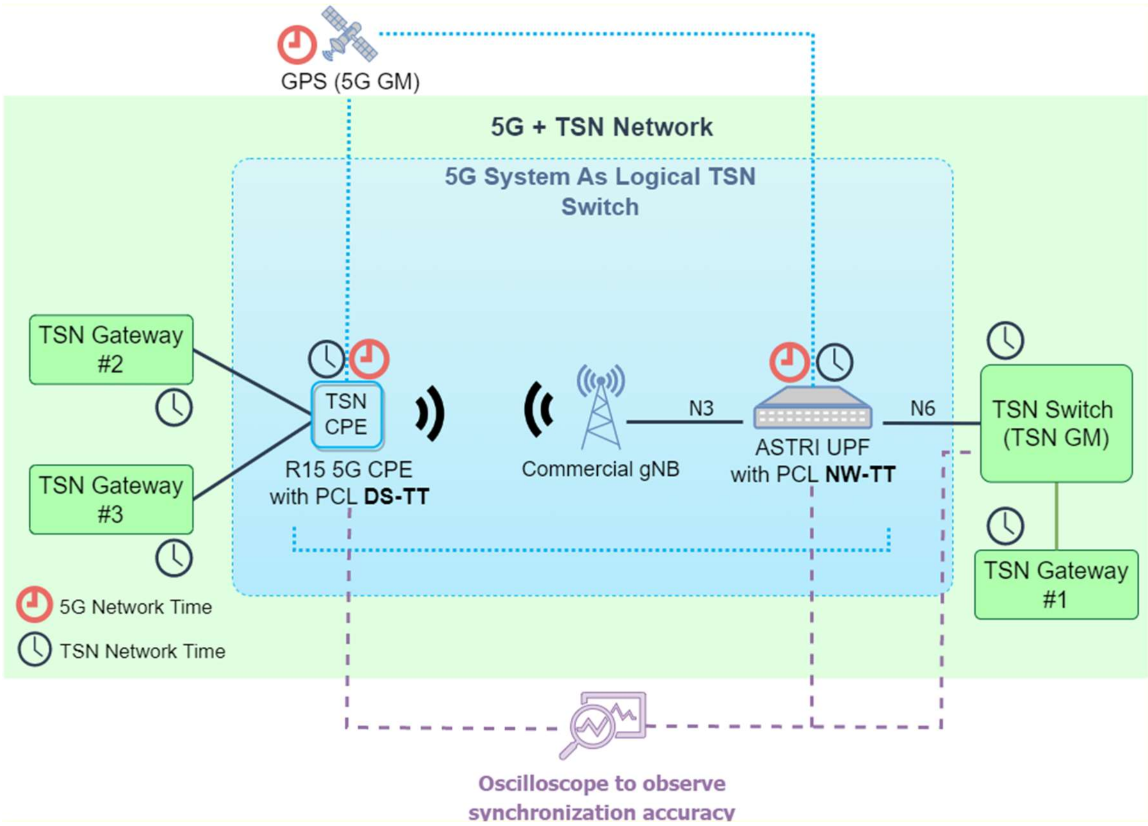

Figure 14 5G System synchronization via GPS

As mentioned in the direct connection approach, the DS-TT and the NW-TT both support the TSN time domain and the 5GS time domain. In the evaluation, the time offset between the two TSN translators (DS-TT and NW-TT) in the 5GS time domain is about 200 nanoseconds, and the time offset between the two TSN translators (DS-TT and NW-TT) and the TSN GM in the TSN time domain have been maintained at 240 nanoseconds on the oscilloscope. The 240ns is being observed as the maximum time observed in the 18 hours duration, which satisfies the requirements defined in 3GPP.

5.3.1.3 Summary

From the above two evaluation, time synchronization via GPS and direct connection, it is concluded that the accuracy of time synchronization in the TSN time domain is mainly dependent on the accuracy in the 5GS time domain. The higher the accuracy of that in the 5GS time domain, the higher the accuracy will be in the TSN time domain.

5.3.2 Jitter in end-to-end packet forwarding

In this test, the performance of the gNB will be studied, esp. in the delay performance with different traffic load. It is observed that under low data throughput (around 150Mbps), the base station can achieve relatively stable delay value, with an average delay of 10ms and a maximum delay of 25ms. However, the situation worsens as the load increases. In the evaluation, it is a scenario of loaded traffic with background traffic throughput of 100Mbps, simulating the transmission of real-time control services and background services:

1. Real-time control service simulation: the TSN service data flow with a packet size of 128 bytes; use the IXIA emulator to simulate the test for different period, varying from 50ms to 250ms.

2. Background service simulation: the background flow with a packet size of 512 bytes and 100Mbps throughput.

Note:

- In the traffic handling, the service data flow (control flow) has lower priority than the background flow, whereas the two service data flows do not interfere with each other.
- The total bandwidth of service data flow shall not exceed the maximum throughput of 150Mbps supported by 5GS virtual switch.

Table 5 Jitter of 5G System synchronization via direct connection, with background flow (512 bytes, 100Mbps)

Service Data Flow period	IEEE 802.1Qbv Configuration	Average delay jitter (ns)	Minimum delay jitter (ns)	Maximum delay jitter (ns)
250ms	Disabled	236418	30	4496800
	Enabled with maximum link delay 30ms	14	0	170
100ms	Disabled	412164	145	5997025
	Enabled with maximum link delay 30ms	16	0	162
50ms	Disabled	1612720	45	15006640
	Enabled with maximum link delay 25ms	12	0	152

Table 6 Jitter of 5G System synchronization via GPS, with background flow (512 bytes, 100Mbps)

Service Data Flow period	IEEE 802.1Qbv Configuration	Average delay jitter (ns)	Minimum delay jitter (ns)	Maximum delay jitter (ns)
250ms	Disabled	1184673	0	6009335
	Enabled with maximum link delay 30ms	41	0	337
100ms	Disabled	2068871	22	6500427
	Enabled with maximum link delay 30ms	62	0	327
50ms	Disabled	1976982	45	6179687
	Enabled with maximum link delay 25ms	54	0	12862

From the evaluation using the direct connection and GPS setup, here are the observations:

1. Test results with direct connection (synchronization accuracy of 30ns)
   a. Before enabling the IEEE 802.1Qbv, the average delay jitter is about 1ms, and the maximum delay jitter is in the millisecond level.
   b. Upon enabling the IEEE 802.1Qbv, the average delay jitter is less than 16ns, the maximum delay jitter is less than 170ns, and the minimum delay jitter is 0ns. The overall improvement in jitter performance is quite significant.

2. Test results with GPS (synchronization accuracy of 240ns)
   a. Before enabling the IEEE 802.1Qbv, the average delay jitter is about 2ms, and the maximum delay jitter is in the millisecond level.
   b. Upon enabling the IEEE 802.1Qbv, the average delay jitter is less than 62ns and the minimum delay jitter is 0ns. The overall improvement in jitter performance is significant.

Based on the above observations, we can see that Scenario 1 (5GS synchronization via Direct Connection) has better jitter performance as compared to Scenario 2 (5GS synchronization via GPS). It is due to the higher accuracy of 5G domain time synchronization in Scenario 1.

5.3.3 Fail over testing

In this evaluation, the reliability of the TSN enabled 5G system will be investigated by having redundancy in the air interface (redundancy in dual transmission). The setup will emulate 1 TSN devices with 2 PDU sessions (1 CPE for 1 PDU session) connecting to a commercial gNB, thus simulating dual-channel redundancy on the air interface with dual transmission and selective reception.

In the setup, both TSN Gateway #1 and #2 will have IEEE 802.1Cb enabled, thus having a redundant path, whereas:

- Path 1: Network Emulator -> 5G System -> CPE1 -> TSN Gateway #2
- Path 2: Network Emulator -> 5G System -> CPE2 -> TSN Gateway #2

All packets received from the emulator at the TSN Gateway #1 will be duplicated and sent along the two paths, whereas TSN Gateway #2 will receive packets from the two paths and send to the emulator. The service data rate is 50Mbps.

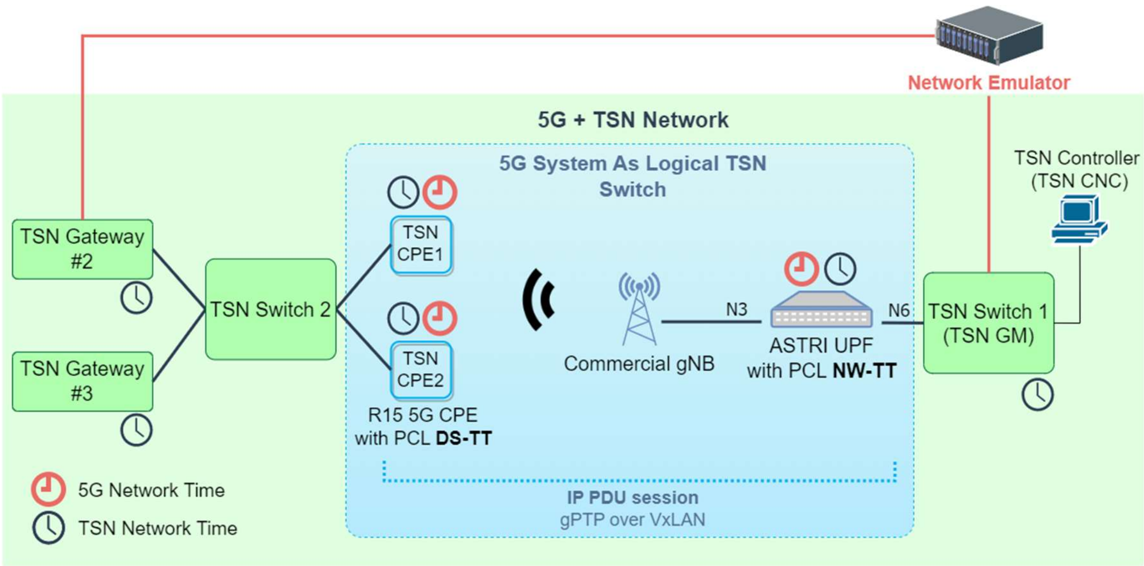

Figure 15 Failover test with two CPEs and 2 gNB

The failover testing procedure is to evaluate when either CPE1 or CPE 2 lost connection to the network (power or connection failure), the failover capability could ensure there is no data packet loss. Here are the steps and observations:

1. Establish PDU sessions for CPE1 and CPE2, make sure the TSN data forwarding on both CPEs are working without packet loss.
2. Upon failure of either CPE1 or CPE2, the TSN end-to-end services are not affected, the active session has no packet loss.
3. Re-establish the PDU session of the fail CPE, the TSN end-to-end services remain normal, no packet loss is being observed.

From the above observations, it is shown that the IEEE 802.1CB Frame Replication and Elimination (FRER) itself could be providing reliability in the end-to-end TSN network.

5.3.4 Simulated industrial use-case

In the section, the industrial use case is studied in the TSN enabled 5G network, as shown in Figure 16. The evaluation includes enabling IEEE 802.1Qbv for deterministic delay transmission, which resulting in significant improvement of the end-to-end delay jitter.

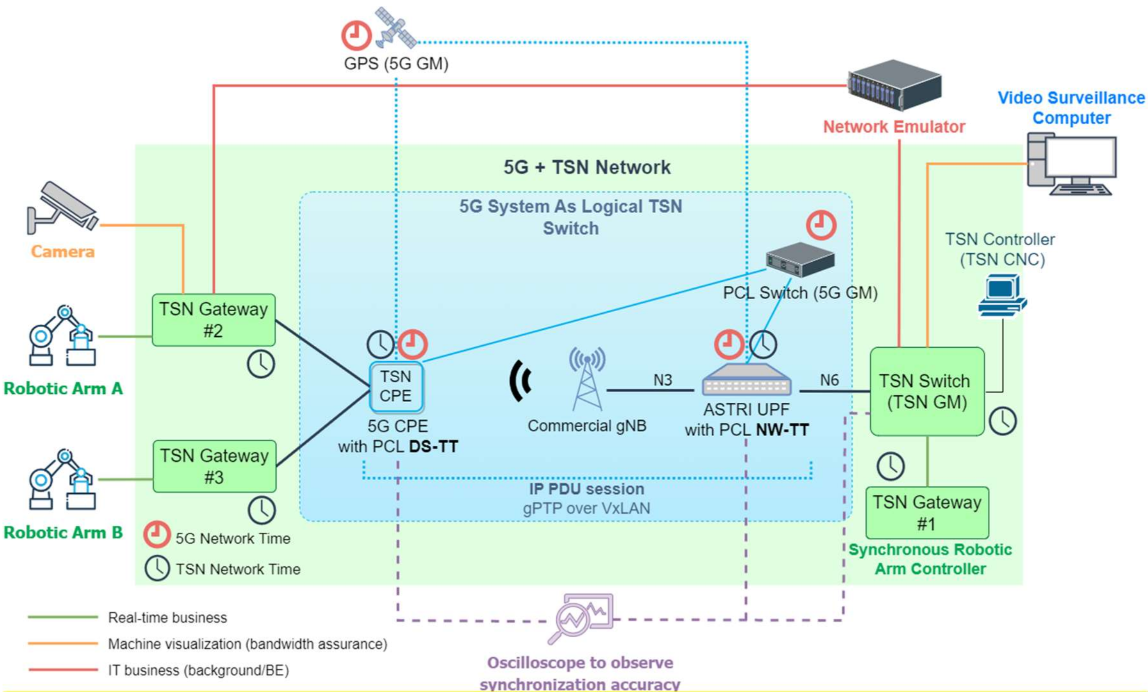

Figure 16 Simulated industrial use case

In the laboratory, the topology as shown in Figure 16 has been setup for the evaluation. The background traffic flow is being added to interfere in the downlink direction (on the network path for the Robotic Arm A) simulating network congestion. Different QoS priorities are applied to the service flows: robotics arm traffic with Q3, background traffic Q5 and surveillance camera traffic Q0 (Q5 being the highest and Q0 the lowest). Two scenarios are being evaluated:

Scenario A: Dedicated bandwidth allocated for robotic arm, while others shared the remaining bandwidth

1. When IEEE 802.1Qbv is not enabled, the two robotic arms cannot be synchronized in their movement, the video streaming of the camera is interrupted.
2. When IEEE 802.1Qbv is enabled, the two robotic arms are synchronized in their movement, the video streaming of the camera is interrupted.

Scenario B: Dedicated bandwidth allocated for robotic arm **and** camera, while others shared the remaining bandwidth

1. When IEEE 802.1Qbv is not enabled, the two robotic arms cannot be synchronized in their movement, the video streaming of the camera is interrupted.
2. When IEEE 802.1Qbv is enabled, the two robotic arms are synchronized in their movement, the video streaming of the camera is normal.

5.3.5 Test result evaluations

From the above evaluations, the results have shown that in the setup, the end-to-end synchronization accuracy of the TSN-enabled 5G System, is under 30ns when 5GS synchronizing via direction connection, whereas under 240ns (max value observed) when 5GS synchronizing via GPS. Both of them meet the end-to-end synchronization accuracy requirements in the field of industrial automation as defined by 3GPP in TS 22.104.

Before enabling the IEEE 802.1Qbv, the end-to-end jitter performance is poor, and the average delay jitter (average delay variation) is in the millisecond level. However, after it is enabled, the end-to-end jitter performance is significantly improved, and the average delay jitter is less than 16ns in Scenario 1 (5GS synchronization via Direct Connection) and less than 62ns in Scenario 2 (5GS synchronization via GPS), which meets IEC/IEEE 60802 specification, where it defines extremely low jitter requirements in the field of industrial automation (Refer to Table 2).

The realization of end-to-end TSN time synchronization is based on the internal time synchronization of the 5GS. It can be seen from the experiment that the end-to-end TSN synchronization accuracy of 5GS through GPS synchronization is worse than that of 5GS through direct connection synchronization. Therefore, the end-to-end TSN synchronization accuracy depends on the wireless synchronization accuracy in the air interface.

Considering the capabilities of the commercial gNBs and UEs that are 3GPP R15 based, thus don’t support the time synchronization via the signaling. In order to overcome this, two simplified solutions are adopted for achieving the 5GS internal synchronization. First, the direct connection synchronization method is used instead of the wireless synchronization over the air interface method for preliminary testing, and then a more feasible commercial deployment scenario is simulated using GPS to realize the internal synchronization of 5GS. This test is to simulate the deployment of TSN-enabled 5G System for typical indoor application scenarios. The tests are carried out under relatively ideal conditions. However, the synchronization accuracy of GPS depends on the performance of GPS satellites, GPS receivers, and the stability of the wireless environment. To ensure the performance of GPS synchronization, it is required to deploy GPS antennas outdoors, which also increases the difficulty of deploying indoor industrial terminals. In addition, GPS is synchronized once every 1s. Compared with IEEE 1588, the time synchronization frequency is even lower, which also affects the synchronization accuracy.

There are still room to improve in synchronization accuracy and 5G control plane. 3GPP has supported time information transfer between base stations and terminals starting from R16. In the future, the support of 5GS devices will be updated from R15 to R16. Compared with the simplified solution using GPS for synchronization inside 5G system, it is expected to significantly improve the end-to-end time synchronization performance. Moreover, 3GPP R17 has further evolved in the air interface synchronization, showing that the 5G RAN time synchronization accuracy will be enhanced to meet the TSN requirement. Other than the 5GS time synchronization, in the evaluation, as the ethernet PDU sessions are not readily available in the base station and in the user equipment. The IP PDU session with the VxLAN tunnel is used instead of the ethernet PDU session. It is expected that the performance will also be improved when ethernet PDU session is used as in the industrial scenarios. With the enhancement in 5G control plane solution, the end-to-end QoS guarantee will be more agile and reliable.

6. Summary/Conclusion

6.1 Industrial Internet use cases

5G is a key enabling technology for the research and development of the Industrial Internet. The International Telecommunication Union (ITU) has defined three major application scenarios for 5G, including Enhanced Mobile Broadband (eMBB), Ultra Low Latency and High Reliability (URLLC), and Massive Machine-type Communications (mMTC), the latter two scenarios are mainly designed for the needs of the Industrial Internet. 5G technology can effectively solve the problems of poor mobility and inflexible of industrial wired networking, and difficult deployment in special and high-risk environments, go beyond the limitations of existing industrial wireless technologies such as 4G and WIFI in terms of mobility, reliability, connection density, and throughput, and effectively meet large-scale mission-critical data transmission, precise control, remote control, and assist innovations. The TSN-enabled 5G system could further fulfill the requirements of low and deterministic latency, high availability, sync accuracy, and low jitter in the industry internet use cases. TSN-enabled 5G System lays the foundation of the deterministic communication system for many Industrial Internet use cases such as smart manufacturing, smart grid, smart mining, smart port, and smart transportation.

- **Automated Guided Vehicles (AGV):** AGV has become more and more popular nowadays in the manufacturing and transportation industries. It could greatly increase efficiency and reduce manpower costs. However, a non-deterministic WIFI network could not maintain a stable connection for many vehicles in a large warehouse or factory area, where TSN-enabled 5G system is the perfect fit for supporting AGV.

- **Drone inspection:** In a high-risk work environment such as an underground mine, a controlled drone inspection for safety analysis is the key to improving the safe work environment and avoiding accidents. This is a mission-critical use case with requirements of high availability and guaranteed transmission. TSN-enabled 5G system could help to identify and transmit multiple real-time sensor data including video, sound, infrared, and LiDAR data back to the data center for safety inspection.
- **Remote control:** In the smart port and other similar scenarios, the crane could be remote controlled to improve efficiencies and work conditions. With TSN-enabled 5G system, bi-directional mission-critical control, and sensor data could be transmitted in the deterministic network, and the remote-control engineer could control 4 cranes simultaneously in a much better working condition.
- **Video Surveillance and Machine Vision:** Factories could improve manufacturing efficiency, safety, and product quality with video surveillance and machine vision applications. TSN-enabled 5G system could assist real-time video transmission to 5G MEC for local machine vision and AI program analysis, it helps to ensure the real-time video data could be transmitted with low and deterministic latency to increase video quality on the receiving end.
- **Cloud-controlled PLC and Robot:** In smart manufacturing, the cloud controller Programmable Logic Controller (PLC) and robot are cutting-edge innovations for assisting automation. In traditional factories, where there are multiple hierarchies for non-deterministic wired or wireless networks, the latency could be varied in a very large range, and there is no high precision time synchronization supported. In the accuracy control PLC and robot use cases; the latency should be deterministic and high precision time synchronization should be supported to keep the movement and related control accuracy in the exact time frame.
- **Augmented Reality (AR) / Virtual Reality (VR) assisted collaboration in the design, installation, and maintenance of a complex system:** In the design, installation, and maintenance of large and complex systems such as the production of commercial airplanes, requires a large group of engineers in different locations to collaborate. AR/VR applications could help to connect people and could greatly improve work efficiency and reduce communication costs. The TSN-enabled 5G system could satisfy the requirement of real-time design, installation, and maintenance data transmission between two geographically located warehouses with many people and devices connected.
- **Multi-equipment collaboration & automation, and Flexible automation:** In the manufacturing industry, the collaboration of multiple automation devices such as robot arms is critical to automation efficiency and accuracy. The time sequence of the movements and actions of a group of devices is

critical for the automation process. With one failed action or one wrong collaboration on the time sequence of equipment, the whole automation process might fail. TSN-enabled 5G system could assist a group of equipment in automation staying on the same time frame. Flexible automation could also benefit from the TSN-enabled 5G system.

- **Digital Twin:** In the digital twin use cases, there are multiple sensors collecting a large volume of data with time sequence records. The time information is the key to constructing the digital twin. Without the TSN-enabled 5G system, the time and time sequence of the different sensors may be incorrect.
- **V2X Roadside Infrastructure:** In smart transportation, the roadside infrastructure especially the smart poles require high-precision inter-pole time synchronization for LiDAR, radar, and camera sensor data fusion, or multi-pole UWB-assisted high-precision positioning. TSN-enabled 5G system lay the foundation for inter-pole connection with the support of high precision time synchronization. Without the high precision time synchronization, the fusion data and positioning result could be incorrect with insufficient precision.

6.2 What’s next

The integration of 5G and TSN involves changes in 5GS including 5G Core, 5G base station and 5G UE. In this demonstration, we did not carry out excessive function development on 5G base station and 5G control plane according to the requirements of 3GPP Release 16, just to verify the possibility of integration of 5G technology and TSN on the 5G data plane.

There is still a lot more to discuss and to test in the future research and development of the TSN-enabled 5G system. First of all, TSN is based on the Ethernet layer, ASTRI and PCL will work together to enable Ethernet PDU session on 5GS for TSN end-to-end testing at the next stage. Second, as a logical TSN switch, TSN-enable 5GS should be managed by CNC, and the 5GS TSN bridge management and port management which is defined by TS23.501 section 5.28 should be supported. Third, a new 5G Network Function TSN-AF will be developed to interface with CNC for mapping and translation of the parameters between the TSN domain and the 5G domain. Fourth, for the NW-TT module inside UPF, ASTRI and PCL will work together to develop a well-defined API between the NW-TT module and UPF, so the NW-TT configuration parameters could be sent from UPF to the NW-TT module. Finally, ASTRI and PCL will use URLLC-enabled base station and UE to reduce the 5G end-to-end latency and jitter caused by the wireless network and base station, these replacements will further improve the TSN-enabled 5G system performance.

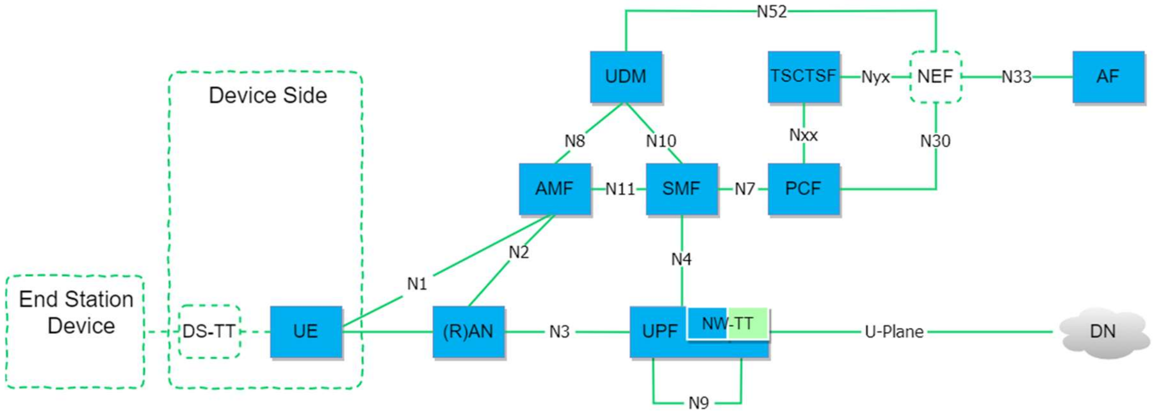

Figure 17 Release 17 architecture of TSC

3GPP Release 17 expands the support for Time Synchronization and Time Sensitive communications for any application. It has introduced new network function Time Sensitive Communication Time Synchronization function (TSCTSF) and the 5GS is now modelled as PTP instance for supporting time synchronization, in Figure 13.

List of Acronyms and Abbreviations

3GPP	3rd Generation Partnership Project
5G	5th Generation
5GS	5G System
5QI	5G QoS Identifier
AF	Application Function
AMF	Access and Mobility Management Function
ARP	Allocation and Retention Priority
AW	Averaging Window
BAR	Buffering Action Rules
BMCA	Best Master Clock Algorithm
CNC	Centralized Network Function
CQF	Cyclic Queuing Forwarding
CUPS	Control and User Plane Separation
DN	Data Network
DNN	Data Network Name
DS-TT	Device-Side TSN Translator
eMBB	Enhanced Mobile Broadband
FAR	Forwarding Action Rule
GBR	Guarantee Bit Rate
GCL	Gate Control List
GM	Grand Master
gNB	5G Base Station
gPTP	General Precise Time Protocol
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
MAR	Multi-Access Rule

MDBV	Maximum Data Burst Volume
MEC	Multi-Access Edge Computing
mMTC	Massive Machine Type Communications
NF	Network Function
NR	New Radio
NW-TT	Network-Side TSN Translator
PCC	Policy Control and Charging
PCF	Policy Control Function
PDR	Packet Data Rule
PDU	Packet Data Unit
PL	Priority Level
PSA	PDU Session Anchor
QER	QoS Enforcement Rule
QFI	QoS Flow Identifier
QNC	QoS Notification Control
QoS	Quality of Service
RAN	Radio Access Network
RC	Rate Estimation
RTC	Real Time Clock
SBA	Service Based Architecture
SMF	Session Management Function
TAS	Time Aware Shaper
TSC	Time Sensitive Communication
TSCAI	TSC Assistant Information
TSCTSF	Time Synchronization Function
TSe	Egress Timestamp
TSi	Ingress Timestamp

TSN	**Time Sensitive Network**
UAR	**Usage Reporting Rule**
UE	**User Equipment**
UPF	**User Plane Function**
URLLC	**Ultra-Reliable Low Latency Communications**

References

[1] 3GPP. (n.d.). *3GPP Technical Specification 22.104*. Retrieved from Service requirements for cyber-physical control applications in vertical domains: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3528

[2] 3GPP. (n.d.). *3GPP Technical Specification 23.501*. Retrieved from System Architecture for the 5G System: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3144

[3] IEEE. (2017, 10 27). *802.1CB-2017 - IEEE Standard for Local and metropolitan area networks--Frame Replication and Elimination for Reliability.* doi:10.1109/IEEESTD.2017.8091139

[4] IEEE 802.1 WG - Higher Layer LAN Protocols Working Group. (2016, 8 30). *IEEE Standard for Local and metropolitan area networks -- Bridges and Bridged Networks -- Amendment 26: Frame Preemption*. Retrieved from https://standards.ieee.org/ieee/802.1Qbu/5464/

[5] IEEE 802.1WG - Higher Layer LAN Protocols Working Group. (2016, 3 18). *IEEE Standard for Local and metropolitan area networks -- Bridges and Bridged Networks - Amendment 25: Enhancements for Scheduled Traffic*. Retrieved from https://standards.ieee.org/ieee/802.1Qbv/6068/

[6] The 5G Alliance for Connected Industries and Automation. (2021). *Integration of 5G with Time-Sensitive Networking for Industrial Communications*. ZVEI – German Electrical and Electronic Manufacturers' Association 5G Alliance for Connected Industries and Automation (5G-ACIA), a Working Party of ZVEI.

[7] *Time-Sensitive Networking (TSN) Task Group*. (n.d.). (IEEE) Retrieved from https://1.ieee802.org/tsn/

[8] 工业互联网专项工作组. (2020, 12 22). *关于印发《工业互联网创新发展行动计划（2021-2023 年）》的通知*. Retrieved from 中华人民共和国中央人民政府: http://www.gov.cn/zhengce/zhengceku/2021-01/13/content_5579519.htm