A Practice of TSN over 5G for Industry

White Paper

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Revision History

Date	Revision	Description
January 2021	v0.9	Add hardware information and some test result
November 2020	v0.8	Fix some comments
October 2020	v0.7	Add more diagrams
October2020	v0.6	Add gNB and 5GC contents
October 2020	v0.5	Completed main contents
September 2020	v0.1	Draft the title/outline of the white paper

1.0 Introduction

This document is produced by a joint effort of Comba Telecom and Intel, to introduce a converged network of time-sensitive networking (TSN) over 5G for industrial user scenarios. It is not only elaborated the whole network setup, but also introduced a use case of vision inverted pendulum system (VIPS) running on the converged network. This exploration combines TSN and 5G to meet key industrial communication requirement. Developers could refer to this document for building an industrial network with 5G and time-sensitive networking (TSN capabilities).

1.1 Terminology

Table 1. Terminology

Term	Description
BMCA	Best Master Clock Algorithm
CNC	Centralized Network Configuration
CPE	Customer Premise Equipment
CUC	Centralized User Configuration
DS-TT	Device-Side Time Sensitive Networking (TSN) Translator
eMBB	Enhanced Mobile Broadband
EPC	Evolved Packet Core
ETF	Earliest TxTime First
gNB	Next Generation NodeB
IoT	Internet of Things
IIoT	Industrial Internet of Things
NIC	Network Interface Controller
NR	New Radio
NW-TT	Network-Side Time Sensitive Networking (TSN) Translator
PDCP	Packet Data Convergence Control
PDU	Protocol Data Unit

Term	Description
PMIC	Port Management Information Container
PTP	Precision Time Protocol
PSFP	Per-Stream Filtering and Policing
QoS	Quality of Service
RAN	Radio Access Network
RLC	Radio Link Control
RRC	Radio Resource Control
TAPRIO	Time Aware Priority Shaper
TSC	Time Sensitive Communications
TSCAI	Time Sensitive Communications assistance information
TSN	Time Sensitive Networking
TSN AF	TSN Application Function
uRLLC	Ultra Reliable and Low-latency Communication
VID	VLAN ID
VLAN	Virtual Local Area Network
5GC	5G Core Network
5GS	5G System
5QI	5G QoS Identifier

1.2 Reference Documents

Table 2. Reference Documents

Document	Document No./Location
[1] IEEE 802.1 Time-Sensitive Networking (TSN) Task Group (TG) Overview	http://www.ieee802.org/1/files/public/docs2018/detnet-tsn-farkas-tsn-overview-1118-v01.pdf
[2] 5G evolution: 3GPP releases 16 & 17 overview	https://www.ericsson.com/en/reports-and-papers/ericsson-technology-review/articles/5g-nr-evolution

Document	Document No./Location
[3] 5G-TSN integration meets networking requirements for industrial automation	https://www.ericsson.com/en/reports-and-papers/ericsson-technology-review/articles/5g-tsn-integration-for-industrial-automation
[4] Time-Sensitive Networking: From Theory to Implementation in Industrial Automation	https://www.intel.com/content/dam/www/programmable/us/en/pdfs/literature/wp/wp-01279-time-sensitive-networking-from-theory-to-implementation-in-industrial-automation.pdf
[5] The Business Impact of TSN for Industrial Systems	https://avnu.org/wp-content/uploads/2014/05/TSN-Business-Impact-paper-FINAL.pdf
[6] 3GPP TS 23.501 V16.5.1	https://www.3gpp.org/ftp/Specs/archive/23_series/23.501/23501-g51.zip
[7] User Guide PCIe-0400-TSN (userguide_pcie-0400-tsn_v0.14.pdf)	https://www.kontron.com/products/systems/ethernet-solutions/network-interfaces-tsn/pcie-0400-tsn-network-interface-card.html
[8] TAPRIO	https://man7.org/linux/man-pages/man8/tc-taprio.8.html
[9] ETF	https://man7.org/linux/man-pages/man8/tc-etf.8.html
[10] Beckhoff Automation EK1000 EtherCAT TSN Coupler	https://www.materialhandling247.com/product/ek1000_ethercat_tsn_coupler
[11] EtherCAT and TSN – Best Practices for Industrial Ethernet System Architectures	https://www.ethercat.org/download/documents/Whitepaper_EtherCAT_and_TSN.pdf

2.0 Background

2.1 5G Overview

5G is the 5th generation technology standard for mobile networks. It is a new global wireless standard designed for three main types of connected services [2]:

- eMBB (Enhanced Mobile Broadband)
    - eMBB provides greater data-bandwidth complemented by moderate latency improvements. It can usher in new immersive experiences such as Augmented Reality (AP) or Virtual Reality (VR) media, Ultra HD or 360-degree streaming video and many more.
- uRLLC (Ultra Reliable Low Latency Communications)
    - uRLLC can transform industries with ultra-reliable, available, low-latency links like remote control of critical infrastructure, vehicles, and medical procedures.
- mMTC (Massive Machine Type Communication)
    - mMTC is designed for massive machine-type communication for many connected devices or sensors through the ability to scale down in data rates, power, and mobility.

Manufacturers could benefit substantially from 5G technology, including, for example, increased flexibility, cables reduction, and support of new use cases. 5G networks offer manufacturers a chance to build smart factories and truly take advantage of technologies such as automation, artificial intelligence, and augmented reality and, etc. Both efficiency and profitability could be achieved.

2.2 Time-Sensitive Networking (TSN) Overview

TSN is a collection of Ethernet standards developed by IEEE TSN task group which is part of IEEE 802.1 working group. TSN standards define new functions for Ethernet networking, such as traffic shaping, frame pre-emption, traffic scheduling, ingress policing, and seamless redundancy, etc. They provide deterministic services over Ethernet networks, i.e., guaranteed packet transport with bounded latency, low packet delay variation, and low packet loss [1].

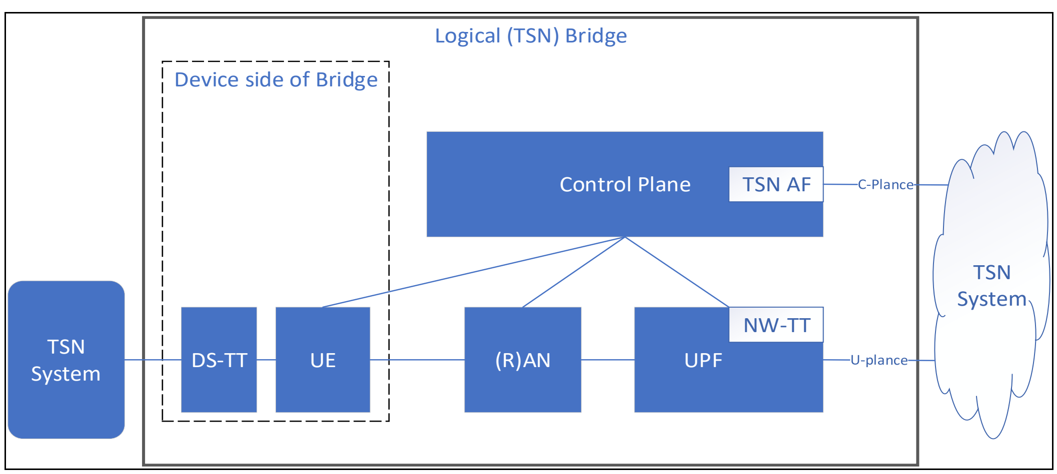
In the industrial market, industrial control applications require consistent and deterministic delivery of data from sensors to controllers and actuators. The data exchanged between these components is critical. With the evolution of the Internet of Things (IoT), manufacturers are looking to glean insights and analytical information from the same sensors and devices. Besides industrial control applications, the data generated by these sensors and devices are also needed for both the information and analytical system. Therefore, the total amount of data communicated over the same network increases [4].

TSN technologies provide the capability to enable the convergence of different data traffic on the same physical network. Its ensure that time-critical data traffic is delivered in a timely manner by securing bandwidth in the network infrastructure, while simultaneously allowing non-critical data traffic to coexist on the same network. TSN reshapes the industrial communication landscape and lay the foundation for the convergence of Information Technology (IT) and Industrial Operations Technology (OT).

2.3 Time-Sensitive Networking (TSN) over 5G

As part of the effort for 5G to support new industrial use cases, 5G NR in Release 16 released on July 3, 2020, added support for TSN, which includes system components such as synchronizing with precise time using generalized precision timing protocol (gPTP), mapping of TSN configuration into 5G quality-of-service (QoS) framework for deterministic messaging and traffic shaping, and providing efficient transport of Ethernet frames via header compression. 5G supports TSN by seamlessly integrating 5G system as a logical TSN bridge as shown in Figure 1 [6].

Figure 1. System Architecture View with 5GS Appearing as TSN Bridge

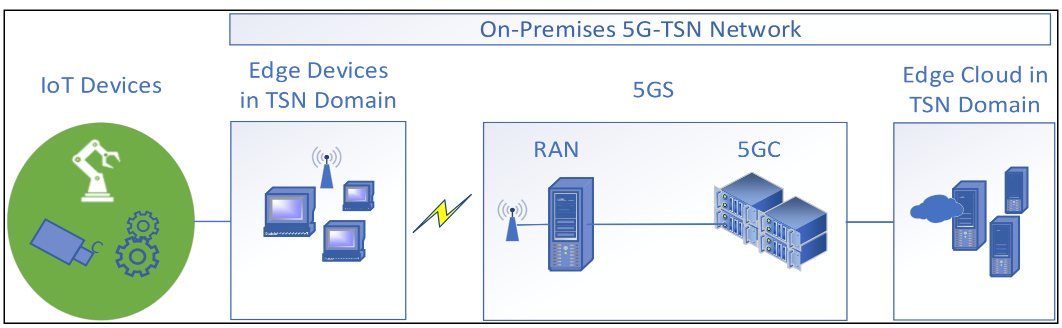


3.0 A Converged Network of Time-Sensitive Networking (TSN) over 5G

3.1 Overview

The integration of 5G and TSN can meet the key communication requirements of industrial automation, such as 5G for flexibility and TSN for extremely low latency [3]. An on-premises 5G-TSN network has been shown in Figure 2. Edge devices in TSN domain can provide real-time controls on IoT devices. Through a 5G system with TSN integrated, these edge devices are connected to the edge servers in an edge cloud, which is behind the 5G system. Data collected from IoT devices can be transmitted to the edge cloud for storing, processing and analytics.

Figure 2. On-Premises 5G-TSN Network for Industry



3.2 Implementation

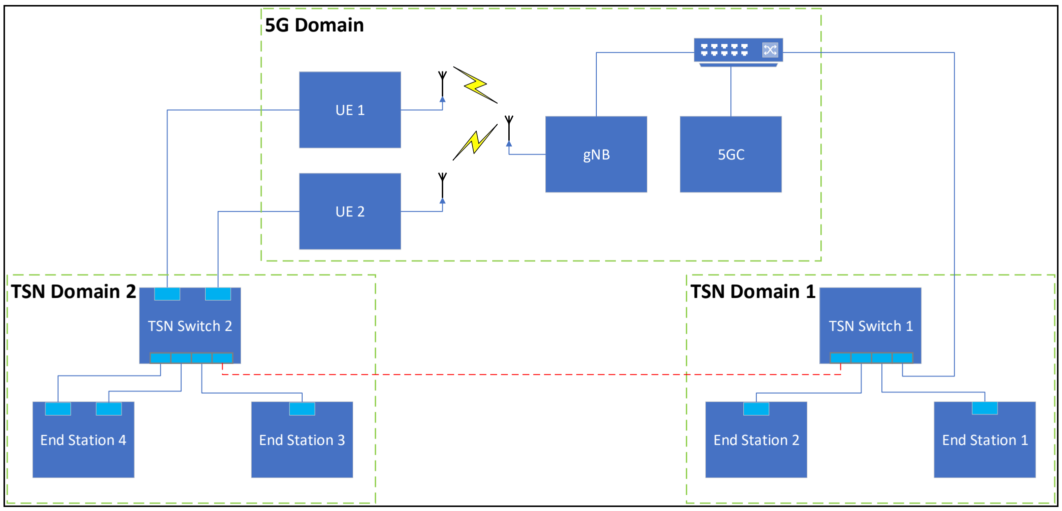
3.2.1 Network Architecture

As shown in Figure 3, a converged network with TSN and 5G technologies is built as implementation of the on-premises 5G-TSN network. It consists of one 5G domain and two TSN domains. The two TSN domains are located on the network and the device sides of the 5G domain respectively.

There are two UEs, a gNB, and a 5GC in the 5G domain. Each TSN domain is composed of a TSN switch and two end stations. On the device side of the 5G domain, two UEs are connected to the two NICs of the TSN Switch 2 respectively. The gNB, the 5GC and the TSN Switch 1 are connected via a 10-Gigabit switch.

This network is built based on couple of technologies from different providers.

Figure 3. Network Architecture of TSN over 5G

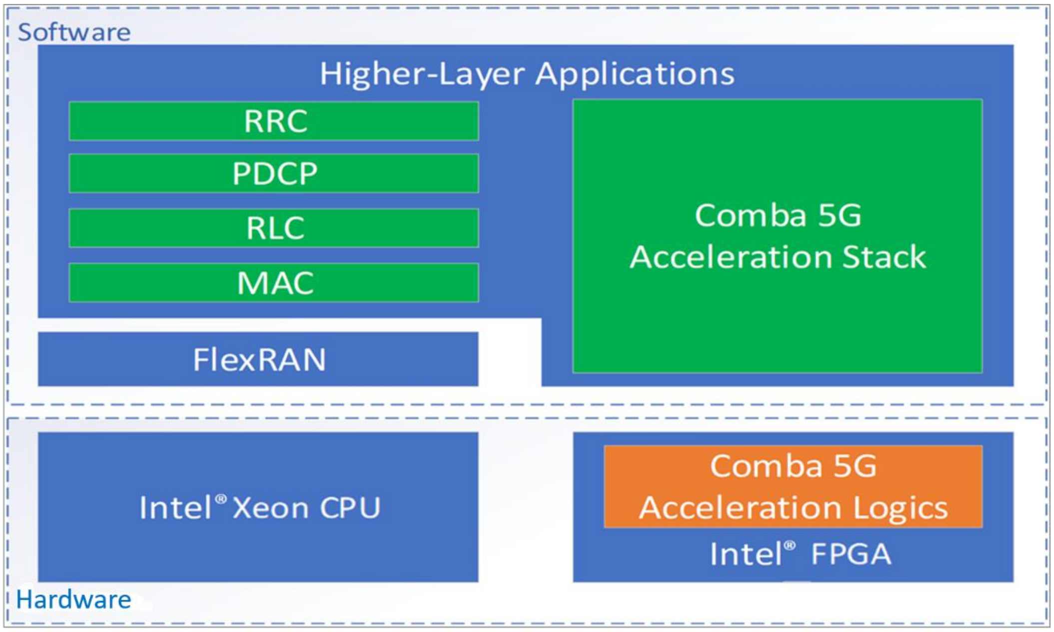


3.2.2 gNB

An Intel IA-based gNB solution from Comba Telecom was adopted. The architecture, as shown in Figure 4, composed of two sub-systems, the baseband processing, and the radio. The former is running on top of an Intel® Xeon® -based computing platform, which can support up to four carriers with 100MHz bandwidth individually. In addition, an accelerator card, based on Intel® Stratix® series FPGA, is used for accelerating some customized algorithms and front-haul interfaces. The physical-layer software is built on top of Intel® FlexRAN technology. The radio equipment is also Intel® FPGA based, which can support up to 4T4R at 100MHz bandwidth.

The peak data rate the gNB can achieve is up to 1.7 Gbps for the downlink, and 280 Mbps for the uplink (depends on frame structure). Some important 5G features, such as carrier aggregation, stand-alone mode, and numerologies, are also supported. One gNB can support up to 64 radios which can cover at least 20,000 square meters.

Figure 4. Intel IA Platform based gNB Architecture



Detailed information about the base station is shown in Table 3.

Table 3. 5G Base Station

<table>
<tr><td rowspan="10">5G Base Station (BS):
Comba 5G open-platform small cell is a small, low-power, distributed base station system, which adopts digital technology and fiber infrastructure, providing 5G indoor coverage signal.</td><td rowspan="4">5G iCell AU</td><td>Model No.</td><td>ENB-50, A01SA</td></tr>
<tr><td>Frequency Band</td><td>Support NSA and SA 5G</td></tr>
<tr><td>Bandwidth/Carrier</td><td>100MHz</td></tr>
<tr><td>Description</td><td>AU is the baseband of iCell solution which connects to core network through IP interface and provides cellular signal for users.</td></tr>
<tr><td rowspan="2">5G iCell SW</td><td>Model No.</td><td>ENB-50, A01SE</td></tr>
<tr><td>Description</td><td>SW (Extension Unit) is the data aggregation and forwarding part of iCell. It can greatly increase the Small Cell coverage by daisy chain connection.</td></tr>
<tr><td rowspan="4">5G iCell DP</td><td>Model No.</td><td>610005-000107-0000</td></tr>
<tr><td>Frequency Band</td><td>NR N41 and N78</td></tr>
<tr><td>Bandwidth/Carrier</td><td>50/60/80/100MHz</td></tr>
<tr><td>Description</td><td>DP (Distributed Unit) connects to SW (Extension Unit) and serves as an active cellular signal provision.</td></tr>
</table>

3.2.3 5GC

A commercial Intel IA-based 5GC software solution with some customizations was adopted, which is optimized for low-latency and high reliability. Compared with 4G EPC, the major change is the service-based architecture. In addition, using virtualization technology decoupled the hardware and software of the 5GC solution, brings more flexibility and improves the hardware resource utilization. Moreover, network slicing for vertical user cases and the separation between control and user planes are also supported by this 5GC solution.

The 5GC software is running on an Intel® Xeon®-based workstation. Hardware information has been shown in Table 4.

Table 4. 5GC Server

CPU	**Product**	Intel® Xeon® CPU E3-1275 v5 @ 3.60GHz,
	Number of cores	4 cores/1 socket
Cache	**Size**	8192 KB
I/O	**NIC**	Ethernet Controller X710 for 10GbE

3.2.4 UE

In this setup, a commercial CPE product has been chosen as a UE device. It can expose back-end end stations by traffic forwarding.

3.2.5 Time-Sensitive Networking (TSN) Switch

The two TSN switches were built from a generic PC with a Kontron PCIE-0400-TSN* card inserted. Kontron PCIE-0400-TSN* is a FPGA based TSN PCIe add-in card with four 10/100/1000Base-T Ethernet ports. The FPGA is Intel Altera Cyclone® V SoC. PCIE-0400-TSN supports a couple of TSN standards, for example, IEEE 802.1AS, 802.1Qbv, 802.1 Qbu and 802.1 Qcc.

The generic PCs were installed with Fedora Linux* version 25 with a real-time kernel 4.9.11. The driver for Kontron PCIE-0400-TSN* and some utilities were also installed. Two programs, “ptp4l” and “phc2sys”, from the project LinuxPTP, were used for time synchronization. In addition, the software package of PCIE-0400-TSN has a utility called “tsntool” for PCIE-0400-TSN configuration. With it, developer enabled IEEE 802.1 Qbv on each port of PCIE-0400-TSN.

For more details about the TSN switch configuration, refer to the user guide of Kontron PCIE-0400-TSN [7].

3.2.6 End Station

The four end stations are all IPC (Industrial PC) with two Intel® Ethernet Controller I210 NICs. Detailed hardware information is shown in Table 5.

Intel® Ethernet Controller I210 is a single-port Gigabit Ethernet card. It supports a couple of TSN standards, for example IEEE 802.1 Qav and 802.1 AS. In addition, it supports a feature called "Launch Time", which can provide a powerful capability of traffic scheduling.

Table 5. End Station

CPU	**Product**	Intel® Core™ i7-8809G CPU @ 3.10GHz
	Number of cores	4 cores/1 socket
Cache	**Size**	8192 KB
I/O	**NIC**	Intel® Ethernet Controller I210

Ubuntu* 18.04 with a preempt-rt kernel was installed into the four end stations. "ptp4l" and "phc2sys" were used for time synchronization. The utility of "tc" was used to enable two Qdiscs, TAPRIO (Time Aware Priority Shaper) and ETF (Earliest TxTime First) [8][9]. TAPRIO is a software implementation of IEEE 802.1 Qbv. ETF allows applications to control the instant when a packet should be dequeued from the traffic control layer. It requires NICs to support the feature of Launch Time.

3.3 Limitations and Interim Solutions

The standardization for the integration of TSN over 5G is ongoing. 3GPP just published the R16 version of 5G specification on July 3, 2020. In this version, it has standardized a few TSN standards support, including IEEE 802.1 Qcc, 802.1 AS and 802.1 Qbv. As shown in Figure 1, the 5GS is modeled as a logical TSN bridge. TSN translator is used on the UE/Device side (DS-TT) and on the UPF/Network side (NW-TT).

Even though 3GPP has standardized on how 5G integrates with TSN, the support in existing 5GS solutions were not ready yet by the time developer started the work on this white paper. Developer has adopted a couple of interim solutions in the setup.

3.3.1 Time Synchronization

5G R16 has standardized on how TSN time synchronization should be supported in 5GS. For TSN synchronization, the entire E2E 5GS can be considered as an IEEE 802.1 AS "time-aware system". Only the TSN translators, DS-TT and NW-TT, need to support the IEEE 802.1 AS operations, e.g. gPTP support, timestamping, Best Master Clock Algorithm (BMCA), rateRadio[6].

5G R16 specified the process of the distribution of TSN clock and timestamping. UPF/NW-TT stamps downlink gPTP event (Sync) frames with ingress timestamping (TSi), then forwards the gPTP message from TSN network to the UEs via all PDU sessions corresponding to this 5GS TSN bridge. The UE forwards the original TSN clock timing information and the gPTP message with the TSi to the DS-TT which then makes egress timestamping (TSe). DS-TT needs to calculate the residence time spent within the 5GS and put it into the correction field of the gPTP header [6].

The first stage of our work, the 5GS system has not supported TSN time synchronization yet. To synchronize the two TSN domains, developer has connected the two TSN switches with a cable, namely the red dotted line as shown in Figure 2. The TSN Switch 1 was set as a primary clock. The TSN Switch 2 synchronized its clock with the TSN Switch 1. The four-end stations synchronized the time with the switch they are connected to.

3.3.2 Time-Sensitive Networking (TSN) QoS Mapping in 5G Domain

In order to support TSN traffic scheduling over 5GS Bridge, as specified in 5G R16, the 5GS needs to support the following functions [6]:

- Configure the bridge information in 5GS.
- Report the bridge information of 5GS Bridge to TSN network after PDU session establishment.
- Receive the configuration from TSN network, such as the configuration information of scheduled traffic on ports of DS-TT and NW-TT.
- Map the configuration information obtained from TSN network into 5GS QoS information (e.g. 5QI, TSC Assistance Information) of a QoS Flow in corresponding PDU Session for efficient time-aware scheduling.

The TSN AF is responsible to receive the bridge information of 5GS Bridge from 5GS, as well as register or update this information to the TSN network.

The TSN QoS scheduling has not been supported in the 5GSs solution yet. A simple IP-based QoS strategy was adopted in this setup. Priorities will be determined according to which UE packets to go through. The UE 1 obtains high priority, and the UE 2 is low priority.

3.3.3 Centralized Network Configuration/ Centralized User Configuration (CNC/CUC) Configuration

5G R16 standardized on how port and bridge management is exchanged between CNC and TSN AF. The port management information is related to Ethernet ports located in DS-TT or NW-TT. 5GS shall support transfer of standardized and deployment-specific port management information transparently between TSN AF and DS-TT or NW-TT, respectively inside a Port Management Information Container (PMIC).

The 5GS solution in this setup has not supported CNC/CUC yet. For the time being, user requirements for bandwidth are pre-defined and TSN related configurations are manually determined. All configurations are applied by a couple of scripts.

3.4 Testing

To measure performance of the converged network, the end-to-end latency between two end stations located at a different TSN domains, developer has developed two programs, which is tsn_tx and tsn_rx, based on the project "https://github.com/intel/iotg_tsn_ref_sw". tsn_tx can get a timestamp and put it into the payload of packets just before sending out them. On the receiver side, once tsn_rx receives a packet, it will record the timestamp when it receives the packet and extract the timestamp contained in the payload. With the two timestamps, developer can calculate the end-to-end latency. The data flow is

End Station 1→ TSN switch 1→ 5G system → TSN switch 2 → End Station 4

To mitigate the impact of OS process scheduling and get a reliable result, developer has isolated a core from the CPUs of the two end stations and attached the test programs, tsn_tx and tsn_rx, to the isolated cores.

In the test, tsn_tx sent 1000 packets to tsx_rx per second and the payload size is 12 bytes. The test lasted 15 mins. Table 6 shown the result that developer got. For almost all packets, the latency is no more than 5000us.

Table 6. Test Results of Latency

Latency Distribution				
Range/us	<=3000	(3000, 4000]	(4000, 5000]	>5000
Frequency	71442	701470	164736	61
Percentage	7.34%	72.07%	16.93%	0.01%

4.0 Converged Network Use Case

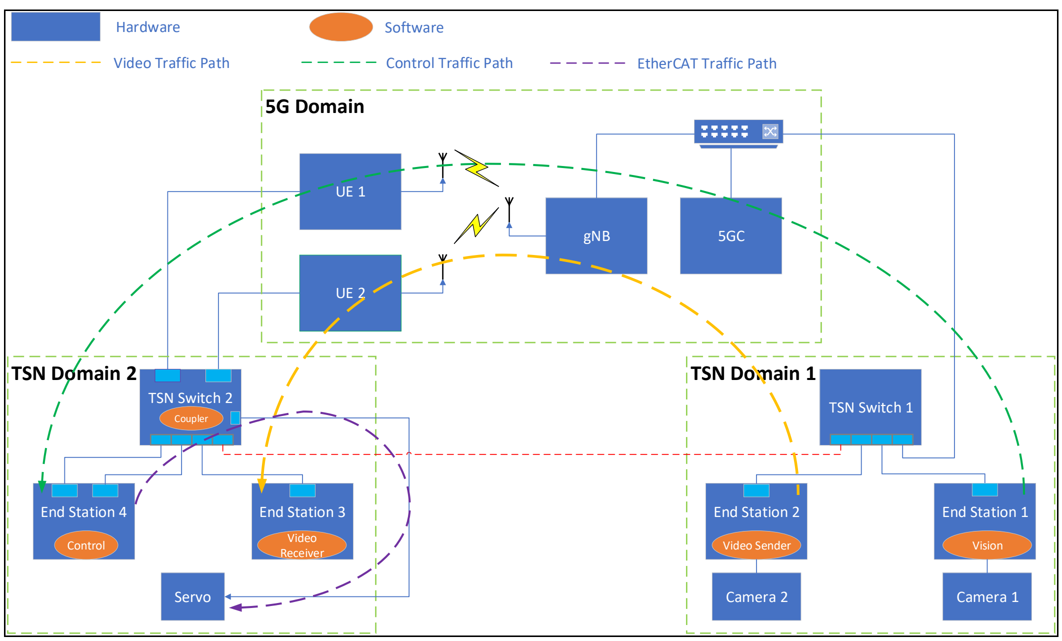
4.1 Introduction to the Use Case

To verify the functionality and performance of the network that developer setup, a use case, vision inverted pendulum system (VIPS), was put in place.

VIPS includes a pendulum, a motion control cart, a control system and a vision system. The vision system is responsible for determining the position of the cart and the pendulum angle via vision algorithms and giving the information to the control system. Based on the inputs from the vision system, the control system generates specific commands to control the motion of the pendulum via the servo.

4.2 System Architecture

Figure 5. Architecture of VIPS over the Converged Network of 5G over TSN



As shown in the Figure 5, two cameras are connected to the End Station 1 and 2 respectively. A servo is directly connected to a NIC on the TSN Switch 2.

The vision system is running on the End Station 1. It will send the video analysis result to the control system running on the End Station 4 via CPE 1. The control system leverages the technology of EtherCAT over TSN. The control system generates EtherCAT commands and sends them to the Coupler running on the TSN Switch 2. The Coupler is responsible for converting TSN traffic to EtherCAT traffic [10][11].

Another traffic path is for video traffic. The Video Sender program is running on the End Station 2. It captures images from the Camera 2 and sends the images to the Video Receiver program running on the End Station 3 via the CPE 2.

4.3 Results

With this setup, after homing for initialization, the pendulum begins to swing. In a few seconds, it can stand up. Even applying an external force on the pendulum, it still can keep the stand-up state.

5.0 Conclusion and Future Work

The work done as explained in this white paper is an exploration of combining TSN and 5G technology together to provide flexibility and low latency for industrial user scenarios. A practical TSN-5G converged network has been setup, and its usefulness has been proved through a low-latency use case.

There are still a couple of technical gaps to be resolved as mentioned in the previous chapters such as PTP and 802.1Qbv support in the 5G domain. In the next stage, focus will be given in these remaining issues.

§§