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FIRST REPORT ON NEW TECHNOLOGICAL FEATURES TO BE SUPPORTED BY 5G STANDARDIZATION AND THEIR IMPLEMENTATION IMPACT

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First report on new technological features to be supported by 5G Standardization and their implementation impact

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Short abstract:	This deliverable presents 5G technological features addressing the requirements of the 5G-SMART smart manufacturing use cases. It describes an in-depth investigation of technical features that relates to integration of 5G with time-sensitive networking (TSN), end-to-end time synchronization and 5G-supported positioning in manufacturing use cases.
Keywords:	5G and TSN integration, 5G-based positioning, time synchronization

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Disclaimer

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Executive summary

5G standardization is moving forward to further enable new technical features and enhancements to support smart manufacturing use cases. This document, by considering use cases identified within 5G-SMART project, describes in depth the required 5G technical features which are not yet standardized or currently being discussed for standardization. Key technical features relating to end-to-end time synchronization, integration of 5G with time-sensitive networking (TSN) and 5G based positioning mechanisms are analyzed. A thorough state-of-the-art analysis is performed for each feature. Further, this deliverable develops a system view, lists down the potential improvements or gaps observed comparing to use case requirements. The report further provides recommendations towards future standardization and solution development.

Concerning 5G-TSN integration, significant efforts has been already made to provide 5G-TSN integration features. The fully centralized TSN configuration model is supported by 5G system. Also, fully centralized TSN configuration is being enhanced in the ongoing P802.1Qdj Configuration Enhancements for Time-Sensitive Networking, which enhancements should be then considered for the 5G System as well. Concerning this, main gaps are described including end-to-end (E2E) TSN system configuration and 5G system capability to provide an exposure function. E2E TSN stream configuration need to be considered to ensure desired performance in integrated 5G-TSN network. Several recommendations for 5G-TSN aspects are proposed, some of them are already being provided as contribution to the industry alliance 5G-ACIA. For time synchronization a thorough analysis of the time synchronization specification is performed from SDO such as ITU, IEEE and 3GPP. Key gaps for realizing E2E time synchronization in integrated 5G-TSN networks are identified. This comprises support for an arbitrary placement of the grand master (GM) clock which would require mechanism for uplink 5G TSN time distribution. Recommendations toward development of the ITU specification and clarification of the TSN time synchronization accuracy budget for 5G in integrated 5G-TSN system are explained. For radio-based positioning techniques a thorough analysis for the positioning mechanism is provided – including both mechanisms based on network synchronization as well solutions not requiring synchronization. Further, 3GPP based positioning methods are analyzed and explained. For positioning techniques several practical development aspects are considered for identified 5G-SMART use case. These include for example the need for accurate synchronization of the base station, system integrity information and knowledge about the locations of the base stations inside the factory. Further elaboration on planned recommendations is provided for an ongoing Release 17 plans to study NR positioning for industrial IoT use cases.

Contents

1 Introduction

There are two major trends driving the development of smart manufacturing: 1) More flexible production to meet increased customization increased customization needs and 2) more autonomous operations to increase productivity and improve production quality.

Future of industrial shop floor is envisioned with machines being equipped with wide range of seamlessly connected sensors generating huge amount of the data, collected and analyzed in real-time at a level not seen today in manufacturing. On the other hand, mobile robots and automated guided vehicles (AGVs) will perform work tasks and intra-factory logistics side-by-side with augmented human operators (i.e., human workers equipped with, for example, augmented reality glasses and wearable sensors).

Connectivity plays an important role in digital transformation of smart manufacturing sector supported with seamlessly integrated wired and wireless communication infrastructure. Reliable and secure transport of data in timely fashion among sensors, actuators and controlling devices is one of the key requirements for communication infrastructure supporting end-to-end (E2E) connectivity.

5G with capabilities to support communication services including ultra-reliable and low-latency communication (URLLC) and massive machine type communication (mMTC) has potential to provide such wireless and time sensitive communication required for wide range of smart manufacturing use cases. At the same time, time sensitive networking (TSN) is set to be standard ethernet based technology for converged networks of smart manufacturing. Together 5G integrated with TSN can offer seamless connectivity with the deterministic communication service required for manufacturing applications. 3rd Generation Partnership Project (3GPP) has already introduced key technical features to support such communication requirements in 5G during phase 1 (Release 15) and phase 2 (Release 16, finalized in March 2020).

In the 5G-SMART project, we focus on key technologies that are fundamental for future manufacturing, as shown in Figure 1. 5G-based positioning and E2E time synchronization are critical for applications such as mobile robotics, AGVs and augmented reality (AR)- equipped workers. Easy and fast integration of 5G with TSN networks is also a key to meet the requirements of flexible production, which is empowered by wireless communication technologies.

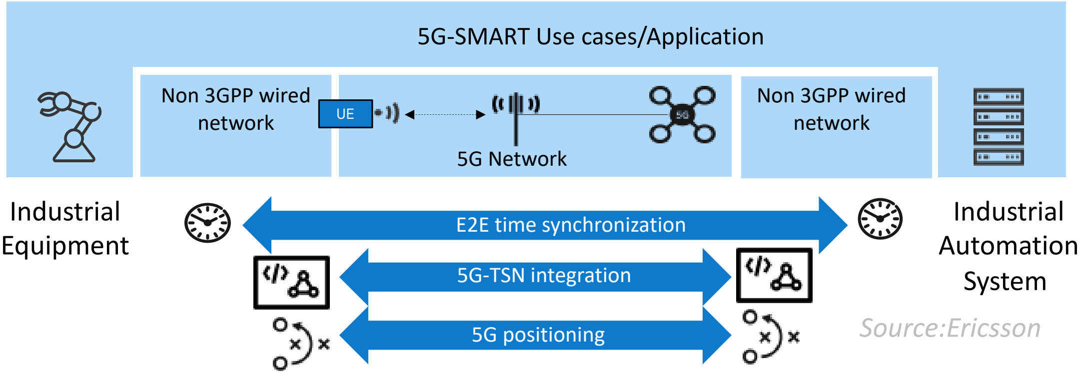

Figure 1: 5G features to support the 5G-SMART manufacturing use cases

1.1 Relation to other work packages in 5G-SMART

In 5G-SMART, work package (WP)5 will analyze and design 5G technical features for smart manufacturing. It takes a further leap from trial work packages (WP2, 3 & 4) by deep diving in technical aspect beyond those that are already standardized or are currently being standardized. It also looks into needed enhancements and their integration within manufacturing ecosystem.

Figure 2 shows the overall workflow of WP5. WP5 takes input from use case requirements defined in in WP1 [5GS20-D11] provides output to dissemination activities in WP6 with various enhanced technological features. In WP5, new and future-looking 5G technical features are investigated and evaluated against the wide range use case requirements. Figure 2 shows three main pillars of work undertaken in WP5. Present deliverable provides first output from development and evaluation of the new technological features and concept beyond trials work. This outcome serves as input to standard developing organizations (SDOs) and industry fora.

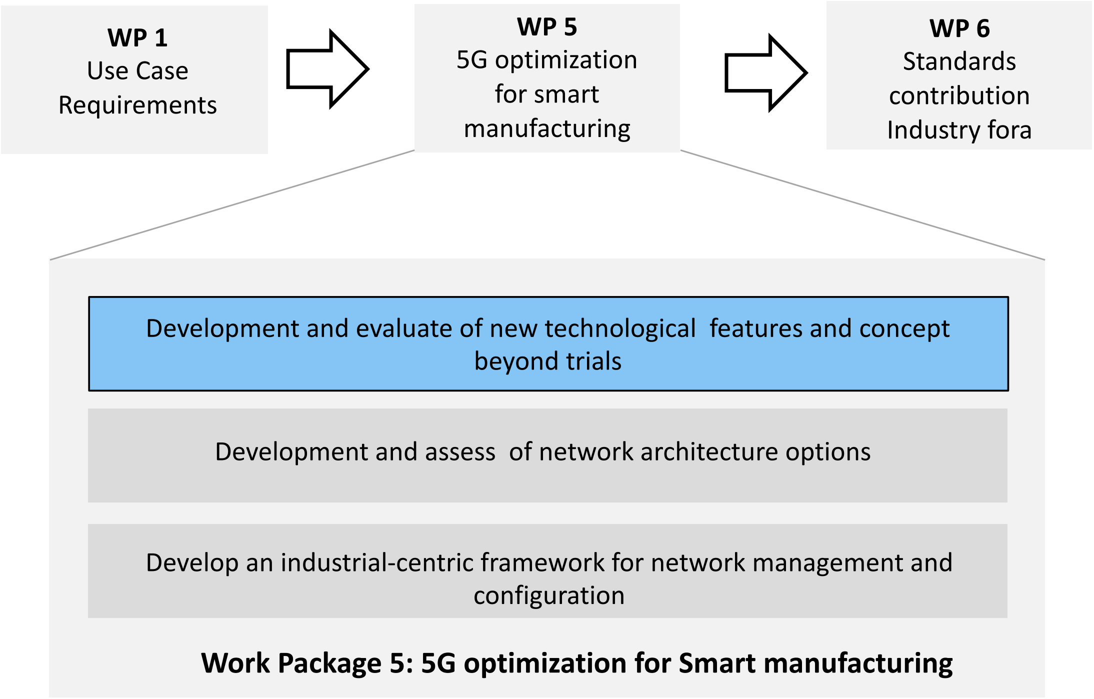

Figure 2: Workflow of WP5 and its relation to 5G-SMART project

1.2 Structure and scope of the document

This deliverable presents an in-depth analysis of the 5G technical features, which are being developed in various standardization bodies (such as 3GPP). In addition to this, a gap analysis is performed on state-of-the-art analysis and desired performance for selected use cases by the 5G-SMART project.

The document starts with providing a general overview of the technical features required to realize the 5G-SMART use cases. Further, sections provide a detailed analysis of each such feature. Section 2 focuses on 5G integration with TSN, section 3 investigates E2E time synchronization over the 5G system, and Section 4 presents 5G-based positioning solutions.

Each section includes:

1. A thorough analysis of technical features developed and discussed in various SDOs.
2. A gap analysis on what support is missing in context of the desired performance from use cases.
3. Recommendations towards SDOs and industry fora.

1.3 General overview of the use cases

5G-SMART has analyzed and identified several key use cases in the manufacturing sector where 5G is envisioned to play an important role. These use cases include mobile robotics and AGVs, augmented operators, industrial sensor networks and 5G-TSN integration. A detailed overview and description of the use cases can be found in [5GS20-D11]. In this deliverable, we only list the key technical features and their characteristics which are particularly relevant in the context of 5G (summarized in Table 1).

Focus in the different trials will be to explore the capabilities of 5G for the selected use cases. This means measuring e.g. the obtained communication latency, jitter and reliability of the 5G system and study the impact it has on the performance of each use case. This will provide an excellent view on current state-of-practice and support further 5G development. For the features studied in WP5 we already know that more development and standardization effort is needed in order to fully meet requirements in smart manufacturing.

In the “5G connected robot” use case, three robots collaborate and perform a pick-and-place task. This particular task does not require high-precision time synchronization, but there are many tasks where industrial robots need to move in a synchronized fashion where 5G, in the future, could provide this feature.

Time synchronization is also critical in TSN for scheduling the communication. Thus, when considering 5G-TSN integration end-to-end time synchronization is key. Other features, like TSN/5G support for mobile devices, also needs to be developed and standardized.

Positioning is key for mobile devices like AGVs. Most solutions today rely on on-board sensors and this is also the case for the 5G-SMART trials. But having a 5G network that can support high accuracy positioning in a very challenging indoor environment has many benefits. It could, e.g. reduce the need for sometimes costly and power-hungry on-board sensors and utilize the 5G infrastructure that is available “for free”. In Table 1 summary of the use cases being trialed and the relation to the three key 5G features being explored in WP5 is shown.

Use Case	**Requirements and description**	**5G relevant feature**
5G Connected robot & Vision assisted human-robot interaction	Seamless mobility to avoid service interruption and E2E QoS requirements for periodic, deterministic and symmetrical traffic	End to End QoS Mobility
5G-Aided Visualization of factory floor	AR headset requires seamless mobility and E2E QoS for aperiodic, deterministic and asymmetrical traffic	End to End QoS, Mobility
5G for wireless acoustic workpiece monitoring	Time synchronization to align sensor data of application	Time synchronization
5G versatile multi-sensor platform (MSP) for digital twin	Multiple synchronized sensors in the same network	Time synchronization
Cloud-based mobile robotics	AGVs mobility support along with E2E QoS for periodic, deterministic and asymmetrical traffic	Mobility
TSN/Industrial local area network (LAN) over 5G	5G-TSN integration requires time synchronization and maybe benefit from network slicing	5G-TSN integration Time synchronization

Table 1: 5G relevant features relevant to 5G-SMART trialed use case and their characteristics

2 5G-TSN integration

Time-Sensitive Networking (TSN) is foreseen as the open standards for wired deterministic low latency industrial communication. The main goal of TSN is provide deterministic services over IEEE standard 802.3 Ethernet wired networks. TSN standards can applied to many verticals including industrial automation. At the same time, 5G has also introduced features to support URLLC type of communication services. Report [E2E19-5GNGMN] provides an overview of the technical enablers to support industrial automation use cases.

As seen in section 1, it is quite clear that 5G-TSN integration will ensure seamless adoption of the 5G for smart manufacturing application. Together 5G and TSN can meet the demanding requirements of the Industry 4.0 [JBG+19].

2.1 State-of-the-art analysis

This section provides an overview of the 5G-TSN integration.

2.1.1 IEEE 802.1 Time-Sensitive Networking

Time-Sensitive Networking is a set of open standards defined by the IEEE 802.1 Time-Sensitive Networking Task Group (TG)[1]. The TSN TG specifies TSN functionalities that can be seen as a toolbox to provide deterministic services through IEEE 802 networks to enable bounded low packet loss, guaranteed packet delivery, bounded low latency and low packet delay variation.

A first core set of TSN standards have been published between 2015 and 2018, which are described in the following. These standards provide a suitable set of features to address the needs and requirements of industrial automation. Various vendors have implemented these standards, have run interoperability tests and made the technology ready to be deployed.

Figure 3 shows the overall status of TSN specifications focusing on time synchronization, bounded low latency, dedicated resources and high availability. It also includes ongoing projects. TSN standards and projects can be classified into three groups:

1. Base technology: these are TSN building block functionalities to enable deterministic communication services, which include timing and synchronization (IEEE 802.1AS)[2], stream reservation protocol (IEEE 802.1Qat)[3], credit based shaper (IEEE 802.1Qav)[4], frame preemption (IEEE 802.1Qbu)[5], scheduled traffic (IEEE 802.1Qbv)[6], per-stream filtering (IEEE 802.1Qci)[7], frame replication and elimination (IEEE 802.1CB)[8], and link-local registration protocol (IEEE 802.1CS)[9].

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[1] https://1.ieee802.org/tsn/
[2] http://www.ieee802.org/1/pages/802.1as.html
[3] http://www.ieee802.org/1/pages/802.1at.html
[4] http://www.ieee802.org/1/pages/802.1av.html
[5] https://standards.ieee.org/standard/802_1Qbu-2016.html
[6] http://www.ieee802.org/1/pages/802.1bv.html
[7] https://1.ieee802.org/tsn/802-1qci/
[8] https://1.ieee802.org/tsn/802-1cb/
[9] https://1.ieee802.org/tsn/802-1cs/

2. Configuration: This includes standards, ongoing projects elaborating configuration models, and data models. It includes include YANG data model (IEEE 802.1Qcp[10]), TSN configuration (IEEE 802.1Qcc) and YANG for Link Level Discovery protocol (LLDP) (IEEE 802.1ABcu[11]).

3. Profiles: From the wide breath of the IEEE 802 standards, TSN profiles for particular verticals define how to build a TSN network for a particular use and provide configuration if needed. TSN profiles narrow the focus to ease interoperability and deployment. Already published TSN profiles includes IEEE 802.1BA for audio-video bridging (AVB) networks systems[12] and IEEE 802.CMde TSN [13] Amendment (TSN for fronthaul). Ongoing TSN profile projects includes IEC/IEEE 60802 TSN profile for industrial automation[14], P802.1DF TSN profile for service provider networks[15] and P802.1DG TSN profile for automotive in-vehicle Ethernet communications[16]

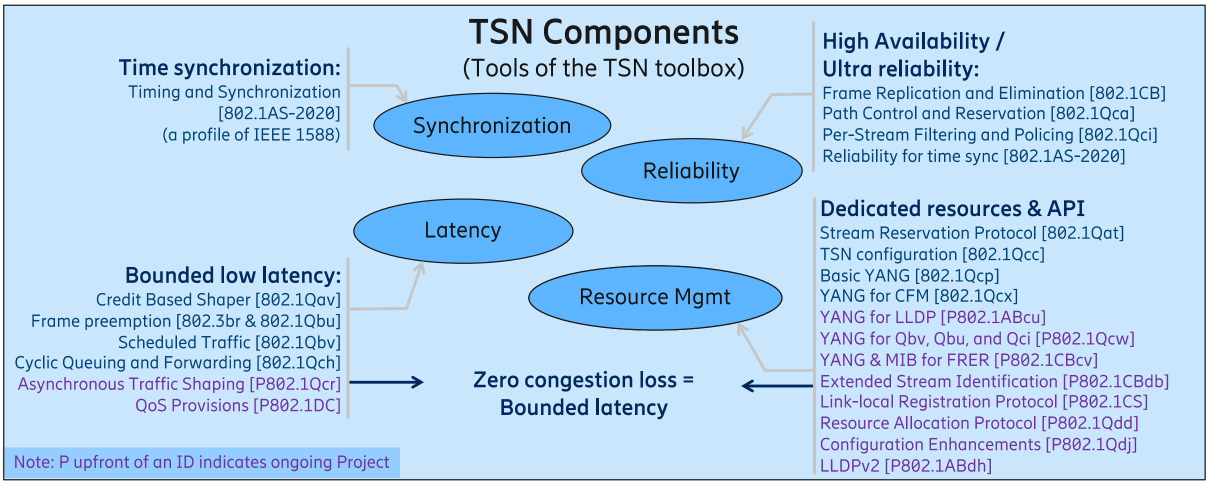

Figure 3: TSN specification overview

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[10] https://standards.ieee.org/standard/802_1Qcp-2018.html
[11] https://1.ieee802.org/tsn/802-1abcu/
[12] http://www.ieee802.org/1/pages/802.1ba.html
[13] https://1.ieee802.org/tsn/802-1cm/
[14] https://1.ieee802.org/tsn/iec-ieee-60802/
[15] https://standards.ieee.org/project/802_1DF.html
[16] https://1.ieee802.org/tsn/802-1dg/

TSN components and basics

In IEEE 802.1 networks, there are two main type of devices:

1. Bridges: These are layer 2 interconnection devices that conform to IEEE 802.1Q specifications. A bridge consists of control plane and data plane. The data plane comprises the Medium Access Control (MAC) Relay and at least two ports.
2. End stations: it can be a Talker that produces a TSN stream. An end station according to [IEEE17-8021QCB] is a device attached to a local area network (LAN), which acts as the source or producer for data traffic carried on the LAN. It can be a Listener, which receives or consumes a stream. A stream can have one Talker and multiple Listeners.

A TSN stream is unidirectional flows of time-sensitive data from one Talker to one or multiple Listener(s). Each stream is identified by a stream ID, which provides a unique identifier for the stream configuration and is used by the network elements to associate the user's stream with TSN resources. The TSN stream ID can consist of the MAC address associated with the Talker producing the TSN stream towards the bridged network and a unique ID. This unique ID is used to distinguish multiple streams within an end-station that is identified by its MAC address. QoS functions such as filtering and policing, shaping and queuing are applied to TSN streams at TSN bridges during the frame forwarding process.

As observed in the smart manufacturing use cases, an industrial network may have multiple traffic streams with varying latency, bandwidth and reliability requirements, and at the same time, the network needs to carry non-time-critical traffic. TSN supports such manufacturing applications with a combination of functions, including traffic scheduling, per-stream filtering and policing, and cyclic queuing and forwarding.

A real-time traffic stream can be realized with zero loss from congestion and bounded deterministic latency in an Ethernet network, which is shared along with traditional best-effort traffic [JM18]. This can be done by e.g. combining TSN capabilities of cyclic queuing and forwarding (802.1Qch), per-stream filtering and policing (802.1 Qci), and traffic scheduling (802.1 Qbv). However, this requires time synchronization, planning and coordination of the resources across the network. TSN tools to address this include resource management, as e.g. defined by IEEE 802.Qcc and described later in section 2.1.2. The generalized Precision Time Protocol (gPTP) is specified in IEEE 802.1AS, which is a profile of Precision Time Protocol (PTP), enabling reliable time synchronization across the TSN network.

In addition, high reliability is achieved with the TSN Frame Replication and Elimination (FRER) functionality specified in IEEE 802.1CB. It is improving reliability of the system by means of replicating TSN stream and sending over disjoint paths across the network between its Talker and Listener(s). To summarize, a set of features from the TSN toolbox functionalities along with some of the existing IEEE 802.1 bridging functions can enable TSN networks for smart manufacturing applications. A careful consideration on how-to deploy the network and the configuration required for the TSN profile of industrial automation is currently being developed as explained below.

TSN profile for industrial automation

TSN standardization is still in progress. TSN profiles are developed to address different requirements in different sectors. Concerning industrial automation, the IEC/IEEE P60802 joint project specifies TSN profiles for various industrial automation use cases. It is a joint project between IEC SC65C/MT9 and IEEE 802 working groups. The profiles select TSN features, options, configuration, defaults, protocols and procedures in bridges, end stations and LANs to build industrial automation networks. Further details can be found in reference [IEC/IEEE P60802].

2.1.2 IEEE 802.1 TSN configuration models

In a TSN network, the end stations communicating with each other are referred to as Talkers and Listeners. A concept of streams is introduced in the standards for transmission of frames from a Talker to one or more Listener(s). As described above, each TSN stream is identified by a unique “stream ID” attribute. User network interface (UNI) is introduced which enables the user to specify stream requirements without knowledge of the network, thereby making the network configuration transparent to the user.

There are three user-network configuration models defined, which are the following:

1. Fully distributed model.
2. Centralized network/distributed user model.
3. Fully centralized model.

For centralized network/distributed user model an entity, called centralized network configuration (CNC), with complete knowledge of all TSN stream in the network is introduced. All the configuration message originates in the CNC. Fully centralized models allow a centralized user configuration (CUC) entity to retrieve end station capabilities and configures TSN features at end stations. CUC interfaces and configures end stations and CNC interfaces with bridges. Figure 4 shows the fully centralized model, it allows a central user configuration entity to retrieve end station capabilities and configure TSN features in end stations.

Concerning to the 5G-SMART use cases and its requirements, fully centralized model is more suitable as it enables the configuration of end stations from a central entity of the network. Here, the UNI is between the CUC and the CNC Centralized Network Configuration (CNC) is an entity that has the complete view of the physical network and knowledge of the network topology. CNC is responsible for configuration of the bridges for TSN streams from Talkers to Listeners. CNC has information of all the bridges, including the address and capabilities of each bridge. The configuration of TSN features in the bridges is done utilizing a remote network management protocol. YANG is the state-of-the-art data modelling language for remote management. In the Figure 4, dotted arrows show the remote management protocol where CNC acts as the management client and each bridge as management server. CNC uses remote management to discover the physical topology, retrieve Bridge capabilities and configure TSN features in each bridge. CUC is connected to a CNC via the UNI interface and provides the necessary information required for the stream configuration. Specifically, CUC provides CNC with Talker and Listener group, which is collection of the TSN configuration information (known as elements) such as Traffic specification, user to network requirements, etc. Details elements are listed in [IEEE18-8021QCC]. For fully distributed and Centralized network/distributed user configuration model information between the end stations and a TSN network is transferred over the User-Network Interface (UNI).

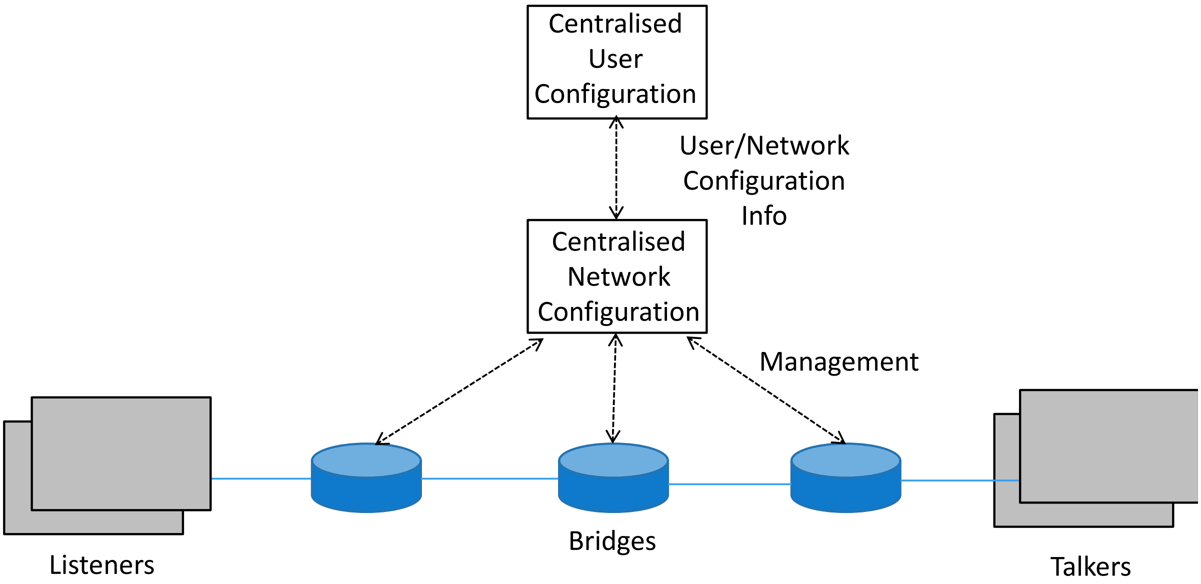

Figure 4: Fully centralized TSN configuration model [IEEE18-8021QCC]

The following TSN features can be configured by the CNC:

1. Credit based shaper algorithm.
2. Frame Preemption.
3. Scheduled traffic.
4. FRER (Frame Replication and Elimination for reliability).
5. Per-stream filtering and policing.
6. Cyclic queuing and forwarding.

CNC and CUC are both logical functions in the network. The interactions and data attributes of the TSN configuration are specified in IEEE TSN 802.1Qcc.

Figure 5 shows the sequence of the TSN stream configuration according to the fully centralized network configuration model. The steps are as follows, also described in [EG17] and [IEEE18-8021QCC].

1. The CUC discovers Talker and Listener end stations.
2. The CUC reads the capabilities of the end stations, it includes number of the ports and MAC address of each ports, IEEE 802.1 capabilities of each port and traffic specification including maximum frame size and maximum frames per interval. The user interacts with this stream data information and create stream requirements.
3. Based on this above information, the CUC creates the following:
    - StreamID: stream identifier
    - StreamRank: the importance of each stream is related to its use in application
    - User-to-Network Requirements

4. The CNC discovers the physical topology using LLDP along with a network management protocol
5. The CNC reads TSN capabilities (IEEE 802.1Q, IEEE 802.1AS, IEEE 802.1CB) from bridges via a remote management protocol. MIB/YANG models are used for that purpose (for example, the CNC reads bridge delays and propagation delays)
6. The CUC initiates the join requests to configure streams in order to configure network resources for this stream's data transfer, it includes a Talker and a group of Listeners,
7. The CNC configures the TSN domain by checking the physical topology and verifies that the time-sensitive streams are supported by bridges on the transmission path(s). Further, it performs path selection and computation of the time schedules for delivery of the streams. According [IEC/IEEE P60802], TSN domain is a set of end stations, their port and the attached LANs that transmit time sensitive streams using TSN standards which include transmission selection algorithm, preemption, time synchronization and enhancement for scheduled traffic and also this station shares a common management mechanism.
8. The CNC configures TSN features in bridges. CNC uses the IEEE 802.1Q management to configure TSN features between Listener and Talker path.
9. The CNC returns the status (success or failure) on resource assignments for the streams to the CUC.
10. The CUC further configures end stations to prepare execution of the applications. CUC provides interface configuration for each stream which contains MAC address.

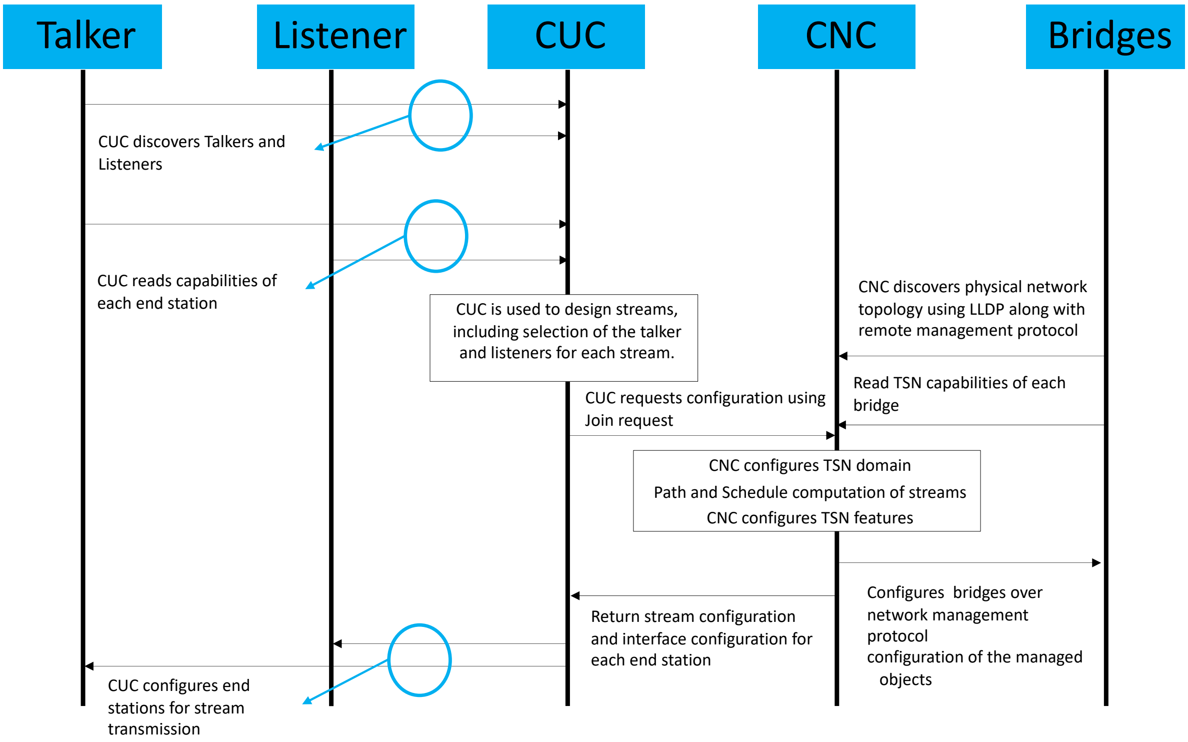

Figure 5: TSN stream setup in a fully centralized configuration model based on [IEEE18-8021QCC]

Other TSN configuration models – besides the *fully centralized* model described above – are the *centralized network/distributed user* model and the *fully distributed model*. These two configuration models rely on the Stream Reservation Protocol (SRP), which uses the Multiple Stream Registration Protocol (MSRP), the Multiple VLAN Registration Protocol (MVRP), and the Multiple MAC Registration Protocol (MMRP). However, it has been shown that SRP cannot fulfil the needs of industrial automation networks[17]. Therefore, completely new protocols are being developed to provide distributed resource reservation. The P802.1CS Link-local Registration Protocol (LRP) will provide a new base protocol, similarly to the Multiple Registration Protocol (MRP) being a base protocol for MSRP, MVRP, and MMRP. The P802.1Qdd Resource Allocation Protocol (RAP), which builds upon LRP will be the actual resource reservation protocol suitable for industrial automation. However, the standardization of RAP is in a very early stage, the draft is still very much incomplete and has had by the time of writing this deliverable a single review only. Project Authorization Request (PAR) for the P802.1Qdd RAP indicates completion in October 2022. Even if would be standard is ready by now, a new reservation protocol would be premature for deployment and usage.

Implementations from multiple vendors need interoperability testing and early installations are needed to be able to use RAP. Given the complexity of the task and distributed protocols, bugs in the standard may be discovered during early implementations, which then have to be fixed via the standardization process. Overall, it is expected to take a significant amount of time until RAP will be a mature technology to build upon or to be considered for wireless networks. Taking into consideration above concerns with the centralized network/distributed user model and the fully distributed model; furthermore, the benefits of the fully centralized model, 5G standards apply the fully centralized configuration model.

2.1.3 Work on IEEE 802.1 TSN support in 3GPP

Starting from Release 16 in the 3GPP standardization work, a 5G system has introduced features to support interworking with TSN-based wired networks. The set of specifications enables seamless transmission of a TSN stream over the 5G system.

5G-TSN integration architecture

In the Release 16 specification of the 5G System, the a fully centralized model of TSN was adopted, enabling a centralized SDN-like architecture [JBG+19]. The interaction of the 5G system with a TSN network is illustrated in Figure 6, which shows both the control plane communication and the user plane connections. The 5G System is modelled as a “virtual” or logical bridge providing control plane connectivity and TSN ports at the user plane. This model includes the TSN Translator (TT) functionalities, which is described below.

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[17] https://1.ieee802.org/tsn/802-1qdd/

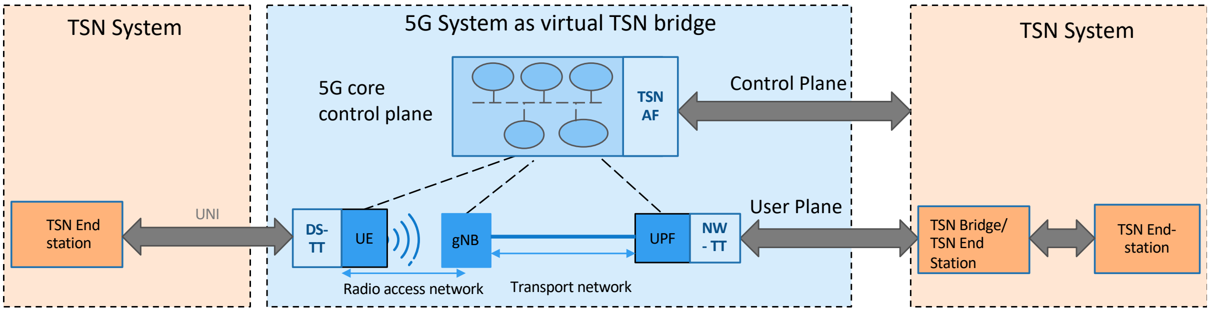

Figure 6: End-to-End 5G-TSN integration architecture based on [TS20-23501]

TT functionality that is available at TSN AF (control plane), UE side or Device-Side TT (DS-TT) and at the UPF side or Network-side TT (NW-TT). The 5G System connects via its 5G base stations (gNB) to wireless 5G devices (UE), which terminates the other end of the 5G virtual TSN bridge. From time synchronization perspective, this 5G virtual bridge acts as a time-aware system as per IEEE 802.1AS.

For the control plane, the interaction is between the Application Function (AF) and the control entity of the TSN network, i.e., the CNC. The AF entity interacts with the 3GPP Core Network to provide the service such as QoS mapping to 5G System for TSN streams transmitting over 5G System. Traditionally, the AF influences traffic routing and also enables interaction for policy control. In case of the 5G-TSN architecture, the AF (also referred to as TSN AF) acts as a TSN Translator (TT) to exchange TSN QoS, bridge, and port management information with the CNC and on behalf of the 5G System. Standardized and deployment-specific port management information is transparently transferred between TSN AF and DS-TT or NW-TT.

For the user plane, the TSN translators at the User Plane Function (UPF) and at the UE act as gateways that interconnect the 5G System to the TSN network and support gPTP-based time synchronization. To determine the representation of the 5G System as one or multiple virtual TSN bridge(s), two aspects should be considered:

1. multiple packet data unit (PDU) sessions may be established from a UE to different UPFs,
2. Ethernet shared media is not allowed for TSN networks.

Modern Ethernet networks use point-to-point duplex links and avoid shared media. Therefore, an Ethernet link always connects two nodes (bridge or end-station). Shared media could slow down convergence of the Ethernet control protocols significantly. 5G System’s TSN model shall, therefore, be based on the point-to-point links and avoid mimicking shared Ethernet media.

5G System TSN Translators

In order to integrate the 5G System with an external TSN network, the 5G System acts as if it is a TSN bridge, thus hiding 5G internal aspects, e.g. the characteristics of the radio connections. These "logical" TSN bridges shown in Figure 6 are included in both ends of the 5G network. Thus, devices, which include 5G connections will be treated as standard TSN devices. These bridges include TSN translator functionality for interoperation between the TSN system and the 5G System, both for the user plane and the control plane.

5G System TSN translator functionality consists of Device-side TSN translator (DS-TT) and Network-side TSN translator (NW-TT). DS-TT and NW-TT optionally support the following functionalities:

1. Link layer connectivity discovery and reporting as defined in IEEE 802.1AB.
2. TSN configuration models defined in IEEE P802.1Qcc, specifically the fully centralized configuration model is supported.
3. interworking with TSN scheduled traffic as defined in IEEE 802.1Qbv based QoS scheduling.

5G virtual bridge per UPF

Considering the 5G System architecture, the granularity of the 5G virtual bridge is per UPF, as shown in Figure 7. Here Granularity means per UPF there can be one 5G virtual bridge, the bridge-ID of the logical TSN bridge is bound to the UPD ID of the UPF. Data plane of this 5G virtual bridge includes ports at the NW-TT side of single UPF, data plane from UPF to UE and ports on the DS-TT side. Every DS-TT is associated to a specific PDU session in the 5G System. UPFs TSN AF delivers the capabilities of each port in UEs and UPF to CNC for the TSN bridge configuration.

UPF can implement a data plane switching functionality. Multiple PDU sessions from a UE to different UPFs can be established for redundant traffic transmission; in this case, each DS-TT port belongs to one virtual bridge. Considering a separate virtual bridge for each UPF, inter-UPF coordination is not required for switching functionality, as each UPF will have its own switching functionality.

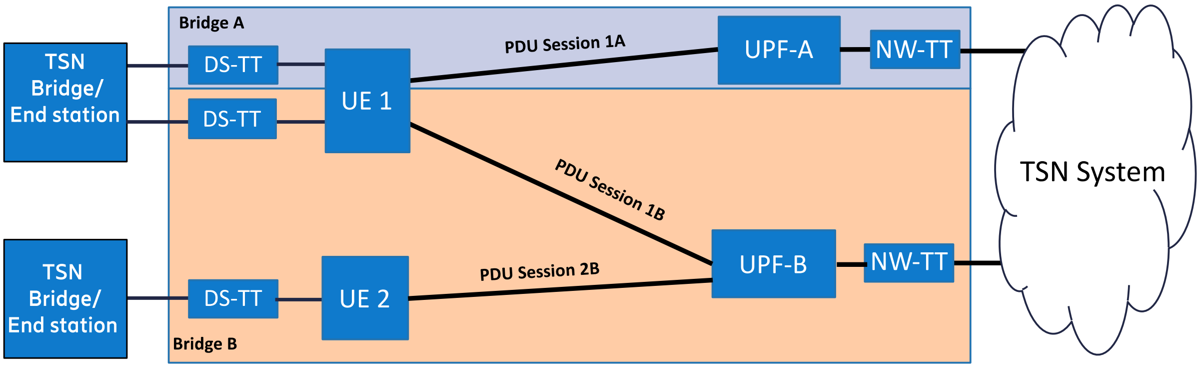

Figure 7: UPF based 5G virtual bridge

5G System -TSN QoS Mapping

For a TSN bridge, QoS is related to so-called traffic classes. Each traffic class is tightly linked to a priority level. Considering IEEE 802.1Qcc centralized configuration model, for a TSN stream transmission over 5G System, the 5G System bridge also reports some node specific characteristics, for example, bridge delay per traffic class and per port pairs, as an indication of the offered service for a given traffic class. QoS mapping consists of the following two phases:

1. Bridge capability report phase
   a. The 5G virtual bridge provides its capabilities to the TSN CNC. Capabilities include bridge & port information, e.g. bridge delay per traffic class. At this point, only PDU session has been established.
   b. The CNC uses this information to perform path and scheduling calculations.

2. Bridge QoS configuration phase
    a. CNC distributes configuration to 5GS bridge via TSN AF, this incudes port configuration e.g. IEEE 802.Qbv schedule parameters.
    b. TSN QoS mapping to 5G QoS, by means of a 5G core network mapping table that provides the mapping from TSN QoS information to a 5G QoS profile. 5G QoS profile consist of the QoS parameters and certain QoS marking utilized to control the QoS forwarding treatment in access network.
    c. The 5G System configures a QoS flow for the TSN stream based on the mapping table at the policy control function (PCF).

As shown in Figure 8, mapping tables are pre-configured in the TSN AF by operations, administrations and maintenance (OAM) functions. Mapping tables represents what is being exposed to TSN system (CNC) via relevant TSN information objects such as Traffic Class Tables for every port, more details are provided in [IEEE18-8021QCC]. After PDU session establishment, and after calculation of the UE-DS-TT residence time related information, the AF can update its mapping table with bridge delays per port pair and traffic class. UE-DS-TT residence time is the time take within UE and DS-TT to forward packet between UE/DS-TT port. It is used to calculate 5G System bridge delay for each port pair. This information is further reported to the CNC. 5G System also specifies a PCF mapping table, which provides a mapping from TSN QoS information to 5G System QoS profiles. The TSN AF can trigger the PCF, resulting in a PDU session modification procedure to establish a new 5G QoS flow or the use of preconfigured 5G QoS Identifier (5QIs) for 5G QoS flows for the requested traffic class according to the selected QoS policies and the TSN AF traffic requirements [TS20-23501]. 5QI is QoS parameters, it is scalar that is used as reference to a specific QoS forwarding behavior [TS20-23501].

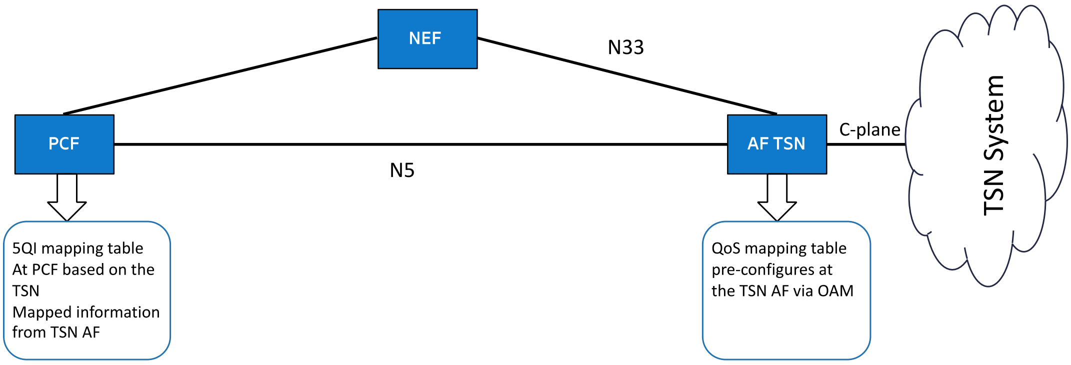

Figure 8: QoS mapping tables from TSN parameters to a 5G System QoS profile (Clause 5.28.4 [TS20-23501])

Periodic deterministic QoS

The 5G System supports periodic deterministic communication by enabling mapping of the QoS flow with appropriate QoS configuration. Further, the features below enable deterministic communication including bounded latency performance in the 5G System:

1. Hold and forward buffering mechanism at DS-TT and NW-TT to guarantee the bridge delay reported to CNC for TSN traffic traversing the 5G system.
2. Enabling Time Sensitive Communication Assistance information (TSCAI) at gNB ingress and UE egress interfaces for traffic in downlink and uplink directions. TSCAI includes flow direction (uplink or downlink), periodicity (refers to time period between start of two bursts) and burst arrival time (the arrival time of data burst either at ingress of RAN or egress interface of the UE).

Within the 5G System, TSCAI describes Time Sensitive Communication (TSC) traffic characteristics. TSC is a communication services that supports deterministic communication with high reliability and availability [TS20-23501]. TSCAI knowledge can help the radio access network (RAN) to efficiently schedule radio resources. The 5G System virtual bridge can utilize information specified by IEEE 802.1Qci Per-Stream Filtering and Policing (PSFP) to obtain per-stream configuration information. It is possible with current specification to extract traffic patterns on per-TSN stream basis on PSFP information. Such traffic patterns information can be used to derive the TSCAI parameters. The TSCAI parameters are derived per QoS flow basis and are signaled to the RAN.

5G System Reliability mechanism to support TSN transmission

5G System has introduced various technical enhancements that increase reliability for TSN stream transmission in the integrated 5G-TSN architecture. Figure 9 shows various mechanisms for different parts of the 5G network. Report [E2E19-5GNGMN] further provides a brief overview on various technical enablers for improving reliability. Below, various mechanisms are explained.

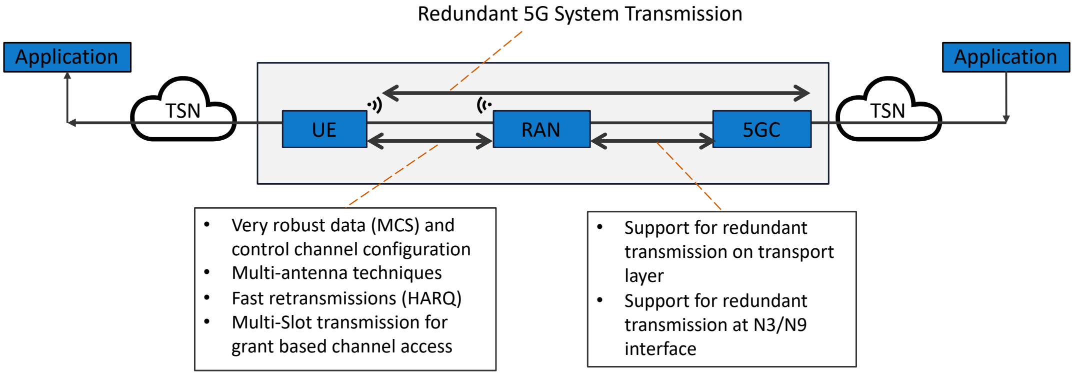

Figure 9: 5G reliability mechanisms for the TSN transmission

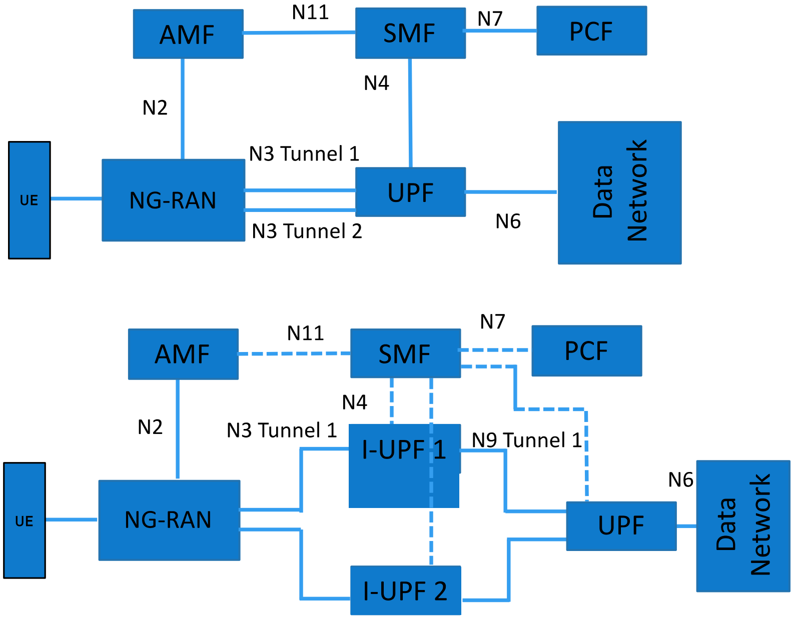

Figure 10: Redundant transmission over N3/N9 interfaces

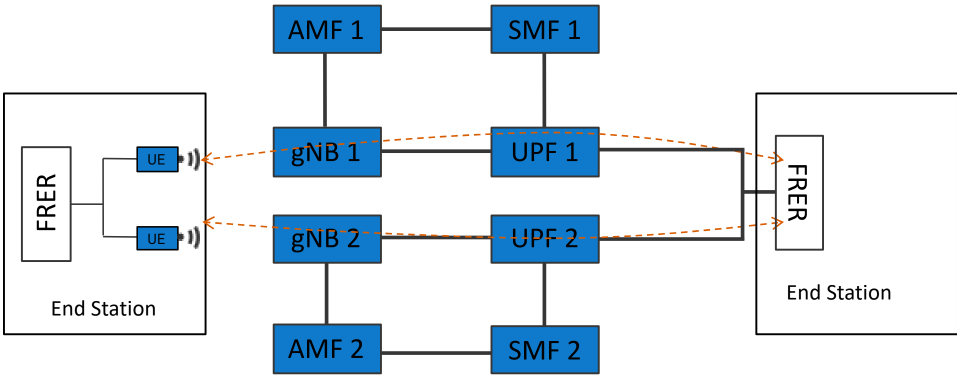

Figure 11: Redundant transmission based on multiple UEs

RAN reliability mechanisms include

1. **Multi-antenna technique**: Multi-antenna utilization results in high throughput, and at the same time increases effective SINR, thus increasing a system's robustness. Multiple antenna elements can also be used to create directional antenna beams at the transmitter and/or receiver side to increase the received SINR and, thus, reliability.
2. **Multi-slot transmission for grant based channel access:** This feature enables a transport block transmission of multiple times in consecutive 5G New Radio (NR) slots without waiting for Hybrid automatic repeat request (HARQ)ACK and NACK messages. Further details are provided in [E2E19-5GNGMN].

3. **Robust control channel configuration:** To enable high reliability over the air interface, very low Block Error Rate (BLER) is required. For this purpose, several enhancements have been made including:
    a. Channel Quality Indicate (CQI) table has been introduced for reporting a BLER target of 10^{-5} [3GPP18-38331]. This new table contains highest modulation order in 64 QAM.
    b. A low spectral efficiency Modulation Coding Scheme (MCS) table [3GPP18-38331] has been introduced for use without transform precoding.
    c. uplink control channel (PUCCH) enhancement: Physical Uplink Control Channel (PUCCH) carries a control information called Uplink Control Information (UCI). UCI contains different type of information such as HARQ-ACK/NACK, Scheduling Request and Channel State Information (CSI) from UE to gNB. By enabling long duration of PUCCH, uplink channel control information can be transmitted over multiple slots, thereby increasing the reliability of the control channel.

CN-related enhancements for high reliability and availability include,

1. **Support for redundant transmissions in transport layer:** In order to increase the reliability and availability for the backhaul network, transport layer is selected for user plane traffic transmission between UPF and RAN, which supports redundant transmission [TS20-23501].
2. **Support for redundant transmission over N3/N9 interface:** In order to increase reliability and availability, redundant transmission is done through two N3 tunnels and also at the N9 interface as shown in Figure 10.
3. **Support for twin UE:** This solution relies on having multiple UEs on the same end device as shown in Figure 11 (in case of TSN, it can be an end station or a bridge). 3GPP has not specifically defined the TSN Frame Replication and Elimination for Reliability (FRER) feature within a 5G System. Rather, various features described below are combined to enable TSN FRER.

Support for Mobility in Integrated 5G-TSN Networks

Mobility is a fundamental aspect that needs to be considered when integrating fixed TSN network with cellular 5G technology. In a fixed network, components are assumed stationary, whereas the cellular network has intrinsic support for mobile UEs including advanced roaming functions. TSN support for roaming functionality is therefore needed in an integrated 5G-TSN network solution.

The main use case for mobility in smart manufacturing involves AGVs or mobile robots. In large factory settings, the, AGVs or mobile robots can operate in an area that is not covered by a single base station. In this case, the UE will need to handover its connection between different base stations and the TSN network needs to support this mobility. Mobility of the device is hidden from the external TSN network and the CNC; it is rather a 5G internal procedure that occurs within the 5G virtual TSN bridge. In order to avoid that mobility results in a performance glitch due to a short moment of disconnection, a low latency 5G handover scheme based on dual-active protocol stack is used [OPC20]. For the assumed mobility within a local area, it is expected that the performance characteristics of the 5G system due to mobility does not change significantly and no updates of the capabilities of the 5G virtual TSN bridge is required. However, a validation of performance impact of 5G device mobility on the TSN performance needs to be further investigated.

2.2 Gap analysis

Considering the 5G-TSN integrated network to support 5G-SMART use cases, below are the main gaps identified. In addition to the ongoing work on reliability and QoS mechanisms as discussed in the previous sections the 5G-SMART, project also sees a need to investigate the alignment of the management and configuration of the TSN Ethernet domain with the 5G system. If not properly addressed the network configuration and the device/application engineering could be decoupled. This will introduce unnecessary complexity and ultimately slow down the adoption of 5G-TSN integrated networks in manufacturing. This is further elaborated on in the following sections.

2.2.1 End to End TSN stream configuration and 5G system capability exposure

Efficient stream configuration requires a system-level approach to ensure full performance from the integrated 5G-TSN network. This configuration also needs to consider device provisioning, including devices joining and leaving the network.

Efficient stream configuration requires a system-level approach to ensure full performance from the integrated 5G-TSN network. This configuration also needs to consider device provisioning, including devices joining and leaving the network.

In general, industrial devices (e.g. robots, sensors, controllers, etc.) have dedicated engineering tools and methods for provisioning and configuration. In fact, most devices in a factory today are TSN-unaware end points but still provide QoS support. In these cases, the integrated 5G-TSN network can still be realized using e.g. bandwidth allocation or VLAN separation. Depending on the configuration model this will likely require interaction between the device engineering tools and the CNC, it can also between CUC and device engineering tools which requires further investigation.

The CUC is a role defined in the IEEE 802.1Qcc standard with the task of configuring the end nodes (or their applications – the users of the network). However, in addition to ongoing standardization efforts more work is needed to ensure a holistic view on network configuration and application configuration. A clear understanding on how industrial devices and applications are configured today will facilitate network convergence also for non-native TSN devices.

An exposure of 5G network capabilities to applications has been described in upcoming 5G-ACIA paper focusing on exposure of 5G capabilities for connected industries and automation application. It allows for device management in the 5G system, as well as communication service monitoring and 5G network management and configuration capabilities. The standardization of such an exposure interface remains future work. Exposure of Time Sensitive Communication (TSC) services (including TSN) is one of the key issues under study in 3GPP Release 17 work at the time of this document release.

2.2.2 5G-TSN configuration according to the fully distributed and the hybrid centralized network/distributed user configuration models

A TSN network configuration according to the distributed or hybrid configuration model for TSN according IEEE 802.1Qcc may be desirable in the future if those models are adopted for industrial automation. As described above in Section 2, those configuration models are still in an early phase of standardization within IEEE 802.1. A finalization of this standardization in IEEE is required first in order to be able to specify the required features that would need to be specified within 3GPP for a future release of 5G.

2.3 Recommendation towards standardization bodies and fora

Considering gap analysis against functional requirements (shown in Table 1) for the use case identified within 5G-SMART project it is recommended to specify a secure exposure framework for the 5G System that enables the integration, configuration and management of the 5G System within the end-to-end industrial LAN/TSN network. Such a framework should comprise device management functionality such as device provisioning and onboarding, as well as, device connectivity management and monitoring. This framework should further enable 5G network management including network configuration and network monitoring.

Further, it is recommended to investigate different 5G-TSN deployment and connectivity options. The main aspect to be included here is to look into what type of TSN features are utilized between nodes and how TSN configuration can be handled for such deployment options. The investigation of such deployment options should consider specific use case deployment scenario.

In an integrated 5G-TSN network, 5G acts as logical TSN bridge offering certain bridge capabilities and technical enablers that can be activated to support TSC communication services. The specific combination of which features and trade of between feature and efficient resource utilization should be investigated and recommended for certain use cases.

5G-SMART has so far provided recommendation in terms of contribution towards 5G-ACIA on some of the above aspects including, 5G System technical features to support bounded latency and reliable communication. Also, how 5G System can handle TSN traffic.

3 End to End time synchronization

Time synchronization is one of the important timeliness aspects to synchronize industrial processes, as highlighted in report [5GS20-D11]. Time accuracy is understood as maximum absolute value of the time difference between a sync master and any device operating on the time sensitive application. Section 1 provides a general motivation of time synchronization for 5G-SMART use cases. In general, time synchronization among different industrial devices allows performing coordinated tasks and is used by industrial communication technologies to enable deterministic communication behavior (such as for TSN). Concerning 5G-SMART use cases, time synchronization is, for example, utilized for coordinating measurements from different end industrial equipment's (MSPs) deployed in the smart manufacturing plant. To summarized time synchronization in smart manufacturing is required for

1. Industrial control to perform coordinated task.
2. Industrial communication, example include TSN IEEE 802.1Qbv utilize common time for all switched for time aware scheduling.
3. Industrial measurement.

Considering scenarios of 5G integration into industrial environment, different standardization bodies have already started investigating the feasibility of time synchronization solutions on industrial communication network. Below, Section 3.1 provides an overview of state-of-the-art on the work done by different SDOs, including IEEE, 3GPP, ITU. Section 3.2 provides gap analysis. Furthermore, Section 3.3 provides recommendation of standards.

3.1 State-of-the-art analysis

Considering end-to-end the E2E time synchronization aspect, this section provides a detailed overview of the time synchronization mechanisms being developed and standardized in different SDOs.

3.1.1 Time synchronization efforts in IEEE 802.1 TSN

Time synchronization is one of the building blocks of TSN standardized by the IEEE 802.1 TSN Task Group (TG).

The initial work of the TSN TG was to build audio and video bridges within a LAN environment, thus allowing audio and video devices to align time streams coming from various sources. This initial use case has now been expanded towards a general add-on to traditional Ethernet to offer bounded and low latency, low jitter and extremely low packet losses for many use cases, including (but not limited to) industrial automation and automotive in-vehicle communication.

Nowadays, the TSN toolbox includes more than 20 standards. Among those, IEEE 802.1AS is the standard regulating time synchronization in TSN networks and has been recently updated in IEEE 802.1AS-Rev [IEEE19-8021AS]. This standard is based on the PTP protocol defined in IEEE 1588-2008. Specifically, IEEE 802.1AS defines generic PTP as a specialized IEEE 1588-2008 profile, as explained in detail in [Kston18].

Clock distribution mechanism in TSN networks

Industrial automation devices in a TSN network align their activities in time through a shared clock according to the gPTP protocol, thus forming a gPTP domain. The shared clock can either be a universal clock (also known as "wall clock"), or a working clock based on an arbitrary timescale. One node in the gPTP domain acts as the source of the shared clock and it is denoted as GM. Clock information is distributed from the GM to all the nodes in the domain with dedicated messages defined by the gPTP protocol.

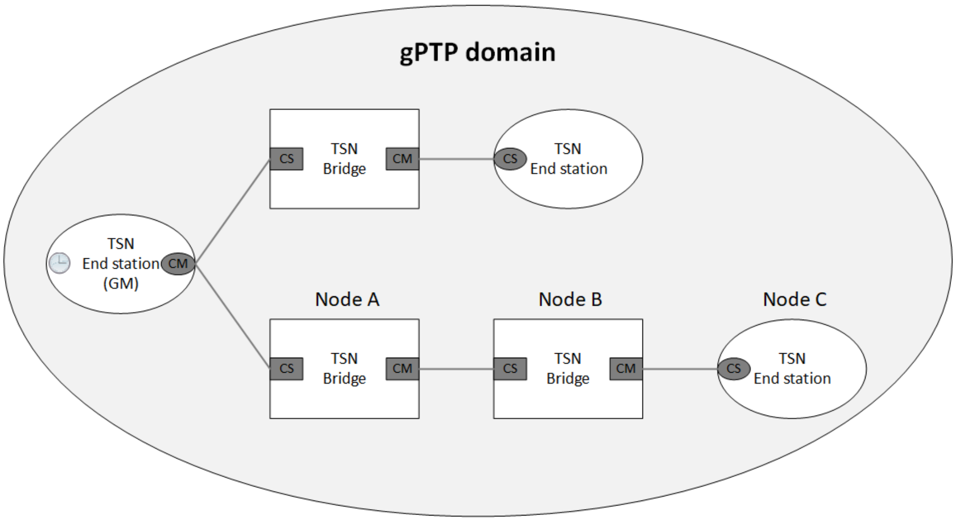

Figure 12: Example of a typical gPTP domain where a clock is shared according to IEEE 802.1AS

To provide an example of clock distribution, consider a typical gPTP domain represented in Figure 12. The domain includes TSN end stations, one of which is the GM, as well as TSN bridges. The gPTP protocol is implemented in a distributed way by each node in the network.

With respect to Node B in Figure 12 (TSN bridge), consider the following sequence of operations:

1. Receive a gPTP Packet Data Unit from its direct CM (Node A) containing the cumulative time delay from the GM.
2. Compute the propagation delay of the link with its direct Clock Master (CM).
3. Combine the information in Step 1 and 2 to compute the total delay from the GM and update its internal clock.
4. Compute its residence time, i.e., the time elapsed from the reception of the gPTP PDU (ingress) and its transmission (egress).
5. Send the gPTP PDU to its direct Clock Slave (CS)s (e.g., Node C), which contains the time delay from the GM (computed in Step 3) and the residence time (computed in Step 4).

Two additional features defined in IEEE 802.1AS are the Best Master Clock Algorithm (BMCA) and the rateRatio. The first feature is used to establish which node in the network has the most accurate clock source and, hence, should be selected as GM. The rateRatio is used to compensate deviations in the clock frequencies of different nodes, by taking into account the ratio between the local clock and both the direct CM clock (to correctly compute the propagation delay in Step 2) and the GM clock (to update the internal clock correctly in Step 3).

Time synchronization requirements in IEC/IEEE 60802

Time synchronization requirements are discussed in the IEC/IEEE 60802 Joint Project both for working clock and universal clock. In the first case, the maximum deviation between a node's clock and the GM's working clock is between 100 ns and 1 µs. In addition, redundant working clock domains can be setup for the same set of devices, so that zero failover time can be achieved in case a GM node experiences a failure. In practice, redundant domains can be realized through "cold standby" or "hot standby". In both cases a node in the gPTP domain is ready to take the role as GM in case of failure of the primary GM, but only in the "hot standby" case the back-up GM shares its clock through gPTP PDUs even when the primary GM is active. The current practice suggests the use of "hot standby" backup GMs as a mean of achieving the highest synchronization availability. Hot standby will be specified by the IEEE 802.1ASm [18]amendment to IEEE 802.1AS-2020.

In case time synchronization to a universal clock is implemented, the clock is provided by an external source (e.g., Global Positioning System) to the GM and shared within, e.g., the plant via gPTP mechanisms. One possible use case for universal time synchronization is the need to record sequence of events (SOEs) [IEC/IEEE P60802] by different devices within a plant, to enable root-cause analysis and plant optimization. In this use case, a more relaxed synchronization error is allowed (up to 100 µs) and no redundant clock domain is required.

In the IEEE 802 standardization group, systems and protocols are developed for providing time synchronization within computer networks, and these standards may also be applied between UE devices, using the cellular network as a bearer.

However, rather than putting this functionality in the UE, it would be more effective if the communication features of the 5G network provided the necessary timing signals and information to allow synchronization.

3.1.2 3GPP

Time synchronization is an integral part of the 5G radio system, and it is essential for its operation. Radio network components are themselves time synchronized for advanced radio transmission, such as synchronized Time Division Duplexing (TDD) operation, cooperative multipoint transmission (CoMP) and carrier aggregation. The user equipment's (UEs) are phase synchronized to the base stations to enable orthogonal radio transmissions with minimal spectral interference.

The new capability introduced in the context of integrating a 5G System with a TSN network enables to provide a reference time delivery (of the 5G RAN internal clock) as a service to UEs over the 5G System.

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[18] https://1.ieee802.org/tsn/802-1qdj/

5G system enhancements to support gPTP

3GPP working groups conducted studies on how 5G can support industrial automation use cases together with TSN, including time synchronization. The 5G System needs to interwork with the gPTP of the connected TSN network, as gPTP is the default time synchronization solution for TSN-based industrial automation.

As shown in Figure 6, the 5G System acts as a bridge between two TSN systems. The 5G System is considered as a virtual bridge for each User Plane Function [TS20-23501], which is connected to a TSN bridge. The UPF is a gateway that interconnects the 5G system to external networks (in this case a TSN network). The 5G System connects via its 5G base stations (gNB) to wireless 5G devices (UE), which terminates the other end of the 5G virtual TSN bridge. From a time synchronization perspective, this 5G virtual bridge acts as a time-aware system as per IEEE 802.1AS.

Several alternative options to deliver the TSN timing information through the 5G System were investigated during standardization. The scenario addressed in Release 16 of the 5G standard, is that the reference time of a timing grand master (GM) is located in the TSN domain connected to the fixed side of the 5G system (i.e., “behind” the UPF) [TS20-23501]. The GM synchronizes other nodes via gPTP messages, and some of these nodes can be connected wirelessly via a UE, or through the 5G system to the network segment containing the GM. With the selected solution in the standard, the TSN timing information is delivered from NW-TT to DS-TT as gPTP messages via the 5G user plane as shown in Figure 13. This approach is scalable, builds on the established 5G security model, and is flexible in various deployments, including network sharing and the support of non-public networks.

The 5G System is modelled as an IEEE 802.1AS time-aware system for supporting TSN time synchronization as specified in [TS20-23501]. There are two synchronization processes running in parallel in an integrated 5G-TSN system: a 5G System synchronization process and a TSN synchronization process.

1. **5G System synchronization**: the 5G Grand Master provides the reference clock for 5G System-internal synchronization, so the user-plane nodes UPF, gNB and the UE are synchronized to the 5G reference clock.
2. **TSN domain synchronization**: It provides synchronization service to devices in the TSN domain. The gPTP Grand Master and the devices that are synchronized are outside the 5G System. Only the TSN translators at the edge of the 5G System track the gPTP domain. That is, only the TTs need to support IEEE 802.1AS operations, e.g. gPTP, timestamping and best master clock algorithm (BMCA).

The two synchronization processes can be considered independent from each other. For example, the gNB only needs to be synchronized to the 5G GM clock, the 5G synchronization process that guarantees RAN function is kept intact and independent from the external gPTP synchronization process. The independence of the two synchronization processes brings flexibility in time synchronization deployment, e.g., when upgrading an existing deployment. For example, if an operator has already deployed a 5G System in one area, in order to further support factories in the neighborhood with gPTP, only the UPF and UE side need additional enhancement while the overall 5G time synchronization remains untouched. Also, if 5G is added to a fixed TSN network with time synchronization, the TSN time synchronization is not modified due to the introduction of 5G.

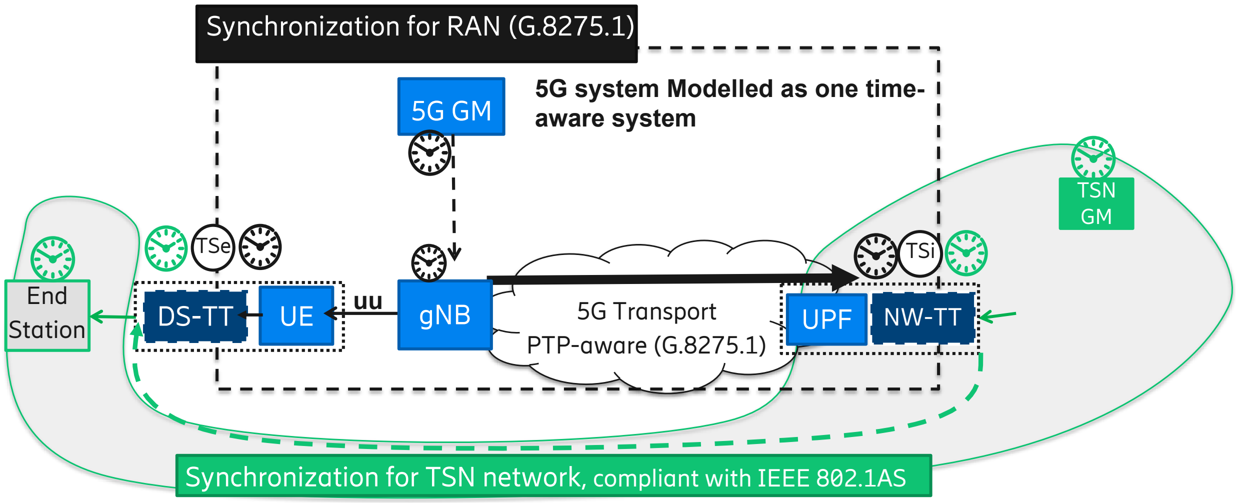


Figure 13: Synchronization of TSN across 5G System

Downlink time synchronization

For every gPTP PDU entering the 5G System at the UPF, the NW-TT entity generates ingress timestamps (TSi) based on the 5G System internal clock and embeds the timestamp in a gPTP message. The UPF forwards the gPTP message to the UE via the user plane (i.e., via a PDU session). The UE receives the gPTP message and forwards it to the DS-TT. The DS-TT then creates an egress timestamp (TSe) for the gPTP PDU of the external gPTP working domain. As the UE and UPF and their corresponding TSN translator functions DS-TT and NW-TT are time synchronized to the same 5G reference clock, the difference between TSi and TSe is considered as the calculated residence time that the given gPTP message has spent within the 5G System. The DS-TT modifies the TSN timing information received from gPTP messages based on the calculated 5G System residence time and sends it towards the next time-aware system. As the gPTP messages are transmitted via the user plane path of the 5G System, they are subject to the security mechanisms that 3GPP has specified, like encryption and integrity protection.

Support for multiple working clock domains

Considering smart manufacturing scenario, multiple gPTP domains can coexist in a single shared communication network infrastructure, where each gPTP domain consists of the commonly managed industrial automation devices, which can have a common timescale [IEC/IEEE P60802]. According to the ongoing standardization [IEC/IEEE P60802], the minimum number of domains that a TSN industrial equipment needs to support depends on its device class. A constrained (currently called Class B) device has to support at least two gPTP domains: one working clock domain and one universal time domain. Working clock domain contain primary timescale utilized within TSN domain whereas universal time domain can contain global traceable timescale. For redundancy, a feature rich device (currently called Class A) has to support at least two of each time domains, i.e., at least four gPTP domains altogether. 3GPP requires the 5G System in Release 16 to support networks with up to 32 working clock domains [TS20-23501]. A gPTP working clock domain is characterized with a specific domain number in the gPTP PDUs. To support multiple gPTP domains in the 5G System, as shown in Figure 14, the NW-TT generates an ingress timestamp for every gPTP message carrying a specific domain number (where the domain number indicates a specific gPTP domain).

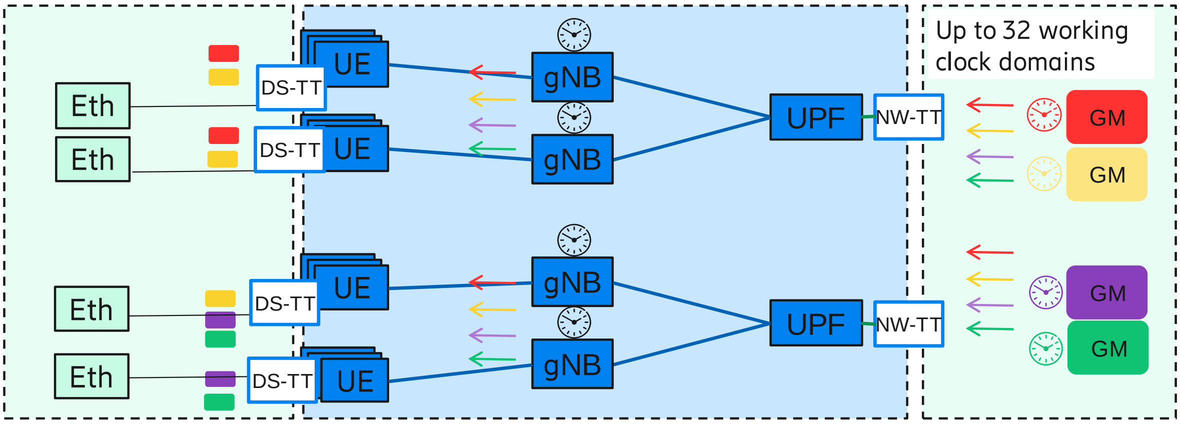


Figure 14: Illustration of multiple gPTP working clock domains

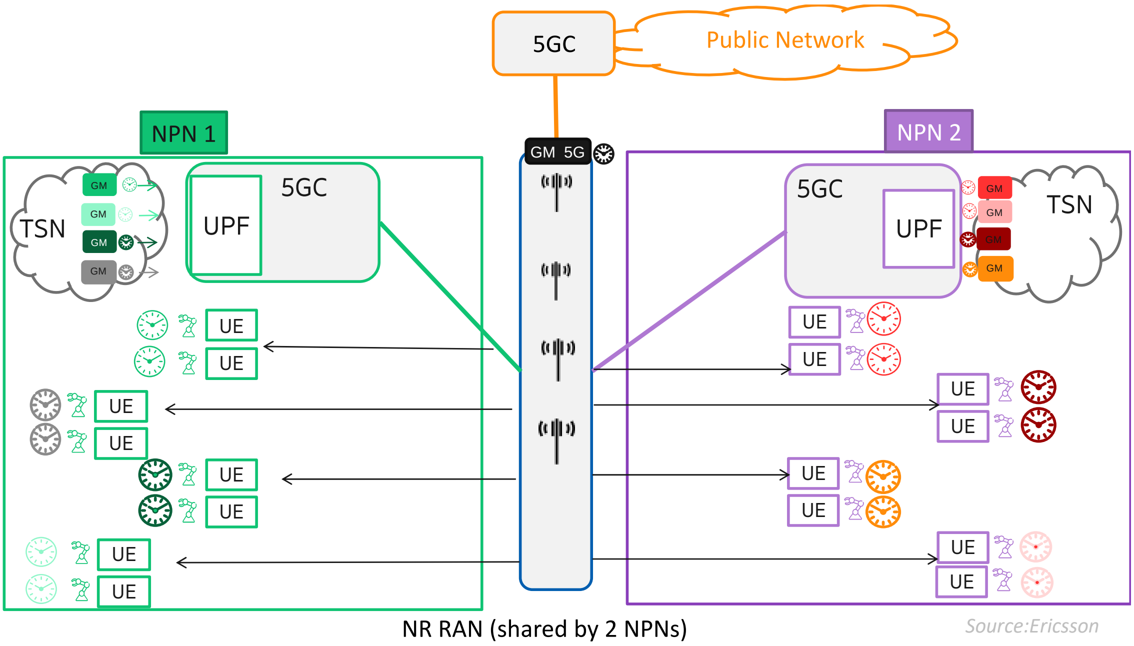
A UE receives gPTP messages and forwards them all to the DS-TT. The DS-TT receives the original gPTP clock timing information and the corresponding TSi via gPTP messages for one or more working domains. The DS-TT generates TSe for the gPTP PDUs for every external gPTP working domain. Ingress and egress time stamping are based on the 5G system clock to which the NW-TT and DS-TT are synchronized. An end station can select timing information of interest based on the domain number in the gPTP PDU.

A special case that is supported by the 5G System, where 5G System clock acts as a general grandmaster and provides the time reference not only within the 5G System, but also to the rest of the devices in the deployment, including connected TSN bridges and end stations, where the time domains are merged into one common single time domain.

Support for non-public networks and RAN sharing

3GPP defines Non-Public Networks (NPN) for industrial IoT in which the access to the NPN is restricted to a private group of authorized devices. There are two variants of NPN. A standalone NPN is a dedicated and isolated 5G network deployment for a private entity, like a factory. A public network integrated NPN is a private network that is partly sharing communication infrastructure with a public network.

It is also possible to share a common infrastructure for multiple NPNs. Considering a scenario when multiple companies are located in an industry park, which provides common facilities to its enterprise tenants. Each company can use a dedicated 5G NPN, where the core network nodes are deployed in the company premises and connected to, e.g., its local TSN infrastructure. In such a case, a common 5G RAN can be used in the entire industry park in order to provide good coverage and capacity, meanwhile prohibiting interference and coexistence challenges of multiple local RANs within close vicinity. This RAN is shared among the multiple NPNs, but the NPNs are logically separated and capacity reservations can be provided per NPN. Each NPN can have its own working clock domains, which remain isolated, even if a shared RAN is used, as depicted in Figure 15. The proposed solution is not limited in the number of working domains that are supported, which means that each NPN can support multiple working domains independently without limitations of the 5G System.



Source:Ericsson

Figure 15 Time synchronization in two NPNs with a shared RAN

5G reference time delivery method over Radio Access Network (RAN)

An 5G System supports an internal 5G clock which can be based on the very accurate and stable clock source. The timing information distributed throughout the 5G network as needed, including delivery to gNBs and UEs as reference time information.

Time reference delivery over the RAN from the gNB to UE is essential component in end-to-end time synchronization solution over 5G. gNB acquires a reference time value from the clock, gNB project the time at the antennas reference points (ARP) for a system frame. Further gNB transmits to the UE the time reference at the end of a certain System Frame Number (SFN) as shown in Figure 16. This transmission can be periodic broadcast of a system information block (SIB) or can be unicast message. Now UE knows the reference time valid at the end of the SFN.

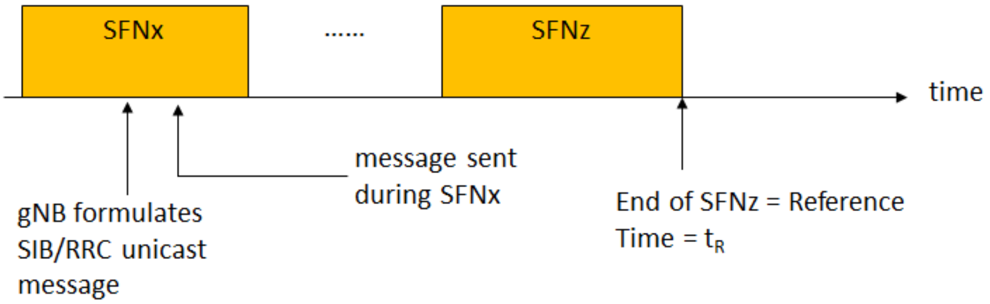


Figure 16 gNB SFN transmission

Enabling time synchronization between gNB and UE in RAN, below are the main aspects to be considered when considering accuracy of the time accuracy budget [AMD+19]:

1. Mitigation of the propagation delay between UE and gNB.
2. Base station related time alignment error.
3. RF channel dynamics.
4. Device related time adjustment error.

3.1.3 ITU-T's role in time and phase synchronization

The following section details the various ITU-T standards associated with timing and synchronization. The list of ITU-T recommendations presented in this section is non-exhaustive. It is a representative of the standards, which are either consented or under consent. It contributes to the transport and distribution of timing over mobile networks, notably transport networks.

In general, 3GPP and ITU-T play a key role to determine and develop network synchronization solutions and architectures. While 3GPP defines the time synchronization requirements, ITU-T develops solutions and architectures based on these requirements. ITU-T has defined synchronization as the process of delivering a 'common reference' (in frequency and/or in time/phase) to the mobile base stations within a given accuracy and stability.

Generally speaking, every base station is equipped with a Local Oscillator (LO). This is common for all the era of technology (e.g. 2G, 3G, 4G, etc.). These LOs, which are present in the base stations, must be locked to a particular reference frequency in order for the base stations to be synchronized to each other. What changes over time is the accuracy and stability with which these LOs must be locked, so that the base station complies to deliver the features as per Table 2.

Application	**Time/ phase requirement**	**Why you need to comply**	**Impact of non-compliance**
LTE (FDD) / NR (FDD)	N/A	Call initiation	Call interference and dropped calls
LTE (TDD) /NR (TDD)	±1.5	Time Slot alignment	Packet Loss/collision and spectral inefficiency
LTE-A eICIC	±1.5 to ±5µs	Interference coordination	Spectral inefficiency and service degradation
LTE-A (TDD or FDD) CoMP/MU-MIMO	± 500 ns (Note: this is not standardized by 3GPP)	Coordination of signals to/from multiple base stations	Poor signal quality at the edge of cells
LTE-A MBSFN (TDD or FDD)	±500 ns	Proper alignment of video signal encoding from multiple e-NBs	Video broadcast interruption

Table 2: LTE and NR requirements set by [3GPP20-36133] [3GPP19-36104] [3GPP20-38133] [3GPP19-38104]

Thus, from above, synchronization refers to the following three modes of operation:

Frequency synchronization (also called "syntonization") means equipment (gNBs) A and B receive a common reference signal within a given accuracy and stability, but significant instants of the signal need not be aligned in phase or time.

Phase synchronization means equipment (gNB) A and B receive a common reference signal and significant instants must be aligned in phase within a given accuracy and stability, but are not necessarily traceable to a common time scale (for example, Coordinated Universal Time (UTC)).

Time synchronization means equipment (gNB) A and B receive a common reference signal carrying a time information and with significant instants aligned in time as well as are in-phase to each other with a known traceable reference clock (e.g. UTC, etc.).

Synchronization in Frequency

3G mobile generation necessitated base stations to be synchronized only in frequency. That is, the application requirements (for instance detection of frame timing, cell acquisition) for 3G technology required simply maintaining consistency between the 'frequencies' of several clock signals. This ensured that all the base stations are synchronized. This had to be done via a common physical frequency reference (common reference rhythm). This method of synchronizing cellular networks is referred to as 'Frequency synchronization' or otherwise, 'syntonization'.

Synchronous Ethernet (SyncE) technology [JSMMLSS+08] emerged out as a means to synchronize 3G base stations. SyncE is a physical layer technology. It allows recovering the clock from the code stream on the Ethernet link. As Ethernet is an asynchronous system, it cannot function properly without a high-precision clock. Consequently, most Ethernet devices do not provide high-precision clocks. With the use of SyncE over Ethernet equipment, a common frequency reference is delivered to 3G base stations and therefore synchronization is achieved. This turned-out to be very fundamental not only for 3G, but also for 3.5G and even for 4G LTE-FDD networks. Several standards (ITU-T Recommendation G.8261 [ITU08-G82861], ITU-T Recommendation G.8262 [ITU07-G8262], ITU-T Recommendation G.8264 [ITU08-G8264]) were quickly developed to roll-out the rapid deployment of SyncE over operator networks. These recommendations primarily focused on the architecture, clock quality, protection switching, etc.

Advantages and Disadvantages of SyncE Technology: On a positive side, the performance of syntonization provided by SyncE is affected neither by network load nor by length of the network chain. On the other hand, in order to deploy SyncE, every node in the network must be enabled with SyncE. This directly results in Capital Expenditure (CAPEX) for operators; however, this has become now a generally supported function. It should be noted that SyncE technology is restricted to deliver frequency synchronization. This implies that, to satisfy the time synchronization needs of accuracy requirements of LTE-A, 4G+ and 5G Systems, PTP must also be used. The performance of phase/time synchronization could be enhanced by SyncE (explained below).

Synchronization in Phase and Time

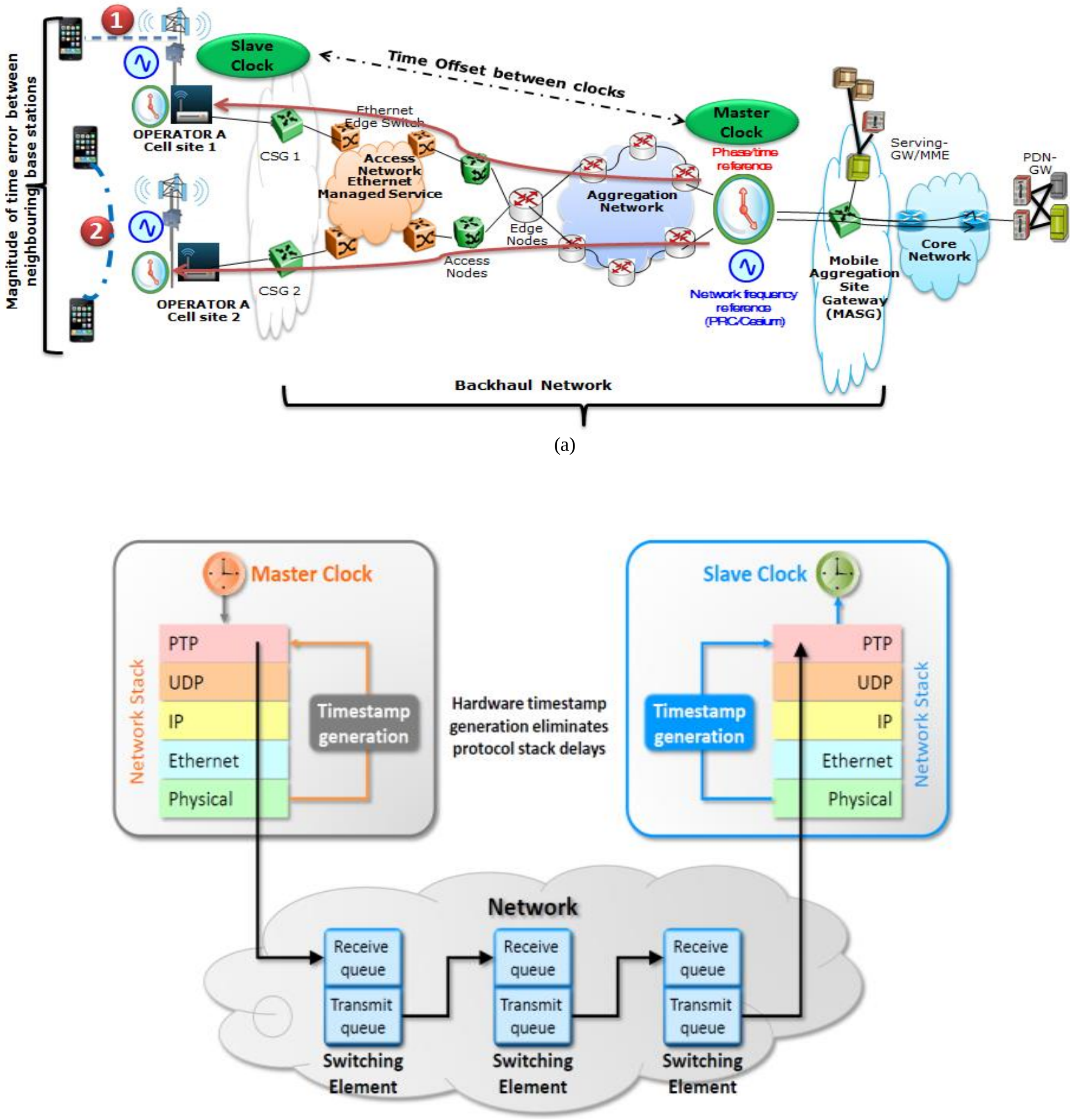
In recent times, the need for more accuracy between base stations has been observed. This is due to the result of the mobile access technology evolution (Please refer to Table 2). Here in addition to transmitting a common frequency reference, an accurate phase/time reference signal is also needed to be maintained between neighboring gNBs.

For any of the features from Table 2 to be rolled-out in live network, synchronization accuracy in the order of at least ±5 µs is required, i.e., the magnitude of the error tolerated by neighboring base stations should be ±1.5 µs.. Without any doubt, this is very stringent compared to what is delivered by SyncE in the frequency domain. This implies new methods and solutions to design the synchronization network. This gave birth to phase/time synchronization; the process of maintaining two or more carrier frequency signals from different gNBs aligned in time as well as in-phase in order to guarantee performance.

While Global Position system (GPS) or Global Navigation Satellite System (GNSS) topped as a clear choice, it found its limitations within the operator community. Even though this is considered as the simplest of all the solutions, it has its own set of drawbacks. Some of them include the management and cost of deploying GPS receiver antennas across every base station, installation issues (sky visibility, indoor deployment), risk of jamming (intentional or accidental), etc.

This resulted in protocol-based technology capable of supplying the level of accuracy demanded by the 4G LTE applications. Among others, Network Time Protocol (NTP) and IEEE 1588 [IEEE08-1588] are two widely assuring time keeping methods. These two are standardized to date, but deployment is in progress. NTP, (even NTP version 4) did not meet the high precision requirements for cellular networks, particularly the requirements detailed in Table 2. IEEE 1588-2008 or PTP version 2 (PTPv2) emerged as an alternative effort to offer even higher clock synchronization accuracy to deploy the next generation networks. The IEEE 1588 standard specified PTPv2 to synchronize independent clocks running on individual nodes of a distributed system. It was then adapted and developed for LTE networks by ITU-T study Group 15 in order to distribute phase/time [ITU15-8275] to offer timing accuracy of up to ±1.5 µs.

In its basic form, PTPv2 protocol behavior can be characterized as Master-and-Slave behaviors shown in Figure 17. While the slave clock is always embedded in the eNBs, the master clock could be placed anywhere in the network (pre-aggregation, aggregation, core) based on operators needs and strategies. The basic PTP dialog is based on the message exchanges containing timestamps sent from master to slave. The slave clock, with the information gained through this message exchange, updates its internal clock’s time accordingly to maintain tight synchronization with the master clock. The disapproval of GNSS based systems and the need to rapidly roll-out 4G services to end customers lead to very strong interest and push towards the development of PTPv2 in ITU-T. Several standards and recommendations (ITU-T Recommendation G. 8275, G.8275.1 [ITU15-8275], have emerge over a very short time span, which makes this protocol find its way within the operator networks.



(a)

(b)

Figure 17 a). Illustration of synchronizing two wireless base station, where (1) indicates the need for synchronization of a single base station for Radio Framing Accuracy and (2) indicates the need for synchronization of two base stations to perform Handover between them, 19(b) Illustration of Master-Slave message exchanges for phase/time synchronization in mobile backhaul between the Master clock node and Slave clock node using PTPv2.

Advantages and Disadvantages of PTPv2 Technology: Some known advantages of PTP are that it uses IP over Ethernet for network connectivity. It takes advantage of the existing Ethernet networks deployed by operators and thus allows considerable reuse of in-place hardware and cabling, facilitating to reduce costs for physical deployment. Another major takeaway is that PTP eliminates

Ethernet latency and jitter issues through hardware time stamping to cancel out a measured delay between nodes at the physical layer of the network. This enables to achieve accuracy in the range of ±1 to ±5 microseconds. While not a major disadvantage, it can be noted that PTPv2 performs best only when all the network nodes are upgraded, implying increased cost for operators. Another setback is that the performance of PTPv2 reduces when the size of the network topology increases.

Evolution of ITU-T standards, in the context of 5G

Thus far, new requirement for 4G+, 5G from 3GPP has pushed ITU-T to develop new standards or modify/enhance existing standards. At the time of writing this document, there are several new recommendations, which have been recently released in ITU-T. These include the specification of new synchronization equipment such as enhanced primary reference time clock (ePRTC) [ITU15-8272], enhanced primary reference clock (ePRC) [ITU17-G811], eEEC [TU19-G8262], T-BC Class C. Others are still under progress (e.g., definition of new network limits in G.8261 and G.8271.1 revisions). The goal is to meet more both the TDD needs (+/-1.5 us) and to meet the relative time error of 260 ns (or 130 ns in case of co-located radio equipment) required by some radio coordination feature, through the combination of that new equipment in the network.

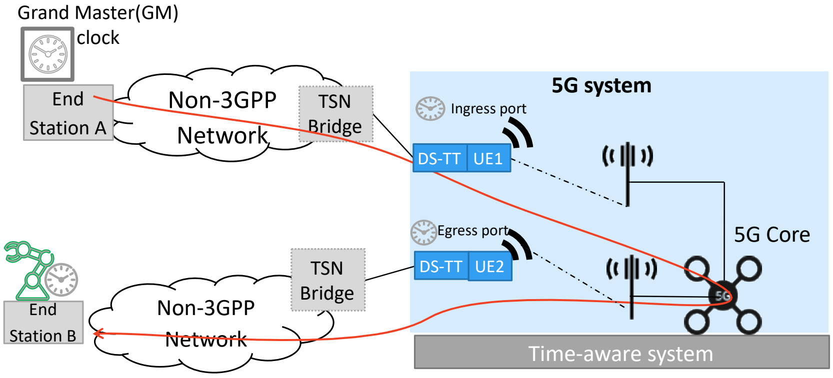
3.2 Gap analysis

Considering end-to-end time synchronization, this section provides insights into the main gaps identified by the 5G-SMART project.

3.2.1 Arbitrary placement of the Master clock in 5G-TSN architecture

Considering 5G deployment in smart manufacturing use cases, there is possibility of the having GM clock connected wirelessly to the system. Considering such a scenario, gPTP GM clock when connected to network via UE, 5G System must support TSN time distribution both in uplink (UE-to-UPF) as shown in Figure 18 and to other direction (UE-to-UE) as illustrated in Figure 19. With the current specification from 3GPP release 16, TSN time distribution is only supported in the downlink direction (UPF-to-UE).

UE-to-UE time synchronization imposes more stringent accuracy requirement on the synchronization performance as two radio links are involved thereby doubling the radio propagation.



Source:Ericsson

Figure 18 UE to UE time synchronization

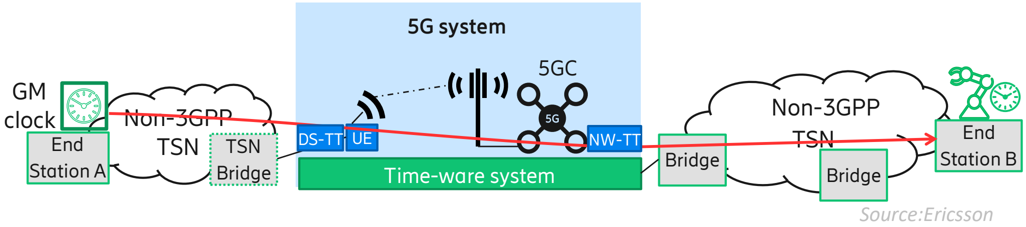


Figure 19 TSN Grand Master clock attached to UE

3.2.2 5G system’s contribution to the end-to-end synchronization accuracy

When integrating 5G in a TSN network, it is important to know the maximum timing error that the 5G System may introduce when delivering timing information, or in other words, the contribution of the 5G System to the end-to-end synchronization accuracy. This is illustrated in Figure 20.

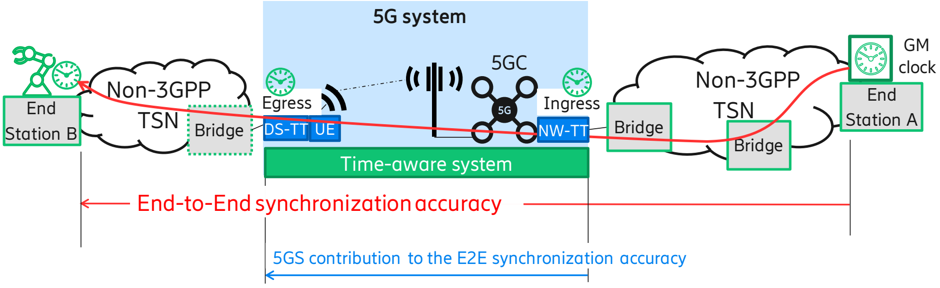


Figure 20 Contribution of the 5G System to the E2E synchronization accuracy

To determine how much of the total end-to-end time synchronization budget may be consumed by the 5G System, assumptions need to be made as to how many hops (e.g. time-aware relays in case of IEEE 802.1AS) may be present outside the 5G System. This is done assuming the required end-to-end synchronization accuracy for the most demanding use cases, i.e. <1 µs.

As described in section 2, the 5G System is modelled as a single time-aware system (or virtual bridge). As such, the 5G System can replace many hops of a wired network with a single-hop wireless connection (as seen by the TSN network) that can reach any part of the factory.

To understand how many hops may be present outside the 5G System, we break down the problem into three main segments.

GM clock to 5G network ingress (network side)

The NW-TT function can be placed anywhere in the factory, including next to the GM clock. If multiple GM clocks are present in the factory (e.g. a universal clock and one or more working clocks), then multiple NW-TT instances can be deployed in the factory and placed close to the relevant GM clock.

It is therefore reasonable to assume that there will be no more than two hops between a GM clock in the TSN network outside the 5G System and the nearest NW-TT instance.

UE to end station

It is unlikely that a large network is connected behind a single UE. If multiple end devices are connected to a UE, they are likely to be in close proximity to the UE and connected through a single bridge.

Considering a very large machine comprising many devices that need to be synchronized with each other (e.g., a large digging machine), a local working clock domain would likely be defined, with a local GM clock. If any time synchronization with the "outside world" would be needed, it would likely be a global clock with coarser precision, or at least without any tight synchronization with the local working clock of the machine. Alternatively, multiple UEs could be used to connect different parts of a large machine.

It can therefore be assumed that there will be no more than two hops between the UE (DS-TT) and any end device connected to it.

GM clock to UE

When the GM clock is on the UE side, the UE can be placed as close as necessary to the GM clock. Potentially, the UE itself could be the sync master. It can therefore reasonably be assumed that there will be at most one hop between the GM clock and the UE.

Resulting time synchronization budget for the 5G system

Summing up the different cases described above, it can reasonably be assumed that a properly engineered solution integrating a 5G System into a TSN network can and should be designed so that the sync messages exchanged between a GM and any end station cross at most four hops outside the 5G System (when the 5G System is in the path).

Assuming each of the four hops implements a ITU-T rec. G.8273.2 class C clock (i.e., with ±10 ns constant time error accumulating linearly and +/- 5 ns dynamic time error accumulating as root mean square (RMS) and a total of six links (three on each side of the 5G System) contributing 5 ns each, the resulting time error introduced by components outside the 5G System should be at most 80 ns. This translates into a time synchronization budget for the 5G System of ≤920 ns (1 µs end-to-end synchronization budget – 80 ns, allowing for some extra margin, a maximum time error of ≤900 ns constitutes a reasonable target for the time synchronization budget of the 5G System).

3.3 Recommendation towards standardization bodies and industrial fora

As discussed in the previous section, there are several SDOs which are involved in the development of network synchronization and time distribution performance. Among these, 3GPP defines requirements for current and future timing and synchronization and also mechanism to enable 5G System as time aware system. On the other hand, the ITU-T Study Group 15 (SG15) is very actively involved in the development of the recommendations of solutions and architectures addressing the current and future timing and synchronization requirements (defined by 3GPP).

In this context, there are major development activities, which are ongoing targeting the study on 5G Phase II synchronization requirements. The time synchronization budget allocated to the 5G System is a major open question in 3GPP. That is, how much of the total end-to-end clock synchronicity budget in the most demanding case, i.e. 1 µs, may be consumed by the 5G System.

Industry 4.0 use cases which are based on enablers such as geo-location, indoor positioning, etc. are typical example use cases in this category. In the context of 5G-SMART project, there are proposals about typical use cases.

In this regard, enhanced solutions and architectures to transport high accuracy such as the ePRTC equipment, Telecom Boundary Clocks (T-BCs) equipment, that generate low time error (such as T-BC class C, T-BC class D) are under development. Hypothetical Reference Models (HRMs) representing how a target accuracy could be achieved and delivered for the use cases described above is also very actively under discussions.

Towards this end, there are contributions which are submitted regularly to ITU-T (SG15) standard meetings from 5G-SMART partners who are actively participating (notably Orange). Contributions are most notably submitted for the development of ITU-T recommendations series G.8272, G.8272.1, G.8275, G.8273.2, and G.8271. The above said ITU-T recommendations deal with how timing could be transported over mobile transport networks to the end-applications. The end-applications here could refer to a mobile base station (eNB, gNB, etc.) or robots/machines inside an industrial campus. In a way, this is directly related to the on-going studies within the context of 5G-SMART project, as most of the use cases identified in WP1 require proper timing and synchronization to be able to work (either in a WAN environment or in a LAN environment). In particular, technical contributions most notably were submitted in order to advance the progress on (i) Telecom Boundary Clocks (T-BC class C and T-BC class D). These are PTP enabled equipment that would enable to transport timing packets. (ii) Developing and designing the number of transport network hops inside and outside the 5G System that would enable to properly transport timing packets, (iii) Error accumulation that could be tolerated when PTP packets are transported over transport equipment, namely constant time error and dynamic error. What is not covered by these ITU-T recommendations so far is how to synchronize an end-application over-the-air (OTA). This is considered as out-of-scope of ITU-T SG15 at the time of writing this deliverable, since it is covered by 3GPP as described above. However, ITU-T SG15 plans to contribute towards this aspect as well in future.

In conclusion, contributions to SDOs play a very crucial role; especially at this point of time since today the need to deploy Industrial IoT applications are becoming more and more important and urgent. In the context of 5G-SMART project, various use cases have been identified (in WP1). The corresponding requirements (from timing and sync point of view) are being studied and being pushed into SDOs regularly to be standardized (now on-going). Once there is a decision on the standardized values, this will then allow defining synchronization architectures based on technical solutions which are contributed (described above). Based on the identified gaps for 5G-TSN time synchronization aspect, realization options of the such solution by utilizing 5G System internal clock for integrated 5G-TSN system is provided as contribution to 5G-ACIA.

4 5G positioning techniques

Positioning is foreseen as an important feature for advanced manufacturing applications such as personnel tracking, safety (e.g. when working close to mobile robots), location of manufacturing tools, and tracking of manufacturing goods. The required accuracy for positioning and the environment can vary significantly between use cases. Most of the manufacturing applications are realized in indoor or indoor-like environments, which makes global navigation satellite system(GNSS) based solutions difficult to utilize because of very low signal strength levels received indoors from satellite transmission, resulting in bad or no coverage.

In this section, time-of-arrival (ToA) based positioning algorithms are discussed as well as the impact of time synchronization errors on the positioning accuracy. It will be shown that the positioning time synchronization requirements are much tighter than requirements of other features, such as carrier aggregation and coordinated multi-point transmission/reception. Finally, network synchronization improvement features and alternative positioning methods not relying on accurate network synchronization are discussed. Time synchronization among the base stations is crucial for positioning methods based on ToA measurements.

4.1 Background

The use of radio-frequency signals to perform positioning (but also mapping) is well known. A lot of methods exist for positioning purpose, which are generally based on measurements of reference signals. It is possible to use signal power level or signal phase (fingerprinting or pattern recognition), time dimension (Round Trip Time (RTT), TOA (trilateration), TDOA (multilateration) see Figure 21), angle dimension (AOA (triangulation), AOD, ZOD).

4.1.1 Time-difference-of-arrival (TDOA) based positioning and network synchronization

The basic ToA-based positioning method is described here in terms of observed time-difference-of-arrival (OTDoA), also called downlink-TDoA (DL-TDoA), where the ToA is measured in the downlink. The UE receives positioning reference signals from neighboring gNBs, estimates ToA for each gNB using reference signal time difference (RSTD) measurements, and reports the TDoA with respect to a reference cell. Afterwards, the evolved serving mobile location center (E-SMLC) estimates the position of the UE based on the known gNB positions. TDoA (that is, time difference with respect to a reference cell) is used instead of ToA, because this removes the time synchronization requirement of the UE with the network, although the network, i.e., the base stations, needs to be synchronized. By principle, a minimum of three gNBs are required for 2D positioning and a minimum of four gNBs are required for 3D positioning.

Figure 21 illustrates how the horizontal (2D) UE position can be estimated from three gNBs by the TDoA principle. The UE position is the intersection of hyperbolas, where each hyperbola represents one TDoA estimate. In practice, the position is estimated by the E-SMLC using Gauss-Newton search or similar numerical algorithms. A timing uncertainty between the gNBs corresponds to an uncertainty when determining the hyperbolas, which has been conceptually marked with yellow color in the figure. Given the synchronization uncertainties, the estimated UE position can be anywhere within the parallelogram drawn around the actual UE.

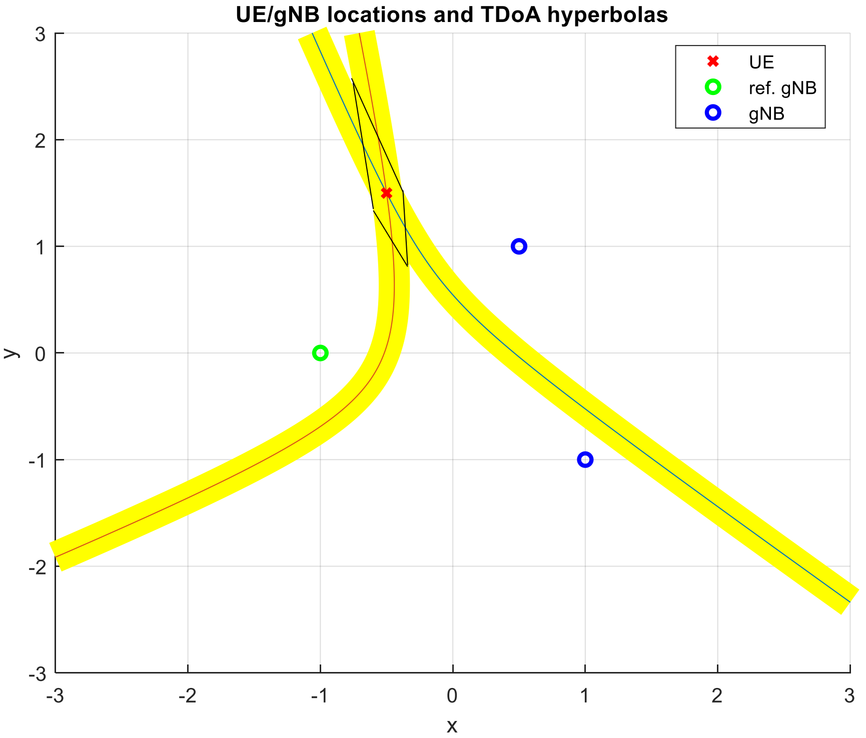


Figure 21: Conceptual plot of 2D TDoA-based positioning. Each TDoA (ToA of reference gNB minus ToA of gNB) translates into a difference in distance when multiplied by the speed of light. Each TDoA measurement returns a hyperbola on the 2D plane of possible UE positions. The intersection of such hyperbolas gives the UE position. The yellow marking corresponds to synchronization uncertainty.

TDoA-based positioning can also be implemented with uplink measurements, e.g. based on sounding reference signals (SRS), and is then called uplink TDoA (UTDoA). As UTDoA is also TDoA-based, accurate network synchronization is required. One advantage of UTDoA compared to OTDoA (downlink) is related to the time stamping accuracy, which in turn affects the time measurement accuracy. Time stamping accuracy depends on clock frequency and clock drift in the hardware. For OTDoA, the ToA is measured at the UE, which typically gives worse performance than measurements at the gNB. If measurements are performed at separate occasions, time drift between measurements becomes an additional source of error. Hence, for high accuracy, UTDoA is preferred over OTDoA.

As shown in Figure 21 each TDoA measurement translates into a difference in distance, resulting in a hyperbola, when multiplied by the speed of light. If the timing error between the gNB's is X nanoseconds (ns), this can in principle be translated to a positioning error component of approximately $3*10^{8} * X * 10^{-9}$ m = X * 0.3 m. It should however be noted that this is just one of the error components. The actual positioning accuracy will depend on a number of other factors as well, such as the positioning method used, the gNB deployment, the propagation environment, etc.

A promising alternative to improve the "virtual" network synchronization and the positioning accuracy is over-the-air radio measurements, for example using a feature called radio-interface based monitoring (RIBM). This solution is based on base station timing measurements of positioning reference signals from neighboring base stations, and it estimates the synchronization offset between base stations so that virtual synchronization with much better accuracy can be provided. The synchronization errors must be communicated to the positioning server that takes the errors into account when calculating the position. The measurements have thus not improved the actual synchronization of the network, but the impact on the positioning calculations has been removed.

4.1.2 Alternative positioning solutions not requiring network synchronization

As very accurate network synchronization is difficult and costly to achieve, positioning techniques that do not require network synchronization, e.g. techniques based on the round-trip time (RTT) and/or angle of arrival (AoA) measurements, can be considered. Such methods can be used either on their own or in combination with the TDoA-based methods.

Using the AoA measurements from at least two base stations, the location of the UE can be estimated using triangulation. An accurate estimate of the AoA can be realized in the uplink provided that the amplitude and phase of an uplink signal, for example, the sounding reference signal (SRS), are available for each antenna element or group of antenna elements. At least three channel measurements are needed from antenna elements in two directions. AoA measurements are thus possible for antenna arrays using digital beamforming or hybrid beamforming.

In RTT-based positioning, the time-of-flight from the base station to the UE and back to the base station again is measured. There are also variants where the RTT measurements is initialized by the UE. RTT measurements between a UE and at least three different base stations can be used to determine the UE position using triangulation in a similar way as in the case of ToA measurements. The main advantage of RTT measurements is that it is not dependent on accurate synchronization between the base stations. Different base stations will however initiate RTT measurements consecutively (at different time instants) and the Rx-Tx delay at the UE might not be identical for different measurements, which will decrease the positioning accuracy. There are two types of RTT measurements in LTE and 5G NR, one based on the random-access procedure and the other based on the Reception and Reception and Transmission (Rx-Tx) time difference measurements performed by the UE. However, the standardization for the UE Rx-Tx time difference is not finalized yet and it is unclear what will be the measurement accuracy requirements.

By combining AoA measurements with power measurements (e.g. reference signal received power, Reference Signal Receive Power) (RSRP), etc.) or RTT measurements, a position can be estimated using only measurements from one base station. This can be advantageous in environments with lots of clutter and machinery, where the requirement of line-of-sight to at least four base stations may require a very dense deployment. If measurements from several base stations are available, the extra information can be used to enhance the precision and/or reliability of the position estimate.

4.2 State-of-the-art analysis

The section provides positioning techniques description.

4.2.1 Overview

The GSM standard prior to 3GPP already included E-OTD (Enhanced Observed Time Difference) in the standards, where time difference of arrival of signals from two different base stations is measured. This gave around 100 m accuracy using GSM networks and was the basis of Cambridge Positioning

Systems' business in the late 1990's and 2000's. As a result, 3GPP Release 5 (2002) already included E-OTD, OTDOA and UTDOA, including novel techniques like Idle Period Downlink (IPDL) to solve the hearability problem of CSMA networks. Assisted GPS (A-GPS) was also introduced at that stage. In parallel, open mobile alliance (OMA) introduced the first version of secure user plane location (SUPL) (~2004), which included E-OTD and A-GPS. 3GPP Release 9 (2010) was the point at which an updated set of joined up positioning specifications and protocols was harmonized.

Positioning solutions standardized in 3GPP can be broadly classified as Radio Access Technology (RAT)-dependent and RAT-independent methods. A brief summary of standardized positioning methods in 3GPP are listed in the Table 3 below.

1. RAT-dependent: include Cell ID (CID), enhanced Cell ID (E-CID), OTDOA, UTDOA, Radio Frequency Position Location (RFPM).
2. RAT-independent: incl. A-GNSS, Terrestrial Beacon Systems (TBS), WLAN, Bluetooth, Barometric Pressure sensor, GNSS RTK/SSR.

These positioning methods are broadly categorized as either UE-assisted, in which the network and external application obtain the position in order to track the whereabouts of the UE, or UE-based, in which the UE computes its own position for the purpose of navigation and guidance. Table 3 below indicates which of the versions are supported in the NR positioning specification 3GPP [3GPP20-TS38305].

Method	UE-based	UE-assisted, Location Management Function (LMF)	NG-RAN node assisted	SUPL
A-GNSS	Yes	Yes	No	Yes (UE-based and UE-assisted)
OTDOA Note1, Note 2	No	Yes	No	Yes (UE-assisted)
E-CID Note 4	No	Yes	Yes	Yes for E-UTRA (UE-assisted)
Sensor	Yes	Yes	No	No
WLAN	Yes	Yes	No	Yes
Bluetooth	No	Yes	No	No
Terrestrial Beacon Systems (TBS) Note 5	Yes	Yes	No	Yes (MBS)
DL-TDOA	Yes	Yes	No	No
Downlink angle of departure (DL-AoD)	Yes	Yes	No	No
Multi-RTT	No	Yes	Yes	No
NR E-CID	No	Yes	FFS	No
UL-TDOA	No	No	Yes	No
UL-AoA	No	No	Yes	No

NOTE 1: This includes TBS positioning based on Position Reference Signal (PRS) signals.
NOTE 2: In this version of the specification only OTDOA based on LTE signals is supported.
NOTE 4: This includes Cell-ID for NR method.
NOTE 5: In this version of the specification only for TBS positioning based on MBS signals.

Table 3 3GPP standardised positioning methods. Table reproduced from [3GPP20-TS38305] (Table 4.3.1-1).

While the main driver for location-based services has been demanded from regulatory authorities, today, several public and private companies including hardware and equipment manufacturers, space agencies, and mobile network operators are pushing for the delivery of higher accuracy and precision by cellular location services to enable a new generation of commercially motivated location-based services. As a result, 3GPP are taking a fresh look at the application space and performance requirements for cellular positioning in 3GPP Release 16 and Release 17.

This includes a study item (SI) on 5G Positioning Use Case carried out in 3GPP SA1 group in Release 16, which has identified new requirements for 5G positioning services, as well as a broad range of use cases that stand to benefit from improved high precision positioning services, including industry, asset tracking, automotive, traffic management, smart cities, shared bikes, hospitals, unmanned Aerial vehicles (UAVs), public services, augmented reality (AR), and consumer and professional wearables. The SI was completed in March 2018.

Overall, 5G technology aims to offer a variety of cellular-based and hybrid positioning services delivering both absolute and relative positioning, depending on the needs of each specific use case.

4.2.2 UE Positioning Architecture

Figure 22 shows the architecture in Evolved Packet System (EPS) applicable to positioning of a UE with E-UTRAN access, per 3GPP TS36.305. Brief descriptions of the functionality of each entity is as follows:

1. The Mobility Management Entity (MME) receives a request for some location service associated with a particular target UE from another entity (e.g., Gateway Mobile Location Centre (GMLC) or UE) or the MME itself decides to initiate some location service on behalf of a particular target UE (e.g., for an IMS emergency call from the UE) as described in [3GPP19-TS23271]
2. The MME then sends a location services request to an Evolved Serving Mobile Location Centre (E-SMLC)
3. The E-SMLC processes the location services request which may include transferring assistance data to the target UE to assist with UE-based and/or UE-assisted positioning and/or may include positioning of the target UE
4. For the uplink method, the E-SMLC processes the location services request which includes transferring configuration data to the selected Location Measurement Unit (LMU)(s)
5. The E-SMLC then returns the result of the location service back to the MME (e.g., a position estimate for the UE and/or an indication of any assistance data transferred to the UE)
6. In the case of a location service requested by an entity other than the MME (e.g., UE or E-SMLC), the MME returns the location service result to this entity

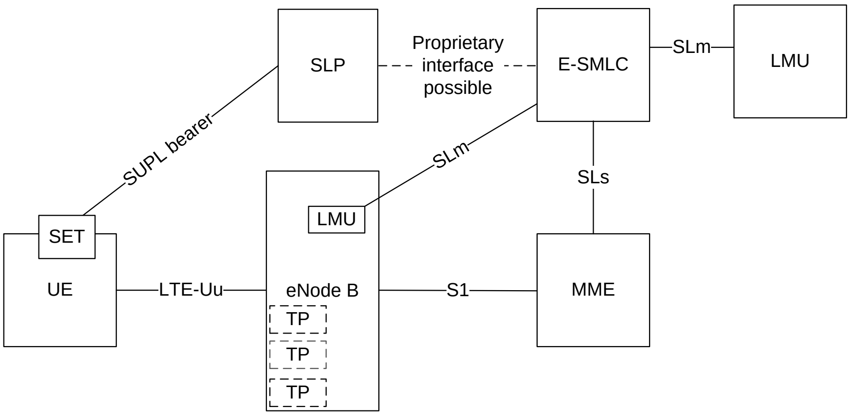


Figure 22 UE Positioning Architecture applicable to E-UTRAN [3GPP20-TS36305]

In the context of NR-RAN, different architecture solutions for the support of location management functionality in NG-RAN have been discussed in 3GPP SA2 are captured in [3GPP19-24731]. Below is an example of supporting location management functionality in NG-RAN, which involves a location management component (LMC) in NG-RAN.

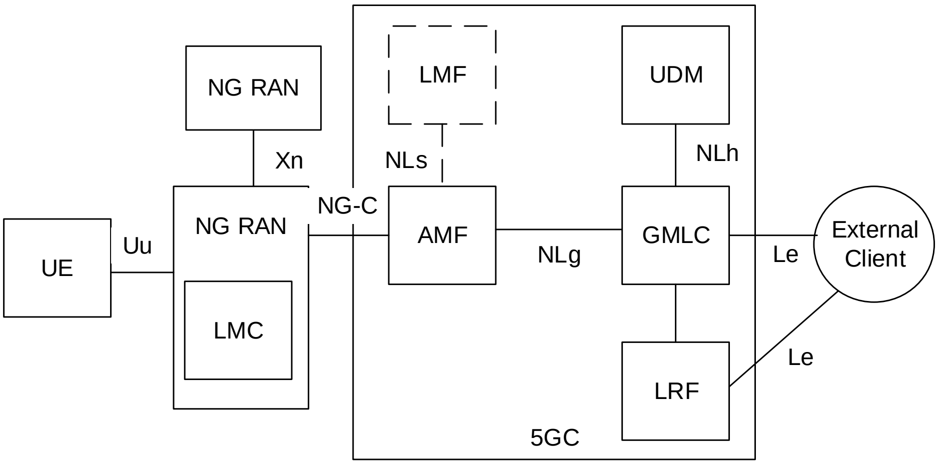


Figure 23 Local location services architecture [3GPP19-24731]

From RAN perspective the support of location management functionality in NG-RAN impacts:

1. NG-C interface: signalling between NG-RAN and Access and Mobility management functions (AMF).
2. Protocol/signalling between NG-RAN and UE.
3. Protocol/signalling between NG-RANs.
4. Architecture of location management component within NG-RAN.

4.2.3 Positioning in NR

The introduction of 5G NR technology in Release 15 has opened doors for a wide range of location capabilities:

1. New operating frequency bands (Frequency Range 1 (FR1) and Frequency Range (FR2)) and the possibility to use wide signal bandwidth in low and especially in high bands to bring new performance bounds for established positioning techniques based on DL-TDoA, UTDoA, CID and E-CID, etc.
2. Utilization of massive antenna systems (massive MIMO) to provide additional degrees of freedom to enable more accurate user location, by exploiting spatial and angular domains of propagation channel in combination with time measurements.

The Release 3GPP Release 15 work item on positioning specified NR-based CID, inter-RAT and RAT–independent positioning methods by reusing Location and Positioning Protocol (LPP), but NR standalone based RAT-dependent positioning was not specified in Release 15.

An NR positioning study was carried out in 3GPP Release 16 and considered various NR positioning technologies. Based on the conducted analysis in 3GPP, the following reference signals were recommended to be defined for UE and gNB measurements, to support especially RAT-dependent NR positioning technologies:

RAT-dependent NR positioning technologies

1. Downlink-based solutions includes DL-TDOA and DL-AoD based positioning techniques.
2. Uplink-based solutions includes UTDOA and UL-AoA based positioning techniques.
3. Downlink- and uplink-based solutions includes RTT-based positioning technique and E-CID based positioning technique.

At least the following set of measurements was identified as necessary for NR RAT dependent positioning solutions and recommended to be specified:

1. UE measurements based on reference signals from serving and neighbouring gNBs
    a. DL RSTD measurements.
    b. DL RSRP measurements.
    c. UE RX-TX time difference measurements.
2. gNB measurements at serving and neighbouring gNBs
    a. UL RTOA measurements.
    b. UL AoA measurements (including Azimuth and Zenith Angles).
    c. UL RSRP measurements.
    d. gNB RX-TX time difference measurements.

Figure 24 shows a illustration of positioning illustration by the OTDOA method using the Position Reference Signal (PRS) (the times τ_{xy} to be measured have a zero second index because they correspond to the first-arrival path signals, without multipath) and the time-frequency structure of SSB (which is SS/PBCH block in 5G NR, where SS is Synchronization Signal and PBCH is Physical Broadcast Channel).

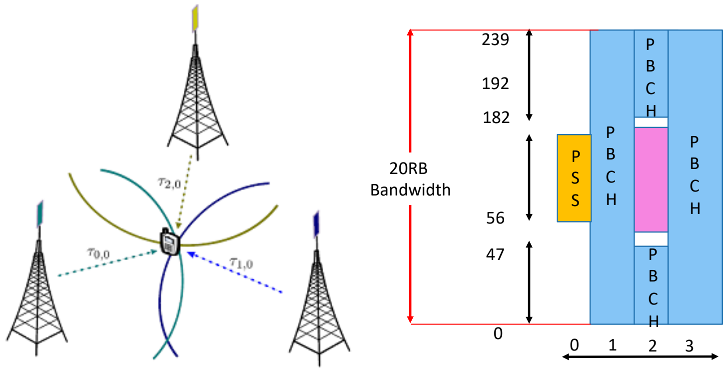


Figure 24 left shows positioning with PRS signals from 3 gNBs based on OTDOA (note : the time τxy to be measured have a zero second index because they correspond to the first-arrival path signals, without multipath) right shows PSS (Primary Synchronization Signal, yellow) and SSS (Secondary Synchronization Signal, pink) sequences in 5G NR signals

In 5G NR, PRS can be build using two elementary sequences for downlink signals, PSS and SSS (respectively, Primary and Secondary Synchronization Signals) as shown in Figure 24. These signals are used to get a synchronization for symbol-level and slot-level and also frequency tuning for UE. These signals are present in each beam emitted by multiple-input and multiple-output (MIMO) 5G antenna and are crucial for initial access.For NR positioning protocols, it was concluded in 3GPP that LPP is reused and will be extended to support the NR RAT dependent positioning methods; NR Positioning Protocol (NRPP)is reused and will be extended to support the NR RAT dependent positioning methods.

There is a complete process for managing the positioning of a UE, see for details [3GPP20-38305] and LPP protocol (LTE positioning protocol). Processing measurements in local servers can reduce latency while yielding results but can also improve the results with multiple correlation processes for example. A system view with relation to LPP protocol can be seen in Figure 25.

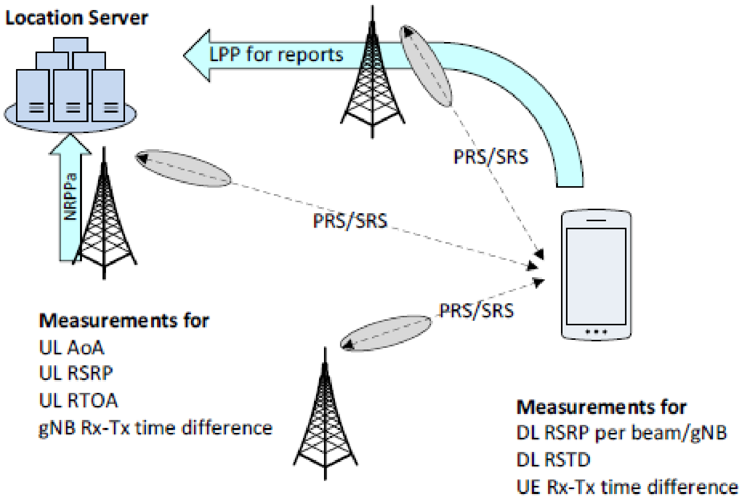


Figure 25 Use of the LPP protocol to assist positioning processing [3GPP20-38305]

For NR positioning architecture:

1. Regarding NR positioning methods, the location of the transmission measurement function under disaggregated architecture (CU-DU) should be further considered.
2. Regarding location management functionality in 3GPP could not reach a common understanding on any recommendation.
3. Regarding NG-RAN acting as LCS client, 3GPP needs more justification in terms of scenarios and foresee also further consideration on the authorization and privacy aspects.

OTDA Performance considerations

Concerning OTDOA performance, several features are enhanced thanks to 5G:

1. Use of 3.5 GHz for NR: more bandwidth improves the delay resolution measurements[19].
2. Use of MIMO antennas: better angle resolution, which can help other measurements.
3. Use of access nodes, which can be additional location references, also use of anchor.
4. UE tracking feature by 5G beam lobes: AOD to complement OTDO.

But similar to LTE, NR based positioning has several key points to consider:

1. Bad geometric distribution of antennas (they are too close to each other),
2. Insufficient number of measurable gNBs (three is the preferred number),
3. Bad synchronization between gNBs (relative synchronization for measurements process),
4. Too many Non-line-of-Sight (NLOS) signals to be measured by the UE,
5. Too much multipath (first-arrival path signals are preferred).

Also, OTDOA can be complemented with Centralized or Distributed Localization Protocols (CLP and DLP). These protocols can help to determine the clock offset of the UE in case of single-base station localization.

The impact of lack of precise time synchronization between gNBs is not limited to a conversion between the offset value and the positioning error. The accuracy of timestamping is also to be taken into account.

Nevertheless, the interest of using NR signals for positioning purpose in industrial use cases is contained in the great variety of combinations of techniques and variation of the operating parameters of radio signals (e.g., enhancements of physical-layers procedures to have a better NR positioning). It is the case in 3GPP Release 16 (example: work on compensation for network synchronization error) and even more so in the following Release 17.

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[19] Note for bullet 1: An example for France: 70 or 80 MHz blocks in the 3.5 to 3.8 GHz band, against 10 or 20 MHz blocks for 4G bands.

Release 3GPP Release 16 High Precision Positioning (LTE and NR)

Release 3GPP Release 16 introduced GNSS SSR (also known as Precise Point Positioning – Real-Time Kinematic (PPP-RTK)) based on the CLAS (centimetre level augmentation system) operated on Quasi-Zenith Satellite System (QZSS)[20] for Japan and eastern Asia region.

SSR (State Space Representation) is an extension of PPP in which measurements from a network of reference receivers are used to decompose the GNSS signal errors into their component parts (state space models of the errors): satellite orbit errors, satellite clock error, satellite signal biases, tropospheric errors, ionospheric errors, additional status and integrity information. The satellite errors are global per satellite. The atmospheric errors vary geographically and are modelled across wide geographical areas. This means that the SSR corrections are applicable over large geographic regions and are suitable for broadcasting. Conventional RTK and NRTK methods do not scale efficiently over large areas or to very large numbers of receivers.

The 3GPP GNSS methods support all global satellite constellations: GPS, Galileo, Global Navigation Satellite System (GLONASS) and Beidou, as well as many regional systems including QZSS, Satellite Based Augmented System (SBAS), Indian Regional Navigational Satellite System (INRSS) and Release 17 NR Positioning.

Carrier-phase based positioning techniques were discussed for NR, but not specified, please refer to [3GPP19-TR38855] and references therein. Carrier-phase based positioning refers to the positioning method where the transmitter (either the gNB or the UE) transmits the positioning reference signals at the pre-configured carrier frequency, and the receiver (either the UE or the gNB) obtains the carrier phase measurements by tracking reference signals.

3GPP Release 17 NR Positioning

3GPP has approved a new Release 17 study item [3GPP19-RP193237] on NR Positioning at the RAN plenary #86 during December 2019. The initial six months' study starting from Q1'2020 focuses on potential enhancements and solutions necessary to support high accuracy, low latency, network efficiency and device efficiency requirements for commercial and industrial IoT use cases. This includes:

1. Define additional scenarios (e.g. (I)IoT) based on [3GPP19-38901] to evaluate the performance for the use cases (e.g. (I)IoT).
2. Evaluate the achievable positioning accuracy and latency with the Release 16 positioning solutions in (I)IoT scenarios and identify any performance gaps.
3. Identify and evaluate positioning techniques, DL/UL positioning reference signals, signalling and procedures for improved accuracy, reduced latency, network efficiency, and device efficiency. Enhancements to Release 16 positioning techniques, if they meet the requirements, will be prioritized, and new techniques will not be considered in this case.

In addition, during the study phase, 3GPP RAN Working Group 2 will study solutions necessary to support integrity and reliability of assistance data and position information. This is applicable to both RAT-dependent and RAT-independent positioning methods:

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[20] https://qzss.go.jp/en/

1. Identify positioning integrity KPIs and relevant use cases.
2. Identify the error sources, threat models, occurrence rates and failure modes requiring positioning integrity validation and reporting.
3. Study methodologies for network-assisted and UE-assisted integrity.

4.2.4 Legacy Positioning techniques

The purpose of this section is to provide background information on the standardized RAT dependent and RAT independent techniques. They are essential building blocks which provided foundation for NR positioning in Release 16 and release 17.

Release 3GPP Release 14 Indoor Positioning Enhancements

This section summarizes the relevant indoor positioning methods standardized in 3GPP in Release 14. Although the methods specified are based on the LTE systems, general principles including downlink and uplink positioning methods are applicable to 5G technologies.

The further indoor positioning enhancements work item was completed in 3GPP Release 14 in December 2016. This work item introduced UE-based positioning methods for barometric pressure positioning, TBS positioning and WLAN positioning, as well as the introduction of supporting network assistance data from the location server to the target UE, for both UE-assisted mode and UE-based mode of these positioning solutions.

Enhanced Cell-ID (E-CID) Positioning

In 3GPP Release 14, several enhancements were introduced to improve the UE location estimates in E-CID positioning: enable the eNB to report information to the location server such as WLAN Received Signal Strength Indicator (RSSI), BSS identifier (BSSID), Service Set Identifier (SSID), Homogeneous Extended Service Set Identifier (HESSID), channel(s), operating class, country code and band, if corresponding WLAN measurement information is already available in the eNB.

OTDOA Positioning

The downlink (OTDOA) positioning method makes use of the measured timing of downlink signals received from multiple transmission points (TPs) at the UE. The UE measures the timing of the received signals using assistance data received from the positioning server, and the resulting measurements are used to locate the UE in relation to the neighboring TPs.

Release 3GPP Release 14 introduced the transmission-point-specific PRS sequence generation using a TP specific Identifier (TP ID). This is to solve the problem of identical Physical Cell Identifier (PCI) between the transmission points (e.g. Remote Radio Head RRH) and their associated network nodes (e.g. macro cell). The identical PCI could prevent those transmission points being used for PRS transmission, consequently reducing the number of RSTD measurements for OTDOA positioning.

Release 14 also introduced other OTDOA enhancements to improve the accuracy of reported RSTD measurements:

1. Improved granularity of reporting RSTD measurement.
2. Improved granularity of reporting multipath Time of Arrival information of PRS signal and use of combined PRS and CRS signals for RSTD measurement.

3. MBSFN subframe configuration information could be sent from an eNB to the location server and then from the location server to the UE.

WLAN Positioning

This method was specified in 3GPP Release 13. It uses the WLAN measurements (Action Point (AP)) identifiers and optionally other measurements) and databases for UE positioning.

The UE WLAN measurements may include:
1. WLAN Received Signal Strength (RSSI),
2. Round Trip Time (RTT) between WLAN Access Point and the UE.

Three positioning modes are supported [3GPP20-TS36305]:
1. Standalone: UE performs WLAN position measurements and location computation, without network assistance.
2. UE-assisted: UE provides WLAN position measurements, with or without assistance from the network, to the E-SMLC for computation of a location estimate by the network.
3. UE-based: UE performs WLAN position measurements and computation of a location estimate with network assistance.

TBS Positioning

The Terrestrial Beacon System (TBS) in LTE network includes Metropolitan Beacon System (MBS) introduced in LTE Release 13 and PRS Based Beacon System introduced in LTE Release 14. TBS consists of a network of ground-based transmitters, broadcasting signals only for positioning purposes. The UE measures received TBS signals, optionally aided by assistance data, to calculate its location or to send measurements to the positioning server for position calculation.

MBS positioning supports UE-assisted mode and standalone mode without network assistance in LTE Release 13, and UE-assisted mode and UE-based mode with optional network assistance in LTE Release 14.
Three positioning modes are supported [3GPP20-TS36305]:
1. UE-Assisted: The UE performs TBS measurements with or without assistance from the network, and sends these measurements to the E-SMLC where the position calculation takes place, possibly using additional measurements from other (non-TBS) sources;
2. UE-Based: The UE performs TBS measurements and calculates its own location, possibly using additional measurements from other (non-TBS) sources;
3. Standalone: The UE performs TBS measurements and calculates its own location, possibly using additional measurements from other (non-TBS) sources, without network assistance.

Barometric Pressure Positioning (BPP)

The barometric pressure method makes use of barometric sensors to determine the vertical component of the position of the UE. The UE vertical component of the position is estimated by combining the measured atmospheric pressure and a reference atmospheric pressure. This is accomplished through barometric sensors measuring atmospheric pressure at the UE and applying a height determination algorithm using the reference atmospheric pressure.

Three positioning modes are supported [3GPP20-TS36305]:

1. UE-Assisted: The UE performs barometric pressure sensor measurements, with or without assistance from the network, and sends these measurements to the E-SMLC, where the vertical component of the position calculation may take place, possibly using additional measurements from other sources;
2. UE-Based: The UE performs barometric pressure sensor measurements and calculates its own vertical component of the position, possibly using additional measurements from other sources;
3. Standalone: The UE performs barometric pressure sensor measurements and calculates its own vertical component of the position, possibly using additional measurements from other sources, without network assistance.

3GPP Release 15 UE Positioning Accuracy Enhancements for LTE

Release 15 introduced GNSS Real-time kinematic (RTK), Network RTK (NRTK) and basic Precise Point Positioning (PPP) following RTCM standard 10403.3. RTK is a method whereby the GNSS receiver measures and uses the carrier phase of the GNSS signal in order to compute very precise positions (centimetre level). However, in order to do this, it needs accurate corrections quantifying the error in the received GNSS signal. The approaches adopted by 3GPP include:

1. Basic RTK, in which a nearby (within about 20 km) reference receiver at a precisely known location measures the received GNSS signals and computes the observed error, which is sent to the mobile receiver that subtracts these errors from its own signal measurements.
2. NRTK (Network RTK), in which a network of reference stations provides observed errors, which are interpolated to derive an estimated error at a different location (referred to as a non-physical reference, typically that of the receiver) before being sent to the receiver.
3. MAC and FKP are two gradient-based methods standardised by RTCM for generating interpolated corrections using multiple reference receivers.
4. PPP (Precise Point Positioning) is completely different from RTK. Using a network of reference receiver's, accurate measurements for the satellite errors is performed – orbit deviation, clock bias, other signal biases. These errors are per satellite and have global coverage. However, errors introduced by the atmosphere (ionosphere and troposphere) are excluded. A PPP receiver has to make its own estimation of the atmospheric errors (which can amount to several meters); this usually takes a long time (tens of minutes) and is usually only useful in static applications and those with an unimpeded view of the sky.

In general, GNSS-based solutions are only useful outdoors, as the signal strength of the satellite signals is too low indoors. Therefore, manufacturing use cases typically require some other positioning solution. A GNSS-based solution can however be used as a complement to achieve high accuracy positioning outdoors for use cases which require high accuracy positioning both indoor and outdoor, for example for an AGV moving between factory halls.

4.2.5 Positioning in Cellular IoT Narrowband - NB-IoT and LTE Cat-M

Positioning and tracking are important features in many IoT applications. Since the introduction of cellular IoT in 3GPP, i.e., NB-IoT and LTE Cat-M, there is increased interest from the industry to also see positioning capabilities introduced for low-complexity devices constrained by power and form factors. See the section below provides a detailed description of narrowband positioning methods introduced for NB-IoT and LTE Cat-M in 3GPP Release 14, which are mainly based on OTDOA and E-CID.

NB-IoT Narrowband Positioning

New Narrowband Positioning Reference Signal (NPRS) was introduced in 3GPP Release 14. It is based on LTE PRS. It is only transmitted in resource blocks in NB-IoT carriers configured for NPRS transmission. NPRS is defined for normal cyclic prefix only.

The periodicity of NPRS is specified in the [3GPP20-36211] specification. The presence of NPRS can be indicated using:

1. Part A – a bitmap (10 or 40 bits).
2. Part B – start subframe, number of repetitions, and periodicity.

Location and Positioning Protocol (LPP) signalling was introduced as the positioning protocol for NB-IoT. The UE indicates its capability to perform OTDOA, A-GNSS, E-CID, terrestrial beacon service, sensor, WLAN, and Bluetooth-based positioning. OTDOA and E-CID are specified by 3GPP. The UE indicates in the capability signalling when it requires idle mode to perform the measurements.

LTE-M Positioning Enhancements

In 3GPP Release 13, LTE Cat-M1 introduced Enhanced Cell ID (E-CID) and OTDOA support based on 1.4 MHz RF bandwidth and specified necessary LTE positioning signalling methods. In 3GPP Release 14, LTE Cat-M2 introduced 5 MHz RF bandwidth support and full standard support by including measurement performance requirements:

1. E-CID: RSRP/RSRQ measurement.
2. E-CID: UE Rx-Tx time difference measurement.
3. OTDOA: core requirements.

In addition, Release 14 introduced OTDOA enhancements to boost positioning performance of UEs with limited bandwidth and UEs with low signal-to-noise ratio (SNR) operating point in CE mode. Enhancements include introducing denser PRS configurations, more frequent PRS transmissions, frequency hopping and the support for multiple PRS configurations aligned with legacy LTE. Note that the enhancements have been designed for Cat-M but can also be supported by LTE UEs which do not support CE mode.

4.3 Gap analysis

One of the key requirements identified for smart manufacturing use cases is indoor positioning, which suggest that the error should preferably be within 1m for localizing the devices on the factory floor. This positioning requirement is obviously tighter than the performance targets defined in 3GPP Release 16, which specified that the horizontal and vertical positioning error shall be less than 3m for 80% of UEs in indoor development scenarios [3GPP19-TR38855]. For the specific scenario evaluated in 3GPP, many companies have however shown simulation results with much better performance than the target of 3m. The positioning accuracy depends on many parameters that are not specified in the standard, such as deployment density, deployment layout, network synchronization, etc. With favorable assumptions on deployment layout and accurate network synchronization, sub-meter positioning is achievable with the NR positioning features specified in Release 16. However, practical deployment settings should be taken into account in order to assess the achievable positioning performance.

Positioning performance requirements have been sharpened further in 3GPP Release-17 which targets higher accuracy positioning requirements. For Industrial Internet of Things (IoT) use cases, the positioning error is in the range of 10 cm to 1 meter. In addition, several new KPIs were introduced for Industrial IoT use cases, such as positioning end-to-end latency, reliability and energy efficiency. The target latency requirement per 3GPP Release 17 is less than 100ms, but for some Industry IoT use cases, latency in the order of 10ms is desired.

On the latency aspect, tight coordination with time synchronization activities is essential in order to assess the feasibility of existing NR positioning solutions from an end-to-end perspective and take into account different NPN development scenarios. It should also be noted that the baseline for further evaluation in the next 6 month in WP5 may have to be based on Release 16 as the Release 17 study for high accuracy NR positioning is still at its study and evaluation stage and the specification work will not start until after Q4’2020.

In addition to the performance gaps. Several practical development aspects are considered for 5G-SMART smart manufacturing scenarios.

1. Adequate indoor infrastructure development
    a. Wireless communication requires good signals to and from one base station, but positioning using UL or DL TDOA solutions needs the involvement of at least three base stations in order to solve the position and local time.
    b. In particular, depending on the application, vertical 3D positioning may be required, necessitating the involvement of at least four base stations (for TDOA-based solutions), placed in a suitably good vertical configuration inside of the building.
    c. For all cellular positioning techniques except cell-ID, there must be LOS (line-of-sight) paths to the base stations utilized for positioning measurements. In for example an indoor factory floor, NLOS (non-line-of-sight) signals are common as signals may have bounced off machinery or objects. In contrast to positioning, communication typically works well also with NLOS signals.
2. Knowledge about the locations of the base stations (more specifically, of the base station antennas) inside the factory
    a. The accuracy of this information should obviously be commensurate with the accuracy desired for the positioning itself. For indoor factory environments, it may become easier to obtain and manage than outdoor macro-cell environment.
3. Need for accurate synchronization of the base stations
    a. Network synchronization errors translate into time-difference-of-arrival measurement errors and should therefore be minimized. For seamless operation indoors and outdoors, it is desirable that the base stations are synchronized to UTC.
4. Lack of global standards for sidelink-based positioning methods

    a. This is for relative positioning between for example controller and controller inside of a machine cell. But sidelink feature is not in the scope of 3GPP Release 17 and could be something to be address in the future WP5 work.
5. System integrity information
    a. For ensuring reliable operation, particularly for safety-critical applications such as autonomous navigation inside the factory (e.g. drones, AGVs).

4.4 Recommendation towards standardization bodies and industry fora

The standardization direction and performance targets for Industrial IoT positioning in 3GPP Release 17 look promising as it provides additional support for industrial IoT use cases which demand high accuracy positioning. However similar to legacy positioning solutions, to commercially deploy those solutions, tight eco-system collaboration is essential to ensure practical deployment success but also commercial viability. Standardization is an enabler, but commercialization of such feature requires further efforts in the industrial through engagement in for example 5G-ACIA to foster adoption and ultimately help scale the solution. Further enhancements from product improvements perspective as an example would be to provide accurate measurements of network synchronization uncertainties.

As the positioning error is highly dependent on their deployment and especially the number of base stations which have a line-of-sight (LoS) path to the UE to be localized, a dense deployment is beneficial. For indoor use cases, there is therefore typically a main advantage with indoor systems utilizing densely deployed nodes.

As mentioned 3GPP Release 17 plans to study NR positioning for industrial IoT use cases, evaluate the achievable positioning accuracy and latency with the Release 16 positioning solutions in (I)IoT scenarios, and identify any performance gaps. Beyond the performance aspect, the robustness of the solutions implemented must be analyzed (protection of equipment using positioning in the industrial context in the event of disturbances (e.g. interference or loss of references used for positioning)).

5G-SMART will closely monitor the development in 3GPP especially with respect to the above-mentioned gaps and point out any missing aspects that have not been addressed in Release 17.

5 Summary, conclusions and future work

New 5G technical features related to 5G-TSN integration, E2E time synchronization and radio-based positioning will further accelerate the realization of the 5G System for smart manufacturing. The current report provides an in-depth state-of-the-art analysis of those novel 5G capabilities; it also identifies gaps for further improvements or evaluations of each of the above technical features. 5G-SMART recommendations towards standardization bodies and industry fora are also documented for each feature. It is summarized in Table 4. From 5G-TSN integration aspects, it is clearly seen that there is a benefit to have a secure exposure framework for the 5G System with regards to enabling end-to-end 5G-TSN integrated industrial networks. Concerning time synchronization, various SDOs are involved in the development of network synchronization and time distribution performance. Among these, ITU-T Study Group 15 is one of the very active groups involved in the development of the recommendations of solutions and architectures for the current and future timing and synchronization requirements, which form the basis of the end-to-end time synchronization over a 5G System. There are several major ongoing development activities, which target the study on 5G phase II synchronization requirements. Towards this end, some 5G-SMART contributions related to 5G have already been submitted to the ITU-T (SG15) standards meeting.

Technical feature	Gaps identified	Recommendation towards SDOs and industry fora
5G-TSN integration	- End-to-end TSN stream configuration in integrated 5G-TSN system and 5G system capability exposure. - 5G-TSN configuration according to the fully distributed and the hybrid centralized network/distributed user configuration models once the corresponding IEEE standards are completed.	- 5G System bridge model along with 5G System support of bounded latency and reliable communication for the TSN communication submitted as contribution to 5G-ACIA. - Investigation of different 5G-TSN deployment and connectivity options.
End to end time synchronization	- Arbitrary placement of the master clock in 5G-TSN architecture. - Evaluation of 5G System contribution to the end-to-end synchronization accuracy.	- Enhancement of the ITU-T specification such as enhanced ePRTC, T-BCs to be studied and investigated. - Clarification of the time synchronization budget in an integrated 5G-TSN system. - TSN time synchronization provided by 5G System as realization option.

5G positioning techniques	- Tight coordination with the time synchronization activities in order to assess the feasibility of existing NR positioning solution from an end-to-end perspective and taking in different NPN development scenarios. - Practical deployment aspects including adequate indoor infrastructure development, knowledge about the location of the base stations inside the factory, lack of global standards for sidelink-based positioning methods and system integrity information.	- Standardization direction and performance targets for Industrial IoT positioning in Release 17 looks promising however tight system collaboration is essential to ensure practical deployment success but also commercial viability. - Standardization is an enabler, but commercialization of such features requires efforts in industry through engagement in industrial alliance such as 5G-ACIA.

Table 4 Summary of the gap analysis and recommendation towards SDOs and industry fora

For future work, evaluation and concept development of these mentioned technical features are planned. Evaluation in terms of analytical work analysis or system-level simulations will be performed for each technical feature, considering scenarios and requirements from trial use cases. Based on this evaluation, new solutions and recommendations will be provided to various standard development organizations. An upcoming deliverable will focus on the above future topics and also will enhance the gap analysis and recommendation done to SDO's and industry fora.

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Appendix

List of abbreviations

3GPP	3rd Generation Partnership Project
ACK	Acknowledgement
AF	Application Function
AGV	Automated Guided Vehicles
AoA	Angle of Arrival
A-GPS	Assisted-GPS
AP	Action Point
AR	Augmented Reality
ARP	Antenna Reference Point
AvB	Audio-video Bridging
BLER	Block Error Rate
BMCA	Best Master Clock Algorithm
BSSID	BSS identifier
CID	Cell ID
CLAS	Centimeter level augmentation system
CLP	Centralized Localization Protocols
CM	Best Master
CM	Clock Master
CNC	Centralized Network Configuration
CoMP	Coordinated Multipoint Transmission
CQI	Channel Quality Indicator
CS	Clock Slave
CSI	Channel State Information
CUC	Centralized User Configuration
DLP	Distributed Localization Protocols
DS-TT	Device Side TSN Translators
E-OTD	Enhanced Observed Time Difference
E-SMLC	Evolved Serving Mobile Location Centre
E2E	End-to-end
EPS	Evolved Packet System
FDD	Frequency Division Duplex
FR	Frequency Range
FRER	Frame Replication and Elimination
GLONASS	Global Navigation Satellite System
GM	Grand Master
GMLC	Gateway Mobile Location Centre
GNSS	Global Navigation Satellite System

GPS	Global Positioning system
HARQ	Hybrid Automatic Repeat Request
HESSID	Homogeneous Extended Service Set Identifier
INRSS	Indian Regional Navigational Satellite System
IoT	Internet of Things
IPDL	Idle Period Downlink
MAC	Medium Access Control
MCS	Modulation Coding Scheme
MIMO	multiple-input and multiple-output
MME	Mobility Management Entity
MMRP	Multiple MAC Registration Protocol
MSP	Multi-sensor platform
MSRP	Multiple Stream Registration Protocol
MVRP	Multiple VLAN Registration Protocol
NACK	Negative Acknowledgement
NLOS	Non-Line-of-sight
NPN	Non-Public Network
NRPP	NR Positioning Protocol
NRPP	NR Positioning Protocol
NRTK	Network Real-time kinematic
NTP	Network Time Protocol
NW-TT	Network Side TSN Translator
NW-TT	Network Side TSN Translator
OTDOA	Observed time of arrival
PAR	Policy Coordination Function
PAR	Project Authorization Request
PCF	Policy Coordination Function
PCI	Physical Cell Identifier
PDU	Packet Data Unit
PDU	Packet Data Unit
PDU	Packet Data Unit
PPP-RTK	Precision Point Positioning – Real-Time Kinematic
PRS	Position Reference Signal
PRTC	Primary Reference Time Clock
PSFP	Per-Stream Filtering and Policing
PTP	Precision Time Protocol
PUCCH	Physical Uplink Control Channel
QoS	Quality of Service
QZSS	Quasi Zenith Satellite System
RAN	Radio Access Network

RAP	Resource Allocation Protocol
RAT	Radio Access Technologies
RIBM	Radio-Interface Based Monitoring
rms	Root mean square
RPFL	Radio Frequency Position Location
RRH	Remote Radio Head
RRSP	Reference Received Signal Power
RSSI	Received Signal Power
RTT	Round Trip Time
SBAS	Satellite Based Augmented System
SDO	Standard Developing Organization
SFN	System Frame Number
SIB	System Information Block
SoE	Sequence of Events
SRP	Stream Reservation Protocol
SRS	Sounding Reference Signal
SSR	State Space Representation
SUPL	Secure User Plane Location
SyncE	Synchronous Ethernet
TDoA	Time Difference of Arrival
TG	Task Group
ToA	Time of Arrival
TSCAI	Time Sensitive Communication Assistance information
TSN	Time-sensitive Networking
TT	TSN Translators
UAV	Unmanned Aerial Vehicle
UCI	Uplink Control Information
UE	User Equipment
UNI	User-Network Interface
UPF	User Plane Function
URLLC	Ultra-Reliable Low-latency communication
UTC	Coordinated Universal Time
UTDoA	Uplink time-difference-of-arrival
eNB	Enhanced NodeB
ePRC	Enhanced Primary Reference Clock
ePRTC	Enhanced Primary Reference Time Clock
gNB	Next generation NodeB
gPTP	generalized Precision time protocol
mMTC	massive Machine Type Communication

Table 5: List of abbreviations