Technical Outlook for Mobile Networks Using IOWN Technology

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Executive Summary

This document covers the following technical topics related to mobile and transport networks to support IOWN Global Forum’s efforts to develop fundamental technologies on communication, computing, data handling, and energy efficiency that would bring in a quantum leap performance improvement and enable a much smarter world with advanced applications.

- Review of the current transport network landscape to support wireless networks
- Projection of the key requirements of beyond 5G and 6G transport networks
- Offering members' insights about the technology gaps to enable the IOWN Global Forum’s target use cases
- Discussion of various transport network options and configurations from technical and economic perspectives
- Proposals to improve performance of transport network to accommodate emerging wireless technologies and evolving network architecture
- Exploration of future transport network architecture leveraging APN and DCI frameworks being developed by the IOWN Global Forum
- Recommendations

1. Introduction

IOWN Global Forum aims to develop advanced communication, network, and computing infrastructure technologies to meet increasing demands of data bandwidth and fast responding time brought by innovative applications and data explosion.

Based on screen time/day and trending heavy usage of high-resolution video services, a mobile user's data usage will increase by 20-fold from the current 4G usage[1]. IOWN Global Forum System and Technology Outlook [IOWN GF ST Outlook] and Use Cases Documents [IOWN GF AIC UC], [IOWN GF CPS UC] identified many futuristic use cases along with unprecedented performance requirements on mobile networks over IOWN GF infrastructure. Video-centric applications and latency-sensitive use cases such as Area Management, Remote surgery, AR/VR, and Industrial Automation require enormous end-to-end bandwidth capacity, high reliability and availability, and extremely low latency.

The diverse set of applications enabled by 5G and 6G networks necessitates various bandwidth, latency, and reliability levels.

A higher data rate requires wider spectrum bandwidth. The 5G network utilizes the mmWave frequency band to achieve a high data rate for high bandwidth availability.

Emerging mobile technologies such as massive MIMO (Multiple Input, Multiple Output), dynamic spectrum sharing, mmWave wide spectrum, carrier aggregation, etc., enable users to achieve very high data speed with low latency. It is expected that most mobile users in the world will switch to 5G by 2030.

However, higher frequency signals such as mmWave weaken quickly with distance, requiring denser cell sites for coverage. It is estimated that a mobile network of mmWave needs 7-8X more sites than that of a mid-band network (e.g., 3.5GHz) for the same coverage[2]. While it is still in an earlier stage, candidates of 6G technologies include potential new radio access technologies, integrated satellite, terrestrial communication, and Tera-Hz communication. These new technologies will demand a huge number of cells for capacity and coverage and also require more X-Haul capacity.

There are various technologies to provide transport networks to mobile cell sites. For some cell sites, a transport network can be delivered suitably by over-the-air technologies such as microwave, satellite, or, more recently, by mmWave due to various access restrictions. Fiber is the medium of choice and has a bright future for fixed network sites because of its high capacity and widely installed base. The focus of this document is a fiber-based optical transport network for mobile networks as it pertains to IOWN Global Forum's Data-Centric Infrastructure (DCI) and Open All Photonic Network (APN) architectures.

To improve service introductions, provisioning agility, operational cost reduction, and increased diversity of applications, mobile network infrastructures are evolving toward cloud native-based network function virtualization. Transport network serving mobile network needs to align with this trending toward network function virtualization. Features such as CTI and TSN, when deployed, can help to improve network latency, synchronization, and reliability,

The following topics are covered in this document:

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[1] 2020 Baseline (based on market data from deployed 5G commercial networks): 8GB/use/month for 4G and 25GB/use/month for 5G. One method is to project 2030 usage/user/month based on historical growth rate, which yields to ~168GB/user/month for 5G users; Another method considered is based on screen time/day/user (3.25 hours/day) and 25% screen time on 7GB/HR high-quality video + 0.5 GB on other applications, which is about 188GB/user/month. Compared with 4G baseline 8G/user/month in 2020, the projected traffic volume ratio is approximately 20-fold in 2030).

[2] Number of cell sites is based on mobile network coverage areas. The area sizes are determined by inter-cell distance of mmWave (~120 meters) and 3.5 GHz midband (~350 meters). Note that it is very high level and theoretical because it is unlikely MNO will deploy 1 to 1 mmWave network with an underlying midband network.

- examination of the current landscape of transport network supporting mobile network
- technical gap for future wireless and transport network needs
- projections of key requirements of 5G and 6G transport networks resulted from use cases developed by IOWN Global Forum members
- proposed future transport network architecture leveraging Open APN and DCI frameworks being developed by the IOWN Global Forum

Several study items are suggested to improve the performance of the transport network. In addition, various transport network options and configurations from technical and economic perspectives are discussed. Finally, recommendations are made on the transport network to meet future capacity and performance goals demanded by evolving applications.

2. Transport Network Challenges in Mobile Networks

This chapter discusses various challenges future mobile transport networks will need to overcome to achieve key performance requirements and improve network deployment and operational efficiency in realizing the targeted use cases identified by IOWN Global Forum.

2.1. KPI Requirements

New services and applications enabled by 5G include enhanced mobile broadband (eMBB), ultra-reliable low latency communications (uRLLC), massive machine-type communications (mMTC), and high speed fixed wireless access (FWA). These new services and applications generate higher data volume and have very stringent low latency requirements. Mobile network data growth will propagate capacity requirements throughout the transportation network, from fronthaul to data centers. Mobile users' ever-increasing time-sensitive applications require ultra-low network latency on the order of milliseconds.

While 5G deployment is currently in full gear, several industries and standard developing bodies have started planning for 6G mobile networks. 6G technologies will naturally evolve from 5G, but end to end (E2E) key performance indicators (KPIs) will significantly improve. Technologies of 6G are being discussed, though there are a few general consensuses on what 6G should achieve.

Some of the potential 6G features are listed as follows:

- Integrated Satellite & Terrestrial communication
- Mobile Tera-Hz communication
- Pervasive Artificial Intelligence (AI) powered fully autonomous networking
- Highly distributed and flat network architecture

While these features are still being studied, it is clear that they will need more transport network capacity to support wireless network densification and increased airlink capacity.

6G technologies are targeted to improve 5G E2E KPIs by 10-100x. The table below shows 6G's projected E2E KPIs vs. 5G baseline.

Table 1 Projected 6G KPI Improvement over 5G

E2E KPI	5G	6G	Improvement Factor
Peak Data Rate (Gbps)	10	100-1000	10-100
Connection Density	1/m^2	10-100/m^3	10-100
User Plane Latency (m sec)	1	0.1	10
Jitter (m sec)	N/A	0.0001-1	N/A
Reliability	Five 9s	7 9s – 9 9s	100 – 10000

Synchronization	3µs (cell phase)		
	Three ns for 1-meter position accuracy	<1 ns for <0.2-meter position accuracy	10[3]
Position Accuracy	1m-level	1cm-level[4]	100

As shown in Table 1, E2E KPI requirements in 6G would be more stringent compared with those of 5G. These higher requirements lead to new challenges for the transport network.

Elements of a 5G radio access network (RAN) can be disaggregated and virtualized, meaning that they can be resided in different physical locations and run on common off-the-shelf hardware. Therefore, transport network architecture for 5G and future mobile networks can vary depending on RAN architecture and interfaces.

While The 3rd Generation Partnership Project (3GPP) [3GPP TR 38.801], [3GPP TR 38.806] and [3GPP TR 38.816] lists eight possible RAN functional split options, the following two options are generally considered by operators for 5G New Radio (NR) deployments.

- A higher-layer split (Option 2) at layer 2: breaking between CU and DU connected with F1 interface, and
- A lower-layer split (Option 7) is designed to support simpler and lower-cost Remote Radio Unit (RRU) and utilize more pooled virtualized resources.

Compared with Option 7, bandwidth and latency requirements for transport networks are relaxed in Option 2.

A lower layer split (LLS) option (e.g., Option 7), which is gaining popularity, promotes an architecture that allows more functions to be centralized. However, to make RAN LLS more compelling, cost and availability of high capacity of fiber optical fronthaul links must be taken into consideration as more stringent requirements of massive bandwidth and tight latency come with LLS.

The fronthaul latency, bandwidth requirements, and efficiency are critical for selecting optimal RAN functional split options to fit applications and deployment scenarios properly. Table 2 shows fronthaul bandwidth and latency requirements for popular RAN split options. LLS Option in Physical layer (i.e., Option 7 family) has very high bandwidth and very stringent low latency demands of fronthaul bandwidth.

However, to make the RAN and the RAN LLS more compelling, the cost and availability are key. To achieve wide acceptance of the new distributed and virtualized mobile architecture, cost-optimized solutions and high-capacity optical fiber links are needed, especially in the fronthaul network. The LLS requires more stringent requirements for huge bandwidths and tight latency constraints. Equally, new data centers which host the virtual mobile processes will need to be located close to the consumers to ensure low latency. Thus densification of the far edge data centers is expected.

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[3] 10x improvement factor is targeted based on the general expected improvement factor between two wireless generations of technologies

[4] [NTT Docomo 6G]

Table 2 Targeted Fronthaul Bandwidth and Latency Requirements for Various RAN Split Options

KPI	5G (2020)	6G (2030) (Projected)
E2E		
Peak Data Rate	< 10Gbps	< 100Gbps~1Tbps
User Plane Latency (ms)	1	0.1
TRANSPORT: LOWER LAYER SPLIT (OPTION 7)		
Bandwidth	< 25~50Gbps	< 250Gbps~5Tbps
Frame delay (one-way)	0~160us Fiber delay: 0~150us (0~30km) Packet Delay Variation (PDV): 0~10us (0~2 switches)	0~larger than 160us Fiber delay: 0~larger than 150us (0~larger than 30km) PDV: 0~less than 10us
TRANSPORT: HIGHER LAYER SPLIT (OPTION 2)		
Bandwidth	< 10Gbps	< 100Gbps~1Tbps
Frame delay (one-way)	Up to ms order (up to 100km order)	Up to ms order (up to 100km order)

2.1.1. Network Throughput

As identified in IOWN Global Forum's use case documents [IOWN GF AIC UC] [IOWN GF CPS UC], many innovative use cases such as area management and remote operation via AR/VR and Telepresence will generate data rates from 100 Gbps to a few Tbps in extreme interactive Telepresence use scenarios.

As shown in Table 2, current 5G peak data rates (< 10 Gbps) require fronthaul bandwidths < 25~50 Gbps for LLS (Option 7) and < 10 Gbps for higher layer split (Option 2). With an improvement factor of 10-100 for 6G peak data rates compared to current 5G, assuming the same functional splits, the fronthaul bandwidth requirements will also be increased by the same factor. Therefore, in extreme RAN configurations and use cases, the fronthaul throughput requirement in 6G networks can go up to 5 Tbps. To effectively dimension and deliver high bandwidth for a mobile network to achieve the required data throughput is a challenge in future mobile networks.

2.1.2. Network Latency

The use cases studied in IOWN Global Forum's Use Case Documents [IOWN GF AIC UC] and [IOWN GF CPS UC] identify various end-to-end latency requirements for infrastructures, including five groups, i.e., Time to Response (TTR), Time to Present (TTP), Time to Notify (TTN), Motion to Photon (MTP), and Time to Control (TTC). The latency requirements range from the order of sub msec to the order of seconds, depending on the use cases and customer experiences required.

End-to-end latency can be deconstructed into several elements, such as the hardware on which the application or virtual function is being processed, the airlink latency, the end user's device, and latency in the transport network layer. The transport network latency can further be decomposed into switching and queuing latency, possible protocol conversion and associated buffering, and actual fiber propagating latency.

It is important to minimize latency in the transport network to ensure accumulated latency of an actual deployment remains below the requirements for the end-to-end application. Additionally, apart from delay, another important transport networking attribute is the delay variation, also called jitter. The capability to design these extremely low latency features must be built into IOWN Global Forum's APN and DCI architectures from day one.

Concerning fronthaul latency, several classes of latency could be proposed. All of them are targeted to support the mobile network deployment in meeting the overall latency requirements while also leaving a sufficient margin for mobile equipment processing. The fronthaul latency requirement is referenced in Table 2.

For many applications with extremely low latency and highly reliable transport requirements, special Time-Sensitive Networking (TSN) switching techniques may be required in both ends of the fronthaul. As a requirement to the IOWN Global Forum's Open APN and DCI infrastructures, TSN must be considered in the APN network design.

2.1.3. Reliability

Future use cases described in IOWN Global Forum's use case documents [IOWN GF AIC UC] [IOWN GF CPS UC], such as remote surgical operation, Area Management, and Mobility Management, demand deterministic reliability, greater than 99.999% that 5G currently provides.

Transport network reliability can be achieved with a well-designed network architecture. Future transport network architecture leveraging APN and DCI frameworks developed by the IOWN Global Forum should provide better network fast-failover, packet retransmission protocol, application-aware network slicing, and other reliability improvement features.

2.1.4. Energy Efficiency

6G KPIs listed in Table 1 are expected to be improved by 10X-100X over 5G. Energy efficiency of network components needs to improve to remain at today's level (~2020) to achieve suitability. The PARIS targets for the ICT industry require absolute emission reductions by 2030. It requires Mobile Networks to reduce 45% and Fixed Network by 63%, while data volume Compound Annual Growth Rate (CAGR) is at +30% annually [ITU-T L. Sup37]

In wireless networks and cloud data centers, energy efficiency features are mainly based on the sleep mode concept, i.e., turn off or reduce component or resource usage when there is no or low traffic or load. In the transport network, utilizing sleep mode features may have limited potential as it is rare that the transport network does not carry any traffic.

DCI and APN architectures being developed by IOWN Global Forum can provide a more intelligent scalable hardware infrastructure and lower computational redundancy resulting in reduced energy consumption. Other features like smart traffic routing, edge computing to reduce data movement distance, full-duplex, improved network protocols, higher transport data rates may also be explored to improve energy efficiency.

2.1.5. Openness

In contrast to previous generations of mobile networks such as 3G/4G, elements of a 5G RAN network can be disaggregated, the software and hardware functions can be separated into a mix of radio unit (RU), distributed unit (DU), and centralized unit (CU) and be deployed at different locations. Therefore, 5G and presumably future mobile transport network architectures can vary depending on RAN architecture and interface. The disaggregated and modularized RAN network can provide agile feature implementations and leverage the best products from software and hardware vendors to break free from a traditional proprietary model. Standardized open interfaces between different components are essential for a RAN network to perform in a multi-vendor environment. It is also indispensable to have standardization and openness in the transport layer for seamless interaction between the mobile network and the underlying transport network.

2.1.6. Cloudification/Cloud-native

To simplify and modernize the entire mobile network, Mobile Network Operators (MNOs) aim to redesign network architecture by virtualizing the entire network from the core to the edge. The advancements of virtualized technology are critical to building a scalable, agile, flexible, and programmable network to manage solutions that will be capable of adapting to 5G and support the myriad of consumer use cases, massive scale IoT, more robust user devices, and solutions, AR/VR applications, and much more.

In contrast to generic IT environments, a virtualized mobile network needs to meet stringent KPIs, such as deterministic high throughput or low latency. Achieving these high KPI goals is a challenge in deploying IOWN Global Forum's Network architecture (APN and DCI) for a mobile network.

2.2. Automatic Provision, Orchestration, and Management of End-to-end Traffic and Services Delivery

Deployment of APN/DCI in IOWN Global Forum (IOWN GF APN/DCI) as an infrastructure of mobile network presents challenges for the dynamic network service, resource allocation, operation, and management. The dynamic and end-to-end resource provisioning to satisfy the Service-Level Agreement (SLAs) agreed with customers is another challenge because the use cases of the IOWN GF APN/DCI require extremely high performance, and the overall network resources, including APN and DC, must be well-coordinated and optimally allocated to satisfy those requirements. Furthermore, network slicing and orchestration of slices are other challenges of orchestration for mobile networks using IOWN technology.

The critical components of the network orchestration are Application Programming Interfaces (APIs) and data models. The APIs should abstract network characteristics such as network topology, physical configurations, device types, and other related parameters and provide required information and operation features for MNOs through protocols such as RESTconf and Netconf. The data models for orchestration include network service models, network topology models, path computation models, and device models. In the transport domain, IETF YANG and ONF Transport API are often used for data models of Northbound Interface (NBI) or Southbound Interface (SBI) for service orchestration and device control. The TOSCA template is defined as a network service catalog by European Telecommunications Standards Institute (ETSI) in the mobile domain. The challenge of IOWN GF APN/DCI for a mobile network in terms of orchestration is how well the APIs and data models of IOWN GF APN/DCI work together with the mobile network domains' APIs and data model to realize full automation or zero-touch mobile network services and slices.

End-to-end automation processes for orchestration, provision, fault detection et al. are required to manage future high complexity mobile networks, including 6G, to deliver services with agility and speed, adaptation, and assurance while maintaining the economic sustainability of the highly diverse services offered.

In addition to high throughput and low latency requirements, 5G/6G mobile networks also require automatic provision and management of end-to-end traffic and services delivery.

Some of the required features include:

- Deterministic transmission latency and jitter
- Precise precision time synchronization

- SDN automation & advanced packet networking
- Dynamic bandwidth management

2.3. Cell Site Bandwidth Requirement and Distance Profile

Cell site bandwidth requirement and distance from central office or far edge data center vary, depending on markets and user population distribution. In 5G, a general distribution of the site in terms of bandwidth and X-haul distance is shown in Figure 1 and Figure 2.

It is clear from the figures that more than half of sites have a distance of less than 7 KM; only a small portion of sites (~5%) have high bandwidth requirements, e.g., 5% of the total site population needs 25 Gbps capacity. Thus, it is important to have transport solutions adapted to different cell sites to achieve viable cost-effectiveness and ease of use.

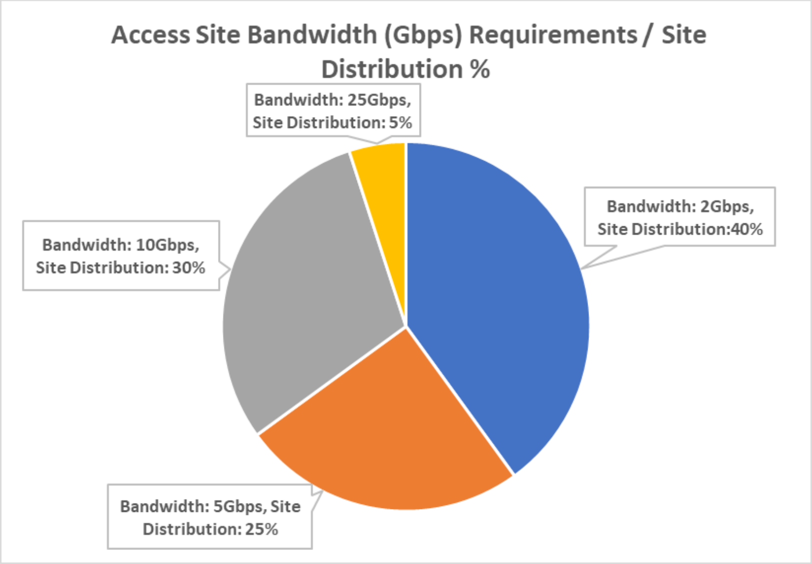

Figure 1 Access site capacity requirements (Gbps) and distribution (%) [N. Zein].

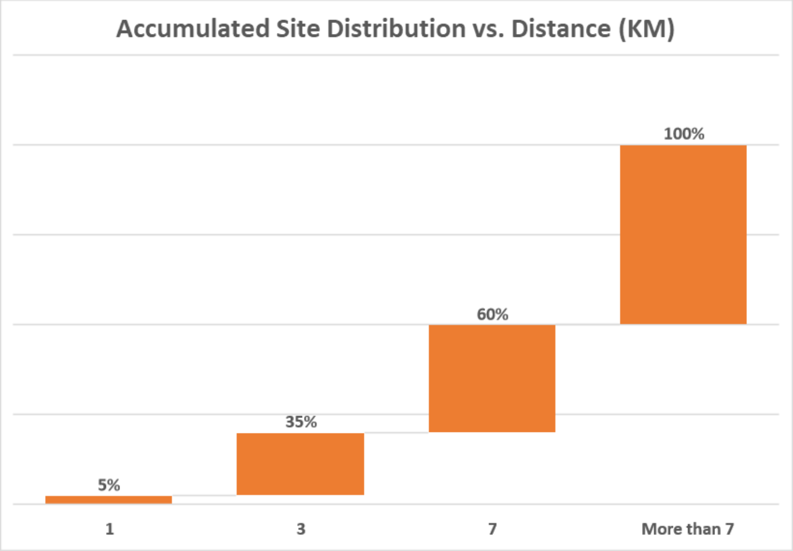

Figure 2 Accumulated site distribution (y-axis) vs. X-haul distance in kilometer (x-axis)

2.4. Automatic Provision and Management of End-to-end Traffic and Services Delivery

End-to-end automation processes for orchestration, provision, fault detection et al. are required to manage future high complexity mobile networks, including 6G, to deliver services with agility, speed, adaptation, and assurance. At the same time, maintain the economic sustainability of the highly diverse services offered.

In addition to high throughput and low latency requirements, 5G/6G mobile networks also require automatic provision and management of end-to-end traffic and services delivery.

Some of the features required include:

- Deterministic transmission latency and jitter
- Precise precision time synchronization
- SDN automation & advanced packet networking
- Dynamic bandwidth management

2.5. Cell-free Architecture

Cell-free architecture utilizes a vast number of distributed access points (APs) simultaneously communicating with all users in the network using joint coherent signal processing based on directly measured channel characteristics. It provides a better uniform user experience because there are no cell boundaries and, hence, boundary users are no longer severely impacted by inter-cell interference. This is realized by dramatically increasing the number of access points (AP). While total fronthaul capacity does not change in a cell free architecture, implementation of fronthaul becomes very complicated because each AP still needs a fronthaul link connecting antennas to the central unit (CU). How does the Open APN handle such potential deployment scenarios? Or is the fronthaul better served by a non-optical medium in such a configuration?

3. State of Art and Gap Analysis

3.1. Brief Review/analysis of Works by Other SDOs

3.1.1. 3GPP/O-RAN

3GPP defines the overall network architecture and specifications. Network function units and management systems are based on the Service Based Architecture (SBA), starting from 5G. Studies in 3GPP also estimate mobile access site transport capacity and performance requirements of various RAN configurations. However, 3GPP does not define all interfaces between disaggregated units.

O-RAN ALLIANCE (O-RAN) provides specifications and requirements for disaggregation, virtualization, open and intelligent radio access networks.

It extends 3GPP's work to define new RAN configuration (7-2X), decomposing DU into O-RAN Distributed Unit (O-DU) and O-RAN Remote Unit (O-RU), introducing an open interface in fronthaul. On RAN management & automation, the Service Management and Orchestration (SMO) framework manages all RAN network functions, including near-Realtime RAN Intelligent Controller (near-RT RIC), CU, DU, RU, as well as the cloud infrastructure. [O-RAN White Paper]

3.1.1.1. RAN Architecture and Interfaces for 5G

3GPP and O-RAN specify interfaces and profiles supporting disaggregated RAN architecture for 5G. This is illustrated in Figure 3.

- Backhaul
    - ➢ 3GPP specifies the backhaul interface between the RAN and Core Network (CN). For the 5G network, this is the NG interface between the gNB and User Plane Function (UPF).
- "Midhaul"
    - ➢ 3GPP also specifies the gNB internal interface to support disaggregated RAN architecture. The gNB can be split into gNB-DU and gNB-CU at higher layers of the radio protocol stack, i.e., higher-layer split. This is the F1 interface and is often referred to as the Midhaul. Compliant and complementary to 3GPP, O-RAN specifies profiles for the F1 interface to facilitate interoperability. [Note: Depending on application performance requirements and RAN deployment consideration, DU and CU can be collocated and hence no Midhaul]
- Fronthaul
    - ➢ O-RAN specifies the fronthaul interface between the O-RU and O-DU, further allowing the gNB to be split within the physical layer of the radio protocol stack, i.e., Lower-Layer Split (LLS). This is the LLS interface. O-RAN also specifies profiles for the LLS interface to facilitate interoperability.

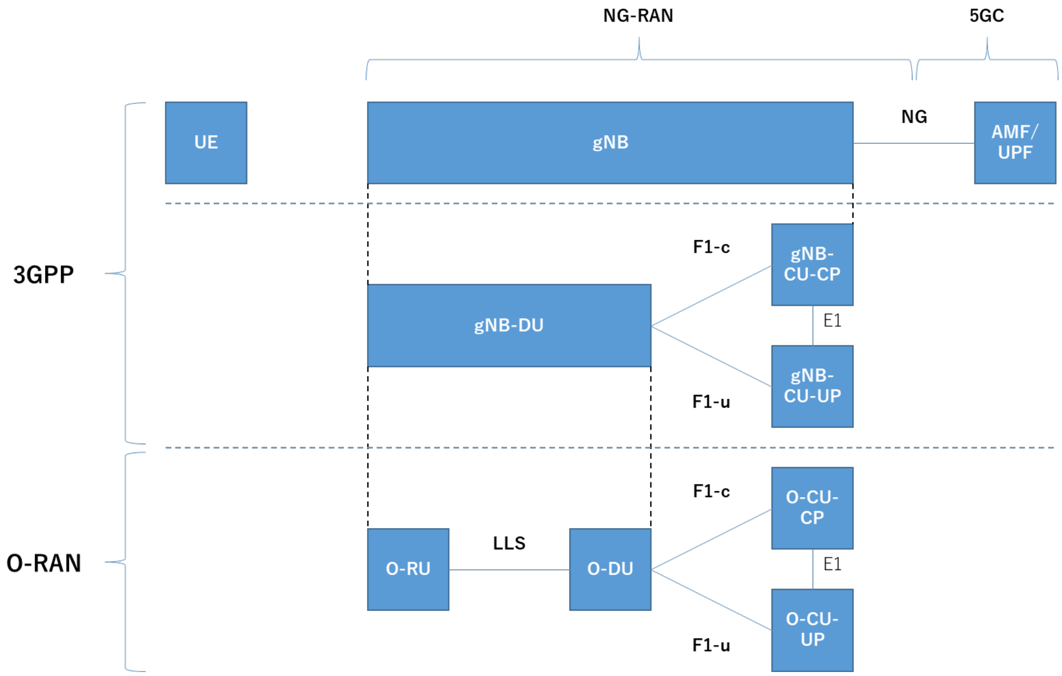

Figure 3 3GPP and O-RAN interfaces for disaggregated RAN architecture

3.1.1.2. Deployment Topologies for Disaggregated 5G RAN Architecture

Multiple deployment topologies are possible for disaggregated RAN. The choice may depend on various aspects, including form factor and power consumption of equipment at the cell site, bandwidth and latency of available transport links, desired level of centralization, service requirements on E2E latency, etc. 3GPP and O-RAN do not specify deployment topologies but have taken assumptions in designing interfaces for disaggregated RAN.

Figure 4 illustrates several possible deployment topologies based on those discussions.

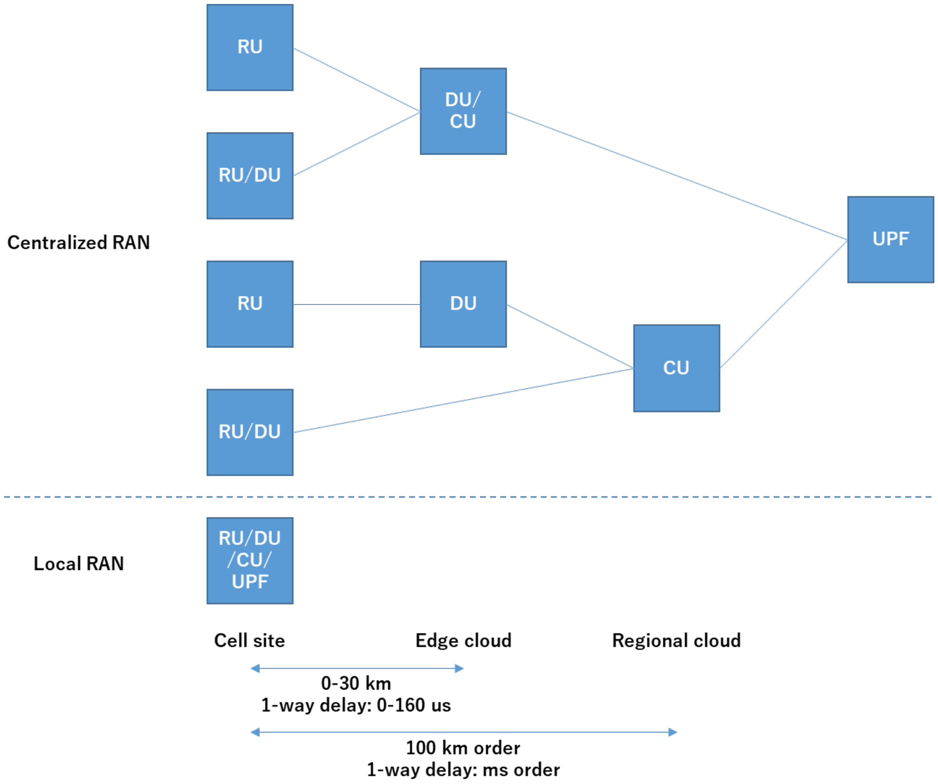

Figure 4 Possible Deployment Topologies for Disaggregated 5G RAN Architecture

Centralized RAN can take different forms. Locations where the RAN functionalities (RU, DU, CU) are placed, can be classified into (1) cell site, (2) edge cloud, and (3) regional cloud.

- RU, which consists of the antenna and lower parts of the physical layer, will be placed at the cell site for all topologies.
- DU, which consists of parts of the physical layer and also the Medium Access Control (MAC) and RAN Intelligent Controller (RLC) sub-layers of the radio layer 2, will be placed at the edge cloud for centralized RAN using LLS or at the cell site for centralized RAN only using higher layer split. For centralized RAN using lower-layer split, DU terminates Hybrid Automatic Retransmit reQuest (HARQ) retransmissions with the UE, the distance and delay between RU / cell site and DU/edge cloud are bound by the HARQ RTT. O-RAN has specified delay management parameters within their interoperability profiles for the lower layer split, where a maximum of 30 km distance and 160-microsecond 1-way delay between RU and DU are assumed.
- CU, which consists of the Packet Data Convergence Protocol (PDCP) sub-layer of the radio layer 2, may be placed at the edge cloud together with DU for centralized RAN using lower-layer split, or at the regional cloud for centralized RAN using either lower layer split or higher layer split. Distance in the order of hundreds of km and 1-way delay in milliseconds is expected between the cell site and regional cloud.

Local RAN, where all RAN functionalities together with the UPF are placed at the cell site, may also be considered for services with stringent E2E delay requirements and/or private network scenarios (e.g., use case for factory).

The impact on transport networks can be considered in terms of the required aggregation/bandwidth and latency/jitter. For example, 1 Edge Cloud may host 100 RUs, and 1 Regional Cloud may host more than 1000 RUs, so the aggregated throughput will be higher towards the backend of the RAN. The latency/jitter requirement is dependent on whether the transport link needs to support LLS or HLS, where there are captured in Table 2 of section 2.1.

3.1.1.3. 5G RAN Requirements and Resulting Transport Requirements

3.1.1.3.1. Performance Requirements

As Massive MIMO and mmWave spectra are increasingly used in the mobile network to deliver higher performance, fronthaul bandwidth and latency requirements to support the mobile network vary with different MIMO configurations and spectrum. Appendix A shows the required fronthaul bandwidth for different radio configurations with Sub6 and mmWave spectra.

3.1.1.3.2. Functional Requirements

Different types of traffic are carried over the RAN interfaces, and transport layers are required to support traffic flow identification and Quality of Service (QoS) differentiation.

For 3GPP defined RAN interfaces in [3GPP TS 38.472] [3GPP TS 38.474], e.g., backhaul interfaces and F1 interface, traffic flow identification is supported by Stream Control Transmission Protocol (SCTP)/IP for C-plane and by GPRS Tunnelling Protocol User Plane (GTP-U)/ User Datagram Protocol (UDP)/ IP for U-plane. Diffserv code points support QoS differentiation. For the fronthaul interface, the Ethernet option is the popular option, and traffic flow identification is supported by MAC address and Virtual Local Area Network (VLAN) ID. QoS differentiation is supported by the Priority Code Point tag in VLAN.

Although network slicing translates into transport network is debated, traffic flow identification and QoS differentiation would serve as the basis. While currently not in place, transport network management and orchestration would most likely enhance network slicing support.

3.1.1.4. Cloudification and Orchestration for RAN Functions

The key capabilities of SMO that provide RAN support in O-RAN are Fault, Configuration, Accounting, Performance, and Security (FCAPS) interface to O-RAN Network Functions, non-real-time RAN intelligent controller (Non-RT RIC) for RAN optimization, and O-Cloud Management, Orchestration and Workflow Management. The SMO performs these services through four interfaces to the O-RAN Element:

- A1 Interface between the Non-RT RIC in the SMO and the Near-RT RIC for RAN Optimization
- O1 Interface between the SMO and the O-RAN Network Functions supporting typical FCAPS
- O2 Interface between the SMO and the O-Cloud supports virtual resource management functions and other O-Cloud-related management functions.
- Open Fronthaul M-plane between SMO and O-RU for FCAPS support

SMO and the relationship of interfaces are summarized in Figure 5.

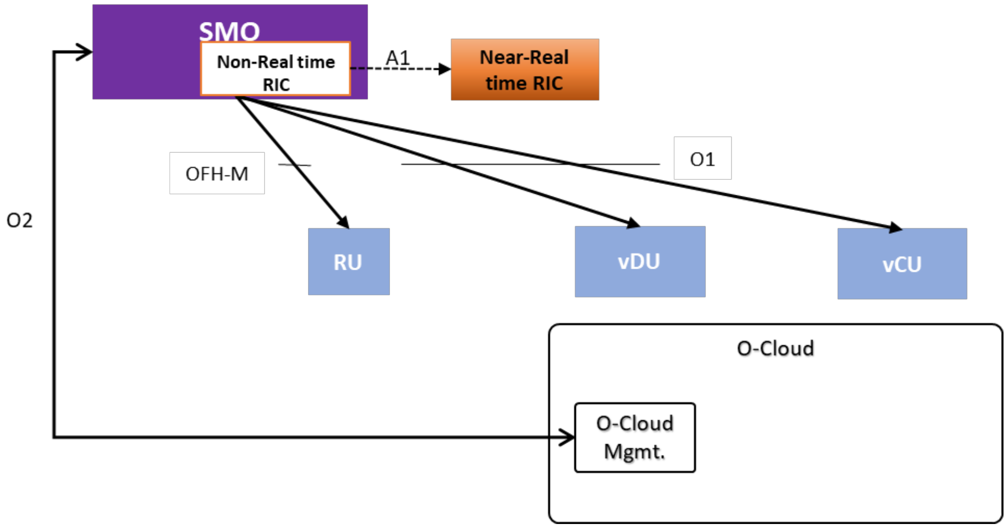

Figure 5 Service management orchestrator and O-Cloud

3.1.1.5. Mobile Network (RAN) Virtualization Study Details

Virtualization of RAN in the mobile network, called vRAN, is studied in several standard development organizations (SDOs) such as O-RAN. In addition, network functionality virtualization [ETSI NFV] is studied in SDOs. vRAN is expected to realize several virtual network functions like O-Cloud, defined in [O-RAN White Paper].

Virtualized functions in telecommunication networks are a set of software-defined functionalities that provide telecommunication network functions. A virtualized infrastructure provides the same capabilities as physical network equipment. In order to harmonize virtual or physical functionalities, network function orchestration is necessary, especially in the case of distributed functions. Orchestration and orchestrator in telecommunication network architecture study area are defined in [ITU-T Y.3100].

3.1.1.6. Cooperative Transport Interface (CTI)

This sub-section describes the Cooperative Transport Interface (CTI). CTI was introduced at the O-RAN Fronthaul Working Group (WG4) in 2020 [O-RAN CTI]. The CTI is an interface between O-DUs and Transport Nodes in a packet-based transport network that interconnects the O-DUs to various O-RUs. The CTI specifically targets transport nodes that manage a shared point-to-multipoint access network. It minimizes transmission scheduling delays of each UE by coordinating between an optical fiber access system and base station equipment.

Relevance of CTI to ITU-T specifications

The [O-RAN CTI] specifies the interface that supports cooperation between a base station and a transport network. An example of a transport network is a Passive Optical Network (PON) system which consists of Optical Network Units (ONUs) and an Optical Line Terminal (OLT).

One of the resource allocation methods of a PON system is the dynamic bandwidth assignment (DBA) that is a primary function in OLT and specified by ITU-T Recommendation [ITU-T G.989.3]. By sending UE scheduling information from the base station to PON (OLT) through CTI, DBA in PON can be made proactive. This proactive (low latency type) DBA is specified as cooperative dynamic bandwidth assignment (CO DBA) in ITU-T. Because the specifications on CTI are closely related to those of the base station, CTI was standardized at O-RAN WG4. On the other hand, CO DBA aligns with the scope of a PON system, which was standardized at ITU-T. For more details on CO DBA in ITU-T, see Section 3.1.5.

3.1.1.7. 5G Time-Sensitive Communications (TSCs)

- To address new and diverse use cases, including industry 4.0 and factory automation, 3GPP has been working to support Time-Sensitive Communications (TSC) by seamlessly integrating the 5G system as a bridge to IEEE 802.1 working group specifications covering Time-Sensitive Networking (TSN). 3GPP Release-16 has specified the TSN Translators supporting IEEE 802.1AS operations at the edges of the 5G system, TSC assistance information providing the deterministic traffic pattern to the 5G RAN for optimized scheduling of time-sensitive Release-17 will define support for uplink synchronization via 5GS, support for multiple working clock domains connected to the UE, and support for Time Synchronization of UE(s) with the TSN GM (Grand Master) attached to the UE side via 5G System. 3GPP specifications and technical reports related to TSN are listed as follows:
- TS 22.104; Service requirements for cyber-physical control applications in vertical domains; Stage 1 [3GPP TS 22.104]
- TR 22.832; Study on enhancements for cyber-physical control applications in vertical domains; Stage 1 [3GPP TR 22.832]
- TS 23.434; Service Enabler Architecture Layer for Verticals (SEAL); Functional architecture and information flows [3GPP TS 23.434]
- TS 23.501; System architecture for the 5G System (5GS); Stage 2 [3GPP TS 23.501]
- TS 23.502; Procedures for the 5G System (5GS) [3GPP TS 23.502]
- TS 23.503; Policy and charging control framework for the 5G System (5GS); Stage 2 [3GPP TS 23.503]
- TR 23.734; Study on enhancement of 5G System (5GS) for vertical and Local Area Network (LAN) services [3GPP TR 23.734],
- TS 24.007; Mobile radio interface signaling layer 3; General aspects [3GPP TS 24.007]
- TS 24.501; Non-Access-Stratum (NAS) protocol for 5G System (5GS); Stage 3 [3GPP TS 24.501]
- TS 24.519; 5G System (5GS); Time-Sensitive Networking (TSN) Application Function (AF) to Device-Side TSN Translator (DS-TT) and Network-Side TSN Translator (NW-TT) protocol aspects; Stage 3 [3GPP TS 24.519]
- TS 24.535; 5G System (5GS); Device-Side Time Sensitive Networking (TSN) Translator (DS-TT) to Network-Side TSN Translator (NW-TT) protocol aspects; Stage 3 [3GPP TS 24.535]
- TS 24.539; 5G System (5GS); Network to TSN translator (TT) protocol aspects; Stage 3 [3GPP TS 24.539]
- TS 28.541; Management and orchestration; 5G Network Resource Model (NRM); Stage 2 and stage 3 [3GPP TS 28.541]
- TS 29.122; T8 reference point for Northbound APIs [3GPPTS 29.122]
- TS 29.244; Interface between the Control Plane and the User Plane nodes [3GPP TS 29.244]
- TS 29.510; 5G System; Network function repository services; Stage 3 [3GPP TS 29.510],
- TS 29.512; 5G System; Session Management Policy Control Service; Stage 3 [3GPP TS 29.512]
- TS 29.513; 5G System; Policy and Charging Control signalling flows and QoS parameter mapping; Stage 3 [3GPP TS 29.513]
- TS 29.514; 5G System; Policy Authorization Service; Stage 3 [3GPP TS 29.514],
- TS 29.521; 5G System; Binding Support Management Service; Stage 3 [3GPP TS 29.521]
- TS 29.522; 5G System; Network Exposure Function Northbound APIs; Stage 3 [3GPP TS 29.522]
- TS 33.501; Security architecture and procedures for 5G System [3GPP TS 33.501]
- TS 38.413; NG-RAN; NG Application Protocol (NGAP) [3GPP TS 38.413]
- TS 38.423; NG-RAN; Xn application protocol (XnAP) [3GPP TS 38.423]
- TS 38.463; NG-RAN; E1 Application Protocol (E1AP) [3GPP TS 38.463]
- TS 38.473; NG-RAN; F1 application protocol (F1AP) [3GPP TS 38.473]

3.1.1.8. Mobile Positioning

Positioning technologies for mobile devices become even more important for future connected digital applications in production, logistics, security, emergency services, and vehicular use cases. 5G and 6G should enable and improve state-of-art positioning techniques embedded in Radio Access Network systems (RAN-embedded and RAN-external, respectively). For 5G, the impact of mobile positioning is defined in different 3GPP releases:

- Rel15: No localization for 5G stand alone. In non-standalone (4G&5G), 4G localization is used based on the existing Time Difference of Arrival method
- Rel16 (June 2021): 5G standalone with localization based on Observed Time Difference of Arrival (OTDOA) and Uplink Time-Difference-of-Arrival (UTDOA) with required precision of Localization less than 3 m and 10 m for indoor and outdoor scenarios, respectively!
- Rel17 (3GPP RP-193237): more stringent requirement for localization
  - <1 m for general commercial use cases with targeted latency < 100 ms
  - <0.2 m for Industrial IoT use cases with targeted latency in the order of 10 ms

In this paper, RAN-embedded technologies based on Cell-ID, Enhanced Cell-ID, downlink angle of departure, uplink angle of arrival, multi-cell round trip time, and down- & up-link time difference of arrival are discussed. Positioning techniques based on time difference are the most common solutions and embedded the difference of time-delays in the fronthaul interface.

The downlink time-based positioning techniques of User Equipment (UE) devices take advantage of the timing difference between several neighbors' Distributed Units (DU) and the UE to calculate the distance by estimating the Time of Arrival (TOA) or Time Difference of Arrival (TDOA) of specific radio signals. The Positioning Reference Signals (PRS) are initialized by the Radio Resource Control (RRC) layer at the CU in relation to the associated DU where time stamping is achieved. The UE measures the Reference Signal Time Difference (RSTD) with multiple iterations between a pair of CUs and DUs corresponding to these PRS. In other words, RSTD corresponds to the difference of flight time between two cell sites (CU&DU) for the UE. Before reaching the UE, the PRS travels across the mid-haul and fronthaul segments, the Radio Unit (RU) itself, and the air segment.

Table 3 proposes RSTD timing values standardized for 4G and calculated for 5G. 3GPP defines the RSTD timing values in the function of the basic timing unit called "Ts." For 4G and 5G, Ts value is 1/(2048xFs) and 1/(4096xFs), respectively, with Fs being the subcarrier spacing frequency. Fs is equal to 15 kHz for 4G, 30 kHz for 5G low carrier frequency (carrier frequency lower than 6 GHz in FR1) with 100 MHz bandwidth, and 120 kHz for 5G high carrier frequencies (typical 24.25-52.6 GHz, in FR2). For 4G, the minimum RSTD resolution is equal to Ts (Ts/2 for high accuracy mode). The UE RSTD measurement accuracy error is ±4xTs. Because 5G RSTD is not yet defined, IOWN Global Forum proposes to re-use the same 4G calculation based on Ts for 5G.

Table 3 RSTD timing values standardized for 4G and calculated for 5G

Unit (ns)	4G	5G FR1	5G FR2
Ts	32.6	*8.1*	*2*
RSTD resolution	32.6	*8.1*	*2*
RSTD accuracy	± 130	*± 32.6*	*± 8,1*

5G and 6G fronthaul support PtP/SyncE to achieve phase/time synchronization at RU. In this case, a one-way measurement is possible because DU and RU are synchronized with a relative Time Error (TE) in relation to Primary Reference Time Clock (PRTC). The fronthaul asymmetry is considered part of the TE contribution that must be below the required RSTD resolution. Three points must be noted: the T_{12} fronthaul measurement is performed by the Control-Plane, the synchronization has its dedicated Sync-Plane, and finally the PRS is embedded in the radio resource element map in the User-Plane. Due to these different references at different levels, the time of the T_{12} fronthaul measurement and PRS transmission could differ. Such time difference in combination with Ethernet transport jitter and wander could considerably impact RSTD resolution and accuracy.

For 5G fronthaul, the relative and absolute fiber asymmetry is defined below the required RU TE (based on Sync. plane), which must also be below the RSTD resolution. Presently, O-RAN specification proposes relative TE margins to consider transport asymmetry between 12 and 60 ns depending on synchronization features. But these specifications are proposed while excluding TDOA applications. IOWN Global Forum can consider that requirements without radio positioning (i.e., those considered by the existing O-RAN specification) as the minimum requirements for supporting radio positioning based on time measurements.

The IOWN Global Forum has to consider the imbalance between latency and synchronization transport requirements compared with mobile positioning requirements.

3.1.2. OIF

3.1.2.1. About OIF

The Optical Internetworking Forum (OIF) is a global industry forum that promotes the development and deployment of interoperable networking solutions and services by developing specifications as Implementation Agreements (IAs). IAs are created for optical network products, network processing elements, and components technologies as follows:

- External network element interfaces
- Software interfaces internal to network elements
- Hardware component interfaces internal to network elements

3.1.2.2. State of the Art of OIF

OIF has published a number of IAs. For optical interfaces, up to 400 Gbps, IAs have been published. And 800 Gbps project has started. For electrical interfaces, up to 50 Gbps class IAs, namely CEI-56G, have been published, and 100 Gbps class IAs, namely CEI-112G development process, is approaching the final step, therefore this IA will be published soon. Discussions on the 200 Gbps class electrical interface began in 2020.

Moreover, OIF leads the standardization of Co-Packaged Optics (CPO). One initial object of CPO standardization is the CPO transceiver module based on 400G Ethernet standards, namely 400GBASE-FR4 and 400GBASE-DR4. This CPO transceiver module will substitute for conventional optical transceivers like Quad Small Form-factor Pluggable - Double Density (QSFP-DD). The other supposed application of CPO is the conversion of conventional electrical interfaces to optical interfaces.

For example, “opticalizing” the Compute Express Link (CXL) interface is a supposed application. But detailed discussions have not been started as of August 2021.

3.1.2.3. Relationship with Mobile Network

OIF is working toward a high capacity (more than 100 Gbps) optical network solution, which is supposed to be used for telecom and datacom applications. Therefore, mobile communication is not considered one of their direct applications currently. Previously, high-capacity optical network standardized in OIF was not targeted for the mobile network, though their standardized electrical interface called Common Electrical Interface (CEI) has been used in the mobile base station widely.

As the mobile network evolves, high-capacity optical network discussion in OIF will be required for the mobile network.

3.1.3. MEF

3.1.3.1. About MEF

MEF is a global industry forum for network and cloud providers. MEF develops a global federation of network, cloud, and technology providers in establishing dynamic, assured, and certified services that empower enterprise digital transformation.

MEF was founded in 2001 as a non-profit international industry consortium. The focus was originally dedicated to Carrier Ethernet networks and services. After 2015, the focus of MEF was extended to include additional underlay connectivity services such as optical transport and IP and overlay services such as Software-Defined Wide Area Network (SD-WAN). Then, MEF tackled orchestration and automation head-on with its Lifecycle Services Orchestration (LSO) framework and related interface reference points and APIs.

3.1.3.2. State of the Art in MEF

3.1.3.2.1. Overview

MEF defined transport services on Layers 1, 2, and 3 (L1, L2, and L3) and defined orchestration between telecommunication service providers and internal networks. MEF also defined mobile fronthaul (FH), middle haul (MH), and backhaul (BH) services and interfaces. MEF published “MEF White Paper: Slicing for Shared 5G Fronthaul and Backhaul” in April 2020, which describes the concept of 5G mobile access network sharing and use cases for providing multiple mobile access network services over a common underlying fronthaul and backhaul infrastructure.

Figure 6 is extracted from the white paper, which shows the MEF service supporting the 5G network. Mobile Network Operator and Transport Network Provider, shown at the top of the figure, have mobile domain orchestrator and transport domain orchestrator, respectively. MEF specifies LSO, implemented by the transport network provider, and underlay transport connectivity standards. In the 5G case, mobile network operators configure mobile network functions such as RUs, DUs, CUs, and 5GC using their internal interfaces. The activities related to the mobile network in MEF are as follows:

(1) LSO framework and APIs

LSO and APIs enable frictionless, end-to-end service automation, within and between providers, direct to the enterprise.

(2) Underlay Connectivity Services standard

Underlay connectivity provides technology-agnostic service capabilities for service providers to connect subscribers, e.g., an enterprise and its office locations.

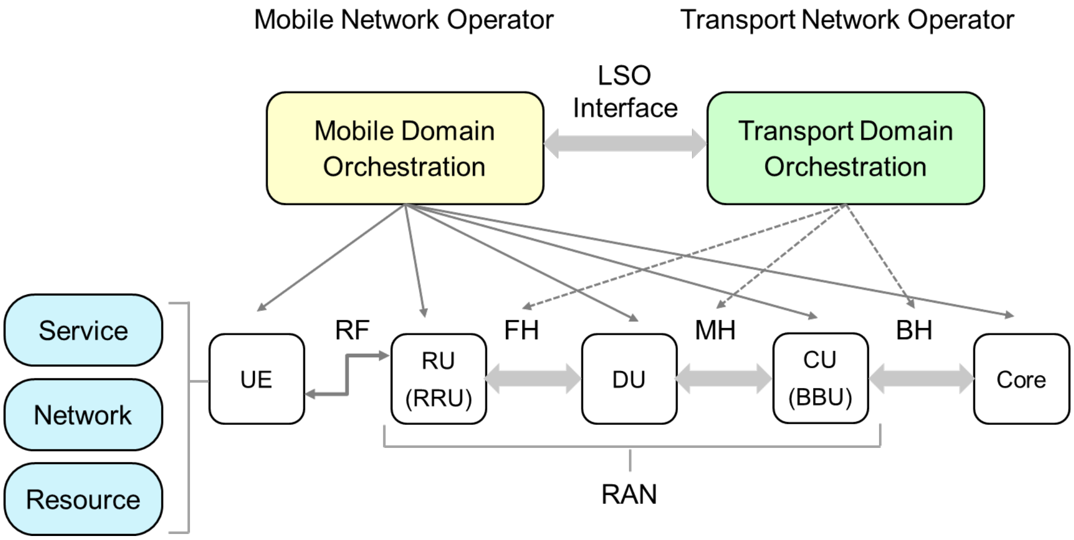

Figure 6 MEF services supporting 5G network [MEF Slice]

3.1.3.2.2. Transport Service

The transport network considered by MEF is shown in Figure 7. There are two interfaces; one is the User-Network Interface (UNI) which connects users and service providers, and another is External Network to Network Interface (E, NNI,) which connects between service providers. At the UNI and the ENNI, transport connectivity specifications were described in several MEF standards for each layer. The specifications between Operation Support System (OSS)/ Business Support System (BSSs) and orchestrators are expected to use CANTARA, SONATA, ALLEGRO, LEGATO, INTERLUDE, and PRESTO.

MEF specifications in the figure are the following:

MEF 61.1: IP Service Attributes

MEF 10.3: Ethernet Services Attributes

MEF 63: Subscriber Layer 1 Service Attributes

MEF 26.2: ENNI and Operator Service Attributes

MEF 64: Operator Layer 1 Service Attributes and Services

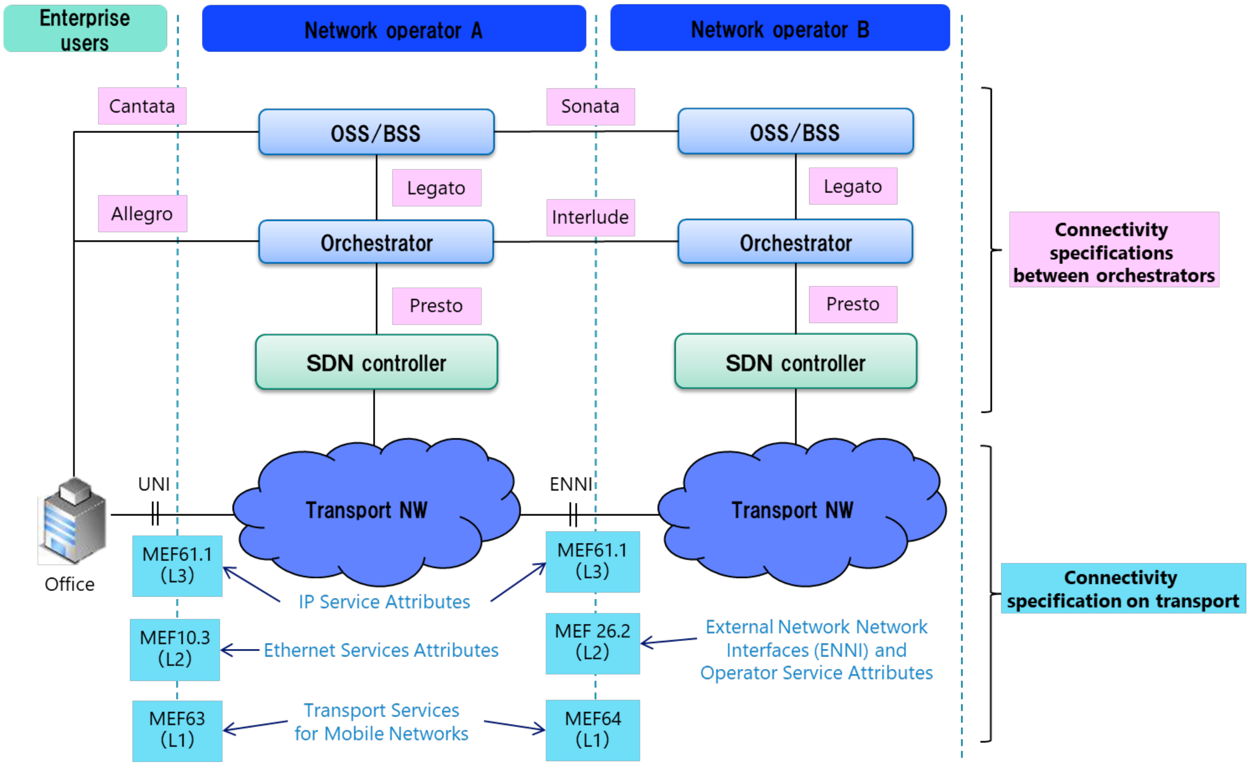

Figure 7 Transport Service in MEF

Considering mobile network, MEF 10.3 and MEF 22.3/22.3.1 series can be utilized to interfaces or attributes between RU and DU, DU and CU, CU, and 5GC. Figure 8 shows the relationship between MEF standards and the mobile network.

(1) MEF10.3：Ethernet Service Attributes Phase 3

This specification defines the values of attributes in basic MEF Ethernet specifications, which are referred to by Ethernet specifications under Enhanced Common Public Radio Interface (eCPRI).

(2) MEF22.3/MEF22.3.1：Transport Service for Mobile Network

MEF22.3 specifies Ethernet specifications for Mobile BH, and MEF22.3.1 enhances the specifications for Mobile FH and MH. These specifications define the detail parameters along with MEF10.3 and provide the functions of time synchronization.

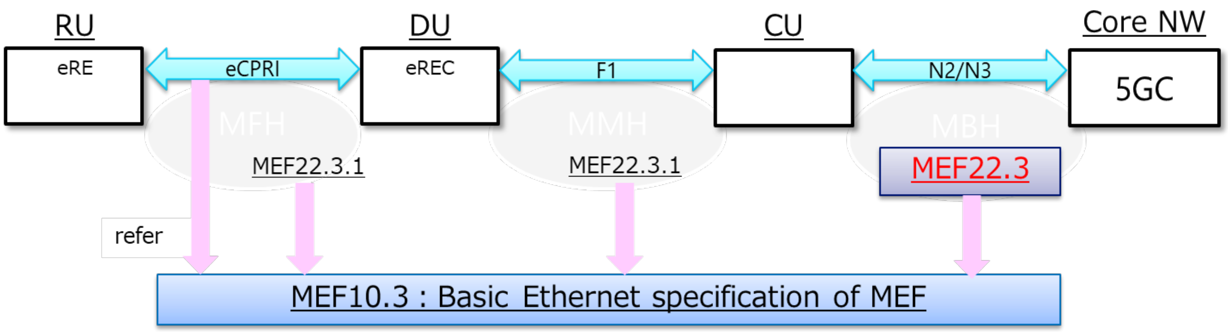

Figure 8 The relation of transport specifications for MEF mobile network

3.1.3.3. Orchestration and Control of Transport Connectivity Services

As for transport service management, the LSO framework is truly relevant. It defines the reference points between service orchestration functions within the service provider and external entities, such as mobile operators. The MEF standardizes these reference points in [MEF 55], developing information models as APIs to support each reference point. The LSO reference points are:

- CANTATA: The Management Interface Reference Point provides a Customer Application Coordinator with capabilities to manage interactions with the Service Provider's Business Applications for a portion of the Service Provider service capabilities related to the Customer's Products and Services.

- ALLEGRO: The Management Interface Reference Point that allows Customer Application Coordinator supervision and control of dynamic service behavior of the LSO service capabilities under its purview, through interactions with the Service Orchestration Functionality.

- LEGATO: The Management Interface Reference Point between the Business Applications and the Service Orchestration Functionality manages interactions supporting connectivity services.

- PRESTO: The Resource Management Interface Reference Point is needed to manage the network infrastructure, including network- and topology-view-related management functions.

- ADAGIO: The Element Management Interface Reference Point needed to manage the network resources, including element-view-related management functions.

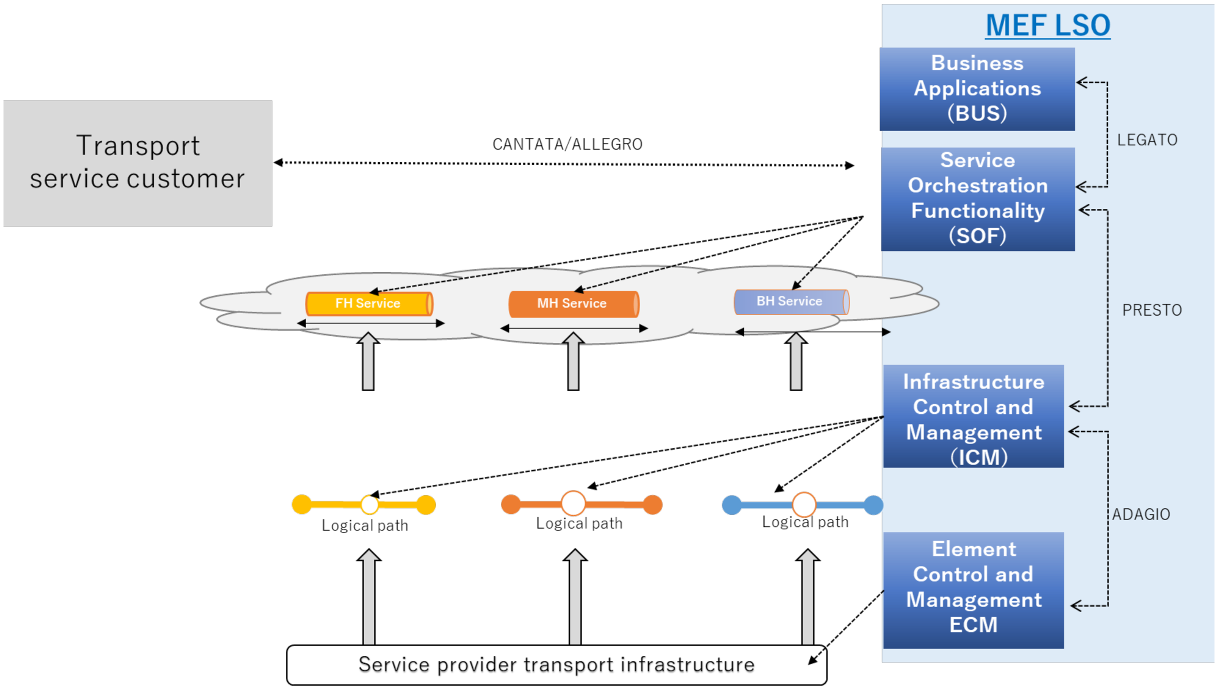

Figure 9 Lifecycle service orchestrator in MEF

3.1.4. TIP

The Telecom Infra Project (TIP) is a global community of operators and vendors that are driving commercially viable infrastructure solutions through proof-of-concepts and trials leveraging TIP Community Labs. TIP projects span from the mobile network to the core network and have extended to much-needed industry solution groups such as 5G private Networks, Connected City Infrastructure, and Network as a Service.

TIP OpenRAN Project Group, formed in 2017, aims to accelerate disaggregation and innovation in RAN technologies. It covers Indoor 5G NR Small Cell, Outdoor Macro, RAN Intelligence & Automation and drives technical requirements for RU, DU & CU based on service provider priority to support different deployment scenarios.

TIP has a Liaison Agreement with O-RAN Alliance to allow TIP OpenRAN to reference O-RAN Alliance specifications and collaborate on industrial events such as PlugFest. TIP Exchange Marketplace lists TIP-verified vendor solutions enabling flexible and interoperable 2G/3G/4G and 5G deployments for operators.

TIP's vRAN Fronthaul group aims to achieve a commercially viable ecosystem in which the transmission between the Virtualized Baseband Unit (vBBU) and the RRU can work over non-ideal fronthaul (lower bandwidth and/or higher latency compared with CPRI).

The Open API proposed by TIP requires the interface between vBBU and RRU not tied to a specific transport layer-1 or layer-2 implementation and be deployable over a variety of links and fronthaul transport networks, including Ethernet and packet-switched networks based on Internet Protocol (IP).

Past projects in TIP focused on 2G, 3G, and 4G access, though the OpenRAN project extends the work toward 5G NR. Given that not all specifications used in TIP programs (e.g., management layer) are fully defined yet, a TIP compliant network is yet to be deployed.

3.1.5. ITU-T

The International Telecommunication Union Telecommunication Standardization Sector (ITU-T) is the telecommunications standardization division of the ITU, which develops international standards known as ITU-T Recommendations. They act as defining elements in the global infrastructure of information and communication technologies (ICTs).

ITU-T consists of several Study Groups (SG), which are categorized by study items. For mobile systems, SG13 and SG15 develop IMT-2020 and related standards.

In SG15, G.989 series standardized Next-Generation Passive Optical Network Stage 2 (NG-PON2) as a 40 Gbit/s class PON system emphasizing economic capacity enlargement and service expandability. They introduced wavelength-division multiplexing (WDM) technology based on the conventional PON system. The primary NG-PON2 solution is TWDM (time and wavelength-division multiplexing)-PON, a hybrid of conventional TDM (time-division multiplexing) and WDM technologies. The PON system consists of an ONU installed on the user side, an OLT installed at the central office, an optical splitter, and optical fibers. In addition to providing broadband services to residential users like a previous PON system, NG-PON2 systems are also expected to accommodate business users and mobile users (mobile service) [ITU-T G.989.3], [K. Asaka].

Optical-mobile cooperative DBA (CO DBA), a cooperative scheduling scheme to minimize optical transmission delay, was introduced to accommodate mobile systems. The CO DBA signaling interfaces enable mobile scheduling information to be sent to an optical access system in advance. The same approach was referred to as the CTI in O-RAN. This technique for low-latency control (CO DBA) of a PON system using mobile scheduling information is described in the ITU-T Recommendation [ITU-T G.989.3], and related technical information is provided in [ITU-T G. Sup66].

3.1.6. IEEE

3.1.6.1. IEEE802.1

IEEE 802.1CM [IEEE 802.1CM] defines synchronization recommendations specifically for fronthaul transport networking. The standard specifies an Ethernet bridged network for connecting RU to a remote controller (DU functionality). TSN for Fronthaul is developed in collaboration with the CPRI Cooperation, which provided the CPRI and eCPRI requirements.

With TSN-enabled Fronthaul, time-sensitive traffic can be transported in the same packet network as non-time-sensitive traffic without performance being negatively impacted. Thus, a single TSN node can serve various types of traffic by aggregating different traffic into high data rate ports.

Two TSN transport profiles are defined for the Fronthaul standard, applicable to CPRI and eCPRI protocols. Profile A treats user data (IQ data) as a high priority class above control and management data. At the same time, Profile B also adds a TSN feature called frame preemption (originally specified in IEEE 802.3br [IEEE 802.1BR] and 802.1Qbu); on top of Profile A components prioritize different traffic types. Profile B enables a greater level of performance in a deterministic network. TSN profiles for various types of networking such as Aerospace, Audio Video Bridging (AVB), Automotive In-Vehicle, Industrial Automation, and Utility, in addition to those for Cellular Fronthaul networks, have also been and/or are being specified.

The IEEE 802.1 TSN Task Group (TG)[5] also specifies Frame Preemption [IEEE 802.1 Qbu] together with Interspersing Express Traffic (IET) Task Force (TF), called 802.3br, Time-Aware Shaper (TAS), called 802.1Qbv, Cyclic Queuing

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[5] See https://1.ieee802.org/tsn/ in detail on IEEE 802.1 Time-Sensitive Networking (TSN) Task Group

and Forwarding (CQF), called 802.1Qch mechanisms, and so on. The IEEE 1914 NGFI Working Group specifies Next Generation Fronthaul Interface as requirements for the TSN.

3.1.6.2. IEEE802.3

3.1.6.2.1. About IEEE802.3

IEEE 802.3 Ethernet Working Group is one of the working groups in the IEEE 802 LAN/MAN standard committee. It is working for the standardization of Ethernet-related issues. They include the physical layer and data link layer's MAC; however objective area is the wired system only.

3.1.6.2.2. State of the Art of IEEE802.3

There are a number of active projects, study groups, and Ad Hoc in IEEE802.3, as listed in Table 4.

Table 4 List of active projects, study groups, and Ad Hoc (All data is as of June 20, 2021)

IEEE P802.3ck	100 Gbps, 200 Gbps, and 400 Gbps Electrical Interfaces Task Force.
IEEE P802.3cp	Bidirectional 10 Gbps, 25 Gbps, and 50 Gbps Optical Access PHYs Task Force
IEEE P802.3cs	Increased-reach Ethernet optical subscriber access (Super-PON) Task Force
IEEE P802.3ct	100 Gbps over Dense wavelength division multiplexing (DWDM) systems Task Force
IEEE P802.3cv	Power over Ethernet (Maintenance #15) Task Force
IEEE P802.3cw	400 Gbps over DWDM systems Task Force
IEEE P802.3cx	Improved PTP Timestamping Accuracy Task Force
IEEE P802.3cy	Greater than 10 Gbps Electrical Automotive Ethernet Task Force
IEEE P802.3cz	Multi-Gigabit Optical Automotive Ethernet Task Force
IEEE P802.3da	10 Mb/s Single Pair Multidrop Segments Enhancement Task Force
IEEE P802.3db	100 Gbps, 200 Gbps, and 400 Gbps Short Reach Fiber Task Force
IEEE P802.3 (IEEE P802.3dc)	Revision to IEEE Std 802.3-2018 Maintenance #16 Task Force
IEEE P802.3dd	Power over Data Lines of Single Pair Ethernet (Maintenance #17) Task Force
IEEE P802.3	Beyond 400 Gbps Ethernet Study Group
IEEE P802.3	Enhancements to Point-to-Point Single Pair Ethernet Study Group
IEEE P802.3	New Ethernet Applications Ad Hoc
IEEE P802.3	PDCC Ad Hoc

The latest major discussions in IEEE802.3 task forces are up to 400 Gbps optical links, 100 Gbps/lane electrical links, and transmission distance extension of 10 Gbps-class PON (Super-PON). In recent years, high-speed Ethernet for automotive has also been discussed enthusiastically.

3.1.6.2.1. Relationship Between IEEE802.3 and Mobile Networks

IEEE802.3 is a standardization for wired networks; however, Ethernet has been widely used for the transport layer of mobile networks. Therefore, in IEEE802.3 standards, support technologies for wireless networks have been also discussed. In P802.3cx, improvement of time stamp accuracy has been discussing to support 5G’s C-RAN architecture.

As just described, IEEE802.3 has been working for cutting-edge Ethernet technologies. In the beginning period of mobile networks, 1 Gbps was suitable for the mobile FH, MH, and BH. Such Optical Ethernet was already standardized and widely used for wired networks. Therefore existing standardized Ethernet technologies could be used for mobile networks as well.

However, as mobile technologies advance, requirements for Ethernet technologies have become increasingly stringent.

In current discussions, when the IEEE802.3 starts developing new standardization, mobile networks are considered a critical application from the beginning of the discussion. In some Call for Interest (CFI) presentations for new standardization, mobile networks are defined as an essential application. For example, 400GbE 40 km standardization was completed in 2019. And this CFI presentation was held in 2017 [*3]. In this CFI presentation, mobile networks are described as one of the critical components of an Ethernet ecosystem.

Recently, in a study group, 800 Gbps, 1600 Gbps optical links, 200 Gbps/lane electrical links, and co-packaging optics have been discussed as the next standardization topics. But these discussions are based on the conventional configuration, that is, PHYs have optical and electrical interfaces. The idea of an All-optical network, such as the Open APN of IOWN Global Forum, has not yet been discussed.

3.1.7. Cloud Native Computing Foundation (CNCF)

The Cloud Native Computing Foundation (CNCF) is a part of the Linux Foundation (LF). CNCF serves as the vendor-neutral home for many of the fastest-growing open source projects, including Kubernetes for container orchestration, Envoy for side-car proxy in service mesh, Container Network Interface (CNI), and Operator Framework for Site Reliability Engineering.

While IT communities adopt the CNCF approach, integrating various CNCF projects in a wireless communication network is challenging because existing tools, products, and different maturity levels toward cloud native deployments may not be optimized or cost-effective.

The CNCF launched Telecom User Group to harmonize cloud native computing and networking. It is now collaborating with LF Networking who is initiating work across the Common NFVI Telco Taskforce (CNTT) to create reference architectures for CNF (Cloud Native Network Function) and VNF (Virtual Network Function).

3.1.8. IETF

3.1.8.1. About IETF

The Internet Engineering Task Force (IETF) is a large, open international community of network designers, operators, vendors, and researchers concerned with the evolution of the internet’s architecture and the smooth operation of the Internet overall. The technical work of the IETF is done in its working groups, which are organized by topic into several areas (e.g., routing, transport, security, etc.). Working Groups are the primary mechanism for developing IETF specifications and guidelines. The IETF publishes Request for Comments (RFCs) authored by network operators, engineers, and computer scientists to document methods, behaviors, research, or innovations applicable to the Internet.

3.1.8.2. Deterministic Networking

The IETF Deterministic Networking Working Group (DetNet WG)[6] addresses Layer 3 and Layer 2 aspects of applications requiring deterministic networking. This DetNet WG is responsible for the overall DetNet architecture[7] and DetNet-specific specifications[8] based on IP and MPLS technologies. The work items are the data plane[9], OAM[10], Data model (YANG)[11], time synchronization[12], management, control[13], and security[14] aspects. Interworking between the DetNet network and IEEE802.1 TSN network is also considered.

3.2. Gap Analysis

3.2.1. Connectivity Service Level and Requirements

The tables below are the gaps in connectivity service level details based on MEF specifications. The values in L2 are extracted from [MEF 10.3] and [MEF 23.2], and the values on L1 and L3, as indicated with round brackets, are predicted from specifications [MEF63] and [MEF 61.1], respectively, since the values are not specified yet.

Table 5 Connectivity service level

		L1: OTN*5	L2: Ether*1	L3: IP*2 *5	Mobile Transport(L2) *3
Service		P-to-P (Ether/SDH/SONET)	P-to-P/MP-to-MP/ Rooted-MP	MP-to-MP	P-to-P/MP-to-MP (MH/BH) Synchronization
Bandwidth		155Mbps-100Gbps	<10Gbps	<10Gbps	<10Gbps
Delay (ms) *4	PT0.3*6	(≤0.5 ms)	≤3 ms	(≤3 ms)	BH: ≤1 ms / FH: N/A
	PT1*6	(≤2 ms)	≤10 ms	(≤10 ms)	BH: ≤10 ms
	PT2*6	(≤8 ms)	≤25 ms	(≤25 ms)	-
Mean Delay (ms) *4	PT0.3*6	-	≤2 ms	(≤2 ms)	BH: ≤0.7ms / FH: N/A
	PT1*6	-	≤7 ms	(≤7 ms)	BH: ≤7 ms
	PT2*6	-	≤18 ms	(≤18 ms)	-
Delay Variation (ms) *4	PT0.3*6	-	≤1ms	(≤1 ms)	BH: ≤0.3ms / FH: N/A
	PT1*6	-	≤3ms	(≤3 ms)	N/S
	PT2*6	-	≤8ms	(≤8 ms)	-
	PT0.3*6	-	≤1.25ms	(≤1.25 ms)	≤0.5ms (BH)

---

[6] See https://datatracker.ietf.org/wg/detnet/about/ for the charter and milestones, and https://datatracker.ietf.org/wg/detnet/documents/ for the DetNet documents

[7] Overall DetNet Architecture including: [IETF RFC8655]

[8] DetNet-specific Problems and Use Cases including: [IETF RFC8557] and [RFC8578]

[9] DetNet Data Plane including: [IETF RFC8938], [RFC8939], [RFC8964], [RFC9023], [RFC9024], [RFC9025], [RFC9037], and [draft-ietf-detnet-ip-over-mpls]

[10] OAM for DetNet including: [draft-ietf-detnet-ip-oam], [draft-ietf-detnet-oam-framework], [draft-ietf-detnet-mpls-oam]

[11] DetNet YANG Model including: [draft-ietf-detnet-yang]

[12] DetNet Time Synchronization aspect including: [draft-ietf-detnet-bounded-latency]

[13] DetNet Management and Control aspect including: [IETF RFC9016]

[14] DetNet security aspect including: [IETF RFC9055]

Delay Range (ms) *4	PT1*6	-	≤5ms	(≤5 ms)	N/S
	PT2*6	-	≤10ms	(≤10 ms)	-
PLR (%)	PT0.3*6	(26 sec)	≤0.001 %	(≤0.001 %)	≤0.001 % (BH) / FH: N/A
	PT1*6	(259 secs)	≤0.01 %	(≤0.001 %)	≤0.01 %
	PT2*6	(259 secs)	≤0.01 %	(≤0.01 %)	-
Orchestration		Ongoing	Available	Ongoing	Not ready

*1 taken from [MEF 23.2]: Carrier Ethernet Class of Service – Phase 3,

*2 taken from [MEF 69]: Subscriber IP Service Definitions

*3 taken [MEF 22.3]: Transport Service for Mobile Network

*4 Represents Frame Delay for L2, Packet Delay for L3,

*5 The delay figures are assumed to be equivalent to the physical distance of layer 1 connectivity

*6 PT0.3 represents sub-Metro distance (<75km, 0.5ms), PT1 represents Metro distance (<250km, 2ms), PT2 represents regional distance (<1200km, 8ms), PT3 (Continental PT) - derived from typical National/Continental distances (<7000 km, 44 ms), PT4 (Global PT) – derived from typical Global/Intercontinental distances (<27500 km,172

The table below shows the requirements on mobile X-Haul based on gaps in a transport implementation

Table 6 Requirements on Mobile X-Haul

	FH			MH		BH	
Interface	CPRI/eCPRI			Control plane : F1-C, E1, Xn-C User Plane: F1-U, Xn-U		Control plane: N1, N2, N4 User Plane: N3, N9	
Connectivity Requirements	-			Multi-point		Multi-point	
Option	WDM	Ether***	IP***	Ether*	IP**	Ether*	IP**
Scale/Distance	0km - 30km			100 km order		More than 100,000 RUs	
Slicing	-			1K slices, with delay and availability assurance, and isolation			
Protection/restoration	Protection			50ms protection of connectivity			
Peak data rate	25Gpbs – 75Gbps			From a few Gbps to 70Gbps per RU			
Frame delay (one way)	25us – 160us			1.5 – 10ms		1ms – 50ms	
Frame Loss Ratio (One way)	10^{-7}			N/A		N/A	
PDV	10us			N/A		N/A	
Synchronization accuracy	65ns			N/A		N/A	

*MEF 6.2 [MEF 6.2], **MEF61.1[MEF 61.1], ***Common Public Radio Interface: Requirements for the eCPRI Transport Network

3.2.2. Gaps on Connectivity Services

IOWN GF Technology for mobile networks will provide a certain level of connectivity. As explained challenges in Chapter 2, there are several gaps in existing L1/L2/L3 connectivity services as follows:

1. High bandwidth services needed, more than 100Gbps for FH/MH/BH
2. Less than 150 μsec delay connectivity service for distance shorter than 30 km, which are specified by MEF standards, especially for FH
3. Less loss rate connectivity servicer for FH
4. Time/frequency synchronization in nanoseconds over connectivity services
5. Protection/restoration feature or equivalent reliability performance

In addition to the above gaps, the following are the gaps for new connectivity services.

6. WDM-like L0/wavelength-based connectivity service enables high data rate and extremely low latency for FH.
7. Support for slicing for MH/BH.

Gaps in the orchestration for connectivity services are:

- Orchestration, control, and management features to new/extended connectivity service for easy deployment and automated operation of X-Haul connectivity over APN.
- Orchestration, control, and management features for synchronization

3.2.3. Orchestration

Network functions in mobile networks have been virtualized in recent years. The 5G microservice architecture based on cloudification is adopted to 5G Core Networks. Along with the virtualization and cloudification, orchestration of network functions, ETSI NFV specs [ETSI NFV] are expected to be common for the implementation of network automation and operations. In the RAN domain, the virtualization or containerization of RAN functions are also being studied in the O-RAN Alliance and are expected to be deployed in the coming years.

The orchestration functions with integrated control, management, and optimization of network services or resources are expected to enable rapid and agile network deployment, network automation, and policy-driven network optimization. Furthermore, one of the 5G mobile network features is network slicing, which uses portions of spectrum to deliver high-performance services, such as eMBB, URLLC, and mMTC with specialized SLAs for specific use cases. The orchestration functions should enable organizations to perform provision, operation, and management for those network slices.

Similarly, in the transport domain such as IP or optical network, Software Defined Networks (SDN) is expected to be common. Many organizations and forums provide API specifications for orchestrating functions of different domains so that most technologies are becoming SDN-enabled.

Network slices of spectrum leveraged by the mobile network may consist of RAN, transport, and CN domains. The orchestration of those three domains is required to provide stable and assured communication quality over the network slice with the agile and on-demand operation.

With consideration of O-RAN SMO, its interfaces, and MEF LSO architecture, the provisioning and management of mobile network over APN should support or comply with these two standardized architectures and interfaces. Because the APN would be the infrastructure for mobile networks as shared transport infrastructure, the APN controller is equivalent to Element Control and Management (ECM) in MEF LSO. The ADAGIO reference point is applicable to control X-Haul connections through the APN controller.

An example scenario of X-Haul connectivity activation in conjunction with O-RAN CU/DU deployment is: after O-RAN SMO triggers O-Cloud mgmt to deploy DU and CU on O-Cloud, Service Orchestration Functionality (SOF) triggers FH/MH/BH connectivity service for them to use Infrastructure Control and Management (ICM) through PRESTO. The ICM determines a logical path based on the resource management module and creates X-Haul connections using APN, and then SMO activates FH/MH/BH protocol running in RU/DU/CU/Core. Figure 10 shows the image of orchestration in this example scenario.

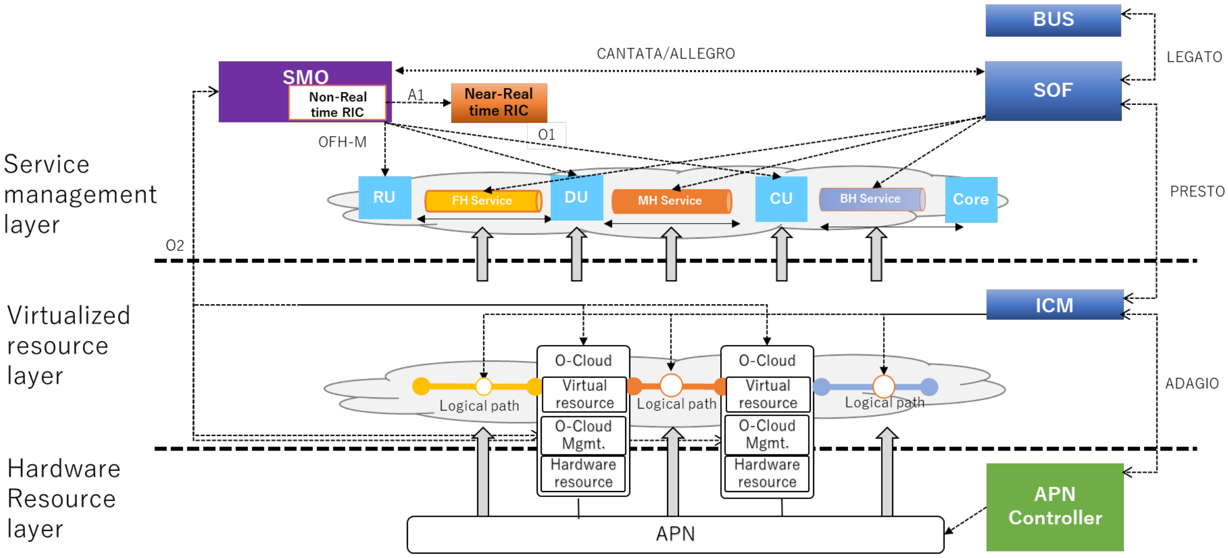


Figure 10 Orchestration

3.2.4. Low Latency Technology

3.2.4.1. Low Latency Services

The IOWN Global Forum Open APN is an ideal network that provides broad bandwidth with minimum latency. On the other hand, as shown in Appendix B, some mobile service flows are expected to be served with much narrower bandwidth than that provided by a single APN lambda channel.

It implies that some packet-based multiplexing is provided by an extra network between RUs and an APN Transceiver. Thus, IOWN Global Forum needs to clarify requirements on the multiplexing/forwarding services by the extra network. (See also Appendix B of the IOWN Global Forum's Open APN Functional Architecture document.)

3.2.4.2. CTI

The IOWN Global Forum aims to develop a network that enables end-to-end low-latency services due to the advantages of APNs. Providing low-latency services through a mobile network over APN, latency control in optical paths, and/or Layer 2 switch (L2SW) in APN by using the information provided by the mobile network are necessary. As mentioned in Sections 3.1.1.6 and 3.1.5, the CTI is one of the key technologies for attaining low latency. However, there are some gaps when applying the CTI between mobile networks and an IOWN GF APN.

- Applicability of short Transmission Time Interval (TTI) considered in uRLLC use case

The reduction of processing time possibly achieved by the interpretation scheme of cooperative information/scheduling scheme in the cooperative control of mobile and optical networks has not been defined.

The APN should be operated in accordance with mobile system requirements. In other words, the APN should be operated in accordance with short TTI (62.5 us) in the uRLLC use case [3GPP TS38.211]. The current specifications for cooperative control and CTI do not support short TTI, but if the cooperative information is sent through the CTI in the same cycle as the short TTI, the interpretation scheme may be required to process the cooperative information at a higher frequency and in shorter time than currently used. Thus, processing needs to be improved in accordance with the length of the TTI, especially for short TTI. This may present a technical issue.

- Applicability to mobile mid/backhaul

The current CTI is only applied to mobile FH. The feasibility of applying this CTI to MH/BH has not been discussed.

If the CTI is applied to MH/BH, the architecture of the APN controller and CU/DU, which has a scheduling function and RRC information, will be changed

Therefore, the CTI feature should be extended to apply short TTI and mobile MH/BH over IOWN GF APN.

4. Mobile Network and DCI

4.1. Cyber-Physical System Network Driven by IOWN GF Use Cases

This section describes an example of how a Mobile Network infrastructure integrates with DCI that is based on heterogeneous & disaggregated computing architecture.

In Today's common practice, all IT workloads are deployed in a centralized Cloud Data Center - for instance, in Security Guarding Services in area management of cyber-physical system use case, Local Aggregation (LA) IT workload collects data from Surveillance camera/sensors and Ingestion (IN) IT workload analyzes data with AI/ML. It then provides an Intelligent Application (IA) service based on the result of the data by AI/ML inference engine. In IOWN Global Forum, each IT workload is distributed to the right place over the Open APN to meet the requirements of use cases specified in the following documents.

AI-Integrated Communications Use Case [IOWN GF AIC UC]

Cyber-Physical System Use Case [IOWN GF CPS UC]

In order to support transferring and processing of large real-time data under extreme QoS requirements, IOWN Global Forum is developing DCI architecture that is a disaggregated and heterogeneous computing architecture. In a DCI architecture, a Logical Service Node (LSN) like a Kubernetes worker node is composed to run necessary IT application workloads from disaggregated device resources. In addition, each mobile network function workload is integrated into a DCI subsystem across Local data center sites and Telco access/edge (or customer edge site) in a scalable manner with secure isolation from the enterprise IT workload running on the general logical service node. Most network function workloads are specialized by the Function-Dedicated Network (FDN) protocol on top of a special logical service node. This means a so-called enhanced LSN to run Cloud native Network Function such as vRAN in the same physical system where a general LSN is running.

Some enterprise IT workloads in the data pipeline can be distributed logically in LSNs to edge access sites and mobile edge network function workloads such as DU, CU, UPF, etc., in enhanced LSNs, by DCI system integration. This gives an advantage to service providers, as it reduces the initial cost to launch new 5G/6G services and increases the flexibility for digital service deployment in a location-agnostic manner. The following figure illustrates an example of mobile networks using IOWN technology to deploy overlay solutions, including Area Management, Mobility Management Applications such as In-vehicle, and Industry Management use cases (Smart plant case) such as Drone. (Each overlay solution is described in each Reference Implementation Model document, and it's out of scope in this IOWN GF Mobile Network document.)

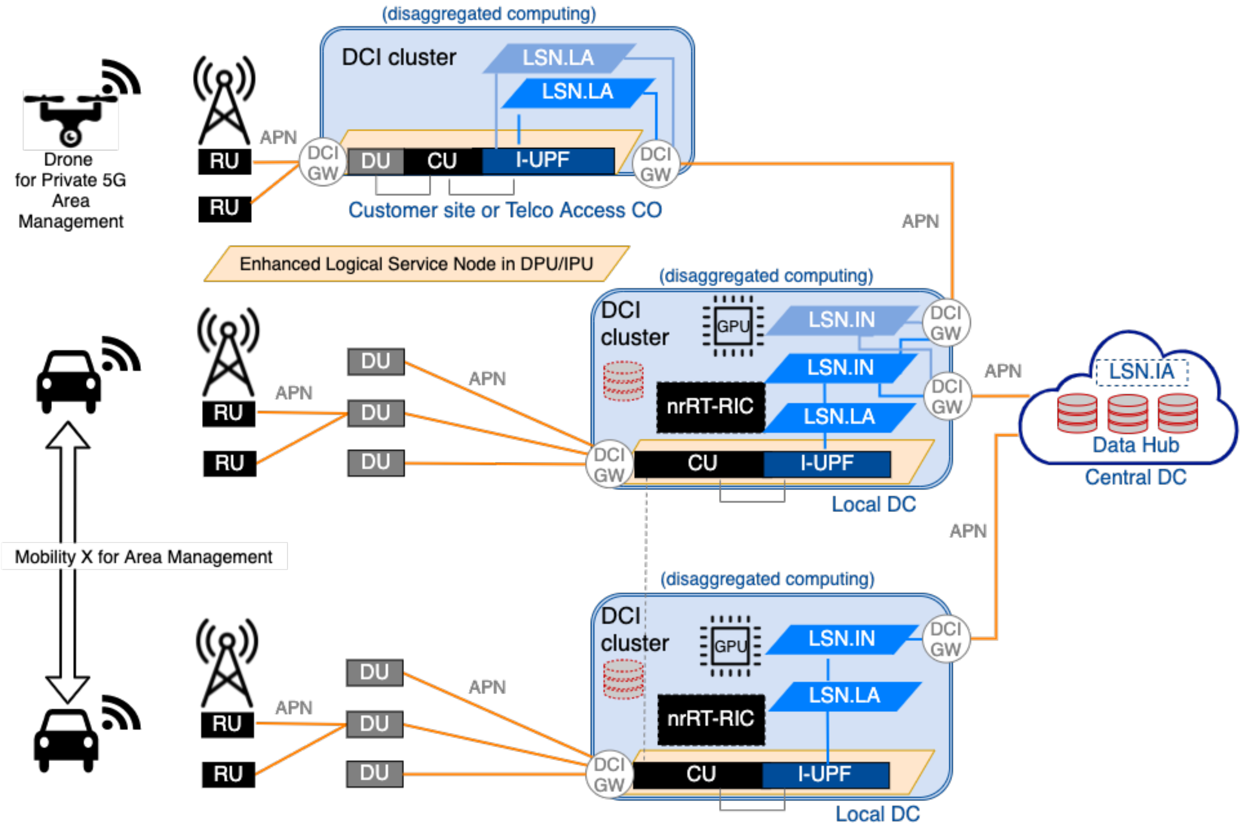


Figure 11 Area Management with mobility environment

Based on the current DCI disaggregated computing architecture, 5G RAN and Intermediate User Plane (I-UPF) may be provided by Enhanced LSN, UE's data traffic in a specific slice can be transited to specific LSN, as listed below.

LSN.LA: Logical Service Node for Local Aggregation

LSN.DH: Logical Service Node for Data Hub application

LSN.IN: Logical Service Node for Ingestion application

LSN.IA: Logical Service Node for Intelligence Applications related to artificial intelligence

In each LSN, multiple container workloads are running. It is possible to run on a service mesh environment such as Istio, and some of container workloads are of a serverless-type architecture such as Knative. To expand the DCI architecture to a 5G mobile far edge site/near-edge site while keeping operating costs low and collecting AI-related data, some integration with disaggregated Open vRAN computing could be needed.

Image data/sensor data collected from UE in vehicle or Drone will be sent to an LSN for Local Aggregation application workload deployed in a DCI cluster at customer site or Telco access site over a 5G network slice (across RU, DU, CUup, and I-UPF). In the case of Drone in a Private 5G network, more RUs can cover the wireless area, and all data can be aggregated into a single Intermediate UPF(I-UPF) through DU and CU in a specific 5G slice. Multiple DUs are also possible to install and aggregate into the same single I-UPF. In automotive use cases, multiple RUs in a 20 km area is a typical distance from DU to RU, and multiple DUs in a 50 km area which is a common distance from DU to CU (in the case of C-RAN), can cover for a mobility area. All UE's data can be aggregated into a single I-UPF through DU and CU in a specific 5G slice in enhanced LSN and transited the UE's data to Local Aggregation application workload in the LSN. When a DU has overlapping coverage in multiple DUs coverage areas, Application Function (AF) relating Traffic Steering xApp on near-RT RIC in LSN might first perform load balance across multiple DUs. The xApp then “Traffic Steers” away from multiple DUs based on Interference reports and detection (inference from UE measurement data over time). These 5G RAN optimizations are under study at the O-RAN Alliance, and the IOWN Global Forum will accept the result of the O-RAN Alliance specification. AF relating to Network Exposure Function (NEF) in 5GC owned by a 5G Core provider exists in different LSN. The AFs interact with the 5GC NFs such as Policy Control Function (PCF) indirectly through the NEF to provide traffic routing, policy control, etc. The following figure shows E2E 5G mobile network integration in a DCI cluster.

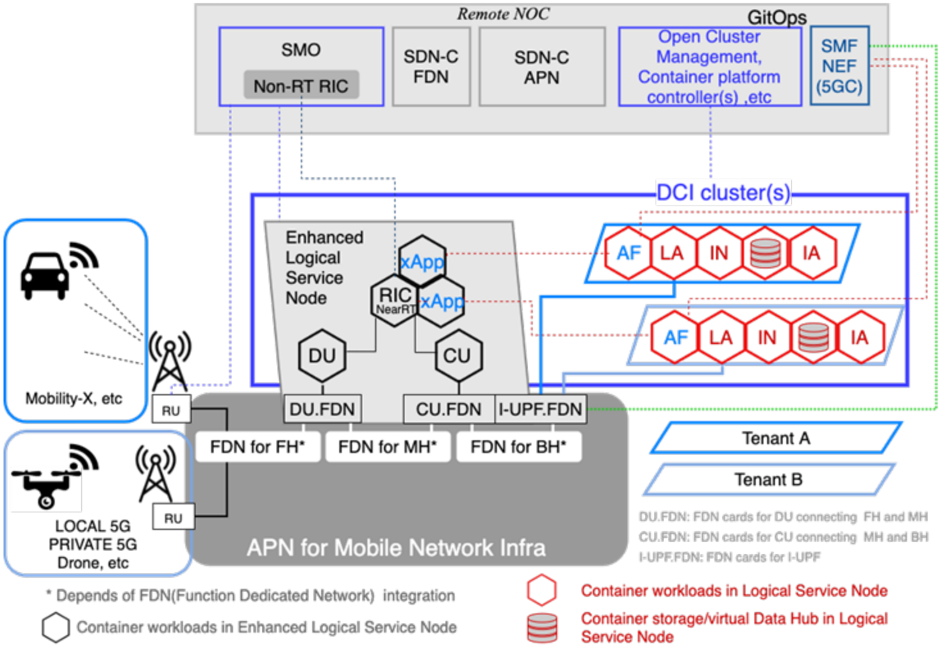


Figure 12 E2E 5G mobile network integration with Data-Centric Infrastructure

Each compute node (enhanced LSN) in a DCI cluster may have multiple FDN interface cards such as Smart NIC, Infrastructure Processor Unit, or Data Processor Unit, depending on the types of network connectivity. DU, CUcp (control plane), CUup (user plane), and I-UPF need to be run with specific FDN interface cards on an Enhanced LSN deployed in a DCI cluster, while most other functions can be run in a general LSN that is out of scope of this section.

FDN interface cards for Mobile Network Functions have three types of data traffic offload architectures against a CPU main system - Lookaside mode, Inline mode, and Composable architecture (IPU, DPU, etc.) mode as follows.

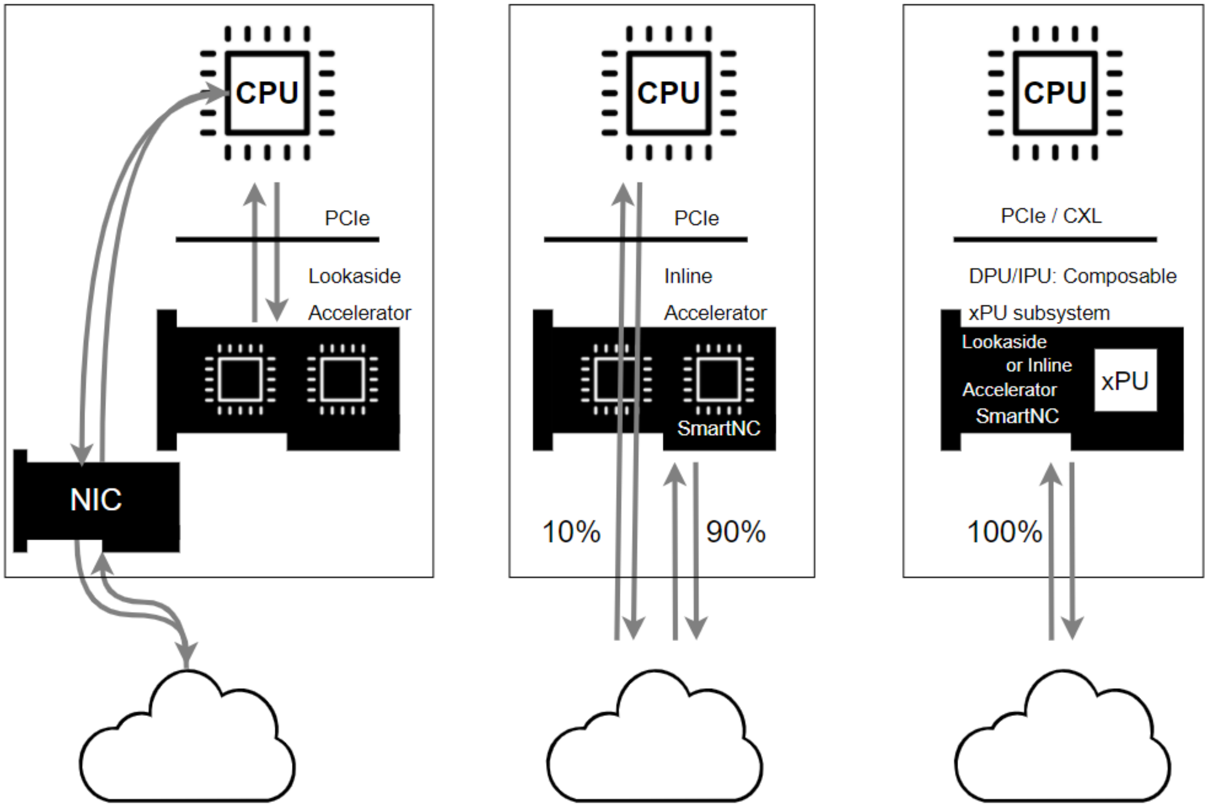


Figure 13 Data traffic offload architectures

With the latest technology, Composable compute architecture can be composed of an Enhanced LSN with its own host OS running in an xPU subsystem that can be set for full isolation from other LSNs (CPU side) with separate cluster from other LSNs. It also can set as a converged cluster with both LSN and Enhanced LSN. DCI architecture can keep flexible computing design while sharing network and storage resources. This secure isolation helps to accelerate IOWN Global Forum's DCI disaggregated infrastructure.

Further detail of the FDN model is described in section 4.3, "FDNs supporting Mobile Networks."

Disaggregated Open RAN computing architecture and the network function virtualization of 5G RAN have been studied in O-RAN Alliance and other standard development organizations. O-RAN alliance studies O-Cloud and vRAN function as the 5G RAN infrastructure, and its orchestration. Since the requirements of 6G services are not defined yet, the following subsection summarizes the latest study of virtualized network architecture for mobile networks in 5G mobile networks and describes the relation and the requirements for the Open APN and DCI in the IOWN Global Forum.

4.2. RAN Deployment Scenario Over IOWN Global Forum APN/DCI

Deployment scenarios that provide Radio Access Network functionalities of 5G over APN and DCI are studied in this section. The deployment scenarios are considered step-by-step manner, that is, the first step is vRAN on telco-cloud, the second step is vRAN on DCI, and the final step is vRAN on the data plane of DCI.

4.2.1. Disaggregated RAN Deployment Over Cloud-based 5G Network

This section describes the scenarios in which vRAN is deployed over conventional server-based telco-cloud based on a 5G network,

- The vRAN functions use virtual resources of CPU/memory/accelerator/NIC of the telco-cloud platform.
- Mainly, Virtualized DU (vDU) uses accelerator (Field-Programmable Gate Array (FPGA), Graphic Process Unit (GPU), etc.) for high performance of radio signaling process.
- Telco-cloud platform divides physical servers into several virtual layers. vDU and Virtualized CU (vCU) functionalities are able to perform parallel and simultaneously on one physical server.
- FDN Function connects network on frame or packet base via Fronthaul (eCPRI), Middle haul, and/or backhaul.
- DCI is not used as vRAN infrastructure. It is utilized to secure connectivity between APN/FDN and telco-cloud and between RU and telco-cloud.
- vRAN functions(vDU/vCU) are orchestrated with SMO and telco-cloud management functions.

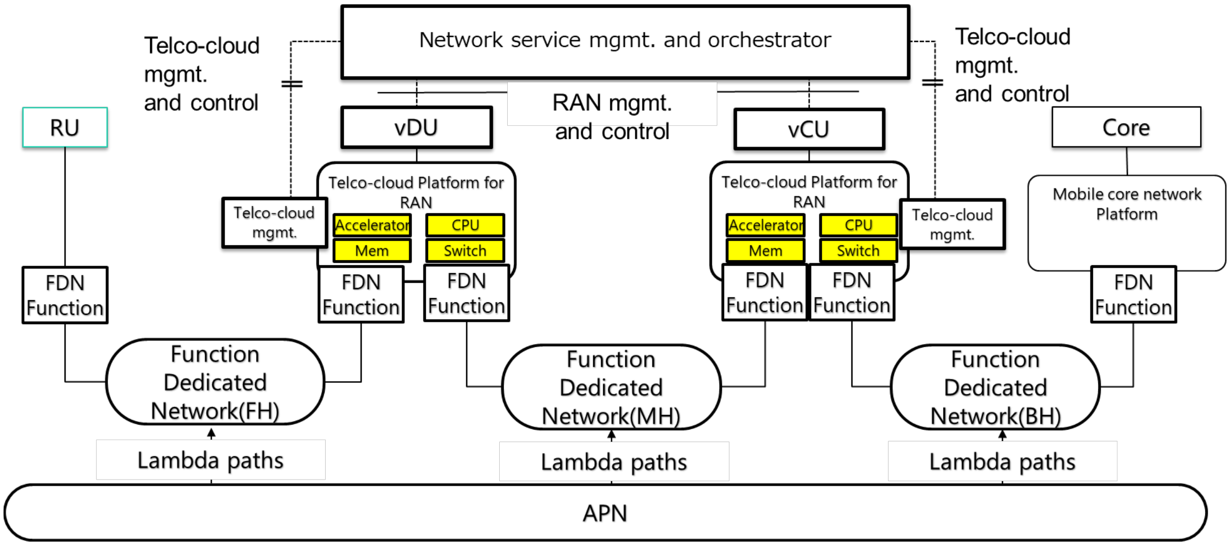


Figure 14 vRAN deployment scenario based on 5G network

4.2.2. vRAN Deployment Using DCI Platform

Based on the scenarios utilized vRAN functionality on the telco-cloud platform in section 4.2.1, this section explains the vRAN deployment scenario, which uses DCI as a computing infrastructure, as follows.

- The vRAN functions use virtual resources of CPU/memory/accelerator/NIC of DCI Enhanced Logical Service Node
- Especially, vDU uses accelerator (FPGA, GPU, etc.) for high performance of radio signaling process.
- Instead of telco-cloud platform, virtual layers are realized over DCI Enhanced Logical Service Node. vDU and vCU functionalities are able to perform parallel and simultaneously on DCI Enhanced Logical Service Node.
- By using FDN, FH/MH/BH are able to communicate based on packet or wavelength base. In addition, communication of Global data-plane between DCI Enhanced Logical Service Nodes can be performed via FDN.
- Considering the evolution of the server platform, the architecture of the mobile network might be affected. Since 6G architecture study is not started in 3GPP and O-RAN yet, this study is based on the existing 5G

architecture. The deployment scenarios will be updated when the study of mobile network architecture is progressed.

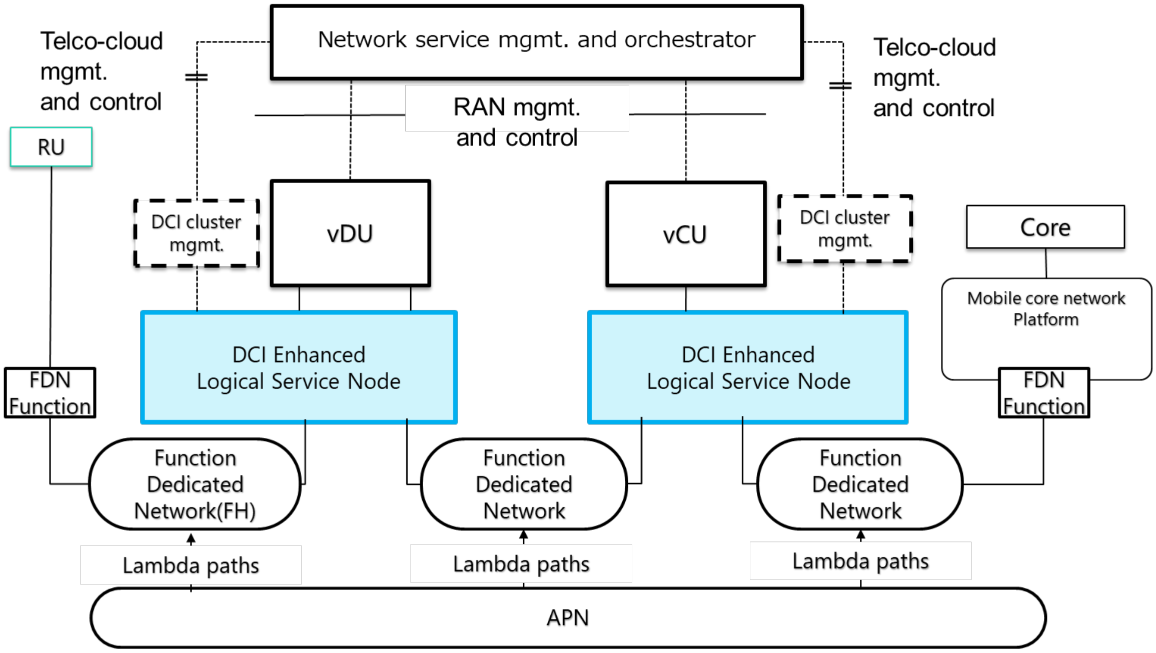


Figure 15 vRAN deployment scenario based on DCI

4.2.3. RAN Deployment over APN

This section describes the way to apply APN (which is defined in [IOWN GF Open APN FA]) to FH/MH/BH.

- APN provides wavelength path as transport for FH/MH/BH and doesn’t terminate any protocol of FH/MH/BH.
- APN allows both L1 multiplexing (L1 mux) and L2 multiplexing (L2 mux), and this deployment scenario doesn’t limit to either one.
- Each RAN functionality is connected to APN by terminating wavelength path with an optical transceiver directly (as shown in Figure 16) or by using a bridge function such as Flexible Bridging Service [IOWN GF Open APN FA] (as shown in Figure 17).
- Flexible Bridging Service defines multiple types of service to support multiple types of QoS depends on various use cases. Type D1, which supports QoS with bandwidth reservation and very strict latency, should be applied for FH transport (both C/U-plane and S-plane), and Type D2, which supports bandwidth reservation and strict latency should be applied for MH/BH transport in order to meet the requirement described in section 2.1.

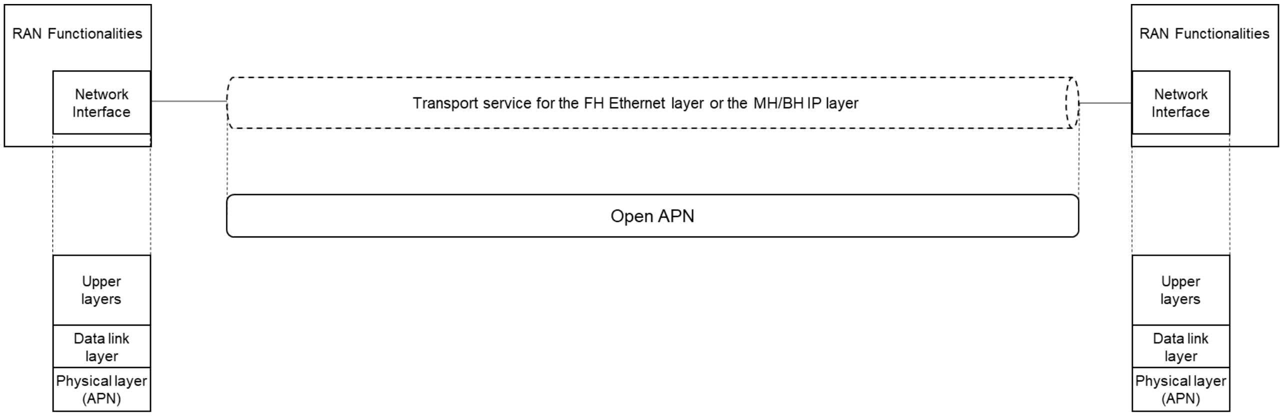


Figure 16 RAN deployment scenario with direct path over APN

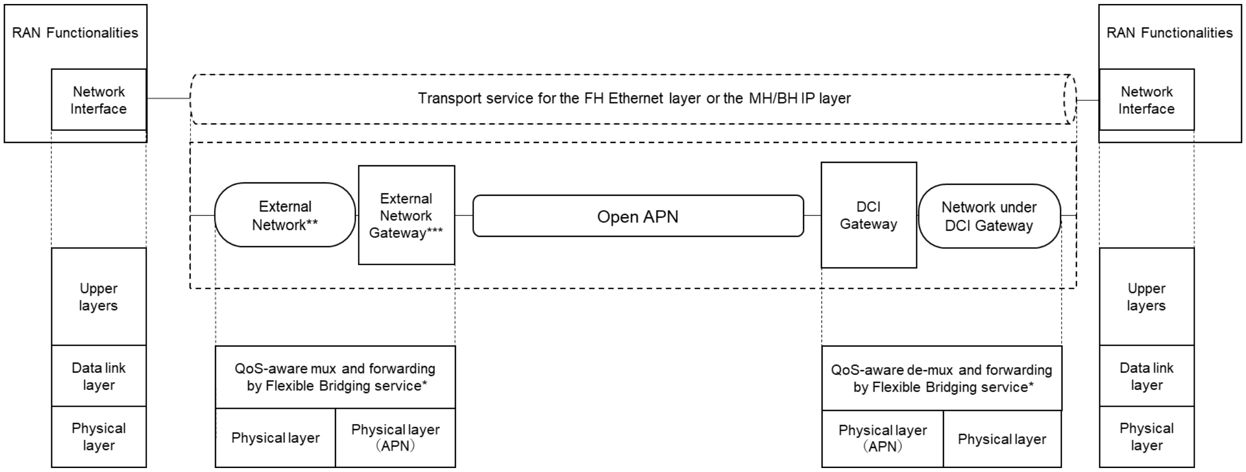


Figure 17 RAN deployment scenario with bridge function over APN

*The implementation technologies should be studied during activities that follow this document. Several multiplexing methods, including packet-based at L3/L2 and non-packet-based at L1, are being considered.
**For MH and BH, this segment is a network under DCI gateway.
***For MH and BH, this segment is a DCI gateway.

4.3. FDNs Supporting Mobile Networks

A general description of high-level functionalities inside the RU, DU, and CU, radio signal processing flow in PHY/RF, and RAN network protocol stack can be found in Appendix C. The description provides background information for the upcoming sections, which list typical FDN models and the requirements for FDN supporting mobile networks based on 5G standard architecture and industry technology trends.

4.3.1. FDN for Mobile Network

This section analyzes typical FDN reference models for mobile networks based on the 5G RAN function architecture and industry implementation trends.

A. FDN for FH

The first typical FDN reference model for the mobile network is FDN for FH, enabling FH protocol processing such as eCPRI/PTP at the endpoints and L2/L3 forwarding implemented in FDN functions. The FDN for FH includes the optical transport connectivity path/service over APN and FDN functions implementing functions above at RU and DU site.

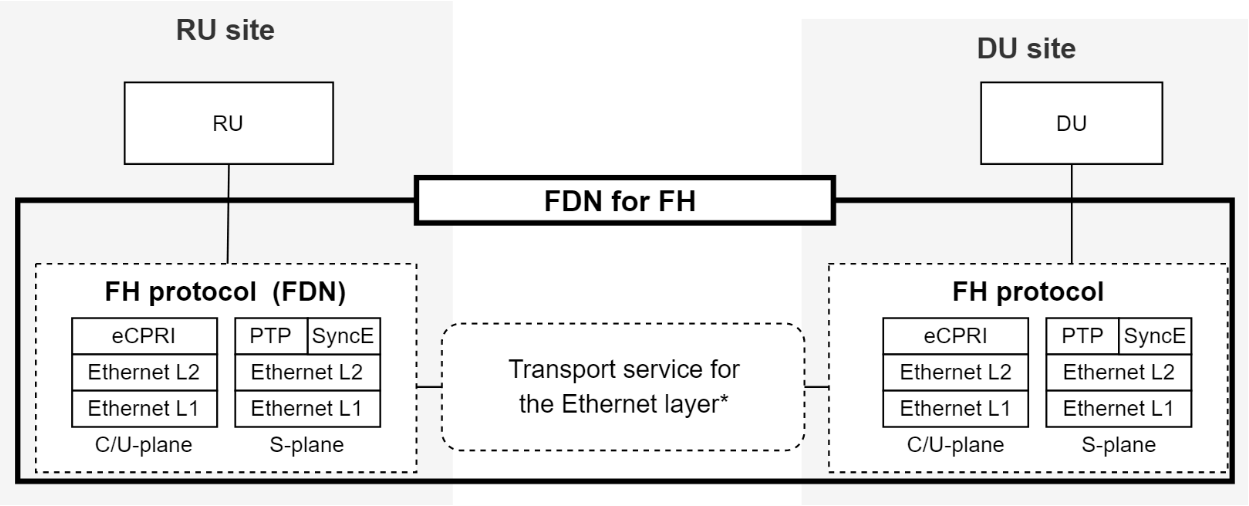


Figure 18 FDN for FH

*How transport service works is described in section 4.2.3

In this model, FH protocols are implemented to connect for RU and DU. As the FH requires low latency, high capacity, and low jitter for timing-sensitive radio signal processing, the hardware-based implementation is more suitable. In addition, point-to-multipoint and multipoint-to-multipoint connectivity and point-to-point connectivity are also possible because eCPRI enables frame or packet-based transmission of radio signals.

B. FDN for MH

The second FDN reference model for the mobile network is FDN for MH, which enables MH protocol handling such as GPRS Tunnelling Protocol (GTP)/SCTP at the endpoints and L2 switching/L3 routing implemented FDN functions. The FDN for MH includes the optical connectivity path/service over APN and FDN functions implementing functions above at DU and CU sites

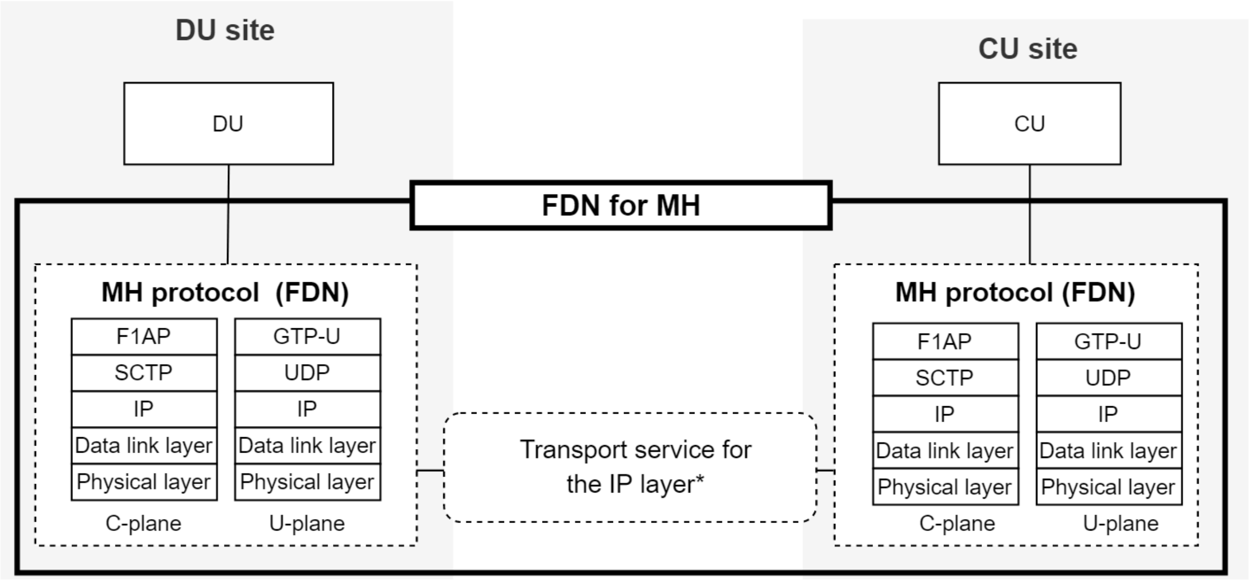


Figure 19 FDN for MH

*How transport service works is described in section 4.2.3

C. FDN for BH

Another FDN reference model for the mobile network is FDN for BH, which enables BH protocol handling such as GTP/SCTP at the endpoints and L2/L3 forwarding over optical connectivity path/service over APN. The FDN for BH includes the optical transport connectivity path/service over APN and FDN functions implementing functions above at CU and CN sites.

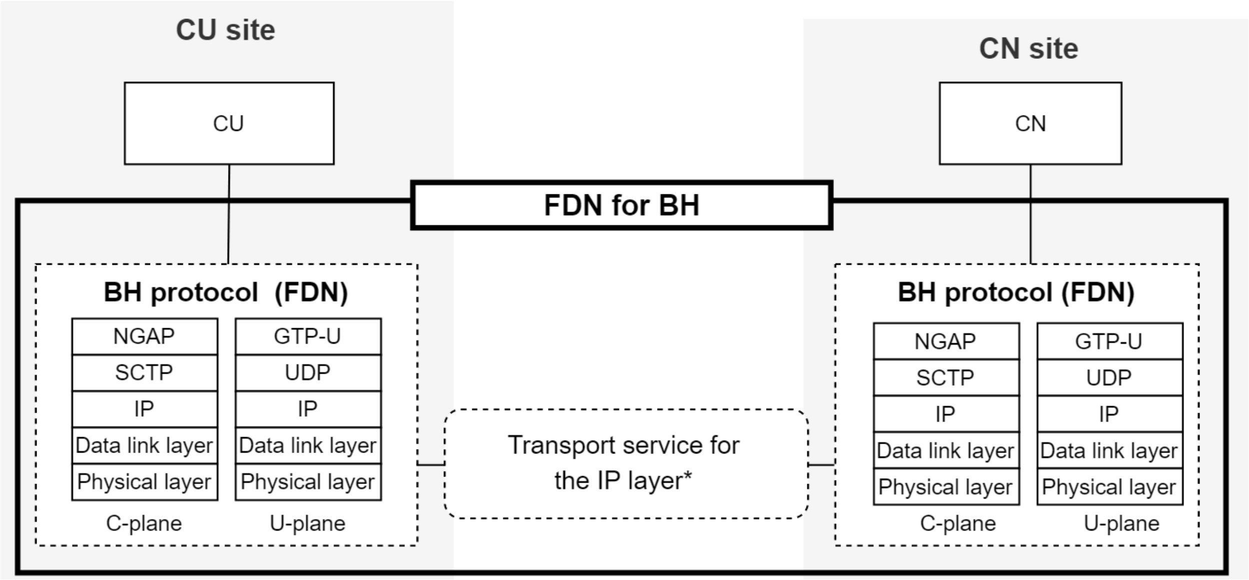


Figure 20 FDN for BH

*How transport service works is described in section 4.2.3

D. FDN for FH + DU Function Offload (optional)

In addition to FH FDN, part of DU PHY functions which need hardware acceleration may be included in FDN functions. This kind of optional deployment scenario can offload some PHY functions, and two types depend on the parts of PHY functions to be offloaded.

Figure 21 illustrates the first option of DU function offload to FH FDN. In this case, all PHY functionalities are offloaded in DU.

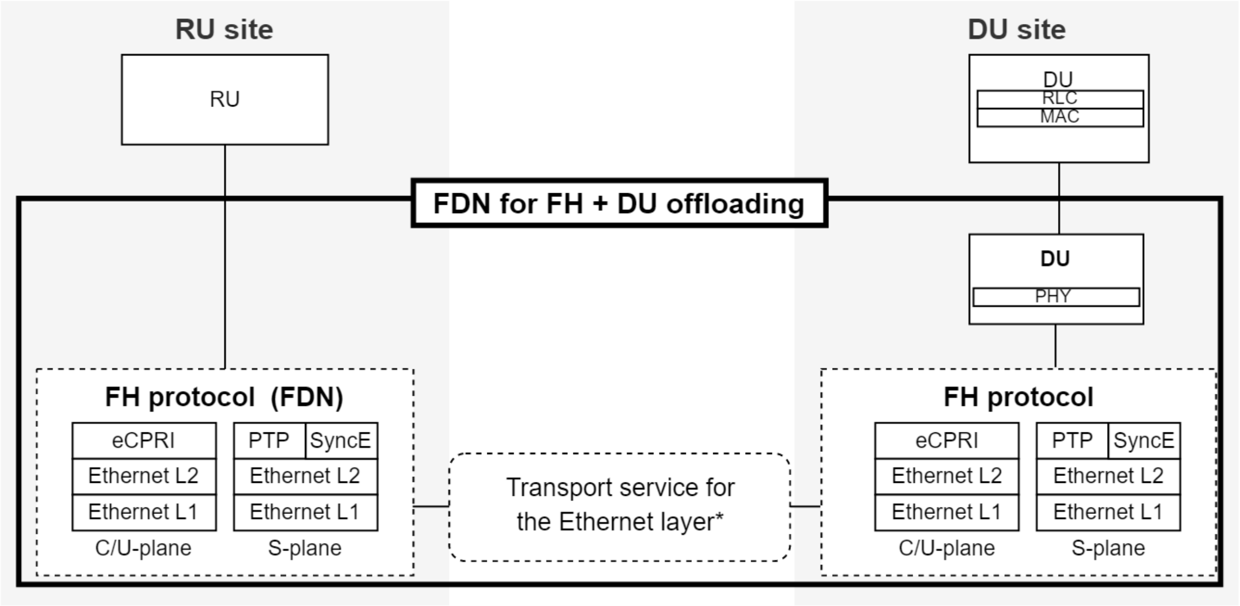


Figure 21 FDN for FH and DU offloading (first option)

*How transport service works is described in section 4.2.3

Figure 22 below illustrates the second option of DU function offload to FH. In this case, only FEC functionality of PHY is offloaded to FH FDN.

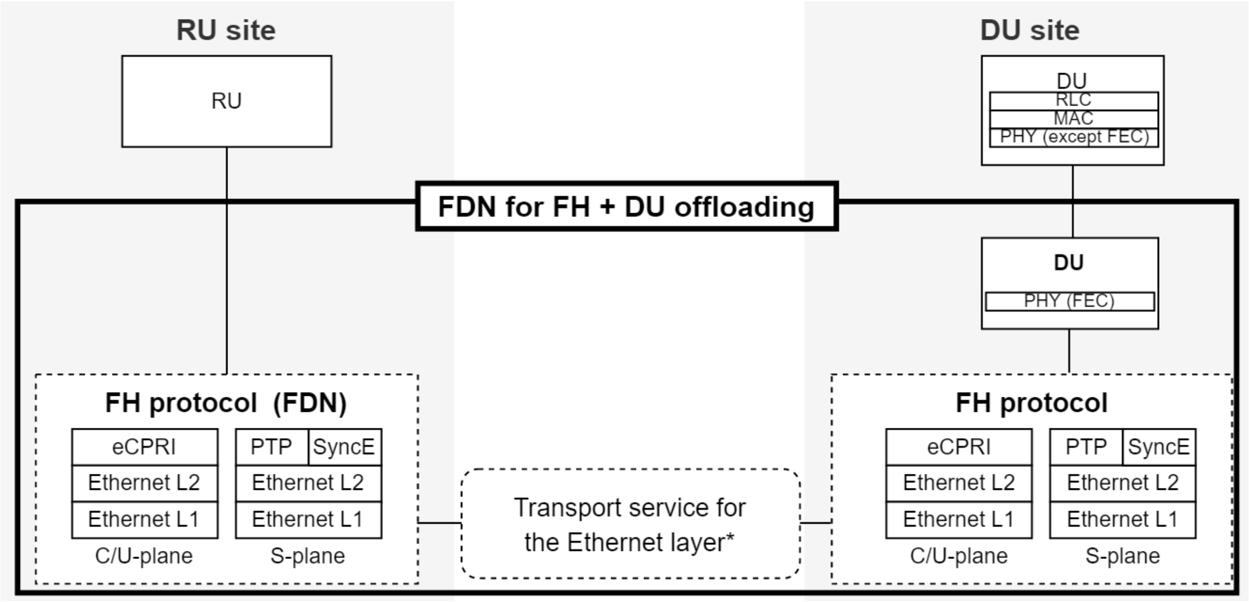


Figure 22 FDN for FH and DU offloading (second option)

*How transport service works is described in section 4.2.3

E. FDN for MH + CU Function Offload (optional)

The security feature in the CU function can also be offloaded using accelerators. There might be an option to FDN for MH. Figure 23 below shows an MH FDN option, meaning Ciphering functions in CU are included in the FDN function.

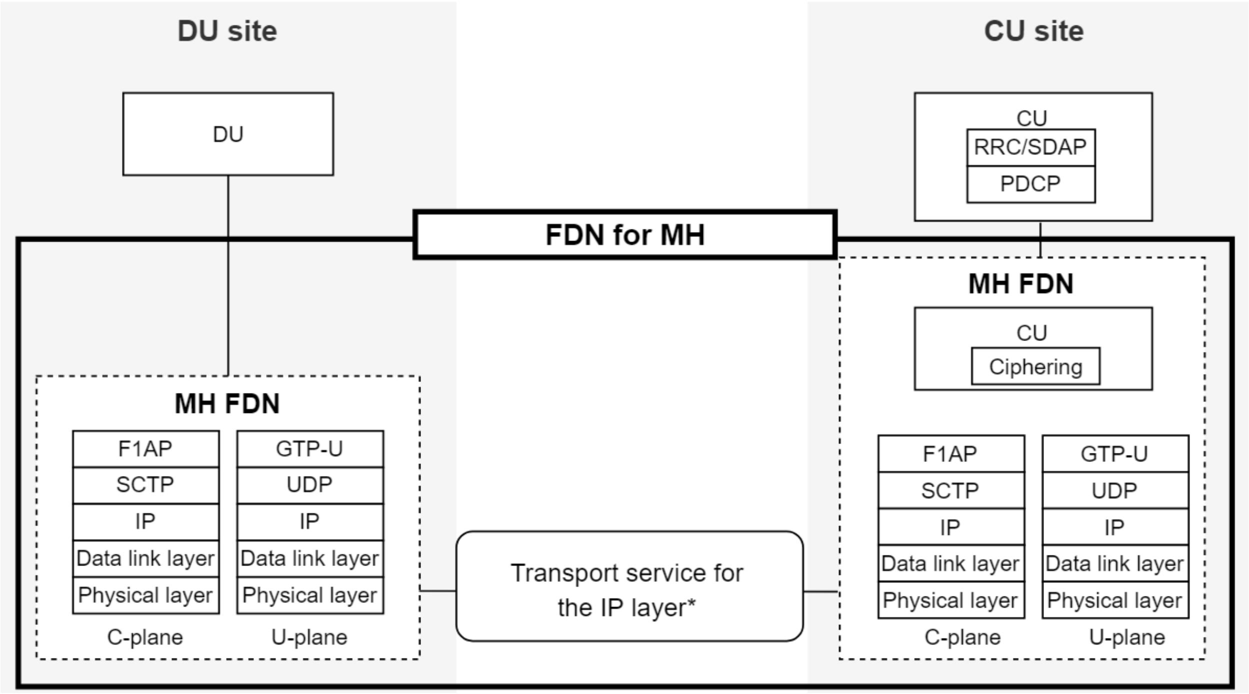


Figure 23 FDN for MH and CU function offloading

*How transport service works is described in section 4.2.3

F. FDN for MH + CU-UP Offload (optional)

In some scenarios, especially in the case of multi-access edge computing (MEC) handling traffic, it might be beneficial to deploy DU and CU-UP in a single site or very close to release user data from the mobile network protocol as close as RU. In this case, the CU-UP function can be offloaded to a single piece of hardware to make it fast-forwarding and simple to implement. The CU-CP can also be placed at the far aggregation site provided its process is not latency-sensitive and accommodation of wide area users is efficient.

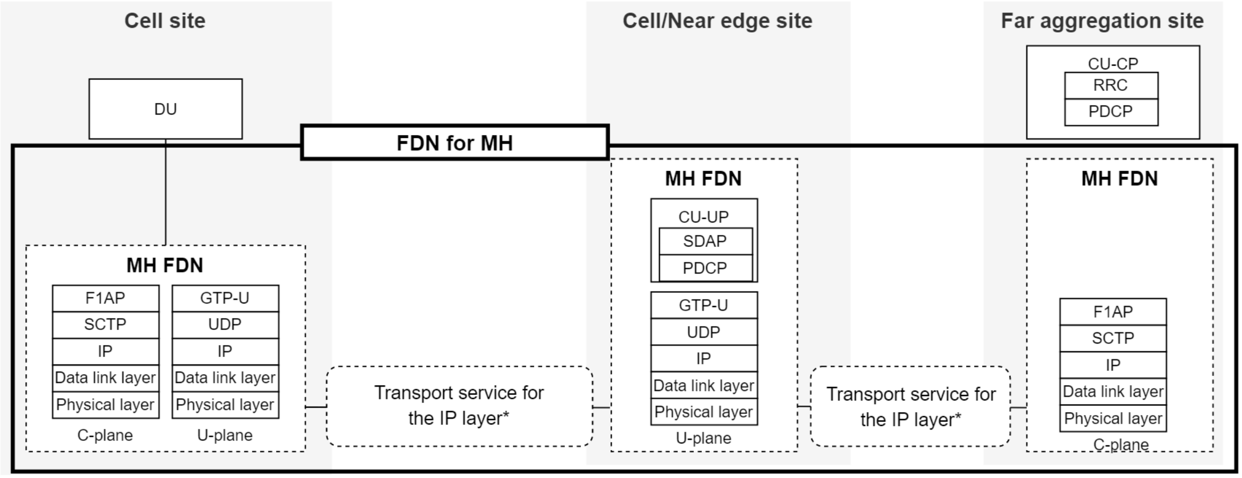


Figure 24 FDN for MH and CU-CP offload

*How transport service works is described in section 4.2.3

4.3.2. Analysis of the Requirements for FDNs Supporting MN

This section summarizes requirements for FDNs supporting mobile networks as described above.

1. Low latency and precise packet processing: FDN, especially for FH, must be low latency and enable timing-sensitive eCPRI frame forwarding.
2. Timing support: FDN is required to support hundreds of nanoseconds synchronization over FH.
3. Huge capacity: FDN, especially for FH, is required to provide more than a hundred Gbps capacity. This depends on wireless part configuration, such as the number of sectors, channel bandwidth, MIMO layers.
4. Aggregate traffic: FDN for MH and BH is required to aggregate traffic from multiple Rus even the traffic does not flow all the time.
5. Logical separation: For the FH/MH/BH, FDN is required to support logical separation and multi-tenancy to accommodate several lower equipment into single hardware and support multipoint connections.
6. Hardware acceleration: FDN can be optionally to enable hardware acceleration of upper functionalities and network protocol such as PHY, CU-UP, ciphering at CU, and UPF for much more capacity or low latency.

5. Study Items

5.1. Study Item 1: Extended Cooperative Transport Interface (CTI) for Mobile NW and APN

This section describes items to be investigated in the future for an extended CTI between a mobile network and APN in order to provide end-to-end low-latency services using IOWN technology and an architecture that explains the relationship between extended CTI and APN/DCI reference architecture.

As mentioned in Section 3.2.4.1, if uRLLC services that require low latency are provided through a mobile network in addition to an APN, latency will need to be controlled in optical paths and/or L2SW in APN by using the information provided by the mobile network. One option for controlling latency is to collect the mobile information from a CU/DU (vCU/vDU), and then an orchestrator, which coordinates the mobile network and APN, transfers the data to an APN controller. However, end-to-end low latency may not be feasible through communicating with the orchestrator that requires time-consuming procedures, so it would be desirable if the APN controller directly receives the mobile information from the CU/DU (vCU/vDU) through the extended CTI as described in section 3.2.4.1. Because the existing CTI specifications do not apply to short TTI and mobile MH/BH in future mobile networks, the CTI specifications should be functionally enhanced as the extended CTI in IOWN GF architecture.

5.1.1. Functional Control Scheme with Extended CTI

This section describes how end-to-end low latency is achieved when the APN controller directly receives mobile information from the CU/DU through the extended CTI. Although the targets of the latency control are mainly optical paths and L2SW, the latency control for L2SW is first discussed. Figure 25 shows the functional control scheme with the extended CTI for controlling the latency of L2SW. This scheme is mainly divided into collection, analysis, and control processes, which are as follows.

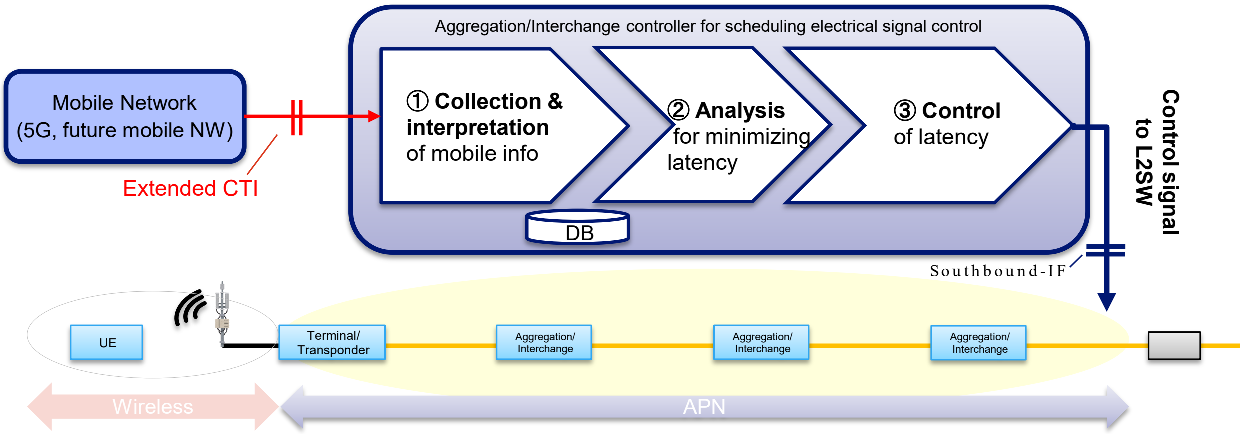


Figure 25 Functional control scheme

① Collection and interpretation of mobile scheduling info: Receive scheduling info through extended CTI and convert it to an optical scheduling form

② Analysis for minimizing latency: Analysis based on mobile scheduling and decision making for L2SW scheduling (timing) to minimize end-to-end latency

③ Control of latency: Control timing for the L2SW controller in accordance with the resulting decision of the previous process

5.1.2. Scope of Extended CTI

The scope of this study item, extended CTI filling the gaps described in section 3.2.4, focuses on the followings:

- Applicability of short TTI considered in URLLC use case

Specifying the interface between a mobile network and APN should be considered to define the functional and performance requirements of the extended CTI.

- Applicability to mobile MH/BH

Architectures and use cases that use the extended CTI need to be specified. Furthermore, it is necessary to identify the kind of information to be exchanged through the extended CTI between mobile networks and APNs.

As described in section 5.1.1, controlling the latency of L2SW using extended CTI is focused, but the application of extended CTI is not limited to L2SW. Table 7 shows examples of applicable targets for the extended CTI, along with information on what to control and the expected benefits.

Table 7 Examples of applicable targets for extended CTI

Target	**What to control (Expected benefits)**
L2SW	Output timing of signals (low latency, low jitter)
Optical SW	Optical path setting (low latency, priority control, bandwidth allocation)
	Optical path switching (congestion control, low latency, priority control)
Optical Transceiver	ON/OFF control (power saving)

5.1.3. Relation between APN/DCI architecture and Extended CTI

The architecture that explains the relationship between extended CTI and APN/DCI architecture to control optical path/L2SW is described in Figure 26 Relation between APN/DCI and extended CTI.

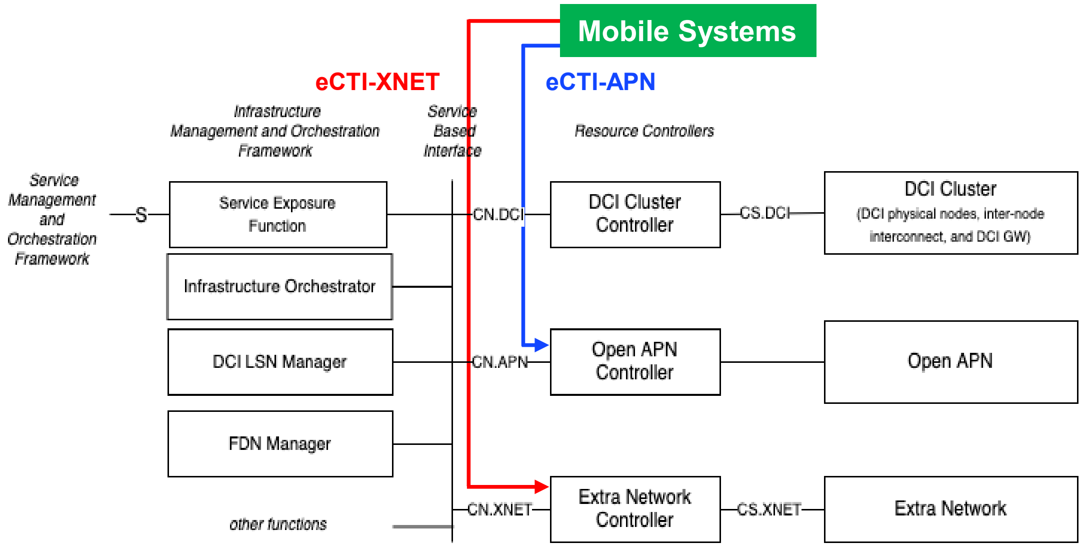


Figure 26 Relation between APN/DCI and extended CTI

Basically, the mobile information (cooperation information) would be obtained from mobile systems via extended CTI (eCTI). As shown in Table 11 in section 5.1.2, extended CTI can be divided into two logical interfaces of eCTI-APN and eCTI-XNET depending on a controlling target. The eCTI between Open APN controller and mobile systems is defined as eCTI-APN. On the other hand, the eCTI between Extra Network controller and mobile systems is defined as eCTI-XNET.

RAN is described as mobile systems in the Figure 26. As for the connection of eCTI, both interfaces connecting to vCU/vDU or near-RT RIC should be covered.

The role of each eCTI is as follows:

(1) The APN controller receives mobile information via eCTI-APN to control the optical switch/optical path and optical transceiver.

(2) Extra network controller receives mobile information via eCTI-XNET for controlling L2SW to realize low latency/low jitter.

5.2. Study Item 2: Mobile Network Deployment Scenario over APN

APN plays a role in the transport network infrastructure for 5G/6G mobile networks. This section describes mobile NW deployment scenarios over APNs, especially for FDN service features and attributes to support multiple MNOs using APN, and detailed applicability analysis of mobile network deployment using APN. Since the 6G RAN architecture study has not yet been started, this section focuses on the 5G mobile network deployment using APNs first based on the O-RAN architecture.

5.2.1. Applicability of APN in Mobile NW

5G RAN consists of RU, DU, CU, and the transport connection, i.e., FH, MH, and BH. Typical examples of the protocol are eCPRI for FH, F1 for MH, and NG for BH. APN as underlying infrastructure should be applicable and support the connections upper layers with features and performance requirements for X-Haul connections. Note that the mobile NW deployment scenario itself should be considered because its architecture will be discussed in 3GPP and other mobile network SDOs. Therefore, this document does not discuss Mobile NW deployment itself, except for layout assumptions.

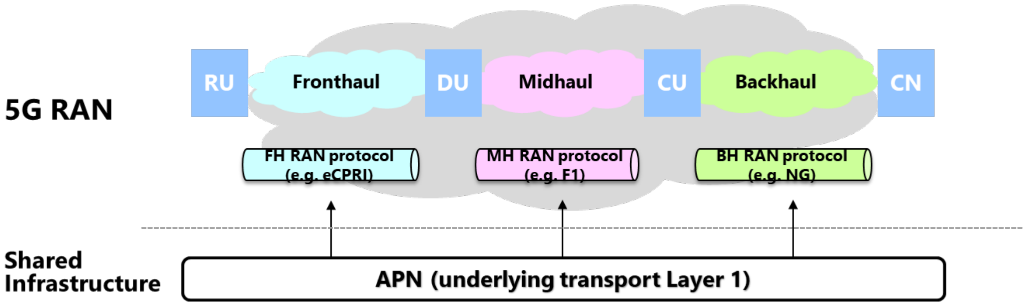


Figure 27 APN and RAN

5.2.2. APN Provisioning Models and Scenarios for Mobile Networks

APN infrastructure can be shared by multiple network operators, including mobile network operators and other services considered in IOWN Global Forum. Under the assumption of shared infrastructure, the transport connectivity services should include transport layer connectivity function and performance.

The 6G mobile network is expected to handle much more traffic volume than the 5G's and is required to guarantee more stringent bandwidth, latency, and jitter. APN transport service for the mobile network should support and provide much more capacity, low latency, and more minor delay variations to meet the growing traffic volume and high-performance demand. This growing demand indicates that Layer 1 connectivity for X-Haul can also be the unique service provided by APN.

The transport connectivity service definitions generally include characteristics, such as topology, UNI, traffic/bandwidth profile/characteristics, protocols, and its service attributes set. For example, eCPRI of FH RAN protocol, provides standardized Ethernet connectivity for underlay, and it can be referred to [MEF10.3]: Carrier Ethernet transport as the typical example for underlay connectivity. Therefore, the APN transport service should support the characteristics of such transport service definitions to connect to the RAN functions.

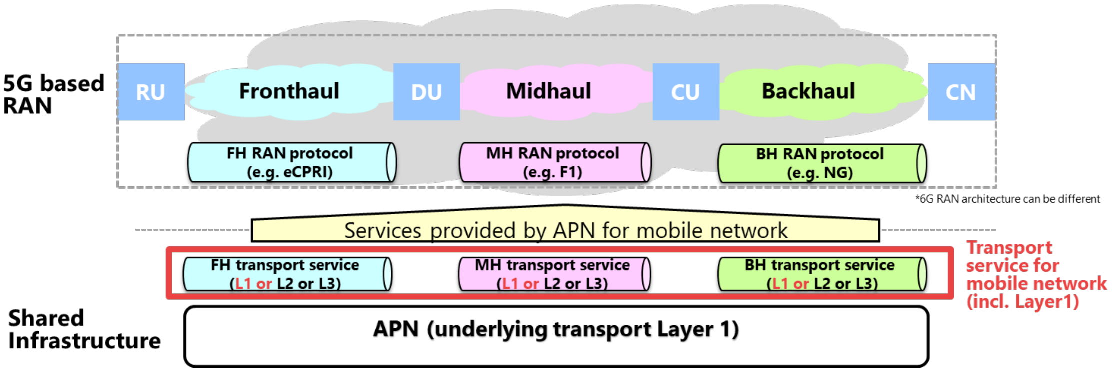


Figure 28 Transport connectivity

The eCPRI can provide a range of data rates between 25Gbps and 50Gbps depending on RAN configuration in 5G. In 6G, the data rate is expected to be increased more and more. As one solution toward 6G to accommodate much more traffic than 5G and to achieve much higher performance in terms of latency and reliability, another example for FH RAN protocol is Analog Radio over Fiber (A-RoF) [ITU-T G. Sup55] [C. Lim][K. Ito].

A-RoF transmits optical signals in the form of radio frequency signals via optical fibers, and then the radio signals can be extracted simply by O/E conversion. Because A-RoF does not require D/A and A/D converters at Rus, the required optical bandwidth can be reduced compared to Digital RoF (D-RoF) [ITU-T G. Sup55] eCPRI, A-RoF might be beneficial in terms of latency and power consumption.

Impacts on mobile network deployment scenarios by such RAN transport protocols need to be studied to reveal the IOWN Global Forum Open APN and DCI architecture requirements.

5.2.3. Requirements for Each APN Service

Considering the RAN transport deployment scenario, this section should study the use cases and requirements defined for the 6G services and systems following past studies for those of the 5G. However, use cases and requirements for 6G services and systems have not been defined yet, so this paper has studied the RAN transport deployment scenario based on existing 5G-based requirements and use-cases.

5.2.4. Requirements for Supported Data Transport

5.2.4.1. Requirements for Supported Data Transport

5.2.4.1.1. 5G RAN Split Architecture

To define latency requirements for C-Plane in the mobile network, a target RAN architecture must be assumed. This section assumes the 5G RAN split architecture studied in 3GPP since no 6G RAN architecture exists. 3GPP has reached the consensus to define two 5G RAN split architectures as opposed to the existing monolithic architecture in which a gNB is defined in [3GPP TR 38.801], [3GPP TR 38.806] and [3GPP TR 38.816] 3GPP has supported the high-level CU/DU split (option 2) and the low-level DU/RU split (option 7) which is re-defined as option 7-2x by O-RAN ALLIANCE as shown in the following figure.

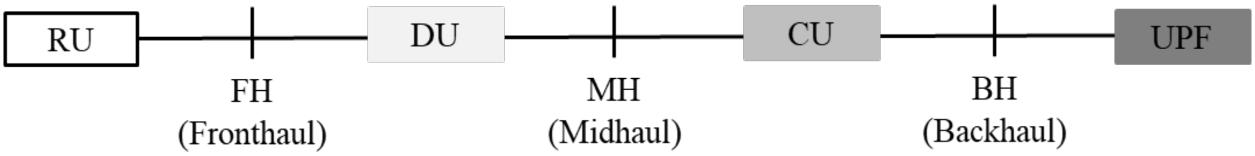


Figure 29 5G RAN split architecture

The 5G architecture has separate functions of C-plane and U-plane, and CPRI (Common Public Radio Interface) specification is enhanced to support not only option 8, but also option 7-2x for FH interface and is referred to as eCPRI. On the other hand, the BH interface is not specified for functional split options. The following table shows the maximum transport latency for C-plane in 5G RAN.

Table 8 The Maximum Transport Latency for C-plane in 5G RAN

	FH	MH	BH
Functional split options	Option 7-2x	Option 2	Not specified
Maximum transport latency (One-way from RU)	0.25ms	10ms	Not specified

5.2.4.1.2. Latency Requirements for C-Plane

To define latency requirements for C-Plane in the mobile network, a target RAN architecture must be assumed. This section assumes 5G RAN functional decomposition studied in Next Generation Mobile Networks Alliance (NGMN) since there is no 6G RAN architecture.

5.2.4.1.3. Latency Requirements for U-Plane

The NGMN alliance has released "NGMN Overview on 5G RAN Functional Decomposition" in 2018 [NGMN alliance]. This document defines the 5G RAN with multi-tier aggregation from transport latency viewpoints and a simplified 5G RAN topology model, composed of one cell site and three-tier, shown in Figure 30. Any traffic routed from these sites towards a central entity will pass through a series of aggregation sites.

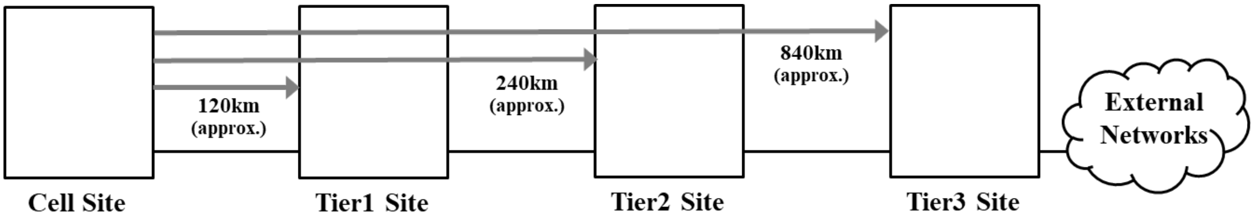


Figure 30 Example 5G RAN with multi-tier aggregation by NGMN alliance

In the document, the NGMN alliance has specified the example maximum latency figures for 5G RAN aggregation sites in the following table.

Table 9 Example Maximum Latency Figures for 5G RAN Aggregation Sites by NGMN Alliance

		Cell Site	**Tier1 Site**	**Tier2 Site**	**Tier3 Site**
Relative Number of sites		Depends on operator's policy	1000	100	10
Transport latency (One-way from cell site)		0 ms	0.6 ms	1.2 ms	4.2 ms
Estimated Latency (RTT)	uRLLC	1 ms (0ms +1ms)	2.2 ms (0.6ms x 2 + 1ms)	3.4 ms (1.2ms x 2 + 1ms)	9.4 ms (4.2ms x 2 + 1ms)
	eMBB	8 ms (0ms +8ms)	9.2 ms (0.6ms x 2 + 8ms)	10.4 ms (1.2ms x 2 + 8ms)	16.4 ms (4.2ms x 2 + 8ms)

Table 9 provides some indicative values of the relative number of sites. For example, for every 1000 tier 1 sites, there are only 100 tier 2 sites and 10 tier 3 sites. On the other hand, the relative number of cell sites depends on the operator's development policy.

If a UPF is located in a tier 1 site, 1000 tier one sites will have to run their own version of that UPF. If the UPF is moved into a tier 2 site, 100 versions of that UPF are required. This level of pooling benefit can save an operator considerable Capital expenditures (CAPEX)/ Operating Expenditure (OPEX) in running the UPF. However, the UPF can only be centralized so far to meet the latency budget and other factors such as transport capability. This table also provides some indicative values for transport latency. The transport latency (one-way latency from the cell site) to a tier 1, tier 2, and tier 3 aggregation site are 0.6ms, 1.2m,s, and 4.2ms, respectively. These latency figures are assumed to be the 95th-percentile of transmission delay (i.e., 95% of cell sites are within this limit) and include overhead for IP.

This table provides some indicative values for the 5G RAN latency if a UPF is located at these various aggregation sites. This paper considers 5G RAN latency for two types of typical 5G use-case (uRLLC and eMBB) and the round-trip times of the transport network. These latency figures are also assumed 95th-percentile of transmission delay (i.e., 95% of cell sites are within this limit) and included overhead for IP same. The estimated latency of eMBB and uRLLC is 8ms and 5ms, respectively, which includes transaction times for 5G New Radio and 5G core network based on 3GPP release 15 specifications [3GPP TS23.401].

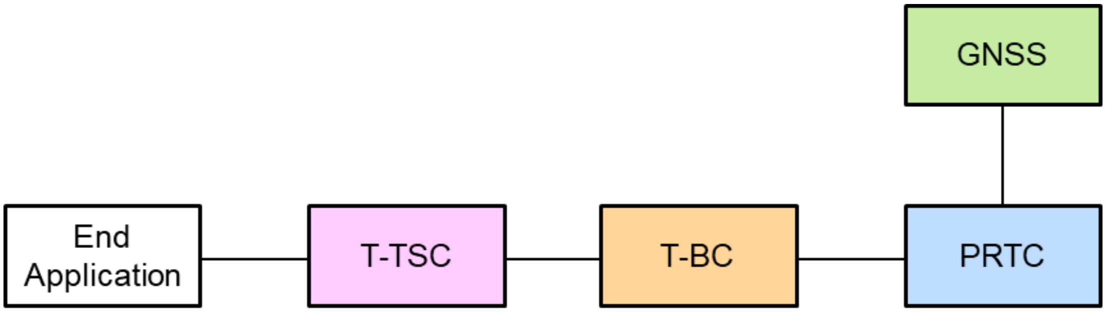
As a result, a 5G RAN operator can see whether it would be proper or not to locate a UPF in a tier 3 site as the service required latency is probably too high. However, for a 5G service with an approximately 10ms latency requirement, an operator will have to look very carefully at cell site/tier1/tier2 locations. While cell site/tier1 has a slightly higher latency performance requirement, tier2/tier3 can provide significant cost benefits.

5.2.4.2. Requirements of Time Synchronization

5.2.4.2.1. Network Architecture for Time Synchronization

5G RAN architecture is expected to handle the increased traffic volume and a diversity of applications. There are some emerging technologies of efficient frequency usage. One example is the dual connectivity, which communicates via several 5G base stations. Another example is carrier aggregation, which bundles several carrier frequencies to one channel. These technologies require a highly accurate time synchronization mechanism to collaborate among 5G base stations.

Figure 31 is functional components for time synchronization, and Table 10 briefly explains its functions (see [ITU-T G.8271/Y.1366] in detail).



GNSS: Global Navigation Satellite System PRTC: Primary Reference Time Clock

T-BC: Telecom-Boundary Clock T-TSC: Telecom-Time Slave Clock

Figure 31 Functional components for time synchronization

Table 10 Functions for time synchronization

Functions	Contents
GNSS	GNSS is the global navigation system that receives the position and distributes signals emitted from satellites.
PRTC	PRTC is the time reference device that receives accurate time from GNSS
T-BC	T-BC is the device to calculate time synchronization information from received PTP (Precision Time Protocol) packets for time synchronization
T-TSC	T-TSC is the device to terminate PTP packets and supply time synchronization information to end applications.

5.2.4.2.2. Requirements of Time Synchronization

3GPP has specified some time synchronization requirements for mobile applications that have been adopted in various standards, for example [IEEE 802.1CM] and [ITU-T G.8271/Y.1366]. These requirements have been adopted by mobile FH and categorized according to accuracy levels by time synchronization (see Table 11 in detail). LTE and 5G systems support category 4A, whose target time synchronization value is 3µs for TDD service [ITU-T G.8271/Y.1366]. This is the fundamental requirement for non-co-located[15] deployments.

More stringent requirements are applicable typically for co-located deployments, where the distance between the antennas does not affect the significant differential delay between the antenna and the UE. This requirement is important for features like MIMO and carrier aggregation.

5G systems support higher throughput compared to LTE systems, and this will be even more true moving towards 6G. For 6G systems supporting advanced features, the requirements of Class of accuracy 6A, 6B, and 6C might become more important. These functions may be important also for other reasons (redundancy, mobility, etc.).

Table 11 Time Synchronization Requirements for Mobile Applications

Class of accuracy	Mobile application	Accuracy level of time synchronization
6C	MIMO or TX diversity transmission at each carrier frequency (LTE and 5G)	65 ns*
6B	Intra-band contiguous carrier aggregation w/ or w/o MIMO or TX diversity (LTE and 5G)	130 ns*

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[15] co-located means that antennas are co-located with or connected to the same baseband unit (BBU or RU) or centralized unit/ distributed unit (CU/DU) through direct links

6A	Intra-band non-contiguous carrier aggregation w/ or w/o MIMO TX diversity, and intra-band carrier aggregation w/ or w/o MIMO or TX diversity (LTE and 5G)	260 ns**
4A	TD-LTE, 5G TDD	3 µs

MIMO: Multiple Input Multiple Output TX: Transmit TD-LTE: Time Division Duplex Long Term Evolution

- *Co-located deployments
- ** Generally co-located deployments (LTE non-contiguous and inter-band Carrier Aggregation is specified by 3GPP also allowing non- co-located deployments)

5.2.5. Deployment Scenarios

5.2.5.1. Deployment Scenarios from Latency Viewpoints

Referring to the abovementioned NGMN alliance [NGMN alliance], this section considers three types of latency model (maximum RTT = 1ms, 10ms, and 30ms) and two types of use-case (uRLLC and eMBB). Table 12 shows five deployment scenarios excluding low latency uRLLC because the maximum RTT of uRLLC is defined as 10ms in 3GPP specification [3GPP TR23.725]. The deployment scenario from latency viewpoints shows 5G RAN topology, which should be located in each function considering C/U-plane requirements. These five RAN architecture models have supported several deployment scenarios; each model can be supported using network slicing. Since actual deployment scenarios depend on the deployment policy of each operator (e.g., SLA conditions and facility conditions), the mixed architecture model is out of scope in this section.

Table 12 Example of Low Latency Types and Use-case

Latency type		**Ultra-low latency**	**Very-low latency**	**Low latency**
Maximum RTT		1ms	10ms	30ms
Use-case	**uRLLC**	Scenario #1	Scenario #3	Out of scope
	eMBB	Scenario #2	Scenario #4	Scenario #5

5.2.5.1.1. Deployment Scenario #1 (Ultra-low latency uRLLC: Max. RTT = 1ms)

This scenario is for the ultra-low latency uRLLC in which max. RTT of 1 ms is required. From U-plane latency viewpoints, all functions (RU/DU/CU/UPF) must be located at the cell site considering 1ms max. RTT.

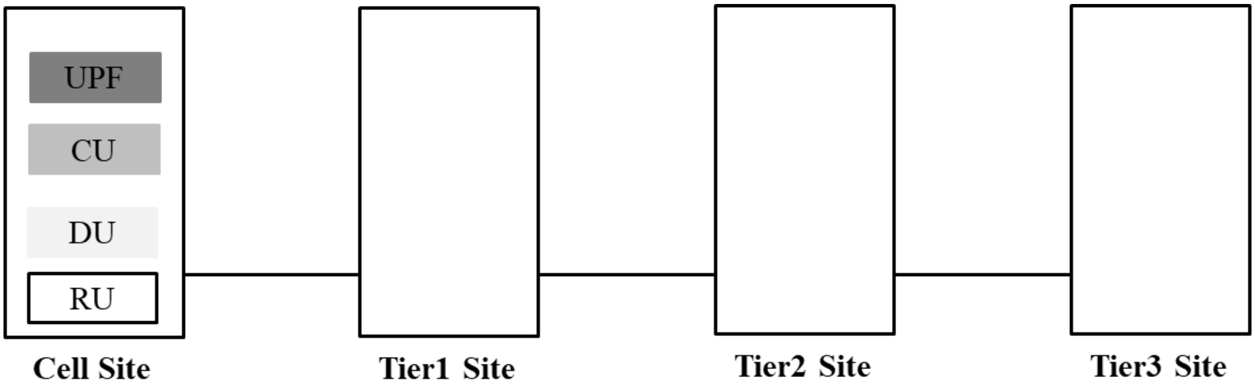


Figure 32 Functional location model for deployment scenario #1

5.2.5.1.2. Deployment Scenario #2 (Ultra-low latency eMBB: Max. RTT = 1ms)

This scenario is for the ultra-low latency eMBB in which max. RTT of 1 ms is required. From U-plane latency viewpoints, RU/DU/CU must be located at cell site considering 1ms max. RTT. However, UPF cannot be located at all sites considering 1ms max. RTT, so this development scenario cannot be satisfied with U-plane requirements for the ultra-low latency eMBB.

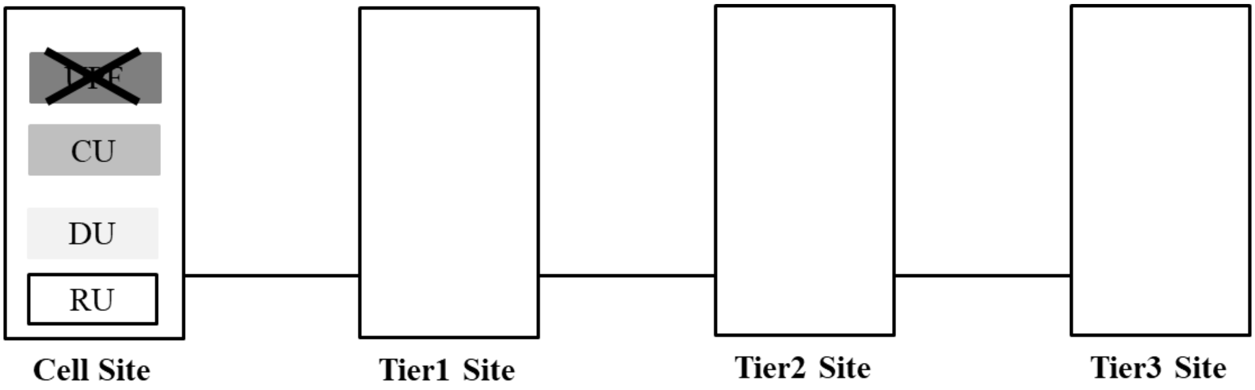


Figure 33 Functional location model for deployment scenario #2

5.2.5.1.3. Deployment Scenarios #3 (Very-low latency uRLLC: Max. RTT = 10 ms)

This scenario is for the very-low latency uRLLC in which max. RTT of 10 ms is required. From C-plane viewpoints, RU/DU must be located only at the cell site considering FH's C-plane latency requirements (within 0.25ms). From U-plane viewpoints, CU/UPF can be located at all sites (cell site/tier 1/2/3 sites) depending on the operator's policy (see 5G RAN architecture models later).

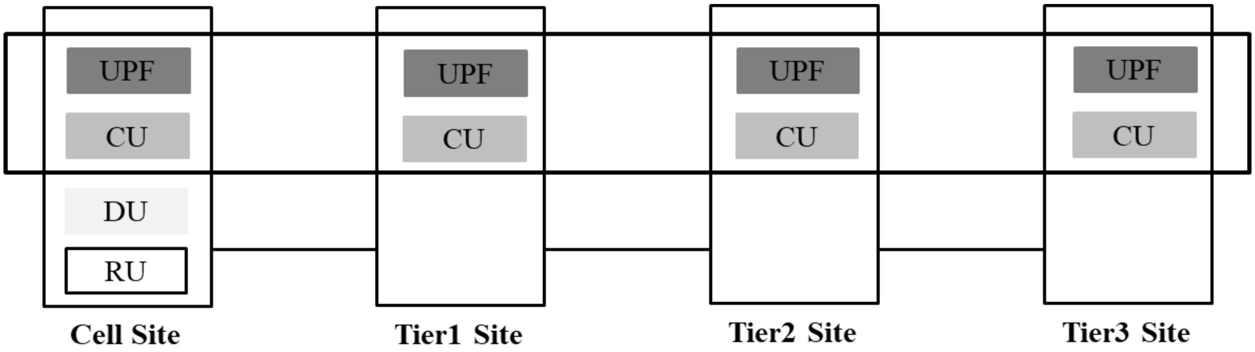


Figure 34 Functional location model for deployment scenario #3

5.2.5.1.4. Deployment Scenarios #4 (Very-low latency eMBB: Max. RTT = 10 ms)

This scenario is for the very-low latency eMBB in which max. RTT of 10 ms is required. From C-plane viewpoints, RU/DU must be located only at the cell site considering FH's C-plane latency requirements (within 0.25ms). From U-plane viewpoints, CU/UPF can be located at cell site/tier1 cite considering MH's C-plane requirements (within 10ms) and eMBB requirements (within 10ms).

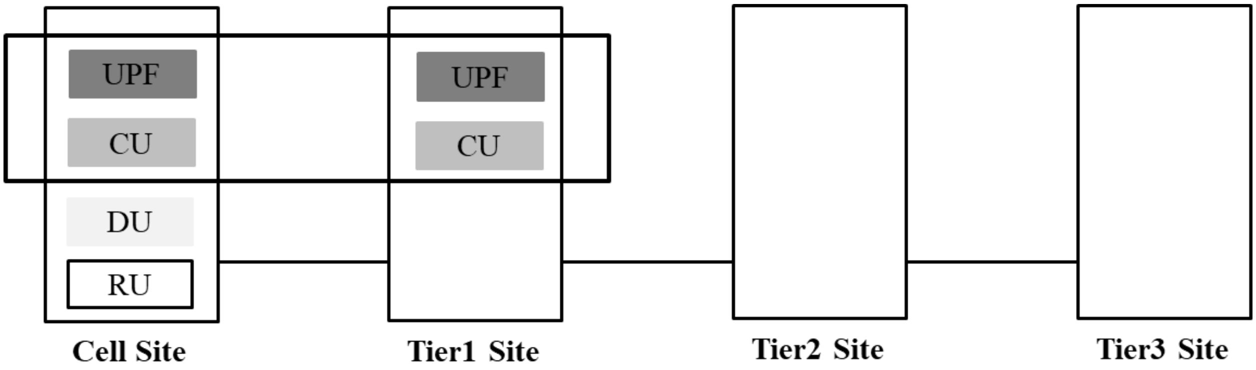


Figure 35 Functional location model for deployment scenario #4

5.2.5.1.5. Deployment Scenario #5 (Low latency eMBB: Max. RTT = 30ms)

This scenario is for the low latency eMBB in which max. RTT of 30 ms is required. From C-plane viewpoints, RU/DU must be located only at the cell site considering FH's latency requirements (within 0.25ms). Otherwise, from the U-plane viewpoint, CU/UPF can be located at all sites (cell site/tier 1/2/3 sites) depending on the operator's policy. Thus, this development scenario is the same functional location model as deployment scenario #3.

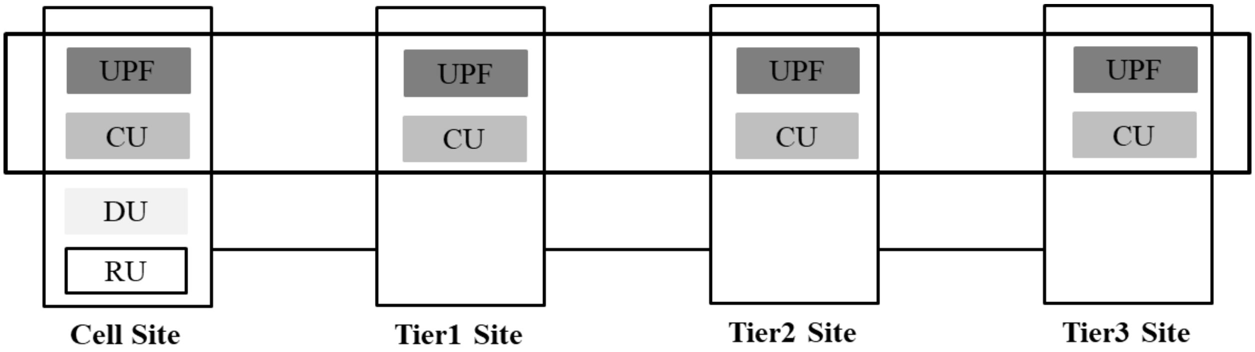


Figure 36 Functional location model for deployment scenario #5

5.2.5.2. Deployment Scenarios from Time Synchronization Viewpoints

5.2.5.2.1. Topology Configuration for 5G Fronthaul

O-RAN Alliance has released the time error budgets across different elements of 5G FH, based on IEEE 802.1CM and ITU-T G.8271.1 guideline [O-RAN-WG4.CUS.0-v02.00].

Table 13 5G fronthaul network requirements from time synchronization viewpoints

5G Features	Topology Configuration for 5G fronthaul	Target Relative |TAE|	Class of Accuracy (See Table 11)
MIMO and Tx Diversity	Out of scope. (These features are supported within 1 RU)	≦ 65ns*	Class 6C (65ns)
CA (intraband contiguous per base station type)	A (see Figure 37 in detail)	≦ 130ns*	Class 6B (130ns)
CA (intraband contiguous per base station type)	B (see Figure 38 in detail)	≦ 260ns*	Class 6A (260ns)
TDD	C (see Figure 39 in detail)	≦ 3000ns	Class 4A (3μs)

*When these features are supported within 1 O-RU, relative |TAE| is impacted by O-RU internal |TE| only. When these features are supported by multiple cooperating O-RUs, relative |TAE| is also impacted by network relative |TE| based on IEEE802.1CM timing category.

From 5G time synchronization viewpoints, TAE (Time Alignment Error) has been defined by 3GPP specifications [3GPP TS 38.104], and TE (Time Error) has been defined by eCPRI network requirement specification [eCPRI Transport Network V1.1]. The defined terminologies are listed in Table 14.

Table 14 Terminology definition of 5G time synchronization

Terminology		Definition
TAE	Relative |TAE|	The time difference between two base stations (including RF antennas).
	Absolute |TAE|	The time difference between two base stations against the time of a specified reference clock (e.g., UTC)
TE	Relative |TE|	The time difference between the time of clock A (TA) and the time of clock B (TB) (e.g., Each RU has the time of clocks for the RF antenna and the T-TSC.)
	Absolute |TE|	The time difference against the time of a specified reference clock (e.g., UTC)

5.2.5.2.1.1. Topology Configuration A for 5G Fronthaul

The relative |TAE| is less than 130ns in topology configuration A for 5G fronthaul to achieve CA (intraband contiguous per base station type). The |TE| of RU (for this application, the “enhanced RU[16]” is assumed) is less than 35ns and includes both |TE|s of RF antennas and T-TSC. These values are defined in O-RAN WG4 [O-RAN-WG4.CUS.0-v02.00]. The relative |TE| of FH is less than 60ns, and this value is defined in the eCPRI specification.

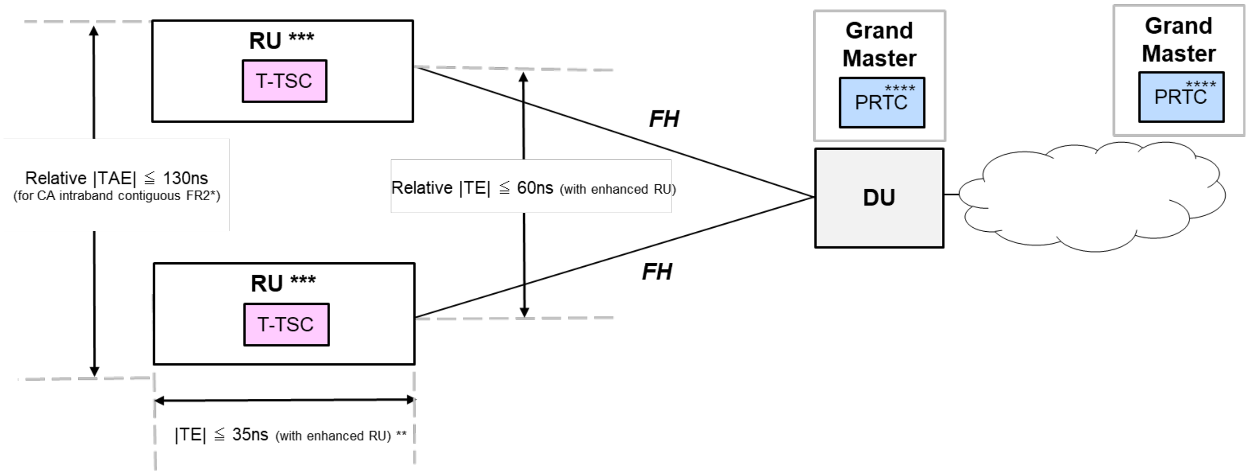


Figure 37 Topology Configuration A for 5G fronthaul

*FR2: Frequency Range2 (24.25 GHz □ 52.6 GHz: defined in 3GPP R15 specification)

**No relative |TE| contribution by PRTC since PRTC is common PTP and SyncE master to all cooperated RU. The relative |TAE| on the radio interface is calculated from the nearest common clock (e.g., a co-located T-BC). Further details are provided in G.8271.1.

***Collocated RUs

****The source of time synchronization is gotten from PRTC that can be located anywhere at the upper network layer of DU. The DU may or may not be part of the synchronization distribution

---

[16] Enhanced O-RU refers to the terminology used in ORAN for the classification of the RU performance. To ensure interoperability among O-RAN O-RU vendors, two types of "O-RU" are defined, a regular O-RU with |TE|= 80 ns and an enhanced O-RU with |TE| = 35 ns

5.2.5.2.1.2. Topology Configuration B for 5G Fronthaul

The relative |TAE| is less than 260ns in topology configuration B for 5G fronthaul to achieve CA (intraband contiguous per base station type). The |TE| of RU has two types of value depending on RU performance and includes both |TE|s of RF antennas and T-TSC. These values are defined in O-RAN WG4 [O-RAN-WG4.CUS.0-v02.00]. The relative |TE| of FH also has two types of value depending on RU performance. These values are defined in the eCPRI specification.

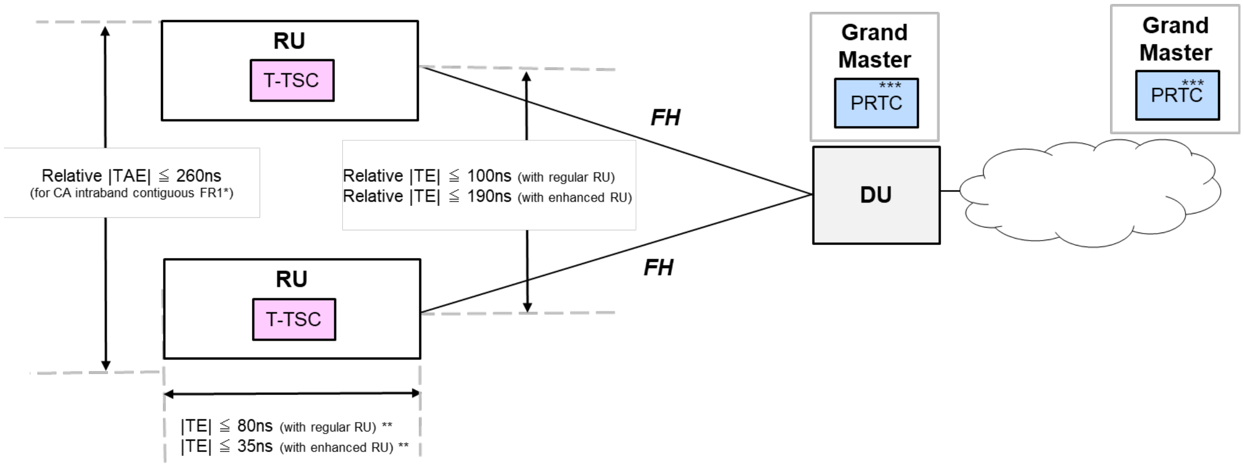
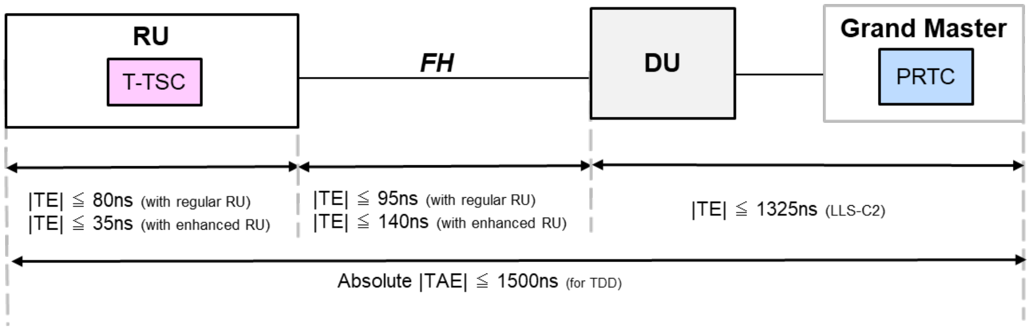


Figure 38 Topology Configuration B for 5G fronthaul

*FR1: Frequency Range1 (450 MHz-6000 MHz: defined in 3GPP R15 specification)
**No relative |TE| contribution by PRTC since PRTC is common PTP and SyncE master to all cooperated RU. The relative |TAE| on the radio interface is calculated from the nearest common clock. Further details are provided in G.8271.1.
*** The source of time synchronization is gotten from PRTC that can be located anywhere at the upper network layer of DU. The DU may or may not be part of the synchronization distribution

5.2.5.2.1.3. Topology Configuration C for 5G Fronthaul

The relative |TAE| is less than 3000ns in topology configuration C for 5G fronthaul to achieve 5G TDD. The |TE| of RU has two types of value depending on RU performance and includes both |TE|s of RF antennas and T-TSC. These values are defined in O-RAN WG4 [O-RAN-WG4.CUS.0-v02.00]. The |TE| of FH also has two types of value depending on RU performance. These values are defined in eCPRI specification [eCPRI Transport Network V1.1].



LLS: Lower Layer Split

Figure 39 Topology Configuration C for 5G fronthaul (LLS-C2 example)

5.2.5.2.2. Deployment Scenario for 5G Fronthaul Network from Time Synchronization Viewpoints

These scenarios from time synchronization viewpoints require ultra-low latency with max. RTT of ms order.

5.2.5.2.2.1. Deployment Scenario #1 (On-premises Model)

Deployment scenario #1 is the On-premises model in which all functions (RU/(DU)/PRTC) are located in the same area. This model is the 5G RAN architecture to achieve time synchronization in which RU supports T-TSC, and DU supports PRTC. This scenario is suited to topology configurations A and B. This deployment scenario from a synchronization perspective is analogous to LLS-C4 defined in O-RAN [O-RAN-WG4.CUS.0-v-2.00].

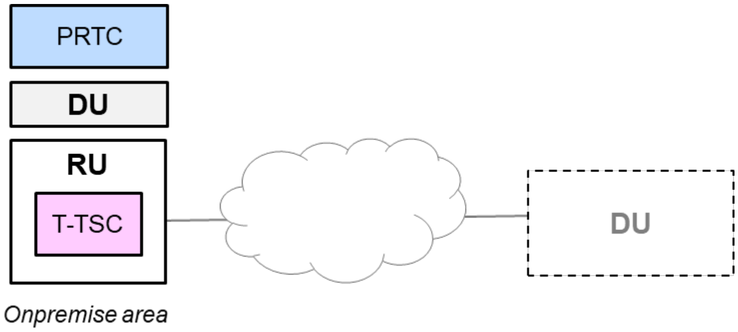


Figure 40 Deployment scenario #1 for 5G RAN

5.2.5.2.2.2. Deployment Scenario #2(DU Supported PRTC Model)

Deployment scenario #2 is the NW architecture model where DU connects RU point-to-point, and the DU is a part of the synchronization chain towards the RU. This model is the 5G RAN architecture to achieve time synchronization which RU supports T-TSC, DU supports T-BC, and PRTC can be located independent of both RU and DU. This scenario is suited to all of the synchronization requirements of A, B, and C. This deployment scenario from a synchronization perspective is analogous to LLS-C1 defined in O-RAN [O-RAN-WG4.CUS.0-v-2.00].

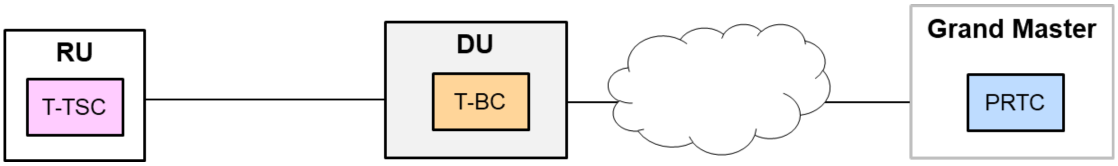


Figure 41 Deployment scenario #2 for 5G RAN

5.2.5.2.2.3. Deployment Scenario #3(DU Supported T-BC Model: DU connected to RU by network)

Deployment scenario #3 is the NW architecture model where DU supported T-BC, with network connections between RU and DU, which differed from deployment scenario #2. This model is the 5G RAN architecture to achieve time synchronization which RU supports T-TSC, DU supports T-BC, and PRTC can be located independent of both RU and

DU. This scenario is suited to all topology configurations A, B, and C. This deployment scenario from a synchronization perspective is analogous to LLS-C2 defined in O-RAN [O-RAN-WG4.CUS.0-v-2.00].

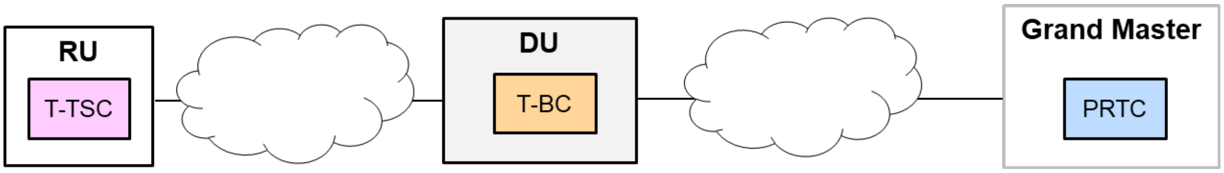


Figure 42 Deployment scenario #3 for 5G RAN

5.2.5.2.2.4. Deployment Scenario #4(FH Supported T-BC Model)

Deployment scenario #4 is the different NW architecture model where the FH network supported T-BC, with connections between RU and DU but differently from Deployment scenarios #2 and #3 in that the DU is not a part of the synchronization chain towards the RU. This deployment scenario from a synchronization perspective is analogous to LLS-C3 defined in O-RAN [O-RAN-WG4.CUS.0-v-2.00]. This model is the 5G RAN architecture to achieve time synchronization, which RU supports T-TSC, FH network supports T-BC, and PRTC can be located independent of both RU and DU. This scenario is suited to all topology configurations A, B, and C.

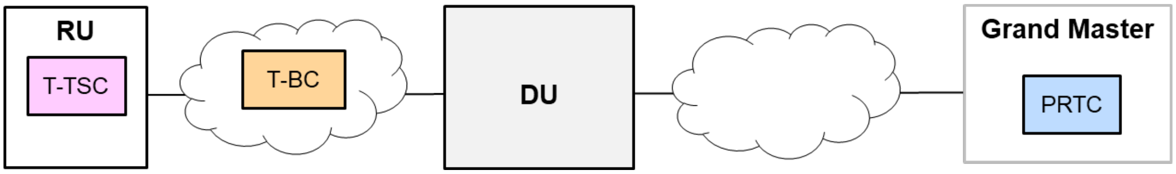


Figure 43 Deployment scenario #4 for 5G RAN

5.2.6. 5G RAN Architecture

5.2.6.1. 5G RAN Architecture Models from Latency Viewpoints

Considering five types of scenarios from latency viewpoints, this section summarizes five RAN architecture models which meet latency requirements. These models are classified into two RAN types (centralized and distributed RAN) shown in the following figure.

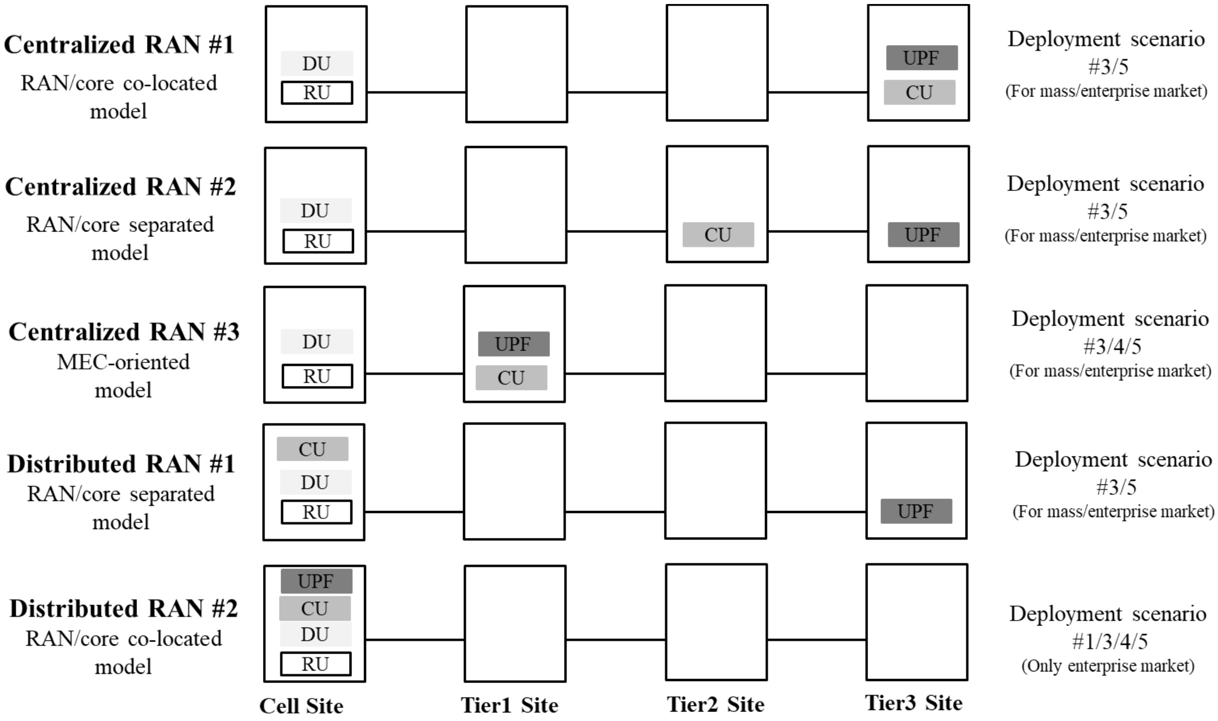


Figure 44 5G RAN architecture models

Centralized RAN #1 is the RAN/core co-located model. RU and DU are co-located at cell site from FH's C-plane latency requirements, and CU and UPF are co-located at tier3 site supporting MH's C-plane and service required latency. This model is expected to be easy-operational because CU and UPF are co-located. This model covers development scenarios #3 and #5 suited for the mass and enterprise 5G market.

Centralized RAN #2 is the RAN/core separated model. RU and DU are co-located at the cell site from FH's C-plane latency requirements. CU is located at tier2 site, and UPF is located at tier3 site. The reason for this is the operator's policy which requires strict RAN/core separation demands (e.g., Mobile Virtual Network Operators (MVNO) services). This model covers development scenarios #3 and #5, which are suited for mass and enterprise 5G markets.

Centralized RAN #3 is the MEC model. RU and DU are co-located at the cell site from FH's C-plane latency requirements. CU and UPF are co-located at tier1 site from U-plane latency requirements (e.g., very-low latency eMBB). This model covers the development scenarios #3, #4, and #5, which are suited for mass and enterprise 5G markets.

Distributed RAN #1 is the RAN/core separated model. RU, DU, and CU are co-located at the cell site from FH's C-plane latency requirements and operator's demands (e.g., easy operation for RAN). UPF is centralized located at tier3 site for easy operation of the core network. This model covers development scenarios #3 and #5 which are suited for mass and enterprise 5G markets.

Distributed RAN #2 is the RAN/core co-located model. All functions (RU, DU, CU, and UPF) are co-located at the cell site from both FH's C-plane latency requirements and U-plane latency requirements (e.g., ultra-low latency uRLLC). This model covers development scenarios #1, #3, #4, and #5, which are suited for only the enterprise 5G market because this model is not a macro network service model.

5.2.6.2. 5G RAN Architecture Models from Time Synchronization Viewpoints

Deployment scenario #1 is expected to be applicable for a very small-scale enterprise market system in a limited area (e.g., private 5G). The reason is that all functions (RU/(DU)/PRTC) are located in an on-premises area that has capacity limitations to support connections outside of that region.

Deployment scenario #2 is expected to be applicable for a small-scale enterprise market system in a limited area (e.g., private 5G). The reason is that DU is connected to RU directly (e.g., direct Ethernet link). It may have capacity limitations to support a wider area.

Deployment scenario #3 can be applicable for a medium-scale system for the mass market and enterprise market. The reason is that DU is connected to the RU by the FH network. It may have more capacity to support a wider area compared to scenario #2. Therefore, this scenario extends the coverage of time synchronization.

Deployment scenario #4, which improves scalability, can be applied to a large-scale system for mass market and enterprise market. The reason is that DU is connected to RU by the FH network, the same as in scenario #3, and the scenario supports the FH network with T-BC delivering time synchronization in place of DU. It can achieve accurate time synchronization between RUs connected to other DU, and the location of the DU has no impact on the synchronization network architecture as it is only an end-user of the synchronization.

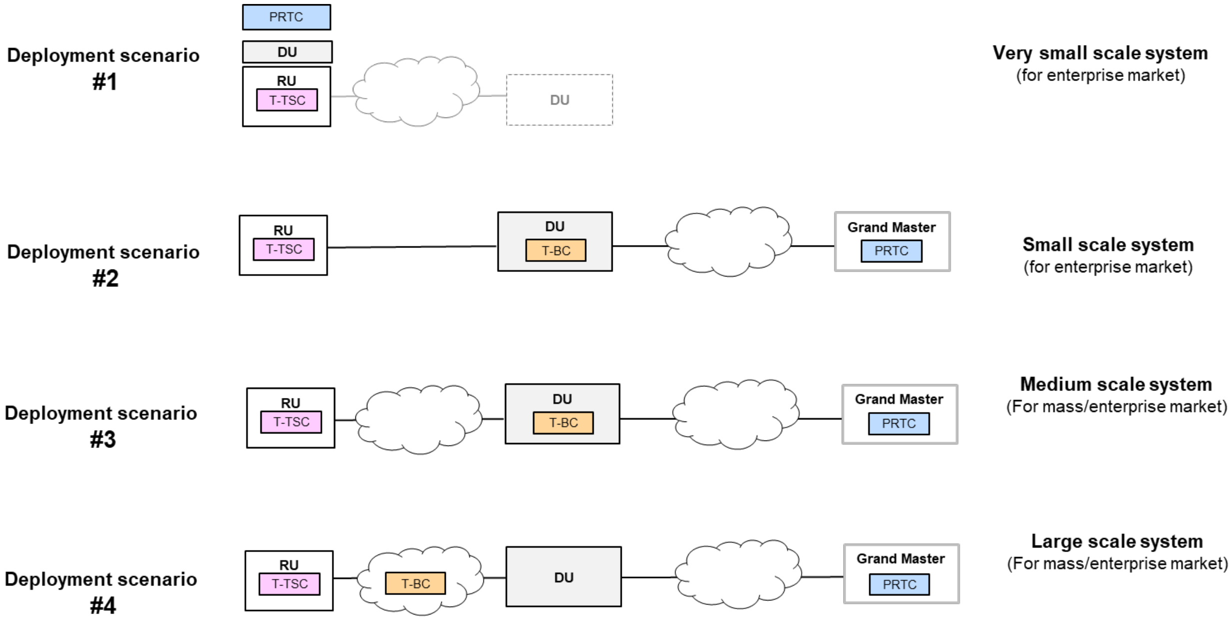


Figure 45 5G RAN architecture model from synchronization viewpoints

5.3. Study Item 3: Optimized Transport Network for Cost-Effective RAN Deployment and Operation Efficiency

Foreseen transport network system for wireless access in 6G era, towards 2025-2030 may require an adaptation of the network and its operations to provide a good level of connectivity everywhere. The traditional network segments will evolve towards a convergent network where the mobile infrastructure will support any service, including enterprises, and the fixed infrastructure will evolve to support mobile traffic. To provide connectivity everywhere and facilitate the management of this connectivity, the traditional network segments are evolving towards reference architectures that assure E2E management of the services. Figure *46* illustrates an example of a reference scenario for the transport network, where the wireless access segment should be managed as part of the E2E network orchestration system.

The wireless-access network segment will require higher bandwidth and lower latency than today and a higher level of automation, comparable with that of the other segments. Today optical communication technology can meet, in principle, high bandwidth and low latency requirements. However, an enhanced level of automation is needed to realize E2E automation. Moreover, just scaling down in performance and cost the optical technology used in today's metro and aggregation networks would be not enough since the capillary distributed terminations of the new access network will demand much smaller equipment size, energy consumption, and lower cost.

Silicon photonics is a promising technology for this purpose, as it has been so far mainly deployed in datacom applications, e.g., to provide high bandwidth intra-data centers connectivity. The datacom applications have different requirements with respect to telecom applications.

Achieving a high level of automation at a reasonable cost is important, and size is one of the requirements for achieving this goal.

The main features to support mobile wireless access are

- Optical & Packet-based transport for X-Haul network architecture
- Low latency transport systems
- Monitoring and management of the optical network for RAN
- Reuse of installed fiber infrastructure
- Technology enablers for the above, such as advanced optical components

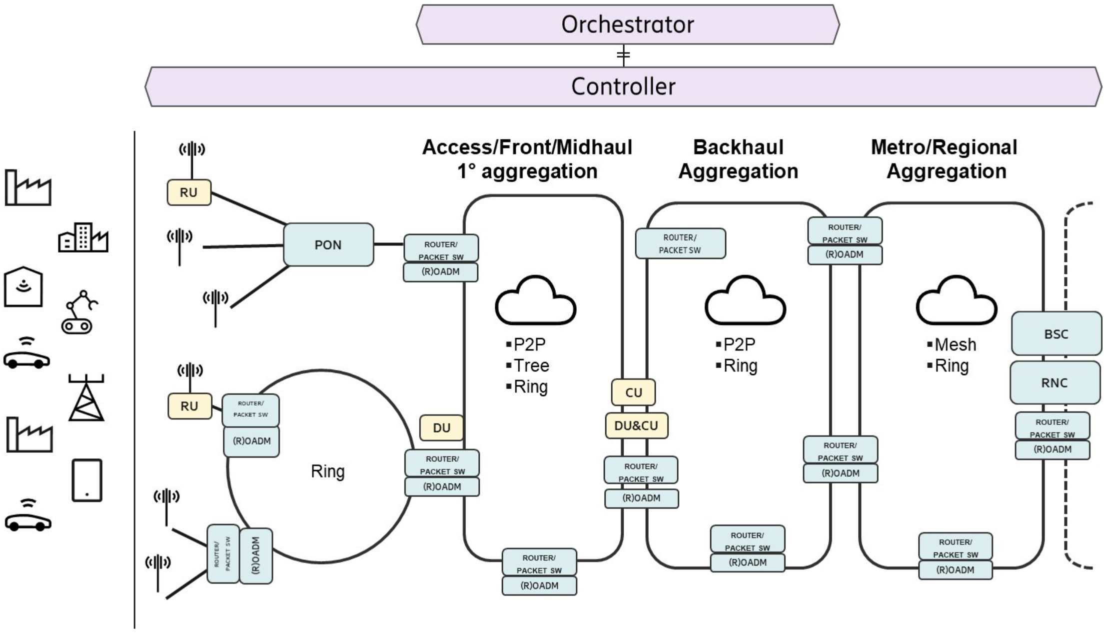


Figure 46 *One scenario of a transport network system for wireless access in 6G*

5.3.1. Deployment Scenarios

5.3.1.1. Scenario 1: Ring Topology

Multiple deployment scenarios should be considered depending on the operator infrastructure. In Figure 47, an example of a mobile X-Haul based on ring topology is shown. In this scenario, the antenna sites are connected to the Local Data Center using different radio interfaces, each one corresponding to a different protocol split: CPRI, which is the most critical in terms of bandwidth and latency requirements; eCPRI, which requires less bandwidth but has similar latency requirements of CPRI; and S1 and F1 that have less demanding bandwidth and latency specifications. Some mobile core network functions need to move to the access edge to comply with low-latency use cases. In contrast, traditional big datacenters in regional network segments will be replaced by smaller ones closer to the antenna sites. Hence, as shown in Figure 47, the CO hosts both VNFs and PNFs.

The main features for such a scenario are:

- Concurrent support of any radio protocol splits and related architectures
- Low cost and size reconfigurable optical nodes are required to support the huge capillary of the distributed terminations in the new access network
- Plug and play Reconfigurable Optical Add Drop Multiplexer (ROADM), enabling a high level of automation at suitable cost and size

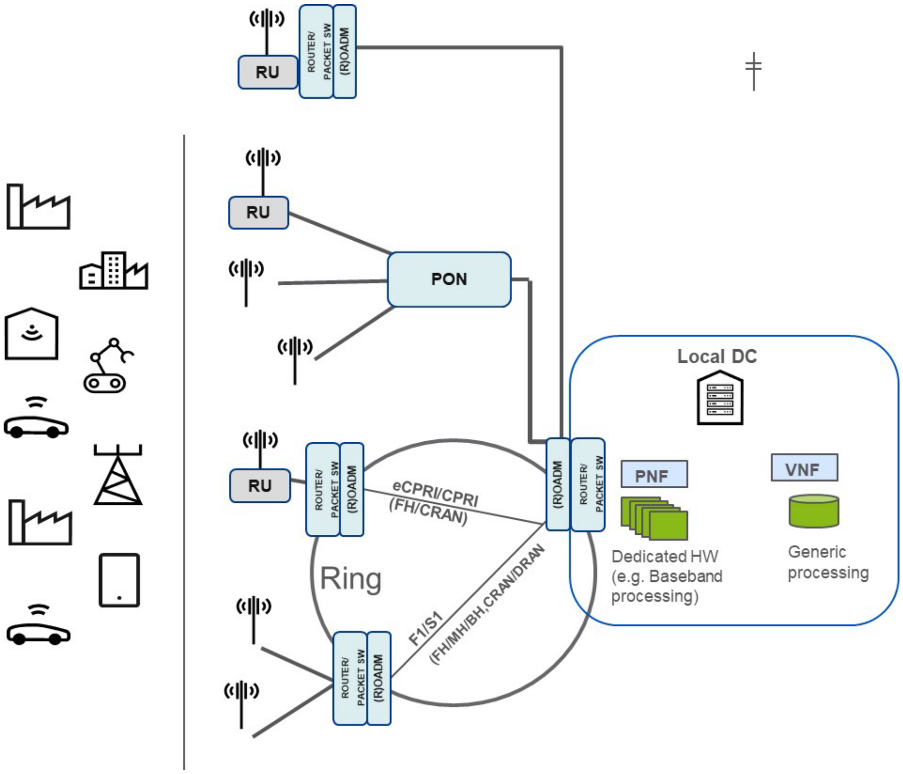


Figure 47 Scenario 1: Ring Topology

In this kind of network, to ensure compatibility with well-established protection mechanisms and optical components widely used in metro networks (transceivers, wavelength multiplexers, and demultiplexers, optical amplifiers, etc.), the use of two fibers, one for each propagation direction, is common. Moreover, DWDM is transparent to the client signal; hence it realizes an agnostic transport infrastructure suitable for any type of mobile traffic.

This scenario depends on the operator infrastructure that must be considered when the future network scenario is considered. In most cases, operators ask for an evolution path from the current architecture towards the new ones.

5.3.1.2. Scenario 2: WDM Overlay over PON

The term PON refers to a series of standards developed by IEEE and ITU-T for fixed access networks. NGPON2 is an architecture capable of total network throughput of 40 Gbit/s, corresponding to up to 10 Gbit/s symmetric upstream/downstream speeds available at each subscriber [ITU-T G.989.2]. In order to increase the system capacity, the NG-PON2 ITU-T standard uses WDM as a further additional aggregation layer in addition to the traditional TDM layer. This twofold multiplexing scheme is called Time-Wavelength Division Multiplexing (TWDM). NG-PON 2 also allows point-to-point connections between ONUs and OLT, using dedicated wavelength. Considering the pervasiveness of mobile devices and their demand for higher capacity, using the PON as a mobile transport infrastructure is a natural choice. This has obvious advantages for network operators, that can reuse existing infrastructure to carry mobile services, saving the cost of new installations. Mobile transport over PON is addressed in the ITU-T Supplement G.sup.66 [ITU-T G. Sup66]. In one of the scenarios described in the Supplement, fixed access services are run over a legacy TDM PON, and WDM overlay is reserved to wireless latency-demanding services on the same physical infrastructure. However, an issue with WDM systems is the high number of wavelengths, leading to an increased number of spare parts (one spare part per wavelength) and labeling each ONU port with the corresponding wavelength. This increases the complexity and cost of the network operation and maintenance processes.

Moreover, the PON optical distribution node (ODN) is based on power splitters that cannot select the wavelength. A full tunable WDM Transceiver (TRX), i.e., a transceiver including a tunable laser at the transmitter and a tunable optical filter at the receiver, is the key device to solve the issues as mentioned above as well as also providing the first level of automation for enabling a plug-&-play operation. The use of the total tunable WDM TRX is mandatory at the ONU and optional, though desirable, at the OLT, where traditional fixed-wavelengths pluggable TRXs and wavelength multiplexers and demultiplexers can be used.

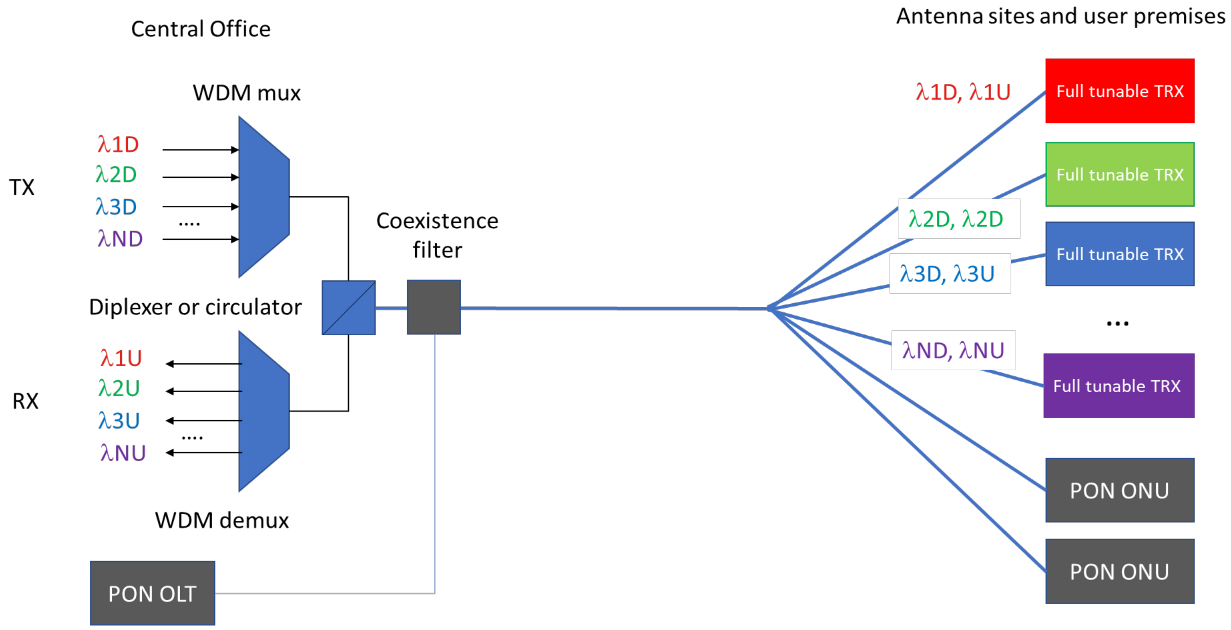


Figure 48: PON with WDM overlay and full tunable TRX

The concept is illustrated in Figure 48. WDM channels are transmitted from the Central Office (CO) to the antenna sites, where full tunable TRX resides. At the CO, a diplexer separates N WDM downstream wavelengths (λ1D, λ2D, λ3D …, λND) from upstream ones (λ1U, λ2U, λ3U …, λNU). A coexistence filter couples the legacy PON OLT to the WDM systems used for mobile services. Full tunable TRXs allow to use of cost-effective direct detection transceivers. Optical filters which can tune over a sufficient number of wavelengths (e.g., 20 WDM channels, 100 GHz spaced in the C band) are the enabling technology of full tunable TRXs. However, current tunable filters based on MEMS, liquid crystals, or thin-film filters do not fit the TRX requirements in terms of size (e.g., 28 Small Form-factor Pluggable (SFP) for a 25 Gbit/s signal), cost and power consumption; and the tunable filters developed for NG-PON2 only support 4 or 8 WDM channels. For this reason, it is necessary to explore new solutions. Silicon photonics is an example of promising technology for realizing cost-effective, small footprint optical filters tunable over a wide range of channels. Examples of designs are provided in [P. Iovanna SION 2021-11(4)]

5.3.2. Proposed Technologies

5.3.2.1. Integrated Photonics ROADM

Current mobile fronthaul networks are static, based on point-to-point fiber links or chains of Optical Add-Drop Multiplexers (OADMs). This architecture starts suffering from scalability and dynamicity issues when different high-bandwidth time-sensitive services coexist and compete on the same infrastructure, sharing the same resources. Reconfigurability and automation, starting from the physical layer, are essential to exploit the potentiality of network function virtualization and software-defined networks. This is why ROADMs, today common in metro and long optical networks, are expected to be used in earlier aggregation stages, like the X-haul segment. For example, interfaced with a packet switch, a ROADM allows automatically allocating and configuring wavelengths to be bypassed since they carry traffic not to be processed locally. Moreover, ROADMs would relieve operators from installing and storing many fixed OADMs, each variant corresponding to a given set of wavelengths, by replacing them with a single reconfigurable device. Unfortunately, the ROADMs used in optical metro networks are based on expensive Wavelength Selective Switches (WSS). Silicon photonics is a promising integrated photonic technology to realize small size, low-cost ROADM that operates over the short distances of an X-Haul network. In these devices, the number of line ports is lower than the ROADMs used in metro networks: two-line ports are enough to operate over fibers rings, and an additional pair port can be added for interconnecting rings. Although no commercial device is yet available in the market, recently significant research advances indicate the absence of fundamental technology bottlenecks, which may make products available in a short time. Examples of system-on-chip ROADMs utilizing silicon micro-ring resonators (MRR) are reported in literature [P. Iovanna JOCN 2016 Issue 12], [V. Sorianello Opt 2016 Issue 24], [V. Sorianello Opt 2016 Issue 1]:

5.4. Study Item 4: Cloud-native Network Function (CNF)/Virtual Network Function (VNF) Model with DCI

This section describes items to explore for deployment management systems related to DCI in the following CNF/VNF environment.

CNF - **C**loud native **N**etwork **F**unction running on enhanced Logical Service Node (LSN on Container Platform such as Kubernetes worker node).

VNF - **V**irtual **N**etwork **F**unction running on KVM hypervisor on NFVI such as OpenStack compute node.

5.4.1. Cloud native Network Function

CNF deployment architecture follows Kubernetes-based cloud platform architecture. The Cloud-native architecture is a paradigm shift to empower diverse 5G services from a network architecture perspective. Key elements of cloud-native network architecture are the use of microservices, vendor-neutral architecture, openness, leveraging DevOps principles, and a Continuous Delivery methodology via GitOps, bring benefits of network efficiency and resiliency, deployment in any cloud, open interface enabling analytical and automation, and community support, and speedy time to market.

As mentioned in Section 4.1, Mobile Network CNF workloads can be deployed on Enhanced Logical Service Node (LSN) with FDN in disaggregated infrastructure across multi-sites or at a single site. CNFs composing DU, CUcp (control plane), and CUup (user plane) are dynamically deployed on Enhanced LSN with FDNs. However, FDN (or DCI gateway) doesn’t have an automated mechanism to set up the following inter-site connectivity over an Open APN.

- Fronthaul connection between RU and DU (CNF on Enhanced LSN)

- Midhaul connection between DU (CNF on Enhanced LSN) and CUcp/CUdp (CNF on Enhanced LSN)

Hence an automated network infrastructure or intelligent network infrastructure is needed in a CNF deployment model.

The proposed Study Items in the CNF model will focus on the following:

- Consistency across DDCI-related orchestrators/managers/controllers and existing SMO (Service Management Orchestrator), and elimination of overlapping management functions among them.
- Exploring the best practice of deployment flow between multi-layers SDN controllers and CNF deployment management system across multi-sites in midhaul and fronthaul. SDN controllers in DCI architecture are FDN controller and Open APN controller.
- Exploring API between each controller in DCI system, other SMOs, and multi-Cluster manager for Kubernetes.
- Exploring mechanism with RAN Intelligent Controller for connectivity quality, such as latency, bandwidth, and availability. Enhanced LSN may choose to create connectivity at the optimal transport layer through FDN such as follows:
    - Optical/ethernet transport connectivity between RU and DU (CNF on Enhanced LSN) via FDN in the case of Fronthaul.
    - Ethernet connectivity between DU (CNF on Enhanced LSN) and CU-UP (CNF on Enhanced LSN) in FDN over Optical transport in the case of Midhaul.
    - IP connectivity between CU-UP (CNF on Enhanced LSN) in FDN and I-UPF (CNF on Enhanced LSN) in FDN deployed in the same DCI cluster.

5.4.2. Virtual Network Function

Since Network Function Virtualization has been adopted by many MNOs (Mobile Network Operators) to deploy VNF for Mobile packet core network and 4G vRAN globally, DCI architecture may need to consider a migration or coexisting scenario from 4G VNF to 5G CNF if required.

As the IOWN Global Forum targets 6G, while starting with 5G at present, VNF for 4G Mobile network is not mandatory to support via DCI over Open APN. However, the service management and orchestration systems may need to integrate into DCI architecture so that MNOs can keep using existing MANO (Management and Orchestration) functional blocks and OSS/BSS to save low CAPEX to deliver network service.

The proposed Study Items in VNF model will focus on the following:

- Exploring migration or coexisting scenarios for VNF and CNF on Enhanced LSN.
- Exploring MANO integration in multi-SMO in the DCI system.

5.5. Study Item 5: Time Sensitive Network (TSN) over APN in Mobile Network

5.5.1. Applicability of TSN Over APN in Mobile Networks

Since the dawn of the 5G era, TSN technology, as described in Section 3.1.1.7, has been increasingly deployed on packet switches in many mobile FH to meet stringent Hybrid Automatic Retransmit reQuest (HARQ) criteria. It is expected that uRLLC services will begin in earnest after completing 5G phase 2 standardization (3GPP Release 16). Towards 2030, it is expected that low-latency services will be increasingly available as described in Appendix B Low Latency Services, and TSN technology will be widely deployed to leverage beyond-human response speed enabling paradigm shifts in smart and connected world applications.

In mobile networks, as shown in Figure 49, cell sites, edge Central Office (CO) sites located in the edge cloud, regional CO sites located in the regional cloud, and Mobile Switching Centers (MSCs) are physically connected through the

APN. In addition, logical connections among RAN components such as O-Rus, O-Dus, and O-RAN Central Units (O-Cus), and UPFs will be provided using packet switches to encourage network slicing. The TSN technologies are expected to be deployed to enable deterministic low-latency connection among possibly virtualized RAN components and UPFs implemented across multiple servers, as described in section 4.2.

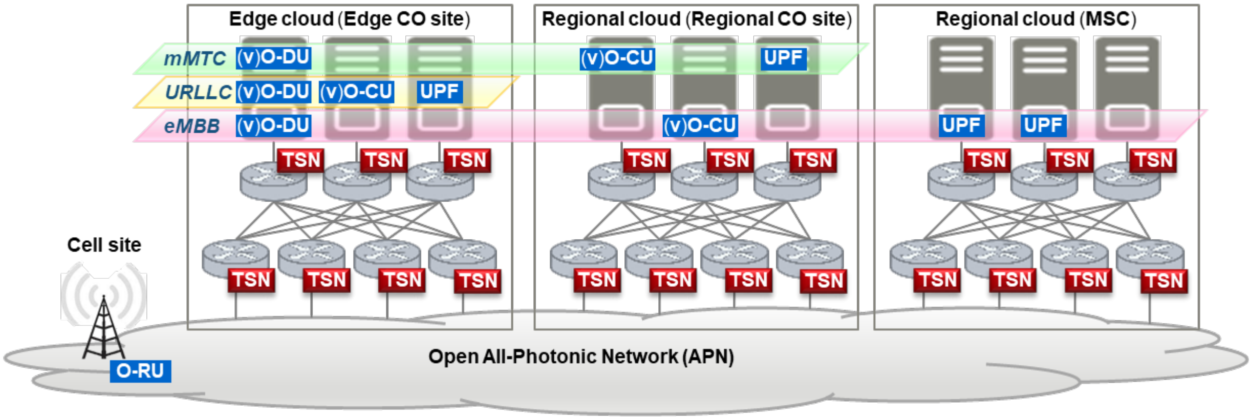


Figure 49 Mobile networks with TSN-enabled packet switches for network slicing

5.5.2. Scope of the Study on TSN Technologies

As described in section 3.1.6.1, the IEEE 802.1 TSN WG has proposed several base technologies for realizing low latency. For example, Frame Preemption is an approach to reduce the latency due to packet collision by interrupting a low-priority packet and transmitting a high-priority packet.

In the Time-Aware Shaper (TAS), gates are provided at the exits of up to eight class queues, and Open/Close is controlled by a Gate Control List (GCL). The delay's upper limit can be guaranteed since the bandwidth can be allocated in a time-division manner. Moreover, if the timing of the gate opening can be matched with the timing of the packet arrival, the ultra-low delay similar to the preemption can be realized.

On the other hand, for this accurate control of the GCL, today's TAS requires sensitive GCL setting and precise time synchronization. For the broad availability of TAS technology to succeed, autonomous management of this procedure will be desired. Figure *50* shows an example mechanism for realizing low latency using Intelligent Time-Aware Shaper (iTAS) with autonomous operation capability, encouraging easy and quick deployment. Also, it is desired to further optimize the bandwidth utilization efficiency in TAS.

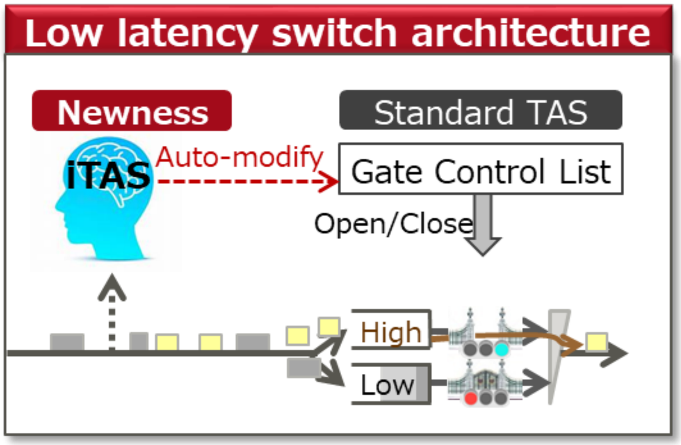


Figure 50 *An example mechanism for realizing low latency using intelligent Time-Aware Shaper (iTAS)*

The scope of this study item focuses on the following:

- ✓ Investigations on technologies enabling autonomous GCL setting for TAS without precise time synchronization, including:
  - feasibility assessment of each of the candidate technologies
  - applicability of each of them to the IOWN Global Forum Mobile Networks operating over the Open APN infrastructure, and
  - comparison among them with considering their pros and cons from usability, performance, CAPEX, and OPEX perspectives, in addition to the feasibility and applicability perspectives
- ✓ Investigations on technologies enabling optimization of the bandwidth utilization efficiency in TAS, including:
  - feasibility assessment of each of the candidate technologies,
  - applicability of each of them to the mobile networks operating over IOWN Global Forum’s Open APN infrastructure, and
  - comparison among them with considering their pros and cons from efficiency, performance, CAPEX, and OPEX perspectives, in addition to the feasibility and applicability perspectives

The expected outputs of this study item, *i.e.,* investigation results, will be used:

- ✓ to publish core technical documents in the short term, which include minimum performance requirements for TSN, including autonomous GCL setting for TAS, technical reports for optimization of bandwidth utilization, and so on, to engage in collaborations with external standards bodies, and in turn
- ✓ to publish a core set of technical specifications of TSN in the medium term.

6. Recommendation

The continuing progress of mobile networks from 5G toward 6G drives the evolution of transport networks serving the mobile communications network. APN and DCI architecture innovations developed by the IOWN Global Forum will enable quantum improvement of network performance, realizing diversified use cases envisioned for the 6G era in the IOWN Global Forum Use Case Docs [IOWN GF AIC UC] [IOWN GF CPS UC].

For 6G to achieve 10-100 times improvement of KPI compared with 5G and support more complex and challenging use cases, the following actions are recommended:

- Harmonization of orchestration, assurance, and ML/AI from E2E perspective to be fully dynamic and automatic for each specific vertical service
- Global standards including open interfaces in FH/MH/BH to embrace open network architecture
- Specify Interface between APN controller and resource management of other network elements or Kubernetes master (with Kubernetes operator in O-Cloud)
- Adopt cloud-native architecture to deliver agile, resilient, flexible, and scalable services
- Enhance and extend performance improvement features, such as CTI, TSN, between mobile networks and IOWN Global Forum APN
- Provide solutions for a smooth and economically viable path to evolving current FH/MH/BH architecture to APN
- E2E QoS such as deterministic latency and reliability needs to be applied to all elements of infrastructure, including radio, transport, and cloud
- Technologies developed by IOWN Global Forum need to support:
    - synchronization features and network imbalance timing compatible with 6G equipment positioning due to diversified RAN configurations
    - autonomous setting of parameters to optimize bandwidth utilization efficiency
    - 2-way mini-ROADM (?)
    - exploring integrated photonic technology to realize small size, low-cost ROADM that operates over the short distances of an X-Haul network
    - lossless network
    - elastically deployment of workloads by AI application owner across Mobile Edge/5G RAN, Regional Edge, Mobile Core, and center cloud in a scalable manner
    - accelerating conversion from electrical to optical components to improve energy efficiency
    - integration between electronics and photonics in on-board and co-packaged components

Appendix A
Fronthaul Performance Requirements for Different Radio Configurations

Fronthaul bandwidth and latency requirements observed today were captured in

Table 2 of Section 2.1, where both are based on O-RAN interoperability profiles.

Table A- 1 shows the required fronthaul bandwidth for different radio configurations. Those configurations initially addressed by O-RAN in their interoperability profiles, i.e., Sub6 with classical Four transmit and four receive antennas to transmit and receive signals simultaneously (4T4R) and mmW, are categorized as "5G (2020) scenarios". The latest configurations being addressed by O-RAN, i.e., Sub 6 Massive MIMO, are categorized as "5G (202x) scenarios".

Table A- 1 Required Fronthaul Bandwidth for Different Radio Configurations

5G (2020) scenarios	**Required fronthaul bandwidth**
Sub6 – Classical 4T4R (100MHz, 4 spatial streams)	25Gbps x 1 lane
mmW (400MHz, 2 spatial streams)	25Gbps x 1 lane
mmW (800MHz, 2 spatial streams)	25Gbps x 2 lanes
5G (202x) scenarios	**Required fronthaul bandwidth**
Sub6 – Massive MIMO (100MHz, 16 spatial streams)	25Gbps x 2 lanes
Sub6 – Massive MIMO (200MHz, 16 spatial streams)	25Gbps x 3 lanes

Some of the other key fronthaul performance requirements are captured in Table A- 2

Table A- 2 Other Key Fronthaul Performance Requirements

Fronthaul KPIs	**5G (2020) Target**
Synchronization - Jitter/Wander	ITU-T G.8262 (for Synchronous Ethernet Equipment Clock (EEC))
Air interface frequency error	+/50ppb for O-RU
Air interface time error (relative Time Alignment Error (TAE))	3 µs (Time-Division Duplexing (TDD), DC, inter-band CA)
Frame loss ratio	10^{-7}

Appendix B
Low Latency Services

As shown in Table 1, the E2E user plane latency requirement in 5G is 1 ms, and that in 6G is expected to be 0.1 ms. The IOWN GF Open APN is an ideal network that provides broad bandwidth with minimum latency. On the other hand, as shown in Table A- 3, some mobile service flows are expected to be served with much narrower bandwidth than those provided by an APN lambda channel. It implies that a statistical multiplexing scheme using packet switches needs to be deployed in the APN architecture. Thus, there is a gap in applying low latency technologies to packet switches using IOWN technology.

Table A- 3 Communication service performance requirements (Source: [3GPP TS 22.104][17])

Example Services	**End-to-end latency: maximum**	**Service bit rate: user experienced data rate**	**Message size [byte]**	**Transfer interval: target value**	**Survival time**
Periodic deterministic communication service					
Motion control	< transfer interval value	–	50	500 µs	500 µs
Motion control	< transfer interval value	–	40	1 ms	1 ms
Motion control	< transfer interval value	–	20	2 ms	2 ms
Electrical Distribution – Distributed automated switching for isolation and service restoration	< 5 ms	1 Kbps (steady-state) 1.5 Mbps (fault case)	< 1,500	< 60 s (steady-state) ≥ 1 ms (fault case)	transfer interval
Control-to-control in motion control	< transfer interval value		1 k	≤ 10 ms	10 ms
Wired-2-wireless 100 Mbps link replacement	< transfer interval value	50 Mbps		≤ 1 ms	3 x transfer interval
Wired-2-wireless 1 Gbit/s link replacement	< transfer interval value	250 Mbps		≤ 1 ms	3 x transfer interval
Control-to-control in motion control	< transfer interval value		1 k	≤ 50 ms	50 ms
Mobile robots	< transfer interval value	–	40 to 250	1 ms to 50 ms	transfer interval value
Mobile control panels – remote control of, e.g., assembly robots, milling machines	< transfer interval value	–	40 to 250	4 ms to 8 ms	transfer interval value
Mobile Operation Panel: Emergency stop (connectivity availability)	< 8 ms	250 Kbps	40 to 250	8 ms	16 ms
Mobile Operation Panel: Safety data stream	< 10 ms	< 1 Mbps	<1024	10 ms	~10 ms
Mobile Operation Panel: Control to visualization	10 ms to 100 ms	10 Kbps	10 to 100	10 ms to 100 ms	transfer interval
Mobile Operation Panel: Motion control	< 1 ms	12 Mbps to 16 Mbps	10 to 100	1 ms	~ 1 ms
Mobile Operation Panel: Haptic feedback data stream	< 2 ms	16 Kbps (UL) 2 Mbps (DL)	50	2 ms	~ 2 ms
Mobile control panels -remote control of, e.g., mobile cranes, mobile pumps, fixed portal cranes	< transfer interval	–	40 to 250	< 12 ms	12 ms
Process automation – closed-loop control	< transfer interval value	–	20	≥ 10 ms	0
Primary frequency control	~ 50 ms	–	~ 100	~ 50 ms	TBD
Distributed Voltage Control	~ 100 ms	–	~ 100	~ 200 ms	TBD

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[17] Table 9 is based on tables below in [3GPP TS 22.104]
- ✓ Table 5.2-1: Periodic deterministic communication service performance requirements
- ✓ Table 5.2-2: Communication service performance requirements for industrial wireless sensors
- ✓ Table 5.3-1: Aperiodic deterministic communication service performance requirements
- ✓ Table 5.4-1: Non-deterministic communication service performance requirements
- ✓ Table 5.5-1: Mixed traffic communication service performance requirements)

Mobile robots – video-operated remote control	< transfer interval value	–	15 k to 250 k	10 ms to 100 ms	transfer interval value
Mobile robots	< transfer interval value	–	40 to 250	40 ms to 500 ms	transfer interval value
Plant asset management	< transfer interval value	–	20 to 255	100 ms to 60 s	≥ 3 x transfer interval value
Robotic Aided Surgery	< 2 ms	2 Mbps to 16 Mbps	250 to 2,000	1 ms	transfer interval value
Robotic Aided Surgery	< 20 ms	2 Mbps to 16 Mbps	250 to 2,000	1 ms	transfer interval value
Robotic Aided Diagnosis	< 20 ms	2 Mbps to 16 Mbps	80	1 ms	transfer interval value
Cooperative carrying – fragile workpieces (ProSe communication)	< 0.5 x transfer interval	2.5 Mbps	250 500 with localization information	> 5 ms > 2.5 ms > 1.7 ms	0 transfer interval 2 x transfer interval
Cooperative carrying – elastic workpieces (ProSe communication)	< 0.5 x transfer interval	2.5 Mbps	250 500 with localization information	> 5 ms > 2.5 ms > 1.7 ms	0 transfer interval 2 x transfer interval
Communication service for industrial wireless sensors					
Process monitoring, e.g., temperature sensor	< 100 ms	≤ 1 Mbps	20	100 ms to 60 s	3 x transfer interval
Asset monitoring, e.g., vibration sensor	< 100 ms	≤ 200 Kbps	25 k	≤ 1 s	3 x transfer interval
Asset monitoring, e.g., thermal camera	< 100 ms	≤ 2 Mbps	250 k	≤ 1 s	3 x transfer interval
Aperiodic deterministic communication service					
Mobile robots – video streaming	10 ms	UL: > 10 Mbps			
Mobile control panels - parallel data transmission	< 30 ms	> 5 Mbps			
Mobile Operation Panel: Emergency stop (emergency stop events)	<8 ms	250 Kbps	40 to 250		16 ms
Smart grid millisecond-level precise load control	< 50 ms	0.59 Kbps 28 Kbps	< 100		–
Augmented reality; bi-directional transmission to image processing server	< 10 ms				
Wired-2-wireless 100 Mbps link replacement	< 1 ms	25 Mbps			
Wired-2-wireless 1 Gbps link replacement	< 1 ms	500 Mbps			
Non-deterministic communication service					
Motion control - software updates		DL: ≥ 1 Mbps			
Mobile robots; real-time video stream		UL: > 10 Mbps			
Mixed traffic communication service					
Wind power plant – control traffic	16 ms				
Mobile Operation Panel: Manufacturing data stream		12 Mbps	250 to 1,500		

Appendix C
High-level Functionalities Description of RU, DU, and CU

C1. High-level Functionalities inside the RU, DU, and CU

5G RAN consists of CU, DU, and RU, and the high-level functionalities are shown in Figure A- 1. CU is a logical node hosting RRC, Service Data Adaption Protocol (SDAP), and Packet Data Convergence Protocol (PDCP). DU is a logical node hosting RLC/MAC/High-PHY layers based on a lower layer functional split. The details of architecture and interfaces are defined in 3GPP [3GPP TR 38.801]. RU is a logical node hosting a Low-PHY layer and RF processing based on a lower layer functional split. Specifically, O-RAN RU (O-RU) includes the Low-PHY layer (FFT/iFFT, PRACH extraction).

CU can be split into two logical nodes: CU-CP (Control Plane) and CU-UP (User Plane). CU-CP hosting the RRC and the control plane part of the PDCP protocol aims to control sessions at the aggregation site, and CU-UP hosting the user plane part of the PDCP protocol and the SDAP protocol aims to release traffic at the cell site.

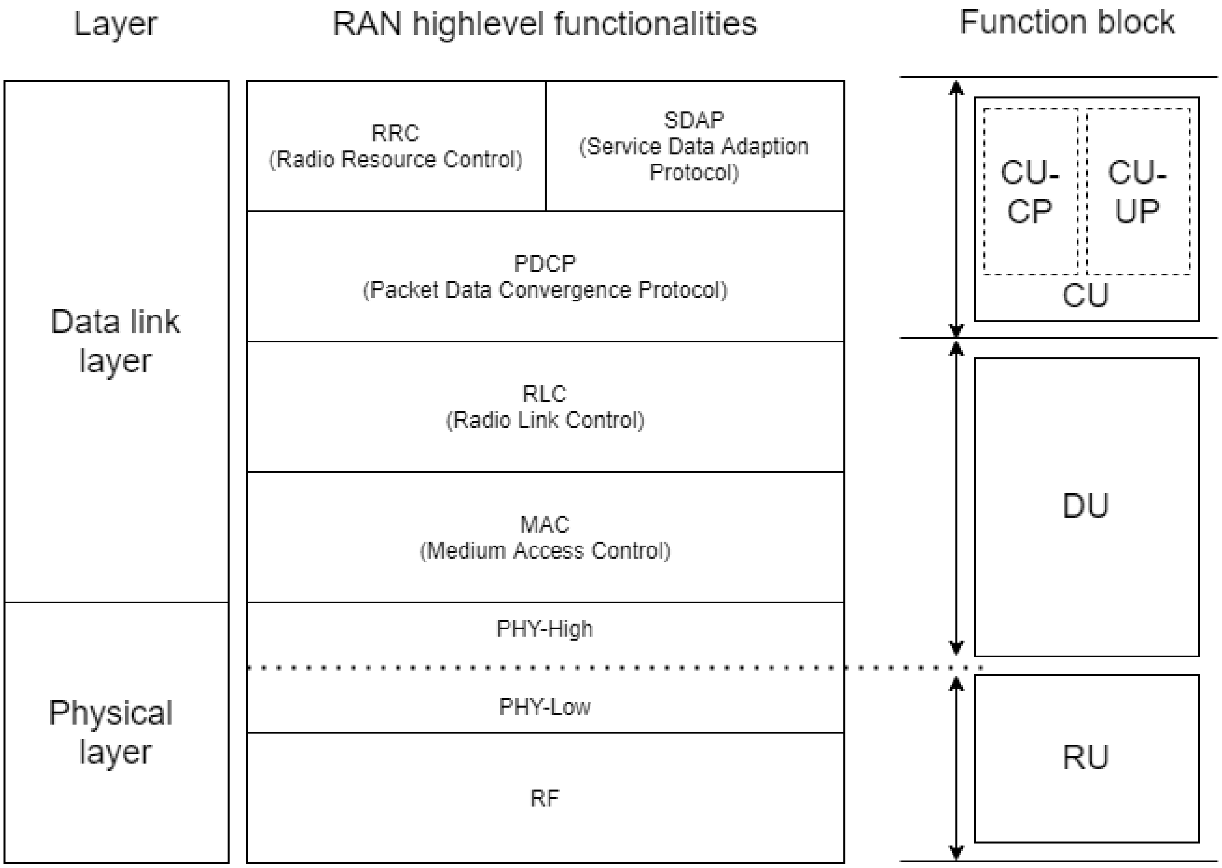

Figure A- 1 High-level functionalities in FDN

These functionalities are summarized in the following table:

Table A- 4 Detail functionalities of FDN functionality

Name of Functionality	Detailed functionality
RRC	System information broadcast, connection control, mobility, and measurement related functions
SDAP	mapping between QoS flow and radio bearers
PDCP	Header compression, Packet reordering and duplicate detection, security, timer-based packet discard, and duplicate packet transmission
RLC	Packet segmentation and reassembly, duplicate detection, protocol error detection, and lossless transmission by ARQ
MAC	Mapping between logical channels and transport channels, multiplexing/de-multiplexing data of same and different logical channels, scheduling, error correction by HARQ, priority control between logical channels, beam management control
PHY	(Detailed feature is described in 4.3.2)
RF	(Detailed feature is described in 4.3.2)

C2. Radio Signal Processing Flow in PHY/RF

In the DU and RU, radio signals are processed in PHY and RF layers and transforms the signals into MAC frames that are processed in upper layer functions such as MAC, RLC, and PDCP as shown in Figure A- 2. DU transforms signals from RLC SDUs to IQ samples of Orthogonal Frequency Division Multiplexing (OFDM) symbols for downlink (denoted as DL) (e.g., Physical Downlink Shared Channel (PDSCH)) and vice versa for uplink along with the following flows. In the following figure, Physical Uplink Shared Channel (PUSCH) is an example of uplink (denoted as UL).

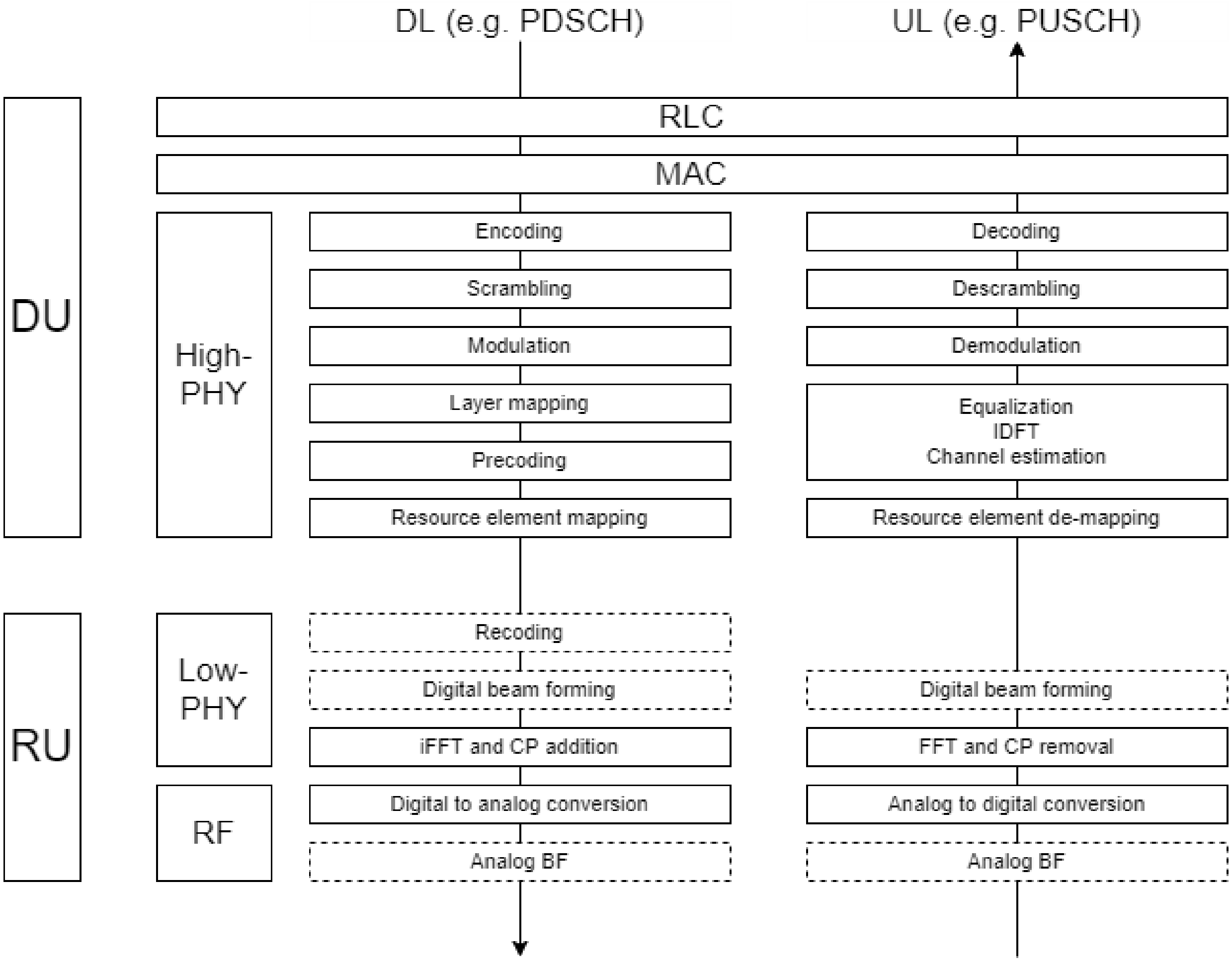

Figure A- 2 Signal procession flow in DU and RU

C3. RAN Network Protocol Stack

The networks between CU, DU, and RU are called BH, MH, and FH, respectively. The protocol stacks of MH and BH are depicted in Figure A- 3, as defined in 3GPP [3GPP TS 38.470], [3GPP TS 23.501].

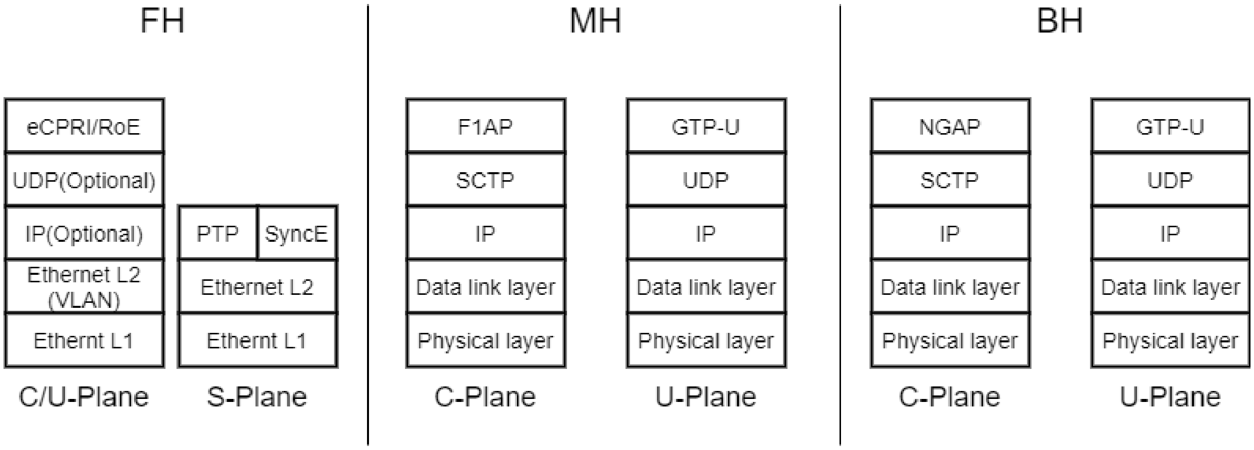

Figure A- 3 Protocol stacks in FH/MH/BH

For the FH, eCPRI is a packet-based fronthaul interface developed by the CPRI forum, and it provides the same level of interoperability as CPRI. eCPRI, a widely used FH protocol, provides flexible radio signal transmission through a packet-based network, i.e., IP or Ethernet [eCPRI Spec V2.0].

Definitions and Abbreviations

Definitions

For the purposes of this Reference Document, the following definitions apply:

Backhaul [Y.3100]:	A network path between base station systems and a core network.
FDN [IOWN GF ST Outlook]:	A Function-Dedicated Network (FDN) function is a network built on top of the Open APN to provide dedicated connection among endpoints to support various traffic and QoS requirements.
Fronthaul [Y.3100]:	A network path between centralized radio controllers and remote radio units of a base station function.
gNB [3GPP TR 38.801]:	A node that supports the NR as well as connectivity to Next-Generation Core (NGC).
Midhaul [MEF 22.3]:	The Carrier/Metro Ethernet Network between RAN BS sites. Typically, one of these sites would be a Macro RAN BS site
O-Cloud [O-RAN White Paper]:	The O-Cloud is a cloud computing platform that is made up of the physical infrastructure nodes using O-RAN architecture. It also creates and hosts the various virtual network functions (VNFs) used by the RICs and other infrastructure elements.
Orchestration [Y.3100]:	In the context of IMT-2020, the processes aiming at the automated arrangement, coordination, instantiation, and use of network functions and resources for both physical and virtual infrastructures by optimization criteria.
GitOps:	GitOps is a way of implementing Continuous Deployment for cloud native applications by using tools including Git and Continuous Deployment tools
Istio	An open platform to connect, manage, and secure microservices
Knative	Kubernetes-based platform to build, deploy, and manage modern serverless workloads
Global data-plane	A logical instance of hub that enables Function Dedicated Computing (FDC)/ Function Dedicated Network (FDN) Functions to exchange data directly or indirectly between different locations. Some types of DP may provide central shared memory for FDC/FDN Functions to exchange data indirectly.

Abbreviations and acronyms

For the purposes of this Reference Document, the following abbreviations and acronyms apply:

3GPP: The 3rd Generation Partnership Project

4T4R: Four transmit and four receive antennas to transmit and receive signals simultaneously

5GC: 5G Core network

5GS: 5G System

AF : Application Function

AI : Artificial Intelligence

AMF: Access & Mobility Management Function

AP: Access Points

API: Application programming interface

APN: All Photonic Network

AR/VR: Augmented Reality/Virtual Reality

A-RoF: Analogue Radio over Fiber

BH: Backhaul

BSS: Business Support System

CA: Carrier Aggregation

CAGR: Compound Annual Growth Rate

CAPEX: Capital expenditures

CEI: Common Electrical Interface

CN: Core Network

CNCF: Cloud Native Computing Foundation

CNF: Cloud native Network Function

CNI: Container Network Interface

CNTT: Common NFVI Telco Taskforce

CO: Central Office

CO DBA: optical-mobile cooperative DBA

COTS: Commercial off-the-shelf

C-Plane: Control Plane

CFI: Call For Interest

CPO: Co-Packaged Optics

CPRI: Common Public Radio Interface

CPU: Central Process Unit

C-RAN: Centralized RAN

CTI: Cooperative Transport Interface

CU: Centralized Unit

CXL: Compute Express Link

DBA: Dynamic Bandwidth Assignment

DC: Data Center

DCI: Data-Centric Infrastructure

DevOps: A compound of development (Dev) and operations (Ops)

DU: Distributed Unit

DPU: Data Processing Unit

D-RoF: Digital Radio over Fiber

DWDM: Dense wavelength division multiplexing

E2E: End to end

ECM: Element Control and Management

eCPRI: Enhanced Common Public Radio Interface

EEC: Synchronous Ethernet Equipment Clock

ENNI: External Network to Network Interface

eMBB: enhanced Mobile Broadband

ETSI: European Telecommunications Standards Institute

FCAPS: Fault, Configuration, Accounting, Performance, and Security

FDN: Function-Dedicated Network

FEC: Forward Error Correction

FFT/iFFT: Fast Fourier Transform/Inverse Fast Fourier Transform

FH: Fronthaul

FPGA: Field-Programmable Gate Array

FWA: Fixed Wireless Access

GCL: Gate Control List

gNB: Logical 5G Radio Node

GNSS: Global Navigation Satellite System

GPRS: General Packet Radio Service

GPU: Graphic Process Unit

GTP: GPRS Tunnelling Protocol

GTP-U: GPRS Tunnelling Protocol User Plane

HARQ: Hybrid Automatic Retransmit reQuest

IA: Implementation Agreement

ICM: Infrastructure Control and Management

ICT: Information and Communication Technologies

IEEE: Institute of Electrical and Electronics Engineers

IOWN: Innovative Optical and Wireless Network

IP: Internet Protocol

IPU: Infrastructure Processor Unit

IQ: Quadrature signals

ITU-T: The International Telecommunication Union Telecommunication Standardization Sector

I-UPF: Intermediate User Plane

KPI: Key Performance Indicator

L2SW: Layer 2 Switch

LF: Linux Foundation

MANO: Lower Layer Split

LSO: Lifecycle Services Orchestration

MAC: Medium Access Control

MANO: Management and Orchestration

MEC: Multi-access Edge Computing

MEMS: Micro-electromechanical systems

MH: Midhaul

MIMO: Multiple Input, Multiple Output

ML/AI: Machine learning/Artificial Intelligence

MNOs: Mobile Network Operators

mMTC: massive Machine Type Communications

MRR: Micro-Ring Resonator

MSC: Mobile Switching Center

MTP: Motion to Photon

MVNO: Mobile Virtual Network Operators

NBI: Northbound Interface

near-RT RIC: near-Real Time RAN Intelligent Controller

NEF: Network Exposure Function

NFV: Network Function Virtualization

NFVI: Network Function Virtualization Infrastructure

NGMN: Next Generation Mobile Networks Alliance

NG-PON2: Next-Generation Passive Optical Network Stage 2

NIC: Network Interface Controller

Non-RT RIC: non-Real Time RAN Intelligent Controller

NR: New Radio for 5G

OADM: Optical Add Drop Multiplexer

O-CU: O-RAN Control Unit

ODN: PON Optical Distribution Node

O-DU: O-RAN Distributed Unit

OFDM: Orthogonal Frequency Division Multiplexing

OIF: Optical Internetworking Forum

OLT: Optical Line Terminal

ONF: Open Networking Foundation

ONU: Optical Network Unit

OPEX: Operating Expenditure

O-RU: O-RAN Remote Unit

OSS: Operation Support System

OTDOA: Observed Time Difference Of Arrival

PaaS: Platform-as-a-Service

PCF: Policy Control Function

PDCP: Packet Data Convergence Protocol

PDSCH: Physical Downlink Shared Channel

PDV: Packet Delay Variation

PF: Platform

PHY: Physical Layer

PNF: Physical Network Function

PON: Passive Optical Network

PRACH: Physical Random Access Channel

PRS: Positioning Reference Signals

PRTC: Primary Reference Time Clock

PTP: Precision Time Protocol

PUSCH: Physical Uplink Shared Channel

QoS: Quality of Service

QSFP2-DD: Quad Small Form-factor Pluggable - Double Density

RAN: Radio Access Network

RLC: Radio Link Control

RIC: RAN Intelligent Controller

ROADM: Reconfigurable OADM

RoF: Radio over Fiber

RRC: Radio Resource Control

RRU: Remote Radio Unit

RSTD: Reference Signal Time Difference

RTT: Round-Trip Time

RU: Radio Unit

SBA: Service Based Architecture

SBI: Northbound Interface

SCTP: Stream Control Transmission Protocol

SDU: Service Data Unit

SDAP: Service Data Adaption Protocol

SDN: Software Defined Network

SD-WAN: Software-Defined Wide Area Network.

SDO: Standard Development Organization

SFP: Small Form-factor Pluggable

SG: Study Group

SLA: Service-Level Agreement

SMO: Service Management and Orchestration

SOF: Service Orchestration Functionality

TAE: Time Alignment Error

TAS: Time-Aware Shaper

TDD: Time-Division Duplexing

TDM: Time Division multiplexing

TDOA: Time Difference Of Arrival

TE: Time Error

TIM: Telecom Infra Project

TOA: Time Of Arrival

TRX: Transceiver

TSN: Time-Sensitive Networking

TTC: Time to Control

TTI: Transmission Time Interval

TTR: Time to Response

TTP: Time to Present

TTN: Time to Notify

T-BC: Telecom-Boundary Clock

T-TSC: Telecom-Time Slave Clock

TWDM: Time-Wavelength Division Multiplexing

UDP: User Datagram Protocol

UE: User Equipment

UNI: User Network Interface

UPF: User Plane Function

U-Plane: User plane

uRLLC: ultra-Reliable Low Latency Communications

UTDOA: Uplink Time-Difference-of-Arrival

vBBU: Virtualized Baseband Unit

vCU: Virtualized CU

vDU: Virtualized DU

VLAN: Virtual Local Area Network

VNF: Virtual Network Function

vRAN: virtualization of RAN

WDM: Wavelength-Division Multiplexing

WSS: Wavelength Selective Switches

X-Haul: Fronthaul/Midhaul/Backhaul

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History

Revision	Release Date	Summary of Changes
1.0	January 27, 2022	Initial Release