TELECOMMUNICATION ENGINEERING CENTRE
दूरसंचार अभियांत्रिक केन्द्र
MINISTRY OF COMMUNICATIONS AND INFORMATION TECHNOLOGY
संचार एवं सूचना प्रोधोगिकी मंत्रालय
DEPARTMENT OF TELECOMMUNICATIONS
दूरसंचार विभाग
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A Study Paper On

5G TRANSPORT REQUIREMENT

(A Guiding Tool for Planning 5G Transport Network)

Abdul Kayum

Director

Fixed Access Division

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FOREWORD

Telecommunication Engineering Centre (TEC) functions under Department of Telecommunications (DOT), Government of India. Its activities include:

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Abstract

This study paper enumerates the various requirements arising from 5G wireless systems for construction of a transport network, concentrating on the fronthaul and midhaul portion of the network, and considers how they compare with current optical access transport systems and suggesting how to proceed in constructing 5G transport.

Keywords

5G wireless, Access, Aggregation, Backhaul, Bandwidth, CPRI, C-RAN, Core, D-RAN, eCPRI, F1, Fronthaul, Fx, Latency, Midhaul, Networks, PON, Synchronisation, Transport, V-RAN.

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1 Introduction

Ultra-Reliability Low Latency Communication (uRLLC) application is going to be the hall mark of fifth generation wireless network (5G) in addition to enhanced Mobile Broadband (eMBB) and massive Machine Type Communication (mMTC). Stringent end to end (e2e) requirements of **very high throughput**, **ultra-low latency** and **RAN virtualization** in 5G require underlying transport network to be sensitive towards it. Many of these requirements are very different from that of currently deployed 4G network or fixed line networks. 5G nodes like DU, CU and NGC are clients to a transport network, therefore, characteristics of these nodes with respect to throughput, latency, synchronisation and OAM requirements have been dealt in detail to understand underlying demands from transport network. PON as prospective candidate for 5G fronthaul and midhaul transport network has been evaluated at length.

2 Definitions

2.1 Latency

In 5G, e2e latency [1] refers to the duration between the transmission of a data packet from the application layer of source node and successful reception at the application layer of the destination node. The over-the-air latency constitutes only one part of the e2e latency, whereas the latency of transport network and 5G core network constitute the remaining part.

2.2 Reliability

3GPP [2] defines the reliability by the probability of successful transmission of a packet from one radio unit to another radio unit within the given time constraint required by the targeted service. 3GPP defines the target packet failure rate of 10^{-5} within 1 ms over-the-air latency for uRLLC whereas 10^{-4} has been defined for HRLLC.

2.3 Distributed RAN (D-RAN)

DU is deployed near to RU, or RU/DU/CU are integrated. No transport in fronthaul.

2.4 Centralized RAN (C-RAN)

DU is located far away from RU at a centralized location, the distance between DU and RU is longer. Fronthaul transport network required.

2.5 Virtualized RAN (V-RAN)

CU is located away from DU, at a centralized location with Data Centre, known as Mobile Edge Computing (MEC).

3 5G RAN Architecture and new Interfaces

5G RAN architecture is defined in 3GPP *[3]* and shown in *Fig. 1* . In order to meet stringent e2e requirement of throughput, ultra-low latency and RAN virtualization in 5G, 3GPP proposed processing of radio signal chain (RRC-PDCP-RLC-MAC-PHY) at three different units, some parts in Central Unit (CU), some in Distributed Unit (DU), and some in Remote Radio Unit (RRU or simply RU) in contrast to 4G where all the processing of radio stack is done in Baseband Unit (BBU). This distribution of functions has given rise to two new interfaces, one between CU and DU, and another between DU and RU which are called Next Generation Fronthaul Interface-II (NGFI II or F1) and Next Generation Fronthaul Interface-I (NGFI I or Fx), respectively, and the associated transport links are frequently called Fronthaul-II or Midhaul and Fronthaul-I or just Fronthaul, however in 3GPP terminology both midhaul and fronthaul altogether is addressed as fronthaul. Interface NG links CU to NGC (CN) and interface and Xn links two CUs or CU and eNB. Illustration of different type of logical interfaces is given in *Fig. 1* , where emphasis has been given to interfaces and not to any specific deployment scenario.

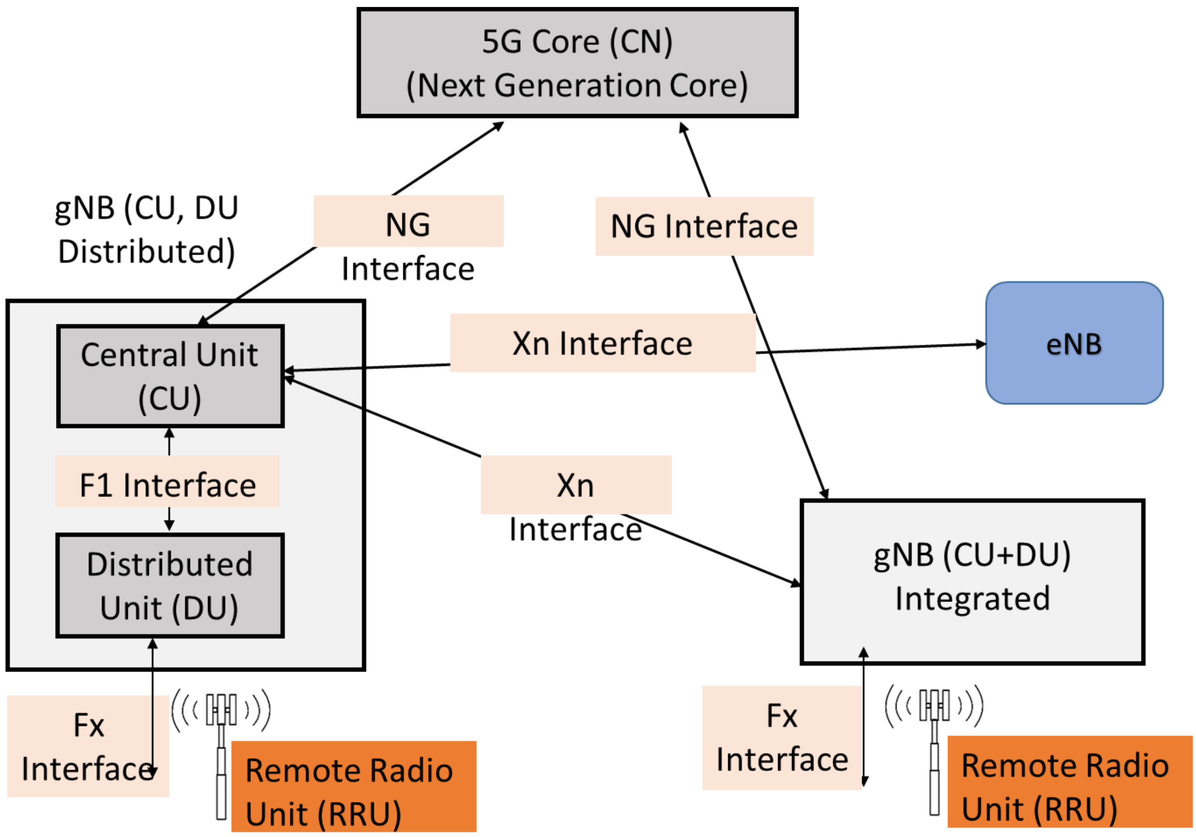

Fig. 1 5G RAN Architecture showing different Interfaces

4 Constraints of Classical approach to Fronthaul

Hitherto, in 4G wireless network, the fronthaul link is between RRH and the BBU using CPRI/OBSAI [4] protocol without using any transport network (usually BBU and antenna units are co-located at less than100m distance at cell site).

This CPRI [5] fronthaul is based on transport of digitized time domain IQ data. For very high capacity applications, such as eMBB (enhanced mobile broadband) or for radio sites with many independent antenna elements (massive MIMO or multi-layer MIMO), these fronthaul solutions require unreasonable high transport capacities (CPRI efficiency is ~6%) i.e. many times that of IP traffic it will carry (see appendix-II Table II 1 Required fronthaul data rate in 5G wireless network [3GPP TR 38.801], while allowing for transport latencies between RU and DU/CU of only up to a few hundred microseconds. If we continue with this approach, there is no problem in D-RAN deployment (CU/DU/RU or DU/RU are co-located), however, in C-RAN (DU, RU are far from each other), then a transport network will be required to carry digitalised radio signals within these constraints which are very difficult to meet at a reasonable cost.

5 Choices for fronthaul and midhaul in 5G wireless network

Unlike D-RAN, the increase in data rates *Table II 1* in 5G makes it impractical to continue with the conventional CPRI/OBSAI fronthaul implementation in C-RAN. However, moving towards higher level in radio signal chain split as depicted in *Fig. 2* would relax *[6]* the latency and bandwidth requirements, but at the cost of centralization processing functions. So distribution of radio processing functions in different units should take into account the technical and cost-effective tradeoffs between throughput, latency, and functional centralization.

Standardization bodies like 3GPP, xRAN [7], eCPRI [8], and the Small Cell Forum [9] have identified different points of split in the radio signal processing chain Fig. 2 that allow for substantial reduction of the transport requirements in C-RAN architectures compared to the current approach (CPRI based). The choice of optimal 5G New Radio (NR) points of functional split depends on specific deployment scenarios. So the transport capacity and latency requirement will depend upon the split points between which transport link will be required to be deployed. In Fig. 2 F1 and Fx interface have been shown distinctively as midhaul and fronthaul respectively although both F1 and Fx are called as fronthaul in RAN architecture of 3GPP.

Fig. 1and Fig. 2 below, there are 8 functional splits points from split option 1 to option 8 in both downlink and uplink direction. Option 8 is lowest layer Split and option 1 is called Highest Layer Split (HLS) point. Option 2,4,6 are inter layer split whereas option 3,5,7 are intra layer splits. Lower the split, higher is the bandwidth required and least latency margin. Split option 7 which is intra PHY is further sub-divided into option 7a, 7b and 7c taping advantage of reduced bandwidth at some functional splits than the other. *(PHY DL Functions- Coding rate matching, scrambling, modulation, layer* *mapping, precoding Tx power, resource element mapping, beamforming, iFFT, cycle prefix insertions)*

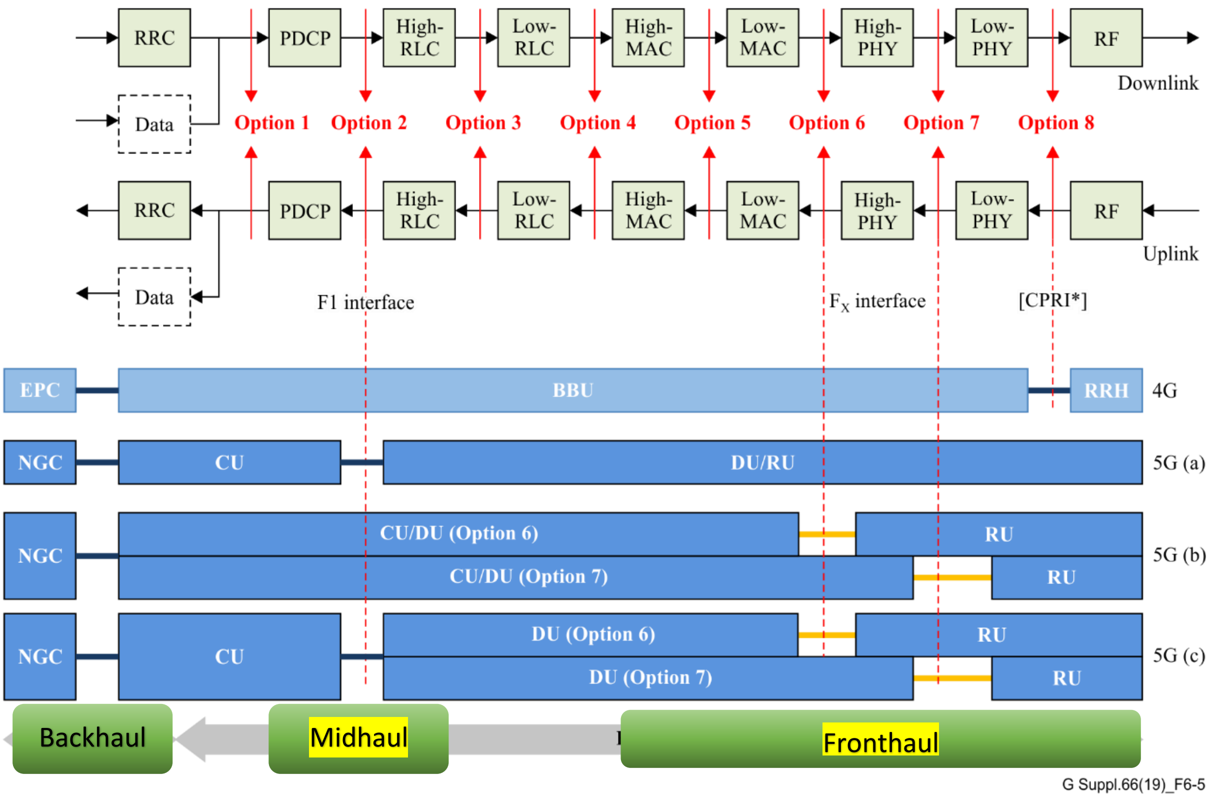

Fig. 2 Functional split points in Fronthaul

6 5G Transport Networks

The architecture (ITU-T G.8300) *[10]* of the transport network (ITU-T G.805) *[11]* is generally described in terms of metro access/aggregation/core, and backbone domains. The terms fronthaul, midhaul, and backhaul are used in this paper in describing the 5G transport network to support Fx interface, F1 interface and NG interface respectively between 5G nodes. Support to Xn interface that provides interconnection between different NG-RAN nodes (CU-CU/gNB or eNB) can be provided by either or both midhaul or backhaul transport network. It will be useful to map corresponding 5G transport network which can be supported by these domains. Mapping is illustrated in Fig. 3 with four different examples of CU and DU deployment.

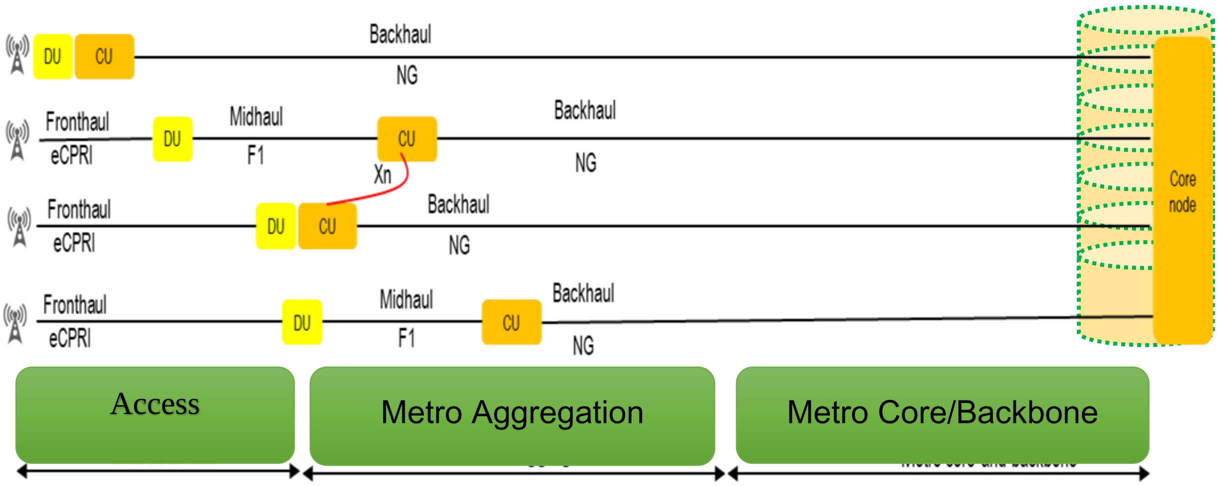

Fig. 3 Mapping of 5G Transport with Transport Network Domains

As a matter of fact, support to these interfaces can be provided by any domains of transport network but it is not prudent to do that as all the transport node need not to have all kind of interfaces, distance support etc. Mapping of transport network domain with 5G transport is summarised below.

Transport network terms	**Access domain**		**Metro Aggregation domain**	**Metro Core or Backbone Network domain**
5G transport terms	Fronthaul	Midhaul and Backhaul	Midhaul and Backhaul	Backhaul
5G Interface supported	Fx (CPRI/eCPRI)	F1, NG, Xn (Ethernet)	F1, NG, Xn (Ethernet)	NG, Xn (Ethernet)
5G Nodes involved	RU-DU	DU-CU, CU-NGC, gNB-gNB	DU-CU, CU-NGC, gNB-gNB	CU-NGC, gNB-gNB
Distance	<10/20km	< 40km	< 40-80km	< 40-80km or >100 km

7 5G RAN Deployment Scenarios

The deployment (ITU-T G.8300) [10] of 5G RAN can be characterized D-RAN, or C-RAN on the basis of the location of the DU and CU and V-RAN if a data centre is present in RAN. The different deployment scenarios are illustrated in Fig. 4.

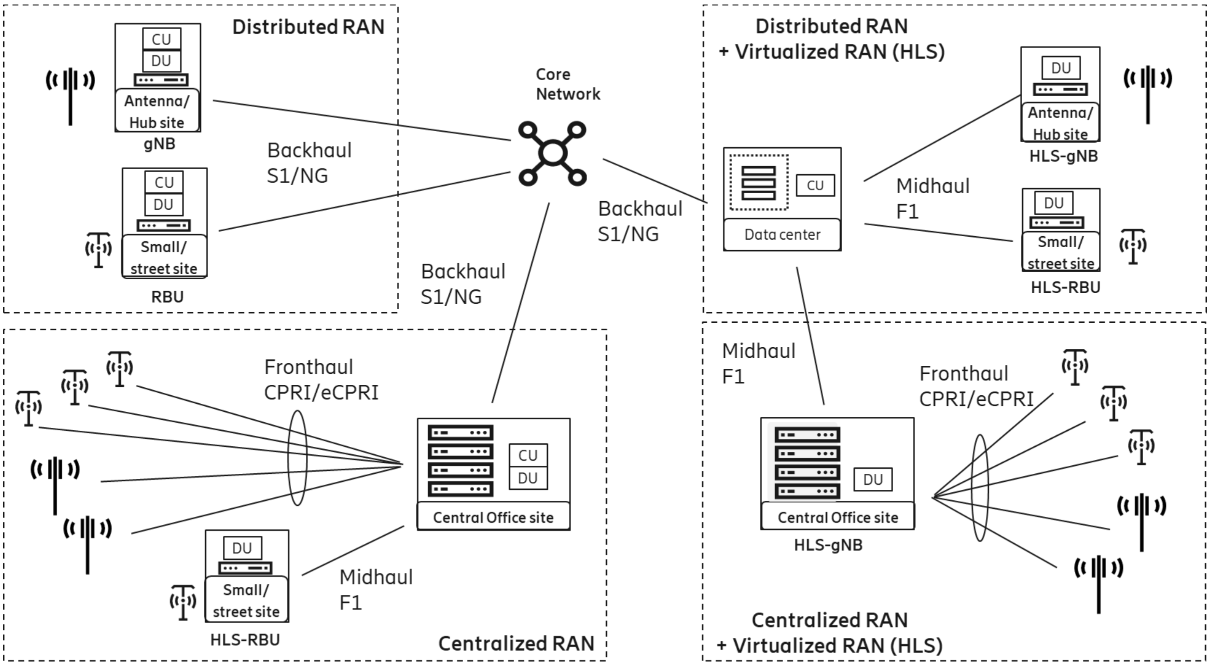

Fig. 4 5G RAN Deployment Scenarios

7.1 Distributed RAN (D-RAN):

DU is deployed near to RU, or RU/DU/CU are integrated. In this scenario, the distance between DU and RU is generally very short (less than 100m) as such no transport network required between RU and DU. However, either midhaul or backhaul or both transport network will be required depending upon location of CU. If CU is away from DU then both midhaul to support F1 interface and backhaul to support NG interface are required. If CU is deployed with DU then only backhaul transport network is required.

7.2 Centralized RAN (C-RAN):

In this scenario, DU is located far away from RU at a centralized location, the distance between DU and RU is longer. In this scenario, fronthaul transport network to support Fx interface (CPRI/eCPRI) is required for sure along with either midhaul (for F1) or backhaul (for NG) or both transport networks.

7.3 Virtualized RAN (V-RAN)

In this scenario, CU is located far away from DU at a centralized location with Data Centre (also called as Mobile Edge Computing (MEC)). DU may or may not be co-located with RU. If DU is not co-located with RU then all the three fronthaul, midhaul and backhaul will be required, else only midhaul and backhaul will be required.

In actual deployment there may be exclusive D-RAN, C-RAN or a mix of the above scenario as illustrated in Fig. 4 (ITU-T G.8300) [10].

8 5G Transport Network Design Consideration

5G NR and services that affect the requirements for the fronthaul transport layer bandwidth, latency, synchronization/jitter, and OAM requirements are discussed below.

8.1 RAN and Service requirements

3GPP considers RAN architectures that include 5G wireless network along with 4G wireless network in one common wireless network (3GPP TR 38.801 V2.0.0 (R14) [12]. Apart from this mixed architecture, 5G networks alone will comprise (ITU-T G series Supplement 66) [13] a variety of services with traffic characteristics that are very different from each other (Table 1) (ITU-R M.2083) [14], as well as a variety of Radio Access Technologies (RAT) with different Radio Frequency (RF) configurations (e.g. massive MIMO, multi-layer MIMO, below 6 GHz and above 6 GHz etc.). However, simultaneous use of all of these technologies and services are unlikely in the same network. Multiple mobile services may use the same RU, but the differentiated fronthaul transport network may have to be provided to suit different services, depending on traffic and latency needs. A high-level overview of expected traffic characteristics for various 5G services is given in Table 1 below which is copied from ITU-R M.2083.

Table 1 High-level overview of expected traffic characteristics for various 5G services (see for example Fig. 3 in ITU-R M.2083 [14]

Radio technology	Peak rate	Average rate	e2e delay (service level)
Enhanced Mobile Broadband (eMBB)	5-10 / 20 Gb/s (UL/DL)	Normal- 100 Mbps/ user Hot spot- 1 to 4 Gb/s	10 ms
uRLLC / Critical MTC (incl. D2D)	much lower than in eMBB: N x Mb/s	much lower than in eMBB: n x Mb/s	1- 2.5 ms
Massive Machine Type Communication (mMTC)	much lower than in eMBB: N x Mb/s	much lower than in eMBB: n x kb/s to n x Mb/s	1-50 ms

Note: N and n represents number of users at peak and average rate respectively.

8.2 Latency requirements

In C-RAN scenario, processing of radio chain stack (RRC-PDCP-RLC-MAC-PHY) is distributed among CU, DU and RU. Latency requirement of transmission network will depend upon which layer of stack is processed in RU/DU/CU. Higher the layer of stack processed in RU, lower the level of stringency of latency. If part or full of radio signal stack MAC or PHY or both are processed in RU then transport latency requirement between DU and RU is in order of µsec **but bandwidth requirement is considerably reduced**; if it does not, then transport latency is specified solely by the requirements of the application layer which is typically in the milli second range which most of the transmission system will be able to support.

The latency requirements of fronthaul interface eCPRI on the transport network are specified in eCPRI Specification [8]. Four different classes of (one way) latency are defined for eCPRI i.e. 50, 100, 200, 500 µsec. However other standardization bodies have different approach. For example, the xRAN group has taken an approach in which the latency requirement is derived from the processing capabilities of the radio equipment at either end of the Fronthaul (Fx) link [7]. The equipment is categorized into different classes, depending on the combination of the equipment, the one-way residual latencies can be as large as 350 µsec or even higher. A typical latency requirement is given in Table 2 and Fig. 5 to understand magnitude of requirements.

8.3 Bandwidth Requirements

As discussed in previous sections, transport bandwidth requirement depends upon which layer of radio signal is processed in RU and DU. Even low PHY processing in RU reduces the bandwidth requirement by about 2-15% (ITU-T G series Supplement 66) *[13]* as compared with traditional CPRI approach. Calculations methods for bandwidth required at Fx, F1 and NG interface is given in appendix II. *Table 2* and *Fig. 5* provides bandwidth requirement at different layer of radio process chain at Fx and F1. It is to be noted that the values given in the *Table 2* is specific to a cell configuration (3GPP TR 38.801 V2.0.0 (R14)) *[12]* which may change with different cell configuration. It just provides a glimpse of magnitude of bandwidth requirement to foresee and plan for 5G transport network.

Table 2 Transport bit rates and latency ranges at different functional split interfaces [12]

<table>
<tr><th>Protocol split option</th><th>Required downlink bandwidth</th><th>Required uplink bandwidth</th><th>One way latency (order of magnitude)</th></tr>
<tr><td>Option 1</td><td>4 Gb/s</td><td>3 Gb/s</td><td rowspan="3">1-10 ms</td></tr>
<tr><td>Option 2</td><td>4016 Mb/s</td><td>3024 Mb/s</td></tr>
<tr><td>Option 3</td><td colspan="2">[lower than Option 2 for UL/DL]</td></tr>
<tr><td>Option 4</td><td>4000 Mb/s</td><td>3000 Mb/s</td><td rowspan="3">100 to few 100 µsec</td></tr>
<tr><td>Option 5</td><td>4000 Mb/s</td><td>3000 Mb/s</td></tr>
<tr><td>Option 6</td><td>4133 Mb/s</td><td>5640 Mb/s</td></tr>
</table>

Option 7a	**10.1-22.2 Gb/s**	**16.6-21.6 Gb/s**	
Option 7b	**37.8-86.1 Gb/s**	**53.8-86.1 Gb/s**	
Option 7c	**10.1-22.2 Gb/s**	**53.8-86.1 Gb/s**	
Option 8	157.3 Gb/s	157.3 Gb/s	

[Cell configuration: RF 100 MHz, 256-QAM, 8 MIMO layers, 32 antenna ports from Annex A in (3GPP TR 38.801 V2.0.0 (R14)) [12]

It must be noted, however, that in general there is not a fixed ratio of transport bandwidth between different split options. In field deployments, the throughput on the air interface changes with the actual conditions of the radio channel (environmental conditions, interferences, reflections, etc.). This throughput variation will in turn require varying transport capacities at the different split options which is often less than the calculated values (except for Option 8).

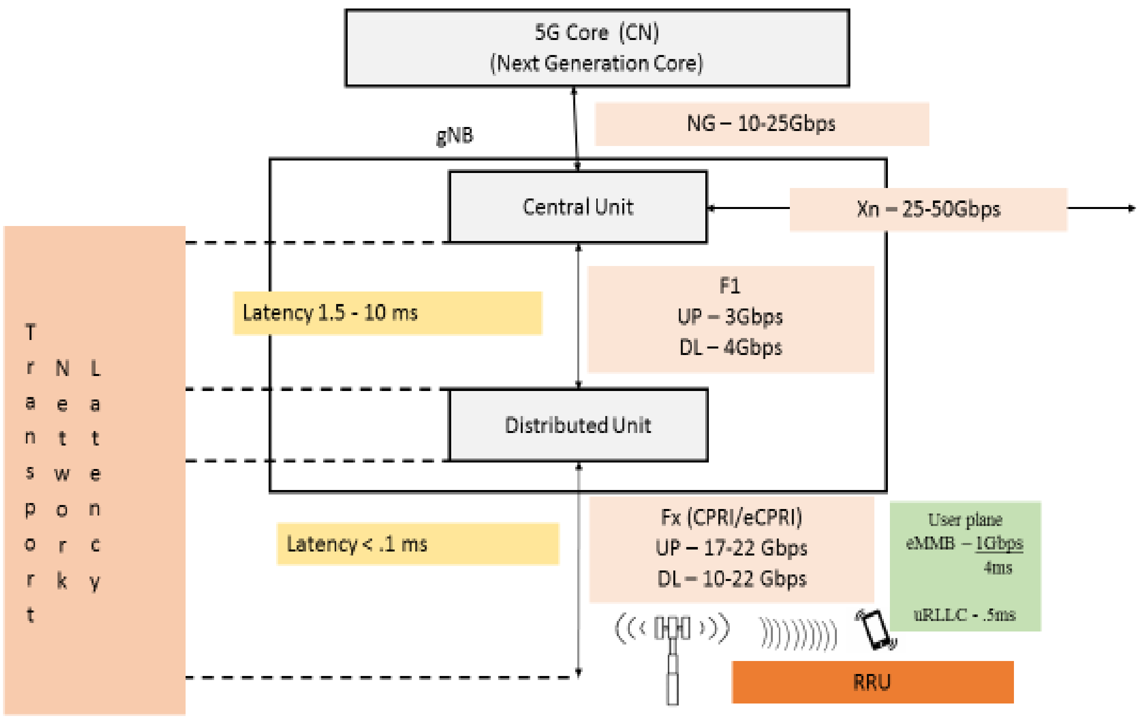

Fig. 5 A typical bandwidth and latency requirement of 5G RAN

8.4 OAM Requirements

In the 5G C-RAN architecture, especially in fronthaul, there is a need for coordination between the transport network layer and the radio network layer. OAM functions (ITU-T G.8013) [15] like monitoring of degradation of performance and fault detection etc., will need to be implemented to enable co-ordination between radio network operator and transmission network operator to monitor its own network segment and hand over the information to each other. Even there may be need for coordination for specific services delivery as well.

Depending on the service, both out-of-service and in-service delay measurements may be required. Some services may need only an out of service measurement prior to activating the service, while others may require monitoring of delay at regular intervals to ensure performance requirements are being met. Both one-way and two-way delay measurements are required.

8.5 Synchronization Requirement

As per 3GPP [16], (ITU-T G.805) [11], the frequency offset at the air interface of every RRU should be less than the value in the following table.

Table 3 Frequency offset requirement

BS class	Accuracy
Wide Area BS	±0.05 ppm
Medium Range BS	±0.10 ppm
Local Area BS	±0.10 ppm

8.6 Network Slicing Requirements

Recommendation (ITU-T Y.3112) [17] describes the concept of network slicing and use cases when a single user equipment (UE) simultaneously attaches to multiple network slices in the 5G network. The use cases introduce the slice service type to indicate a specific network slice and the slice user group for precisely representing the network slice in terms of performance aspects and business aspects. This

Recommendation also specifies high-level requirements and framework for the support of network slicing in the 5G network. The transport network is, in general, a multi-service network and, in most cases, a common transport network infrastructure will be shared between 5G services and other mobile and fixed services. It is necessary to provide isolation between each of these services [10].

8.7 Protection Requirements

As compared to 4G, 5G is expected to carry more traffic and some of them are very critical for example autonomous vehicle and remote surgery. Therefore, it calls for better protection and restoration of its transport network. Protection or restoration mechanisms should be used in the 5G transport network as necessary to meet the requirements of the services being carried over the 5G network [10].

9 Transport Networks choices

There is general consensus (IEEP1914) [18], (ITU-R M.2083) [14] (ITU-T G series Supplement 66) [13] on the type of interface CU, DU and RU should have eCPRI or CPRI at RU/DU and Ethernet at DU/CU. Accordingly, transport network operating between DU and RU are required to have devices with eCPRI or CPRI at both UNI and SNI (RU-DU link) operating at 25GE for eCPRI, multiples of 10G/25GE for CPRI and multiples of 10GE, 50G or a few 100GE at SNI/NNI (DU-CU/CN) in the access network. There are a numbers of transport technologies (some of them shown in Table 4) such as point to point SDH, OTN, Ethernet, mm wave wireless, point to multi-point PON, Time Sensitive Network (TSN) and Software Defined Network (SDN) which may be used in fronthaul. Undoubtedly OTN meets most of the requirement of 5G transport including latency but cost may be a factor to bother. At this point of time, PON [13] is being considered as one of the promising technologies because of its sheer presence in access network ecosystem and cost but it does not go without challenges. For the backhaul and F1 interfaces, TDM-PON with data rates over 10 Gb/s should be sufficient to meet both the bandwidth and latency requirements. However, Fx interface will require PON with much higher data rate and lower latency. We will discuss deployment of PON in detail in subsequent sections. Other technologies can also be evaluated on the lines of PON.

Table 4 Data Rates of different Technologies

TECHNOLOGY	**DATA RATE**						
SDH	STM-1	STM-4	STM-16	STM-64	STM-256		
	155 Mbit/s	622 Mbit/s	2.5 Gbit/s	10 Gbit/s	40 Gbit/s		
OTN	OTU-1	OTU-2	OTU-3	OUT-4	OUT-C2		
	2666 Mbit/s	10709 Mbit/s	43014 Mbit/s	100 Gbit/s	200 Gbit/s		
PON	GPON	XGPON	XGSPON	NGPON2	WDMPON*		
	2.5/1.25 Gbit/s	10/2.5 Gbit/s	10/10 Gbit/s	40 Gbit/s	1,2.5,10 Gbit/s	25 Gbit/s	50 Gbit/s

**ITU Standard for 50G PON is under study and likely to be published in 2020.*

9.1 OAM Solutions

In the fronthaul link, it could be implemented through Out-of-band monitoring or In-band monitoring. Choice of in band and out of band will primarily depend upon requirement of bandwidth and latency by radio network layer and availability channel for OAM functions. OAM signalling should not consume too much of bandwidth or introduce too much latency into the fronthaul network. It is desired that OAM messages are inserted in low layers near the physical line, e.g., PMD, PCS, or MAC layers, instead of the IP or upper layers [14] [13].

9.2 Synchronization solution for transport network

Synchronisation solution defined in (G.8275/Y.1369) [19] should be used in the transport network to support 5G frequency and phase/time synchronization requirements. As per this this solution, every node between the clock server and the end application node should support the SEC/eSEC and T-BC or T-TC clock (ITU-T

G.8271.1) [20]. The figure below is a generic construct for synchronization for the transport network and depicts one example of how such a network could be designed.

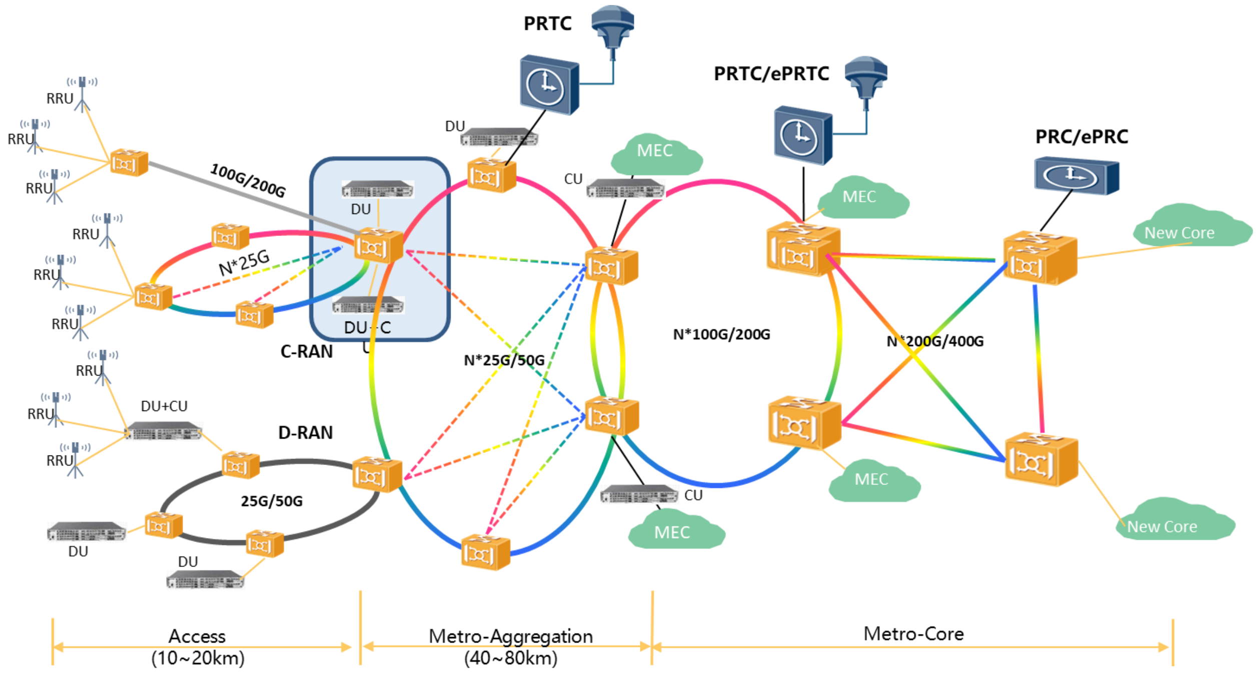

Fig. 6 Example Synchronization Transport Network Topology

- The deployment position is limited by the number of hops from the clock server to the RRU, which is described in the HRMs of [20].
- In general, the frequency reference master PRC/ePRC is deployed in the core network, and the phase/time master PRTC/ePRTC is deployed in the access, aggregation, or core network.
- For the frequency synchronization solution, the transport nodes between the PRC/ePRC and RRU shall support the appropriate SEC or eSEC physical layer clock.
- For the phase/time synchronization solution, the transport nodes between the PRTC/ePRTC and RRU shall support the T-BC PTP layer clock. The clock specification is (ITU-T G.8273.2) [21], and the network limit is defined in (ITU-T G.8271.1) [20], and the PTP full timing support profile is (ITU-T G.8275.1) [22].

- Optical layer nodes without optical protection/restoration are not required to support the OEC, eOEC or T-BC. This is because these nodes do not affect the accuracy of transport synchronization network.

9.3 Network Slicing Solutions

From a management perspective, the Network Slicing services are supported by Virtual Networks (VNs). The forwarding plane must ensure that the traffic from one VN does not get delivered to a different VN due to any reason. It is also necessary for the forwarding plane to provide sufficient isolation that limits the interaction between the traffic in different VNs.

9.4 Protection/ Restoration Solution

General transport protection mechanisms are described in the (ITU-T G.808.1) [23] (ITU-T G.808.2 [24] series of Recommendations. In order to allow for deployment of survivability mechanisms in multiple layers, any new protection or restoration mechanisms should support the use of hold-off timers.

10 An Analysis of PON as a Transport for 5G Midhaul and Fronthaul Application

The PONs which can support bandwidth consumption (see Table 2) of fronthaul and midhaul are TDM-PON (XG-PON [25]/XGS-PON [26]), TWDM-PON (NGPON2 [27]) and WDM-PON.

The single-channel TDM PON systems inherently require a quiet window to allow activation of new or returning ONUs/ONTs. Both XG-PON and XGS-PON with 20 km differential fibre distance, requires a 250 μs general quiet window for ONU/ONT discovery and for a 200μs targeted quiet window for each discovered ONU/ONT. During the quiet window, the OLT CT pauses upstream transmission of the in-service ONUs, thus contributing to the instantaneous latency and jitter experienced by all upstream traffic flows on the PON.

The multi-channel TWDM PON [27] systems have capacity to sacrifice to allocate a subset of wavelength channel pairs to perform new and returning ONT activation, while keeping one or more wavelength channel pairs for low latency operation without having to do discovery and activation functions. Once an ONT is activated in an allocated activation wavelength channel pair, it is handed over to the operational low latency wavelength channel pair. The active ONU/ONT handover does not impede services of other ONTs in the low latency operation channel, as long as the system implements consistent ranging or other method of equalization delay coordination. WDM-PON does not share its bandwidth as each ONT uses independent wavelength channel pairs so there is no queuing.

Since Fx has strict latency requirement, WDM-PON and TWDM-PON (NGPON2) are good candidate for this use case. A dedicated TWDM-PON would be more resource efficient due to its ability of statistical multiplexing but with appropriate ranging schemes and bandwidth allocation. Compared with Fx, the requirement of both bandwidth and latency are much relaxed at F1 interface so any PON of required capacity can be used for it.

10.1 PON Architecture for 5G fronthaul and midhaul transport

By definition, OLT/ONT belong to the Transport Network Layer (TNL) and CU/DU/RU belong to the Radio Network Layer (RNL). PON may be used to support for both F1 and Fx interfaces. Same PON system may serve both F1 and Fx interfaces or it may be two different PON systems as illustrated in

Fig. 7. The architecture may be called cascaded as shown in figure below or it may be parallel or it may be just single serving either F1 or Fx. It may consist of a single PON technology like TDM-PON, WDM-PON, TWDM-PON (NGPON2) or with WDM PtP overlay. The ODNs topology could be point-to-point (PtP), star, or tree. The choice of the architecture would be decided by specific deployment scenarios, service-based

latency and performance requirements as well as operator's priority. Required throughput, latency and cost will ultimately decide the choice of PON devices.

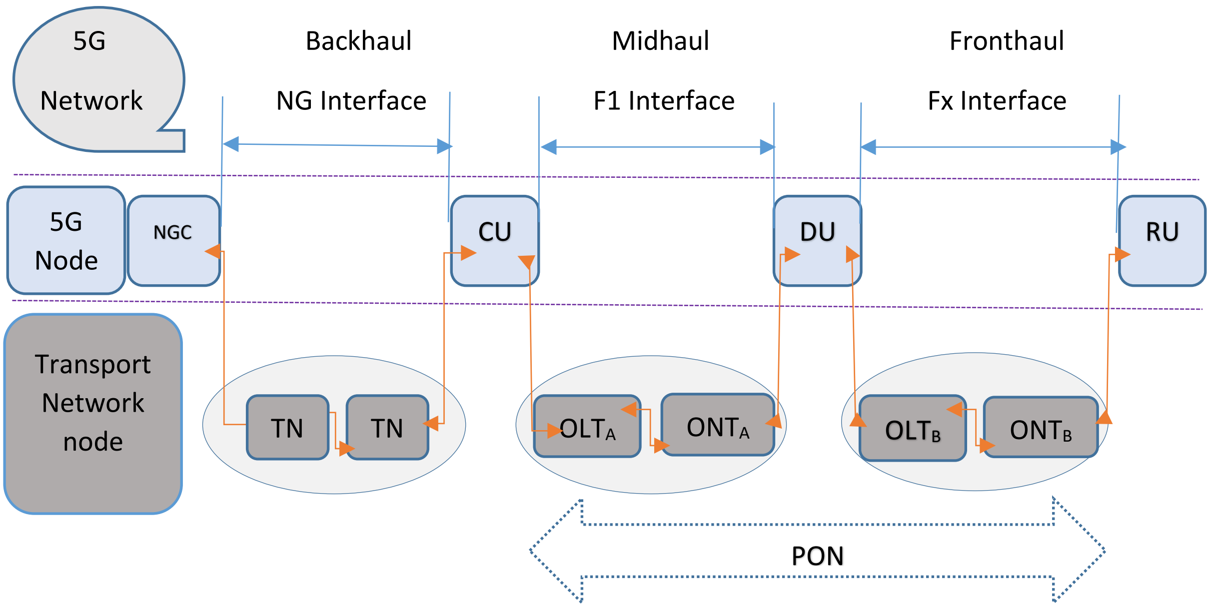

Fig. 7 Concept of layered structure showing RNL (CU, DU, RU) and TNL (OLT, ONT).

The existing PON systems may have to support the followings interfaces unless exclusive PON network is constructed for 5G [13];

- Several F1 interfaces (one per 5G carrier) in addition to existing mobile and fixed services;
- Several F_X interfaces (one per 5G RUs) in addition to existing mobile and fixed services;

10.2 Legacy PON with WDM overlay to support 5G interface

Readily available solution to support midhaul and fronthaul could be to overlay new wavelengths in a legacy PON, without sharing bandwidth with legacy fixed access services. Both NG-PON2 TWDM and PtP WDM could be used for this scenario. TDM-PON (XG-PON/XGS-PON) may also be considered purely on the ground that it may be cheaper compared with other two PON referred here with a caveat discussed latter.

In TWDM-PON and WDM-PON signals from the OLTs, each on a different wavelength channel, are combined in a wavelength multiplexer before transmitting to the cell sites.

In the ODN, a wavelength splitter, usually a power splitter except if it is a pure WDM deployment where it may use an Array Waveguide Grating (AWG) device, routes the individual wavelengths to different ONTs, each of which is connected to an RU supporting one of the three sectors of an antenna.

10.3 Dedicated PON to support 5G interface

In Indian telecom access network, fixed services are provided through GPON [28] which in any way can't support bandwidth requirement of 5G, so a more practical solution is to build dedicated PONs using a separate fibre from the existing ODN specifically for mobile fronthaul and midhaul. Network architecture of dedicated PON will look like as given in Fig. 8 minus legacy TDM-PON i.e. GPON.

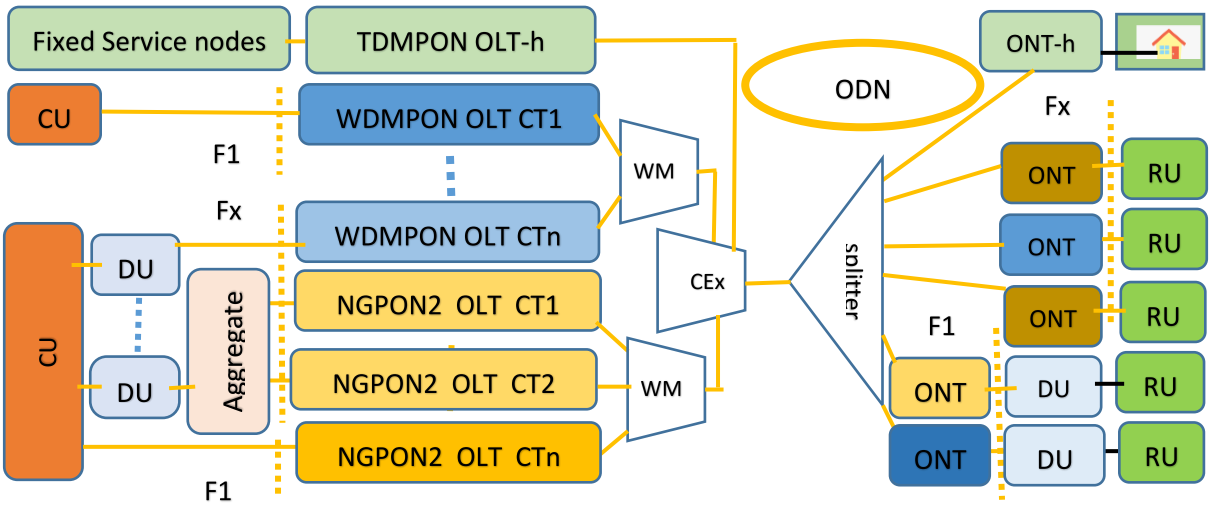

Fig. 8 F1 and Fx based on legacy PON with WDM overlay

Although not all connectivity shown in Fig. 8 but following connectivity should be possible in PON architecture

- Each OLT can connect to multiple CU/DUs;
- Each CU/DU can have RUs over multiple PONs hence can connect to multiple OLTs;
- Each PON can serve a mix of RUs pertaining to different CU/DUs;
- Each RU pertains to only one CU/DU;
- Each RU can have multiple interfaces, each interface connects to a ONT UNI.

A PON with mixed F1 and Fx is as shown above in Fig. 8 is possible but the different requirements on bandwidth and latency could pose implementation challenges.

10.4 Dimensioning of aggregate data rates at F1 interface to select an appropriate PON system

To calculate required aggregate data rate at F1 interface to arrive at per PON port capacity, consider a PON system where a CU is connected to multiple DUs through single OLT and multiple ONTs. Each DU is connected to multiple RUs via dedicated CPRI/eCPRI point-to-point links. Since F1 rates are just upto 3% above backhaul rates, backhaul rates as calculated from the formula given in Appendix II can be used to arrive at aggregate data rates required at PON port. Taking an example of a single DU serving a single RU with one UE, required peak backhaul data rate is given for different cell configuration in Table 5 [13].

Table 5 Peak backhaul data rate from a single DU serving a single RU

MIMO	Peak backhaul data rate from a single DU serving a single RU (Mbps						
16	718	1436	2872	7180	19008	38016	76032
8	359	718	1436	3590	9504	19008	38016
4	180	359	718	1795	4752	9504	19008
2	90	180	359	898	2376	4752	9504
1	45	90	180	449	1188	2376	4752
	10	**20**	**40**	**100**	**200**	**400**	**800**
							RF Bandwidth (MHz)

Considering single DU serves 10 RUs, aggregate bandwidth can be calculated using formula given in appendix II corresponding to the values in Table 5.

Table 6 Aggregated F1 interface rate from a single DU serving 10 RUs [13]

MIMO	aggregated F1 interface data rate from a single DU, serving 10 RUs (Mbps)						
16	1465	2930	5860	14649	38780	77560	155120
8	732	1465	2930	7324	19390	38780	77560
4	366	732	1465	3662	9695	19390	38780
2	183	366	732	1831	4848	9695	19390
1	92	183	366	916	2424	4848	9695
	10	**20**	**40**	**100**	**200**	**400**	**800**
							RF Bandwidth (in MHz)

See the calculated value in Table 6. One or multiple DUs can be served by a single optical channel operating at 2.5 Gb/s (no colour), 10 Gb/s (green), 25 Gb/s (light pink), or 50 Gb/s and beyond (pink) depending on the radio configuration considered. Alternative way of dimensioning can be done using methods suggested by NGMN [29]. According to it, a cell site is considered operating at its peak capacity when one of its antenna sectors (RUs) is running at peak rate and the other two at average rate. Considering the example of 64T64R in Table II 2 (values rounded off), the total transport data rate for this (peak rate) cell site is 6.72 Gb/s (= (1*4 Gb/s + 2*0.8 Gb/s) *1.2) (factor 1.2 is transmission channel overhead). However, a cell site is considered operating at the average value when all its RUs are running at average rate and total transport data rate (average rate) would be 2.88 Gb/s (= 0.8 Gb/s*3*1.2). The capacity requirement for a CU port in Fig. 9 would be **21.12** Gb/s which can be supported by a single 25 Gb/s PON port [13]. In the figure below, peak RU/ peak site shown in red colour and average RU/Sites shown in green colour.

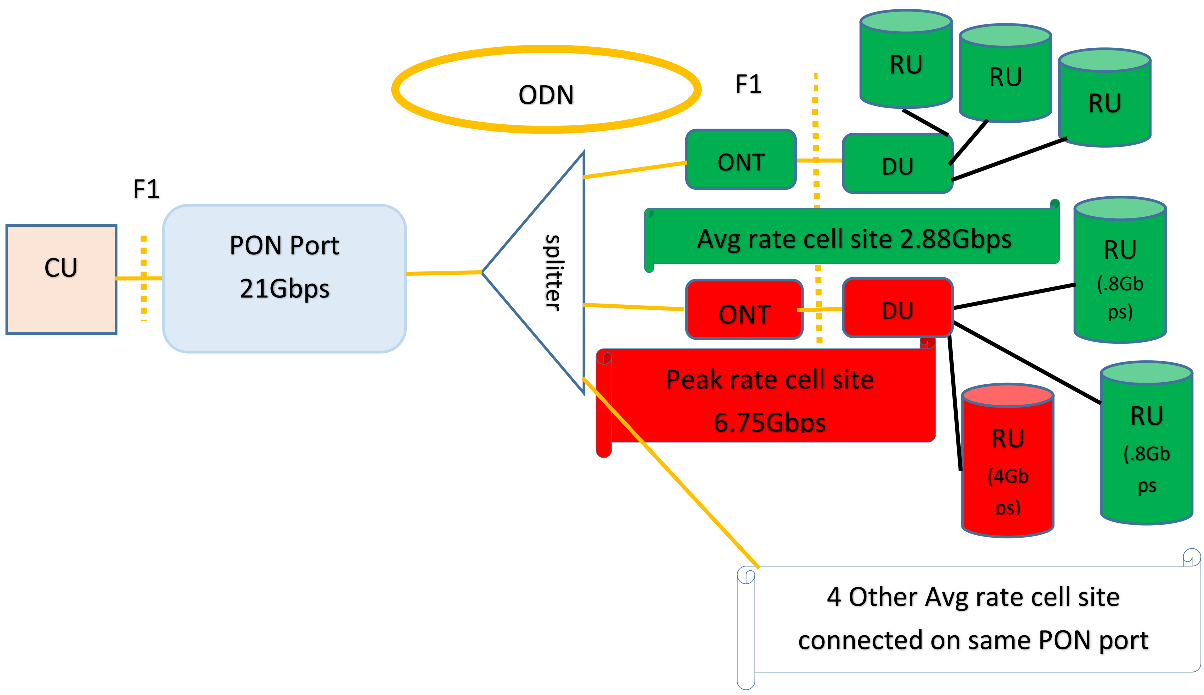

Fig. 9 NGMN method for calculation of capacity requirements per PON port

10.5 PON System Implementation Challenges and Resolution

10.5.1 Dynamic Bandwidth Allocation (DBA)

In a TDM-PON, DBA mechanism can cause delay in the order of ms, which is not compatible with delay sensitive 5G services, especially over the Fx interface. In TDM-PON, the downstream latency is low, but upstream latency remains in the order of several milliseconds. This is because each ONU/ONT must send a request to an OLT first, and then the OLT grants an upstream bandwidth of each ONU/ONT to avoid any upstream data collisions. In order to use TDM-PON for low-latency demanded fronthaul transport, it is necessary to reduce upstream latency. Many latency improving mechanisms have been proposed, some of the solutions to this TDM-PON problem are discussed below.

10.5.2 Differentiated Service

One method could be to provide differentiated service to upstream traffic coming from RU to ONT with highest priority *[30]* to reduce wait time of mobile traffic at ONT as shown in *Fig. 10* below compared to other traffic hitting same PON port at OLT. Priority could be provided by allocating fixed bandwidth (bw) or assured bandwidth by DBA. Flip side of this approach is that bandwidth remains locked and is not available for any other service even if there is no mobile traffic.

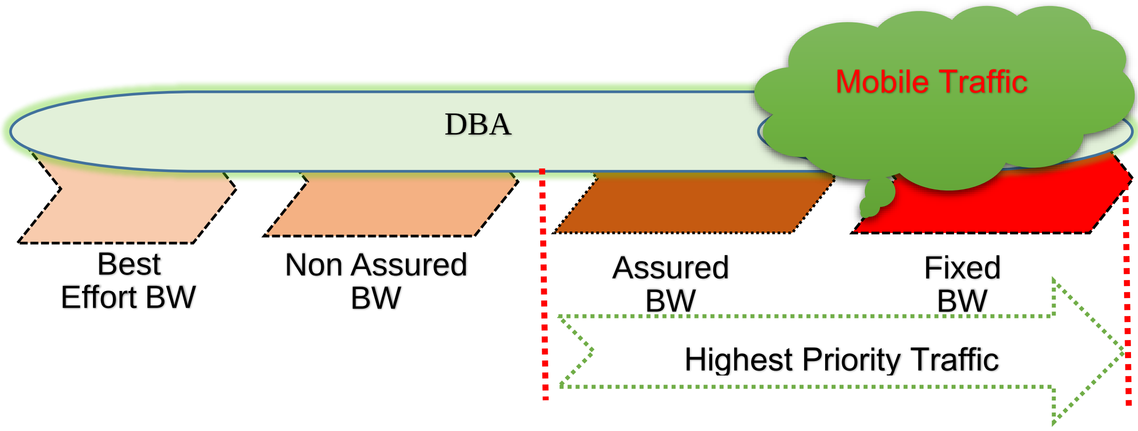

Fig. 10 Dedicated bandwidth for Low latency 5G fronthaul transport

10.5.3 CO DBA

Another way to reduce wait time of upstream traffic of ONT could be through advance [31] allocation of upstream time slot through exchange of information between OLT and mobile equipment where upstream time slot is allocated as per demand from mobile equipment (UEs). This mechanism is called Coordinated DBA (CO DBA). See Fig. 11.

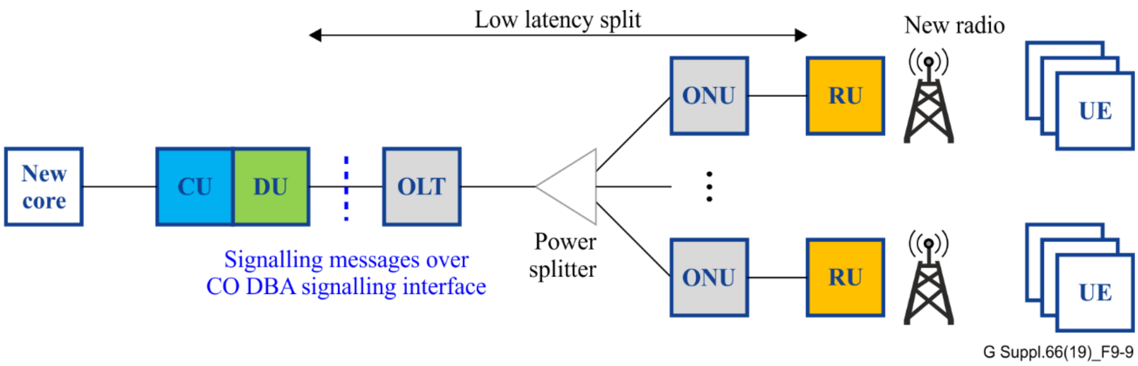

Fig. 11 CO DBA mechanism for mobile fronthaul

10.6 Fibre reach and split ratio limitations

When using PON for 5G transport, the fibre reach is limited by the latency requirements of the service (Appendix-I) and the split ratio is limited by the bandwidth consumption (Appendix-II). The typical PON reach and number of splits in residential implementations may not apply. Current PON systems are designed to support 20km reach for services with maximum 1.5ms mean signal transfer delay [28] while they still may work fine for fixed services but low latency services may fail in the same span.

For example, for 100 μs one-way latency (Table 2), it is not possible to support 20 km reach because the propagation time in fibre alone (5μs/km) would exceed 100μs.

For the Fx interface, the tight latency requirement between DU and RU could limit the fibre reach to be shorter than the typical reach of residential implementations. The bandwidth requirement could limit the TDM-PON split ratio to be much lower.

In summary, when designing a new PON system for 5G transport, requirements on bandwidth and latency need to be carefully considered to decide the PON fibre reach and split ratio.

10.7 Synchronization challenges in PON

In order for PON to be a viable solution for 5G NR transport, it is critical that PON meets the synchronization timing error requirements described in Table 3 . Several factors affecting the synchronization timing precision are discussed as an example for TDM-PON [26]:

- **Fibre propagation delay of different wavelengths used as upstream and downstream wavelengths**: Using XG-PON as an example, the difference in the index of refraction of the downstream (1577 nm) and upstream (1270 nm) wavelengths result in a systematic error of 61.2 ns when transmitting over 20 km;
- **Equalization Delay (EqD) accuracy**: as limited by drift of window (DOW) threshold, the EqD accuracy should stay within ±3 ns for XGS-PON;
- **Internal timing correction**: these are delays due to logical computation and/or other events inside OLT and ONT. One large contributing factor is the downstream SerDes delay, which is about ±6.4 ns for XGS-PON;
- **System hardware internal error**: different signals may have different transmission paths due to the printed circuit board design. These errors can generally be calibrated in the system level.

For higher speed PONs, constraints in the synchronization timing requirements would impose even more challenges that need to be solved in order to use PON for 5G transport.

10.8 Coordination between the PON and wireless interface

For requirements at the PON-wireless interface, the CO-DBA interface needs to be supported by TDM-PON. Since WDM-PON provides point-to-point connections in the physical layer, its interaction with wireless network is much easier than that of TDM-PON to implement. For both TDM-PON and WDM-PON, multiplexing schemes to interconnect OLT and CU/DU need to be chosen so that one CU/DU can flexibly support more than one OLT wavelength channel.

11 Conclusion/Recommendation

Considering the discussion in preceding sections, latency budget in Appendix-I and bandwidth requirement in appendix-II for 5G transport network, following conclusion is drawn.

a) In C-RAN, for eMBB services, throughput requirement in fronthaul is astronomically high compared with what is seen in 4G. Neither Current radio SDH link used in 4G backhaul (which comprises 80%) nor low order optical SDH and GPON used in 4G backhaul will be able to cater 5G fronthaul capacity requirement.

b) Latency requirement in fronthaul is in order of 100 to a few 100µs so apart from processing delay in transmission equipment, delay due to optical fibre itself becomes significant. So while a transmission network designed according to optical budget may still work fine but low latency service on the same transmission network might fail due to exceeding latency budget. This may put a restriction on how long a fronthaul should be, not on the basis optical budget of devices alone but required latency budget.

c) If PON has to become a real challenger for 5G fronthaul, infact it has to address issues of bandwidth allocation, ranging and synchronisation from ab initio as current generation of PON is designed primarily to support fixed broadband services. In this regard development of 25G and 50G WDM PON around the requirement of 5G is heartening which might increase the uptake of PON as a fronthaul transport.

d) Though there may be common wireless hardware to support different 5G services but it may require different fronthaul solution depending upon latency needs so transport network in fronthaul has to be flexible to serve varying traffic and latency demands.

e) At present, wireless network and transmission network are monitored independently as there is clear separation between these two layers, however in fronthaul, it is not an IP data but a digitalised radio signal that needs to be controlled by radio network, and to make it happen, transmission network has to insert necessary message in its OAM which can be retrieved by radio controllers to serve its purpose.

f) Every node between the clock server and the end application node should support synchronisation.

g) Assumptions and step by step calculation of bandwidth and suggested network topology is given in appendix II for constructing the transport network for 5G including support to existing services.

h) Though not directly related with current topic but an important requirement in field will arise for co-locating high capacity transmission device like OTN, DWDM etc. with CU, DU and RU to meet high capacity demand. Current flavour of deployment of radio network in outdoor to reduce energy consumption will pose a challenge for co-locating these devices.

i) A broader view of 5G transport network is illustrated in Fig. 12 and Table 7a generalised 5G transport network requirement is summarised in the Table 7 to support all the services envisaged in 5G wireless network.

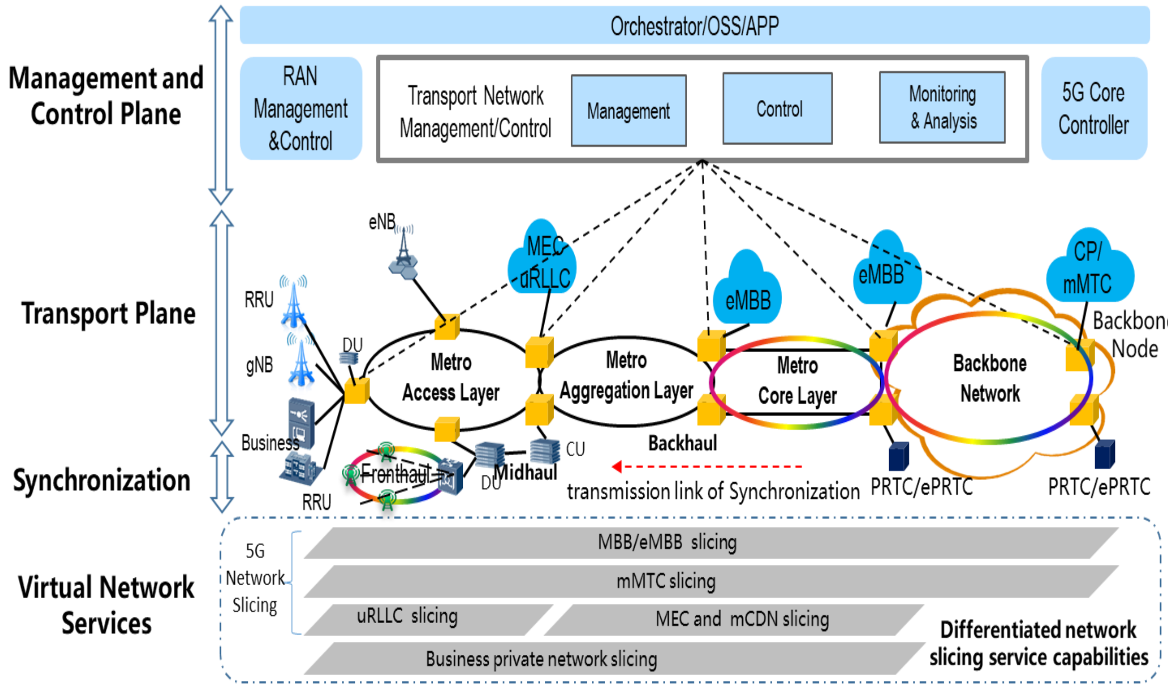

Fig. 12 5G transport network overview [10]

Table 7 Summary of Transport network for 5G

Transport network	**Access domain**		**Metro Aggregation domain**	**Metro Core or Backbone Network domain**
	Fronthaul	Midhaul and Backhaul	Midhaul and Backhaul	Backhaul
5G Interface supported	Fx (CPRI/eCPRI)	F1, NG, Xn (Ethernet)	F1, NG, Xn (Ethernet)	NG, Xn (Ethernet)
5G Nodes involved	RU-DU	DU-CU,CU-NGC, gNB-gNB	DU-CU,CU-NGC, CU-CU (gNB-gNB)	CU-NGC, CU-CU (gNB-gNB)
Topology	Hub-and-spoke, chain or ring	Ring, chain or star links	Ring or dual homing uplink	Ring or dual homing uplink
UNI	eCPRI: 25GE CPRI: N×10G/25Gb/s or1×100Gb/s	10GE/25GE/50GE	10GE/25GE/50GE/100GE	10GE/25GE/50GE/100GE/400GE
NNI/SNI	10/25/100Gb/s or N×25G/50Gb/s WDM	N×25G/50Gb/s 100Gb/s	N×25G/50G100G/200Gb/s	N×25G/50G/100G/200G/400Gb/s
Distance	<10km	< 40km	< 40-80km	< 40-80km or >100 km

Notwithstanding what is given in the Table 7 above each 5G application will require different transmission solution especially in fronthaul and thus will require careful planning specific to deployment scenario.

12 Way Forward

It was not possible to include all 5G technologies and all deployment scenario and its impact on all transport technologies in the study paper due to limited resources, it is therefore required that following areas which have not been covered, may be taken up for further study. Areas that may be taken for further study are;

a) For the air interface, only MIMO is considered in the above discussion. However, in 5G, other technologies like massive MIMO, mmWave MIMO, Fibre Bank Multi Carrier (FBMC), full-duplex radio Non-Orthogonal Multiple Access (NOMA) etc. will be used. Their deployment scenario, impact of different technologies on the transport network may be examined.

b) Various architecture may be defined with latency requirements. For example, if latency requirement is <1 msec, it is required to integrate CU+DU+RU in a single unit. Similarly, other architectures may also be defined.

c) Constraints of latency may be linked with latency requirements on the opted 5G and transport technologies.

d) Separate deployment scenarios and transport technologies for eMBB, uRLLC, and mMTC may be examined.

e) Further elaboration on Network slicing, isolation among slices and control and management may be carried out.

f) Deliberation on each transport technologies like OTN, TSN, SDN, DWDM with respect to 5G transport requirement may be studied.

g) Network security aspects of 5G transport may be included in future study.

13 Appendix I: Latency

13.1 End-To-End Service Latency Budget in 5G Networks

End-to-end service latency is an important characteristic of 5G networks. Table I 1 summarizes requirements for end-to-end latency for some types of services based on (3GPP TR 38.913, V14.3.0) [2]

Table I 1: End to end latency requirements for selected service types

Service Type		Latency Requirement
eMBB	User plane（UE-CN）	4ms
	Control plane（UE-CN）	10ms
uRLLC	User plane（UE-CU/MEC）	0.5~1ms
	Control plane（UE-CN）	10ms

Figure I-1 illustrates an example of how the end-to-end latency budget could be allocated to different nodes and transport networks within the 5G architecture.

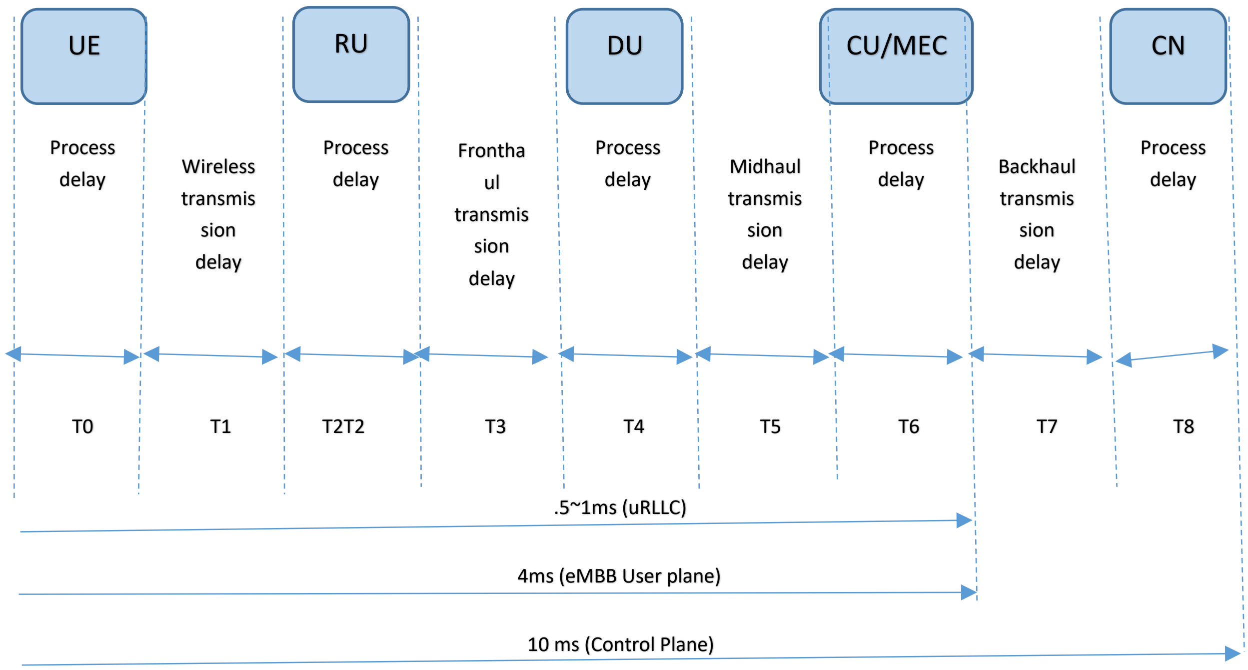

Fig. I 1 End-to-end latency budget [10]

14 Appendix II-Bandwidth Calculations

14.1 Base Station Fx Bandwidth Requirements Calculation Methods

3GPP has decided to specify a low layer split point for the gNodeB architecture based on an Option 6 (MAC-PHY) or on Option 7 (Mid PHY) split but the decision is awaited.

The peak throughput for an option 6 split is comparable to that for an option 2 split (F1). The same NGMN Alliance aggregation dimensioning as used for F1 below can also be used for option 6 split architectures. So in this case, transport capacity required at Fx is same as F1.

It is to be noted that the ratio between peak and mean of the option 7 splits do not follow the same analysis as is used for the F1-interface below (20% as a rule of thumb). *Therefore, the aggregation algorithm and the average throughput calculation for intra-PHY splits needs further study.* However, an approximate calculation is given below in formula $\mathbf{BR_{IU}/_{IID}}$.

The total bit rate needed at option 8 to deliver the appropriate number of fast CPRI [5] streams to the gNB-DU/RRH, via the F1/Fx interface, can be determined based on the formula [32] (1)

$$\mathbf{BR_8 = S \cdot A \cdot fs \cdot bs \cdot IQ \cdot HF \cdot LC} \qquad \mathbf{(1)}$$

where S—the number of sectors per gNB-DU, A—the number of antenna modules in array per one sector, fs—speed of sampling , bs—number of bits per sample (depending on the format of the sampled signal: is equal 15 per one I/Q subcarrier for 4G/5G-Rel-15 (cyclic prefix orthogonal frequency division multiplexing (CP-OFDM))), IQ—a factor indicating a separate sub-sampling I as in-phase and Q as quadrature (is equal 2), HF (Headers Factor)—a factor indicating the redundancy of CPRI headers (redundancy is 1/15, therefore, amounts to 16/15), LC—alphabet nB/mB line code (8B/10B—ratio of 10/8—used in CPRI Options 1-7, 6. 4B/66B—ratio of 66/64—used in CPRI Options 7A-10).

Table II 1 shows the approximate data rates for time domain IQ data fronthaul (CPRI rates without line coding) needed to support various radio frequency bandwidths and numbers of antenna ports in wireless networks using parameter ranges given by 3GPP in [3GPP TR 38.801].

Table II 1 Required fronthaul data rate in 5G wireless network [3GPP TR 38.801]

Number of antenna ports	Radio Channel Bandwidth			
	10 MHz	20 MHz	200 MHz	1 GHz
2	1 Gb/s	2 Gb/s	20 Gb/s	100 Gb/s
8	4 Gb/s	8 Gb/s	80 Gb/s	400 Gb/s
64	32 Gb/s	64 Gb/s	640 Gb/s	3,200 Gb/s
256	128 Gb/s	256 Gb/s	2,560 Gb/s	12,800 Gb/s

The rate consumption calculations that will occur at the Split 6 during the maximum load, according to the CPRI Forum, can be carried out on the basis of a simplified and adapted formula [33] [34] (2)

$$\mathbf{BR_6 = S \cdot NL \cdot NSC \cdot NSY \cdot RC \cdot K \cdot HF \cdot LC / TF} \quad \mathbf{(2)}$$

where S—the number of sectors per gNB-DU/RRH, NL—the number of layers (related to the number of layers needed to create and form space beams directed to mobile UE), NSC—the number of active CP-OFDM subcarriers in BB channel (the number of subcarriers for the new waveform from the 5G-NR interface should be used—in the channel with a specified frequency bandwidth [MHz]), NSY—the number of CP-OFDM symbols or newest waveform per standard time-frame (in the non-standalone 5G-Rel-15 interface a coherent value was assumed in relation to FDD-LTE), RC—the factor of FEC code efficiency, K = log2 M—bits per modulation symbol, where M—modulation order (usually for M-QAM format), HF (Headers Factor)—CPRI frame redundancy factor (redundancy at 1/15 for CPRI, so the ratio is 16/15—much smaller and variable for the eCPRI, depending on the size of the charge in a frame matched to the Ethernet frame and/or OTN/PON , LC—a line code also used as a scrambling (for faster streams it is 64B/66B, so the code rate is 66/64) and a physical Ethernet link control (also applicable to the RoE technology]). The line code in the optical Ethernet link applies only to the LAN format. Ethernet WAN interface is devoid of this code, because physical layer functions are taken over by the transport system, e.g., PON/OTN. When the radio samples are transported in the fronthaul/midhaul paths using Ethernet (RoE) frames only, the LC value is included in the HF redundancy [35].

At option 7 corresponding to option I_U/II_D of CPRI forum an additional parameter appears which determines the number of quanta in the process of converting the frequency sub-carriers. Thus, the coding and modulation rules will not be taken into account, as the frequency components will be quantized. In order to estimate the bit rate that will occur in the F1/Fx path at Split I_U/II_D, an approximate formula [33] (3) can be used

$$BR_{IU/IID} = 2 \cdot S \cdot NP \cdot NSC \cdot NSY \cdot NQF \cdot HF\ TF \quad (3)$$

where S—the number of sectors per gNB-DU/RRH/AAU, NP—the number of ADC/DAC chains (used in digital beamforming (DBF)—special application in massive-MIMO mode), NSC—the number of active CP-OFDM subcarriers in BB channel (the number of subcarriers for the 5G-NR waveform interface should be used), NSY—the number of CP-OFDM or newest waveform symbols per standard 4G/5G time-frame, NQF—the quantizer resolution in the frequency domain, HF (Headers Factor)—eCPRI frame header redundancy factor and higher IP/Ethernet network layers, TF—frame duration (4G/5G system parameter) [35].

14.2 Base Station F1 Bandwidth Requirements Calculation Methods

The peak throughput for an option 2 split (F1) is comparable to that for an option 1 split (Backhaul). It is higher than the backhaul bandwidth by up to 3%.

The peak user data rates for the F1 interface can be calculated using the same formula as that is used for calculating backhaul bandwidth given following sections.

As per NGMN [29], the ratio of peak-rate and average-rate per cell site is between 4 to 6 in a typical operating condition. Therefore, for dimensioning the transport network capacity at F1, an "average rate at busy time" can be safely assumed as 20% of the peak rate at quiet time or it can be calculated using the formula given below.

The above value of F1 is only pay load for transmission network. The bandwidth required for transporting the data at the F1 interface over a transmission network will be higher because of transmission networks own overhead introduced by the transmission protocols, scheduling and synchronization mechanisms. To account for these overheads, 20% increase of data rate is added to the value calculated above. So far F1 interface

The peak transmission bandwidth aggregated at **DU** of one 5G base station (Peak value of B_{agr}) could be assumed as the sum of one cell with peak value of B_{CELL} and the other (N-1) cell is with average value of B_{CELL}, as shown in Equation 4, and N is the number of cells aggregated at **DU**.

$$Peakvalueof B_{agr} = 1.2 * [Peakvalueof B_{CELL} + Averagevaluef B_{CELL} \times (N-1)] \quad (4)$$

The average transmission bandwidth of single IMT-2020/5G station (Average value of B_{agr}) could be calculated by Equation 5 as following,

$$Averagevalueof B_{agr} = 1.2 * Averagevaluef B_{CELL} \times N \quad (5)$$

Calculated value for F1 is given in *Table II 2* for a given cell configurations.

Table II 2 F1 signal bandwidth requirements for 256-QAM per carrier

Radio frequency band (GHz)	Number of Tx/Rx antennas	MIMO layers	Radio channel bandwidth (MHz)	Peak backhaul data rate per RU (Gb/s)	Average backhaul data rate per RU (Gb/s)	Average transport data rate for F1 [1.2*3*Avg /RU](Gb/s)	Peak transport data rate for F1 [1.2*(1*Peak /RU+2*Avg/ RU)] (Gb/s)
5G, low freq (3.5/3.7)	16T16R	4	100	2	0.4	2.8	3.36
	64T64R	8	100	3.3	0.675	4.65	5.58
5G, high freq (26/28)	4T4R	2*2	2*400	9.9	2.442	14.78	17.7

14.3 Base Station Backhaul Bandwidth Requirements Calculation Methods

In order to calculate backhaul bandwidth certain assumptions are made which are listed below.

- The peak user data rates for the backhaul interface can be calculated using the formula published by the Small Cell Forum in the Appendix C of SCF document 159.07.02 [9] for the PDCP-RLC split point and using radio channel parameters taken from the 3GPP documents TS 36.213 for LTE [36] or TS 38.214 for 5G [37]. This model yields the *maximum data* rate that needs to be transported in case there is only one UE in the cell, communicating with the cell under perfect channel conditions at maximum possible rate (peak rate at quiet time). This rate scales approximately linearly with the RF bandwidth, with the number of independent data streams (MIMO layers) and with the QAM order.
- The aggregate data rate for multiple UEs communicating simultaneously in the cell will be less than this peak rate due to non-optimal channel conditions, dynamic traffic variations, and interferences etc. As per NGMN [29], the ratio of peak-rate and average-rate per cell site is between 4 to 6 in a typical operating condition.

- According to NGMN [29], a cell site is considered operating at its peak capacity when one of its antenna sectors (RUs) is running at peak rate and the other two at average rate. In some 4G deployments, the radio unit and antennas are separate, while in 5G they could be integrated in a single RU.
- To improve coverage and increase cell site density in 5G New Radio, it is envisioned that both high and low radio frequency bands will be used. The low frequency band (e.g., 3.5/3.7 GHz) will be for macro cells to provide general coverage, while high frequency band (26/28 GHz) will be mainly for microcells in hot spot areas.

The transmission bandwidth of one cell (B_{CELL}) is calculated by Equation 6 as following,

$$B_{CELL} = B_s \times E_s \times (1 + 0.1) \times P_{TDD} \quad (6)$$

Here, $B_s$is the wireless spectral bandwidth of this cell; E_s represents the wireless spectral efficiency, which has peak and average value, and the exact values depends on the wireless vendors' product solution; Factor 0.1 is the additional encapsulated overhead information; P_{TDD} represents the proportion of TDD downlink.

Using the peak and average value of E_s, the peak and average value of B_{CELL} could be calculated by Equation 7 and 8 as following,

$$Peakvalueof B_{CELL} = B_s \times Peakvalueof E_s \times (1 + 0.1) \times P_{TDD} \quad (7)$$

$$Averagevalueof B_{CELL} = B_s \times Averagevalueof E_s \times (1 + 0.1) \times P_{TDD} \times (1 + P_{Xn}) \quad (8)$$

The peak transmission bandwidth of single 5G base station (Peak value of B_{BS}) could be assumed as the summary of one cell with peak value of B_{CELL} and the other (N-1) cell is with average value of $B_{CELL,}$ as shown in Equation 9, and N is the number of cells in one station.

$$Peakvalueof B_{BS} = Peakvalueof B_{CELL} + Averagevaluef B_{CELL} \times (N - 1) \quad (9)$$

The average transmission bandwidth of single 5G station (Average value of B_{BS}) could be calculated by Equation 10 as following,

$$Average value of B_{BS} = Average valuef B_{CELL} \times N \tag{10}$$

Table II 3 provides some vendors' specific values of E_s for reference and *Table II 4* provides calculation based on the formula discussed above for a particular cell configuration.

Table II 3 Vendor Specific Values of Wireless Spectral Efficiency of gNB (CU+DU+RRU)

	Wireless Vendor	Low Frequency Station		High Frequency Station	
		$Peak E_s$ (bit/Hz)	$Average E_s$ (bit/Hz)	$Peak E_s$ (bit/Hz)	$Average E_s$ (bit/Hz)
1	A	40	7.8	15	3.7
2	B	48	12	12	3
3	C	50	10	25	4

Table II 4 Examples of bandwidth requirements of LF and HF gNB

Parameters	**Low Frequency (LF)**	**High Frequency(HF)**
Bs	100MHz	800MHz
BS Cell Parameters	3 Cells, 64T64R	3 Cells，4T4R
Es	Peak value: 40bit/Hz; Average value: 7.8bit/Hz	Peak value: 15bit/Hz; Average value: 3.7bit/Hz
P_{TDD}	0.75, Up: Down = 1:3	0.75, Up: Down = 1:3
$Peak value of B_{CELL}$	100MHz×40bit/Hz×1.1×0.75= **3.3 Gbit/s**	800MHz×15bit/Hz×1.1 ×0.75= **9.9G bit/s**

$Average value of B_{CELL}$	100MHz×7.8bit/Hz×1.1×0.75×1.05 =**0.675Gbit/s** （Assume that Xn traffic mainly occurs in the mean scenario）	800MHz×3.7bit/Hz×1.1 ×0.75 =**2.442Gbit/s** (The HF station is mainly used for hot-spot, and the Xn traffic is calculated in the LF station.)
$Peak value of B_{BS}$	3.3 +（3-1）*0.675=**4.65Gbit/s**	9.9G +（3-1）*2.442G=**14.78Gbit/s**
$Average value of B_{BS}$	0.675G*3=**2.03Gbit/s**	2.442G*3=**7.33Gbit/s**

Table II 5 and Table II 6 provide examples of vendor specific bandwidth requirements of LF and HF gNB.

Table II 5 Examples of Vendor specific per cell bandwidth requirements of LF and HF gNB

Vendor	LF per cell Bandwidth (Gbit/s)		HF per cell Bandwidth (Gbit/s)	
	Peak Value of B_{cell}	Average Value of B_{cell}	Peak Value of B_{cell}	Average Value of B_{cell}
A	3.3	0.675	9.9	2.442
B	3.96	1.040	7.92	1.98
C	4.125	0.866	16.5	2.64

Table II 6 Examples of Vendor specific backhaul bandwidth requirements of LF and HF gNB

Vendor	LF base station Bandwidth (Gbit/s)	HF base station Bandwidth (Gbit/s)

	Peak Value of B_{BS}	Average Value of B_{BS}	Peak Value of B_{BS}	Average Value of B_{BS}
A	4.65	2.03	14.78	7.33
B	6.04	3.12	11.88	5.94
C	5.86	2.60	21.78	7.92

14.4 Transport Network Node Capacity Calculation Methods for Backhaul

The transport network model assumption for D-RAN (CU+DU+RU at one place) capacity requirements calculation method for 5G is listed below: Similar calculations can be done in case F1 and Fx if they are to be put on ring.

- Access layer: Assuming there are 4 to 8 base station sites per access ring; The capacity requirements are estimated for two typical scenarios: general scenario (Scenario 1) and hot-spot scenario (Scenario 2). Scenario 1 is an access ring with 4 low frequency stations; Scenario 2 is an access ring with 8 base stations including 6 low frequency stations and 2 high frequency stations;
- Aggregation layer: Each aggregation ring has six transport network aggregation nodes, and six access rings are connected to each pair of aggregation nodes;
- Core layer: Eight aggregation rings are connected to each backbone core nodes, and capacity requirements are estimated based on three backbone aggregation nodes;
- Assuming the bandwidth convergence ratio of access, aggregation, and core is 8:4:1.

A general view of transport network is given in Fig. II 1 which will give a bird's eye view of the kind of network 5G is needed. It will also help in conceptualising various ring formations.

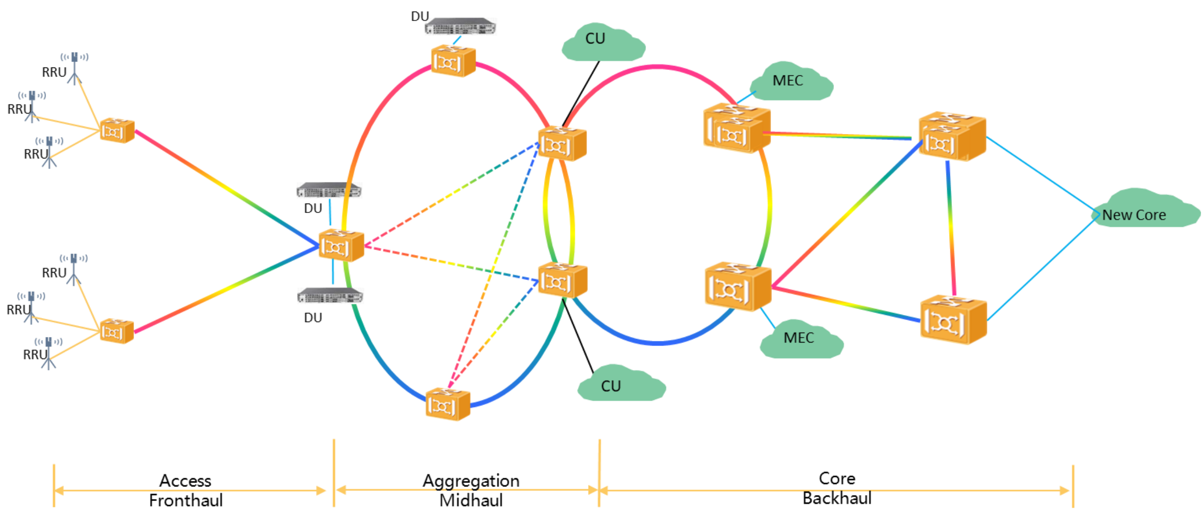

Fig. II 1 5G Transport layers

For D-RAN deployment, the capacity requirements for transport network are estimated as below based on the LF and HF gNB's bandwidth requirements example in Table II 6.

1) Access layer:

For scenario 1 : General area.

Capacity of access ring = $Averagevalueof B_{BS}$ for LF × (N-1) + $Peakvalueof B_{BS}$

=2.03 × (4-1) + 4.65 = 10.74G

For scenario 2 : Hot spot areas.

Capacity of access ring = $Averagevalueof B_{BS}$ for LF × (N-2) + $Peakvalueof B_{BS}$ + frequency single station peak + high frequency single station

=2.03 × (8-2) +14.78+7.33=34.29G

2) Aggregation layer:

For scenario 1:

Capacity of Aggregation layer = Capacity of access ring × 6 × 3 × convergence ratio

=10.74 × 3 × 6 × 1/2 = 96.66G

For scenario 2:

Capacity of Aggregation layer = Capacity of access ring × 6 × 3 × convergence ratio

= 34.29 × 3 × 6 × 1/2 = 308.61G

3) Core ring

Calculate the bandwidth of the backbone convergence ring based on the eight aggregation rings that are connected to each backbone aggregation node.

For scenario 1:

Capacity of Core layer = Capacity of Aggregation layer × number of aggregation ring × convergence ratio = 96.66 × 8 × 3 × 1/4=579.96G

For scenario 2:

Capacity of Core layer = Capacity of Aggregation layer × number of aggregation ring × convergence ratio = 308.61 × 8 × 3 × 1/4 = 1851.66G

The 5G transport network may also support 4G services and private line services. As shown in Fig. II 1, at each base station site 5G services from RRUs are connected to a metro access transport node. A metro access transport node may also support 4G CPRI signals and private line services (e.g. Ethernet, SDH), which are not shown in this figure. The metro access transport nodes are connected to an aggregation node co-located with a DU.

Analysis of client bandwidth for each type of client (5G, various options for 4G, and private line) is shown in Table II 7 . In cases where 4G traffic is present, typically only one of the CPRI rates would be present.

Table II 7 Client information of metro edge node

	Client type	Client bandwidth	Client interface	Number of clients
5G	eCPRI	25GE	Ethernet	3 or 6
4G	CPRI3	2.4576G	CPRI	3

	CPRI4	3.072G	CPRI	3
	CPRI5	4.9152G	CPRI	3
	CPRI6	6.144G	CPRI	3
	CPRI7	9.8304G	CPRI	3
PL	GE	1GE	Ethernet	1+
	10GE	10GE	Ethernet	1
	STM-N	Maximum 10G	SDH	1+

At the early deployment stage each base station has 3 RRUs while at the mature deployment stage the number of RRU increases to 6. It is worth noting that 4G/5G client signals originate from RRU and terminate at DU/BBU, while PL client signals may terminate in the core network. It is also noted the fronthaul topology is point to point for most application scenarios.

For the D-RAN case, RRUs are deployed together with DUs/CUs. One to three DUs/CUs are deployed in each edge site, and each DU/CU serves 3 RRUs. There are 4-6 edge transport nodes in an edge ring, which connect to an aggregation node. Fig. II 2 D-RAN Network CaseFig. II 2 illustrates a typical D-RAN network case.

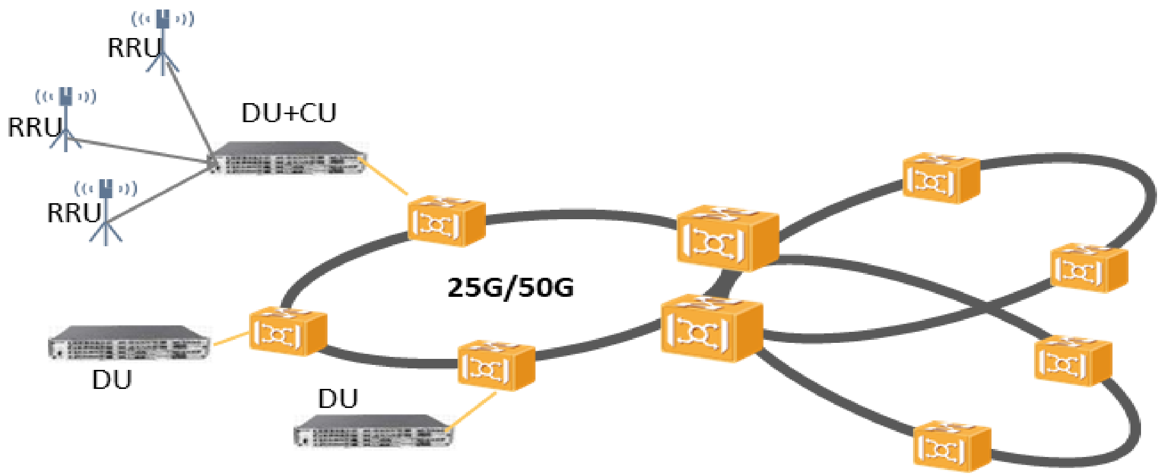

Fig. II 2 D-RAN Network Case

The backhaul bandwidth of each base station (based on edge node clients' BW) is calculated in Table II 8.

Table II 8 Backhaul Bandwidth of edge node clients

RRUs	Average value (Gb/s)	Peak value (Gb/s)
3*1=3	2.03	4.65
3*2=6	2.03*2=4.06	2.03*1+4.65=6.68
3*3=9	2.03*3=6.09	2.03*2+4.65=8.71

Bandwidth for the aggregation node is shown in Table II 9, assuming that one edge node is at peak bandwidth and the others are at average bandwidth. For a mixed 5G and 4G scenario, the 4G traffic would add 4-6 Gb/s.

Table II 9 Bandwidth at aggregate node in 5G scenario

	Edge nodes	RRUs	BW(Gb/s)/ring
5G	4	3	2.03*3+4.65=10.74
		6	4.06*3+6.68=18.86
		9	6.09*3+8.71=26.98
	5	3	2.03*4+4.65=12.77
		6	4.06*4+6.68=22.92
		9	6.09*4+8.71=33.07
	6	3	2.03*5+4.65=14.8
		6	4.06*5+6.68=26.98
		9	6.09*5+8.71=39.16

For small C-RAN application scenario, DUs are centrally deployed at edge sites, with 5-10 DUs located in an access site, and each DU serving 3 RRUs. Fig. II 3 illustrates a typical small C-RAN network case.

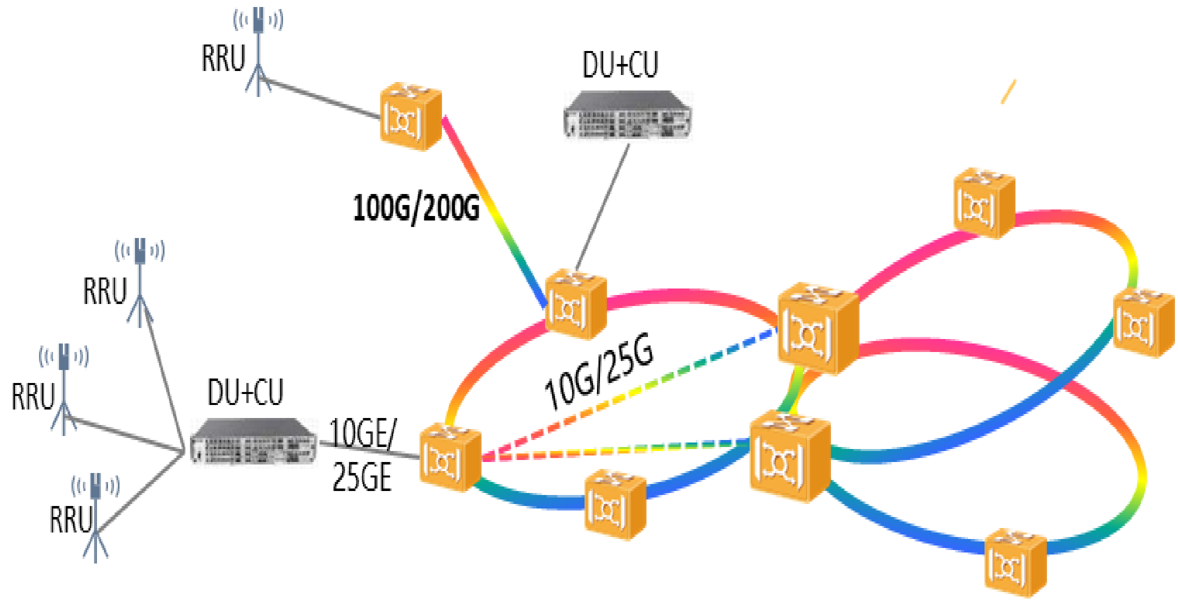

Fig. II 3 Small C-RAN Network Case

As described above for the D-RAN case, the average backhaul bandwidth of each base station (3 RRUs) is 2.03Gb/s and the peak value of each base station is 4.65 Gb/s. There are 2-3 edge nodes for each edge ring. The client information of these edge nodes is shown in Table II 10. As in the D-RAN case, the assumption is that only one edge node has peak bandwidth, and the others have average bandwidth. 4G and private line traffic will increase the required bandwidth.

Table II 10 client information of edge node for small C-RAN scenario (5G traffic only)

RRUs	Average BW (Gb/s)	Peak BW (Gb/s)
3*5	2.03*5=10.15	2.03*4+4.65=12.77
3*6	2.03*6=12.18	2.03*5+4.65=14.8
3*7	2.03*7=14.21	2.03*6+4.65=16.83
3*8	2.03*8=16.24	2.03*7+4.65=18.86
3*9	2.03*9=18.27	2.03*8+4.65=20.89
3*10	2.03*10=20.3	2.03*9+4.65=22.92

15 Abbreviations and acronyms

This document uses the following abbreviations and acronyms:

Abbreviations	Description
3GPP	3rd Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
AWG	Array Waveguide Grating
BBU	Baseband Unit
CP	Control Plane
CPRI	Common Public Radio Interface
Co-DBA	Cooperative Dynamic Bandwidth Allocation
CRAN	Centralized Radio Access Network
CU	Central Unit
CN	Core Network or Next Generation Core
D2D	Device-to-Device
DBA	Dynamic Bandwidth Allocation
DL	Down Link
DOW	Drift of Window
DRAN	Distributed Radio Access Network
DU	Distributed Unit
DWDM	Dense Wavelength Division Multiplexing
e2e	end to end
eCPRI	evolved Common Public Radio Interface
eMBB	enhanced Mobile Broadband
eNB	eNodeB
ePRTC	enhanced Primary Reference Time Clock
EqD	Equalization Delay
FBMC	Filter Bank Multi Carrier (Modulation)
gNB	Next Generation NodeB
GPON	Gigabit Passive Optical Network
HLS	High Layer Split
HRM	Hypothetical Reference Model

HRLLC	High Reliability Low Latency Communication
iFFT	Inverse Fast Fourier Transform
MAC	Media Access Control
MEC	Mobile Edge Computing
MIMO	Multiple Input Multiple Output
mMTC	massive Machine Type Communication
NGC/CN	Next Generation Core/CN
NGFI	Next Generation Fronthaul Interface
NGMN	Next Generation Mobile Networks Alliance
NGPON2	Next-Generation Passive Optical Network 2
NNI	Network-Network Interface
NOMA	Non Orthogonal Multiple Access
NR	New Radio
OAM	Operations, Administration and Management
OBSAI	Open Base Station Architecture Initiative
ODN	Optical Distribution Network
OLT	Optical Line Terminal
ONT/ONU	Optical Network Termination/Unit (used interchangeably)
OTN	Optical Transport Network
PCS	Physical Coding Sublayer
PDCP	Packet Data Convergence Protocol
PHY	Physical Layer
PMD	Physical Medium Dependent
PON	Passive Optical Network
PRTC	Primary Reference Time Clock
PtP	Point to Point
QAM	Quadrature Amplitude Modulation
RAN	Radio Access Network
RF	Radio Frequency
RLC	Radio Link Control
RNL	Radio Network Layer
RRC	Radio Resource Control

RRH	Remote Radio Head
RRU/RU	Remote Radio Unit
SDH	Synchronous Optical Networking
SDN	Software Defined Network
SNI	Service Network Interface
STM	Synchronous Transport Module
T-BC	Telecom Boundary Clock
TNL	Transport Network Layer
TSN	Time Sensitive Network
T-TC	Telecom Transparent Clock
T-TSC	Telecom Time Slave Clock
TWDM-PON	Time and Wavelength Division Multiplexed Passive Optical Network
UL	Up Link
VN	VIRTUAL NETWORK
UE	USER EQUIPMENT
UNI	USER NETWORK INTERFACE
UP	User Plane
uRLLC	ultra-Reliable Low Latency Communication
VRAN	Virtualised Radio Access Network
WDM-PON	Wavelength Division Multiplexing-Passive Optical Network
XG-PON	10-Gigabit-capable passive optical network
XGS-PON	10-Gigabit-capable symmetric passive optical network

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