Nokia Bell Labs

Low cost 5G xhaul with Nokia Passive Optical Network (PON) solution

White paper

Contents

Introduction and executive summary

Mobile networks require a high-performance link for mobile transport, the most common solution being a dedicated point-to-point (P2P) fiber. However, an attractive alternative for converged operators who offer mobile and fixed services is to leverage a common fiber infrastructure for both services. It is possible to leverage different technologies on a common fiber and/or to leverage common technologies on dedicated fibers. In this white paper, we explain the key characteristics of a Passive Optical Network (PON), and detail how such a network can help accelerate the deployment of mobile networks and reduce the total cost of ownership (TCO).

We demonstrate that XGS-PON, a commercially available 10 Gbps symmetric PON, is well suited for backhaul and midhaul of 5G mobile networks. Higher speed PON, including a 25Gbps symmetric PON will soon become available for further scaling.

Beyond what is available today, PON technologies are being developed to ensure that mobile xhaul over the Fiber to the Home (FTTH) network can be scaled to future needs. Work is ongoing at ORAN to define the low-layer-split Fronthaul (lls-FH) interface in support of the low latencies required for the Fx interface. Over time, this will enable mobile fronthaul over 25G PON.

Further network scaling can be achieved by wavelength division multiplexed (WDM) PON, stacking multiple 25 Gbps wavelengths onto a single fiber to effectively support the low-latency requirements of Fx. These wavelengths can be overlaid on an existing PON fiber placed or a new PON dedicated for Fx carriage.

Passive Optical Networks

Fixed broadband operators use PON to deliver FTTH. The optical network is passive in the sense that there is no active equipment in the field. The active equipment is located at the extremities, while the outside plant is passive. The Optical Line Termination (OLT) modems in the access node are located in the Central Office (CO) and the Optical Network Units (ONU), or the home gateways, are located in the customer premises. The use of only passive elements (i.e. passive splitters) in the Optical Distribution Network (ODN) mitigates deployment hurdles and reduces operational maintenance. To further keep the cost of ownership low, a single OLT terminates multiple ONUs; typically 64-128. This effectively makes PON a point-to-multipoint (P2MP) network, where the capacity resources on a single wavelength are shared across multiple end users through Time Division Multiplexing (TDM).

The TDM PON technology family continues to evolve to support an ever-growing demand for speed. GPON is the most commonly deployed PON technology to date, offering 2.5 Gbps downstream and 1.25 Gbps upstream capacity on a single wavelength pair per OLT. XGS-PON is the latest mature technology with ongoing volume deployments. XGS-PON offers 10 Gbps symmetric capacity, i.e. 10 Gbps downstream and 10 Gbps upstream on a single wavelength pair (wavelengths for downstream and upstream are different). IEEE is currently finalizing 802.3ca that defines 25G-EPON and 50G-EPON, composed of respectively 1 and 2 wavelength pairs of 25 Gbps TDM PON each in the downstream direction and a corresponding 10 Gbps and 25Gbps upstream for asymmetric or symmetric operation. Similar work is being done in ITU G hsp working group. The driver for these high-speed PONs is not so much residential use, but rather mobile transport and enterprise connections. All TDM PON technologies employ a single fiber to carry both the upstream and downstream traffic, allowing a very efficient use of fibers.

In this paper we will examine the potential to use the same PON architecture for still immature Point-to-Point Wavelength Division Multiplexed PON (P2P WDM PON) technology. P2P WDM PON uses a set of wavelengths in an optical distribution network (ODN) to serve multiple radio units (RUs) that are either collocated or in different locations. The wavelengths, both up and downstream, are distributed from a single feeder fiber to multiple end points via a passive split location, typically inside a flexibility cabinet, just like with FTTH. Either a power splitter is used (like FTTH) to divide the power of all wavelengths in the feeder fiber to an exact copy on all distribution fibers, or a wavelength multiplexer (WM) is used to distribute individual wavelength pairs over the distribution fibers. From a logical point of view, P2P WDM PON is identical to P2P fiber which is the de facto solution for mobile xhaul. The big difference from P2P fiber is that P2P WDM PON makes much more efficient use of the fiber resources in the fiber access network and it maps directly onto the PON infrastructure already deployed for FTTH. A first P2P WDM PON standard was defined at 10 Gbps as part of ITU G.989 (P2P NG-PON2). A similar standard was defined tailored to metro networks in ITU G.698.4. Discussions in ITU Q2 have started to develop a 25G WDM PON standard.

The benefits of using a PON network for mobile transport, which is understood to include backhaul, midhaul and fronthaul variants, is twofold. First, converged operators can benefit from using the PON network for dual purpose – fixed broadband and mobile transport – thereby reducing cost of infrastructure ownership significantly. Secondly, PON offers a lower cost of deployment compared to P2P fiber, by converting the mobile transport network into a shared P2MP xhaul link. Both benefits are independent of each other, and depending on the architecture, one can opt to benefit from the first only, the second only or both. With these two dimensions, PON networks offer the flexibility of multiple architectural options for satisfying a diverse set of mobile transport requirements. The two dimensions are depicted in Table 1, which shows four levels of network sharing in the rows, and the two multiplexing options in the columns. Various combinations will be detailed later in this document.

Table 1. PON networks offer the flexibility of multiple architectural options for mobile transport.

Fiber sharing options	P2P (WDM)	P2MP TDM
Dedicated ODN	Y	Y
Fiber in shared cable	Y	Y
Wavelength on shared fiber	Y	Y
Time slot on shared wavelength	N	Y

The installation of massive mobile networks is enabled at slashed cost and reduced time to market by sharing the optical distribution network. A study by FTTH Council Europe indicates that the fiber deployment cost for 5G xhaul is reduced by 65% (for high cell density in low fixed density areas) to 95% (for low cell density in high fixed density areas)[1]. Over time, on the same fiber network, the reach and density can easily be further scaled with mobile network growth.

Mobile transport and PON in the same distribution area

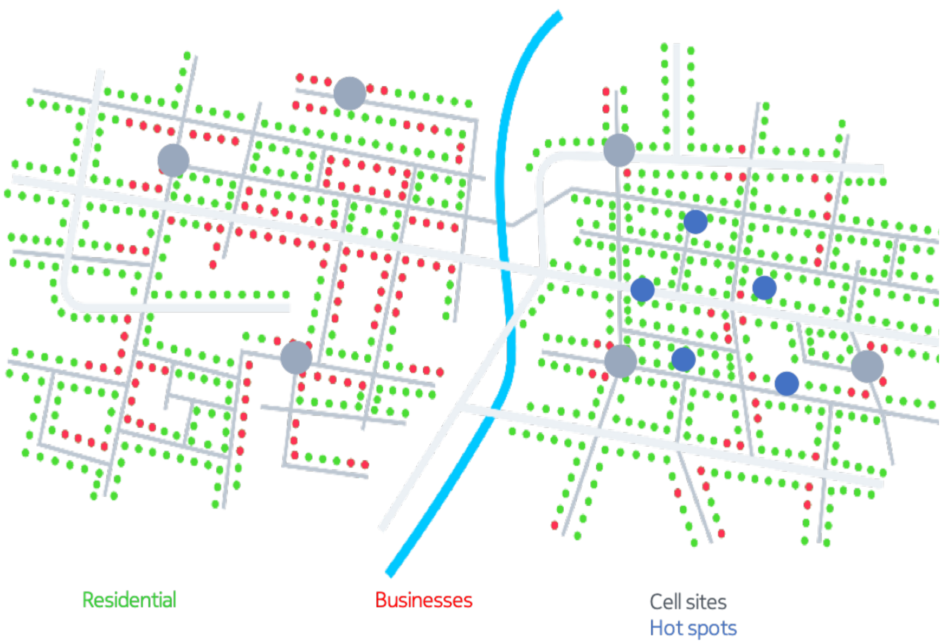
In order to understand how a PON network can be leveraged for mobile transport, we start by describing the typical topology and dimensions of an ODN, as used for fixed broadband services. A PON ODN typically comprises a feeder section, a distribution section and a drop section. The Central Office hosts hundreds

1 R. Meersman et al., “5G and FTTH: The Value of Convergence,” presented at FTTH Conference, 12-14 March 2019.

of OLTs which terminate the individual feeder fibers. The feeder section contains several fiber cables with many fibers, connecting the CO to several tens of Fiber Management Points (FMP) located in cabinets within a distance of 20 km of the CO. Each FMP serves a Distribution Area (DA) comprising about 500 homes and enterprises. The signal to each end user is tapped off from the distribution fiber using a drop box and is connected to the ONU through a drop fiber.

Figure 1 depicts a sample distribution area of about a square kilometer and 500 homes and requiring about 10 feeder fibers to terminate on 10 PON OLTs. As a typical number, about 85% of the end users are residential and the remaining 15% are businesses users, including micro-businesses, and Small and Medium Enterprises (SMEs). The number of mobile cells located within a PON DA depends on the desired cell density. Figure 1 graphically depicts potential cell sites (large grey dots), with an approximate 400 m spacing between cells.

Figure 1. A PON Optical Distribution Network



Scenarios of Sharing between FTTH and Mobile xhaul

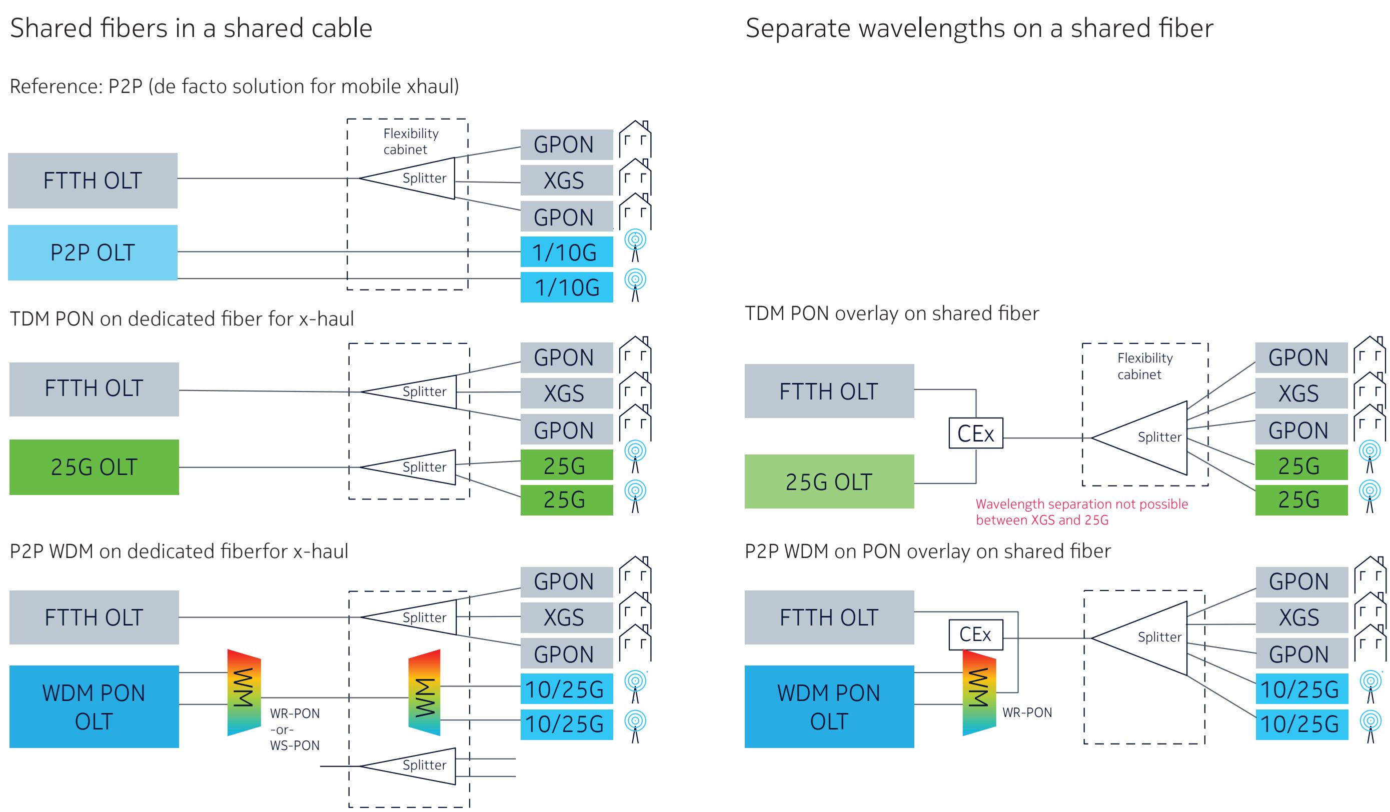
Four degrees of network sharing between fixed broadband and mobile transport can be identified. These scenarios are depicted in Table I and described below.

1. **ODN dedicated to mobile transport:** The existing fixed broadband infrastructure is not used for mobile transport. Instead, a separate ODN is build dedicated to mobile transport, but architected according to the design principles of a PON ODN in order to benefit from the economy of scale in terms of number of fibers required and from the low TCO thanks to the passive outside plant. There is no leveraging of common civil works between the two deployments (FTTH and mobile) in this model. Because of the high inefficiencies, this approach is seldom used, especially by a carrier that has both mobile and fixed assets.
2. **Separate fiber in a shared cable (structural convergence).** Mobile transport makes use of a dedicated fiber in the existing fixed broadband ODN. In this way, deployment is accelerated, and cost is reduced by provisioning a single fiber infrastructure, including a single feeder network, common FMPs, and common

distribution fiber cables. This is the most common approach in today's deployments since it provides separation between mobile and FTTH while avoiding the duplication of civil works. The de facto solution is P2P dedicated fibers for mobile xhaul but splitter-based PON solutions provide equivalent separation. The industry has referred to this as structural convergence.

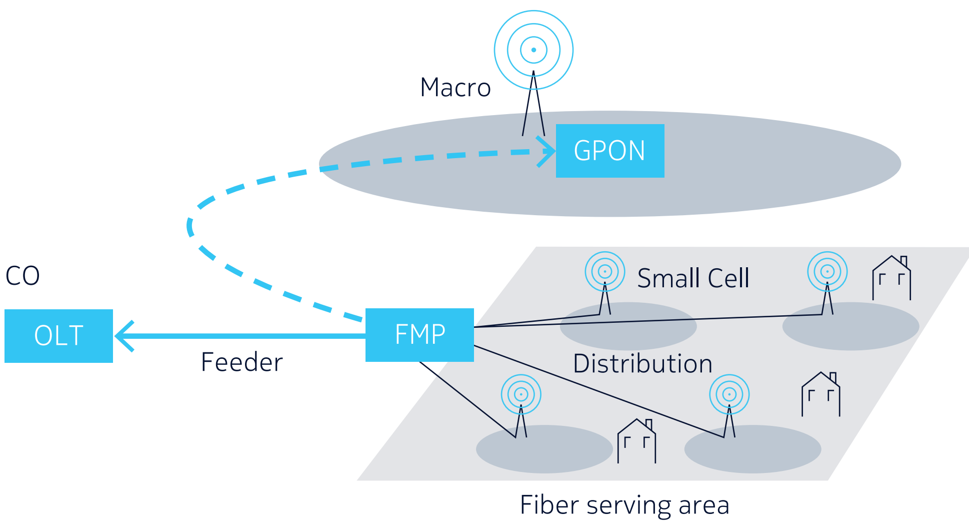
3. **Separate wavelength on a shared fiber.** In this way, mobile transport co-exists with fixed broadband on the same fiber through wavelength separation. This method has similar infrastructure savings as the previous and can further save on the cost of fiber. It is particularly attractive if the PON ODN is fiber-poor. As mobile nodes are being deployed deeper into the FTTH footprint, this approach is of increased interest since it leverages the synergies while maintaining a degree of separation between mobile and FTTH traffic.
4. **Separate time slots on a shared wavelength.** The highest level of ODN sharing is achieved when the mobile cell is connected to an ONU that xhauls the traffic on the same PON wavelength that is used for fixed broadband. In this way, further cost reduction is achieved by re-use of the OLT in the fixed access node and by avoiding any fiber manipulation in the FMP. Separation of services is ensured through end-to-end slicing in networks. This approach may be considered by highly integrated fixed & mobile service providers.

Figure 2. TDM PON and P2P WDM PON used for xhaul in shared cable versus shared fiber.



Scenarios 2 is currently the most prominent solution. While scenario 4 has some deployment already for LTE, scenario 3 is being heavily investigated for future deployments. The use of TDM PON and P2P WDM PON are shown for both the case of a dedicated fiber in a common cable and a dedicated wavelength in a common fiber. (in Figure 2, CEx is a coexistence element and WM is a wavelength multiplexer)

Figure 3. Small cells homed on the CO macro cell



High level of fiber infrastructure sharing between mobile and FTTH can easily be achieved when the mobile cells can be terminated in the FTTH central office location or routed through the CO location. Even if this is not the case, significant fiber infrastructure sharing can still be achieved for more complex mobile topologies, for example when small cells fan out from a macro cell (Figure 3). In such case, mobile operators can at least leverage the common fiber infrastructure and civil works of the FTTH network, as described by scenario 2, but cannot share the OLT equipment in the CO. Instead an OLT termination dedicated to mobile xhaul will be present in the macro cell location. Even in this case TDM PON or P2P WDM PON are completely valid solutions for the xhaul of this portion of the network. The architectures described in this paper still apply to this situation.

Transport requirements for Mobile xhaul

It is useful to briefly summarize the requirements for mobile xhaul before discussing the different PON solutions. A good description of these requirements is found in the ITU Supplement entitled, 5G Wireless Fronthaul Requirements in a PON Context (G.sup66).

Mobile x-Haul types (split configurations)

Although there are many options, the industry has settled on three types of mobile xhaul for 5G, corresponding to the split in functionality between the radio node and the centralized radio equipment. As shown in Figure 4 and summarized in Table II, these are:

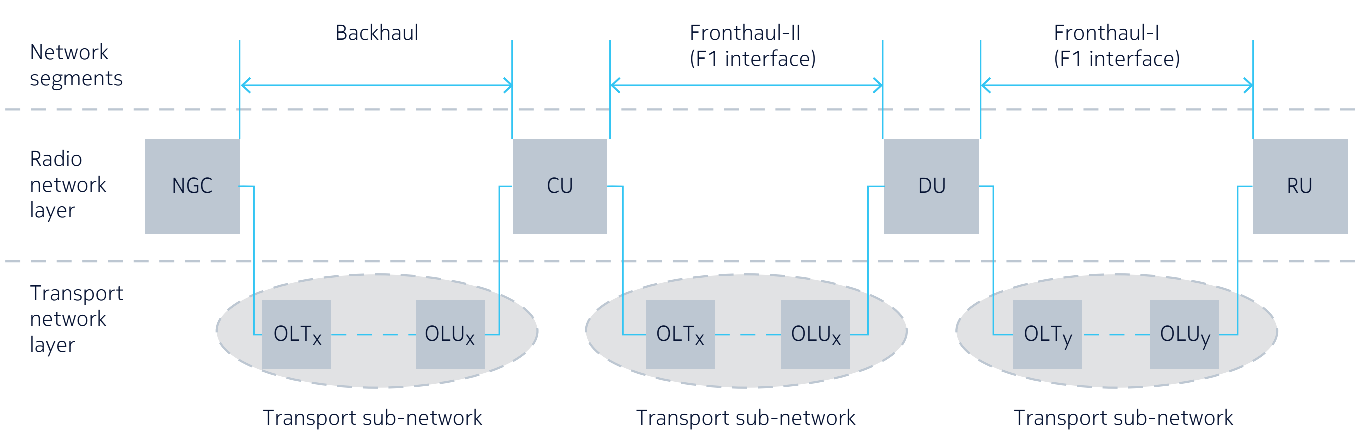
- Traditional backhaul – where,
  - the bit rate is very close to the consumed data rate of the end users
  - latency is very relaxed (1-10ms).

  - Time Sync requirements should comply with Accuracy level 4 as defined in ITU-T G.8271 (ie max 1,5μs absolute time error (TE))
- F1 interface (“midhaul”) – where
  - both the bit rate and latency are very relaxed and similar to backhaul.
  - Time Sync requirements should comply with Accuracy level 4
- FX interface (“fronthaul”) – where,
  - the peak bit rates are in the order of 2.5-20x that of backhaul
  - the latency is much more stringent than backhaul (100-200 μs) NB: The definition of this option is still in progress.
  - extra ‘relative’ TE requirements in the cluster of base stations (= accuracy level 6)

Table 2. Summary of high-level requirements for the various split architectures.

	Capacity	Latency	Timing accuracy
Backhaul	1x	1-10 ms	Level 4
Midhaul	1.2x	1-10 ms	Level 4
Fronthaul	2.5-2-x	100-200 μs	Level 6

Figure 4: Three x-Haul types corresponding to Optional Split Configurations of Mobile Functionalities (from ITU G.sup66). ‘Fronthaul-II’ corresponds with the terminology ‘midhaul’ used in current paper.



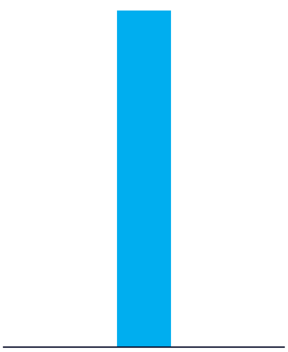
Capacity requirements

The usable over-the-air transmission capacity of a radio transmitter varies throughout the course of a day depending on the number of mobile users, their proximity to the transmitter and the applications they are using. Ironically, the overall peak capacity is achieved when there is a single user close to the transmitter. The busy time mean capacity, with all Physical Resource Blocks (PRB) assigned but multiple User Equipment (UE) geographically distributed can be significantly lower than this peak capacity because of less efficient transmission and radio interference. According to a reference model simulation by the Next Generation

Mobile Networks (NGMN) Alliance 2011 Guidelines for LTE Backhaul Traffic Estimation, the busy hour mean downlink (uplink) capacity is about 4x to 6x (2x to 3x) lower than the peak capacity This dimensioning rule can apply to the F1 interface. A similar consideration applies also to the transport capacities at the Fx interface. However, the variation of radio channel conditions among UEs and over time can lead to a spread of required transport capacities even when the user data rates remain unchanged. Furthermore, there is a burstiness to the content transmission that can allow for statistical aggregation.

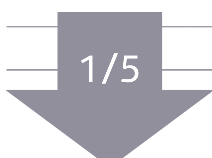
Exact air interface bit rate calculations depend heavily on mobile network design assumptions and are outside the scope of this document. For sake of discussion, Table III provides the peak air interface and busy hour mean F1 throughputs per RU for various bandwidth and MIMO layer configurations. Bandwidths up to 100 MHz are representative for sub-6GHz, with 100 MHz and 8 MIMO layers as proto-typical. Bandwidths of 200 MHz and above apply to mmW, with 400 MHz and 2 MIMO layers as prototypical. For sake of numerical argument, the F1 interface bandwidth is assumed 10% higher than the air interface throughput, which reflects framing overhead given a typical packet size mix.

Table 3. Peak and busy hour mean air interface bit rates per RU



RU peak

MIMO Layers	Peak data rate of the air interface 5g NR					
16	750	1595	3316	8540	11408	22816
8	375	797	1658	4270	5704	11408
4	187	398	829	2135	2852	5704
2	93	199	414	1067	1426	2852
1	46	99	207	533	713	1426
	10	20	40	100	200	400
						RF Bandwidth, MHz



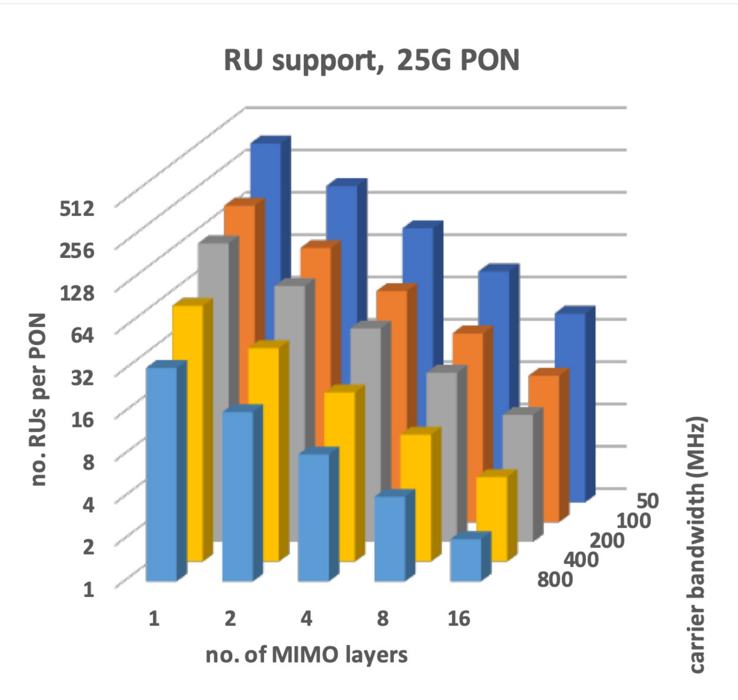
MIMO Layers	Mean data rate of the air interface 5G NR + transport ovhd (10%)					
16	165	351	729	1878	2509	5019
8	82	175	364	939	1254	2509
4	41	87	182	469	627	1254
2	20	43	91	234	313	627
1	10	21	45	117	156	313
	10	**20**	**40**	**100**	**200**	**400**
						RF Bandwidth, MHz

RU busy hour mean F1

It is clear from Table III that a single PON provides ample capacity to midhaul multiple RUs in most scenarios. Figure 5 provides an indication of the number of RU's that can be served from F1 midhauled (from one or several DU's) on a single 25G interface. The amount of achievable multiplexing gain is a design factor and depends (among other things) upon the number of multiplexed cells. Some studies suggest a multiplexing gain of 6 is conservative when the number of F1 midhauled cells is larger than about 10[2].

2 Bartelt et al. EURASIP J. Wireless Communications and Networking p89, 2017.

Figure 5: The number of RU's that can be served from F1 midhauled DU's on a single 25G (PON) interface depends primarily on the number of MIMO layers and carrier bandwidth.



Latency Requirements

For most user services such as video streaming and data services, the end-to-end (e2e) latencies are dominated by transmission over long distance networks, adding up to the range of 100 ms. For the PON, being only a small segment in the e2e connection, the tolerable latency lies in the order of 1 to 10 ms. This applies, when the PON is used e.g. for higher layer split F1 fronthaul transport in mobile networks providing enhanced Mobile Broadband (eMBB) services. F1 latencies are essentially given by the requirements of the user applications.

With some Machine Type Communication (MTC) and Internet of Things (IoT) traffic, be it in public networks or in industrial sites (cf. Ultra-Reliable Low Latency Communication, URLLC), or with intra-Data-Center traffic, the e2e latencies are required not to exceed values in the range of 1 ms. Taking into account the delay induced by data processing in the network nodes, the fraction of the e2e application latency that can be spent on PON transport will be well below 1 ms. This application dominated transport latency is comparable to the ultra-low latency that is required when the PON is used for low layer split Fx transport. Similar mechanisms as for guaranteeing e2e low latency services will hence be applied for the Fx interface.

For mobile processing chains being split between MAC and PHY layer (Option 6, Fx interface) or within the PHY layer (Option 7, Fx interface), the transport latencies are required to remain in the low 100 μs range, as a result of the Hybrid Automatic Repeat Request (HARQ) process. In LTE, this process is strictly synchronous and leaves only few 100 μsec roundtrip time (RTT) for fronthaul transport. In 5G, the process is asynchronous and generally more flexible. However, with eMBB and non-realtime mMTC services, where HARQ will be implemented, the acceptable transport latency will again be in range of few 100 μsec, i.e. similar as with LTE.

Timing requirements

The synchronization requirements on the radio side are relevant for certain use cases as well as for some operational modes of the radio nodes. Different categories have been defined, addressing various options of how to aggregate radio bands, or of how to let multiple antennas cooperate, as well as UE localization precision for emergency calls. The related absolute and relative, as well as differential, timing accuracy requirements in current specifications range from 20 ns up to 3 μs. The fronthaul network must take these requirements into account. However, the work into this field has only been started.

xhaul using TDM PON

Unlike with ptp links over the ODN using a dedicated wavelength pair per end node, the sharing of an optical channel by TDM-PON principles allows for taking advantage of statistical multiplexing which substantially reduces the number of optical transceivers in the CO as compared to WDM-PON. Moreover, the optical transceivers in the end-nodes are more cost-efficient than an equivalent WDM transceiver. This approach is the basis, and has proven successful, for low cost fiber networks for residential and business services. We will detail the considerations when it comes to using TDM-PON as shared medium for back-, mid-, and fronthaul for radio sites in wireless networks.

Transport capacity

In the end-to-end link from User Equipment (UE) to the wireless core network each radio site is an aggregation node. The fiber link connecting a radio site to the wireless processing nodes in the network in general experiences a smoother variation of data volume over time as compared to the traffic generated by each individual UE. This effect is more pronounced for macro cells than for small cells. So for small cells the statistical multiplexing gain of TDM-PON will be higher, meaning that multiple small cells can beneficially be served by a common TDM-PON, be it dedicated to wireless services alone, or be it mixed with residential services. This consideration applies alike to backhaul, midhaul (F1) and fronthaul (Fx). However, the required bandwidths for Fx fronthaul are higher than for backhaul or for F1 midhaul. The total bandwidth required for a group of cells in either case will be less than the sum of the individual peak values which makes the TDM-PON approach a viable option for saving on equipment and operational costs.

Transport latency

The latency requirements for backhaul and midhaul are commonly met on TDM PON. To also support the stringent latency constraints for Fx fronthaul on TDM PON, a number of challenges are being addressed. We will consider them in the rest of this section.

Fiber distance: The propagation RTT over fiber takes 10 µs/km. Due to the system related latency contributions discussed below, only a part of the tolerated latency budget (e.g. 200 µs) can be spent on fiber distance. In TDM-PON all ONUs are virtually located at the same distance as a result of the ONU's individually assigned equalization delay. In a CPRI-over-XGS-PON proof of concept experiment a supported distance of 6 km was achieved.

Upstream burst period and frame synchronization: The regular burst repetition period in TDM-PON is 125 µs, setting a lower limit to the achievable transport RTT. Assigning multiple bursts to each ONU per 125 µs frame greatly reduces this effect. As demonstrated by Nokia Bell Labs, with 4 bursts per frame the minimum e2e queuing delay (hence the lower limit for RTT, in absence of fiber propagation delay) is reduced to 31.25 µs.

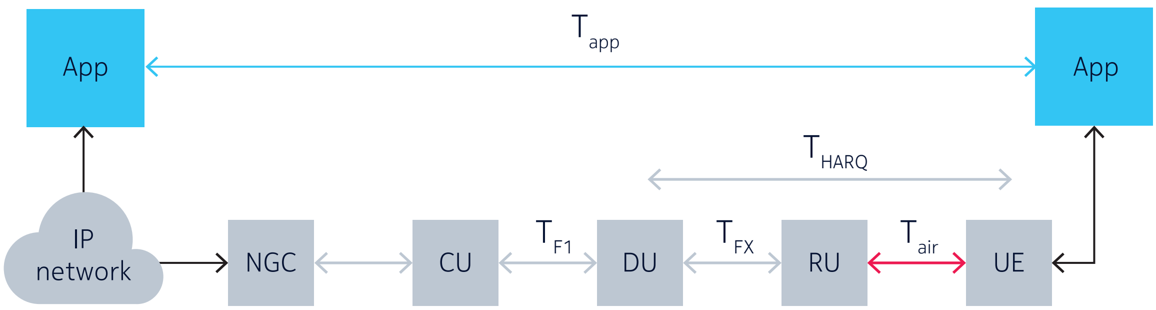
Dynamic bandwidth at the Fx interface: In contrast to the static traffic volumes in CPRI, the transport capacity at the lower layer split Fx interfaces varies dynamically with the amount of user data. Fronthaul latency requirement over TDM-PON can be achieved today by configuring a static Constant Bit Rate (CBR) for each cell connected to the PON. Yet, the variability of the Fx capacity allows for statistical multiplexing in TDM-PON with multiple antenna sites connected, or with additional higher layer split F1 fronthaul, or with additional fixed line services on the same PON. However, in a converged fixed-mobile architecture with independently operating fixed and mobile segments the conventional upstream dynamic bandwidth assignment (DBA) mechanisms in TDM-PON cannot meet ultra-low latency requirements. As has been demonstrated by Nokia Bell Labs, a synchronized bandwidth assignment in both the wireless network and the PON can reduce DBA related delays to a minimum. A bidirectional interface named Cooperative Transport Interface (CTI) is currently being standardized at ORAN. The CTI link between the wireless processing node and the PON OLT allows for alignment on available transport capacities and for timely bandwidth assignment.

ONU activation and ranging: In the most general case, where the fiber distances of the ONUs from the OLT are not known, the processes invoked for a new ONU joining the network, increase the RTT latency by 250 or 500 µs, depending on the maximal e2e fiber length in the PON. This can, however, be reduced to about 5 µs, if either the approximate ONU distance is known beforehand (e.g. from fiber plant data), or can be measured using e.g. an Optical Time Domain Reflectometer (OTDR). Another option is using a second PON system for this process that is operating on the same fiber network. If the PON is exclusively used for mobile Fx fronthaul or for URLLC services over the F1 interface, then the rare process of attaching a new ONU to the network can be precisely planned, so that short outages of the network can be scheduled to occur at times of low or even no data traffic. In this case, no other special measures have to be considered.

Time synchronization

Exchange of precise timing information and synchronization of end nodes is essential for mobile fronthaul. Access to high quality signals from Global Navigation Satellite Systems (GNSS) cannot be guaranteed in all cases. To offer precise time synchronization, the PON can terminate protocols such as SynchE and IEEE 1588v2 at the Service Network Interface of the OLT. The 8 kHz frame rate is used for frequency synchronization of the ONUs, and time stamps are sent to the ONUs through the OMCI channel. The ONU's User Network Interface in turn synchronizes the attached mobile devices employing the same mechanisms. The asymmetry of downstream and upstream propagation delays on the PON does not affect the timing precision, since the IEEE 1588v2 processes at either side of the PON are working separately.

Figure 6: Latency contributions from fronthaul segments in an e2e link and their relation to the application latency (NGC: Next Generation (5G) Core)



Availability

The commercially available XGS-PON is a 10 Gb/s symmetric TDM PON that meets the latency and timing accuracy requirements for back- and midhaul, while benefitting fully from statistical multiplexing across cell sites. By configuring XGS-PON such that each cell site is provisioned a Constant Bit Rate in upstream, XGS-PON also meets the latency and timing requirements for fronthaul. In this case, the downstream still benefits from statistical multiplexing across cell sites, but the upstream is provisioned a static rate. This may be acceptable considering downlink/uplink asymmetry.

Higher speed PON is currently being standardized at ITU, and will enable aggregating more cells on a single PON. Standardization of a Cooperative Transport Interface is ongoing at O-RAN, and will enable leveraging statistical multiplexing in upstream of fronthaul traffic.

Benefits of TDM PON

TDM PON is particularly well suited for back- and midhaul, for the following reasons:

- XGS-PON is available now. Back- and midhaul over XGS-PON is already being used in live networks.
- Capacity: Back- and midhaul have reasonable bandwidth requirements. In many scenario's, multiple CUs or DUs can be aggregated on a single TDM PON wavelength. The back- and midhaul bandwidth is also time-varying, allowing to benefit from multiplexing gain on TDM PON
- Full convergence possible: Converged operators can choose to transport xhaul traffic on the same PON that serves residential users. This is particularly interesting in case the cell density per PON distribution area is too low to warrant a dedicated PON for xhaul. The control to ensure the desired QoS for xhaul is already present.
- Latency: The relaxed back- and midhaul latency requirements allow the use of TDM PON as is.
- Timing and synchronization: The TDM PON protocol already supports time synchronization between both ends of the fiber.
- Fiber efficiencies: Thanks to the P2MP nature of the PON network, TDM PON makes extremely efficient use of fibers and optical transceivers.

xhaul using P2P WDM PON

P2P WDM PON in a nutshell

P2P WDM PON stacks multiple P2P wavelength pairs onto a PON to reach multiple distributed ONTs from a single feeder fiber. For mobile xhaul, it provides a one-to-one uncontended connection between a single head end and a remote radio unit, even though a P2MP fiber architecture is used. The split between a single feeder fiber and the multiple distribution fibers occurs in a fiber flexibility point in the field via a power splitter or a wavelength multiplexer.

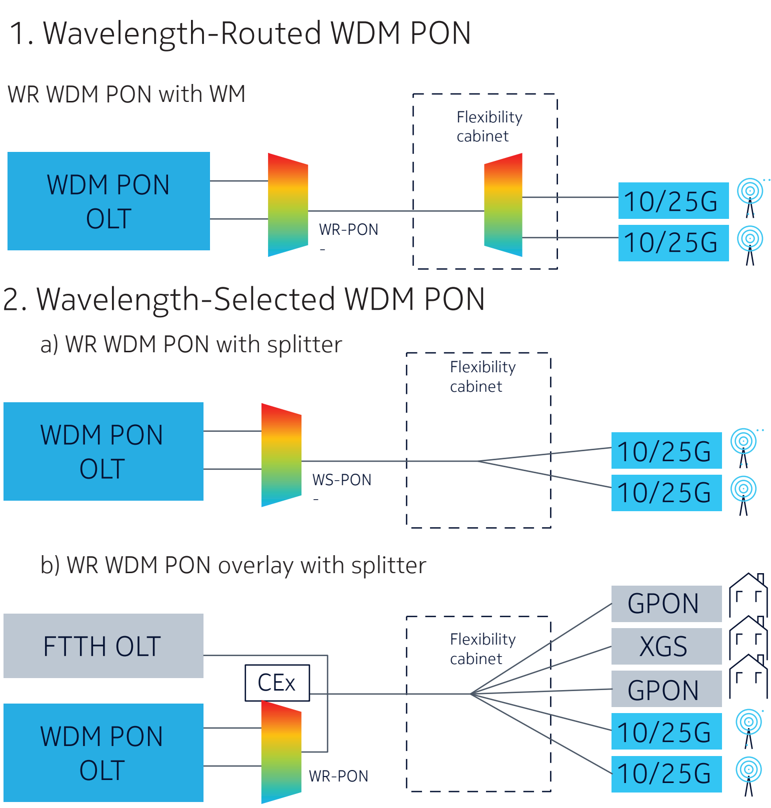
Flavors of P2P WDM PON

There are two basic types of P2P WDM PON defined by either the use of a wavelength multiplexing (WM) or a power splitter at the split point, as shown in figure 7.

Wavelength Routed WDM PON:

In the case where a WM is used, the wavelengths are routed to the appropriate end points and it is referred to as a Wavelength Routed or WR WDM PON. The advantages of this solution are that the optical path loss is much lower and there is no need for tunable receivers in the RU end. However, operators must be prepared to install a WM inside the FMP. This is generally possible as long as the splitter cabinet is accessible and connectorized. Coexistence with TDM PON on the same fiber is possible but requires a rearrangement of the outside plant, inserting a WM before the power splitter in order to strip off the WDM wavelengths. WR WDM PON is best suited for the scenario of structural convergence (i.e. the use of separate fibers on a common infrastructure).

Figure 7. Flavours of P2P WDM PON



Wavelength selected WDM PON:

In the case where a power splitter is used, all wavelengths appear at each end point, so the correct wavelength must be selected by the ONT. This is referred to as a wavelength selected or WS WDM PON.

Additional challenges for this solution (relative to WR PON) are that a tunable filter is needed in the ONT and the optical path loss is somewhat high due to the presence of a power splitter.

However, this approach is well suited to an installed base with power splitters, especially in the case where they are hard-wired and inaccessible. WS WDM PON can be used as a dedicated PON for only mobile x-haul as shown in option 2a) or alternatively as an overlay on a common fiber with an existing TDM PON deployed for FTTH, as shown in option 2b) of Figure 7.

Technical considerations and choices for P2P WDM PON

There are a few additional technical considerations and choices that need to be made to build the optimal cost efficient P2P WDM PON system. Some of these include:

- Wavelength band: All wavelengths are open for a P2P WDM PON system that is dedicated for only mobile xhaul. The choice will need to weigh the lower path loss in the C or L-band against the lower chromatic dispersion in the O-band. However, if the P2P WDM PON is overlaid on a PON network carrying legacy TDM PONs, then the wavelength must be chosen to coexist. The C band may have more available spectrum for this case. For the 25G-based WDM, there seems to be an emerging consensus on the C-band for both cases; but this needs to be confirmed.
- Optical budget: The optical path loss is lower for a Wavelength-Routed WDM PON with a WM in the field than it is for a Wavelength-Selected splitter-based PON. The former is in the range of 17dB versus approximately 29dB for the latter. Choosing the former allows for lower cost optics. However, it has been shown that the optical budget of the latter can also be achieved using optics similar to TDM PON with the appropriate use of FEC.
- Tunable optics: An important challenge for WDM PON is tunable optics in order to have 'colourless' optical modules that can be used interchangeably at any end-point. Wavelength-Routed WDM PON has the advantage of not needing a tunable receiver since only the correct wavelength is routed to the end point, whereas, Wavelength-Selected WDM PON requires a tunable filter at the receiver. Both cases require a tunable transmitter. A number of solutions exist including the more traditional DBR (Distributed Bragg Reflector) lasers and some more novel thermally tuned, parallel and ring resonator lasers. The tuning range (i.e. number of channels) is an important design parameter.

Many of the elements of the solution exist today but will need significant innovation effort to optimize, reach maturity and market readiness of P2P WDM PON

Technology evaluation of P2P WDM PON demonstrates the capabilities of currently deployed PON networks to leverage the wavelength dimension as additional growing path. However, P2P WDM PON will require larger access node footprint and structural convergence may not be preferred by highly integrated service providers due to the additional fiber manipulation.

Availability

R&D and standardization work is ongoing to mature WDM PON and crystalize the flavors and use cases mentioned above.

Benefits of P2P WDM PON

In principle, P2P WDM PON can be used for backhaul or midhaul (F1). However, it is particularly well suited to mobile FX fronthaul and this is the application of primary interest. Some of the benefits of this use case are:

- Capacity: The throughput of FX traffic is high (10 Gbps today evolving to higher bit rates) on dedicated stream
- Latency: There is no significant additional latency associated with P2P WDM PON.
- Timing and synchronization: These can be provided in essentially the same way as the default P2P fiber connections.
- Fiber efficiencies: Relative to P2P fiber, the use of a P2P WDM PON has a more efficient use of feeder fiber.

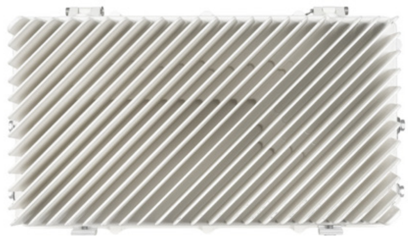
Nokia PON solutions for 5G xhaul

A portfolio for OLT and ONT solutions exists that can meet a variety of mobile networks demands. On the OLT side, form factors range from traditional central office equipment (ISAM FX) over stand-alone indoor (ISAM DF) or sealed (ISAM SF) units to data center practices (Lightspan). All integrate well in Software Defined Networks, either natively or through the Altiplano software plugin. On the ONT side, form factors range from modem-like ONTs (U-050X) to small form factor SFP ONTs (G-010S) that can directly be plugged into a small cell or small cell router. Specific devices are mentioned to sketch the range of possibilities, even if some of the mentioned devices don't currently support the full bandwidths and features desired for mobile fronthaul.

Inherent to Nokia's approach is automated transport slices. The 5G network cloud architecture provides the operator the ability to build multiple service slices orchestrated over the same 5G end to end network. These service slices (eg per application type like eMBB, mMTC) are translated in transport (QoS) blue prints that will be managed by E2E mobile transport controller (in Nokia the NSP). When deploying P2MP PON xhaul, the Nokia Altiplano that performs the PON domain control is integrated hierarchically with the 5G transport control for end to end transport slices. As such, all network entities are viewed and coordinated as a whole. In network slice-aware mode, a transport network is fully optimized for network slicing, when different traffic flows are individually identified and transported according to their own QoS requirements in all xhaul transport. This can be deterministic, see WDM-PON, where a slice is associated to specific wavelength(s) , and then is multiplexed in frequency domain over a line. Or this can be statistical, as in a TDM-PON, where slices are respectively identified by flows (VLAN), pseudo-wire (PW) and tunnels (IP tunnel/LSP), and then are logically multiplexed over a physical channel. These transport slices are fully automated to match the agility requirements of the 5G networks.

Figure 8. A wide scale of form factors for any mobile deployment model.

OLT: Lightspan/ISAM FX



OLT: SAM SF

OLT: SAM DF

ONU: G-010 SFP

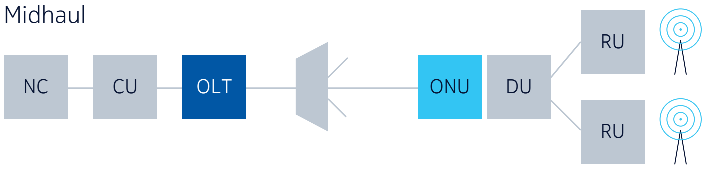
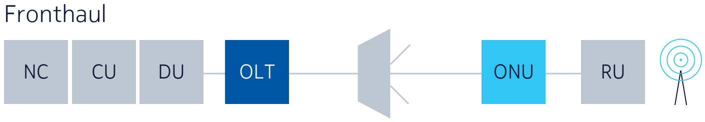
ONU: U-050X

Conclusions

In conclusion, we have demonstrated the capability of PON networks to meet capacity, latency and timing requirements for 5G xhaul. This enables converged operators to exploit their FTTH network for mobile xhaul. An overview of the ability of PON to satisfy 5G xhaul requirements is given in Table IV.

- XGS-PON is a 10 Gbps symmetric TDM PON and is readily available today. It is particularly well suited for backhaul and midhaul. From the typical radio dimensions shown in Table III, it is clear that XGS-PON can support the majority of F1 scenarios on a separate fiber dedicated to mobile mid-haul. On fiber shared with residential customers, the required bandwidth for xhaul transport can be provisioned through SDN paradigms.
- The upcoming higher speed TDM PON allows scaling to larger mobile networks, and will become available soon. .
- The Cooperative Transport Interface specification at ORAN will take a bit longer to mature (beyond 2020). Once commercially available, it will enable mobile fronthaul over PON.
- In the future, further mobile network growth could be supported through exploiting the wavelength dimension. WDM-PON is capable of supporting backhaul and midhaul but it is particularly well suited for the high transport rates and low latencies required in mobile fronthaul.

Table 4. Overview of the ability of PON to satisfy 5G xhaul requirements.

Architecture	XGS PON Available today	25G PON 2020+	WDM PON 2025+
Backhaul 	✓	✓✓	✓
Midhaul 	✓	✓✓	✓
Fronthaul 	X	✓	✓✓

Further reading

"5G Mobile anyhaul", Nokia white paper https://onestore.nokia.com/asset/201272

"5G New radio network", Nokia white paper https://onestore.nokia.com/asset/205407

Abbreviations

CEx	Coexistence Element
CO	Central Office
CU	Central Unit
CPRI	Common Public Radio Interface
CTI	Cooperative Transport Interface
DA	Distribution Area
DBA	Dynamic Bandwidth Allocation
DBR	Distributed Bragg Reflector
DU	Distributed Unit
eMBB	enhanced Mobile Broadband
FEC	Forward Error Correction
FTTH	Fiber to the Home
FMP	Fiber Management Point

GNSS	Global Navigation Satellite Systems
HARQ	Hybrid Automatic Repeat Request
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
ITU	Intenational Telecommunications Union
LTE	Long Term Evolution
MAC	Medium Access
MIMO	Multiple Input Multiple Output
mMTC	massive Machine Type Communication
MTC	Machine Type Communication
NC	New Core
NGC	Next Generation Core
NGMN	Next Generation Mobile Networks
NR	New Radio
ODN	Optical Distribution Network
OLT	Optical Line Termination
OMCI	ONT Management and Control Interface
ONU	Optical Network Unit
ORAN	Open Radio Network Architecture
OTDR	Optical Time Domain Reflectrometry
P2MP	Point to Multipoint
P2P	Point to Point
PHY	Physical Layer
PON	Passive Optical Network
PRB	Physical Resource Block
RTT	Round Trip Time
RU	Remote Unit
SME	Small and Medium Enterprise
TCO	Total Cost of Ownership
TDM	Time Division Multiplexing
TE	Time Error
UE	User Equipment
URLLC	Ultra Reliable Low Latency Communication

WDM	Wavelength Division Multiplexing
WM	Wavelength Multiplex(er/ed)
WR	Wavelength Routed

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