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Evolution of PON and Coherent Optics Technology in the Access Network

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Executive Summary

Today's world relies heavily on fast and reliable information exchange. The ever-increasing demand for higher data rates and more network capacity continues to exceed the currently installed system capabilities. Passive optical networks (PONs), which have developed rapidly over the past two decades, represent one of the most attractive access network solutions for the delivery of high-speed data and video services.

The first-generation Broadband Passive Optical Network (BPON), followed by Gigabit Passive Optical Network (GPON) and Ethernet Passive Optical Network (EPON), relied on relatively simple and loose specifications of the components with relatively limited transmission performance. They were followed by 10 Gbps Ethernet PON (10G-EPON) and 10 Gigabit Symmetric PON (XGS-PON), which increased capacity significantly. More recently, Next-Generation PON 2 (NG-PON2) and the next-generation EPON (single-wavelength 25G NG-EPON or dual-wavelength 50G NG-EPON) add yet more network capacity to meet the increasing demand for bandwidth. Recent developments in PON—i.e., NG-PON2 or dual-wavelength 50GEPON—leverage time-division multiplexing (TDM) and wavelength-division multiplexing (WDM) to balance the cost and performance flexibility path. These types of PON architectures require multiple optical light sources, which come with increased operational complexity and cost.

As we look to the future, optical access networks must take full advantage of developments in the field of optics and photonics in order to effectively address the ever-growing demand for bandwidth. Though the most important requirement for next-generation optical access networks is increased capacities that support data rates of several gigabits per second or more per user, increases in reach and split-ratio can greatly improve the economics of optical network design and deployments. Mindful of these requirements, coherent optical access technology has attracted increasing attention because of its superior performance and huge capacity potential. Whereas intensity modulation–direct detection (IM-DD) optics, widely used in today’s PON technology, rely on intensity modulation of light with data rate limited by the electrical analog bandwidth, coherent technology takes advantage of the combination of optical amplitude, phase, and polarization to encode information. This approach results in a significant increase in data rate without the need for super-fast analog electronics. Additionally, compared to IM-DD optics, coherent optics offer much higher sensitivity and more powerful digital equalization of fiber transmission impairments.

In this paper, we will discuss the evolution of PON technology, coherent optical technology, and its applications in the access network.

1. Passive Optical Network Evolution

A PON is a fiber-based, low-cost, and effective optical communication network technology that delivers a variety of broadband services to the end user. PON architecture implements a point-to-multipoint (P2MP) topology and utilizes passive optical components to build connections between service provider and customers. Passive fiber optic splitters split the signal so that each port gets the same data signal, but different ports can have different power levels depending on how the splitter is built; these splitters are critical components of PON architecture.

A typical PON, as depicted in Figure 1, consists of the following: an optical line terminal (OLT) at the hub/central office (CO), an optical distribution network (ODN) connecting the hub/CO and the end users, one or multiple-cascade passive optical splitters/combiners as part of the ODN, and a number of optical network units (ONUs) at the customer premises. PON architectures typically serve 16, 32, or 64 ONUs per OLT port (in some limited cases, they can support up to 128 or 256 ONUs). Compared with other network architectures such as active optical network (AON), which uses electrically powered switches to manage signal distribution, PON does not contain any electronic devices or electric power supply in its ODN, thus offering advantages such as low installation and operational cost, simple network infrastructure, and low energy consumption.

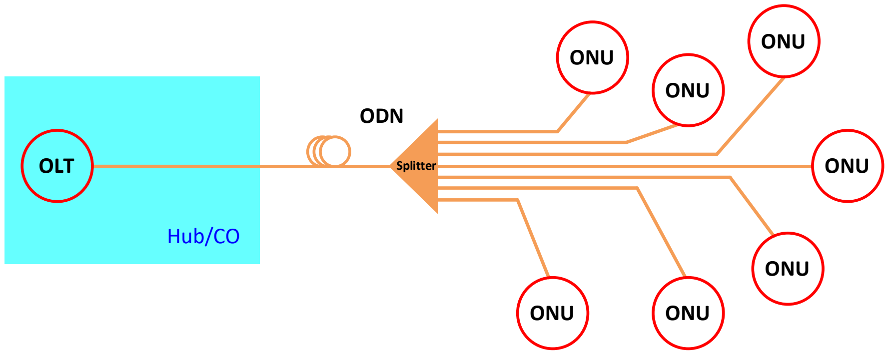
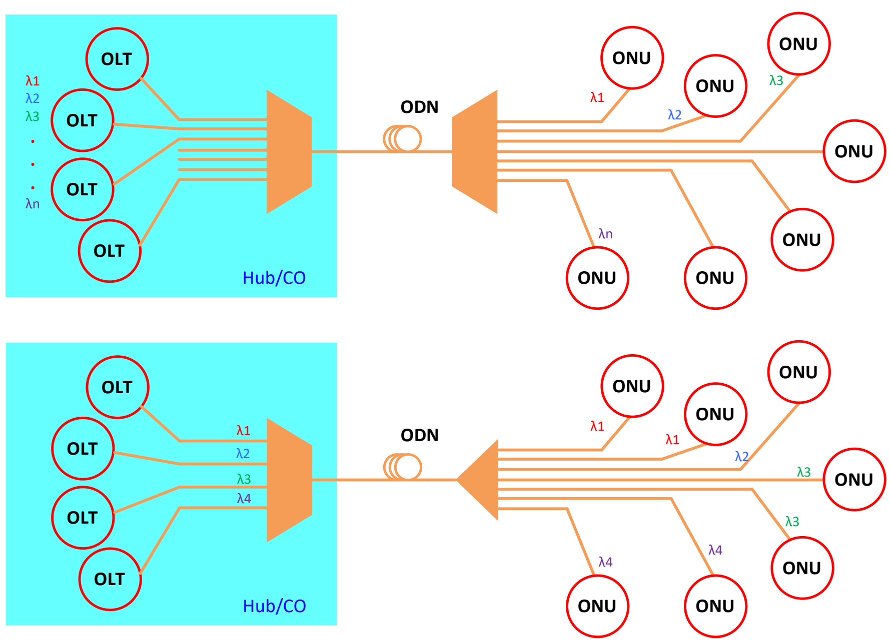


Figure 1. Example of PON Architecture: Time-Division Multiplexing (TDM)

As seen in Figure 1, the point-to-multipoint topology of PON usually requires different modes for downstream (OLT to ONU) and upstream (ONU to OLT) transmission. In the case of downstream transmission, typically all ONUs receive the same optical signal from the OLT; this allows the OLT to broadcast in continuous mode. In the case of upstream transmission, to prevent signal overlapping at the OLT, the ONUs cannot broadcast in continuous mode. Instead, the ONUs transmit upstream signals in burst mode and share the upstream channel using time-division multiplexing (TDM) through a dynamic bandwidth allocation (DBA) process. For a TDM PON, each ONU is assigned specific timeslots to transmit a burst of upstream data, and at any given time, the OLT is only receiving signals from a designated ONU. Because of the random distance between the OLT and the ONUs and the random phase of the burst mode packets received by the OLT, the phase and amplitude variation in the PON network needs to be compensated by adopting clock and data recovery.

Other PON architectures include wavelength-division multiplexing (WDM) PONs and time-and-wavelength-division multiplexing (TWDM) PONs. Figure 2A shows an example of a typical WDM PON, where multiple wavelengths are used to allow each ONU to receive and transmit on its own wavelength. A WDM PON uses WDM multiplexers (MUXs) instead of splitters to separate and combine wavelengths. It offers great flexibility and scalability as each wavelength can run at a different data rate and protocol. Because virtual P2P connections between OLT and ONU can be realized in the wavelength domain, the media access control (MAC) layer of a WDM PON can be simpler than a TDM PON. However, a WDM PON also suffers from a higher cost associated with the initial setup, the WDM components, wavelength resource, and the requirement of precision temperature control and multiple transceivers at the OLT side. No common standard for WDM PONs has been defined.



A.

B.

Figure 2. Example of PON Architecture: A, Wavelength-Division Multiplexing (WDM); B, Time-and-Wavelength-Division Multiplexing (TWDM)

TWDM, in contrast, uses a combination of TDM and WDM (time and wavelength) technologies. Figure 2B shows an example of a TWDM PON architecture, where a WDM device is used in the downstream direction to combine light with different wavelengths from four OLTs. At each ONU, a tunable optical filter passes the desired downstream wavelength to its receiver. In the upstream direction, each ONU is assigned to a transmitting wavelength. Multiple ONUs can be operated at the same wavelength through TDM for upstream transmission.

Over the last two decades, several generations of PON systems have been standardized through the efforts of two major industry standardization organizations: the ITU-T/ FSAN Group and the IEEE 802.3 Ethernet Working Group. The first generation BPON, followed by GPON and EPON, relied on relatively basic and relaxed specifications on the opto-electronic components. Soon after, the PON standards evolved into 10G-EPON and XGS-PON with tightened tolerances. Over the last few decades, the access speed of PON over single wavelength has increased almost 100 times to support the ever-growing bandwidth demand from emerging services. The Nx25G-EPON specification was approved by IEEE in 2020, based on 25 Gbps per wavelength. Most recently, the ITU-T 50 Gbps PON standard, based on 50 Gbps using a single wavelength, was approved in 2022. Table 1 shows a summary of the existing PON standards and the supported downstream/upstream transmission rates.

Table 1. PON Standards, Transmission Rates, and Wavelength Allocation

PON Acronym	Standard Organization	Standard	Downstream | Upstream Data Rate	Downstream | Upstream Wavelength Allocation (nm)
BPON	ITU-T	ITU-T G.983	622 Mbps | 155 Mbps	1530 (1490) | 1410
GPON	ITU-T	ITU-T G984.x	2.5 Gbps | 1.25 Gbps	1490 | 1310
XG-PON1	ITU-T	ITU-T G.987.x	10 Gbps | 2.5 Gbps	1577 | 1270
NG-PON2	ITU-T	ITU-T G.989.x	10 Gbps | 10 Gbps per wavelength 40 Gbps | 40 Gbps (80 Gbps | 80 Gbps) aggregated	1524–1544 | 1596–1602
XGS-PON	ITU-T	ITU-T G.9807.1	10 Gbps | 10 Gbps	1577 | 1270
50G-PON	ITU-T	ITU-T G.9804.3 (G.hsp.50Gpmd)	50 Gbps | 12.5 Gbps 50 Gbps | 25 Gbps	1340–1344 | 1260–1280 (wideband GPON compatible) 1340–1344 | 1290–1310 (wideband XGS-PON compatible) 1340–1344 | 1298–1302 (narrowband)
1G-EPON	IEEE	IEEE 802.3ah	1 Gbps | 1 Gbps	1490 | 1310
10G-EPON	IEEE	IEEE 802.3av	10 Gbps | 10 Gbps	1577 | 1270
NG-EPON	IEEE	IEEE 802.3ca	25 Gbps | 25 Gbps 50 Gbps | 50 Gbps	DW0: 1358 DW1: 1342 UW0: 1270 UW1: 1300 UW2: 1320
25GS-PON	25GS-PON MSA Group	25GS-PON MSA	25 Gbps | 25 Gbps 25 Gbps | 10 Gbps	DW0: 1358 DW1: 1342 UW0: 1270 UW1: 1300 UW2: 1320 UW3: 1286

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The next logical step for PON technology is to move towards 100 Gbps capacity. Figure 3 shows the evolution of PON technology and its path towards 100 Gbps PON.

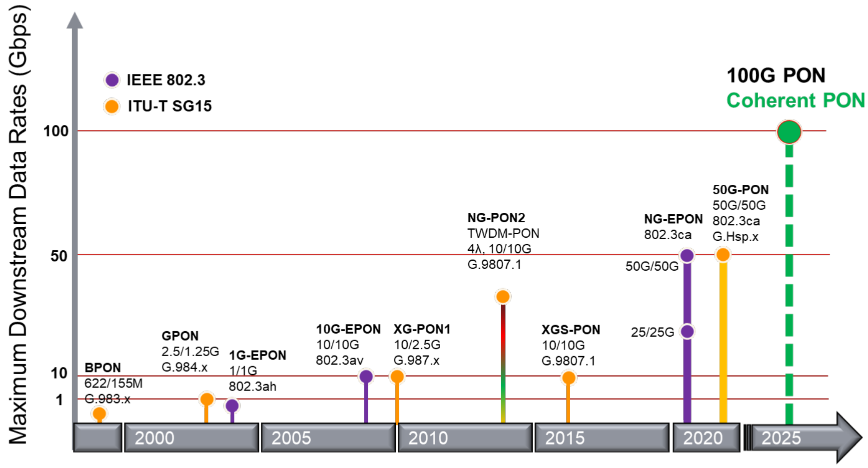

Figure 3. PON Evolution Toward 100 Gbps TDM PON

2. Coherent Optics

In the 1980s, there was significant initial research interest in coherent optics driven by the high receiver sensitivity obtained through the local oscillator's coherent amplification. Nevertheless, its use in commercial systems had been hindered by the additional complexity of active phase and polarization tracking. In the meantime, the emergence of a cost-effective erbium-doped fiber amplifier (EDFA) as an optical pre-amplifier reduced the urgency to commercialize coherent detection because EDFAs and WDM effectively extended link distance and capacity. More recently, since about 2008, the need to keep up with the exponential growth in traffic, forcing an equivalent need in cost-per-bit reduction of optical transport, and advancements in complementary metal-oxide-semiconductor (CMOS) processing nodes and powerful DSP have led to a renaissance in coherent optical technology development.

Coherent optics is a technique that uses amplitude and phase of light, as well as two orthogonal polarizations, to transmit multiple bits per symbol across fiber. There are several efficient modulation formats available, such as M-ary phase shift keying (e.g., quadrature phase-shift keying (QPSK)) and quadrature-amplitude-modulation (QAM). The modulation formats have an in-phase (I) component and a quadrature phase (Q) component. Additionally, as shown in Figure 4, the modulation format can be carried by two orthogonal polarizations, represented as X polarization and Y polarization; this is known as polarization multiplexing.

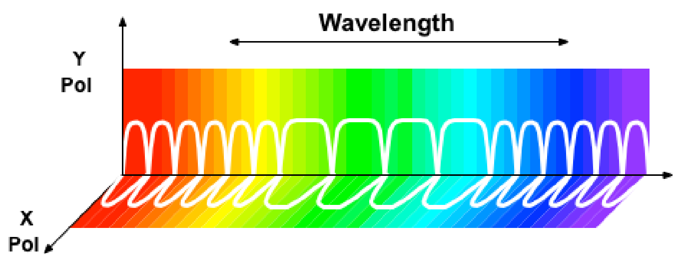

Figure 4. Polarization Multiplexing

The coherent optical link consists of the transmitter, the receiver, and the fiber in between. In most cases, two fibers are used so that the coherent optical link can use the same wavelength for both transmitting and receiving. In this case, the coherent optical transceiver uses the same laser for transmitting as it does for receiving (local oscillator). In the case of a single fiber, the coherent optic link typically uses a different wavelength for sending than it does for receiving, in which case the coherent optical transceiver needs two different lasers, one for each direction.

The coherent optical transmitter receives bits from its host device and maps the data into a symbol based on modulation format. If the transmitter uses polarization multiplexing (PM), it maps two symbols onto two orthogonal polarizations (IQX, IQY). It then multiplexes the two polarizations, which allows the transmitter to send two symbols simultaneously, thus doubling the bit rate. The transmitter also controls the number of symbols it sends per second, expressed as the symbol or baud rate. This means that to increase the bit rate, the transmitter can either use a higher order modulation format or increase the baud rate.

For example, using the QPSK modulation format with 2 bits per symbol and multiplexing two polarizations at 25 Gbaud (symbol rate), a single wavelength can achieve 100 Gbps per channel.

$$\frac{2\text{ bits}}{\text{symbol}} \times \frac{25\text{ G symbols}}{\text{second}} \times 2\text{ polarizations} = \frac{100\text{ Gb}}{\text{second}}$$

As another example, by using a WDM configuration with 8 wavelengths carrying 100 Gbps each, the raw bit rate across the fiber can reach 800 Gbps (0.8 Tbps (terabits per second)).

Each data channel contains two polarization tributaries. Each polarization contains in-phase and quadrature components. Each symbol has a defined duration determined by the symbol rate. For example, the number of bits per symbol period for QPSK with two polarizations is 4. Figure 5 is a visualization of these relationships for QPSK with two polarizations.

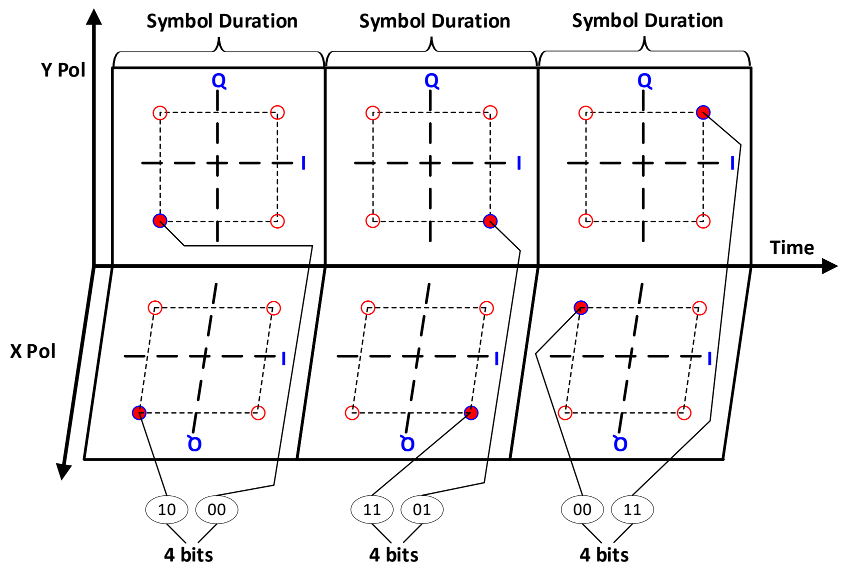

Figure 5. Data Channel Visualization

If polarization multiplexing is used, the coherent optical receiver separates two polarizations and then demodulates the received signal on each polarization into I and Q components. Once the receiver converts the analog signal to digital, it can use a digital signal processing (DSP) to compensate for any transmission impairments introduced along the path. Ultimately, the coherent optical receiver retrieves the bits encoded in the symbol and passes that onto the host device.

Figure 6 shows a high-level functional view of the coherent optical transmitter and receiver. The transmitter takes in bits and maps them into symbols with four degrees of freedom (XI, XQ, YI, YQ). The receiver demultiplexes the two orthogonal polarizations and demodulates the symbols to retrieve the transmitted bits. Additional coherent receiver components and process not shown here are covered in P2PCO-PHYv1.0.[1]

[1] P2P Coherent Optics Physical Layer Specification, P2PCO-SP-PHYv1.0-I03-200501, May 1, 2020, Cable Television Laboratories, Inc.

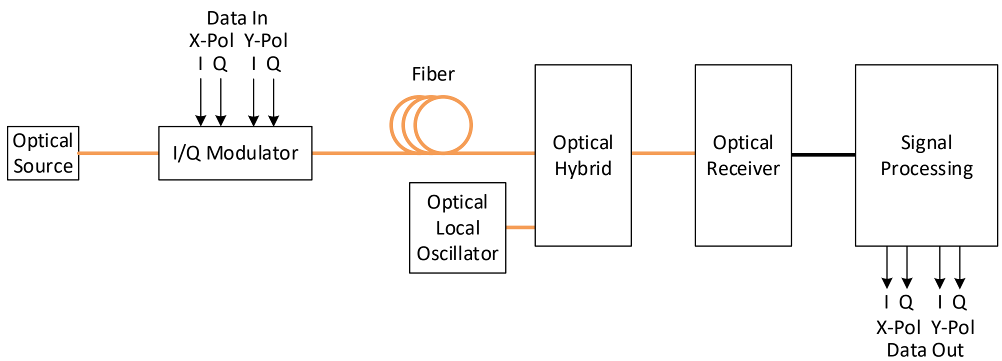

Figure 6. Coherent Transmitter and Receiver High-Level Functions

Compared to alternative direct-detect solutions that use a one-dimensional amplitude to represent the signal, coherent optical solutions use a local laser source as a reference to achieve linear conversion of the optical field instead of optical power used in direct detection. This enables modulation and detection using four dimensions, including amplitude and phase in two polarizations over time. With a local oscillator, significant coherent gain is provided along with wavelength selection without the need of an optical filter. Additionally, power fading induced by chromatic dispersion in a direct-detection system is no longer an issue because of optical field recovery in coherent detection. All these features that coherent optics bring to optical transport systems enable greater modulation efficiency and receiver sensitivity. Coherent detection for short-haul networks enables a superior receiver sensitivity that allows for an extended power budget. Its high spectral efficiency enables dense WDM (DWDM) and leads to higher capacity channels and fewer optical ports, providing operational simplicity that may lead to overall network savings.

3. P2P Coherent Optics in Access Networks

Coherent optical technology plays a dominant role in long-haul and core networks and is currently moving into metro edge and access aggregation networks to provide a common transport platform to a variety of services, such as residential broadband connectivity based on PON or a Data Over Cable Service Interface Specification (DOCSIS)-based HFC network, business and enterprise services, data centers, and wireless xhaul services.

Coherent optical P2P links can deliver higher capacity over the existing fiber, thereby avoiding retrenching. In most cable access networks, the distance between the hub/CO and the fiber node is less than 40 km, with 80 km covering almost all (about 98%) connectivity scenarios. Because of these distances, the access network does not need some of the components needed for long-haul and metro coherent networks, i.e., EDFAs required to amplify the signal between transceivers and more expensive components used to deal with impairments of the signal, such as chromatic dispersion (CD) and polarization mode dispersion (PMD), that worsen with distance. With shorter distances to fiber nodes, within tens of kilometers instead of hundreds or thousands of kilometers, P2P coherent optics for access networks are less complex than for metro and long-haul, so they can use simpler components including reduced-size DSPs. Common interface definitions enable interoperability between vendors, which in turn allows for greater scale and competition, greatly reducing cost. Therefore, P2P coherent optics designed for the access network can deliver a lower cost per bit than counterparts in long-haul and metro networks while leveraging similar technology.

With shorter links and a lower distortion level, solutions utilizing P2P coherent optics for access networks have a better signal-to-noise ratio (SNR), which allows for higher modulation orders than other technologies. This leads to more efficient use of the fiber and a more scalable network. For instance, the P2P coherent optical transceiver is able to provide 100, 200, or even 400 Gbps per wavelength. By using WDM technology, P2P coherent optics offers a scalable access solution by supporting multiple 100–200 Gbps (or higher) wavelengths on a single fiber at a higher density than competing technologies. WDM technology also allows P2P coherent optics to coexist with analog, IM-DD, and PON technologies.

P2P coherent optical technology targets the C-Band spectrum. However, other services are already using portions of the C-Band, so not all wavelengths are available to the P2P coherent optical solution when it coexists with other technologies on the same fiber.

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Figure 7 shows a high-level diagram of the wavelengths that make up the C-Band as defined by ITU in ITU-T G Supplement 51,[2] ITU-T G.9804.1,[3] and ITU-HDB-OUT.[4] For initial deployments, operators would like to reuse existing WDM equipment that uses 100 GHz spacing between channels within the C-Band. Even though the C-Band is the initially targeted spectrum, it may be possible in the future to expand P2P coherent optics for the access network into part of the L-Band to further increase the capacity a single fiber could support.

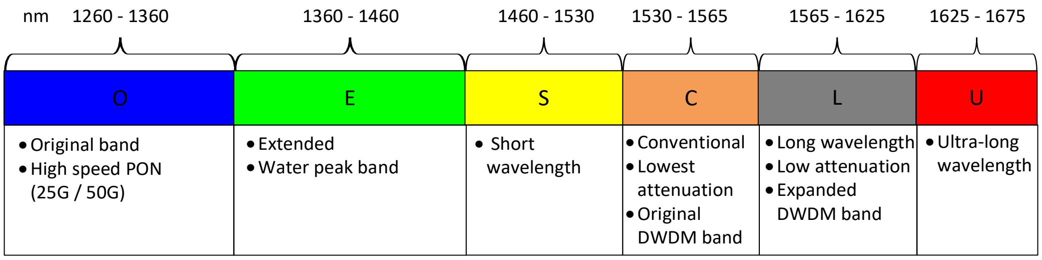

Figure 7. Spectral Bands Diagram

There are two main use cases for P2P coherent optics that operators can use to provide services.

The first is an aggregation use case as shown in Figure 8, where the coherent link is terminated at an aggregation point and other links are used to reach the end customer. The aggregation use case is the most likely first use of a P2P coherent optical link. It supports any Distributed Access Architecture, including Remote PHY, Remote MAC-PHY, and Remote OLT architectures. In the aggregation use case, an aggregation node with a coherent termination device (defined in P2PCO-CTD[5]) terminates the downstream P2P coherent optical link that originated at the hub/CO and outputs multiple optical or electrical Ethernet interfaces operating at lower data rates to connect devices that are co-located with the aggregation node and/or exist deeper in the network. This coherent termination device could be an Ethernet switch, a router, or a muxponder. The Ethernet switch can support output to optical or electrical links using Ethernet at varying data rates depending on the needs of the end device or user. The aggregate muxponder tributary traffic at fixed sub-rates equals the traffic on the main port facing the hub/CO; therefore, the data rate out is always equal to data rate in.

Figure 8 shows the entire system, with a variety of possible different devices connected to the other side of the coherent termination device (such as remote OLTs or Remote PHY Devices (RPDs)). The P2P coherent optical link will go from the hub/CO device with a P2P coherent optical transmitter to the coherent termination device with a P2P coherent optical receiver. The coherent termination device terminates the P2P coherent optical link and performs an optical/electrical/optical process to convert the P2P coherent optical link into several Ethernet links, which could be 10 Gbps or greater.

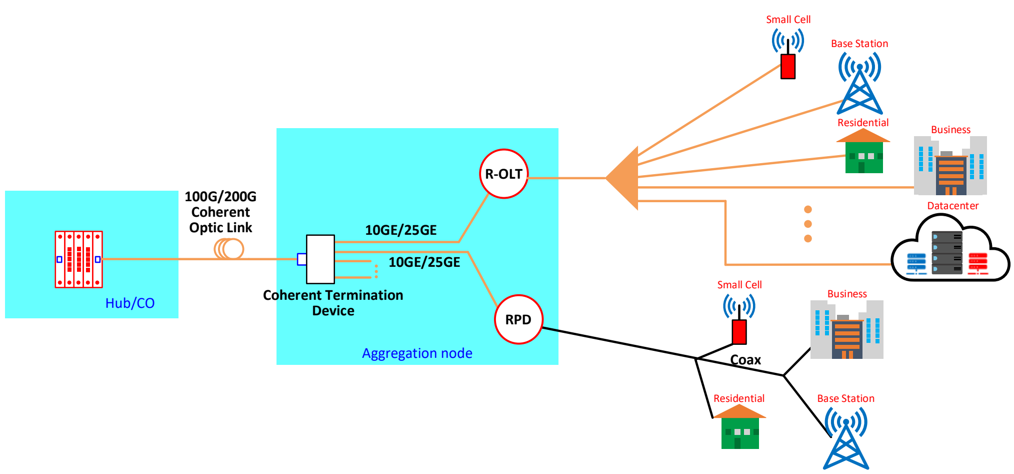

Figure 8. Aggregation Use Case with P2P Coherent Link

[2] "Passive Optical Network Protection Considerations," June 2017, ITU-T, Series G, Supplement 51
[3] "Higher Speed Passive Optical Networks," November 2019, ITU-T, Series G, G.9804.1
[4] "Optical Fibres, Cables and Systems," 2009, ITU-T Manual
[5] Coherent Termination Device Requirements Specification, P2PCO-SP-CTD-I01-210609, June 9, 2021, Cable Television Laboratories, Inc.

The second is an edge-to-edge use case as shown in Figure 9, where each P2P coherent optical link is terminated at the end customer location. In this use case, the coherent optical links are terminated at the edge customer, as compared to the aggregation use case where the coherent optical links are terminated at an aggregation node. In this use case, there is a WDM multiplexer/demultiplexer at the hub/CO that combines multiple P2P coherent optical links onto a fiber. At the aggregation node, another WDM multiplexer/demultiplexer routes the wavelengths and puts each on its own fiber strand. As shown in Figure 9, the demultiplexed P2P coherent optical links connect directly to the endpoint. The P2P coherent optical links from the hub/CO could be a mix of different link rates, and there could still be a mix of aggregation links with the edge-to-edge links.

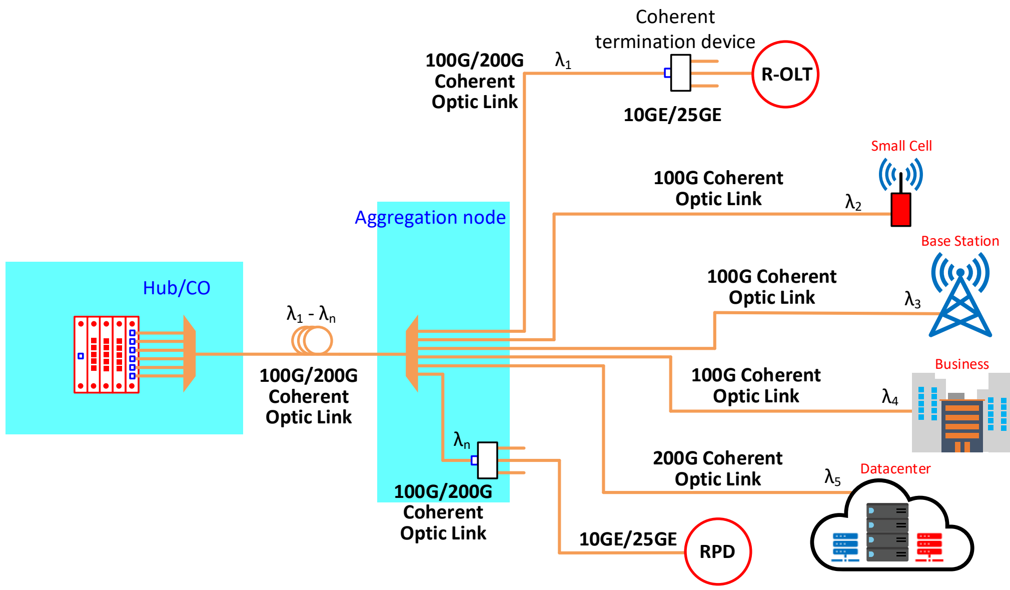

Figure 9. Edge-to-Edge Use Case with P2P Coherent Optic Links

Note that the edge-to-edge use case with P2P coherent optical links differs from a PON-based solution because it requires

- many router ports in the hub/CO,
- dedicated constant bit rate wavelengths for each customer premise equipment (CPE), and
- complex operational IP and management processes for each CPE.

Conclusion

In this work, we reviewed the development of PON technology based on IM-DD optics, driven by ever-increasing bandwidth demands. We also reviewed coherent optical technology and its applications in access networks utilizing P2P links to provide dramatically increased optical network capacity to support increasing numbers of distributed network devices.

A new opportunity exists to bring these technologies together to further benefit operators: Coherent PON or CPON. To learn more, please see the CableLabs CPON family of specifications.

APPENDIX A Acknowledgements

CableLabs would like to thank the participants of the CPON Working Group, representing the following companies.

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Izzi Telecom
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