GFiber

ciena
Tibit Technologies

Optimizing Passive Optical Networks with Coherent Innovation

A technical paper prepared by

Edward A. Walter
System Design Architecture Engineer
Ciena Corporation
ewalter@ciena.com

Hani Elmalky
Head of Network Planning & Engineering
Google Fiber
helmalky@google.com

Vikas Veerareddy
Specialist, Strategic Accounts
Ciena Corporation
vveerare@ciena.com

Together with its affiliates, Ciena Corporation is a supplier of certain networking solutions to GFiber.

Abstract

This paper examines coherent passive optical networks (CPONs) and their role in advancing optical distribution networks (DNs). It covers CPON background, objectives, and impact on ODN efficiency, including AI integration for enhanced management. The paper reviews relevant standards, network slicing, and the optical network terminal configuration management interface (OMCI) for interoperability. It contrasts intensity modulation-direct detection (IM-DD) with coherent optical technologies, explores wavelength coexistence, and integrates dense wavelength division multiplexing (DWDM) with CPON. Practical aspects of deploying cascaded ODNs for residential and multi-dwelling unit (MDU) coverage are discussed, highlighting the benefits of CPON in coverage and efficiency. The

paper concludes with a discussion on how 100G CPON can future-proof fiber networks, addressing growing bandwidth and service demands.

Contents

Figures

Tables

1 Introduction of CPON: Evolving the optical distribution network

1.1 Background

Passive optical networks (PONs) have traditionally focused on serving residential and small-to-medium business (SMB) markets. Early PON technologies such as gigabit PON (GPON) and Ethernet PON (EPON) were instrumental in delivering high-speed fiber broadband access to these segments. The architecture and capabilities of these networks were well-suited to the bandwidth demands of residential and SMB customers, where a balance between cost, performance, and simplicity was paramount. However, the rapid increase in data traffic, driven by the proliferation of connected devices and the rise of bandwidth-intensive applications, began to strain the capacity of these traditional PON systems. As a result, there has been a significant push within the industry to evolve PON technology to meet the needs of not just residential and SMB customers, but also more demanding applications such as mobility xHaul (fronthaul/midhaul/backhaul) and enterprise service level agreement (SLA) business services.

1.2 Expanding the scope of PON

To address the growing demand for higher data speeds and to expand into new markets, service providers are looking beyond traditional PON architectures. Coherent PON (CPON) has emerged as a promising solution for extending the capabilities of fiber networks. CPON enables higher data rates, enhanced reach, increased numbers of subscribers per PON, and better spectral efficiency, making it ideal for applications that require more robust performance than what is offered by GPON or EPON. These include mobility xHaul, which demands low-latency and high-bandwidth connectivity to support the deployment of 5G networks, and enterprise services that require reliable, scalable connections to support a wide range of mission-critical applications.

The expansion into these new markets is not only driven by the need for higher bandwidth but also by the economic imperative to maximize the return on fiber infrastructure investments. By leveraging advanced PON technologies like CPON, service providers can extend the utility of their existing networks, enabling them to serve a broader range of customers and applications with minimal additional fiber investment.

1.3 Problem statement

As service providers expand the scope of their networks to include mobility xHaul and enterprise services, they face the challenge of meeting the increasing demand for higher data speeds and longer reach while maintaining cost-effectiveness. Traditional PON technologies, designed primarily for residential and SMB markets, are insufficient to address the evolving requirements of these new applications. There is a pressing need for innovative PON solutions, like CPON, that can scale to meet these demands and support the expanded split ratios and fiber distances necessary for modern optical distribution networks (ODNs).

1.4 Objectives

The primary objective of this paper is to explore the development and deployment of CPON and its implications for an ODN. Specifically, the paper aims to:

- Examine how PON technology has evolved from focusing on residential and SMB markets to addressing the needs of mobility xHaul and enterprise services.

- Assess the impact of CPON on optimizing the ODN by exploring expanded split ratios and extended fiber distances to enhance efficiency and cost-effectiveness.

- Investigate CPONs role in meeting the high-performance requirements of modern applications.

- Evaluate the integration of dense wavelength division multiplexing (DWDM) with CPON to maximize fiber optic capacity and support various service needs.

This paper will delve into the architecture, standards, and wavelength coexistence strategies as part of the evolution of PON systems from their origins in residential and SMB markets to their expansion into mobility xHaul and enterprise services. A key factor in this evolution is the optimization of the ODN, where expanding split ratios and extending fiber distances play crucial roles in meeting the demands of modern applications. In the following section, we will delve deeper into the architectural components of modern PONs, focusing on how these ODN design strategies and advanced PON technologies can be effectively implemented to support a wide range of services while ensuring network scalability and cost efficiency.

1.5 Enhancing ODN efficiency and management

For an operator, a critical aspect of PON deployment is optimizing the ODN plant, which forms the backbone of the architecture. The deployment of fiber for an ODN represents one of the most significant cost components of a PON, particularly when considering the expenses associated with trenching and boring fiber in urban environments. The ODN's design must be carefully planned to balance coverage area, subscriber density, and the need to support expanded split ratios and extended fiber distances.

Traditionally, split ratios of 1:32 or 1:64 were often deployed in residential and SMB deployments. However, as operators expand into converged services—including mobility xHaul and enterprise services—and extend into underserved areas, it becomes crucial to explore the optimal split ratios to meet service metrics while maximizing fiber infrastructure use. Higher split ratios can lower feeder fiber costs and reduce the number of required PON ports, but they may compromise service quality. Conversely, CPON's higher optical budget allows for longer fiber distances and supports higher split ratios within the ODN, making it easier to reach larger geographic areas, such as rural or low-density regions, where deploying new fiber is costly. This approach reduces fiber deployment costs and minimizes the need for active electronics, such as remote optical line terminals (OLTs), which can be costly in terms of power, maintenance, and cabinetry. By relying more on passive fiber runs, operators can enhance network efficiency and reliability.

1.5.1 Incorporating AI into ODN management

As the complexity of ODNs increases, integrating artificial intelligence (AI) into network management becomes essential for optimizing operations. AI-driven solutions enhance the efficiency, scalability, and resilience of 100G OLT nodes, enabling service providers to maintain high performance across diverse environments. The following subsections outline key areas where AI integration can significantly benefit ODN management.

1.5.1.1 Predictive maintenance

AI can analyze data from OLT nodes and connected optical network units (ONUs) to predict potential failures or performance degradation. By identifying issues early, operators can proactively address maintenance needs, minimizing downtime and ensuring continuous service delivery.

1.5.1.2 Fault detection and root cause analysis

AI systems could rapidly detect and isolate faults within the ODN, pinpointing root causes with high accuracy. This accelerates troubleshooting, reduces mean time to repair (MTTR), and enhances network reliability, ensuring a stable service environment.

1.5.1.3 Adaptive modulation and coding

AI dynamically adjusts modulation formats and coding schemes in 100G OLT nodes based on real-time network conditions. This adaptability ensures optimal signal quality and bandwidth efficiency, even in environments with varying conditions or interference.

1.5.1.4 AI-assisted wavelength management

AI optimizes wavelength allocation across the ODN, reducing crosstalk and interference, especially in densely packed wavelength environments. This optimization is crucial for maintaining signal integrity in networks using multiple wavelengths for various services.

1.5.1.5 Enhanced signal processing

AI enhances signal processing algorithms within 100G OLT nodes, improving signal detection accuracy and error correction. This capability is vital for maintaining high data rates and minimizing latency, particularly in access networks where signal degradation is a concern.

1.5.1.6 Real-time optical performance monitoring

AI continuously monitors the performance of 100G coherent optics, detecting and compensating for degradations in key metrics like optical signal-to-noise ratio (OSNR). This real-time adjustment capability helps maintain optimal performance across the ODN.

By incorporating AI into ODN management, operators can achieve greater efficiency and reliability, supporting the diverse demands of residential, SMB, mobility xHaul, and enterprise applications. This strategic approach optimizes network performance and future-proofs the infrastructure against evolving service requirements.

1.6 General PON architecture

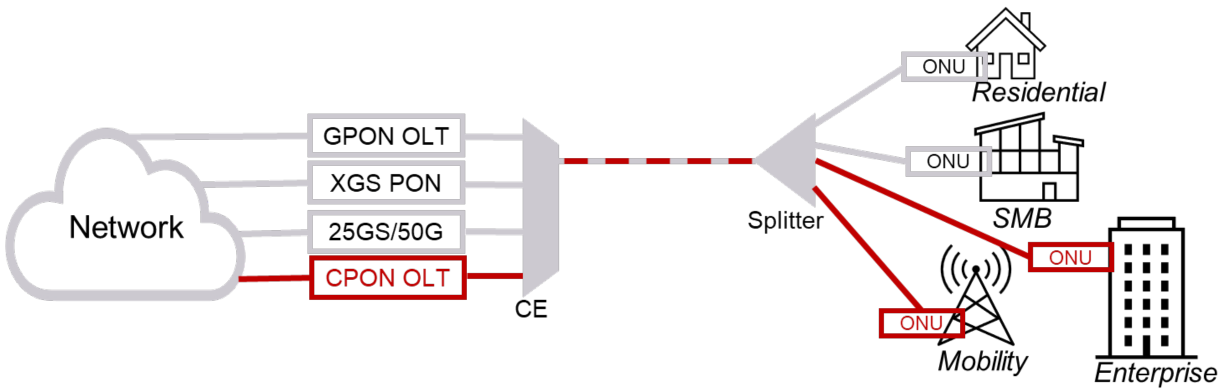

Figure 1. Residential ODN with example coherent PON overlay

A PON architecture represents a highly efficient and scalable solution for fiber broadband access, characterized by its reliance on a single optical fiber for data transmission. The fully passive ODN extends between the OLT at a central location and the ONUs at the endpoints. This architecture is distinguished by the absence of active components within the ODN, which employs a single optical fiber and passive optical splitters to distribute signals and manage multiple connections. This design ensures a simple and reliable connection between the OLT and ONUs and supports the coexistence of different PON generations through wavelength filtering mechanisms.

Building on this architecture, PON operates on a point-to-multipoint (P2MP) basis. In this setup, a single OLT connects to multiple ONUs using passive optical splitters, which helps optimize infrastructure costs and simplifies deployment. Data transmission within PON is managed through time-division multiplexing (TDM) for downstream communication, organizing data into frames and time slots. For upstream communication, time-division multiple access (TDMA) is used, assigning specific time slots to each ONU to prevent data collisions.

A key feature of PON is its ability to support the coexistence of different PON generations on the same fiber infrastructure by deploying a passive coexistence element (CE). Coexistence capability is facilitated through this CE that allocates specific ports for various PON standards. Additionally, ONUs use blocking filters to manage the wavelengths they receive, ensuring seamless integration of different generations within the network.

1.7 Benefits

PON is widely adopted for residential and SMB services due to several key advantages:

1. **Cost efficiency:** Using a single optical fiber shared by multiple endpoints reduces infrastructure needs, lowering both capital and operational costs.
2. **Scalability:** The P2MP structure facilitates easy and cost-effective scaling as demand grows in residential and business environments.
3. **High-speed capability:** PON delivers high-speed broadband essential for data-intensive activities, such as streaming and remote work, and is also well-suited for SMB operations.
4. **Simplicity and reliability:** The passive nature of ODN simplifies network management and enhances reliability by eliminating the need for power between the central office and endpoints.
5. **Support for diverse services:** PON supports internet, voice, and video services over a single network infrastructure, catering to both residential and SMB needs.
6. **Future proofing:** Standards like GPON and EPON enable seamless upgrades to newer technologies, ensuring long-term viability and adaptability to increasing bandwidth demands.
7. **Robust global market demand:** Growing global demand for broadband drives the adoption of PON, with substantial volume contributing to its widespread deployment. This demand underscores PON's role as a cost-effective, scalable, and reliable solution.

Globally, PON has been widely embraced by telecommunications and cable operators, supported by standards such as GPON from the International Telecommunication Union Telecommunication Standardization Sector (ITU-T) and EPON from the Institute of Electrical and Electronics Engineers (IEEE). These standards are implemented extensively across North America, Europe, and Asia. PON serves as a versatile network solution for high-speed internet, voice, and video services in residential and SMB areas.

2 Standards

2.1 Standards development over time

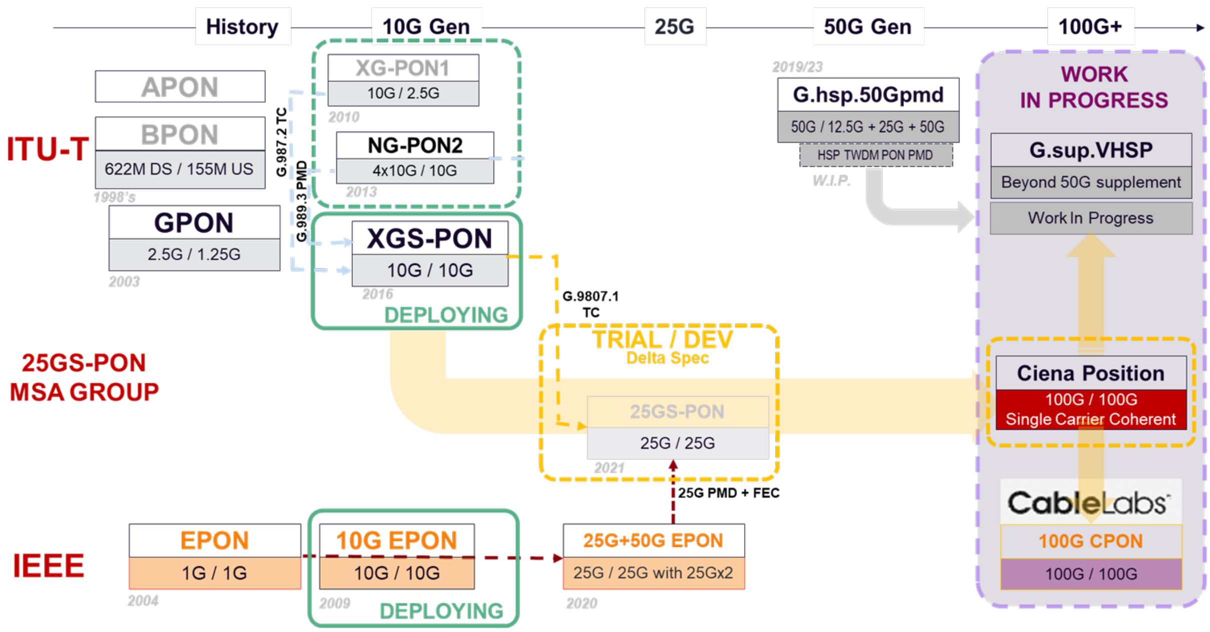

Figure 2. PON evolution via standards

Since the 1990s, the fiber broadband access industry has undergone remarkable evolution, beginning with the introduction of APON, or asynchronous transfer mode (ATM) PON. APON pioneered high-speed internet, voice, and video services over optical networks. This progress continued with the ITU-T G.983 family of specifications for broadband PON (BPON) in 1998.[1 2 3 4 5]

The stage was then set for the introduction of much higher—1 Gb/s—speed tiers through GPON (G.984 series[6 7 8]) and EPON (802.3[9] clause 64, 65).

The next significant phase in the development of fiber broadband can be characterized as "The Race to 10G," though the maximum speed tier was limited to much less (around 8.7 Gb/s) due to implementation of forward error correction (FEC).

The IEEE kicked it off with ratification of 10G EPON (802.3[9] clause 74, 75, 76, 77) in 2009. ITU-T followed with three specifications: XG-PON1 (G.987[10 11 12] series), NG-PON2 (G.989[13]), and XGS-PON (G.9807.1[14]) in 2010, 2013, and 2016, respectively. Note that NG-PON2 provides up to four symmetric channel pairs of PON services at 10 Gb/s each, with an aggregate OLT capacity of 40 Gb/s using a time and wavelength division multiplexing (TWDM) method.

Efforts for 25G and 50G began to take shape between 2020 and 2021, with the IEEE 802.3ca working group (802.3[9] clause 141, 142, 143, 144) developing a single wavelength pair (upstream and downstream) for 25G PON and a dual wavelength pair for 50G PON.

At a high level, the 25GS-PON[18] Multi-Source Agreement (MSA) Group specification builds on the IEEE 802.3ca physical media dependent (PMD), FEC specification, and the ITU-T G.9807.1 transmission control (TC) specifications. The 25GS-PON specification is a delta document, meaning it builds on existing standards. See the 25GS-PON specification for more details.[18]

Meanwhile, the ITU-T developed a single wavelength 50G PON solution via the G.9804 series of specifications.[15 16 17]

2.2 Network slicing: Enhancing multi-service ODNs

One of the key use cases discussed in this paper is CPON supporting a multi-service requirement. Network slicing is an innovative approach that enables operators to maximize the potential of a multi-service ODN. By creating multiple virtualized and independent network slices over the same physical infrastructure, operators can cater to the specific needs of diverse services. For example, a slice could be optimized for low-latency connectivity in mobility xHaul, another for high bandwidth to serve enterprise customers, and yet another for enhanced security in critical applications. This flexibility ensures that the ODN is both efficient in resource utilization and capable of delivering high-quality, tailored services to various customer segments.

2.2.1 Standards supporting network slicing

To effectively implement network slicing in PON, several standards and frameworks have been developed by leading industry bodies such as the Broadband Forum (BBF) and the Internet Engineering Task Force (IETF). These standards provide the necessary guidelines, architectures, and protocols to ensure that network slicing is not only feasible but also robust and scalable in real-world deployments.

2.2.1.1 BBF standards

- **TR-386:** Network slicing in broadband networks
  Outlines the framework for implementing network slicing in broadband networks, including PON. It provides detailed guidelines on how to partition physical network resources to create isolated virtual networks. This standard is pivotal in defining the lifecycle management of slices, ensuring that each slice adheres to its defined SLAs. Operators leveraging TR-386 can effectively optimize their PON deployments by ensuring that each service slice is tailored to meet specific customer requirements, whether it’s for enterprise-grade services, residential connectivity, or specialized industrial applications.

- **TR-370:** CloudCO reference architectural framework
  Provides a reference architecture for Cloud Central Office (CloudCO), which integrates cloud-native technologies within the traditional central office environment. Network slicing plays a key role in this architecture by enabling the dynamic allocation of resources across multiple virtualized services. TR-370 offers operators

a blueprint for deploying PON systems that can dynamically adjust to varying service demands, ensuring that each service slice operates efficiently within a shared ODN infrastructure.

- **MR-453:** 5G transport architecture and network slicing
  Addresses the integration of 5G transport architectures with network slicing. It focuses on how network slices can be extended across the transport network to support the diverse range of services required in 5G, including mobility xHaul. By adhering to MR-453, operators can ensure that the network slices they deploy in PON systems are seamlessly integrated with broader 5G network requirements, providing consistent performance and reliability from the core to the edge.

- **TR-328:** Virtual business gateway
  Introduces the concept of a virtual business gateway (vBG), a software-based solution that supports network slicing by allowing multiple virtual gateways to run on a single physical device. This is particularly useful for operators delivering managed services to SMBs. The standard ensures that each business customer receives a dedicated slice of the network, tailored to their specific needs, while optimizing the use of the underlying PON infrastructure.

2.2.1.2 Internet Engineering Task Force standards

- **RFC 9543:** A Framework for Network Slices in Networks Built from IETF Technologies Developed by the IETF, provides a comprehensive framework for implementing network slices across networks built using IETF technologies. This document outlines how to create, manage, and operate network slices, ensuring that they are isolated and secure while sharing the same physical infrastructure. For operators deploying PON systems, RFC 9543 offers valuable insights into how network slicing can be integrated with existing IP-based networks, enabling end-to-end service delivery that meets the specific requirements of different customer segments.

2.2.2 The value of network slicing in PON

Network slicing allows for the customization of services based on customer needs and ensures that these services are delivered consistently and reliably across a shared ODN infrastructure. This capability is particularly valuable in scenarios where operators need to support a wide range of services, from high-bandwidth enterprise applications to low-latency mobility xHaul connections, all within the same physical network.

2.3 Current and near-term CPON standardization efforts

While a standardized CPON is not yet available, Full Service Access Network (FSAN) did set operator requirements for 100G, and ITU-T Study Group 15 Question 2 (SG15/Q2) is working on setting requirements and evaluating technologies for next-generation optical networks beyond 50G under the G.Sup.VHSP analysis. Coherent technology is a key consideration in the assessment. In addition, ITU-T SG15/Q2 is documenting G.Sup.HSP requirements for TWDM-PON which is expected to use four 50 Gb/s channel pairs, shaping future standards for high-capacity optical access.

At the same time, the CableLabs CPON Working Group is developing a technical requirements (TR) document for 100+ Gb/s CPON. Vendors are anticipated to collaborate with CableLabs to develop and submit proposals for review.

CableLabs has released an architecture specification outlining the use cases and requirements for CPON, but not detailing implementation.[17] Upcoming CPON specifications will include a physical layer (PHY) specification, which will define the physical layer parameters such as modulation formats, signaling rates, FEC, and wavelength allocations. Additionally, the specifications will include a media access control (MAC) and upper layer protocol interface (MULPI) specification. The MULPI specification is crucial as it defines how data is framed, transmitted, and managed across the network. It covers:

- Framing and data transmission: Ensuring efficient and reliable communication between the OLT and ONUs by specifying how data packets are framed and transmitted over the PON.

- Protocol adaptation: Managing the adaptation of standard network protocol data units (PDUs) into a format suitable for PON, allowing for seamless integration of user data such as Ethernet frames or IP packets into the PON system.

- Scheduling and granting protocol: Implementing mechanisms for scheduling and granting time slots for data transmission, which is essential for managing upstream traffic in a P2MP network to prevent collisions.

- PON maintenance and management: Including protocols for maintenance, error handling, and general operational management, ensuring that the PON remains efficient and reliable.

Moreover, as the CPON ecosystem continues to evolve, the need for an open standard that facilitates robust integration of systems and nodes across the ODN becomes increasingly critical. An open standard would provide a unified framework that ensures interoperability among various vendors’ equipment, allowing operators to integrate different nodes seamlessly. This enhances the flexibility of network deployments and significantly reduces the time and resources required for qualifying different nodes within the ODN. By streamlining the integration process, open standards enable operators to deploy new technologies and services more rapidly, fostering a more competitive and innovative environment in the fiber broadband market.

2.4 OMCI openness and interoperability

2.4.1 The role of OMCI in PON interoperability

The optical network terminal management control interface (OMCI), as defined by ITU-T G.988, plays a crucial role in managing ONUs from an OLT within a PON. While the ITU-T G.988 specification offers a comprehensive toolkit of both standard and vendor-specific mandatory and optional managed entities (MEs), this very openness can present challenges. The recommendation in this section focuses on improving the interoperability of OMCI by relying on specific agreed-upon mandatory MEs within an 'OpenOMCI' specification, rigorous interoperability (IOP) testing, and using alternative management systems for more complex services.

2.4.2 Challenges in multi-vendor environments

Vendors often implement OMCI MEs differently, introducing proprietary MEs or customizing standard ones. These inconsistencies lead to operational challenges when deploying ONUs across various OLT platforms. Additionally, attributes tied to these MEs can differ in interpretation and implementation, further complicating interoperability. The sequence in which OMCI messages are processed is another source of potential misalignment, resulting in configuration failures or incomplete service setups.

2.4.3 Promoting interoperability in OMCI

To address these challenges, several strategies are being implemented. One approach is to adhere to an OpenOMCI specification which aims to minimize the use of vendor-specific MEs and promote standard practices across the industry. OpenOMCI specifications have been developed by AT&T and Verizon, and CableLabs is in the process of developing an OpenOMCI specification.

Reducing reliance on proprietary MEs and embracing standard MEs wherever possible can simplify network management and enhance interoperability. Additionally, alternative management systems, such as IP-based addressing and TR-069/TR-369, can manage specific services like voice without relying on those MEs, further reducing OMCI complexity.

Mandatory participation in an IOP events, guided by documents like BBF's TR-255, helps validate multi-vendor compatibility, ensuring that different vendors' equipment can work together as expected. These efforts collectively promote an open and interoperable PON ecosystem, reducing vendor lock-in and enabling operators to optimize their networks with the best available technologies.

Achieving OMCI interoperability is vital for operators seeking ONU flexibility and cost efficiency in their PON deployments. By minimizing proprietary elements, the industry can overcome the challenges of multi-vendor environments, ensuring seamless integration and future-proofing PON networks for emerging technologies like CPON.

3 A robust market: Coherent optics

3.1 Coherent component market size

According to Dell'Oro Group data, the coherent optics market is a mature, multibillion-dollar annual industry.[21] While coherent optics components have traditionally been focused on transport applications, there are emerging opportunities to cost-optimize 100G/200G coherent designs for metro, access, and PON applications.

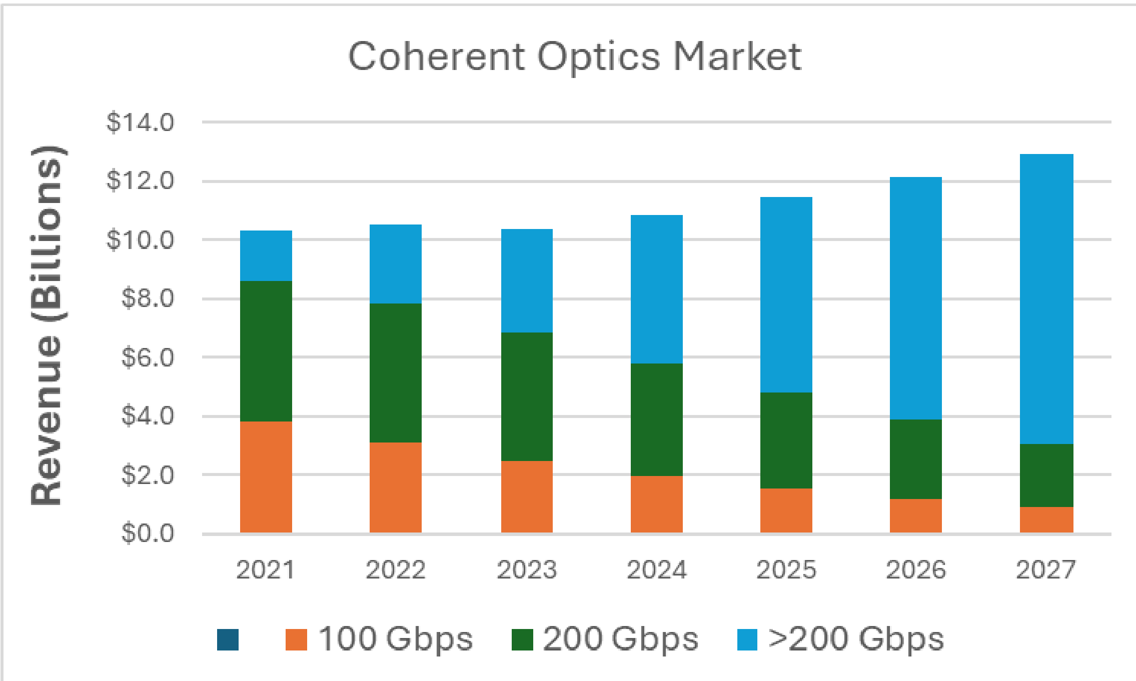

Figure 3. Coherent market revenue view (summarized from Dell'Oro data[21])

Figure 3 illustrates the revenue trends in the coherent optics market from 2021 to 2027, segmented by data rates of 100 Gb/s, 200 Gb/s, and greater than 200 Gb/s. The market is projected to grow steadily over this period, with total revenue increasing from just over $10 billion in 2021 to nearly $13 billion by 2027.

In 2021, 100 Gb/s solutions contributed a significant portion of the revenue, followed by 200 Gb/s and greater than 200 Gb/s solutions. However, as we move towards 2027, the contribution from 100 Gb/s solutions remains relatively stable, while the revenue from 200 Gb/s, and more notably, greater than 200 Gb/s solutions is expected to grow substantially. By 2027, the greater than 200 Gb/s segment is projected to dominate the market, indicating a clear shift towards higher-capacity coherent optics as network demands evolve.

The introduction of high-speed, compact, and power-efficient pluggable modems is crucial for future CPON deployments. Their small size and low power consumption make them ideal for fiber-deep cable uplinks, where minimizing power usage is essential. These modems will be vital in meeting the bandwidth and latency needs of CPON, while also supporting scalable solutions for enterprise networks and high-capacity metro connections.

4 Next-generation PON: IM-DD or coherent technologies

4.1 Intensity modulation-direct detection

Intensity modulation-direct detection (IM-DD) is a well-established technology used in current PON systems like GPON and XGS-PON. It is based on simple modulation schemes, where the intensity of the optical signal is varied in proportion to the data being transmitted, and the receiver directly detects these intensity variations. IM-DD systems have been widely adopted due to their cost-effectiveness and simplicity, particularly at lower data rates like 10G.

However, as the demand for higher data rates increases (e.g., beyond 50G), the limitations of IM-DD become apparent. The transition to higher speeds requires more sophisticated components to meet the necessary link budgets and maintain signal integrity. This includes the use of externally modulated lasers (EMLs) instead of the simpler directly modulated lasers (DMLs), semiconductor optical amplifiers (SOAs), and digital signal processor (DSP) application-specific integrated circuits (ASICs) to handle the increased signal processing demands.

4.2 SOAs in IM-DD systems

As PON systems push towards higher speeds, as well as a combination of greater split ratios and longer ODN distances, maintaining sufficient optical power becomes critical. This is where SOAs may come into play. An SOA is a device that amplifies the optical signal without converting it to an electrical signal, making it an efficient way to boost power in IM-DD systems.

SOAs are particularly important in high-speed IM-DD systems where the signal needs to traverse long distances or where the link budget is stretched due to high split ratios in the ODN. They help compensate for power losses that occur due to fiber attenuation, splitting, and other factors. However, the inclusion of SOAs adds to the complexity and cost to a PON ONU.

4.3 Coherent optical transmission

Coherent optical transmission represents a more advanced approach to optical communication, particularly suitable for high-speed applications like 100G PON. Unlike IM-DD, coherent systems use complex modulation schemes such as quadrature phase shift keying (QPSK) and quadrature amplitude modulation (QAM), which encode data onto both the amplitude and phase of the optical signal, and even across multiple polarization states. This allows coherent systems to achieve much higher spectral efficiency, with more bits per symbol being transmitted.

A key advantage of coherent systems is their enhanced receiver sensitivity. Coherent detection, combined with advanced DSP functions, allows the system to operate with higher losses in the ODN, enabling longer distances and higher split ratios.

4.4 CPON ONU optimization

The CPON ONU architecture is a sophisticated design that leverages coherent detection and advanced signal processing to enable high-speed, cost-effective data transmission. This architecture is divided into three primary functional blocks—digital-to-analog converter/analog-to-digital (DAC/ADC), DSP, and MAC—which collectively ensure robust and efficient operation within a 100 Gb/s symmetric system. The following sections delve into the specifics of each block, highlighting their roles in enhancing the performance and scalability of CPON systems.

4.5 CPON ONU architecture overview

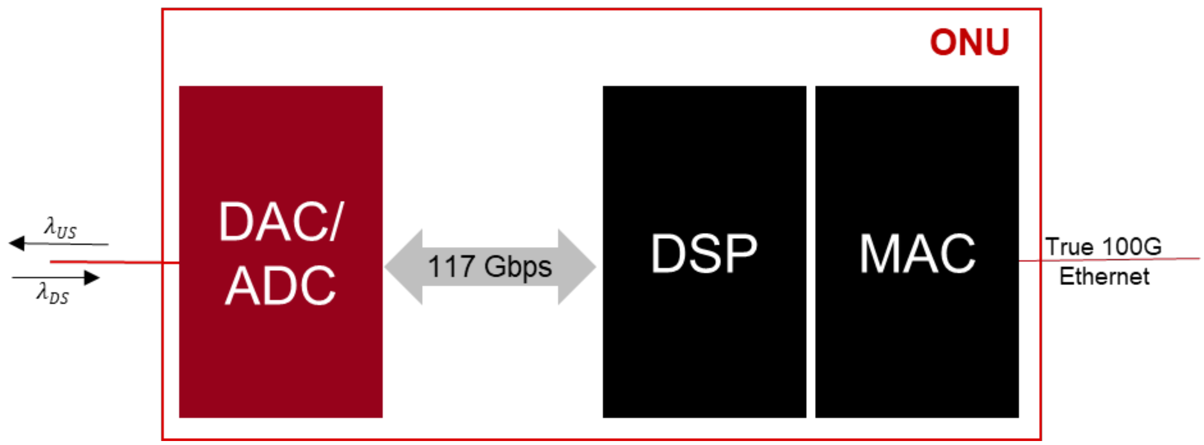

Figure 4. CPON ONU functional block diagram

The CPON ONU architecture can be divided into three primary functional blocks: DAC/ADC, DSP, and MAC. These blocks collectively enable high-speed data transmission in a cost-effective manner, leveraging coherent detection and advanced signal processing techniques.

4.5.1 DAC/ADC

The DAC and ADC convert between the digital and analog domains. In the transmitter path, the DAC converts digital data streams into analog signals, which are then modulated onto an optical carrier. Conversely, the ADC in the receiver path converts incoming analog optical signals back into digital form for further processing. This block interfaces directly with the radio frequency (RF) baseband electronics, which, thanks to polarization multiplexing, require a bandwidth of only 15 GHz. This allows the system to handle approximately 117 Gb/s across four orthogonal lanes at a baud rate of around 30 GBaud for in-phase and quadrature (I/Q) on both X and Y polarizations.

4.5.2 Coherent systems DSP (with IM-DD DSP comparison)

In high-speed IM-DD systems, the DSP primarily handles tasks such as equalization, dispersion compensation, and FEC, including low-density parity-check (LDPC) codes. The

DSP's role in IM-DD systems is crucial for addressing challenges like inter-symbol interference (ISI) and signal distortion. LDPC codes help maintain signal integrity, ensuring reliable performance even as data rates increase.

In coherent systems, the DSP performs a broader range of functions. Alongside equalization and FEC with LDPC codes, it manages phase recovery, polarization demultiplexing, and advanced error correction. These additional functions contribute to the system's ability to achieve high performance and spectral efficiency. Coherent systems leverage these capabilities to handle more complex modulation schemes and a wider range of signal impairments, enhancing overall system performance.

While this analysis assumes the use of LDPC codes in both IM-DD and coherent systems, it is important to note that as of the writing of this paper, neither CableLabs nor ITU-T SG15/Q2 has made a final decision on this matter. Both IM-DD and coherent systems utilize their DSPs effectively, with coherent systems providing enhanced performance and flexibility in handling complex signal conditions.

4.5.3 MAC

The MAC block is responsible for managing the data transmission protocols and ensuring compliance with the relevant PON standards, such as those defined by the ITU-T SG15/Q2. The MAC block uses an ASIC designed to manage the upstream and downstream data flows efficiently. It also handles tasks like packet framing, error checking, and arbitration, ensuring smooth and reliable communication between the ONU and the OLT.

4.6 System description

For a true 100 Gb/s symmetric system with FEC super-rated (around 117 Gb/s), the CPON transceiver can be cost-effective by employing fixed wavelength distributed feedback (DFB) lasers without lockers. This design choice eliminates the need for costly components like SOA or erbium-doped fiber amplifiers (EDFAs). As detailed by Boyd et al. (2024) in their SCTE TechExpo24 paper, "What Could You Do with 100 Gbps Coherent PON?", this approach ensures the CPON ONU delivers high performance while maintaining cost efficiency, making it suitable for broad deployment in residential and business settings.[20]

4.7 CPON value add: Tunability

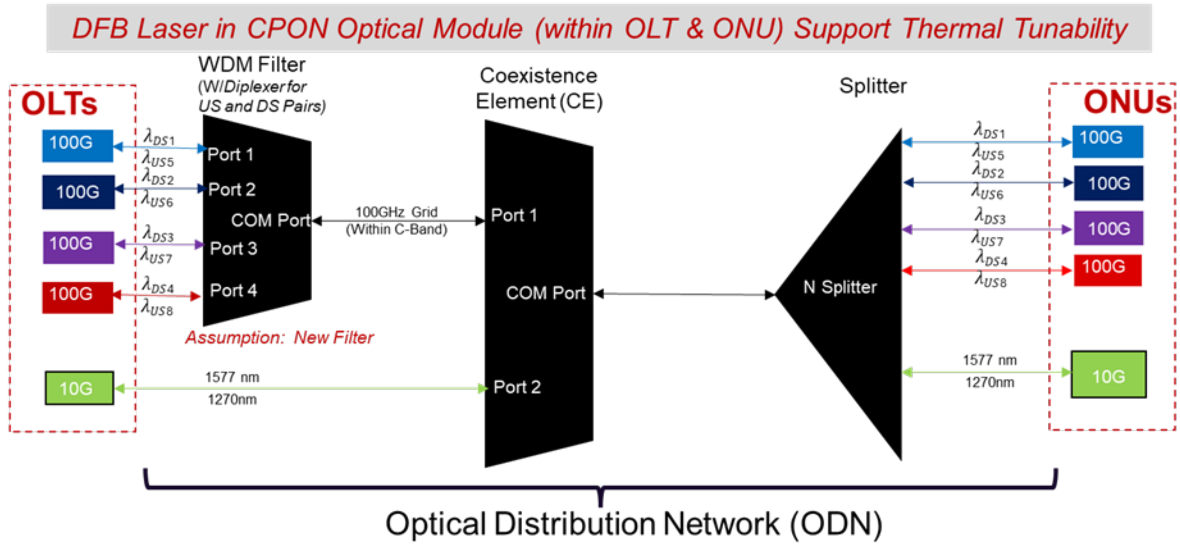

Figure 5. "Residential" access ODN: Fixed-channel CPON tunability

A key benefit of the CPON design is its tunability across four upstream and four downstream channels. This tunability is achieved using DFB lasers with integrated thermal tuning capabilities and a wavelength division multiplexing (WDM) filter. The DFB lasers are fixed wavelength but can be finely tuned by adjusting the temperature, allowing them to align with different channels within a limited wavelength range. The WDM filter further enables the separation and selection of these specific wavelength channels, making it possible for the system to support multiple upstream and downstream channels without the need for expensive tunable lasers. This tunability enhances the flexibility and scalability of the network, allowing for efficient bandwidth management and the stacking of multiple channels on the same ODN infrastructure.

4.8 CPON cost comparison

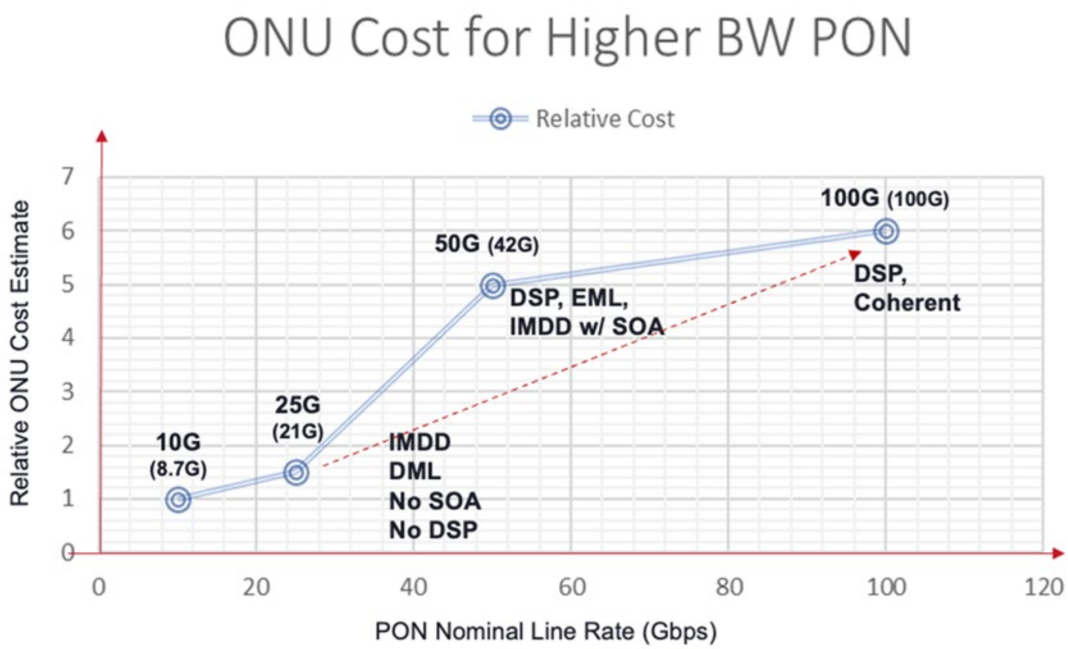

Figure 6. ONU cost for higher BW PON

Using cost forecasts for 400G ZR in quad small form-factor pluggable double density (QSFP-DD) and 100G ZR in QSFP pluggable 28 (QSFP-28) with full-band tunable lasers is not representative of the cost forecast for 100G CPON in QSFP-28. This discrepancy arises due to the use of fixed wavelength lasers and the significantly higher volumes in the PON market compared to Metro Transport. For example, a fixed DFB laser is substantially cheaper—by an order of magnitude—than a full-band tunable laser, which can adjust its output across a wide range of wavelengths within a specific band and represents a large portion of the total module cost.

Based on these assumptions of similar volumes and the use of fixed lasers, a true 100G symmetric CPON ONU is estimated to be only 20% more expensive than a 50G symmetric PON. This aligns with the trend depicted in Figure 6, which shows a steady increase in relative ONU cost estimates as the PON nominal line rate increases from 10 Gb/s to 100 Gb/s. Notably, the cost jumps at the 50G and 100G levels due to the introduction of more advanced optical and electronic components, such as DSP and coherent technology.

Consequently, 100G CPON is more cost-effective on a relative dollar per bit per second basis compared to symmetric 50G PON. Initial samples expected in 2026 are anticipated to have a 50% lower cost per bit per second, especially since 50G symmetric PON carries only 40G of data and is not FEC super-rated. Super-rating is not fully explored in this paper. For greater detail on super-rating, see the Boyd et al. SCTE TechExpo24 Paper, “What Could You Do with 100 Gbps CPON?”[20]

This low-cost coherent optics design with a balanced photodetector also offers the significant advantage of tunability across a limited range of optical channels with minimal performance impact. This feature allows multiple wavelength pairs to operate on the same ODN and is supported with a single SKU. The tunability, achieved by adjusting the thermal control on the DFB laser, is estimated to cover four 100 GHz channels at no extra cost for an external tuning unit. By deploying four OLT PON ports across these 4 x 100 GHz channels, the average data throughput for ONUs can be quadrupled, resulting in a cost per bit well beyond one-fourth that of symmetric 50G PON systems.

5 Wavelength coexistence and ODN architectures

5.1 PON wavelength overview

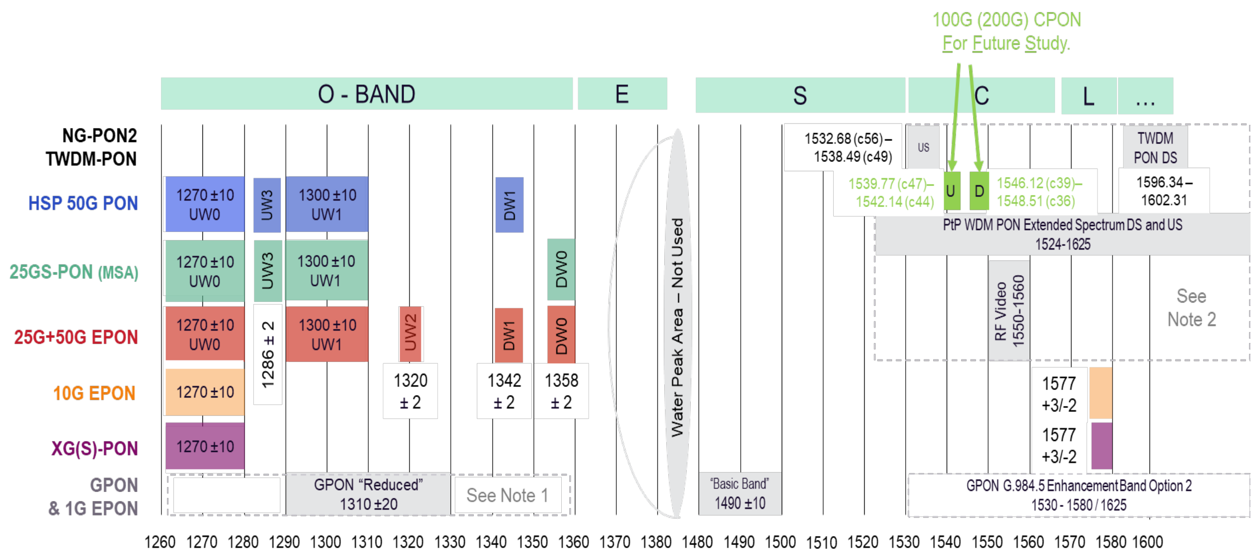

Figure 7. PON wavelengths

The coexistence of CPON with legacy PONs and DWDM is achieved through careful wavelength planning and allocation. By utilizing the 100 GHz grid, operators can repurpose existing DWDM-deployed passive infrastructure to support CPON solutions compliant with the ITU-T 694.1 100 GHz grid.[19] This approach maximizes fiber optic capacity while ensuring compatibility and interoperability with the existing infrastructure.

Wavelength standards in PONs have evolved significantly over the years. The original GPON standard (G.984.2), introduced in 2003, defined upstream lasers with a broad wavelength tolerance of ±50 nm, allowing for variability in laser performance but lacking precision in wavelength control. In 2004, the IEEE 1G EPON standard (802.3ah) aligned with GPON's wavelength specifications, using 1490 nm for downstream and 1310 nm for upstream, with upstream lasers also maintaining a ±50 nm tolerance.

In 2007, the GPON standard was updated (G.984.5), introducing more refined options for upstream wavelength tolerance. This included the original ±50 nm (regular), a reduced tolerance of ±20 nm, and a narrow tolerance of ±10 nm. Additionally, the update defined enhancement bands for downstream and upstream, as depicted in Figure 7: band 1, located in the water peak area (not shown), and band 2 (shown), aimed at improving wavelength precision and supporting advanced network configurations.

A significant advancement came in 2014 with the NG-PON2 standard (G.989 series), which incorporated TWDM-PON and point-to-point (P2P) WDM PON technologies. NG-PON2 defined eight channels for both downstream and upstream, arranged in downstream and upstream channel pairs, and introduced tunable ONTs and ONUs, enhancing flexibility and scalability in network deployments. This development supported more dynamic and high-capacity PON systems.

Recent advancements include the 25GS-PON and ITU-T 50G high-speed PON (HSP) technologies, which provide operators with the flexibility to select from three upstream wavelengths (UW0, UW1, UW3) and a single downstream option. These newer standards represent the ongoing evolution in wavelength management, expanding the options available for high-speed and high-capacity networks.

As PON technologies advance, challenges in wavelength management, particularly in the O-band (1260–1360 nm), become more complex. CPON technologies, which use 100 GHz DWDM channels, require careful management of the O-band to avoid disrupting existing PON technologies operating within this range. Efficient wavelength management is crucial to deploy CPON while still supporting legacy PONs.

The development of high-speed TWDM-PON PMD systems is likely to utilize NG-PON2 channels 5–8, facilitating high-capacity and high-speed data transmission. This approach integrates new technologies with existing infrastructure, reflecting the ongoing evolution of PON systems. Additionally, CPON aims to maximize the use of existing passive networks by leveraging 100 GHz DWDM channels, thus reducing the need for extensive new infrastructure. Operators can use unused RF video ports on existing customer equipment or build outside the video band if necessary, offering flexible and efficient integration of CPON technologies.

Overall, the progression of wavelength standards in PONs underscores continuous advancements in network performance and flexibility, highlighting the critical role of precise wavelength management in supporting both current and future technologies.

5.2 ODN introduction: Cost dynamics

The deployment of fiber for an ODN represents the most significant cost component of a PON. While selecting active electronics involves detailed technical analysis and negotiation, the expenses associated with trenching and boring fiber have a far greater impact on the cost per home passed, particularly in densely populated areas.

When constructing an ODN, operators must weigh trade-offs between coverage area and subscriber density as these factors directly influence the cost per home passed. A general rule of thumb is that aerial fiber is less expensive to deploy than buried fiber, making it a more cost-effective option where feasible. High-density suburban areas tend to be more economical to serve than sparsely populated rural areas due to the lower cost per subscriber.

In optimizing the ODN, operators should prioritize maximizing the optical budget by adjusting splitter ratios and network design rather than relying on remote active electronics. For instance, deploying a 1:32 splitter instead of a 1:64 splitter can recover optical budget, reducing the need for costly electronics in the field. Density is a critical consideration; deploying a chassis OLT that can support thousands of subscribers is not cost-effective in areas with only a few hundred potential customers. Additionally, the supporting backend infrastructure, such as multiple 10/100GE links for resiliency to an aggregation transport, adds further to the overall cost and must be carefully justified based on the expected subscriber base.

5.2.1 Maximizing reach with CPON

The advent of CPON technology presents a transformative opportunity for operators to extend their reach into new subscriber areas without the immediate need to deploy additional OLTs. By leveraging advanced DSP, CPON enhances signal processing, compensates for chromatic and polarization mode dispersion (CMD and PMD), and improves error correction, equalization, and signal recovery. These enhancements allow operators to extend the reach of the ODN far beyond traditional PON architectures.

In business case decisions, this extended reach can make previously marginal or unviable expansion areas economically feasible. The increased power-loss budget and improved CMD and PMD compensation enable longer fiber distances between the OLT and ONUs. This flexibility allows for a more balanced approach between the number of potential splits in the ODN and the increased distance of the fiber. Operators can strategically manage cable attenuation, additional connector and splice losses, and increased splitter port loss, ensuring a cost-effective and efficient network design. By extending the passive network rather than deploying new active components, operators can minimize incremental costs, enhance returns on investment, and achieve a more strategic balance between network performance, cost, and subscriber acquisition.

5.2.2 Reusing the ODN for multi-service applications

Beyond residential services, the reuse of the ODN to support a broader range of services, including mobility xHaul and enterprise business, is becoming an increasingly strategic approach for operators. By leveraging the existing fiber infrastructure, operators can deliver a unified service platform that caters to residential broadband as well as the needs of mobile networks and enterprise customers.

For mobility xHaul, the ODN can be utilized to provide backhaul, fronthaul, and midhaul connections for 4G, 5G, and future mobile network generations. This shared infrastructure approach allows for more efficient use of fiber resources and reduces the need for deploying separate networks for different service types. The “remote device” documented in Figure 9, “WDM and CPON: ODN coexistence with DWDM”, could be a radio unit (RU), distribution unit (DU), or a switch in an enterprise or regional office, depending on the specific service being supported. Similarly, the ODN can be extended to offer high-capacity, low-latency connections required by enterprise businesses. This includes providing dedicated fiber access, point-to-point Ethernet services, and other business-critical connectivity solutions. By consolidating residential, mobile, and enterprise services onto a single ODN, operators can maximize the return on their infrastructure investment, streamline network management, and enhance the overall service offering to a diverse customer base.

5.2.3 Integrating DWDM and CPON for optimized service delivery

Incorporating DWDM technology with 100 GHz channel spacing into the ODN offers a compelling solution for mixing P2P connections with CPON for other applications. DWDM allows for the transportation of high-capacity, dedicated wavelength services, which are particularly valuable for enterprise customers and mobility backhaul. These customers generally have a higher willingness to pay for premium, low-latency, and high-reliability services, making the business case for network expansion more attractive.

By utilizing DWDM for P2P connections, operators can effectively segment high value enterprise and mobility traffic while still using CPON to deliver broadband services. This approach enables operators to generate higher revenue per fiber strand while simultaneously expanding their service footprint. The revenue from enterprise and mobility services can help subsidize the cost of extending the network into underserved residential areas, making it possible to reach more customers with minimal incremental cost.

This integrated strategy of combining DWDM and CPON within the same ODN enhances the overall network efficiency and provides a flexible, scalable platform capable of meeting diverse service requirements. It allows operators to optimize their infrastructure investment, tapping into new revenue streams while ensuring that residential, enterprise, and mobility needs are met with the appropriate service levels.

5.3 The flexibility of the ODN

ODNs offer remarkable flexibility, making them highly adaptable to changing network demands and technological advancements. This flexibility is evident in several key aspects of ODN design and implementation:

- Support for various splitter configurations: ODNs can utilize both balanced and unbalanced splitters to meet diverse network requirements.
    - Balanced splitters, such as 1 x 8 or 1 x 16 splitters, distribute the optical signal evenly among all output ports, ensuring uniform signal strength across all branches. This uniform distribution simplifies network design, particularly when equal performance is desired across multiple endpoints.
    - Conversely, unbalanced splitters allow for customized power distribution, which can be optimized based on specific needs such as varying distances or subscriber densities. By allocating more power to certain branches or segments, unbalanced splitters can enhance performance and cost efficiency, reducing the need for additional active electronics in the network.

- Single or cascaded splitters: The flexibility of ODNs extends to the configuration of splitters. Operators can choose to deploy a single splitter or cascade multiple splitters, depending on the optical budget and network design requirements. Single splitters are ideal for shorter reaches or lower subscriber densities, providing a straightforward solution with minimal signal loss. For more extensive networks requiring longer reaches or higher capacity, cascading multiple splitters allows for broader signal distribution. This approach enables scalable network design while carefully managing signal attenuation to maintain optimal performance across all segments.

- Compatibility with multiple PON technologies: ODNs are designed to accommodate multiple PON technologies simultaneously. By incorporating coexistence elements and blocking filters within ONUs, ODNs can prevent interference from different wavelengths, facilitating the concurrent operation of various PON standards. This capability ensures that network operators can deploy and manage multiple PON technologies, such as GPON and XGS-PON, within the same infrastructure without compromising performance.

- Adaptability to emerging technologies: One of the significant advantages of ODNs is their ability to support new and unforeseen PON technologies without necessitating major infrastructure changes. This adaptability means that as new PON technologies emerge, such as next-generation solutions beyond XGS-PON, they can be integrated into the existing ODN framework without requiring a complete overhaul of the fiber or splitter components.

- Support for next-generation PONs: It is crucial for ODNs to be backward-compatible, allowing for the coexistence of older and newer PON generations within the same network. This requirement ensures that advanced PON systems can be integrated seamlessly while maintaining service continuity for existing deployments. Such backward compatibility is vital for operators looking to upgrade their networks incrementally.

- Scalability for increasing broadband demands: ODNs have demonstrated their capacity to keep pace with rising broadband speed requirements. As demand for higher speeds continues to grow, ODNs can accommodate these needs by integrating higher-speed PON technologies, thus evolving to meet new performance and capacity benchmarks without substantial infrastructure modifications.

ODNs are essential for modern telecommunications, allowing operators to adapt to evolving technologies and deployment scenarios. ODNs support multiple PON technologies, accommodate varying service demands, and ensure long-term viability, making them crucial for optimizing network performance and meeting future requirements.

The integration of different PON technologies within a single ODN is exemplified in Section 6, “Coexistence and service differentiation in an ODN with CPON.” This section explores how CPON can facilitate the coexistence of various PON standards, including GPON, XGS-PON, 25G-PON, 50G-PON, and 100G CPON. By utilizing a CE to manage wavelength separation and a splitter to provide signal distribution, this setup enables multiple PON technologies to operate efficiently within the same network infrastructure.

Section 7, “Coexistence of DWDM and CPON in a shared WDM infrastructure” delves into the integration of DWDM with CPON. This section highlights how the ITU-T 100 GHz channel plan and WDM filters are employed to manage high-capacity data transmission. The central location and field WDM filters work together to separate and combine wavelengths, while the remote PHY device (RPD) bridges the DWDM fiber and coaxial networks. This approach enhances the network’s capacity and performance, supporting a broad range of services and technologies.

In modern PON architectures, cascaded splitter designs play a pivotal role in optimizing network coverage and scalability. Sections 8 and 9 explore the application of these designs within different deployment scenarios. Section 8, “Cascaded residential ODN for plant coverage,” focuses on broader coverage across multiple PON serving areas (PSAs), emphasizing efficient utilization of the ODN. Meanwhile Section 9, “Cascaded residential ODN for MDU coverage”, delves into the specific use case of multi-dwelling units (MDUs), highlighting how cascaded splitters and small, power-efficient OLTs can streamline infrastructure while maintaining high service quality.

Sections 6 through 9 demonstrate the ODN’s capacity to support diverse PON technologies and network configurations. Section 6 covers the coexistence of PON standards within a unified ODN, while Section 7 examines the integration of DWDM with CPON. Sections 8 and 9 highlight cascaded splitter designs for broader coverage and optimized MDU deployment. These sections collectively emphasize the ODN’s adaptability and effectiveness in meeting current and future.

6 Coexistence and service differentiation in an ODN with CPON

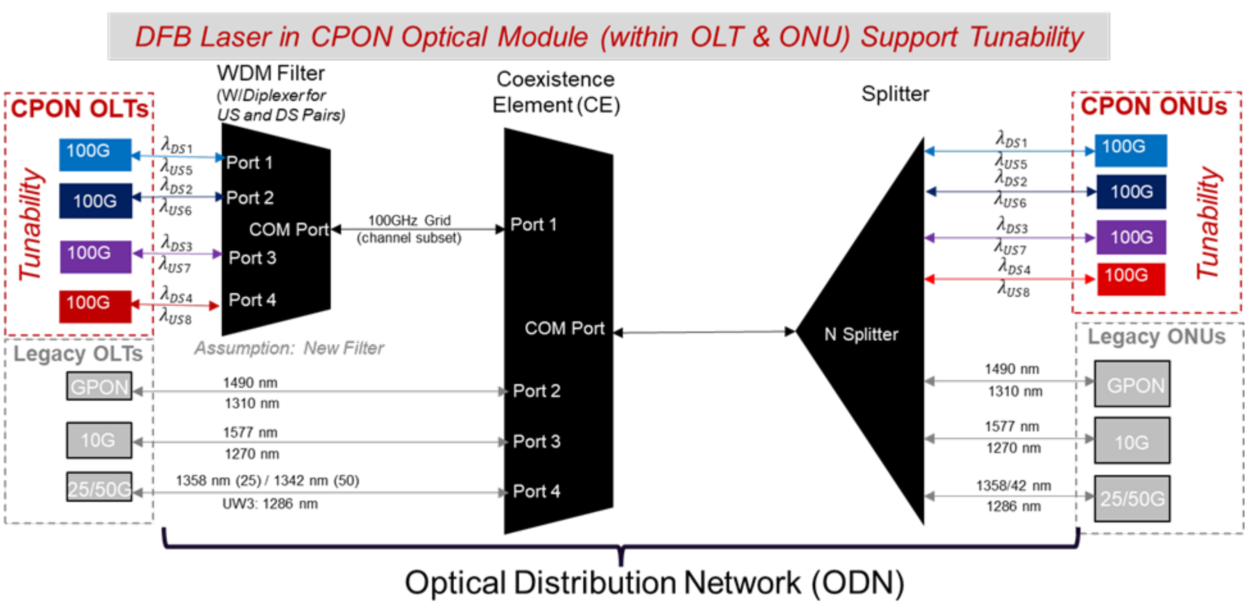

Figure 8. PON coexistence with single-splitter ODN

The figure illustrates an example deployment of CPON and ODN architecture that supports a wide range of services, including residential, enterprise, and mobility front, mid, and backhaul. This architecture highlights the integration of CPON OLTs alongside legacy OLTs, demonstrating the ability of CPON to coexist with GPON, 10G-PON, and emerging 25/50G-PON technologies.

In the context of CPON, supporting multiple PON technologies within a single ODN is crucial for operators in maintaining network efficiency and adaptability. A typical CPON setup must accommodate diverse PON specifications, such as GPON, XGS-PON, 25GS-PON, 50G-PON, and 100G CPON. To achieve this, a CE is employed to manage the combination and separation of various wavelength channels associated with each PON technology. The CE ensures that different wavelengths do not interfere with each other, allowing multiple PON technologies to operate simultaneously across the same ODN.

The CE could be located at a central location closest to the OLTs to reduce feeder fiber costs. It would be equipped with ports dedicated to both CPON wavelengths (denoted as λ_DS and λ_US pairs) and legacy PON wavelengths. This design enables the CE to manage up to four CPON wavelength pairs, supporting different services by assigning specific wavelength pairs to various OLT ports.

Each CPON OLT operates at 100G and can serve different types of services, including MDU, mobility fronthaul, midhaul, enterprise, and mobility backhaul. The wavelength pairs (λ_DS1/λ_US5, λ_DS2/λ_US6, etc.) are allocated based on the specific service type, ensuring efficient service differentiation and optimal performance across the ODN. For example:

- Port 1 utilizes a 100G wavelength pair (λ_DS1/λ_US5) to provide MDU services alongside GPON wavelengths for residential broadband.
- Port 2 is dedicated to mobility fronthaul with another 100G wavelength pair (λ_DS2/λ_US6).
- Port 3 supports enterprise services with its own dedicated 100G wavelength pair (λ_DS3/λ_US7).
- Port 4 serves additional mobility fronthaul needs, with wavelengths assigned accordingly.

Within the ODN, the splitter plays a pivotal role. It distributes optical signals evenly across all output ports without altering the wavelength allocation. This uniform distribution ensures that each PON technology receives equal optical power, which is essential for maintaining consistent performance and service quality across the network.

The CE also includes ports dedicated to legacy OLTs, which handle GPON and 10G-PON services, ensuring backward compatibility. Figure 8 shows how these legacy wavelengths (e.g., 1490 nm, 1310 nm for GPON, 1577 nm, and 1270 nm for 10G-PON) are seamlessly integrated into the overall ODN structure. This allows operators to continue supporting legacy services while gradually transitioning to CPON-based high-capacity networks.

This example showcases the flexibility and scalability of CPON and ODN. The integration with legacy PON technologies, coupled with wavelength management and the uniform distribution of optical signals through splitters, positions CPON as a key enabler for next-generation services.

7 Coexistence of DWDM and CPON in a Shared WDM Infrastructure

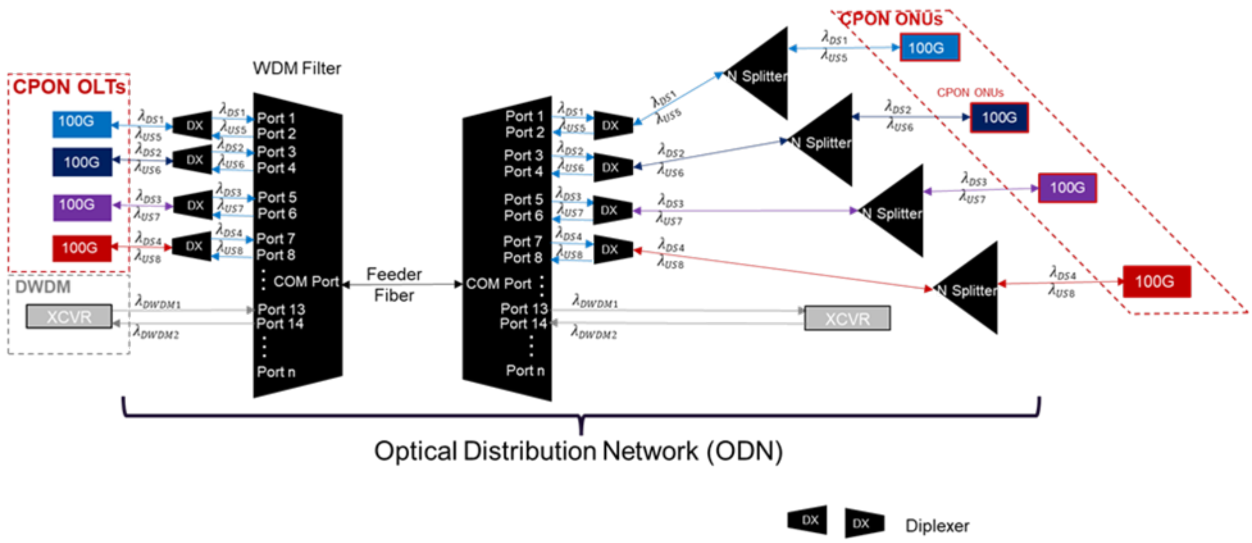

Figure 9. WDM and CPON: ODN coexistence with DWDM

7.1 Overview of DWDM and CPON system integration

The integration of the CPON system within a shared WDM infrastructure represents a critical advancement in optimizing fiber resource utilization and expanding network capabilities. This architecture, as illustrated, leverages the ITU-T 100 GHz channel plan, which provides a standardized framework for managing multiple wavelength channels on a single fiber, thereby maximizing fiber capacity and supporting a diverse array of services across both P2P and P2MP configurations.

7.2 Strategic role of WDM filters in channel management

WDM filters are central to the successful integration of DWDM with CPON systems, playing a crucial role in the precise separation and combination of optical signals across various wavelengths. These filters ensure that each channel is accurately routed through the network, minimizing signal interference and maintaining the integrity of the transmitted data. At the network's central hub, WDM filters are tasked with the critical function of managing both incoming and outgoing wavelength channels, ensuring efficient routing and preventing any potential cross-channel interference.

In a shared WDM infrastructure, the dual management of DWDM and CPON wavelengths places additional demands on WDM filters. For DWDM P2P circuits, these filters must achieve high isolation and minimal insertion loss to ensure that each wavelength channel remains distinct and uncorrupted. In contrast, for CPON P2MP circuits, the filters must efficiently combine multiple wavelength channels into a single fiber path, maintaining high performance and minimizing any degradation in signal quality.

7.3 Integration and optimization of P2P DWDM circuits

DWDM P2P circuits are integral to the high-capacity connections between MDU OLT and the operator's central network. These circuits utilize the extensive channel capacity provided by DWDM to deliver high-speed, reliable fiber broadband access, which is essential for bandwidth-intensive applications such as enterprise services, high-speed internet, and low-latency connectivity required for emerging technologies like 5G.

The integration of DWDM P2P circuits with CPON P2MP circuits requires meticulous planning to avoid any detrimental interference and to ensure peak performance across all services. Effective channel planning and the strategic use of WDM filters are necessary to separate DWDM channels from CPON channels, thus preventing crosstalk and ensuring the integrity of all transmitted data.

7.4 Leveraging CPON P2MP circuits within DWDM infrastructure

The CPON system's deployment within the DWDM infrastructure allows for the efficient delivery of multiple P2MP circuits over a single fiber, significantly enhancing network scalability and resource efficiency. By utilizing the 100 GHz channel plan, operators can support high-density splitter ratios, enabling the efficient management of a vast number of subscriber connections. This capability is particularly beneficial in densely populated urban environments where maximizing fiber utility is essential.

The coexistence of CPON P2MP circuits with DWDM P2P circuits requires the design of highly specialized WDM filter configurations. These filters must adeptly combine and split CPON wavelengths while preserving high channel density and ensuring that performance remains uncompromised. This careful engineering ensures that CPON systems can fully exploit the DWDM infrastructure's capacity, providing reliable, high-quality service to a broad base of end-users.

7.5 Practical considerations and strategic benefits

The integration of DWDM with CPON in a shared WDM infrastructure yields substantial operational and strategic benefits:

- Maximized fiber utilization: By channeling both P2P and P2MP circuits through DWDM, operators can achieve near-complete utilization of available fiber resources, thereby significantly reducing the need for costly and time-consuming additional fiber deployments.

- Enhanced network scalability: DWDM's inherent flexibility allows for seamless network capacity expansion, enabling services and subscribers to be added without major infrastructure changes, thus supporting long-term growth.

- Operational flexibility: A shared WDM infrastructure provides a versatile and adaptable platform for deploying a wide range of services, including high-speed internet, enterprise-level connectivity, and advanced mobility solutions. This flexibility is crucial for meeting the evolving demands of a diverse customer base while maintaining a unified and efficient network architecture.

- Sustainability and efficiency: By transitioning from Ethernet switches that require a dedicated transceiver for each customer to a PON, operators can significantly reduce energy consumption and electronic waste. The passive nature of PONs, which rely on optical splitters instead of active components like switches, minimizes the need for power-hungry equipment, contributing to a more sustainable and efficient network infrastructure.

This integrated DWDM-CPON architecture enhances the technical capabilities of fiber networks and positions operators to efficiently scale and adapt their infrastructure to meet future demands, ensuring long-term sustainability and competitiveness in the rapidly evolving telecommunications landscape.

8 Cascaded residential ODN for plant coverage

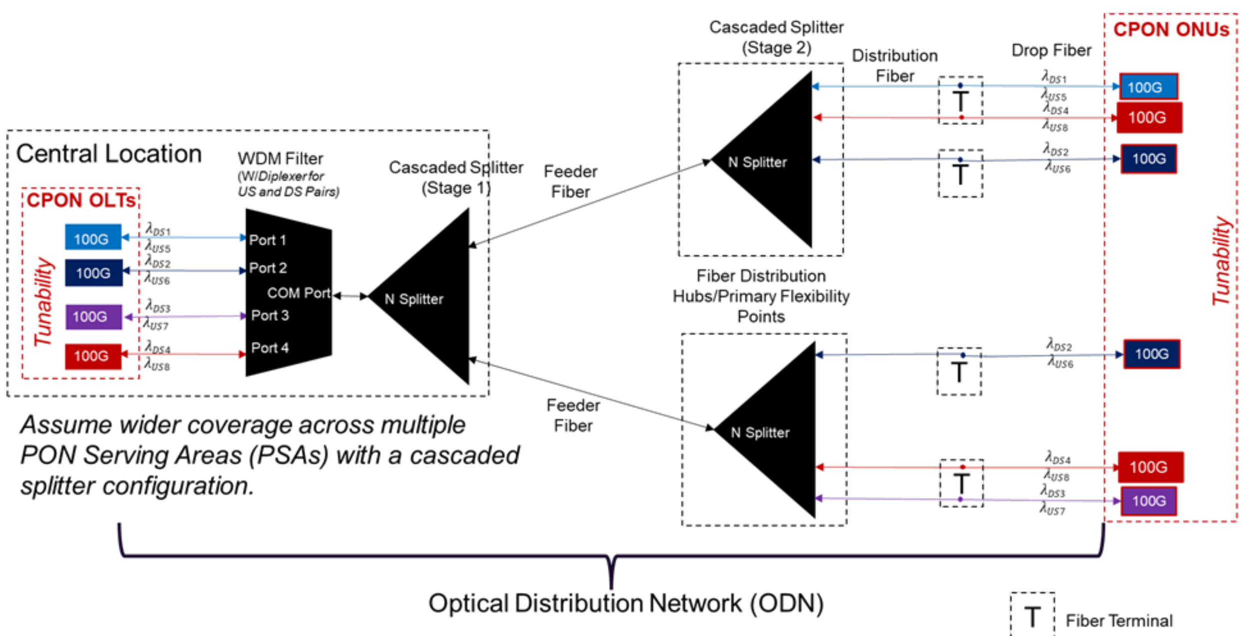

Figure 10. Cascaded residential ODN for plant coverage

Figure 10 illustrates a CPON architecture that employs a cascaded splitter design to achieve broader coverage across multiple PSAs. This architecture focuses on more efficient use of the ODN rather than just saving feeder fiber. The key components of the design are:

8.1 Central location

- **CPON OLTs:** These OLTs support 100G speeds and handle wavelength pairs for both upstream (US) and downstream (DS) traffic. Figure 10 emphasizes the tunable nature of the OLTs, offering flexibility in managing various wavelength pairs.
- **WDM filter:** A WDM filter is used to manage and separate wavelength pairs (both US and DS) as they are distributed throughout the network.
- **Stage 1 splitter:** The WDM filter output is connected to a stage 1 splitter, which further distributes the optical signal across multiple feeder fibers.

8.2 Field deployment

- **Stage 2 splitter:** After the feeder fibers, the optical signal is further divided by a stage 2 splitter located closer to the end-users (in distribution hubs or primary flexibility points). This additional splitting enables the CPON system to cover a wider geographic area.
- **Distribution and drop fibers:** These fibers extend from the stage 2 splitter to the end-user ONUs.
- **Fiber terminals:** Represented by “T” in Figure 10, these terminals connect the distribution fibers to the final drop fibers leading to the ONUs.

8.3 Key points

- **Coverage focus:** This design prioritizes broader coverage over merely optimizing feeder fiber usage. The cascaded splitter approach with multiple stages effectively serves multiple PSAs.
- **Scalability:** The architecture is scalable, allowing more end-users to be connected with fewer OLT PON ports by cascading splitters across wider areas.
- **Wavelength management:** The WDM filter and tunable OLTs are crucial for efficiently managing multiple wavelength pairs, ensuring high-performance service across a large network.

This PON architecture example demonstrates how to extend coverage by leveraging a flexible, scalable ODN that improves utilization per PON port, ultimately reducing the number of PON ports required at the central location. It also provides a perspective that goes beyond simply minimizing feeder fiber usage.

9 Cascaded residential ODN for MDU coverage

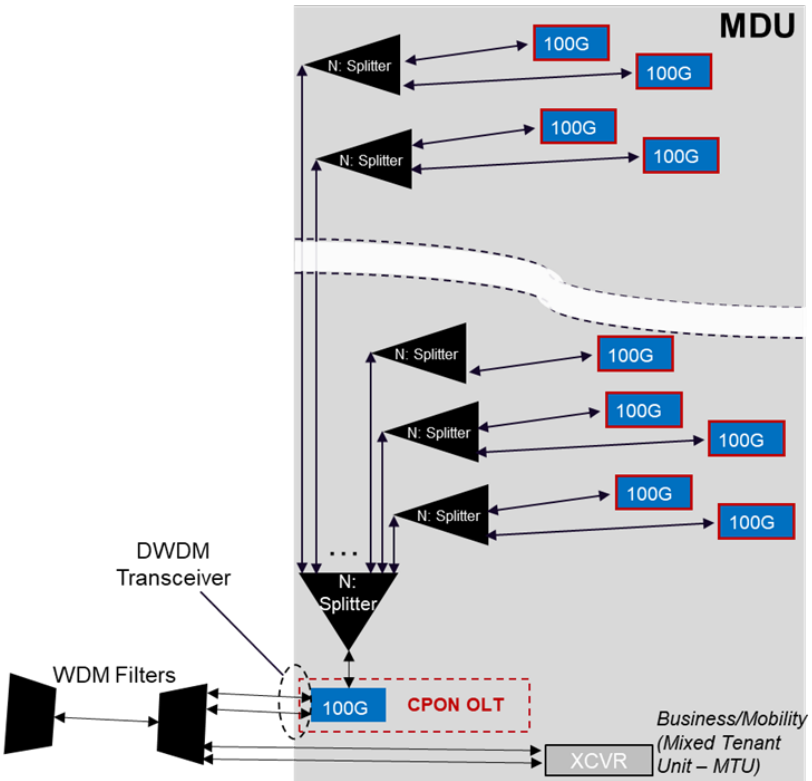

Figure 11. CPON MDU ODN

9.1 Overview

Building upon earlier discussions of PON coexistence, WDM integration with CPON, and cascaded splitters, this section focuses on the deployment of an ODN within MDUs using high splitter ratios, such as 1:256. This setup is important to efficiently deliver broadband services within an MDU. CPON technology plays a key role in managing these high splitter ratios while ensuring service quality.

The use of a WDM filter before the MDU OLT allows for the integration of P2P DWDM circuits, enabling the network to support various services, including those for remote devices, businesses, and wireless applications on the property.

9.2 Key considerations

All passive design:

- **Primary splitter at main distribution frame (MDF):** The primary splitter is in the MDF, where the optical signal is divided into multiple paths.

- **Intermediate distribution frames (IDFs):** Additional splitters are placed in the IDFs on each floor to further distribute the signal, as indicated in Figure 11.

- **Reduced fiber runs:** The cascading splitter design minimizes the number of fiber runs needed from the MDF to individual units, reducing installation complexity and costs.

9.3 Benefits

- **Simplified installation:** The cascading splitter architecture reduces the number of fiber runs, streamlining installation and lowering both labor and material costs.

- **Lower infrastructure costs:** The reduced need for fibers and active components translates into significant cost savings.

- **Enhanced reliability:** The use of passive components, which are less prone to failure and require minimal maintenance, enhances overall network reliability.

9.4 Role of CPON technology

- **High data rates:** CPON technology supports high data rates even with significant splitter ratios, maintaining service quality for large numbers of subscribers while reducing the footprint and power requirements of the OLT in the MDU.

- **Increased sensitivity and dynamic range:** CPON systems, with high-sensitivity receivers, can detect weaker signals and operate over a wide dynamic range, effectively managing the attenuation caused by high splitter ratios.

- **Enhanced flexibility:** WDM integration adds flexibility, allowing the network to support diverse applications and future upgrades. This includes both DWDM P2P circuits directly to end-users and DWDM P2P circuits feeding the OLT.

9.5 Benefits of a small OLT deployment

9.5.1 Power efficiency

- **Lower power consumption:** The deployment of a small 1–2 port OLT, as illustrated in Figure 11, significantly reduces power consumption compared to larger units, leading to cost savings and a reduced environmental impact.

- **Backup power solutions:** Compact backup power systems, such as small uninterruptible power supplies (UPS) or batteries, can effectively support a mini-OLT, ensuring compliance with regulatory reserve power requirements.

- **Compact design for space efficiency:** The small footprint of the mini-OLT allows for installation in confined spaces, such as telecom closets or utility rooms within the MDU.

This streamlined architecture ensures cost-effective deployment and enhances the scalability and reliability of fiber broadband access in MDUs, accommodating high service demand with minimal infrastructure.

10 Conclusion: Future-proofing fiber networks with 100G CPON

As fiber broadband access continues to evolve, operators are under increasing pressure to deliver higher bandwidth and support more diverse services while keeping costs under control. CPON technology presents a forward-looking solution, particularly in the context of existing, brownfield deployments. By integrating 100G CPON into established networks, operators can significantly enhance their service capabilities without the need for extensive infrastructure overhauls.

In brownfield scenarios, the ability to augment rather than replace the outside plant (OSP) infrastructure is a critical advantage. 100G CPON enables operators to upgrade their networks by annexing new capabilities to existing ODNs. This process involves meticulous link budget planning and optical budget optimization to ensure that 100G services can be delivered effectively, even with higher split ratios and extended reach, thus maximizing the use of current fiber resources.

While ITU-T is still investigating the technologies for 100G CPON, ongoing standardization efforts at CableLabs and ITU-T SG15/Q2 are positioning CPON as a versatile and cost-efficient technology for both residential and business applications. The tunability and potential cost advantages of CPON make it an attractive option, particularly as the market for coherent optics expands.

Notably, 100G CPON is expected to offer significant cost savings over symmetric 50G PON, with up to 50% lower cost per bit per second, thanks to its tunable, low-cost coherent optics design. This efficiency, combined with its ability to extend network reach and enhance service flexibility, positions CPON as a leading technology for future-proof fiber networks.

In addition to its cost benefits, CPON's ability to support multi-service applications through the reuse of existing infrastructure and the integration of WDM further highlights its potential. For instance, in scenarios like MDUs with cascaded splitters, CPON overcomes traditional limitations related to split ratios and network reach. This ensures that passive fiber networks can be simplified, yet powerful enough to meet the growing demand for high bandwidth and varied services.

100G CPON represents a significant advancement in the PON architecture. It optimizes the ODN by enhancing wavelength coexistence, extending network reach, and maintaining cost-effective service delivery. By enabling operators to future-proof their networks, 100G CPON offers a versatile, efficient, and cost-effective solution that is set to drive the future of fiber access networks.

Acronyms

ADC	analog-to-digital converter
AI	artificial intelligence
APON	asynchronous transfer mode passive optical network
ASIC	application-specific integrated circuits
ATM	asynchronous transfer mode
BBF	broadband forum
BPON	broadband passive optical network
CE	coexistence element
CloudCO	Cloud Central Office
CMD	chromatic mode dispersion
CPON	coherent passive optical network
DAC	digital-to-analog converter
DFB	distributed feedback
DML	directly modulated laser
DS	downstream
DSP	digital signal processor
DU	distribution unit
DWDM	dense wavelength division multiplexing
EML	externally modulated laser
EDFA	erbium-doped fiber amplifiers
EPON	ethernet passive optical network
FEC	forward error correction
FSAN	Full Service Access Network
GPON	gigabit passive optical network
HSP	high-speed PON
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IDF	intermediate distribution frames
IM-DD	intensity modulation-direct detection
IOP SI	interoperability
ISI	inter-symbol interference
I/Q	in-phase and quadrature
ITU-T	International Telecommunication Union Telecommunication Standardization Sector
LDPC	low-density parity-check
MAC	media access control
MDF	main distribution frame
MDU	multiple dwelling unit
MEs	managed entities

MSA	multi-source agreement
MTTR	mean time to repair
MULPI	MAC and upper layer protocol interface
ODN	optical distribution network
OLT	optical line terminal
OMCI	optical network termination management control interface
ONU	optical network unit
OSNR	optical signal-to-noise ratio
OSP	outside plant
P2MP	point-to-multipoint
P2P	point-to-point
PDU	protocol data units
PMD	physical media dependent
PON	passive optical network
PHY	physical layer
PMD	polarization mode dispersion
PSA	PON serving area
QAM	quadrature amplitude modulation
QPSK	quadrature phase shift keying
QSFP-28	quad small form-factor pluggable 28
QSFP-DD	quad small form-factor pluggable double density
SG15/Q2	Study Group 15 Question 2 (ITU-T)
RF	radio frequency
RPD	remote PHY device
RU	radio unit
SLA	service level agreement
SMB	small-to-medium business
SOA	semiconductor optical amplifiers
TC	transmission control
TDM	time-division multiplexing
TDMA	time-division multiple access
TR	technical requirement
TWDM	time and wavelength division multiplexing
UPS	uninterruptible power supply
US	upstream
vBG	virtual business gateway
WDM	wavelength division multiplexing
XGS-PON	10 gigabit symmetric passive optical network

Table 1. Acronyms

References

[1] ITU-T, G.983.1 (Amendment 1), “Broadband optical access systems based on passive optical networks,” https://www.itu.int/rec/dologin_pub.asp?lang=e&id=T-REC-G.983.1-200505-I!Amd1!PDF-E&type=items, May 2005.

[2] ITU-T, G.983.2, “ONT management and control interface specification for B-PON” (Incorporates G.983.6 thru G.983.10), https://www.itu.int/rec/dologin_pub.asp?lang=e&id=T-REC-G.983.2-200507-I!!PDF-E&type=items, July 2005.

[3] ITU-T, G.983.3 (Amendment 2), “A broadband optical access system with increased service capability by wavelength allocation,” https://www.itu.int/rec/dologin_pub.asp?lang=e&id=T-REC-G.983.3-200507-I!Amd2!PDF-E&type=items, July 2005.

[4] ITU-T, G.983.4 (Corrigendum 1), “A broadband optical access system with increased service capability using dynamic bandwidth assignment,” https://www.itu.int/rec/dologin.asp?lang=e&id=T-REC-G.983.4-200501-I!Cor1!PDF-E&type=items, January 2005.

[5] ITU-T, G.983.5, “A broadband optical access system with enhanced survivability,” https://www.itu.int/rec/dologin_pub.asp?lang=e&id=T-REC-G.983.5-200201-I!!PDF-E&type=items, January 2002.

[6] ITU-T, G.984.1, “Gigabit-capable passive optical networks: General characteristics,” https://www.itu.int/rec/dologin_pub.asp?lang=e&id=T-REC-G.984.1-200303-S!!PDF-E&type=items, March 2003.

[7] ITU-T, G.984.2, “Gigabit-capable passive optical networks: Physical media dependent layer specification,” https://www.itu.int/rec/dologin_pub.asp?lang=e&id=T-REC-G.984.2-200303-S!!PDF-E&type=items, March 2003.

[8] ITU-T, G.984.3, “Gigabit-capable passive optical networks: Transmission convergence layer specification,” https://www.itu.int/rec/dologin_pub.asp?lang=e&id=T-REC-G.984.3-200402-S!!PDF-E&type=items, February 2004.

[9] IEEE, IEEE Std 802.3, “IEEE Standard for Ethernet,” https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9844436, July 2022.

[10] ITU-T, G.987.1, “10-gigabit-capable passive optical networks: General requirements,” https://www.itu.int/rec/dologin_pub.asp?lang=e&id=T-REC-G.987.1-201603-I!!PDF-E&type=items, March 2016.

[11] ITU-T, G.987.2 (Amendment 1), “10-gigabit-capable passive optical networks: Physical media dependent layer specification,” https://www.itu.int/rec/dologin_pub.asp?lang=e&id=T-REC-G.987.2-202306-I!Amd1!PDF-E&type=items, June 2023.

[12] ITU-T, G.987.3 (Amendment 2), “10-gigabit-capable passive optical networks: Transmission convergence layer specification,” https://www.itu.int/rec/dologin_pub.asp?lang=e&id=T-REC-G.987.3-202105-I!Amd2!PDF-E&type=items, May 2021.

[13] ITU-T, G.989.1 (Amendment 1), “40-gigabit-capable passive optical networks: General requirements,” https://www.itu.int/rec/dologin_pub.asp?lang=e&id=T-REC-G.989.1-201303-I!!PDF-E&type=items, March 2013.

[14] ITU-T, G.9807.1 (Amendment 2), "10-gigabit-capable symmetric passive optical network," https://www.itu.int/rec/dologin_pub.asp?lang=e&id=T-REC-G.9807.1-202302-I!!PDF-E&type=items, February 2023.

[15] ITU-T, G.9804.1 (Amendment 2), "Higher speed passive optical networks: Requirements," https://www.itu.int/rec/dologin_pub.asp?lang=e&id=T-REC-G.9804.1-202401-I!Amd2!PDF-E&type=items, January 2024.

[16] ITU-T, G.9804.2 (Amendment 1), "Higher speed passive optical networks: Common transmission convergence layer specification," https://www.itu.int/rec/dologin_pub.asp?lang=e&id=T-REC-G.9804.2-202302-I!Amd1!PDF-E&type=items, February 2023.

[17] ITU-T, G.9804.3 (Amendment 2), "50-gigabit-capable passive optical networks: Physical media dependent layer specification," https://www.itu.int/rec/dologin_pub.asp?lang=e&id=T-REC-G.9804.3-202403-I!Amd2!PDF-E&type=items, March 2024.

[18] 25GS-PON MSA Group, "25GS-PON specification: 25 gigabit symmetric passive optical network, version 3.0," https://www.25gspon-msa.org/wp-content/uploads/2023/11/25GS-PON-Specification-V3.0.pdf, November 2, 2023.

[17] CableLabs, "Coherent passive optical networks 100 Gbps single-wavelength PON: Coherent PON architecture specification (CPON-SP-ARCH-I01-230503)," https://account.cablelabs.com/server/alfresco/25300435-87c8-407d-9ab0-722287c7c7a6, May 3, 2023.

[18] ITU-T, G.652, "Characteristics of a single-mode optical fibre and cable," https://handle.itu.int/11.1002/1000/16060, November 13, 2016.

[19] ITU-T, G.694.1, "Spectral grids for WDM applications: DWDM frequency grid," https://www.itu.int/rec/dologin_pub.asp?lang=e&id=T-REC-G.694.1-202010-I!!PDF-E&type=items, October 2020.

[20] Boyd, E. W., Bender, J., Noll, K., & Harley, J. "What could you do with 100 Gbps coherent PON?" SCTE TechExpo24 paper, 2024.

[21] Dell'Oro Group. "95G16 AR coherent optics forecast tables," https://www.delloro.com/advanced-research-report/coherent-optics/ 4Q, 2023.