Coherent Passive Optical Networks
100 Gbps Single-Wavelength PON

Coherent PON Physical Media Dependent Layer 1.0 Specification

CPON-SP-PMDv1.0-I01-251216

ISSUED

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Trademarks

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1 SCOPE

1.1 Introduction and Purpose

This specification is part of the Coherent Passive Optical Network (CPON) family of specifications developed by Cable Television Laboratories (CableLabs). This specification is one of a series that defines the first generation of CPON systems, or CPON 1.0. These specifications enable the development of interoperable optical network units (ONUs) and optical line terminals (OLTs) using coherent optical technology over point-to-multipoint (P2MP) links. This specification was developed for the benefit of the cable industry and includes contributions by operators and manufacturers from North and South America, Europe, Asia, and other regions.

This specification defines the physical media dependent (PMD) layer requirements for ONUs and OLTs operating at 100 gigabits per second (Gbps) over a P2MP optical distribution network (ODN). It is designed to support both long fiber links of up to 80 km with lower split ratios of around 1:16 and shorter fiber links with higher split ratios of around 1:512.

1.2 Background

1.2.1 Motivation

Today's world relies heavily on a fast and reliable exchange of information. Ever-increasing demands for higher data rates continue to exceed currently installed system capacity. To date, passive optical network (PON) technologies have been one of the dominant architectures to meet the growth in capacity demand for the end users. As the PON evolves toward a data rate of 100 Gbps or higher, PON technologies based on intensity modulation–direct detection (IM-DD) have been pushed to their limit to accommodate the fast-growing demands. In contrast, coherent optical technology is a very promising solution for 100 Gbps single wavelength PON because of its superior performance and vast potential.

Coherent optics technology is common in submarine, long-haul, and metro networks, but it has not yet been widely applied to access networks because of the relatively high cost of the technology for those applications. However, the access network differs from the other types of networks in the following ways:

- is typically less than 80 km, much shorter than long-haul links;
- has lower transmission impairments because of the shorter link distance;
- uses fixed-wavelength passive optical components; and
- typically extends from temperature-controlled environments to the field, where there are no temperature control facilities.

With these differences, the capabilities, performance, and features of transceivers can be relaxed in areas such as

- optical output power levels,
- transmitter wavelength tunability,
- fiber chromatic dispersion compensation,
- laser linewidth, and
- transmitter optical signal-to-noise ratio (OSNR).

As a result, access networks can use cost-optimized designs and components relative to metro and long-haul networks. In a PON application, coherent optics can enhance optical power distribution, improve power/bit consumption, and provide longer link distances and/or high split ratios beyond what existing PON technologies allow. The improved power budget of coherent optics in a PON application can effectively compensate for linear transmission impairments such as chromatic dispersion (CD) and polarization mode dispersion (PolMD). It also facilitates advanced capabilities, including out-of-band (OOB) communication channel, frequency-division multiplexing, and efficient spectrum use by supporting single wavelength data rates of 100 Gbps and higher. Introducing coherent optics into the access network opens new possibilities for cable operators, telecommunication service providers, and data center operators. This CPON initiative aims to deliver these benefits in an economically viable, cost-optimized manner.

1.2.2 Service Goals

A CPON system features symmetric data rates of 100 Gbps over a single wavelength. More significantly, it features an optical power budget of 35 dB, which enables long link distances up to 80 km (with a 1:16 split ratio) or high-split ratios up to 1:512 (with a 20-km link distance). It also supports coexistence with any existing fiber-based technology (such as legacy PON systems or wavelength-division multiplexing [WDM] point-to-point links) and the ability to stack multiple CPON wavelengths on a single fiber by using WDM.

Taken together, these features allow for dramatically enhanced deployment flexibility across a wide variety of scenarios, ranging from high-density interconnect in a densely populated urban area to low-density deployments over wide areas. They also support a wide range of applications, both those known today and the high-bandwidth, low-latency applications of the future. Additionally, given that some of these applications may be critical in nature, a redundancy mechanism to protect against OLT failure and feeder fiber failure is defined.

Figure 1 shows an example of multiple CPON wavelengths on a single fiber link to support mixed use cases or applications simultaneously.

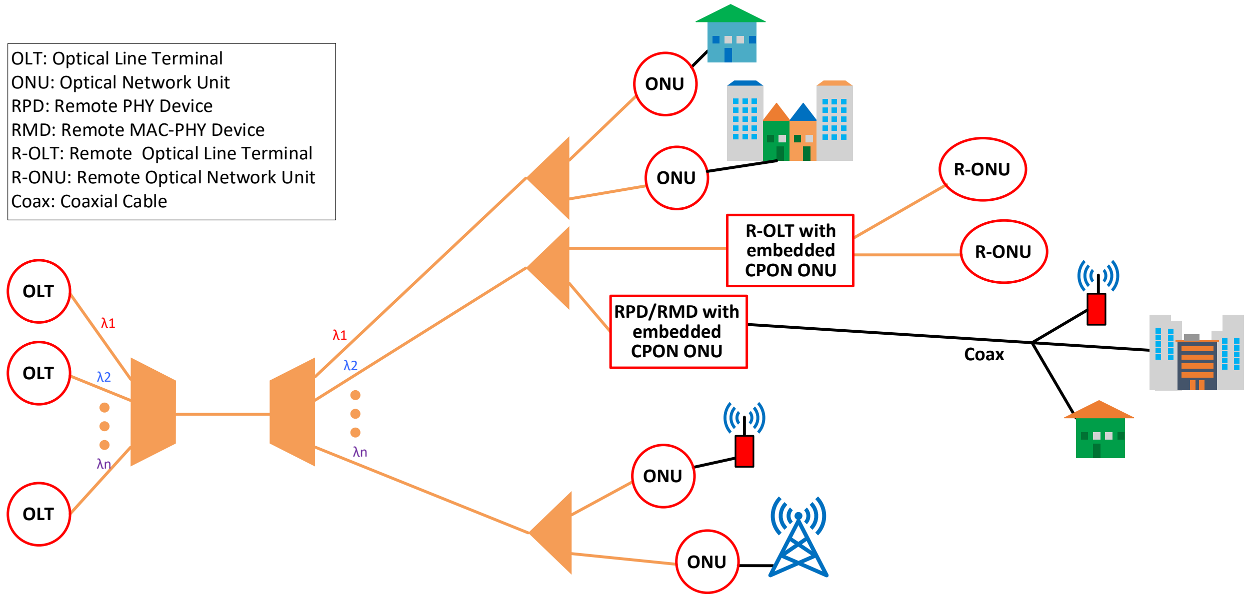

Figure 1 - CPON with WDM Supporting Various Applications

1.2.3 CPON 1.0 Documents

A list of the specifications in the CPON 1.0 series is provided in Table 1. For further information, please refer to https://www.cablelabs.com.

Table 1 - CPON 1.0 Series of Specifications

Designation	Title
CPON-SP-ARCH	Coherent PON Architecture Specification
CPON-SP-PMDv1.0	Physical Media Dependent Layer Specification
CPON-SP-TCv1.0	Transmission Convergence Layer Specification

1.3 Requirements

Throughout this document, the words that are used to define the significance of particular requirements are capitalized.

"MUST"	This word means that the item is an absolute requirement of this specification.
"MUST NOT"	This phrase means that the item is an absolute prohibition of this specification.
"SHOULD"	This word means that there may exist valid reasons in particular circumstances to ignore this item, but the full implications should be understood and the case carefully weighed before choosing a different course.
"SHOULD NOT"	This phrase means that there may exist valid reasons in particular circumstances when the listed behavior is acceptable or even useful, but the full implications should be understood and the case carefully weighed before implementing any behavior described with this label.
"MAY"	This word means that this item is truly optional. One vendor may choose to include the item because, for example, a particular marketplace requires it or because it enhances the product; another vendor may omit the same item.

1.4 Device Under Test

The requirements in this document are written against specific devices under test (DUTs), either a CPON ONU or a CPON OLT.

To simplify the text, a CPON ONU is henceforth referred to as an ONU, and a CPON OLT is henceforth referred to as an OLT. Additionally, note that though the requirements for an OLT are written for the whole device, in many cases the requirements will also apply to each channel termination on the OLT.

1.5 Organization of Document

Section 1 of this document provides an overview of CPON technology and the objectives of this specification.

Sections 2–4 include the references, terms, and abbreviations used throughout this specification.

Section 5 provides a brief overview of the Coherent PON PMD layer.

Sections 6–9 contain the normative material, organized as follows.

- Section 6 covers general device requirements that are not specific to the physical layers defined in this specification.
- Section 7 defines general PMD layer requirements, such as symbol rate, modulation, symbol mapping, and line rate.
- Section 8 defines optical interface requirements for CPON devices.
- Section 9 defines the PMD layer requirements for the out-of-band (OOB) channel used for certain broadcast upstream messages.

2 REFERENCES

2.1 Normative References

To claim compliance with this specification, it is necessary to conform to the following standards and other works as indicated, in addition to the other requirements of this specification. Notwithstanding, intellectual property rights may be required to use or implement such normative references.

All references are subject to revision, and parties to agreement based on this specification are encouraged to investigate the possibility of applying the most recent editions of the document listed.

[CPON-TCv1.0]	Coherent PON Transmission Convergence Layer 1.0 Specification, CPON-SP-TCv1.0-D03-251113, November 13, 2025, Cable Television Laboratories, Inc.

2.2 Informative References

This specification uses the following informative references.

[G.9804.2]	ITU-T Recommendation G.9804.2 (02/2023), Higher Speed Passive Optical Networks: Common Transmission Convergence Layer Specification—Amendment 1
[G.9804.3]	ITU-T Recommendation G.9804.2 (03/2024), Higher Speed Passive Optical Networks: Physical media dependent (PMD) Layer Specification—Amendment 2
[G.694.1]	ITU-T Recommendation G.694.1 (10/2020), Spectral Grids for WDM Applications: DWDM Frequency Grid
[P2PCO-PHYv1.0]	P2P Coherent Optics Physical Layer 1.0 Specification, P2PCO-SP-PHYv1.0-I03-200501, May 1, 2020, Cable Television Laboratories, Inc.
[P2PCO-PHYv2.0]	P2P Coherent Optics Physical Layer 2.0 Specification, P2PCO-SP-PHYv2.0-I02-200501, May 1, 2020, Cable Television Laboratories, Inc.
[CPON-ARCH]	Coherent PON Architecture Specification, CPON-SP-ARCH-I01-230503, May 5, 2023, Cable Television Laboratories, Inc.

2.3 Reference Acquisition

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3 TERMS AND DEFINITIONS

3.1 Terms and Definitions

This specification uses the following terms.

bit error rate (BER)	The ratio of bits that have errors relative to the total number of bits received in a transmission, usually expressed as ten to a negative power.
Coherent Optics	Coherent Optics encodes information in both in-phase (I) amplitude and quadrature (Q) amplitude components of a carrier.
CPON system	A system comprising an OLT and one or more ONUs connected via an ODN and utilizing CPON technology as defined in the CPON family of specifications.
data rate	Throughput data transmitted in units of time, usually in bits per second (bps).
decibel	Ratio of two power levels expressed mathematically as $dB = 10\log_{10}(P_{OUT}/P_{IN})$.
decibel-milliwatt (dBm)	The power ratio in decibels (dB) of the measured power referenced to one milliwatt (mW). A power level of 0 dBm corresponds to a power of 1 mW.
demultiplexer (demux)	Splits a single line-in to many lines-out. See *multiplexer*.
downstream	The direction of transmission from the hub/CO to the subscriber location.
forward error correction	A method of error detection and correction in which redundant information is sent with a data payload to allow the receiver to reconstruct the original data if an error occurs during transmission.
gigabit	10^9 bits
IQ modulation	A method of combining two input channels into one by multiplying the "in-phase" (I) channel by the cosine and the "quadrature" (Q) channel by the sine. This way, there is a phase of 90° between them. When added together, the modulator sends the combined signal through the output channel.
jitter	The fluctuation in the arrival time of a regularly scheduled event such as a clock edge or a packet in a stream of packets.
latency	The time taken for a signal element to pass through a device, system, or network.
layer	A subdivision of the Open System Interconnection (OSI) architecture, constituted by subsystems of the same rank.
media access control (MAC)	The OSI Layer 2 element of the system.
multiplexer (mux)	Combines multiple lines-in to a single line-out. See *demultiplexer*.
optical distribution network (ODN)	A point-to-multipoint optical fiber infrastructure.
optical line terminal (OLT)	A network element in an ODN-based optical access network that provides an optical access network service node interface.
optical network unit (ONU)	A network element in an ODN-based optical access network that provides an optical access network user-network interface.
passive optical network (PON)	A telecommunication network that transmits data over optical fiber links. It uses unpowered passive optical splitters to route data from a central location to multiple destinations.
physical layer (PHY)	The OSI Layer 1 element of the system. It provides services to transmit bits or groups of bits over a transmission link between open systems and entails optical, electrical, mechanical and handshaking procedures.
quadrature amplitude modulation (QAM)	A modulation technique in which an analog signal's amplitude and phase vary to convey information, such as digital data. The name "quadrature" indicates that amplitude and phase can be represented in rectangular coordinates as in-phase (I) and quadrature (Q) components of a signal.
quadrature phase-shift keying (QPSK)	A form of digital modulation in which four phase states separated by 90° support the transmission of two bits per symbol.
upstream	The direction of transmission from the subscriber location toward the head-end.

4 ABBREVIATIONS

This specification uses the following abbreviations.

ADC	analog-to-digital converter
ASE	amplified spontaneous emission
BER	bit error ratio
bps	bits per second
BPSK	binary phase-shift keying
CD	chromatic dispersion
CDC	chromatic dispersion compensation
CFO	carrier frequency offset
CMA	constant modulus algorithm
CPON	Coherent Passive Optical Network
DAC	digital-to-analog converter
dB	decibel
dBm	decibel milliwatts
DGD	differential group delay
DP-QPSK	dual-polarization QPSK
DS	downstream
DSP	digital signal processing
DUT	device under test
DWDM	dense wavelength-division multiplexing
FAW	frame alignment word
FEC	forward error correction
FOE	frequency offset estimation
FTTP	fiber-to-the-premise
Gbps	gigabit per second
GHz	gigahertz
Gbaud	gigabaud
IQ	in-phase and quadrature
IEEE	Institute of Electrical and Electronics Engineers
IM-DD	intensity modulation–direct detection
ITU-T	International Telecommunication Union–Telecommunication Standardization Sector
kHz	kilohertz
km	kilometer
krad	kiloradians
MAC	media access control
mux	multiplexer
nm	nanometer
ODN	optical distribution network
OLT	optical line terminal
ONU	optical network unit
OOB	out-of-band
OPM	optical power meter
OSA	optical spectrum analyzer
OSNR	optical signal-to-noise ratio
P2MP	point-to-multipoint
PBC	polarization beam combiner

PBS	polarization beam splitter
PDM	polarization division multiplexing
PDL	polarization-dependent loss
PHY	physical layer
PolMD	polarization mode dispersion
PMD	physical media dependent
PON	passive optical network
PS	pilot symbol
ps	picosecond
PSBd	PHY synchronization block, downstream
PSBu	PHY synchronization block, upstream
QPSK	quadrature phase-shift keying
RIN	relative intensity noise
Rx	receiver
SoP	state of polarization
TC	transmission convergence
TDM	time-division multiplexing
TIA	transimpedance amplifier
THz	terahertz
TS	training symbol
Tx	transmitter
µs	microseconds
US	upstream
WDM	wavelength-division multiplexing

5 OVERVIEW

5.1 Introduction to Coherent PON

A passive optical network (PON) that leverages the benefits of a P2MP passive topology for highly efficient fiber utilization has become one of the dominant optical access architectures for operators in current fiber-to-the-premise (FTTP) deployments. To meet increasing bandwidth demands driven by data-intensive applications such as video streaming, 5G mobile Internet, and cloud networking, several generations of PON systems have been standardized through the efforts of two major organizations: the ITU-T and the IEEE 802.3 Ethernet Working Group.

Existing PON systems employ IM-DD technology for a good balance of cost and performance. However, this balance no longer holds true when the data rate per wavelength goes over 50 Gbps because IM-DD technology is facing physical challenges that will require higher device costs and higher power consumption for the overall system architecture and optical design:

- A digital-to-analog converter (DAC) and an analog-to-digital converter (ADC) with high sampling rates are required for signal processing in the digital domain.
- Digital signal processing algorithms are needed to compensate for device bandwidth limitation and to mitigate transmission impairments.
- Limited link budgets require optical amplification in both centralized optics and customer premise equipment.
- Wavelength planning and resource management becomes more difficult because of the congestion in the O-band for both downlink and uplink.
- Higher bandwidth opto-electronic components are needed to reduce implementation penalties.

Coherent optical technology has completely transformed optical transmission systems and enabled a widespread upgrade and new deployment of dense wavelength-division multiplexing (DWDM) networks to speeds of 100 Gbps, 200 Gbps, and 400 Gbps per wavelength (and it is still growing). In addition, the use of coherent optics has migrated from a long-link distance model to a short-link distance model, much like the migration of DWDM from long-haul to metro to edge access. Over the past decade, as costs have decreased and scale increased, coherent optics has moved beyond its long-haul application origins to metro networks and more recently to access networks.

Coherent PON (CPON) leverages this decreasing cost and increasing scale to apply the concept of coherent optical transmission to PON. CPON provides many advantages that are desirable in access networks.

- Multiple dimensions (optical amplitude, phase, and polarization) are multiplexed to encode information, enabling higher data rates that can be processed with low-bandwidth analog and digital signal techniques.
- A local oscillator enables coherent gain, improving receiver sensitivity and eliminating the need for high launch power.
- Coherent detection allows digital compensation of linear impairments, such as chromatic and polarization-mode dispersion, without significant optical penalty, enabling ultra-long PON reach.

There are also several benefits for operators that differentiate CPON technology from IM-DD technology.

- Higher link budgets can (1) enable reaching more distant customers from hub facilities without the need for optical amplification and (2) supporting more customers on a single OLT, reducing OLT port counts.
- This enables the elimination of costly facilities (such as hubs) for distant communities.
- C-band wavelength stacking with tunability enables re-use of existing ODNs, coexistence with existing services, and increased capacity without new fiber or truck rolls.
- The flexibility and capability of CPON can significantly expand PON’s applications beyond traditional residential deployment to support convergence needs at the network edge.

Additional information on potential use cases and benefits can be found in [CPON-ARCH].

5.2 Introduction to the CPON PMD Layer

This specification defines the CPON physical media dependent (PMD) layer. It has the following key characteristics.

- It supports a data rate of 100 Gbps on a single wavelength and can support total system capacities of 400 Gbps or more in aggregate (with a maximum per ONU of 100 Gbps).
- It has a super-rated line rate of ~122 Gbps to account for all overheads while supporting the 100 Gbps data rate.
- It operates on a DWDM 100-GHz channel grid, as defined in [G.694.1].
- It supports bi-directional transmission over a single fiber.
- It supports tuning across a minimum of four 100-GHz channels to support coexistence and wavelength stacking.
- It incorporates aspects of the PHY layer defined in [P2PCO-PHYv1.0] and [P2PCO-PHYv2.0] to simplify implementations and leverage technology approaches that are field proven and low cost.
- It supports a 35-dB link budget, which allows a reach of up to 80 km (with a 1:16 split ratio) or split ratios of up to 1:512 (with a 20-km reach).
- It uses an out-of-band (OOB) channel to eliminate the need for in-band discovery windows, significantly reducing latency and jitter.

This PMD layer has been designed to interface with the transmission convergence (TC) layer defined in [CPON-TCv1.0], which is in turn adapted from the Common TC layer defined in [G.9804.2], to enable simpler integration with systems that have already deployed ITU-based PON systems. It could also be adapted to the IEEE 802.3 MAC layer should there be sufficient interest. Further, this specification could be extended in the future to support higher data rates per ONU.

5.3 Upstream Burst Processing

Point-to-point coherent optics applications transmit a continuous signal in both directions. PON, however, uses a P2MP topology, in which the downstream signal (from OLT to ONU) is continuous, but the upstream signal (from ONUs to OLT) is shared. This shared signal requires burst-mode transmission. Applying coherent optics technology to burst transmissions—through the development of robust preamble structures and fast burst-processing mechanisms—was the critical innovation that made CPON feasible.

This section provides an overview of the role and design of the preamble structures and burst-processing mechanisms used for CPON systems. The preamble is provided to the ONU by the OLT and is transmitted upstream by the ONU as a part of the upstream PHY synchronization block (PSBu). The mechanism for providing the preamble to the ONU is defined in [CPON-TCv1.0], but an overview of how the preamble is used is provided here because of its importance in various PMD layer functions.

A preamble is a structured sequence placed before the data payload and serves essential functions at the OLT receiver. Specifically, it facilitates receiver power settling for optimal signal conditioning, ensuring the receiver's gain is appropriately adjusted prior to payload data processing; supports clock recovery and frame synchronization, providing timing information for accurate symbol sampling and precise identification of payload boundaries; and facilitates channel estimation and equalization by providing the receiver with the necessary parameters to mitigate distortions from the optical transmission path.

The design of preambles requires optimization to balance overhead efficiency with robust burst detection and synchronization. Optimal preamble lengths are determined through analytical studies, simulations, and experimental verifications, considering the CPON architecture and anticipated channel conditions. A robust preamble structure needs to adapt effectively to varying channel conditions, ensuring consistent receiver performance.

In CPON, the upstream signals arriving at the OLT from different ONUs exhibit significant variability in several critical parameters. These signals may differ in received optical power because of variations in ONU transmit power and optical path losses. Additionally, the bursts may present offsets in carrier frequency and inconsistencies in phase alignment, necessitating precise compensation techniques to ensure reliable detection. Timing discrepancies can also arise, as ONUs typically operate with independent clock sources, leading to misalignment in symbol timing at the OLT. Furthermore, the state of polarization (SoP) of incoming signals may vary significantly as the result of dynamic changes in the optical fiber path, requiring sophisticated polarization tracking and correction mechanisms. Unlike IM-DD PON systems, where burst-mode recovery primarily focuses on addressing amplitude variations, CPON systems need to manage phase and polarization dynamics. These challenges demand advanced digital signal processing (DSP) algorithms to mitigate impairments and ensure reliable signal recovery across diverse transmission conditions.

The approach used for CPON employs a multi-segment preamble design in combination with burst-mode DSP techniques. The preamble and burst-mode DSP are specifically tailored to single-wavelength 100-Gbps time-division multiplexing (TDM) CPON systems, as illustrated in Figure 2 and Figure 3.

The preamble structure for coherent burst-mode upstream transmission is detailed in Figure 2. It is segmented into three functional components: P1, P2, and P3. Each segment is specifically engineered to facilitate critical receiver functions, including burst detection, power leveling, synchronization, parameter estimation, and adaptive channel equalization.

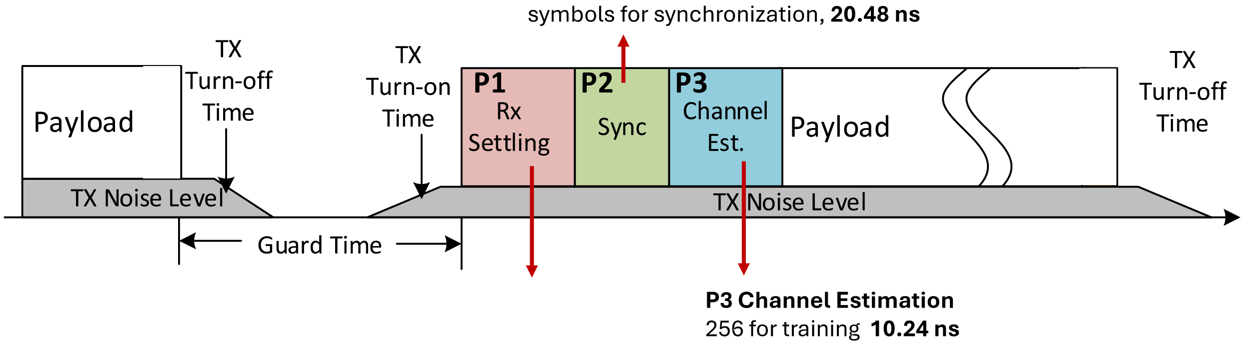


Figure 2 - Upstream Preamble Design

The three functional components are described as follows.

P1 (Burst Detection and Power Leveling)—The P1 segment is fundamental to initiating burst processing and ensuring optimal signal conditioning at the OLT. It analyzes the received signal to detect the presence of an incoming burst, marks the start of a new transmission, and facilitates power estimation to enable dynamic gain adjustment of the transimpedance amplifier (TIA), ensuring the signal remains within the optimal operating range. Additionally, P1 supports clock recovery by extracting timing information from the burst, enabling accurate symbol sampling and data extraction. The recommended P1 segment should consist of at least 1024 symbols.

P2 (Synchronization and Parameter Estimation)—The P2 segment enables channel synchronization and parameter estimation, supporting critical functions such as frame alignment, SoP estimation, and frequency offset estimation. By accurately identifying frame boundaries, P2 ensures proper payload alignment, while SoP estimation facilitates effective estimation of polarization state of the incoming burst. It also estimates residual frequency offsets between Tx and Rx (transmitter and receiver), enabling precise carrier recovery and phase tracking. As an example, P2 employs a structured pattern of 4N symbols per polarization, comprising 2N conjugate symbols and 2N zeros. The conjugate symbols enhance synchronization by mitigating sensitivity to frequency offsets and polarization variations, and the zero symbols enable efficient SoP estimation via inverse Jones Matrix calculations. The recommended P2 segment should consist of at least 512 symbols.

P3 (Channel Estimation and Equalization)—The P3 segment performs adaptive channel estimation and equalization. By analyzing the symbols within this segment, the receiver determines the channel impulse response and dynamically adjusts its equalizer coefficients. The parameters derived from P3 are further used to enable rapid convergence of channel equalization based on, for example, a constant modulus algorithm (CMA) during payload data processing. The recommended P3 segment should consist of at least 256 symbols.

The burst processing DSP flow is implemented by using a feed-forward architecture, as illustrated in Figure 3. This design minimizes processing latency and optimizes the preamble length for efficient operation.

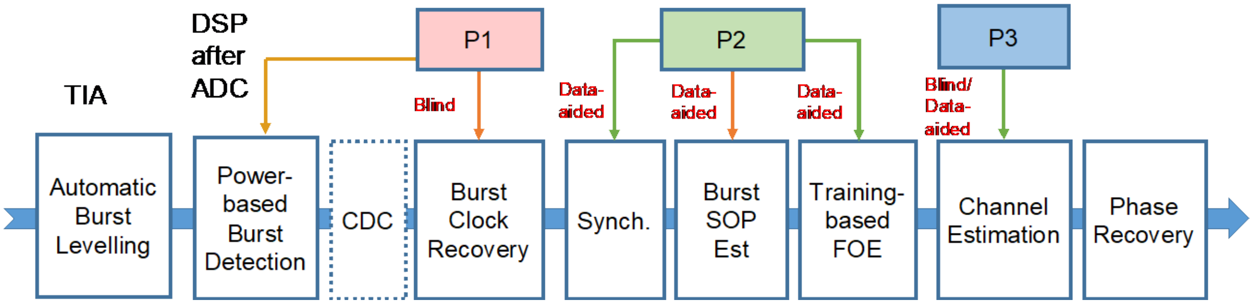


Figure 3 - Upstream Burst Processing

The initial stage P1, including normalization and chromatic dispersion compensation (CDC), is followed by processing blocks that are tightly integrated with the preamble structure. A fast timing recovery algorithm (e.g., square-timing-recovery) is used to perform a clock recovery, ensuring precise extraction of timing information from the incoming burst. Accurate timing recovery is essential for subsequent symbol sampling and data extraction.

Synchronization and SoP estimation are facilitated by the P2 segment, which executes a correlation process to align frame boundaries and estimate SoP parameters. Simultaneously, the P2 pattern aids in determining carrier frequency offset (CFO), a key input for carrier phase recovery. After these preamble-based processes, the P3 channel estimation stage uses preamble-derived parameters to expedite convergence and enhance channel equalization accuracy for the payload data processing.

The feed-forward architecture ensures seamless propagation of critical parameters extracted from the preamble—such as timing recovery information, SoP, CFO, and channel estimates—into subsequent processing stages. This efficient transfer of information enables optimized handling of payload data, ensuring reliable performance in coherent burst-mode operations.

6 GENERAL DEVICE REQUIREMENTS

This section includes requirements that apply to compliant ONUs and OLTs and are not specific to the new PMD layer.

6.1 Environmental Conditions

This specification does not define specific environmental conditions that compliant ONUs and OLTs are required to support; those requirements are expected to be defined by the end customer when defining their purchasing requirements. In many cases, an ONU or OLT will operate in temperature-controlled environments, but a remote OLT or an ONU installed on the exterior of a building, for example, could be installed in exterior (outdoor) locations. It is expected that devices deployed outdoors could be required to operate at start-up temperatures as low as -40°C and may need to operate in conditions with an internal temperature as high as +85°C, also known as I-Temp.

The ONU or OLT manufacturer will define the temperature range supported by the device, and the ONU or OLT will be expected to meet this specification's requirements at any temperature within that range.

> The ONU MUST support all requirements in this specification across the ONU's full operating temperature range.
>
> The OLT MUST support all requirements in this specification across the OLT's full operating temperature range.

6.2 Optical Ports

As noted in Section 5.2, the CPON is designed to use a single fiber for bi-directional transmission of data. Therefore, ONUs will connect to the ODN through a single optical port, and the upstream and downstream signals are separated/combined within the ONU via manufacturer defined means.

However, in some deployment scenarios, it may be desirable for operators to re-use portions of their existing ODNs that use DWDM, which uses a mux to combine signals at different wavelengths from multiple fibers onto a single fiber and a demux to separate them back into individual fibers. Because CPON will use separate wavelengths for the upstream and downstream directions, some scenarios may split the upstream and downstream onto separate fibers across a portion of the ODN. In these cases, use of OLTs with separate upstream and downstream optical ports may help to simplify cabling and minimize optical loss. This specification, therefore, anticipates both single-port (combined upstream/downstream) and dual-port (separate upstream/downstream) OLT implementations.

Note that, for consistency, all optical requirements in Section 8 of this specification are measured at the point where the ONU or OLT connects to the ODN.

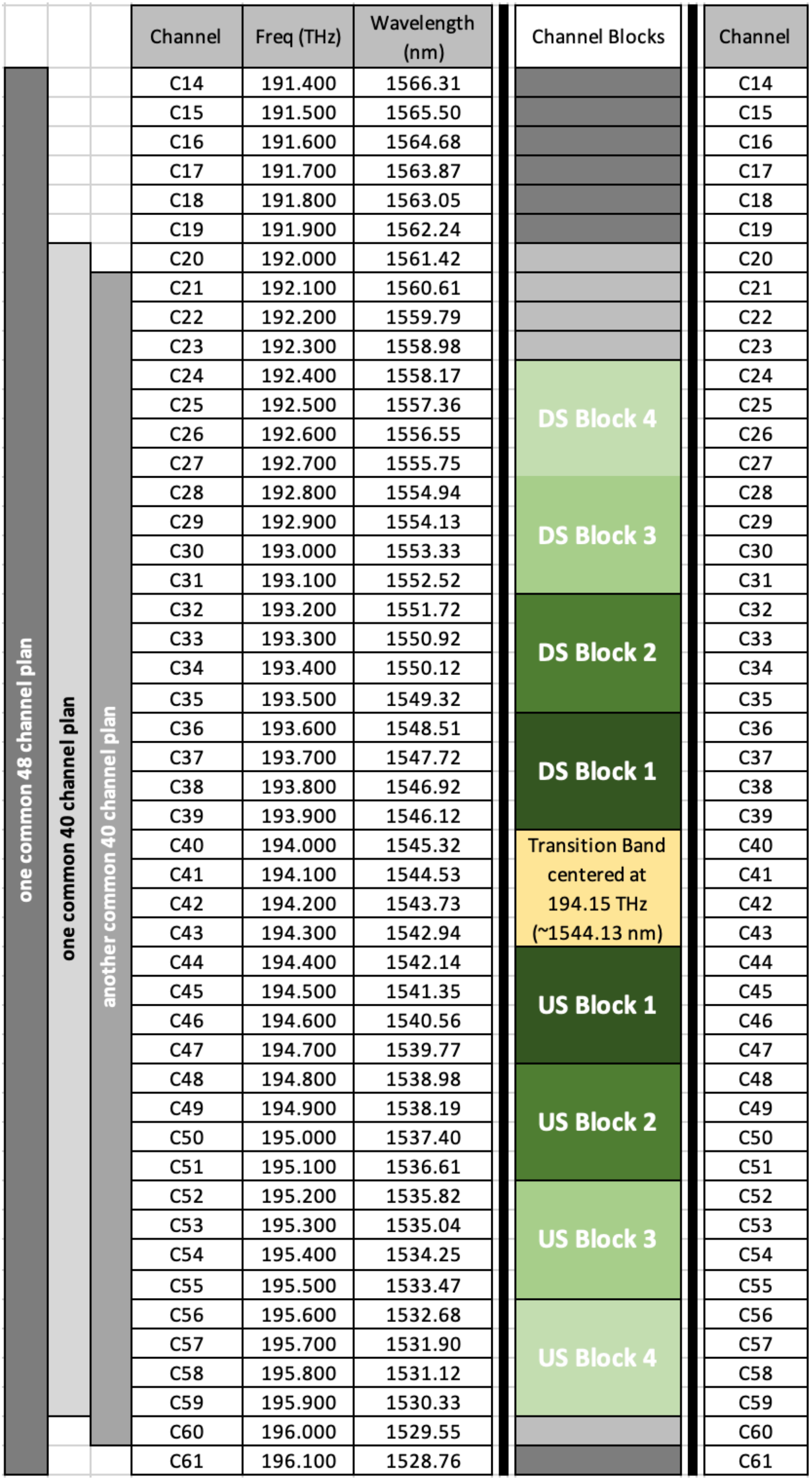
> The ONU MUST have a single optical interface port per PON to connect to the ODN for transmit and receive functions.
>
> The OLT MUST either have a single optical interface port per PON to connect to the ODN for transmit and receive functions or provide separate upstream and downstream optical interface ports per PON.

6.3 Frequency Grid and Tuning

As previously noted, in some deployment scenarios operators will wish to deploy CPON technology over existing ODNs that carry other signals and services, such as point-to-point Ethernet services, video services, or DOCSIS data. These services coexist on the same ODN by transmitting and receiving at different wavelengths utilizing DWDM architectures. The specific wavelengths used for these services will vary from network to network, so for CPON systems to coexist on these same networks, CPON ONUs and OLTs will need to support at least some degree of tunability and the ability to operate over existing deployed DWDM muxes and demuxes.

To enable ONUs and OLTs to operate with operators' existing DWDM systems and equipment, this specification has adopted a subset of the channels identified in Figure 4 using a 100-GHz channel spacing. To support coexistence with existing services, this specification also requires a minimum degree of tunability, with the option to support larger tunability ranges.

To promote tuning interoperability between ONUs and OLTs, this specification defines a series of upstream and downstream tuning blocks, as well as a transition band to separate the upstream and downstream tuning blocks. As shown in Figure 4, each block spans four 100-GHz channels on the ITU DWDM grid, and the transition band is defined as a 4-channel block (400 GHz edge-to-edge, or 500 GHz center-to-center) centered on 194.15 THz. Note that the channel numbers correspond to those defined in [P2PCO-PHYv1.0].



			Channel	Freq (THz)	Wavelength (nm)	Channel Blocks	Channel
one common 48 channel plan			C14	191.400	1566.31	▓	C14
			C15	191.500	1565.50	▓	C15
			C16	191.600	1564.68	▓	C16
			C17	191.700	1563.87	▓	C17
			C18	191.800	1563.05	▓	C18
			C19	191.900	1562.24	▓	C19
	one common 40 channel plan		C20	192.000	1561.42	░	C20
		another common 40 channel plan	C21	192.100	1560.61	░	C21
			C22	192.200	1559.79	░	C22
			C23	192.300	1558.98	░	C23
			C24	192.400	1558.17	DS Block 4	C24
			C25	192.500	1557.36		C25
			C26	192.600	1556.55		C26
			C27	192.700	1555.75		C27
			C28	192.800	1554.94	DS Block 3	C28
			C29	192.900	1554.13		C29
			C30	193.000	1553.33		C30
			C31	193.100	1552.52		C31
			C32	193.200	1551.72	DS Block 2	C32
			C33	193.300	1550.92		C33
			C34	193.400	1550.12		C34
			C35	193.500	1549.32		C35
			C36	193.600	1548.51	DS Block 1	C36
			C37	193.700	1547.72		C37
			C38	193.800	1546.92		C38
			C39	193.900	1546.12		C39
			C40	194.000	1545.32	Transition Band centered at 194.15 THz (~1544.13 nm)	C40
			C41	194.100	1544.53		C41
			C42	194.200	1543.73		C42
			C43	194.300	1542.94		C43
			C44	194.400	1542.14	US Block 1	C44
			C45	194.500	1541.35		C45
			C46	194.600	1540.56		C46
			C47	194.700	1539.77		C47
			C48	194.800	1538.98	US Block 2	C48
			C49	194.900	1538.19		C49
			C50	195.000	1537.40		C50
			C51	195.100	1536.61		C51
			C52	195.200	1535.82	US Block 3	C52
			C53	195.300	1535.04		C53
			C54	195.400	1534.25		C54
			C55	195.500	1533.47		C55
			C56	195.600	1532.68	US Block 4	C56
			C57	195.700	1531.90		C57
			C58	195.800	1531.12		C58
			C59	195.900	1530.33		C59
			C60	196.000	1529.55	░	C60
			C61	196.100	1528.76	▓	C61

Figure 4 - CPON Channel Plan with Tuning Blocks

Each of the 16 downstream and upstream channels defined within the four downstream and upstream blocks has a unique identifier, which is used within the TC layer: the downstream wavelength channel ID (DWLCH ID) and the upstream wavelength channel ID (UWLCH ID), each of which is a 4-bit number. The IDs are defined in Table 2 and Table 3, respectively.

Table 2 - Downstream Wavelength Channel IDs

DWLCH ID	Channel #	Freq (THz)	Wavelength (nm)	DS Block #
0	C39	193.9	1546.12	1
1	C38	193.8	1546.92	1
2	C37	193.7	1547.72	1
3	C36	193.6	1548.51	1
4	C35	193.5	1549.32	2
5	C34	193.4	1550.12	2
6	C33	193.3	1550.92	2
7	C32	193.2	1551.72	2
8	C31	193.1	1552.52	3
9	C30	193.0	1553.33	3
10	C29	192.9	1554.13	3
11	C28	192.8	1554.94	3
12	C27	192.7	1555.75	4
13	C26	192.6	1556.55	4
14	C25	192.5	1557.36	4
15	C24	192.4	1558.17	4

Table 3 - Upstream Wavelength Channel IDs

UWLCH ID	Channel #	Freq (THz)	Wavelength (nm)	US Block #
0	C44	194.4	1542.14	1
1	C45	194.5	1541.35	1
2	C46	194.6	1540.56	1
3	C47	194.7	1539.77	1
4	C48	194.8	1538.98	2
5	C49	194.9	1538.19	2
6	C50	195.0	1537.40	2
7	C51	195.1	1536.61	2
8	C52	195.2	1535.82	3
9	C53	195.3	1535.04	3
10	C54	195.4	1534.25	3
11	C55	195.5	1533.47	3
12	C56	195.6	1532.68	4
13	C57	195.7	1531.90	4
14	C58	195.8	1531.12	4
15	C59	195.9	1530.33	4

The specific frequencies were chosen to align to currently deployed DWDM muxes, splitting the upstream and downstream frequencies roughly in half, and to allow the avoidance of other services that operate on specific frequencies within the C-band (such as NG-PON2). The size of the transition band was set to 400 GHz edge-to-edge and 500 GHz center-to-center based on feedback that this will enable low-cost diplexer designs in the ONU while minimizing the size of the transition band. The size of the tuning blocks was selected to enable minimally compliant ONUs and OLTs to use lower cost tuning implementations relative to full band tuners.

Compliant ONUs and OLTs support tuning across one or more upstream and downstream tuning blocks. To enable interoperability, it is strongly recommended that CPON ONUs and OLTs support tuning within US Block 1 and DS Block 1. The control mechanism for tuning the upstream and downstream channels is defined in [CPON-TCv1.0].

> The ONU MUST support tuning its receiver to the four 100-GHz channels from at least one of the downstream tuning blocks defined in Figure 4 - CPON Channel Plan with Tuning Blocks.
>
> The ONU MUST support tuning its transmitter to the four 100-GHz channels from at least one the upstream tuning blocks defined in Figure 4 - CPON Channel Plan with Tuning Blocks.
>
> The ONU SHOULD support tuning its receiver to the four 100-GHz channels in DS Block 1 defined in Figure 4 - CPON Channel Plan with Tuning Blocks.
>
> The ONU SHOULD support tuning its transmitter to the four 100-GHz channels US Block 1 defined in Figure 4 - CPON Channel Plan with Tuning Blocks.
>
> The ONU SHOULD support tuning its receiver to the channels in more than one of the downstream tuning blocks defined in Figure 4 - CPON Channel Plan with Tuning Blocks.
>
> The ONU SHOULD support tuning its transmitter to the channels in more than one of the upstream tuning blocks defined in Figure 4 - CPON Channel Plan with Tuning Blocks.
>
> The OLT MUST support tuning its receiver to the four 100-GHz channels from at least one of the upstream tuning blocks defined in Figure 4 - CPON Channel Plan with Tuning Blocks.
>
> The OLT MUST support tuning its transmitter to the four 100-GHz channels from at least one the downstream tuning blocks defined in Figure 4 - CPON Channel Plan with Tuning Blocks.
>
> The OLT SHOULD support tuning its receiver to the four 100-GHz channels in US Block 1 defined in Figure 4 - CPON Channel Plan with Tuning Blocks.
>
> The OLT SHOULD support tuning its transmitter to the four 100-GHz channels DS Block 1 defined in Figure 4 - CPON Channel Plan with Tuning Blocks.
>
> The OLT SHOULD support tuning its receiver to the channels in more than one of the upstream tuning blocks defined in Figure 4 - CPON Channel Plan with Tuning Blocks.
>
> The ONU SHOULD support tuning its transmitter to the channels in more than one of the downstream tuning blocks defined in Figure 4 - CPON Channel Plan with Tuning Blocks.

7 CPON PMD LAYER REQUIREMENTS

In digital transmission, strings of ones or zeroes can represent any signal given enough time. The number of bits over time is called a bit rate, measured in bits per second (bps).

To increase bit rate, instead of simply transmitting the ones and zeroes faster, multiple bits can be processed and transmitted at the same time using a collection of relative states called symbols. The number of symbols transmitted over time is defined as the baud rate, measured in gigabaud (Gbaud).

This section describes how the bitstream from the TC layer is formatted for transmission over the fiber and how the received transmissions are converted back into a bitstream for the TC layer. More specifically, the type of symbol used is defined in Section 7.1, the mapping of bits into symbols and the use of symbols to create frames are defined in Section 7.2, and the symbol rate and line rate are defined in Section 7.3.

7.1 Modulation

This specification defines the use of dual-polarization quadrature phase-shift keying (DP-QPSK) for data transmissions.

This non-differential scheme encodes two bits per symbol with the requirement for reference phase awareness between successive symbols. This is accomplished by inserting pilot symbols into the DSP frames (see Section 7.2.2 for downstream and Section 7.2.3 for upstream) to aid the receiver's phase recovery. When dual-polarization multiplexing is used, the scheme is referred to as DP-QPSK. Employing non-differential QPSK on each of two polarizations of the carrier allows the aggregate transmission of four data bits for each symbol period. This aligns with several existing specifications, such as [P2PCO-PHYv2.0].

ONUs and OLTs conformant to this specification are required to support polarization multiplexing and QPSK. On each of the two polarizations, QPSK is used to encode two bits per symbol. The QPSK symbol constellation is illustrated in Figure 5. Data bit mapping to QPSK symbols is specified in Section 7.2.1.

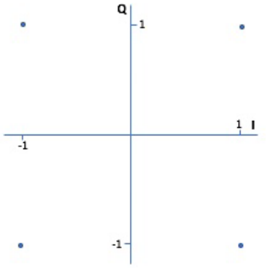


Figure 5 - QPSK Symbol Constellation

The ONU MUST support DP-QPSK modulation.

The ONU MUST use the symbol constellation as illustrated in Figure 5 - QPSK Symbol Constellation.

The ONU MUST use the data to symbol mapping specified in Section 7.2.1, "Symbol Mapping and Polarization Distribution."

The OLT MUST support DP-QPSK modulation.

The OLT MUST use the symbol constellation as illustrated in Figure 5 - QPSK Symbol Constellation.

The OLT MUST use the data to symbol mapping specified in Section 7.2.1, "Symbol Mapping and Polarization Distribution."

7.2 Symbol Mapping and Transmission

This section describes the procedure for mapping downstream PHY frames and upstream PHY bursts from the TC layer, as defined in [CPON-TCv1.0], onto DP-QPSK constellation symbols of each polarization; distributing those symbols across two different polarizations; and adding pilot symbols. It also describes the insertion of training symbols in the downstream.

7.2.1 Symbol Mapping and Polarization Distribution

The bit stream of downstream PHY frames and upstream PHY bursts from the TC layer are mapped to DP-QPSK symbols

$$S = [s_0, s_1, \ldots, s_n],$$

where

(c_{4i}) maps to the in-phase (I) component of the X-pol of s_i,

(c_{4i+2}) maps to the quadrature (Q) component of the X-pol of s_i,

(c_{4i+1}) maps to the I component of the Y-pol of s_i, and

(c_{4i+3}) maps to the Q component of the Y-pol of s_i.

The map from binary label to symbol amplitude in each signaling dimension is defined in Table 4.

Table 4 - Symbol Mapping and Polarization Distribution

(c_{4i}, c_{4i+2}) or (c_{4i+1}, c_{4i+3})	I	Q
(0,0)	-1	-1
(0,1)	-1	1
(1,0)	1	-1
(1,1)	1	1

ONUs MUST support the symbol mapping and polarization distribution defined in Section 7.2.1, "Symbol Mapping and Polarization Distribution."

OLTs MUST support the symbol mapping and polarization distribution defined in Section 7.2.1, "Symbol Mapping and Polarization Distribution."

7.2.2 Downstream DSP Framing

7.2.2.1 Downstream DSP Framing Overview

This section describes the DSP framing format used in the downstream to transmit and receive downstream PHY frames. It is adapted from [P2PCO-PHYv2.0].

A DSP superframe is defined as a set of 3,813,054 symbols in each X/Y polarizations. Thus, each DSP superframe exactly aligns to the portion of a single downstream PHY frame on each polarization when all overheads are accounted for.

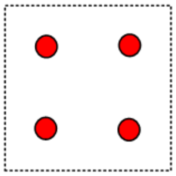
A full DSP subframe consists of 3,712 symbols. The DSP superframe thus consists of 1,028 DSP subframes: 1,027 full DSP subframes and 1 shortened DSP subframe of 830 symbols.

A pilot symbol is inserted every 32 symbols starting with the first symbol of the first DSP subframe. Each DSP subframe starts with an 11-symbol training sequence. The first symbol of the training sequence is a pilot symbol.

Note that, unlike [P2PCO-PHYv2.0], no frame alignment word (FAW) is needed, as the first 8 bytes of each PHY frame will include the fixed pattern Psync field of the PSBd, which is not interleaved and can therefore be used for PHY frame alignment and recovery.

Once the bitstream has been mapped into symbols and distributed onto each polarization, training sequences and pilot symbols are added to create a DSP superframe/subframe structure.

Table 5 - Training Sequence/Pilot Symbol Pattern

Parameter	DP-QPSK
Mapping	
Training sequence	QPSK 11 symbols per DSP subframe
Pilot symbols	QPSK Every 32 symbols

The OLT MUST transmit DSP superframes of 3,813,054 symbols in the downstream, aligned to downstream PHY frames.

The ONU MUST successfully receive DSP superframes of 3,813,054 symbols in the downstream, aligned to downstream PHY frames.

7.2.2.2 DSP Subframes

As seen in Figure 6, every full DSP subframe (subframes 1–1,027 of a DSP superframe) includes

- 11 symbols available for link training (note: the first training symbol (TS) in each DSP subframe is shared as a pilot symbol [PS]) and
- 116 pilot symbols.

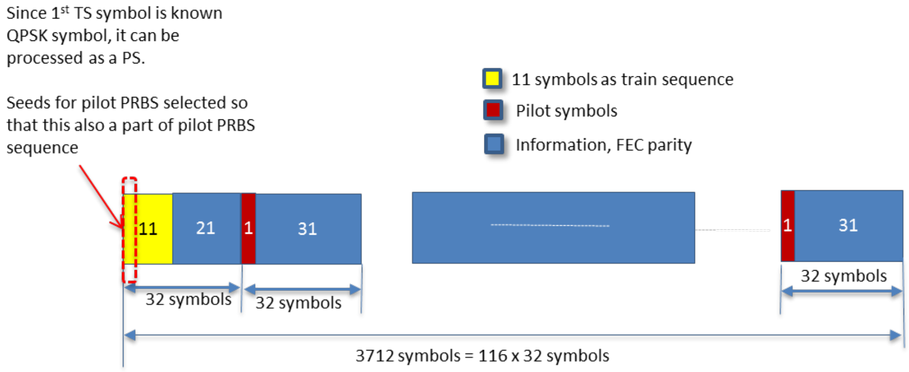


Figure 6 - Full DSP Subframes 1 to 1,027 of the DSP Superframe

The final shortened DSP subframe (subframe 1,028 of a DSP superframe) includes

- 11 symbols available for link training (including the first PS) and
- 26 pilot symbols.

The OLT MUST transmit DSP superframes that each consist of 1,027 full DSP subframes and a single shortened DSP subframe of 830 symbols.

The OLT MUST transmit DSP subframes as described in Section 7.2.2.2, "DSP Subframes."

The ONU MUST successfully receive DSP superframes that each consist of 1,027 full DSP subframes and a single shortened DSP subframe of 830 symbols.

The ONU MUST successfully receive DSP subframes as described in Section 7.2.2.2, "DSP Subframes."

7.2.2.3 Training Sequence

The training sequence referred to in Sections 7.2.2.1 and 7.2.2.2 is defined in Table 6.

Table 6 - Training Symbol Sequence

Index	Training X	Training Y
1*	-3 + 3j	-3 - 3j
2	3 + 3j	-3 - 3j
3	-3 + 3j	3 - 3j
4	3 + 3j	-3 + 3j
5	-3 - 3j	-3 + 3j
6	3 + 3j	3 + 3j
7	-3 - 3j	-3 - 3j
8	-3 - 3j	-3 + 3j
9	3 + 3j	3 -3j
10	3 - 3j	3 + 3j
11	3 - 3j	3 - 3j
* The first symbol of the training sequence is processed as a pilot symbol.		

Note that $j = \sqrt{-1}$.

The OLT MUST support the training symbol sequence shown in Table 6 - Training Symbol Sequence.

The ONU MUST support the training symbol sequence shown in Table 6 - Training Symbol Sequence.

7.2.2.4 Pilot Sequence

Training and pilot symbols are set at the 4 points of the QPSK constellation.

The pilot sequence is a fixed PRBS10 mapped to a QPSK sequence with different seed values for each polarization (see Table 7 and Figure 7).

- Seeds are selected so that pilots generate approximately equal quantities of 0's and 1's.
- Seeds are selected so that the first symbol in the training sequence is also the first symbol in the pilot sequence.
- The seed is reset at the head of every DSP subframe.

Table 7 - Pilot Sequence

Generator Polynomial	Seed X	Seed Y
$x^{10} + x^8 + x^4 + x^3 + 1$	0×19E	0×0D0

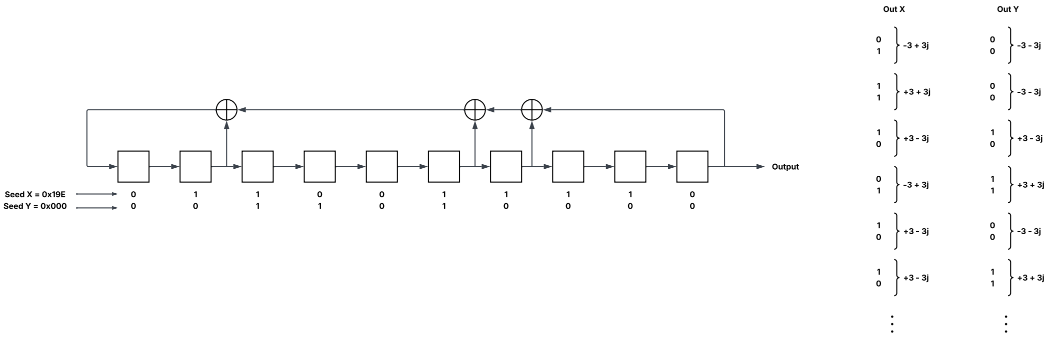


Figure 7 - Pilot Seed and Sequencing

The complete table for a full DSP subframe is shown in Table 8.

Table 8 - Full DSP Subframe Pilot Sequence

Index	Pilot X	Pilot Y	Index	Pilot X	Pilot Y	Index	Pilot X	Pilot Y
1	-3 + 3j	-3 – 3j	41	3 – 3j	3 – 3j	81	3 + 3j	3 – 3j
2	3 + 3j	-3 – 3j	42	3 – 3j	3 – 3j	82	-3 – 3j	-3 – 3j
3	3 – 3j	3 – 3j	43	-3 + 3j	-3 – 3j	83	-3 – 3j	3 + 3j
4	-3 + 3j	3 + 3j	44	-3 + 3j	-3 – 3j	84	3 + 3j	-3 – 3j
5	3 – 3j	-3 – 3j	45	-3 – 3j	3 + 3j	85	3 – 3j	-3 – 3j
6	3 – 3j	3 + 3j	46	-3 + 3j	-3 + 3j	86	-3 + 3j	-3 – 3j
7	-3 – 3j	-3 + 3j	47	-3 – 3j	3 + 3j	87	3 + 3j	3 – 3j
8	3 + 3j	-3 + 3j	48	3 + 3j	-3 + 3j	88	3 – 3j	-3 + 3j
9	-3 + 3j	-3 – 3j	49	3 + 3j	3 – 3j	89	-3 – 3j	-3 + 3j
10	3 + 3j	3 + 3j	50	-3 + 3j	-3 + 3j	90	3 – 3j	3 – 3j
11	3 + 3j	3 + 3j	51	3 – 3j	3 + 3j	91	3 – 3j	3 + 3j
12	-3 – 3j	-3 – 3j	52	3 – 3j	-3 + 3j	92	-3 + 3j	3 – 3j
13	3 + 3j	3 + 3j	53	3 – 3j	-3 + 3j	93	-3 – 3j	3 – 3j
14	3 – 3j	3 + 3j	54	-3 – 3j	3 + 3j	94	3 + 3j	-3 + 3j
15	3 + 3j	3 – 3j	55	3 – 3j	-3 + 3j	95	-3 – 3j	3 – 3j
16	3 – 3j	3 + 3j	56	3 + 3j	-3 + 3j	96	-3 – 3j	3 – 3j
17	3 + 3j	3 + 3j	57	-3 + 3j	-3 – 3j	97	3 + 3j	-3 + 3j
18	3 – 3j	-3 + 3j	58	-3 – 3j	3 – 3j	98	-3 + 3j	3 – 3j
19	-3 + 3j	-3 – 3j	59	3 – 3j	3 – 3j	99	3 – 3j	-3 – 3j
20	-3 – 3j	3 – 3j	60	3 + 3j	-3 + 3j	100	-3 – 3j	3 + 3j
21	3 + 3j	3 – 3j	61	3 – 3j	3 + 3j	101	3 + 3j	-3 – 3j
22	-3 + 3j	3 + 3j	62	-3 – 3j	-3 – 3j	102	-3 + 3j	-3 + 3j
23	-3 + 3j	-3 + 3j	63	3 – 3j	3 + 3j	103	-3 – 3j	-3 + 3j
24	3 – 3j	3 – 3j	64	-3 + 3j	-3 + 3j	104	-3 – 3j	3 + 3j
25	-3 + 3j	3 – 3j	65	3 – 3j	3 – 3j	105	3 + 3j	-3 + 3j
26	-3 + 3j	3 + 3j	66	3 + 3j	-3 + 3j	106	-3 – 3j	3 – 3j
27	-3 + 3j	-3 + 3j	67	3 – 3j	-3 – 3j	107	3 + 3j	3 + 3j
28	-3 + 3j	3 + 3j	68	-3 + 3j	3 – 3j	108	-3 + 3j	-3 + 3j
29	-3 – 3j	3 + 3j	69	3 – 3j	-3 + 3j	109	-3 – 3j	3 + 3j
30	3 – 3j	3 – 3j	70	-3 + 3j	-3 + 3j	110	-3 + 3j	-3 – 3j
31	-3 – 3j	-3 + 3j	71	3 + 3j	-3 + 3j	111	-3 – 3j	-3 + 3j
32	3 + 3j	-3 – 3j	72	-3 – 3j	-3 – 3j	112	-3 + 3j	3 – 3j
33	-3 + 3j	3 – 3j	73	-3 – 3j	-3 + 3j	113	-3 + 3j	-3 + 3j
34	-3 + 3j	-3 – 3j	74	3 – 3j	3 + 3j	114	3 + 3j	3 + 3j
35	-3 + 3j	-3 – 3j	75	-3 + 3j	-3 – 3j	115	3 + 3j	3 – 3j
36	3 – 3j	3 – 3j	76	3 – 3j	-3 – 3j	116	-3 – 3j	3 – 3j
37	3 – 3j	3 – 3j	77	-3 + 3j	-3 – 3j			
38	-3 – 3j	-3 – 3j	78	-3 – 3j	3 + 3j			
39	-3 – 3j	3 + 3j	79	3 + 3j	-3 – 3j			
40	3 – 3j	-3 – 3j	80	3 + 3j	-3 – 3j			

The final shortened DSP subframe uses indexes 1–26 of Table 8.

> The OLT MUST support the pilot sequence shown in Table 8 - Full DSP Subframe Pilot Sequence for downstream transmissions.
>
> The ONU MUST support the pilot sequence shown in Table 8 - Full DSP Subframe Pilot Sequence for downstream reception.

7.2.3 Upstream Burst Framing (Frame Alignment and Pilots)

In the upstream direction, within the ONU, the PMD layer will receive a bitstream from the TC layer that includes an FS burst, an upstream PHY synchronization block (PSBu), and forward error correction (FEC) parity information as detailed in [CPON-TCv1.0]. The PSBu includes the preamble, which is used by the OLT’s receiver to synchronize and align to the bursts being transmitted by the ONU. As such, no FAW or training symbols are required in the upstream.

As noted in Section 7.2.1, the ONU will convert this bitstream into QPSK symbols and distribute those symbols between the two polarizations. Pilot symbols are inserted by the ONU every 32 symbols starting with the first symbol in each upstream burst. The pilot sequence follows the same pattern as the downstream, as detailed in Table 8. See Section 7.2.2.4 for more details.

> The ONU MUST support the pilot sequence shown in Table 8 - Full DSP Subframe Pilot Sequence for upstream transmissions.
>
> The OLT MUST support the pilot sequence shown in Table 8 - Full DSP Subframe Pilot Sequence for upstream reception.

7.3 Symbol Rate and PMD Layer Line Rate

[CPON-TCv1.0] defines the line rate for the transmission of FS frames plus the downstream PHY synchronization block (PSBd) to be 8 times the fundamental line rate, or 99.5328 Gbps. A symbol rate of 30.504432 Gbaud has been chosen to support that line rate once all overheads are accounted for. Thus, the final PMD layer line rate for the system is 4x the symbol rate (at 4 bits per symbol), or 122.017728 Gbps.

Symbol rate accuracy enables the successful reception of the signal.

This value was derived to support the requirements of the downstream. Overheads in the upstream and downstream are different, but to simplify implementations and support a roughly 100 Gbps upstream data rate, the same baud rate applies to both directions.

> The OLT MUST support a symbol rate of 30.504432 Gbaud with the modulation format described in Section 7.1, "Modulation."
>
> The OLT MUST maintain the accuracy of the symbol rate of ±20 ppm.
>
> The ONU MUST support a symbol rate of 30.504432 Gbaud with the modulation format described in Section 7.1, "Modulation."
>
> The ONU MUST maintain the accuracy of the symbol rate of ±20 ppm.

8 CPON OPTICAL INTERFACE REQUIREMENTS

8.1 OLT Transmitter Requirements

This section defines the requirements for the downstream transmitter on a compliant OLT. The requirements are defined at the output port of the OLT.

8.1.1 OLT Transmitter Optical Output Power

OLT transmitter optical output power defines the total optical launch power, measured in decibel milliwatts (dBm), from the output port of an OLT while it is operating. This parameter is measured with a calibrated optical power meter (OPM) capable of power measurement in the 1550-nm wavelength range.

The OLT transmitter optical output power, in combination with the ONU receiver sensitivity, establishes a total link budget of 35 dB, which in turn enables the reach and split ratio goals for this specification. The specific required OLT Tx output power value of 0 dBm was established to keep the cost of the ONU as low as possible while allowing the OLT transmitter to be implemented through a variety of different techniques and still meeting the target link budget.

The OLT MUST support a transmitter optical output power of 0 dBm.

The OLT MAY support adjustment of the transmitter optical output power.

The OLT MUST report the transmitter optical output power with an accuracy of ±1.5 dB.

8.1.2 OLT Transmitter Optical Frequency Parameters

8.1.2.1 OLT Transmitter Laser Frequency Accuracy

The transmitter laser center frequency accuracy is the maximum allowable offset of the actual laser frequency from the selected frequency center in Section 6.3. The transmitter optical signal will be mixed with the local oscillator at the coherent receiver; if the difference between these laser frequencies is too large, the DSP will have more difficulty in compensating the CFO between the transmitter and local oscillator lasers.

Note that the laser carrier frequency accuracy of the local oscillator on the receiver is not defined in this specification because different DSPs may handle different amounts of CFO. Each manufacturer will determine their requirements on the local oscillator to meet overall performance requirements.

The OLT MUST have a transmitter laser center frequency accuracy of ±1.5 GHz.

8.1.2.2 OLT Transmitter Laser Linewidth

The transmitter laser linewidth is the full-width half-maximum (-3 dB from the peak power) of the laser's optical field spectrum. The greater the laser linewidth, the greater the phase noise from the receiver, thus increasing the difficulty for the DSP to determine the phase of the symbol.

The OLT MUST have a transmitter laser linewidth less than or equal to 1000 kHz.

8.1.3 OLT Transmitter Optical Signal-to-Noise Ratio

The transmitter optical signal-to-noise ratio (OSNR) compares the level of the optical signal to the level of the optical noise floor measured at the transmitter output. The transmitter OSNR includes the noise of an optical amplifier if one is integrated in the transceiver; it does not include the noise of optical amplifier(s) that is external to the transceiver and located in the network link. For transmitters without integrated optical amplification, the transmitter OSNR is typically dominated by the laser's relative intensity noise (RIN). For transmitters with integrated optical amplification, noise added by the gain element will typically be the significant contributor to the transmitter OSNR value.

The link OSNR, measured at the receiver input, directly impacts the ability of the receiver to decode the optical signal. The transmitter OSNR contributes to the link OSNR. If there are no external optical amplifiers in the link, the link OSNR will usually be the same as the transmitter OSNR. The OSNR will degrade through optical amplifiers, if present in the network link, because of amplified spontaneous emission (ASE).

The OSNR is measured on an optical spectrum analyzer (OSA) with resolution bandwidth sufficiently large to capture the entire signal spectral power. The optical noise floor is measured at a fixed frequency offset from the center wavelength of the signal and averaged across both positive and negative frequency offset such that a flat noise floor can be observed on the OSA. The exact frequency offset is dependent on signal baud rate and spectral characteristic. To measure the OSNR for 100-Gbps QPSK, which operates at approximately 30 Gbaud, the resolution bandwidth of the OSA is set to 0.5 nm (approximately 60 GHz), and the optical noise floor is measured at a ±100-GHz offset or larger from the center wavelength. The noise bandwidth for OSNR measurements is referenced to an optical frequency of 193.6 THz, resulting in a 12.5-GHz measurement bandwidth corresponding to 0.1 nm. The OSNR is then calculated as the ratio of the total signal power to the ASE noise level in 0.1-nm resolution bandwidth. Most modern OSAs will report the OSNR automatically and determine the appropriate noise floor.

The OLT MUST provide a transmitter OSNR of 35 dB or higher.

8.1.4 OLT Polarization Imbalance

Polarization imbalance is defined as the absolute difference in optical power between the X polarization and the Y polarization at the transmitter output. The transceiver uses polarization division multiplexing (PDM) wherein a polarization beam splitter (PBS) separates the transmit laser's signal into two orthogonal polarizations, each of which is independently modulated by in-phase and quadrature Mach-Zehnder Modulators. After modulation, the two polarizations are recombined by a polarization beam combiner (PBC). In the transmitter, the two polarizations experience different insertion loss, which generates polarization imbalance at the transmitter output. To balance the power for each polarization, variable optical attenuators or semiconductor amplifiers may be used on each path:

$$\Delta P_{\mathrm{pol}} = \mathrm{abs}(10 * \log_{10} (P_{\mathrm{x}} / P_{\mathrm{y}})),$$

where P_{x} and P_{y} are the powers of the two nominally orthogonal polarizations carrying the two data streams.

The OLT MUST have a transmitter polarization imbalance of 1.5 dB or less.

8.1.5 OLT IQ Imbalance

In-phase and quadrature (IQ) imbalance is defined as the amplitude imbalance between the in-phase (I) and quadrature (Q) channels on QPSK signals. Ideally, the I and the Q channels are orthogonal to each other with the same amplitude. However, a variety of issues—such as imperfection of drivers, bias points setting, or (in any of the optical hybrids) balanced photodiodes and TIAs in the front end—may introduce IQ imbalance stemming from the mismatch of the gain and/or the phase between the IQ ports. These mismatches degrade performance of DP-QPSK systems.

IQ imbalance compares the amplitude of the I signal with the amplitude of the Q signal and shows the difference in decibels:

$$\text{IQ imbalance} = 10\log_{10}(A_{\mathrm{Q}} / A_{\mathrm{I}}),$$

where A_{I} and A_{Q} are the amplitudes of I and Q components, respectively.

To minimize the impact on the system, a maximum permitted IQ imbalance has been defined.

The OLT MUST have a transmitter IQ imbalance of 1 dB or less.

8.1.6 OLT Transmitter Skew

The transmitter modulation format uses DP-QPSK. The transmission will be modulated via each of two orthogonal polarization modes and then combined before being launched onto transmission path. After combining, the symbols in the different phases and the different polarization modes can start at different times (i.e., have a relative delay with respect to each other) because of variations in electrical trace lengths to the modulators, delays in tributaries, optical combining, and so on. Quadrature skew is defined as the interchannel delay between IQ channels, whereas polarization skew is defined as the interchannel delay between X- and Y-polarization (X-Y) channels.

To minimize this effect and keep alignment in time of the data propagated via each of the modes, skew requirements are defined in this section.

8.1.6.1 OLT Transmitter Quadrature Skew

A QPSK signal is generated by modulating the I and Q orthogonal signals independently and summing them. These signals are differentially encoded binary phase-shift keyed (phase reversal or shift by 180° and back to reference) and then combined to form a four-symbol format (quaternary phase-shift keying). Misalignment in time of the I and Q signals would lead to eye closure (decreased time when symbol is clean) or inter-symbol interference into the sequential time slot for the next symbol; therefore, a reasonable requirement to minimize this effect is defined in this section.

In Figure 8, each of two Mach-Zehnder Modulator paths is driven by a binary dataset to modulate a binary phase-shift keyed signal. Combining two of these signals (I and Q) with a 90° phase shift leads to a combined signal with four phases at 0°, 90°, 180°, or 270° relative to reference representing two bits per symbol. Quadrature skew is defined as the mismatch in time of the symbol slot placement between I and Q.

Figure 8 shows a QPSK Modulator with I and Q skew Δτ. I and Q are each modulated at an approximate symbol rate of 63 Gbaud, which equates to an approximate symbol duration time of 16 ps.

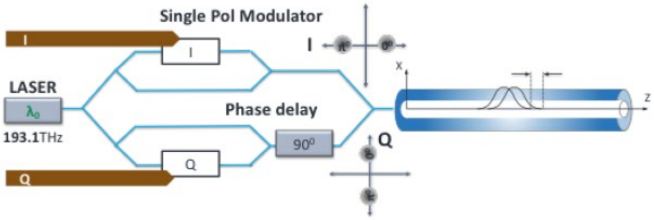


Figure 8 - QPSK Modulator with In-Phase and Quadrature Skew

The OLT MUST have a transmitter quadrature skew of ≤ 1.5 ps.

8.1.6.2 OLT Transmitter Polarization Skew

The DP-QPSK signal is generated by modulating two QPSK signals in each of two orthogonal polarizations, X and Y, and combining them before launching them into the fiber. In Figure 9, the X-axis and Y-axis are perpendicular to the signal propagation in the optical fiber along the Z-axis. The transmitter polarization skew is the time difference between the start and end of symbols in the X and Y polarizations out of the transmitter. The transmitter polarization skew needs to be significantly less than the symbol duration time of 16 ps.

Figure 9 shows a DP-QPSK Modulator with polarization skew Δτ. Polarizations X and Y are each modulated at an approximate symbol rate of 30 Gbaud, which equates to an approximate symbol duration time of 32 ps.

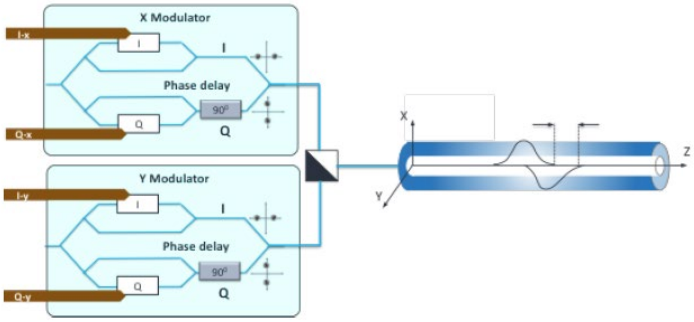


Figure 9 - DP-QPSK Modulator with Polarization Skew

The OLT MUST have a transmitter polarization skew ≤ 5 ps.

8.1.7 OLT Transmitter Tolerance to Reflected Optical Power

System optical return is the amount of the transmitter optical signal that is reflected back to the transmitter port from system elements such as optical connectors or filters. System optical return is defined as the ratio of light power reflected from the network to light power emitted from the transmitter, in decibels:

$$\text{Optical return} = 10 \log_{10} (P_R / P_E),$$

where P_R is the reflected power and P_E is the emitted power.

Figure 10 shows the transmitter optical signal emitted into the network and the return optical signal.

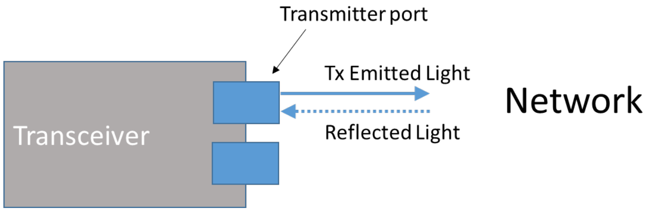


Figure 10 - System Optical Return

The OLT MUST meet the transmitter OSNR requirements in Section 8.1.3, "OLT Transmitter Optical Signal-to-Noise Ratio," in the presence of a system optical return of ≤ -20 dB.

8.2 ONU Receiver Requirements

This section defines the requirements for the downstream receiver on a compliant ONU. The requirements are defined at the input port of the ONU.

8.2.1 ONU Receiver Sensitivity Range

This specification defines a range of power levels over which a compliant ONU is required to achieve a pre-FEC bit error ratio (BER) of $\leq 2\text{x}10^{-2}$ when the link OSNR is ≥ 35 dB (which when combined with the soft decision LDPC FEC defined in [CPON-TCv1.0] results in a post-FEC BER of $\leq 10^{-12}$). The lower value for the ONU Rx of -35 dBm was chosen to achieve the target link budget of 35 dB while keeping the cost of the ONU as low as possible and the cost of the OLT reasonable. The upper value of -15 dBm was chosen to provide a dynamic range of 20 dB, which allows for flexible placement of the ONU within the network without the need for optical attenuation. Compliant ONUs are permitted to exceed these minimum requirements by supporting greater sensitivity and/or a wider dynamic range.

The ONU MUST achieve a pre-FEC bit error ratio of $\leq 2\text{x}10^{-2}$ when the link OSNR is ≥ 35 dB and the received optical power is between -35 dBm (minimum) and -15 dBm.

The ONU MUST report the received optical power with an accuracy of ±2.0 dB.

8.2.2 ONU Chromatic Dispersion Compensation

Chromatic dispersion (CD) causes different wavelengths to travel at different speeds through fiber, resulting in pulse broadening and inter-symbol interference.

The specified value of CD, in picoseconds per nanometer, was determined to support links up to 80 km over standard single-mode fibers.

The ONU MUST tolerate a minimum of 1600 ps/nm of received CD.

The ONU MUST report the measured CD.

8.2.3 ONU Polarization Mode Dispersion Compensation

A fiber optic waveguide supports two optical modes of polarization. Polarization mode dispersion (PolMD) occurs when one of the polarizations travels faster through the fiber than the other. The delay between the two polarizations increases with distance, as shown in Figure 11.

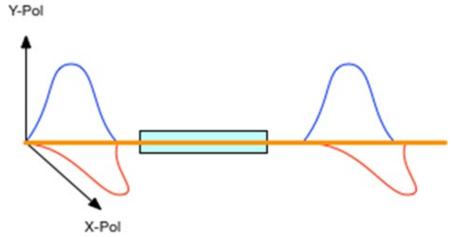


Figure 11 - Differential Group Delay Diagram

In general, PolMD is viewed as a statistical quantity (i.e., a random variable). An instantaneous realization of this statistical quantity in a link is measured as a differential group delay (DGD). In this specification, the PolMD value is understood to stand for the mean PolMD, and the DGD is a realization that can be measured by the transceiver.

To support standard single-mode fibers of around 80 km in length, the transceiver will need to tolerate a PolMD value of at least 8 ps.

The ONU MUST support a minimum received PolMD of 8 ps.

The ONU MUST report the measured differential group delay.

8.2.4 ONU State of Polarization Change Tolerance

Various external actions, such as vibration of the fiber or nearby lightning strikes, can cause changes in the state of polarization (SoP). To ensure the transceiver can continue to receive the signal correctly in the presence of these SoP changes, the transceiver is required to implement SoP tracking and be capable of tolerating an SoP change rate of at least 50 kiloradians per second (krad/s).

The ONU MUST tolerate an SoP change rate of at least 50 krad/s.

The ONU MUST report the measured SoP change rate.

8.2.5 ONU Polarization Imbalance Tolerance

This specification defines "polarization imbalance" or polarization-dependent loss (PDL) as the absolute difference in optical power between the X polarization and the Y polarization seen at the input of a coherent receiver. The total PDL is generated by the combination of transmitter PDL, as outlined in Section 8.1.4, and the transmission network elements (multiplexers, splitters, optical amplifiers, etc.). The receiver is required to tolerate the maximum PDL expected for the optical input signal so it can properly decode the symbols.

The ONU MUST tolerate a total PDL of 2.0 dB for the incoming optical signal.

The ONU MUST report the measured PDL.

8.2.6 ONU IQ Imbalance Tolerance

As noted in Section 8.1.5, IQ imbalance is defined as the amplitude imbalance between the in-phase and quadrature channels on QPSK signals. IQ imbalance compares the amplitude of the I signal with the amplitude of the Q signal and shows the difference in decibels (dB).

It is not expected that the transmission path will introduce additional IQ imbalance; therefore, the source of any IQ imbalance comes from the transmitter and/or the receiver. As this specification defines receiver tolerance at the input to the receiver, the required tolerance is therefore the same as the worst-case requirement for the transmitter.

The ONU MUST tolerate an IQ imbalance of 1 dB for the incoming signal.

8.2.7 ONU Received Frequency Accuracy

To ensure the ability to receive signals successfully, the transceiver needs to be able to receive signals that are within a certain offset of the defined channel grid. This corresponds to the transmitter laser frequency accuracy defined in Section 8.1.2.1.

> For any channel that it supports, the ONU MUST be capable of successfully receiving signals with a center frequency within ±1.8 GHz of the DWDM grid defined in Section 6.3, "Frequency Grid and Tuning."

8.2.8 ONU Skew Tolerance

As noted in Section 8.1.6, skew is defined as the interchannel delay in IQ or X-Y as seen by a receiver.

The receiver is required to tolerate the maximum IQ and X-Y skews expected for the optical input signal in this application so it can properly decode the symbols.

8.2.8.1 ONU Quadrature Skew Tolerance

Quadrature skew is generated by the transmitter, as outlined in Section 8.1.6.1, as well as by the receiver.

Quadrature skew is not expected to change as the optical signal propagates through network, so the quadrature skew of the optical input signal to the receiver is the same as the transmitter quadrature skew. As a result, the quadrature skew tolerance by a receiver is only related to the transmitter quadrature skew and skew variation.

> The ONU MUST have a minimum receiver quadrature skew tolerance of 1.5 ps for the incoming optical signal.

8.2.8.2 ONU Polarization Skew Tolerance

Polarization skew seen at a receiver DSP is the combination of polarization skew (or DGD) generated by the transmitter (as outlined in Section 8.1.6.2), the optical fiber, the receiver, and other optical components in the link.

The required tolerance of 25 ps for polarization skew or DGD is approximately equal to the 8 ps PolMD tolerance defined in Section 8.2.3.

> The ONU MUST have a minimum receiver polarization skew tolerance of 25 ps for the incoming optical signal as seen by the receiver.

8.2.9 ONU Receiver Reflectance

Some amount of the light arriving at a receiver will be reflected back into the fiber plant that connects the receiver to the light source. Because reflections can contribute to noise at the receiver, they need to be controlled, which this specification enables by imposing a limit on reflectance of the receiver port.

The reflectance of the receiver is defined, in decibels, as the ratio of light power reflected from it to the light power incident on it:

$$\text{Reflectance} = 10 \log_{10} (P_R / P_I),$$

where P_R is the reflected power and P_I is the incident power.

Figure 12 illustrates the incident light on the receiver and the reflected light from the receiver.

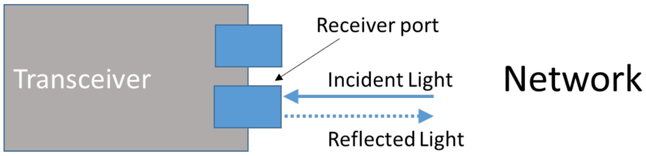


Figure 12 - Receiver Reflectance

> The ONU MUST have a reflectance from the receiver of ≤ -20 dB.

8.3 ONU Transmitter Requirements

This section defines the requirements for the upstream transmitter on a compliant ONU. The requirements are defined at the output port of the ONU.

8.3.1 ONU Transmitter Optical Output Power

ONU transmitter optical output power defines the total optical launch power, measured in decibel milliwatts (dBm), from the output port of an ONU while it is transmitting. This parameter is measured with a calibrated OPM capable of power measurement in the 1550-nm wavelength range.

The ONU transmitter optical output power, in combination with the OLT receiver sensitivity, establishes a total link budget of 35 dB, which in turn enables the reach and split ratio goals for this specification. The specific required ONU Tx output power value of -2.5 dBm was established to minimize ONU cost by keeping the ONU transmitter power as low as possible while allowing the OLT receiver to be implemented at a reasonable cost.

> The ONU MUST support a transmitter optical output power of -2.5 dBm.
>
> The ONU MAY support adjustment of the transmitter optical output power.
>
> The ONU MUST report the transmitter optical output power with an accuracy of ±1.5 dB.

8.3.2 ONU Transmitter Optical Frequency Parameters

8.3.2.1 ONU Transmitter Laser Frequency Accuracy

The transmitter laser center frequency accuracy is the maximum allowable offset of the actual laser frequency from the selected frequency center in Section 6.3. The transmitter optical signal will be mixed with the local oscillator at the coherent receiver; if the difference between these laser frequencies is too large, the DSP will have more difficulty in compensating the CFO between the transmitter and local oscillator lasers.

Note that the laser carrier frequency accuracy of the local oscillator on the receiver is not defined in this specification because different DSPs may handle different amounts of CFO. Each manufacturer will determine their requirements on the local oscillator to meet overall performance requirements.

> The ONU MUST have a transmitter laser center frequency accuracy of ±1.5 GHz.

8.3.2.2 ONU Transmitter Laser Linewidth

The transmitter laser linewidth is the full-width half-maximum (-3 dB from the peak power) of the laser's optical field spectrum. The greater the laser linewidth, the greater the phase noise from the receiver, thus increasing the difficulty for the DSP to determine the phase of the symbol.

> The ONU MUST have a transmitter laser linewidth less than or equal to 1000 kHz.

8.3.3 ONU Transmitter Optical Signal-to-Noise Ratio

The transmitter optical signal-to-noise ratio (OSNR) compares the level of the optical signal to the level of the optical noise floor measured at the transmitter output. The transmitter OSNR includes the noise of an optical amplifier if one is integrated in the transceiver; it does not include the noise of optical amplifier(s) that is external to the transceiver and located in the network link. For transmitters without integrated optical amplification, the transmitter OSNR is typically dominated by the laser’s relative intensity noise (RIN). For transmitters with integrated optical amplification, noise added by the gain element will typically be the significant contributor to the transmitter OSNR value.

The link OSNR, measured at the receiver input, directly impacts the ability of the receiver to decode the optical signal. The transmitter OSNR contributes to the link OSNR. If there are no external optical amplifiers in the link, the link OSNR will usually be the same as the transmitter OSNR. The OSNR will degrade through optical amplifiers, if present in the network link, because of amplified spontaneous emission (ASE).

The OSNR is measured on an optical spectrum analyzer (OSA) with resolution bandwidth sufficiently large to capture the entire signal spectral power. The optical noise floor is measured at a fixed frequency offset from the center wavelength of the signal and averaged across both positive and negative frequency offset such that a flat noise floor can be observed on the OSA. The exact frequency offset is dependent on signal baud rate and spectral characteristic. To measure the OSNR for 100-Gbps QPSK, which operates at approximately 30 Gbaud, the resolution bandwidth of the OSA is set to 0.5 nm (approximately 60 GHz), and the optical noise floor is measured at a ±100-GHz offset or larger from the center wavelength. The noise bandwidth for OSNR measurements is referenced to an optical frequency of 193.6 THz, resulting in a 12.5-GHz measurement bandwidth corresponding to 0.1 nm. The OSNR is then calculated as the ratio of the total signal power to the ASE noise level in 0.1-nm resolution bandwidth. Most modern OSAs will report the OSNR automatically and determine the appropriate noise floor.

The ONU MUST provide a transmitter OSNR of 35 dB or higher.

8.3.4 ONU Polarization Imbalance

Polarization imbalance is defined as the absolute difference in optical power between the X polarization and the Y polarization at the transmitter output. The transceiver uses polarization division multiplexing (PDM) wherein a polarization beam splitter (PBS) separates the transmit laser's signal into two orthogonal polarizations, each of which is independently modulated by in-phase and quadrature Mach-Zehnder Modulators. After modulation, the two polarizations are recombined by a polarization beam combiner (PBC). In the transmitter, the two polarizations experience different insertion loss, which generates polarization imbalance at the transmitter output. To balance the power for each polarization, variable optical attenuators or semiconductor amplifiers may be used on each path:

$$\Delta P_{\mathrm{pol}} = \mathrm{abs}(10 * \log_{10} (P_{\mathrm{x}} / P_{\mathrm{y}})),$$

where P_{x} and P_{y} are the powers of the two nominally orthogonal polarizations carrying the two data streams.

The ONU MUST have a transmitter polarization imbalance of 1.5 dB or less.

8.3.5 ONU IQ Imbalance

IQ imbalance is defined as the amplitude imbalance between the in-phase (I) and quadrature (Q) channels on QPSK signals. Ideally, the I and the Q channels are orthogonal to each other with the same amplitude. However, a variety of issues—such as the imperfection of drivers, bias points setting, or (in any of the optical hybrids) balanced photodiodes and TIAs in the front end—may introduce IQ imbalance stemming from the mismatch of the gain and/or the phase between the IQ ports. These mismatches degrade performance of DP-QPSK systems.

IQ imbalance compares the amplitude of the I signal with the amplitude of the Q signal and shows the difference in decibels.

$$\text{IQ imbalance} = 10\log_{10}(A_{\mathrm{Q}} / A_{\mathrm{I}}),$$

where A_{I} and A_{Q} are the amplitudes of I and Q components, respectively.

To minimize the impact on the system, a maximum permitted IQ imbalance has been defined.

The ONU MUST have a transmitter IQ imbalance of 1 dB or less.

8.3.6 ONU Transmitter Skew

The transmitter modulation format uses DP-QPSK. The transmission will be modulated via each of two orthogonal polarization modes and then combined before being launched onto transmission path. After combining, the symbols in the different phases and the different polarization modes can start at different times (i.e., have a relative delay with respect to each other) because of variations in electrical trace lengths to the modulators, delays in tributaries, optical combining, and so on. Quadrature skew is defined as the interchannel delay between IQ channels, whereas polarization skew is defined as the interchannel delay between X- and Y-polarization (X-Y) channels.

To minimize this effect and keep alignment in time of the data propagated via each of the modes, skew requirements are defined in this section.

8.3.6.1 ONU Transmitter Quadrature Skew

A QPSK signal is generated by modulating the I and Q orthogonal signals independently and summing them. These signals are differentially encoded binary phase-shift keyed (phase reversal or shift by 180° and back to reference) and then combined to form a four-symbol format (quaternary phase-shift keying). Misalignment in time of the I and Q signals would lead to eye closure (decreased time when symbol is clean) or inter-symbol interference into the sequential time slot for the next symbol; therefore, a reasonable requirement to minimize this effect is defined in this section.

In Figure 13, each of two Mach-Zehnder Modulator paths is driven by a binary dataset to modulate a binary phase-shift keyed signal. Combining two of these signals (I and Q) with a 90° phase shift leads to a combined signal with four phases at 0°, 90°, 180°, or 270° relative to reference representing two bits per symbol. Quadrature skew is defined as the mismatch in time of the symbol slot placement between I and Q.

Figure 13 shows a QPSK Modulator with I and Q skew $\Delta\tau$. I and Q are each modulated at an approximate symbol rate of 30 Gbaud, which equates to an approximate symbol duration time of 32 ps.

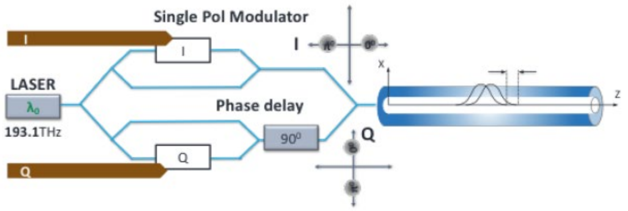


Figure 13 - QPSK Modulator with In-Phase and Quadrature Skew

The ONU MUST have a transmitter quadrature skew of ≤ 1.5 ps.

8.3.6.2 ONU Transmitter Polarization Skew

The DP-QPSK signal is generated by modulating two QPSK signals in each of two orthogonal polarizations, X and Y, and combining them before launching them into the fiber. In Figure 14, the X-axis and Y-axis are perpendicular to the signal propagation in the optical fiber along the Z-axis. The transmitter polarization skew is the time difference between the start and end of symbols in the X and Y polarizations out of the transmitter. The transmitter polarization skew needs to be significantly less than the symbol duration time of 16 ps.

Figure 14 shows a DP-QPSK Modulator with polarization skew $\Delta\tau$. Polarizations X and Y are each modulated at an approximate symbol rate of 30 Gbaud, which equates to an approximate symbol duration time of 32 ps.

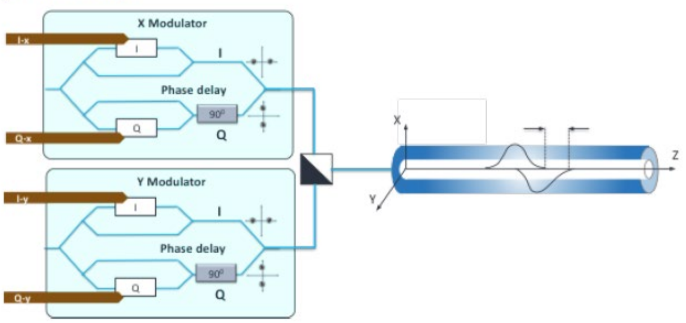


Figure 14 - DP-QPSK Modulator with Polarization Skew

The ONU MUST have a transmitter polarization skew ≤ 5 ps.

8.3.7 ONU Transmitter Tolerance to Reflected Optical Power

System optical return is the amount of the transmitter optical signal that is reflected back to the transmitter port from system elements, such as optical connectors or filters. System optical return is defined as the ratio of light power reflected from the network to light power emitted from the transmitter in decibels:

$$\text{Optical return} = 10\log_{10}(P_R / P_E)$$

where P_R is the reflected power and P_E is the emitted power.

Figure 15 shows the transmitter optical signal emitted into the network and the return optical signal.

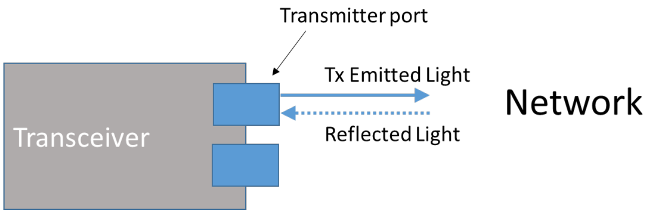


Figure 15 - System Optical Return

The ONU MUST meet the transmitter OSNR requirements in Section 8.1.3, "OLT Transmitter Optical Signal-to-Noise Ratio," in the presence of a system optical return of ≤ -20 dB.

8.3.8 ONU Transmitter Output Power When Not Transmitting

Ideally, when an ONU is not transmitting, it emits no power in the upstream to avoid causing any interference with other transmitting ONUs. However, this is not always practical. Therefore, it is important to establish a requirement to limit the amount of power that an ONU can allow into the upstream when not transmitting to maintain the necessary OSNR at the OLT receiver.

To determine an appropriate value, modeling of the impact of the noise contributions from ONUs was conducted. Given that in some high-density deployment scenarios the ONUs may be very close to the OLT, a worst-case scenario of essentially zero distance and idealized splitters was modeled. The results indicated that even in this worst-case scenario, if the ONU Tx output power remains at or below -50 dBm when the ONU is not transmitting, the impact to the OLT receiver is minimal; as a result, in a real-world scenario, the impact at this level would be even less.

The ONU MUST NOT have an output power greater than -50 dBm when it is not actively transmitting.

8.4 OLT Receiver Requirements

This section defines the requirements for the upstream receiver on a compliant OLT. The requirements are defined at the input port of the OLT.

8.4.1 OLT Receiver Sensitivity Range

This specification defines a range of power levels over which a compliant OLT is required to achieve a pre-FEC bit error ratio (BER) of $\leq 2\text{x}10^{-2}$ when the link OSNR is ≥ 35 dB (which when combined with the soft decision LDPC FEC defined in [CPON-TCv1.0] results in a post-FEC BER of $\leq 10^{-12}$). The lower value for the OLT Rx of -37.5 dBm was chosen to achieve the target link budget of 35 dBm while keeping the cost of the ONU as low as possible and the cost of the OLT reasonable. The upper value of -17.5 dB was chosen to provide a dynamic range of 20 dB, which allows for flexible placement of the ONU within the network without the need for optical attenuation. Compliant OLTs are permitted to exceed these minimum requirements by supporting greater sensitivity and/or a wider dynamic range.

The OLT MUST achieve a pre-FEC bit error ratio of $\leq 2\text{x}10^{-2}$ when the link OSNR is ≥ 35 dB and the received optical power is between -37.5 dBm (minimum) and -17.5 dBm.

The OLT MUST report the received optical power with an accuracy of ±2.0 dB.

8.4.2 OLT Chromatic Dispersion Compensation

Chromatic dispersion (CD) causes different wavelengths to travel at different speeds through fiber, resulting in pulse broadening and inter-symbol interference.

The specified value of CD, in picoseconds per nanometer, was determined to support links up to 80 km over standard single-mode fibers.

The OLT MUST tolerate a minimum of 1600 ps/nm of received CD.

The OLT MUST report the measured CD.

8.4.3 OLT Polarization Mode Dispersion Compensation

A fiber optic waveguide supports two optical modes of polarization. PolMD occurs when one of the polarizations travels faster through the fiber than the other. The delay between the two polarizations increases with distance, as shown in Figure 16.

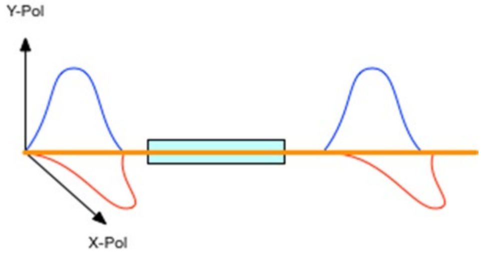


Figure 16 - Differential Group Delay Diagram

In general, PolMD is viewed as a statistical quantity (i.e., a random variable). An instantaneous realization of this statistical quantity in a link is measured as a differential group delay (DGD). In this specification, the PolMD value is understood to stand for the mean PolMD, and the DGD is a realization that can be measured by the transceiver.

To support standard single-mode fibers of around 80 km in length, the transceiver will need to tolerate a PolMD value of at least 8 ps.

The OLT MUST support a minimum received PolMD of 8 ps.

The OLT MUST report the measured differential group delay.

8.4.4 OLT State of Polarization Change Tolerance

Various external actions, such as vibration of the fiber or nearby lightning strikes, can cause changes in the state of polarization (SoP). To ensure the transceiver can continue to receive the signal correctly in the presence of these SoP changes, the transceiver is required to implement SoP tracking and be capable of tolerating an SoP change rate of at least 50 kiloradians per second (krad/s).

The OLT MUST tolerate an SoP change rate of at least 50 krad/s.

The OLT MUST report the measured SoP change rate.

8.4.5 OLT Polarization Imbalance Tolerance

This specification defines "polarization imbalance" or polarization-dependent loss (PDL) as the absolute difference in optical power between the X polarization and the Y polarization seen at the input of a coherent receiver. The total PDL is generated by the combination of transmitter PDL, as outlined in Section 8.1.4, and the transmission network elements (multiplexers, splitters, optical amplifiers, etc.). The receiver is required to tolerate the maximum PDL expected for the optical input signal so it can properly decode the symbols.

The OLT MUST tolerate a total PDL of 2.0 dB for the incoming optical signal.

The OLT MUST report the measured PDL.

8.4.6 OLT IQ Imbalance Tolerance

As noted in Section 8.1.5, IQ imbalance is defined as the amplitude imbalance between the in-phase and quadrature channels on QPSK signals. IQ imbalance compares the amplitude of the I signal with the amplitude of the Q signal and shows the difference in decibels (dB).

It is not expected that the transmission path will introduce additional IQ imbalance; therefore, the source of any IQ imbalance comes from the transmitter and/or the receiver. As this specification defines receiver tolerance at the input to the receiver, the required tolerance is therefore the same as the worst-case requirement for the transmitter.

> The OLT MUST tolerate an IQ imbalance of 1 dB for the incoming signal.

8.4.7 OLT Received Frequency Accuracy

To ensure the ability to receive signals successfully, the transceiver needs to be able to receive signals that are within a certain offset of the defined channel grid. This corresponds to the transmitter laser frequency accuracy defined in Section 8.1.2.1.

> For any channel that is supports, the OLT MUST be capable of successfully receiving signals with a center frequency within ±1.8 GHz of the DWDM grid defined in Section 6.3, "Frequency Grid and Tuning."

8.4.8 OLT Skew Tolerance

As noted in Section 8.1.6, skew is defined as the interchannel delay in the IQ or X-Y as seen by a receiver.

The receiver is required to tolerate the maximum IQ and X-Y skews expected for the optical input signal in this application so it can properly decode the symbols.

8.4.8.1 ONU Quadrature Skew Tolerance

Quadrature skew is generated by the transmitter, as outlined in Section 8.1.6.1, as well as by the receiver.

Quadrature skew is not expected to change as the optical signal propagates through network, so the quadrature skew of the optical input signal to the receiver is the same as the transmitter quadrature skew. As a result, the quadrature skew tolerance by a receiver is only related to the transmitter quadrature skew and skew variation.

> The OLT MUST have a minimum receiver quadrature skew tolerance of 1.5 ps for the incoming optical signal.

8.4.8.2 ONU Polarization Skew Tolerance

Polarization skew seen at a receiver DSP is the combination of polarization skew (or DGD) generated by the transmitter (as outlined in Section 8.1.6.2), the optical fiber, the receiver, and other optical components in the link.

The required tolerance of 25 ps for polarization skew or DGD is approximately equal to the 8 ps PolMD tolerance defined in Section 8.2.3.

> The OLT MUST have a minimum receiver polarization skew tolerance of 25 ps for the incoming optical signal as seen by the receiver.

8.4.9 OLT Receiver Reflectance

Some amount of the light arriving at a receiver will be reflected back into the fiber plant that connects the receiver to the light source. Because reflections can contribute to noise at the receiver, they need to be controlled, which this specification enables by imposing a limit on reflectance of the receiver port.

The reflectance of the receiver is defined, in decibels, as the ratio of light power reflected from it to the light power incident on it:

$$\text{Reflectance} = 10 \log_{10} (P_R / P_I),$$

where P_R is the reflected power and P_I is the incident power.

Figure 17 illustrates the incident light on the receiver and the reflected light from the receiver.

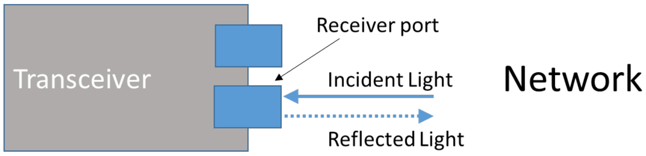


Figure 17 - Receiver Reflectance

The ONU MUST have a reflectance from the receiver of ≤ -20 dB.

9 CPON OUT OF BAND CHANNEL

9.1 CPON OOB Channel Overview

With the increased scalability and extended reach of CPON, the need for an efficient and dedicated management channel for ONU discovery becomes critical. The out-of-band (OOB) management channel provides a low-bitrate unidirectional upstream signaling path from the ONU to the OLT, addressing the limitations of traditional in-band upstream communications, which are no longer sufficient to support the size and capacity of CPON deployments.

In legacy PON systems, ONU discovery processes introduce latency and disrupt normal data transmission. For example, in a 20-km deployment, a discovery window halts data transmission for 250 µs (200 µs for round-trip time plus ~50 µs of random offset time), leading to potential service degradation and inefficiencies. For CPON, given that CPON technology supports up to 512 ONUs and distances of up to 80 km, the discovery window will need to be greater than 800 µs, which would significantly impact latency and jitter in the upstream. Therefore, to provide efficient network operation, a means of eliminating these discovery windows is needed; an independent OOB channel can serve that purpose.

The OOB channel does this by providing a dedicated upstream path for ONU discovery, eliminating the need for separate, dedicated discovery windows. This provides two key benefits:

- Network latency and jitter are significantly reduced, as there is no longer a need to schedule around those discovery windows.
- Scalability and reliability are improved by providing continuous, collision-tolerant onboarding and "last gasp" signaling.

The messages carried over the OOB channel and their format are defined in [CPON-TCv1.0]. This specification does not define the exact implementation details of the OOB channel. In other words, it does not define how ONU and OLT manufacturers should implement the OOB transmitter or receiver within their products. Instead, it defines the requirements for the interface between the ONU and the OLT that enables interoperable implementations and leaves the design open for vendor-specific optimization. To leave that design as simple as possible, the ONU is never required to transmit on the OOB channel and data channel simultaneously, although it is permitted to do so in some cases as per [CPON-TCv1.0].

> The ONU MUST support the transmission of an OOB channel in the upstream when it is not transmitting on the main data channel, carrying messages as required by [CPON-TCv1.0].
>
> The OLT MUST support receiving an OOB channel in the upstream simultaneous with upstream bursts on the main data channel from different ONUs for discovery and other messages as required by [CPON-TCv1.0].

9.2 CPON OOB Channel PMD Requirements

The PMD Layer requirements common for both the ONU and OLT for the OOB channel will be added in a future version of this specification.

9.2.1 OOB Frequency

The OOB channel is defined to exist at a 25 GHz offset relative to the center frequency of the data channel defined within this specification. A 25 GHz offset was chosen for several reasons:

- It keeps the signal within the same 100 GHz DWDM optical bandpass as the main data channel;
- It is sufficiently distant from the center frequency of the main data channel to avoid impacting the received BER of the main data channel while maintaining a BER $\leq 10^{-6}$ on the OOB channel;
- It is a multiple of 6.25 GHz, which aligns with many existing components, easing implementation; and
- It allows multiple implementation approaches at both the ONU and OLT, including both digital and analog implementations.

Given the need for the OLT to be capable of isolating OOB signals from data signals, a reasonable degree of accuracy in transmitting the OOB signal is required. Therefore, this specification establishes a requirement that the center frequency of the OOB signal be within ±1.5 GHz of the OOB target center frequency, with the OOB target center frequency defined as the data channel target center frequency +25 GHz.

For example, for upstream channel 45 (the second channel within upstream block 1, as per Figure 4), the target center frequency is 194.500 THz. Therefore, the target center frequency for the associated OOB channel is 194.525 THz, ±1.5 GHz.

> The ONU MUST support the transmission of an OOB channel in the upstream centered at +25 GHz ±1.5 GHz relative to the target center frequency of the data channel it is associated with.
>
> The OLT MUST support the reception of an OOB channel in the upstream centered at +25 GHz ±1.5 GHz relative to the target center frequency of the data channel it is associated with.

9.2.2 OOB Modulation

Because the OOB channel is only used for discovery and dying gasp messages and therefore does not need to carry much data, low bitrates (relative to the throughput of the data channel) are perfectly acceptable. Rather, given its close proximity to the data channel, the priority for the OOB channel is robustness. Therefore, this specification adopts the use of on/off keying (OOK)—specifically the use of non-return to zero (NRZ)—for the OOB channel. This provides the greatest probability of successful reception, keeps power levels as low as possible to avoid interference with the data channel, and maintains implementation flexibility via simplicity. Additionally, to maintain alignment with other standards (such as [G.9804.3]), this specification adopts the convention that a high level of light emission corresponds to binary one, and a low level of light emission corresponds to binary zero.

> The ONU MUST transmit on the OOB channel using NRZ line coding, with a high level of light emission corresponding to binary one, and a low level of light emission corresponding to binary zero.
>
> The OLT MUST receive an OOB signal using NRZ line coding, with a high level of light reception corresponding to binary one, and a low level of light reception corresponding to binary zero.

9.2.3 OOB Symbol Rate

As noted earlier, given that the OOB channel is only used for discovery and dying gasp messages, a high bitrate is not required. However, given that the OOB channel is unscheduled, it is important to ensure that the bitrate provides enough transmission opportunities to allow a reasonable statistical probability of collision avoidance. For this specification, a symbol rate of 3 megabaud (Mbaud) was chosen, corresponding to 3 megabits per second (mbps). This value was selected because in combination with the backoff algorithm specified in [CPON-TCv1.0], even in a mass registration scenario with 512 ONUs, statistically there should never be more than 4 ONUs transmitting at the same time, and at least some transmissions are likely to be received, reducing the number of ONUs attempting to use the OOB channel.

> The ONU MUST transmit on the OOB channel at a symbol rate of 3 Mbaud.
>
> The OLT MUST receive OOB signals at a symbol rate of 3 Mbaud.

9.2.4 OOB Optical Power

In considering the output optical power of an ONU transmitting on the OOB channel, two extreme scenarios were considered:

1. A scenario where a distant ONU was transmitting data (and therefore the signal arrived at the OLT near the detection threshold required by this specification) while 4 nearby ONUs were transmitting on the OOB channel simultaneously (and therefore a very strong signal was received at the OLT); and
2. A scenario where a distant ONU was transmitting on the OOB channel (which therefore was received with very low power by the OLT) while a nearby ONU was transmitting data (and therefore the OLT received a very strong signal was received by the OLT near the top end of the receiver's dynamic range).

Evaluating the first scenario is necessary to ensure that the OOB channel does not negatively impact the OLT's reception of the data channel, and evaluating the second scenario is necessary to ensure that the OLT is able to successfully receive the OOB channel even when the data channel signal is much stronger. Based on these evaluations, it was determined that an ONU Tx output power of -17.5 dBm for the OOB channel would address both scenarios, permitting the OOB channel to be received with a BER $\leq 10^{-6}$, while still maintaining a data channel pre-FEC BER of $\leq 2x10^{-2}$ as per Section 8.4.1. Note that as the system supports a link budget of up to 35 dB and a maximum power differential of 20 dB, this means that the OLT receiver must be capable of receiving an OOB burst with a received optical power of between -32.5 and -52.5 dBm while achieving a BER of $\leq 10^{-6}$.

The ONU MUST transmit on the OOB channel with an optical output power of -17.5 dBm.

The OLT MUST achieve a BER of $\leq 10^{-6}$ on the OOB channel when the received optical power is between -52.5 dBm (minimum) and -32.5 dBm.

Appendix I Acknowledgements

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In memory of Brian Soloducha, whose technical contributions were invaluable to this effort, and whose cheerful greetings are greatly missed.

* * *