Point-to-Point Coherent Optics

P2P Coherent Optics Physical Layer 1.0 Specification

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Key to Document Status Codes

Work in Progress An incomplete document, designed to guide discussion and generate feedback that may include several alternative requirements for consideration.

Draft A document in specification format considered largely complete, but lacking review by Members and vendors. Drafts are susceptible to substantial change during the review process.

Issued A generally public document that has undergone Member and Technology Supplier review, cross-vendor interoperability, and is for Certification testing if applicable. Issued Specifications are subject to the Engineering Change Process.

Closed A static document, reviewed, tested, validated, and closed to further engineering change requests to the specification through CableLabs.

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1 SCOPE

1.1 Introduction and Purpose

This specification is part of the Point-to-Point Coherent Optics family of specifications developed by Cable Television Laboratories (CableLabs). These specifications enable the development of interoperable transceivers using coherent optical technology over point-to-point 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 optical physical layer requirements for coherent optical transceivers operating at 100 gigabits per second (Gbps). It is designed and optimized to support fiber links up to approximately 40 km. It will also support links of 80 km, and can support links up to 120 km in some circumstances.

1.2 Background

Most operators have a very limited number of fibers available between the Headend (HE)/Hub and the fiber node to use for data and video services: often only 1-2 fiber strands are available to serve groups of fiber nodes. With end users demanding more bandwidth to the home, operators need a strategy for increasing capacity in the optical access network. One way is to add more fiber between the HE/Hub and the fiber node. However, if this is even possible, retrenching is costly and time consuming, making this option unattractive. A solution that re-uses the existing infrastructure much more efficiently would be preferred. One such solution is to use coherent optics technology along with Wavelength Division Multiplexing (WDM) in the optical access network.

Coherent optics technology is common in the submarine, long-haul, and metro networks, but has not yet been applied to access networks due to the relatively high cost of the technology for those applications. However, the cable access network differs from the other types of networks in the following ways: distances from the HE/Hub to the fiber node are much shorter, the network is always a point-to-point architecture, and fixed-wavelength optical passives are utilized. With these differences, the capabilities, performance and features of transceivers can be relaxed in areas such as optical output power level, transmitter wavelength capability, the amount of fiber chromatic dispersion compensation, and transmitter optical-to-signal-noise ratio (OSNR). This potentially allows lower cost designs and the use of lower cost components in cable access networks. Using coherent optics in the access network opens new possibilities for cable operators as well as for other telecommunication service providers.

1.3 Requirements

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

"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 a particular marketplace requires it or because it enhances the product, for example; another vendor may omit the same item.

1.4 Device Under Test

All requirements in this document are written against a specific Device Under Test (DUT), a "Point-to-Point Coherent Optic Transceiver", which is the subject of this specification. In order to simplify the text, the term "transceiver" is used to refer to this device throughout the specification. Therefore, unless specified otherwise, whenever the term "transceiver" is used in the text, it should be assumed to refer to a Point-to-Point Coherent Optic Transceiver.

1.5 Organization of Document

Section 1 provides an overview of the Point-to-Point Coherent Optics series of specifications, including background and conventions.

Sections 2 - 4 include the references, terms, acronyms, and symbols used throughout this specification.

Section 5 provides a technical overview, including a technology overview, reference interfaces, functional block diagrams, and functional assumptions.

Sections 6 - 7 contain the normative material, with Section 6 containing general transceiver requirements, and Section 7 defining the 100G physical layer.

2 REFERENCES

2.1 Normative References

In order 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 documents listed below.

[IEEE 802.3-2015]	IEEE Std. 802.3™-2015, IEEE Standard for Ethernet, 3 September 2015
[ITU-T G.698.2]	ITU-T Recommendation G.698.2, Amplified multichannel dense wavelength division multiplexing applications with single channel optical interfaces. November 2009
[ITU-T G.709]	ITU-T Recommendation G.709/Y.1331, Interfaces for the optical transport network, 06/2016
[ITU-T G.709.2]	ITU-T Recommendation G.709.2, OTU4 long-reach interface
[ITU-T G.798]	ITU-T Recommendation G.798, Characteristics of optical transport network hierarchy equipment functional blocks, 12/2017

2.2 Informative References

This specification uses the following informative references.

[CFP-MIS]	CFP MSA Management Interface Specification, Version 2.6 r06a, March 24, 2017, http://www.cfp-msa.org/Documents/CFP_MSA_MIS_V2p6r06a.pdf
[ITU-T G.694.1]	ITU-T Recommendation G.694.1, Spectral grids for WDM applications: DWDM frequency grid, February 2012
[ITU-T G.Sup39]	ITU-T G-series Recommendations - Supplement 39, Optical system design and engineering considerations, February 2016, https://www.itu.int/rec/T-REC-G.Sup39-201602-I/en
[OpenROADM]	OpenROADM Optical Specifications, v2.00, November 29, 2017, 20171121a, Open ROADM MSA specification ver 2 00.xlsx.
[OPT-P2P-OSSI]	P2P Coherent Optics Operations and Support System Interface Specification, (not yet published), Cable Television Laboratories, Inc.
[OPT-P2P-ARCH]	P2P Coherent Optics Architecture Specification, P2PCO-SP-ARCH-I01-180629, June 29, 2018, Cable Television Laboratories, Inc.
[Smith]	B. Smith, et. al., “Staircase Codes: FEC for 100 Gb/s OTN,” IEEE J. Lightwave Tech., 2011

2.3 Reference Acquisition

- Cable Television Laboratories, Inc., 858 Coal Creek Circle, Louisville, CO 80027; Phone +1-303-661-9100; Fax +1-303-661-9199; http://www.cablelabs.com
- CFP MSA, http://www.cfp-msa.org/documents.html
- Institute of Electrical and Electronics Engineers (IEEE), +1 800 422 4633 (USA and Canada); http://www.ieee.org
- ITU: International Telecommunications Union (ITU), http://www.itu.int/home/contact/index.html
- Open ROADM Multi-Source Agreement (MSA), http://openroadm.org/download.html

3 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.
CFP MSA Management Interface Specification (MIS)	CFP Management Interface is the main communication interface between a Host and a CFP module. Host uses this interface to control and monitor the startup, shutdown, and normal operation of the CFP modules it manages [CFP-MIS].
Client-Side	Refers to the side of the transceiver that faces the electrical rather than optical interface (or line-side).
Coherent Optics	Coherent Optics encodes information in both in-phase (I) amplitude and quadrature (Q) amplitude components of a carrier.
Data Rate	Throughput, data transmitted in units of time usually in bits per second (bps).
Decibels	Ratio of two power levels expressed mathematically as $dB = 10\log_{10}(P_{OUT}/P_{IN})$.
Decibel-milliwatt	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 milliwatt.
Ethernet	Computer networking protocol used to send frames between a source and destination address at OSI Layer 2
Ethernet Switch	A network device for doing Ethernet packet switching
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.
Headend	A central facility that is used for receiving, processing, and combining broadcast, narrowcast and other signals to be carried on a cable network. Somewhat analogous to a telephone company's central office. Location from which the DOCSIS® cable plant fans out to subscribers.
Host-Side	See Client-Side.
Hybrid Fiber/Coaxial System (HFC)	A broadband bidirectional shared-media transmission system using fiber trunks between the head-end and the fiber nodes, and coaxial distribution from the fiber nodes to the customer locations.
Line-Side	Refers to the side of the transceiver that faces the optical rather than electrical interface (or client-side).
Media Access Control	Used to refer to the OSI Layer 2 element of the system.
Multiplexer/Demultiplexer	Combines multiple lines-in to a single line-out. Demultiplexer does the opposite by splitting a single line-in to many lines-out.
Muxponder	Combination transponder and multiplexer in a single device
Network Lane	The term “network lane” refers to the optical data lane between the transceivers. A network lane is equivalent to an optical wavelength of the transceiver. See Network Lane for more details.
Network-Side	See Line-Side.
Physical Layer	Layer 1 in the Open System Interconnection (OSI) architecture; the layer that provides services to transmit bits or groups of bits over a transmission link between open systems and which entails optical, electrical, mechanical and handshaking procedures (PHY).
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.
Radio Frequency (RF)	In cable television systems, electromagnetic signals in the range 5 to 1000 MHz.
Transceiver	A combination of Transmitter and Receiver in the same device or component

4 ABBREVIATIONS AND ACRONYMS

This specification uses the following abbreviations:

ADC	Analog to Digital Converter
APC	Angled Physical Contact
ASE	Amplified Spontaneous Emission
ASIC	Application-specific Integrated Circuit
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
bps	bits per second
CableLabs	Cable Television Laboratories, Inc
CD	Chromatic Dispersion
CFP	C Form-Factor Pluggable
CFP MSA	C Form-Factor Pluggable Master-Source Agreement
CFP2-DCO	CFP2-Digital Coherent Optics
CMA	Constant Modulus Algorithm
CMOS	Complementary Metal-Oxide Semiconductor
CMTS	Cable Modem Termination System
DAC	Digital to Analog Converter
dB	Decibel
dBm	Decibel-milliwatts
DEMUX	Demultiplexer
DFB	Distributed Feedback (laser)
DGD	Differential Group Delay
DP-16QAM	Dual Polarization - 16 point Quadrature Amplitude Modulation
DP-8QAM	Dual Polarization - 8 point Quadrature Amplitude Modulation
DP-QPSK	Dual Polarization - Quadrature Phase Shift Keying
DQPSK	Differential Quadrature Phase Shift Keying
DSP	Digital Signal Processor
DWDM	Dense Wave Division Multiplexing
ECL	External Cavity Laser
EDD	Error Decorrelator De-interleaver
EDFA	Erbium-Doped Fiber Amplifier
EDI	Error Decorrelator Interleaver
EPON	Ethernet Passive Optical Network
FEC	Forward Error Correction
FWM	Four-wave Mixing
GBaud	Gigabaud
Gbps	Gigabit per second
GE, GbE	Gigabit Ethernet
GHz	Gigahertz
HD	High Definition
IF	Interface
ITU-T	International Telecommunication Union - Telecommunications Standardization Sector
kbit/s	Kilobits per second
kHz	Kilohertz
krad	kiloradians
LO	Local Oscillator

MAC	Media Access Control
MLG	Multi-Link Gearbox
MSA	Multi-Source Agreement
MSO	Multiple Systems Operator
MUX	Multiplexer
MZM	Mach-Zehnder Modulator
nm	Nanometer
NRZ	Non-return Zero
ODC	Optical Distribution Center
ODU	Optical Data Unit
OH	Overhead
OIF	Optical Internetworking Forum
OLT	Optical Line Terminal
OOB	Out-of-Band
OOK	On-Off Keying
OPM	Optical Power Meter
OPU	Optical Payload Unit
OSA	Optical Spectrum Analyzer
OSNR	Optical Signal to Noise Ratio
OSSI	Operations Support System Interface
OTN	Optical Transport Network
OTU	Optical Transport Unit
P2P	Point-to-Point
PAM	Pulse Amplitude Modulation
PBC	Polarization Beam Combiner
PBS	Polarization Beam Splitter
PDL	Polarization Dependent Loss
PDM	Polarization Division Multiplexing
PHY	Physical
PIC	Photonic Integration Circuit
PLC	Planar Lightwave Circuit
PM	Polarization Multiplexing
PMD	Polarization Mode Dispersion
PON	Passive Optical Network
ppm	Parts per million
ps	Picosecond
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
QSFP	Quad Small Form-factor Pluggable
RF	Radio Frequency
RIN	Relative Intensity Noise
RPD	Remote PHY Device
Rx	Receiver
SOP	State of Polarization
SMF	Single Mode Fiber
SPM	Self-phase Modulation
Tb	Terabit
TIA	Transimpedance Amplifier
Tx	Transmitter

VOA	Variable Optical Attenuator
WDM	Wave Division Multiplexing
XPM	Cross-phase Modulation

5 TECHNOLOGY OVERVIEW

5.1 Coherent System Components

5.1.1 Coherent Transmitter

For the purposes of this overview, we will look at two key components of the coherent transmitter: the optical sources and external modulator.

5.1.1.1 Optical Sources

A laser diode is implemented from a semiconductor junction operated in forward bias mode. Electrons in that junction transition from a higher to a lower energy state. In that process, a photon that has an energy equal to the difference in energy states of the electron is emitted. This is spontaneous emission of light. In a laser diode, reflective facets or mirrors are implemented so that the generated photons bounce back and forth, stimulating along the way the emission of more photons. This stimulated emission, or lasing, results in light emission at higher intensity levels and with a high degree of coherence. The mirrors or facets on opposite sides of the active region formed by the junction create an optical cavity. The geometry of that cavity along with the range in energy levels generated by the change of state in the junction will determine one or more dominant resonant wavelengths transmitted by the laser diode.

Maintaining operating characteristics is critical for optical systems. In a WDM environment, the system has to maintain its wavelength at the desired value. To have better wavelength control, it is recommended to incorporate thermo-electric-cooling capabilities. Adding minor cost to the optical end devices can go a long way in facilitating wavelength multiplexing and avoiding fiber retrenching costs.

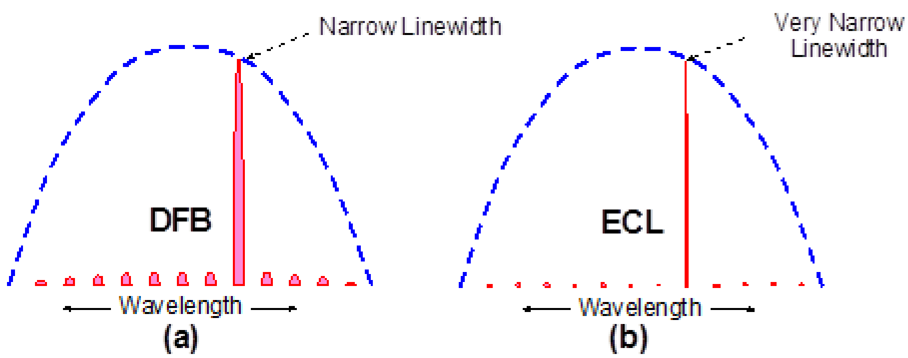

Figure 1 - Emission Spectrum of Coherent Laser Structures for Access Environment

Light emitted by lasers is not strictly monochromatic: based on their structures and characteristics, they have different linewidths. Figure 1 illustrates the emission and linewidth differences of two different diode structures, a Distributed Feedback (DFB) laser and an External Cavity laser (ECL).

The linewidth in wavelength of emitted light is important to higher speeds, higher dynamic range, higher coherence and coexistence among optical carriers on the same fiber. When sharing fiber spectrum with other optical sources (WDM), it is important to have an optical source that can be confined to a narrow spectrum and does not spill over energy to other channels.

5.1.1.2 External Modulators

Two types of external modulation approaches are typically used. One uses electro-absorption effect, which controls the degree of attenuation through an optical transmission path. The second uses an interferometric approach, which changes light amplitude by adjusting the relative phase on the two split optical branches, so that after combination they can add destructively (180 degrees out of phase) with no light leaving the modulator, or add constructively (in-phase) with maximum optical intensity out of the modulator. This is called a Mach-Zehnder Interferometer or Mach-Zehnder Modulator (MZM). Figure 2 shows the structure of the MZM.

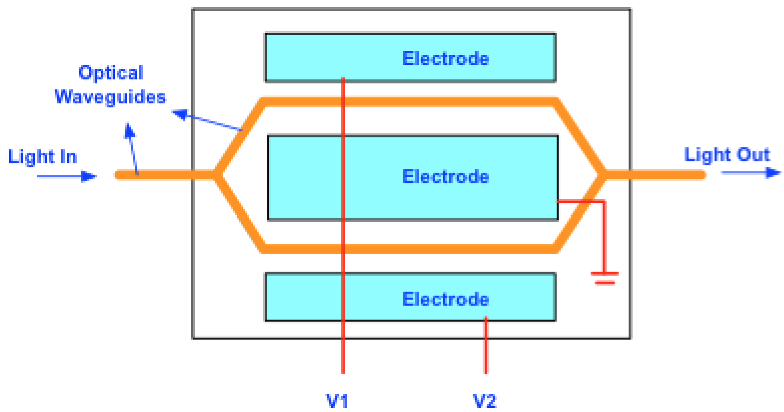

Figure 2 - Mach-Zehnder Intensity Modulator Structure

In coherent systems, rather than modulating only the amplitude of light, both amplitude and phase are modulated. The most popular modulator used in conjunction with coherent receivers is the nested IQ Mach-Zehnder based modulator shown in Figure 3.

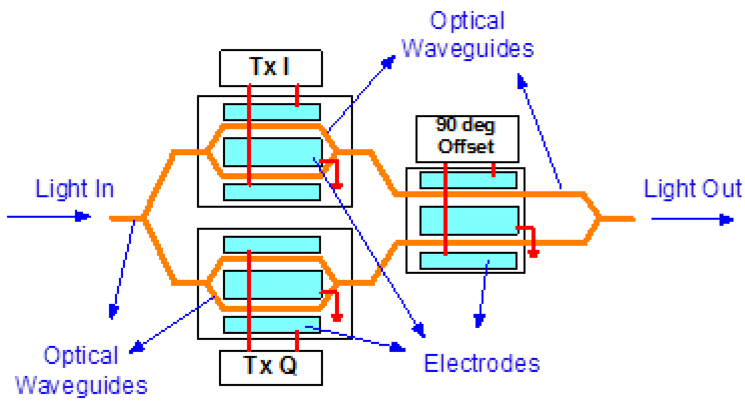

Figure 3 - IQ Modulator Structure Using Two Mach-Zehnder Modulators

In Figure 3, the optical signal is split in two paths, the in-phase (I) and the quadrature-phase (Q) paths. These paths are phase-shifted to be at 90° difference, enabling the I and Q MZMs to operate on orthogonal components of the optical signal.

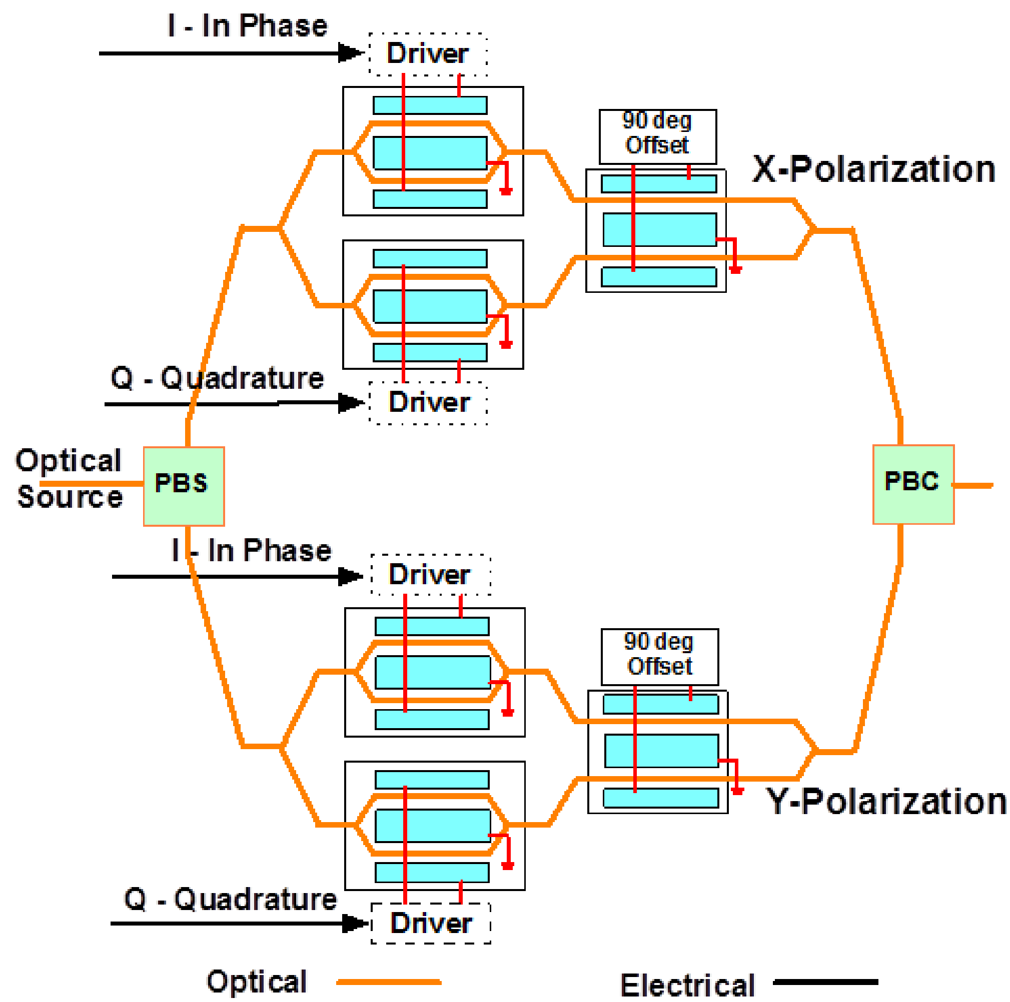

Figure 4 - Dual Polarization Coherent IQ Modulator

Figure 4 shows a dual polarization IQ modulator where two of the IQ modulators shown in Figure 3 and described above are applied to separate polarizations of the transmit laser's signal. A polarization-beam splitter (PBS) splits the optical signal into two polarizations for independent IQ modulation. A polarization-beam combiner (PBC) generates the dual-polarized signal, thereby doubling the transport capacity.

5.1.2 Optical Channel

The fiber access environment is critical in determining the performance of systems that reside and coexist within the fiber strand. There are different fiber-related impairments impacting performance. Some of these impairments are fiber length dependent, and some are dependent on fiber geometry, material, wavelength, bandwidth, and optical power level.

5.1.2.1 Chromatic Dispersion

Dispersion is one of the fiber length dependent impairments. Dispersion occurs when different portions of the signal travel at different speeds. As a consequence, there is a spreading of the signal in time. There are different types of dispersion. There is chromatic dispersion, waveguide dispersion, modal dispersion and polarization mode dispersion. Chromatic or material dispersion is caused by the change of refractive index with optical frequency. Waveguide dispersion relates to how well the index of refraction represents an ideal waveguide throughout the fiber length. The differences from an ideal waveguide cause dispersion. Modal dispersion occurs when different propagating modes are present in fiber. In the cable access environment, the predominantly deployed fiber is single mode fiber (SMF), so fiber modal dispersion is not present and waveguide dispersion is negligible compared to chromatic dispersion. This section focuses on material or chromatic dispersion and briefly discusses polarization mode dispersion. Chromatic dispersion is approximated by the formula:

$$Dispersion(\lambda) = \frac{S_0}{4} * \left[\lambda - \frac{\lambda_0{}^4}{\lambda^3}\right] ps/(nm * km)$$

Where λ_0 is the zero dispersion wavelength which for SMF is typically 1313nm (1302 nm -1322 nm range), and S_0 is the zero dispersion wavelength factor which typically is 0.086 ps/(nm^2*km) and always less than 0.092 ps/(nm^2*km). The variation of dispersion with wavelength for single mode fiber is shown in Figure 5.

5.1.2.2 Attenuation

Attenuation in fiber is dependent on the wavelength or frequency. For the particular type of single-mode fiber typically used in cable access, the attenuation is 0.22 dB/km for 1550 nm transmission and 0.3 dB/km for 1310 nm transmission. Figure 5 also shows attenuation versus wavelength and the optical transmission windows. The transmission window that is highly coveted is the C-Band (1530 nm–1565 nm) because of the option for amplification in addition to its low loss characteristics. However, in the access network, due to the shorter distances in many use case scenarios, there is no need of amplification. This facilitates the use of the L-Band (1565 nm-1625 nm) where production of erbium doped fiber amplifiers (EDFAs) in high volume has not yet occurred.

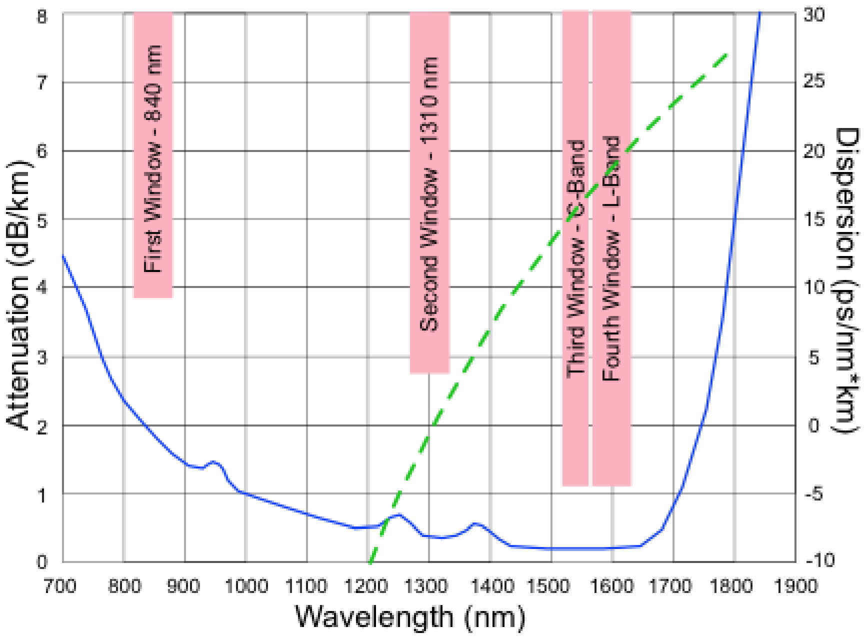

Figure 5 - SMF Fiber Attenuation (blue) and Dispersion (green) versus Wavelength

In the cable environment, the impact of optical reflections is diminished by using angle-faceted connectors. The small angle of an angle-faceted or APC connector causes a reflected signal to exit the fiber. Nevertheless, splice imperfections can also generate reflections which impact performance.

5.1.2.3 Polarization Mode Dispersion

Polarization mode dispersion (PMD) occurs when two orthogonal polarizations travel at different speeds which cause pulse spreading. This is caused by random imperfections such as circular asymmetry. The PMD coefficient is the parameter that specifies PMD characteristics for a particular length of fiber. The unit of the polarization mode dispersion coefficient is ps/√km. PMD in single mode fiber ranges from 0.1 ps/√km to 1 ps/√km. SMF has PMD < 0.1 ps/√km although after cabling the specification calls for < 0.5 ps/√km. A PMD requirement for non-coherent 10 Gbps Non-Return-to-Zero (NRZ) of < 4 ps is typically used. A 40 km link would have at most 0.5*√40 = 3.16 ps which would not require compensation. However, for 40 Gbps the PMD coefficient requirement is < 1 ps/√km and a

40 km link would require compensation. Coherent detection provides a higher tolerance to PMD than non-coherent so, in principle, higher symbol rates can be achieved with minimal or no PMD compensation for the link distances of the access network. PMD is not an issue in analog optical links as the modulation bandwidth is about 1 GHz.

5.1.2.4 Nonlinear Effects

Nonlinear effects in fiber are due to intensity dependence of the refractive index fiber medium, and due to inelastic-scattering present at very high optical intensity levels. There are also nonlinear effects that could be related to optical amplification systems, but in this access scenario evaluation with typically short distances (<60 km), amplification systems are not considered. This section focuses on the refractive index dependence on optical power. These refractive index effects are described as self-phase modulation (SPM), cross-phase modulation (XPM) and four-wave mixing (FWM).

5.1.2.4.1 Self-phase modulation

A time varying signal intensity generates a varying refractive index in a medium with an intensity-dependent refractive index such as fiber. The higher intensity portions of an optical signal, encounter a higher refractive index compared to the lower intensity portions of the signal as it travels through the fiber. Self-phase Modulation (SPM) is the chirping and dispersion generated by variation in the index of refraction. The optical power level and the length of interaction affect the amount of SPM.

5.1.2.4.2 Cross-phase modulation

In principle, cross-phase modulation (XPM) is the same as self-phase modulation but in this case, it is the effect that the intensity varying index of refraction has on other optical carriers that are propagating at the same time as the original signal. As the number of channels increase, the amount of XPM also increases. In a WDM system, XPM converts power fluctuations in a particular channel to phase fluctuations in the other co-propagating channels. XPM is higher with high power levels and greater interaction lengths (longer fiber links).

5.1.2.4.3 Four-wave mixing

Four-wave mixing (FWM) is a third order nonlinear effect of susceptibility. In FWM, if you have three fields propagating at frequencies ω_1, ω_2 and ω_3, a fourth frequency ω_4 is generated such that $\omega_4 = \omega_1 \pm \omega_2 \pm \omega_3$. FWM is independent of modulation bandwidth and is dependent on frequency spacing and fiber dispersion. Since dispersion varies with wavelength, the signal waves and the generated waves have different group velocities. This destroys phase matching of waves and lowers the efficiency of power transfer to newly-generated frequencies. Therefore, dispersion-shifted fibers have more severe FWM effects than standard single-mode fiber. The higher the group velocity mismatch and wider the channel spacing, the lower the four-wave mixing effect.

5.1.3 Coherent Receiver

5.1.3.1 Digital Coherent Receiver Types

In a coherent receiver, a local oscillator (LO) is used to down-convert the electrical field of the incoming optical signal to a baseband intermediate frequency (f_{IF}).

This coherent detection maps an entire optical field into the digital domain allowing, therefore, the detection of the signal's amplitude and its phase and state of polarization. Depending on the intermediate frequency defined as $f_{IF} = f_s - f_{LO}$, coherent receivers fall into three classes: homodyne, intradyne, and heterodyne as illustrated in Figure 6, where $Bandwidth_s$ is optical signal bandwidth.

Intradyne receivers are the *de facto* choice for contemporary 100G coherent systems.

In an intradyne receiver, the f_{IF} is chosen to fall within the signal band by roughly aligning the f_{LO} with f_s. Intra-dyne detection allows the detection of both the in-phase and quadrature component of the received signal, and an intradyne receiver is, therefore, also referred to as a phase-diversity receiver. Digital phase locking algorithms are needed to recover the modulation signal from its sampled I and Q components; this requires high-speed analog-to-digital conversion and DSP.

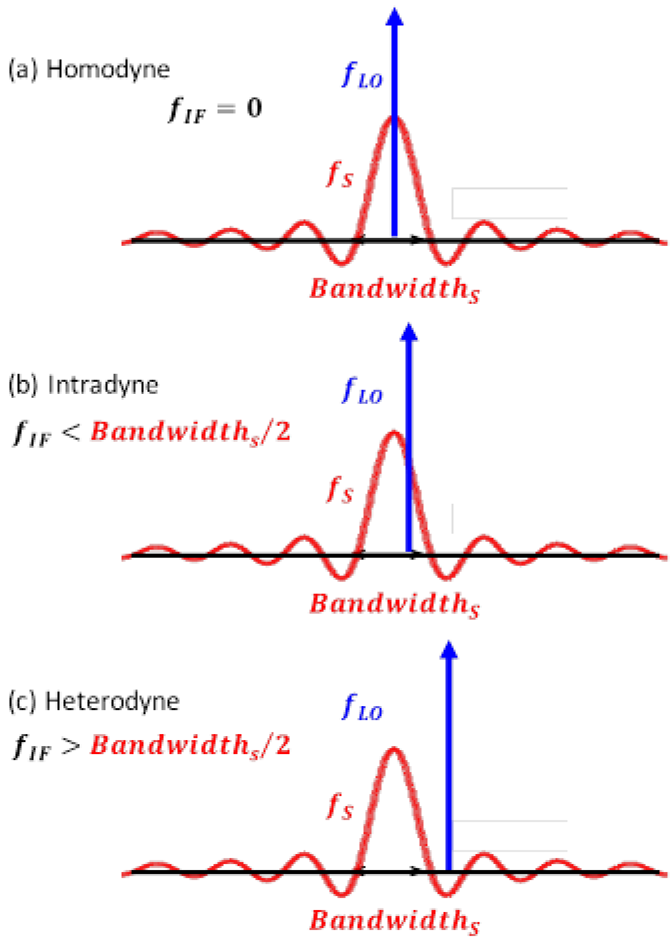

Figure 6 - Three Coherent Detection Schemes: (a)Homodyne, (b)Intradyne, (c)Heterodyne

5.1.3.2 Coherent Receiver Architectures

The fundamental concept behind coherent detection is that the beating product of electric fields of the modulated signal light and the continuous-wave LO is a lower frequency representation of the signal information that can be processed electrically. To detect both IQ components of the signal light, a 90° optical hybrid is utilized. A key building block of such a hybrid is a 2x2 optical coupler with its property of a 90° phase shift between its direct-pass and cross-coupling outputs via multimode interference (MMI) coupler. By combining such optical couplers into the configuration shown in Figure 7, together with an additional 90° phase shift in one arm, a detection of real and imaginary parts can be achieved. Balanced detection is usually introduced into the coherent receiver as a means to suppress the DC component and maximize the signal photocurrent.

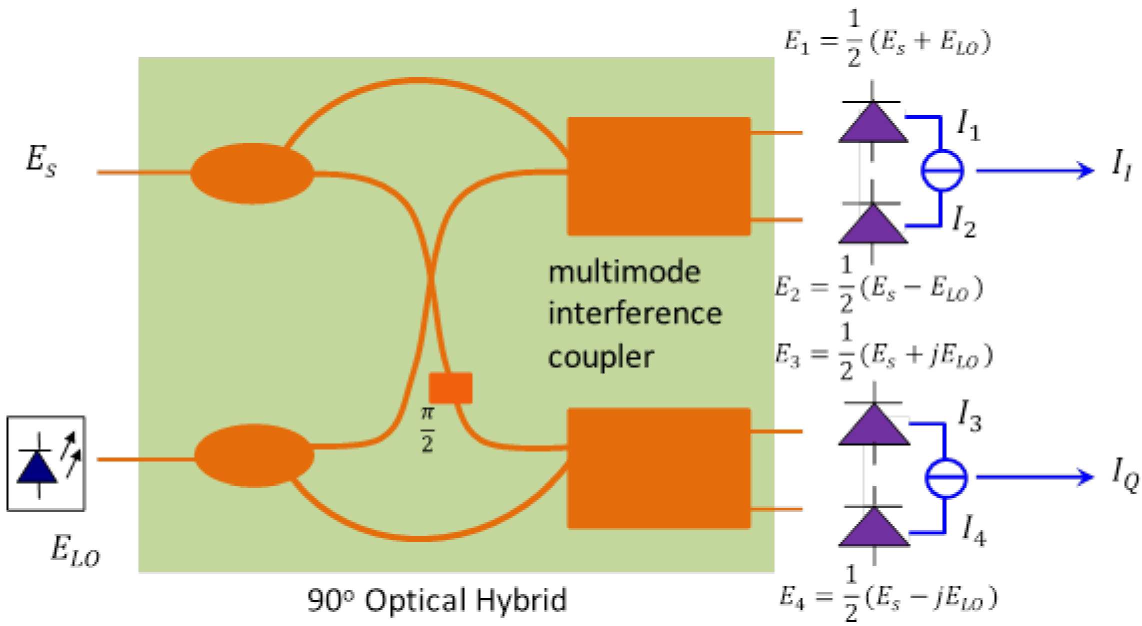

Figure 7 - Configuration of Phase-diversity Coherent Receiver

Output photocurrents from balanced photodetectors are then given as

$$I_I(t) = I_1(t) - I_2(t) = R\sqrt{P_s P_{LO}}\cos\{\varphi_s(t) - \theta_{LO}(t)\}$$
$$I_Q(t) = I_3(t) - I_4(t) = R\sqrt{P_s P_{LO}}\sin\{\varphi_s(t) - \theta_{LO}(t)\}$$

where R is the responsivity of the photodiode, P_s and P_{LO} are the power of the optical fields for incoming and LO signal, respectively. The receiver thus leads to the recovery of both the sine and cosine components. It is possible to estimate the phase noise $\theta_{LO}(t)$ varying with time and restore the phase information $\varphi_s(t)$ through subsequent DSP on the intradyne-detected signal.

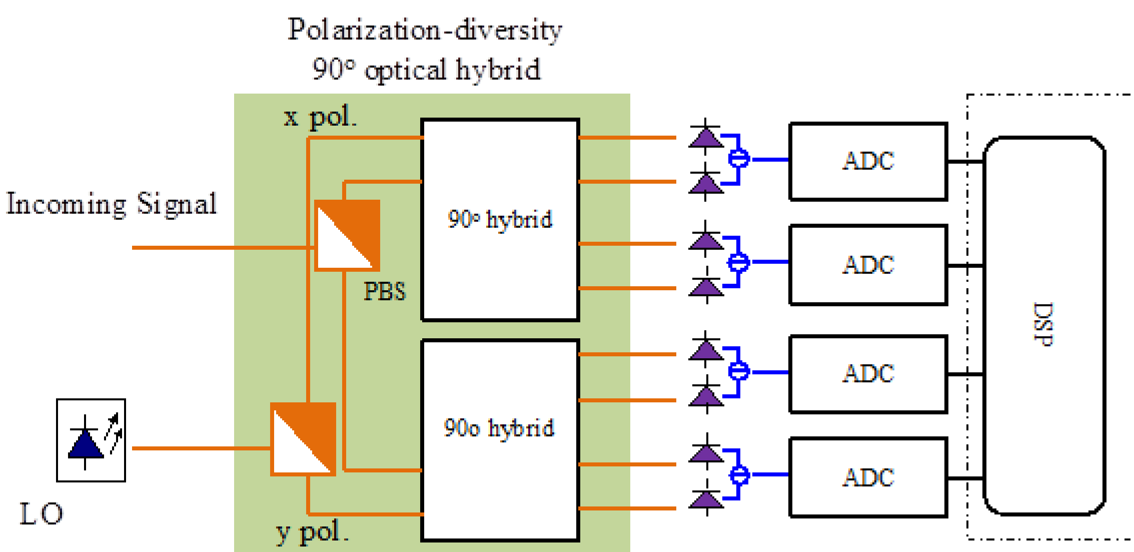

Figure 8 - Configuration of Phase and Polarization Diversity Coherent Receiver Architecture

The schematic diagram of a polarization multiplexed coherent receiver is shown in Figure 8. Both the incoming PM signal and LO are split into two orthogonal polarizations using a polarization beam splitter (PBS), after which the co-polarized signal and the local oscillator are mixed in two 90° optical hybrids to produce in-phase and quadrature components for each polarization. The four signals are then digitized by four analog-to-digital converters (ADC) after which DSP can be performed for signal demodulation.

The fundamental DSP functionality in a digital coherent receiver for PM-QAM signals is shown in Figure 9.

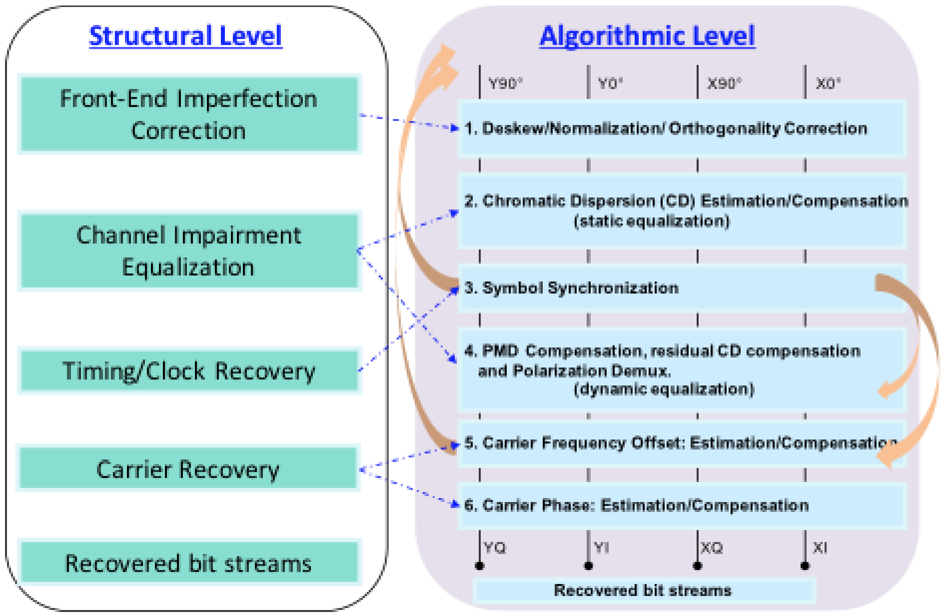

Figure 9 - DSP Flow in a Coherent Optical Receiver

First, the four digitized signals (i.e., in-phase and quadrature components for each polarization) after an ADC are passed through the block for the compensation of front-end imperfections. The imperfections may include timing skew between the four channels due to the difference in both optical and electrical path lengths within a coherent receiver. Other types of front-end imperfections can be the difference between the four channels' output powers due to different responses of PINs and TIAs in the receiver, and quadrature imbalance because the optical hybrid may not exactly introduce a 90-degree phase shift.

Second, the major channel transmission impairments are compensated through digital filters, in particular, chromatic dispersion and PMD. Based on different time scales of the dynamics of these impairments, the static equalization for chromatic dispersion compensation is performed first because of its independence of state of polarization (SOP) and modulation format and the impact on the subsequent blocks before the chromatic dispersion estimation is needed to achieve accurate compensation. Then the clock recovery for symbol synchronization can be processed to track the timing information of incoming samples. Note that it is possible to perform joint process between the blocks of clock recovery and polarization demultiplexing for achieving the symbol synchronization after all channel impairments are equalized (see arrows in Figure 9). A fast-adaptive equalization is carried out jointly for two polarizations through a butterfly structure and the stochastic gradient algorithms, such as commonly used constant modulus algorithm (CMA) and its variants. Then, the frequency offset between the source laser and the local oscillator (LO) is estimated and removed to prevent the constellation rotation at the intradyne frequency.

Finally, the carrier phase noise is estimated and removed from the modulated signal, which is then followed by symbol estimation and hard or soft-decision FEC for channel decoding. Note that for a particular digital coherent receiver, the ordering of DSP flow may differ slightly from those detailed in Figure 9 because of different design choices. Besides feed-forward process, it is possible to perform joint process and feedback among different process blocks such as clock recovery and polarization demultiplexing as mentioned above. It is also possible to perform the same functions by either training sequence based data-aided or totally blinded algorithms.

Coherent detection and DSP were the key enabling technologies in the development of 100G optical transmission systems. The next-generation coherent optical systems will continue this trend with DSP playing an even more ubiquitous role at both transmitter and receiver. Although the specific algorithms for each process block are typically different because there are various realizations of the same process block in the implementation level, the generic functions in the structural level or function abstractions are similar for all major commercial products.

There are some fundamental components used in the optical access network. The components that have most widely been used in the access, as well as the components that may play a significant role in the access network of the future, are described below. At a high level, these components can be grouped into three categories: the optical transmitter, the optical channel, and the optical receiver.

5.2 Reference Interfaces

The transceiver has multiple interfaces (IFs) that are specified in this document and depicted in Figure 10. The line-side corresponds to the optical interfaces. The client-side (or host-side) corresponds to the electrical interfaces. In addition, there is a management interface that will be specified in detail in the OSSI specification [OPT-P2P-OSSI].

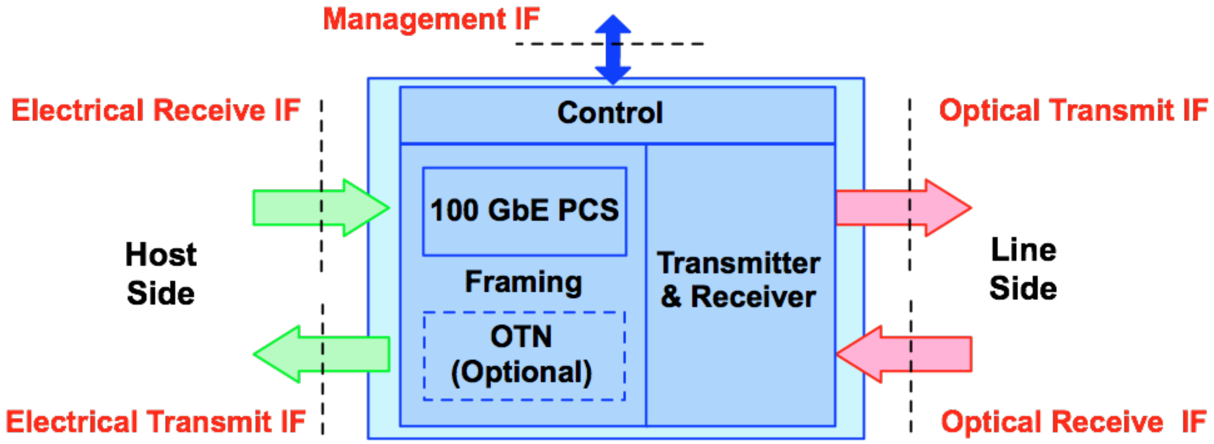

Figure 10 - Transceiver Optical, Electrical and Management Interfaces

5.3 Functional Block Diagrams

The sequence of key processes that take place in the transmitter as well as the receiver are illustrated in Figure 11 and Figure 12. The transmitter and receiver process sequences are only provided as examples. Actual transmitter and implementations may follow different sequences and different feedback dependencies.

Figure 11 shows functions that take place in the transmitter from the electrical input on the host-side to the optical output on the line-side.

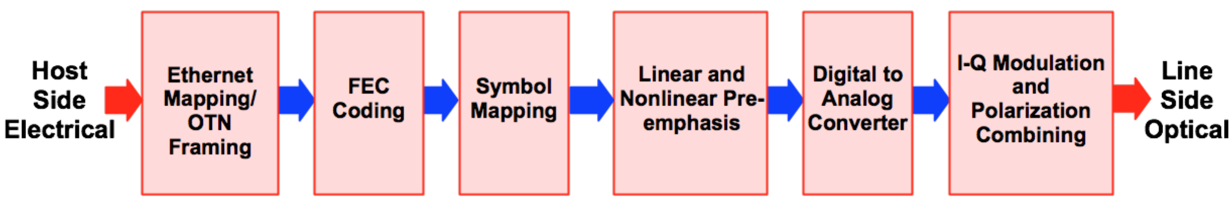

Figure 11 - Transmitter Functional Diagram

The transmitter processes include:

- Ethernet Mapping and OTN Framing
- FEC Coding
- Symbol Mapping

- Linear and Non-linear Compensation
- Digital to Analog Conversion
- IQ Modulation and Polarization Combining

The parameters describing the transmitted optical signal include:

- Encoding Scheme
- Line Rate
- Polarization Imbalance
- Quadrature and Polarization Skew
- Tx Clock Jitter
- Frequency Tolerance
- Optical Output Power
- Laser Wavelength
- Laser Linewidth
- Tx OSNR

The optical distribution medium in cable may include fiber, optical splitters, optical circulators, wavelength multiplexers, demultiplexers and other optical passives. The impairments impacting the optical signals traversing the link include:

- Optical Loss or Gain
- Chromatic Dispersion
- Polarization Mode Dispersion
- Polarization Dependent Loss
- Polarization Rotation
- Optical Crosstalk
- Optical SNR degradation

The optical signal generated by an imperfect transmitter and degraded by impairments from the optical distribution medium enters the line-side of the transceiver for detection, compensation and processing.

Figure 12 shows the functions that take place in the receiver from the optical input on the line side to the optical output on the host side.

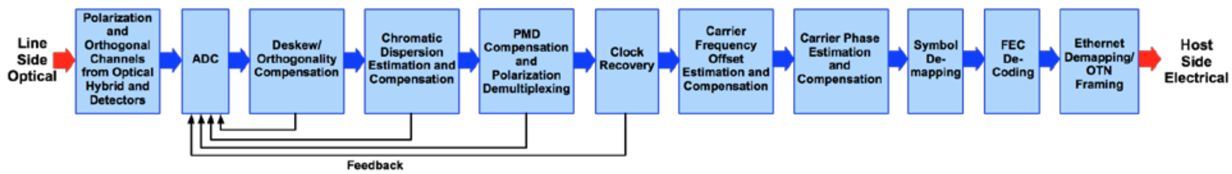

Figure 12 - Receiver Functional Diagram

The receiver processes include:

- Detection of in-phase and quadrature orthogonal channels for each X and Y polarizations
- Analog to Digital conversion
- Deskew and Orthogonality Compensation
- Chromatic Dispersion Estimation and Compensation
- Polarization Mode Dispersion Compensation and Polarization Demultiplexing
- Clock Recovery
- Carrier Frequency Offset Estimation and Compensation
- Symbol Demapping

- FEC Decoding
- Ethernet Demapping and OTN Framing

The parameters describing the received optical signal include:

- Modulation
- Symbol Rate
- Symbol Mapping
- FEC
- Line Rate
- Encoding Scheme
- Frequency Tolerance
- Frame Format and Mapping
- Optical Input Power
- Laser Wavelength
- Laser Linewidth
- Rx OSNR
- Polarization Imbalance
- Quadrature and Polarization Skew
- Tx Clock Jitter
- Chromatic Dispersion
- Polarization Dispersion
- Polarization Rotation (SOP Track)

There are some general transceiver characteristics as well. The end-to-end link latency consists of the transmitter and receiver latencies along with the optical channel transmission delay. The reflectances of transmitter and receiver optical interfaces are characterized by its optical return loss. Transceiver operation may be impacted by ambient temperature which may require compensation. In the receiver, the data re-acquisition time is a useful metric that indicates the time the receiver takes to turn back on after loss of signal.

6 GENERAL TRANSCEIVER REQUIREMENTS

This section includes requirements that apply to a compliant transceiver, and which are not specific to the optical PHY layer.

6.1 Environmental Conditions

This specification does not define specific environmental conditions that compliant transceivers are required to support; those requirements are expected to be defined by the end customer when defining their purchasing requirements. However, for those transceivers that will operate in the field, it is expected that they could be required to operate at startup temperatures as low as -40C, and may need to operate in conditions with an internal temperature as high as +85C.

For whatever range of temperatures the transceiver does actually support, it will be expected to meet the requirements in this specification across that entire supported range, and to do so over the defined lifetime of the device.

The transceiver MUST support all of the requirements in this specification across the transceiver's full operating temperature range and operating lifetime.

6.2 Client-Side Interface

Solutions utilizing the PHY layer defined in this specification will need to support Ethernet transport. Therefore, compliant transceivers will need to support Ethernet input and output on the client-side interfaces. Other layer 2 protocols may be supported as well, but are not defined by this specification.

The specification does not mandate specific electrical interfaces, defining them as specifically outside the scope of the specification, and leaving them to product definitions.

The transceiver MUST support the transport of Ethernet frames.

6.3 Optical Ports and Frequencies

Transceivers compliant with this specification can have either one or two optical ports to handle transmit and receive functions. A typical transceiver has two separate ports for transmit and receive so that they can use the same frequency. It is also possible to develop a transceiver that uses a single port for both transmit and receive, either by using two separate frequencies or by using some technology to support bi-directional transmission on a single fiber at the same frequency. A two-frequency, two-port solution is also possible. All of these approaches are permitted by the specification.

The transceiver MUST support either one or two optical ports for transmit and receive functions.

The transceiver MUST support using the same frequency for transmit and receive functions.

The transceiver MAY support transmitting and receiving on two different frequencies.

7 REQUIREMENTS FOR 100G P2P COHERENT OPTIC TRANSCEIVER

7.1 100G PHY Introduction

This section defines the optical physical (PHY) layer requirements for a point-to-point (P2P) coherent optics transceiver operating at 100 Gbps (100G), as well as providing some of the background for why the requirements were chosen.

In general, the requirements described here align with those defined in other bodies such as the ITU and OpenROADM, and in some cases point directly to external specifications for certain requirements. This was done specifically to enable the re-use of existing components in the construction of a transceiver targeted at the access network market, thereby enabling rapid product development and early product availability.

The requirements in this section are grouped into the following categories:

- Common Requirements, which apply to both the transmit and receive operation of the transceiver
- Transmitter Requirements, which are unique to the transmit operation of the transceiver
- Receiver Requirements, which are unique to the receive operation of the transceiver

7.2 Common Requirements

7.2.1 Symbol Rate

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). In addition to simply transmitting the ones and zeroes faster, one method for transmitting data more quickly is to transmit multiple bits at the same time using a collection of relative states, called symbols. The number of symbols transmitted over unit time is defined as baud rate.

The specific type of symbol used for the 100G PHY is defined in Section 7.2.3.

The value of 27.95 Gbaud was chosen for the symbol rate in order to allow 100 Gbps transmission of data as described in the following sections. The symbol rate accuracy enables the successful reception of the signal.

The transceiver MUST support a symbol rate of 27.95 Gbaud with the modulation format described in Section 7.2.2.

The transceiver MUST maintain the accuracy of the symbol rate of +/- 20 ppm.

7.2.2 Modulation

The modulator generates *symbols* that are *mappings* (see Section 7.2.3) of the data being transmitted. A wide range of modulation schemes are used in contemporary optical systems from simple on/off keying through complex phase and/or amplitude modulations. Implementation tradeoffs balance complexity and cost against efficiency, the key consideration being that of limiting channel bandwidth or, alternatively, using that bandwidth most efficiently.

The 100G transceivers specified by this specification use polarization multiplexing and non-return-to-zero differential quadrature phase shift keying. This aligns with multiple existing specifications, such as the [ITU-T G.698.2] and [OpenROADM] specifications.

Quadrature Phase Shift Keying (QPSK) encodes two bits per symbol. Differential QPSK (DQPSK) removes the need for precise measurement of absolute phase at the receiver; changes in the phase of the received signal indicate symbols.

Employing DQPSK on each of two polarizations of the carrier allows the aggregate transmission of four data bits each symbol period. See [ITU-T G.Sup39] for further discussion of DQPSK and other modulation schemes.

We refer to the modulation scheme specified here for 100G transceivers as DP-DQPSK: Dual Polarization Differential Quadrature Phase Shift Keying.

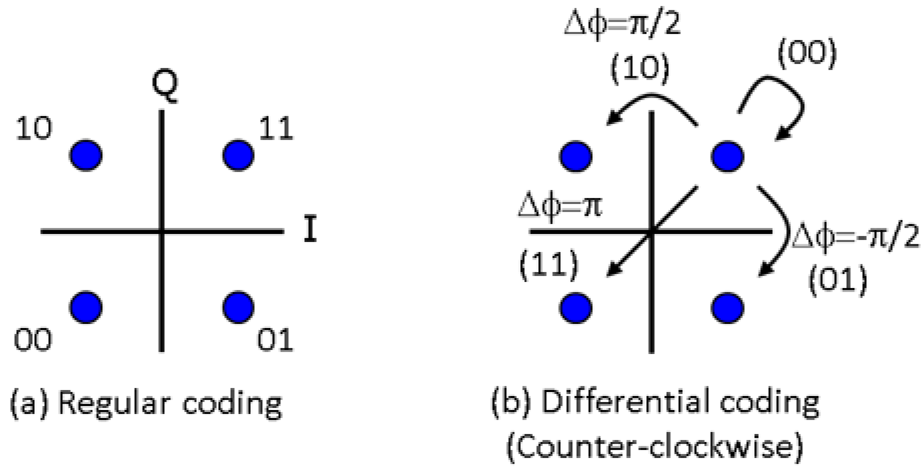

Figure 13 - Differential QPSK encoding

The Transceiver MUST support DP-DQPSK modulation as defined in ITU-T G.698.2 [1].

7.2.3 Symbol Mapping

The modulator generates optical symbols mapped from digital data being transmitted. The 100G transceivers described by this specification use the DP-DQPSK modulation format (see Section 7.2.2) in which the symbols are encoded as phase shifts of the optical signal. This section describes and then specifies how the digital signal is mapped to those optical signals.

Because the 100G transceiver uses DQPSK and Dual Polarizations (DP), there are effectively four parallel signaling lanes on the optical interface - XI, XQ, YI, and YQ - where I and Q denote the In-phase and Quadrature-phase components, and X and Y the two orthogonal polarizations.

The 100G transceivers described by this specification use the four-lane digital client frame format specified in [ITU-T G.709.2] (see Section 7.2.7). Each of these four lanes is self-identifying (at the receiver the recovered bitstreams are identified and appropriately processed in the framer) and thus any digital lane can be applied to any one of the XI, XQ, YI or YQ (optical) signaling lanes with the restriction that the mapping may not change while the link is operational.

Table 1 below shows the mapping between the digital lane bit values, which we arbitrarily label b1 and b2, and the corresponding phase change in the optical signal. The same mapping is used for both polarizations, but different pairs of digital lanes are applied to each of those polarizations.

Table 1 - Symbol Mapping Table

Inter symbol phase change (radians)	Digital signal lane bit values (b1,b2)
0	00
π/2, -3π/2	10
π, -π	11
3π/2, -π/2	01

The transceiver MUST choose a mapping of digital client lanes to optical lanes when the link is initialized.

The transceiver MUST maintain the digital to optical lane mapping it establishes during link initialization for the lifetime of that connection.

The transceiver MUST use the values in Table 1 to map between client layer digital signal values and optical symbols.

7.2.4 Forward Error Correction (FEC)

Forward Error Correction (FEC) is used in optical transmission systems to overcome the effects of noise and other system impairments on the transmitted signal. All FEC schemes add symbols to the transmitted data in such a way that the receiver can recognize and recover from symbol detection errors. The extra symbols – FEC overhead – are added at the transmitter and removed at the receiver.

The symbols traversing the optical network can become degraded, causing the detectors in receivers to make errors as they attempt to discriminate between and identify those symbols. As a result, some data bits out of the receiver may be incorrect; in other words, there may be some bit errors in the data output. This is quantified with Bit Error Rate (BER) which is the ratio of bit errors over the number of bits transmitted. For example, BER equal to 10^{-3} is 1 bit error out of every 1000 bits transmitted. Pre-FEC BER is the error rate from the receiver before FEC attempts to correct errors. In this application, the pre-FEC BER at the receiver is $\leq 4.5 \times 10^{-3}$. Post-FEC BER is the error rate after FEC attempts to correct errors. It is the function of the FEC to improve the received BER so that the residual post-FEC BER meets the system specification which, for this application, is $\leq 10^{-15}$.

Devices compliant with the 100G PHY defined within this specification are required to support the Hard-Decision (HD) Staircase FEC defined in [ITU-T G.709.2] which provides a net coding gain of 9.38 dB and post-FEC BER of $\leq 10^{-15}$ for a compliant transceiver in this application. Detailed descriptions of this FEC are provided in [Smith] and in Annex A and Annex B of [ITU-T G.709.2].

The transceiver MUST use the Hard-Decision Staircase FEC described in Annex A of [ITU-T G.709.2].

The transceiver MUST generate the FEC codes for the OTU4-LR signal by implementing the mappings and procedures specified in Annex B of [ITU-T G.709.2].

The transceiver MUST report the measured pre-FEC BER for received data.

The transceiver MUST report the total block count for received data.

The transceiver MUST report the uncorrectable block count for received data.

7.2.5 Line Rate

The Telecommunication standardization sector of International Telecommunication Union (ITU-T) approved a recommendation on "Interfaces for the optical transport network" in 2001 [ITU-T G.709]. Several editions have been released since then, including bit rate information for 100 Gbit/s signals. [ITU-T G.709] is used as the basis for the definition of the coherent signal line rate in this specification.

[ITU-T G.709] describes a digital Optical Transport Network (OTN) signal structure which maps payload signals into an Optical Payload Unit (OPU) and adds specific overhead areas, which for example are used for operations, supervision, and management of optical networks. These areas are the OPU, the Optical Data Unit (ODU), and the Optical Transport Unit (OTU) specific overhead areas. A detailed description of this structure can be found in reference [ITU-T G.709].

[ITU-T G.709] defines following OTU4 nominal bit rate: 111,809,973.568 kbit/s.

The transceiver MUST support a nominal signal line rate matching the OTU4 bit rate of 111,809,973.568 kbit/s.

7.2.6 DWDM Frequency Grid

In order to enable interoperability between transceivers operating in Dense Wavelength Division Multiplexing (DWDM) environments, and to interoperate with existing cable operator DWDM systems and equipment, the specification has adopted a subset of the channels identified in [ITU G.694.1] using a 100 GHz spacing. Specifically, Table 2 lists the specific DWDM wavelengths, frequencies, and associated channel numbers on which compliant transceivers can operate.

In order to enable low cost implementations, transceivers are only required to support one channel from the Table 2. However, in order to support greater flexibility, devices are also permitted to support multiple channels from that list, and may comprise the entire list or just portions of it.

Table 2 - DWDM Frequency Grid Table

Channel Number	Central Frequency (GHz)	Central Wavelength (nm)
13	191300	1567.13
14	191400	1566.31
15	191500	1565.50
16	191600	1564.68
17	191700	1563.86
18	191800	1563.05
19	191900	1562.23
20	192000	1561.42
21	192100	1560.61
22	192200	1559.79
23	192300	1558.98
24	192400	1558.17
25	192500	1557.36
26	192600	1556.56
27	192700	1555.75
28	192800	1554.94
29	192900	1554.13
30	193000	1553.33
31	193100	1552.52
32	193200	1551.72
33	193300	1550.92
34	193400	1550.12
35	193500	1549.32
36	193600	1548.52
37	193700	1547.72
38	193800	1546.92
39	193900	1546.12
40	194000	1545.32
41	194100	1544.53
42	194200	1543.73
43	194300	1542.94
44	194400	1542.14
45	194500	1541.35
46	194600	1540.56
47	194700	1539.77
48	194800	1538.98
49	194900	1538.19
50	195000	1537.40
51	195100	1536.61
52	195200	1535.82
53	195300	1535.04
54	195400	1534.25

Channel Number	Central Frequency (GHz)	Central Wavelength (nm)
55	195500	1533.47
56	195600	1532.68
57	195700	1531.90
58	195800	1531.12
59	195900	1530.33
60	196000	1529.55
61	196100	1528.77
62	196200	1527.99

The transceiver MUST support at least one channel from Table 2 above.

The transceiver MAY support multiple channels from Table 2 above.

The transceiver MUST report the channels from Table 2 above which it supports.

If the transceiver supports multiple channels from Table 2 above, it MUST provide some mechanism for assigning a specific channel to operate on using the relevant management interface definition for the form factor of the transceiver module.

The transceiver MUST report the channel that it is currently transmitting on using the relevant management interface definition for the form factor of the transceiver module.

7.2.7 Frame Format and Mapping

This section describes the line and client-side framing, and the mapping of the client-side data into the coherent line-side.

Line and client-side framing and mapping specifications are defined by several standards. The following standards are used in this specification:

- IEEE 802.3-2015
- ITU-T G.709 06/2016
- ITU-T G.798 12/2017
- ITU-T G.709.2

The client-side refers to the source of incoming data; the line-side refers to the modulated data being transmitted to/from the coherent optics.

On the client side, 100GbE is required to be supported, while an OTN client-side interface is optional.

For OTN applications, OTL4.10 and OTL4.4 are defined in [ITU-T G.709] Annex C.

Line-side framing and mapping standards are provided in [ITU-T G.709.2] “OTU4 long-reach interface” and [ITU-T G.709] “Interfaces for the optical transport network”. The adaptation to the coherent interface is as defined in [ITU-T G.709.2].

The OTU4-LR interface in [ITU-T G.709.2] is defined based on the OTN interface in [ITU-T G.709]. The framing format is defined based on an OTU4 frame, extended with a higher coding gain FEC. The FEC defined for OTU4-LR occupies the same byte allocation as the RS(255,239) FEC defined in [ITU-T G.709] for OTU4.

In order to transport the OTU4-LR data over multi-lane interfaces, [ITU-T G.709.2] clause 11 specifies that the approach defined in [ITU-T G.709] Annex C is used, by adapting the OTU4 signal to OTL4.4. Each of the OTL4.4-LR lanes carries five logical lanes, as defined in [ITU-T G.709] Annex C.

OTL4.4-LR is the handoff to the optical bit/symbol mapping procedure.

7.2.7.1 100GBASE-R Client-side Requirements

The Transceiver’s client-side MUST support framing of 100GbE PCS as defined in [IEEE 802.3-2015] clause 82.

The transceiver MUST support the method of [ITU-T G.709] Annex E for adaptation of 64/66B encoded 100GBASE-R interfaces.

The transceiver MUST map the 100GBASE-R signal into an OTU4/ODU4/OPU4 structure as defined in [ITU-T G.709].

The transceiver MUST map the 100GBASE-R payload into the OPU-4 using GMP as defined in [ITU-T G.709] subclause 17.7.5.

The transceiver MUST support [ITU-T G.709] subclause 17.7.5.1 100GBASE-R multi-lane processing.

7.2.7.2 OTU4 Client-side Requirements

The transceiver’s client-side MAY support OTU4 clients, as defined in [ITU-T G.709].

If OTU4 clients are supported, the transceiver’s client-side MUST support either an OTL4.10 or an OTL4.4 interface.

If OTU4 clients are supported, the transceiver MUST implement OTU4 signal flow as defined in [ITU-T G.709] clause 11.

7.2.7.3 Line-side OTU and OTL Framing Requirements

The transceiver MUST use a frame format that follows the OTU4 definitions as defined in [ITU-T G.709] clause 6.1.

The transceiver MUST support OTU4 framing and monitoring as defined in [ITU-T G.709] clause 15.6.

The transceiver MUST support consequent actions and insertion of fault / maintenance signals as defined in [ITU-T G.709] and [ITU-T G.798].

The Transceiver line-side MUST support OTL4.4 as specified in [ITU-T G.709] on the line-side.

The transceiver line-side MUST support OTU4 lane frame alignment and recovery as defined in [ITU-T G.798] subclauses 8.2.5 and 8.2.6 on the line-side.

The transceiver line-side MUST support requirements for OTL recovery and processing as defined in [ITU-T G.798] on the line-side.

The transceiver line-side MUST support lane deskew of at least 180ns differential delay on the line-side.

7.2.7.4 Frame Structure Requirements

The transceiver MUST support the frame structure as defined in [ITU-T G.709.2] Section 8.1, based on ODU4 extended by FEC.

7.3 Transmitter Requirements

7.3.1 Transmitter Optical Output Power

Transmitter optical output power defines the total optical launch power measured in dBm from the output port of a transceiver while it is operating.

This parameter is measured with a calibrated optical power meter (OPM) that is capable of power measurement in 1550 nm wavelength range.

Note that during startup, the transmitter may generate “fast transients,” or sudden spikes in power across a range of frequencies, which could briefly impact any operating channels that are on the same optical plant as the transceiver that is starting up. As a result, some transceivers might include the ability to do blanking, the suppressing of optical output until such time as the transceivers output has stabilized.

The transceiver MUST support a transmitter optical output power of -6 dBm or higher. The transceiver MUST NOT permit a transmitter optical output power of +7 dBm or higher.

The transceiver MUST report its minimum and maximum supported optical output power.

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

The transceiver SHOULD support adjustment of the transmitter optical output power. If adjustment of transmitter optical output power is supported, the transceiver SHOULD support adjustments in steps of 0.1 dB.

The transceiver MAY support blanking to protect the optical plant during startup.

7.3.2 Transmitter Optical Frequency Parameters

7.3.2.1 Transmitter laser center frequency accuracy

The transmitter laser center frequency accuracy is the maximum allowable offset of the actual laser frequency from the selected frequency center in Table 2. 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 Digital Signal Processor (DSP) will have more difficulty in compensating the central frequency offset (CFO) between the transmitter and local oscillator lasers.

Note that the laser center frequency accuracy of the local oscillator on the receiver is not specified in this document because different DSPs may handle more or less CFO – each vendor must determine their requirements on the local oscillator to meet overall performance requirements.

The transceiver MUST have a transmitter laser center frequency accuracy of less than or equal to 1.8 GHz.

7.3.2.2 Transmitter laser linewidth

The transmitter laser linewidth is the maximum allowable width of the laser optical signal. The greater the laser linewidth, the greater the phase noise from the receiver thus increasing the difficulty for the Digital Signal Processor (DSP) to determine the symbol.

Laser linewidth is defined as Full-Width at Half-Maximum (the width of the optical signal at -3 dB down from peak power).

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

7.3.3 Transmitter Optical Signal-to-Noise Ratio

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. Transmitter OSNR includes the noise of an optical amplifier if one is integrated in the transceiver; transmitter OSNR does not include the noise of optical amplifier(s) that is external to the transceiver 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. 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, due to amplified spontaneous emission (ASE).

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, where 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 OSNR for 100G DQPSK, which operates at approximately 28 Gbaud, the resolution bandwidth of the OSA is set to 0.5 nm (approximately 60 GHz) and the optical noise floor is measured at ±100GHz offset or larger from the center wavelength. For OSNR calculations, the total signal power is used, and the noise floor is converted to calculate the noise power in 0.1 nm bandwidth. 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 OSNR automatically and determine the appropriate noise floor.

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

7.3.4 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 PBC. In the transmitter, the two polarizations experience different insertion loss, which generates polarization imbalance at the output. In order to balance the power for each polarization, variable optical attenuators or semiconductor amplifiers may be used on each path.

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

7.3.5 Transmitter Skew

The transmitter modulation format uses Dual Polarization Differential Quadrature Phase Shift Keying (DP-DQPSK). 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., having a relative delay with respect to each other) due to variations in electrical trace lengths to the modulators, delays in tributaries, optical combining, etc. Quadrature skew is defined as the inter-channel delay between in-phase and quadrature-phase (I-Q) channels, while polarization skew is defined as the inter-channel delay between X- and Y-polarization (X-Y) channels.

There are two factors in both the transmitter I-Q and X-Y skews: (a) the static inter-channel skews which can be mostly calibrated out except residual skews, and (b) the dynamic skew variation over temperature, wavelength, and aging, which cannot be calibrated out. The latter is called I-Q and X-Y skew variation.

In order to minimize this effect of (a) and (b) and keep alignment in time of the data propagated via each of the modes, skew and skew variation requirements are defined in this section.

7.3.5.1 Transmitter Quadrature Skew

A DQPSK signal is generated by modulating two phase orthogonal signals, in-phase (I) and quadrature-phase (Q), independently and summing them. Each of these signals are differentially encoded binary phase shift keyed (phase reversal or shift by 180 degrees 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 sequential time slot for the next symbol; hence a reasonable requirement to minimize this effect is defined in this section.

In Figure 14 below, 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 14 shows a DQPSK Modulator with I and Q skew $\boldsymbol{\Delta\tau}$. I and Q are each modulated at an approximate symbol rate of 28 Gbaud which equates to an approximate symbol duration time of 36 ps.

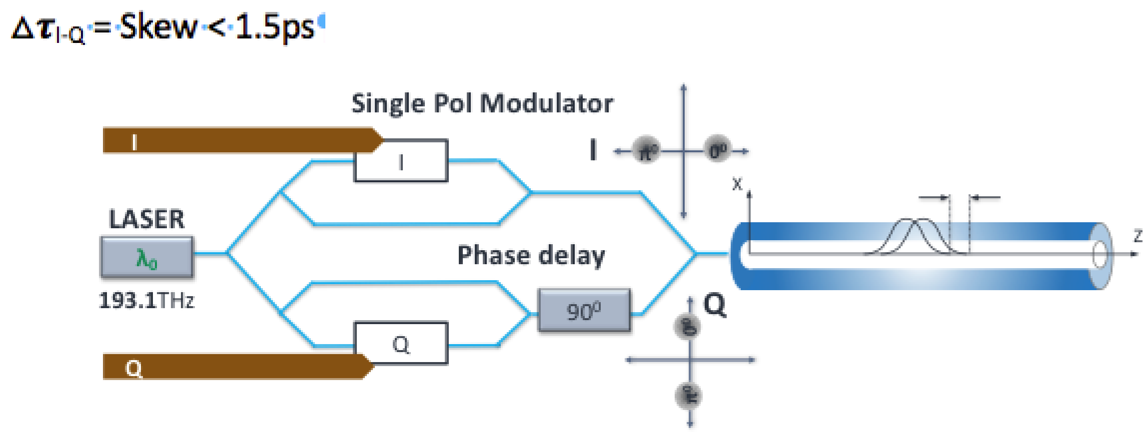

Figure 14 - DQPSK Modulator with In Phase and Quadrature Skew

The transceiver MUST have a quadrature skew of ≤ 1.5 ps.

The transceiver MUST have a quadrature skew variation of ≤ 2 ps.

7.3.5.2 Transmitter Polarization Skew

DP-DQPSK signal is generated by modulating two DQPSK signals in each of two orthogonal polarizations labeled X and Y and combining them before launching them into the fiber. In Figure 15 below, 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/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 36 ps.

Figure 15 shows a DP-DQPSK Modulator with Polarization Skew Δτ**.** Polarizations X and Y are each modulated at an approximate symbol rate of 28 Gbaud which equates to an approximate symbol duration time of 36 ps.

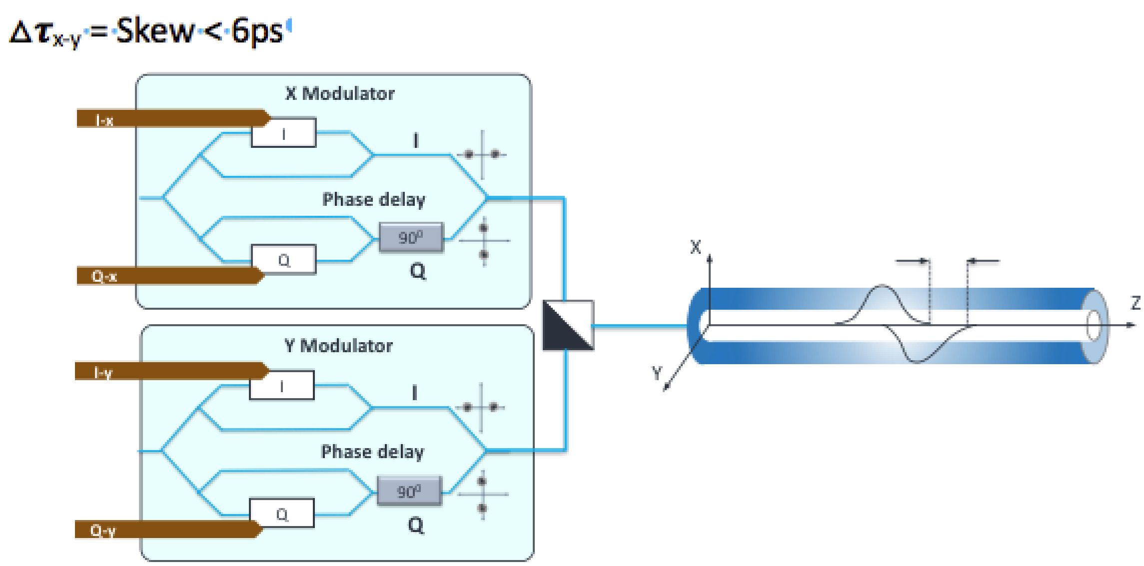

Figure 15 - DP-DQPSK Modulator with Polarization Skew

The transceiver MUST have a transmitter polarization skew ≤ 6 ps.

The transceiver MUST have a transmitter polarization skew variation ≤ 2 ps.

7.3.6 Transmitter Reflectance

The transceiver MUST support an optical transmitter reflectance of ≤ -25 dB.

7.4 Receiver Requirements

7.4.1 Received Optical Power and OSNR

This specification defines the requirements for receiver sensitivity related to received optical power and received OSNR by defining baseline numbers that are intended to be verified under "back-to-back" test conditions, which is defined as a condition with no optical transmission fibers except short jumper cables and no optical impairments. These requirements are then relaxed in the presence of certain optical impairments, such that the baseline requirement is adjusted by up to a certain amount of received power and OSNR to achieve the required BER.

The requirements for the baseline conditions are found in Sections 7.4.1.1 - 7.4.1.2, and the relaxations against these requirements can be found in Sections 7.4.2 - 7.4.5.

Note that all of the requirements in this section should be considered "Beginning of Life" requirements. Over the operational lifetime of the transceiver, it is expected that these requirements could degrade by up to as much as 1 dB. Therefore, operators should take this potential degradation into account as a part of their plant design.

7.4.1.1 Received Optical Power Baseline

In some scenarios, the received OSNR may be very high, while the received optical power may be very low. Under ideal conditions, it is expected that the OSNR at the receiver will be the same as at the transmitter, which in this specification is required to be at least 35 dB. Under that condition, the transceiver is limited by its sensitivity to received optical power. This is referred to as a "received optical power-limited case", and represents the baseline requirement for received optical power.

The transceiver MUST achieve a post-FEC bit-error-ratio (BER) of $\leq 10^{-15}$ when the link OSNR is ≥ 35 dB and the received optical power is ≥ -31 dBm, which is referred to as the baseline received optical power requirement.

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

7.4.1.2 Received OSNR Baseline

Under other conditions — such as when there is an optical amplifier close to the receiving transceiver — the optical received power may be high, but the OSNR may be low (since the optical amplifier amplifies both the signal and the noise). In this case, the transceiver is limited by it's sensitivity to OSNR rather than power. This is referred to as an "OSNR-limited case," and represents the baseline requirement for received OSNR.

The transceiver MUST achieve a post-FEC bit-error-ratio (BER) of $\leq 10^{-15}$ when the received optical power is ≥ -10 dBm and link OSNR is ≥ 14.5 dB, which is referred to as the baseline received OSNR requirement.

The transceiver MAY report the received OSNR.

7.4.2 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 was determined in order to support links up to 120 km over standard single-mode fibers.

The transceiver MUST support a minimum of 2400 ps/nm of chromatic dispersion.

In the received optical power-limited case, when the chromatic dispersion is 2400 ps/nm, the transceiver MUST achieve a post-FEC bit-error-ratio (BER) of $\leq 10^{-15}$ when the received optical power is 0.5 dB greater than the baseline optical power requirement defined in Section 7.4.1.1.

In the received OSNR-limited case, when the chromatic dispersion is 2400 ps/nm, the transceiver MUST achieve a post-FEC bit-error-ratio (BER) of $\leq 10^{-15}$ when the received OSNR is 0.5 dB greater than the baseline OSNR requirement defined in Section 7.4.1.2.

The transceiver MUST report the measured chromatic dispersion.

7.4.3 Polarization Mode Dispersion Compensation

Polarization Mode Dispersion (PMD) is when one of the polarizations travels faster than the other through the fiber. The dispersion between the two polarizations increases with distance as shown in Figure 16.

The specified value was determined in order to support links up to 120 km over standard single-mode fibers.

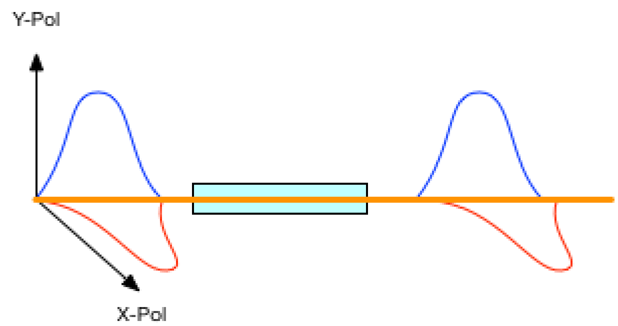

Figure 16 - PMD Diagram

The transceiver MUST support at least 10 ps of polarization mode dispersion.

In the received optical power-limited case, when the PMD is 10 ps, the transceiver MUST achieve a post-FEC bit-error-ratio (BER) of $\leq 10^{-15}$ when the received optical power is 0.5 dB greater than the baseline optical power requirement defined in Section 7.4.1.1.

In the received OSNR-limited case, when the PMD is 10 ps, the transceiver MUST achieve a post-FEC bit-error-ratio (BER) of $\leq 10^{-15}$ when the received OSNR is 0.5 dB greater than the baseline OSNR requirement defined in Section 7.4.1.2.

The transceiver MUST report the measured differential group delay (DGD).

7.4.4 State of Polarization Tracking

Various external actions, such as vibration of the fiber or nearby lightning strikes, can cause changes in the state of polarization (SOP). In order 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. The tracking rate is a minimum value that all transceivers are required to support in order to handle most cases without loss of data. Transceivers are permitted to support faster tracking rates, which may be required in some less common circumstances (such as long aerial runs in windy areas, areas with large numbers of lightning strikes, etc.).

The transceiver MUST support an SOP tracking rate of at least 50 krad/sec.

In the received optical power-limited case, when the SOP tracking rate is 50 krad/sec, the transceiver MUST achieve a post-FEC bit-error-ratio (BER) of $\leq 10^{-15}$ when the received optical power is 0.5 dB greater than the baseline optical power requirement defined in Section 7.4.1.1.

In the received OSNR-limited case, when the SOP tracking rate is 50 krad/sec, the transceiver MUST achieve a post-FEC bit-error-ratio (BER) of $\leq 10^{-15}$ when the received OSNR is 0.5 dB greater than the baseline OSNR requirement defined in Section 7.4.1.2.

The transceiver MUST report the SOP tracking rate in use.

The transceiver MAY support multiple SOP tracking rates.

If the transceivers supports multiple SOP tracking rates, the transceiver MUST support configuration of the SOP tracking rate.

7.4.5 Polarization Imbalance Tolerance

Here the "polarization imbalance" or polarization-dependent loss (PDL) is defined 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 7.3.4, and the transmission network elements (i.e., 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 transceiver MUST tolerate a total PDL of 2.0 dB for the incoming optical signal.

In the received optical power-limited case, when the PDL is 2.0 dB, the transceiver MUST achieve a post-FEC bit-error-ratio (BER) of $\leq 10^{-15}$ when the received optical power is 1.5 dB greater than the baseline optical power requirement defined in Section 7.4.1.1.

In the received OSNR-limited case, when the PDL is 2.0 dB, the transceiver MUST achieve a post-FEC bit-error-ratio (BER) of $\leq 10^{-15}$ when the received OSNR is 1.5 dB greater than the baseline OSNR requirement defined in Section 7.4.1.2.

The transceiver MUST report the measured PDL.

7.4.6 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 ITU-T 100 GHz grid. This corresponds to the transmitter laser frequency accuracy defined in Section 7.3.2.

The transceiver MUST be capable of successfully receiving signals with a center frequency within +/-1.8 GHz of the DWDM grid defined in Table 2 for any channel that it supports.

7.4.7 Skew Tolerance

Skew is defined as the inter-channel delay in the I-Q or X-Y as seen by a receiver. There are two factors in the observed I-Q and X-Y skews by the receiver: (a) the static inter-channel skews which can be mostly calibrated out except residual skews, and (b) the dynamic skew variation over temperature, wavelength, and aging, which cannot be calibrated out. The latter is called I-Q and X-Y skew variation.

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

7.4.7.1 Quadrature Skew Tolerance

Quadrature skew is generated by the transmitter, as outlined in Section 7.3.5.1, 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. The receiver quadrature skew, however, is much easier to be compensated by the receiver due to the fact that the receiver skew is not combined with phase distortion/rotation. As a result, the quadrature skew tolerance by a receiver is mainly related to the transmitter quadrature skew and skew variation.

The transceiver MUST have a minimum receiver quadrature skew tolerance of 3.5 ps for the incoming optical signal.

7.4.7.2 Polarization Skew Tolerance

Polarization skew seen at a receiver DSP is the combination of polarization skew (or differential group delay, DGD) generated by the transmitter (as outlined in Section 7.3.5.2), the optical fiber, the receiver, and other optical components in the link.

The requirement to tolerate 30 ps polarization skew or DGD is approximately equal to the 10 ps PMD tolerance defined in Section 7.4.3.

The transceiver MUST have a minimum receiver polarization skew tolerance of 30 ps for the incoming optical signal as seen by the receiver.

7.4.8 Receiver Reflectance

The transceiver MUST support an optical receiver reflectance of ≤ -25 dB.

7.4.9 Data Re-acquisition Time

In an optical link, an event such as a fiber break-triggered protection switch or transmitter failure can cause a loss of optical signal to the receiver. The data re-acquisition time is defined as how soon the received signal can be demodulated with post-FEC error free performance as soon as the fiber link is re-established with a valid incoming signal.

The transceiver MUST operate with a data re-acquisition time of 250 ms or less.

Appendix I Acknowledgements (Informative)

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