Point-to-Point Coherent Optics

Physical Layer 2.0 Specification

P2PCO-SP-PHYv2.0-I01-190311

ISSUED

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Document Status Sheet

Document Control Number:	P2PCO-SP-PHYv2.0-I01-190311			
Document Title:	Physical Layer 2.0 Specification			
Revision History:	D01 – Released 12/20/2018 D02 – Released 02/07/2019 I01 – Released 03/11/2019			
Date:	March 11, 2019			
Status:	~~Work in Progress~~	**Draft**	~~Issued~~	~~Closed~~
Distribution Restrictions:	~~Author Only~~	~~CL/Member~~	**CL/ Member/ Vendor**	~~Public~~

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 200 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-signal-to-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 technology overview, reference interfaces, functional block diagrams, and functional assumptions.

Sections 6 - 9 contain the normative material, organized as follows:

- Section 6 covers general transceiver requirements that aren't specific to the physical layers defined in this specification,
- Section 7 defines the Framing, FEC, and Symbol Mapping that applies to any device that is compliant to this specification,
- Section 8 defines the additional requirements for a device operating at 200G using QPSK modulation,
- Section 9 defines the additional requirements for a device operating at 200G using 16-QAM modulation.

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 802.3-2018]	IEEE Std. 802.3™-2018, IEEE Standard for Ethernet, 8 August 2018.
[ITU-T G.709]	ITU-T Recommendation G.709/Y.1331, Interfaces for the optical transport network, 06/2016.
[ITU-T G.709.1]	ITU-T Recommendation G.709.1/Y.1331.1, Flexible OTN short-reach interfaces, 06/2018.
[ITU-T G.709.2]	ITU-T Recommendation G.709.2/Y.1331.2, OTU4 long-reach interface, 07/2018.
[ITU-G.709.3]	ITU-T Recommendation G.709.3/Y.1331.3, Flexible OTN long-reach interfaces, 06/2018.
[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
[Campopiano and Glazer]	Campopiano, C. and Glazer, B. 1962, A Coherent Digital Amplitude and Phase Modulation Scheme, IEEE Transactions on Communications (originally published by IRE Transactions on Communications Systems (Volume: 10, Issue: 1, March 1962), https://ieeexplore.ieee.org/document/1088634
[ITU-T G.694.1]	ITU-T Recommendation G.694.1, Spectral grids for WDM applications: DWDM frequency grid, 02/2012.
[ITU-T G.957]	ITU-T Recommendation G.957, Optical interfaces for equipments and systems relating to the synchronous digital hierarchy, 03/2006.
[ITU-T G.Sup39]	ITU-T G.Sup39, Optical system design and engineering considerations, 02/2016, 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, P2PCO-SP-OSSI-D01-190311, March 11, 2019, Cable Television Laboratories, Inc.
[OPT-P2P-ARCH]	P2P Coherent Optics Architecture Specification, P2PCO-SP-ARCH-I02-190311, March 11, 2019, Cable Television Laboratories, Inc.
[OPT-P2P-PHYv1.0]	P2P Coherent Optics, Physical Layer 1.0 Specification, P2PCO-SP-PHYv1.0-I02-190311, March 11, 2019, 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-T: International Telecommunications Union, Telecommunication Standardization Sector, https://www.itu.int/en/ITU-T/Pages/default.aspx
- Open ROADM Multi-Source Agreement (MSA), http://openroadm.org/download.html

3 TERMS AND DEFINITIONS

This specification uses the following terms:

Aggregation Node	A device that aggregates multiple client-side interfaces into one or more line-side interfaces. For example, it might aggregate multiple 10 Gbps client-side interfaces into a single 200 Gbps coherent optics line-side interface.
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.
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:

100G	100 Gigabits per second
200G	200 Gigabits per second
ADC	Analog to Digital Converter
AM	Alignment Marker
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
CFO	Carrier Frequency Offset
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-16-QAM	Dual Polarization - 16 point Quadrature Amplitude Modulation
DP-8-QAM	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
FAW	Frame Alignment Word
FEC	Forward Error Correction
FS	Fixed Stuff
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
MMI	Multimode Interference
MSA	Multi-Source Agreement
MSO	Multiple Systems Operator
MUX	Multiplexer
MZM	Mach-Zehnder Modulator
NCG	Net Coding Gain
nm	Nanometer
NRZ	Non-return to Zero
ODC	Optical Distribution Center
ODU	Optical Data Unit
oFEC	Open Forward Error Correction (openFEC)
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
PAD	Padding
PAM	Pulse Amplitude Modulation
PBC	Polarization Beam Combiner
PRBS	Pseudorandom binary sequence
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
SC FEC	Staircase FEC
SD	Soft Decision
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 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.

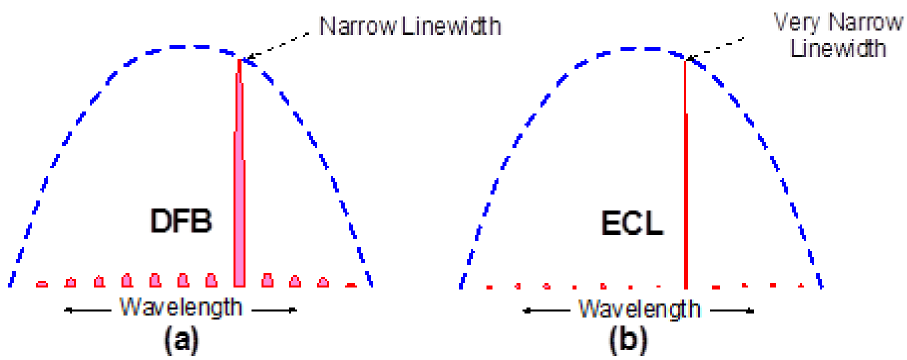


Figure 1 - Emission Spectrum of Coherent Laser Structures for Access Environment

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.

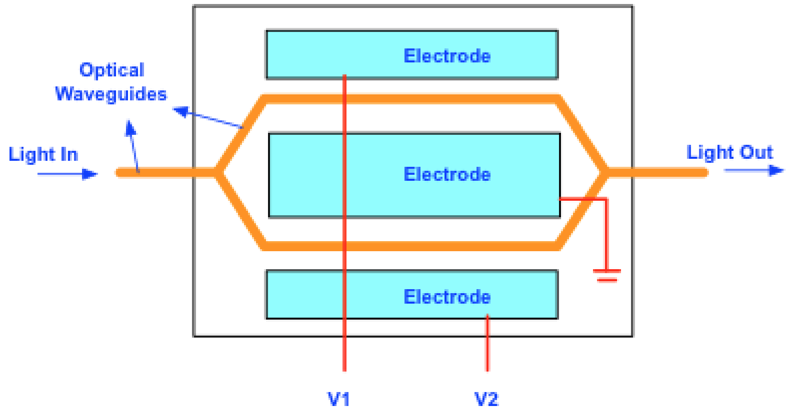


Figure 2 - Mach-Zehnder Intensity Modulator Structure

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.

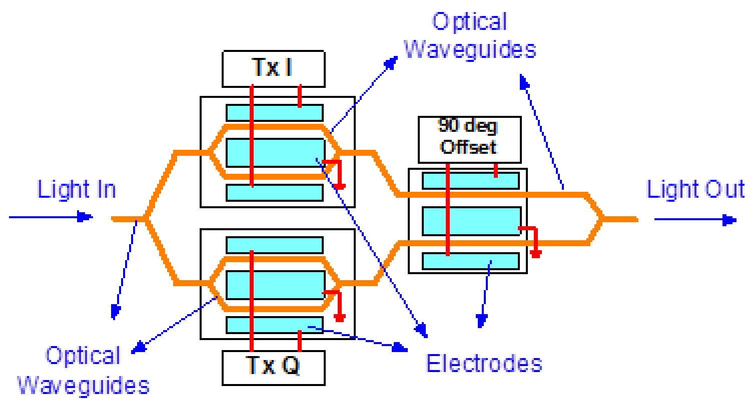


Figure 3 - IQ Modulator Structure Using Two Mach-Zehnder Modulators

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.

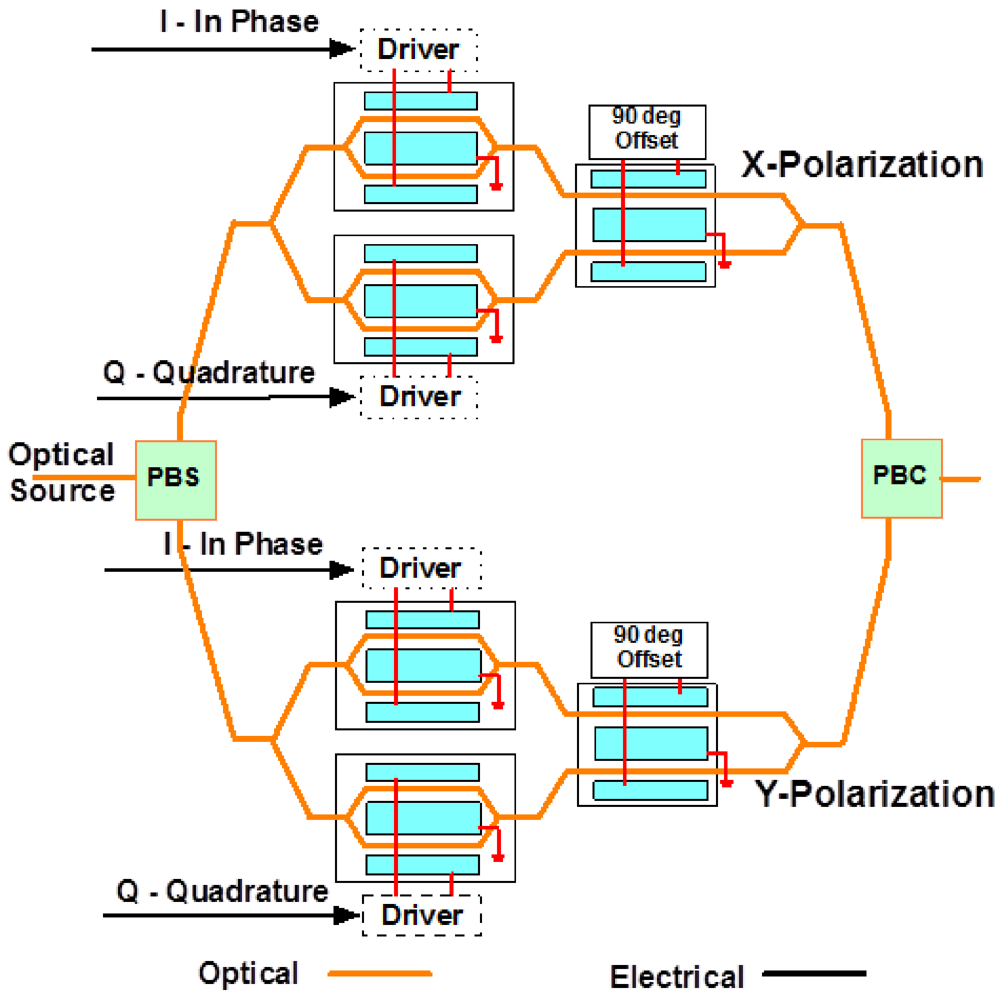


Figure 4 - Dual Polarization Coherent IQ Modulator

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 1313 nm (1302 nm -1322 nm range), and S_0 is the dispersion slope at λ_0, 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.

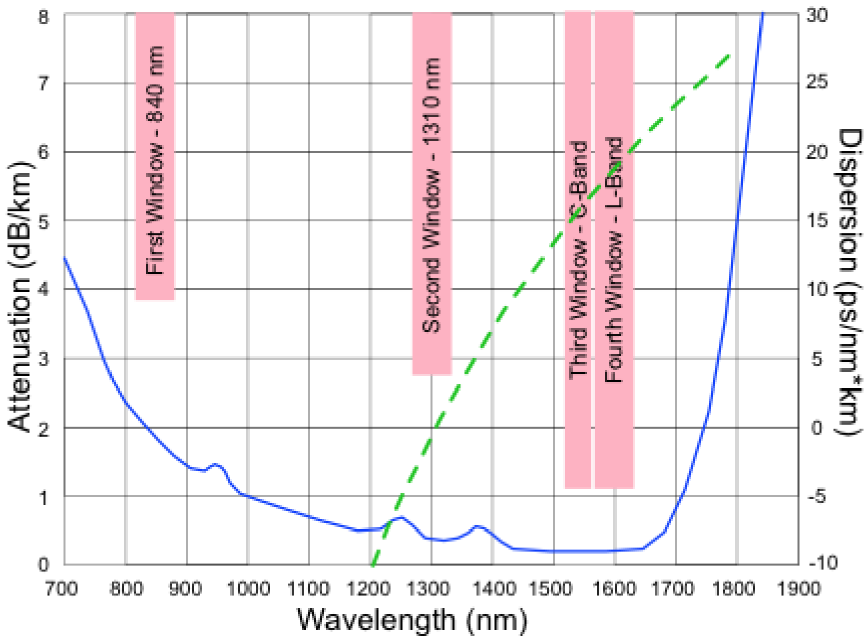


Figure 5 - SMF Fiber Attenuation (blue) and Dispersion (green) versus Wavelength

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 causes 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. And the PMD of the fiber is the average value of the differential group delay (DGD). 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), inline 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 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, therefore allowing 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.

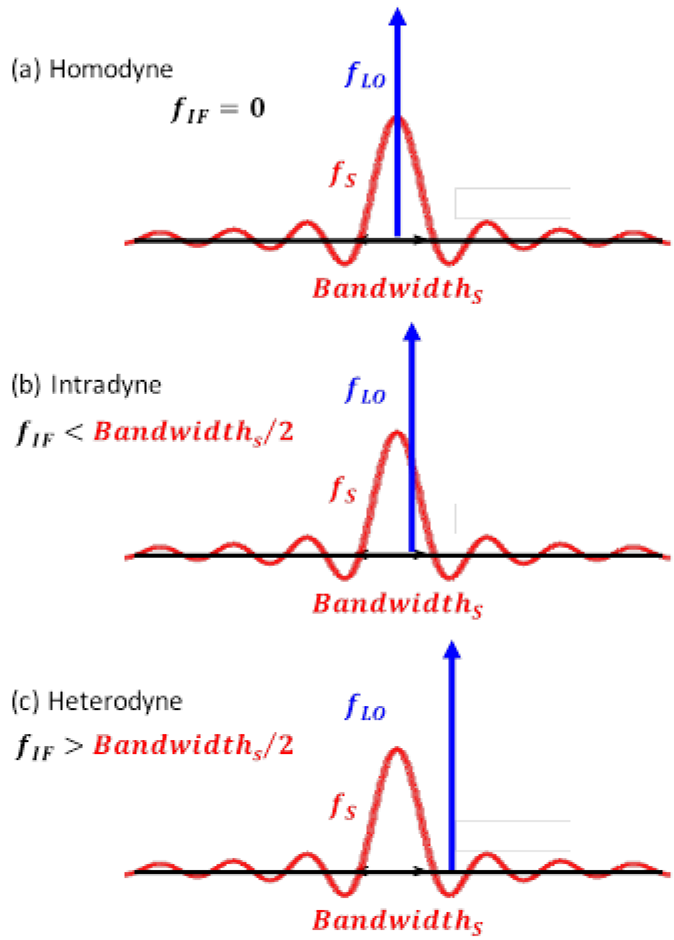


Figure 6 - Three Coherent Detection Schemes: (a)Homodyne, (b)Intradyne, (c)Heterodyne

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.

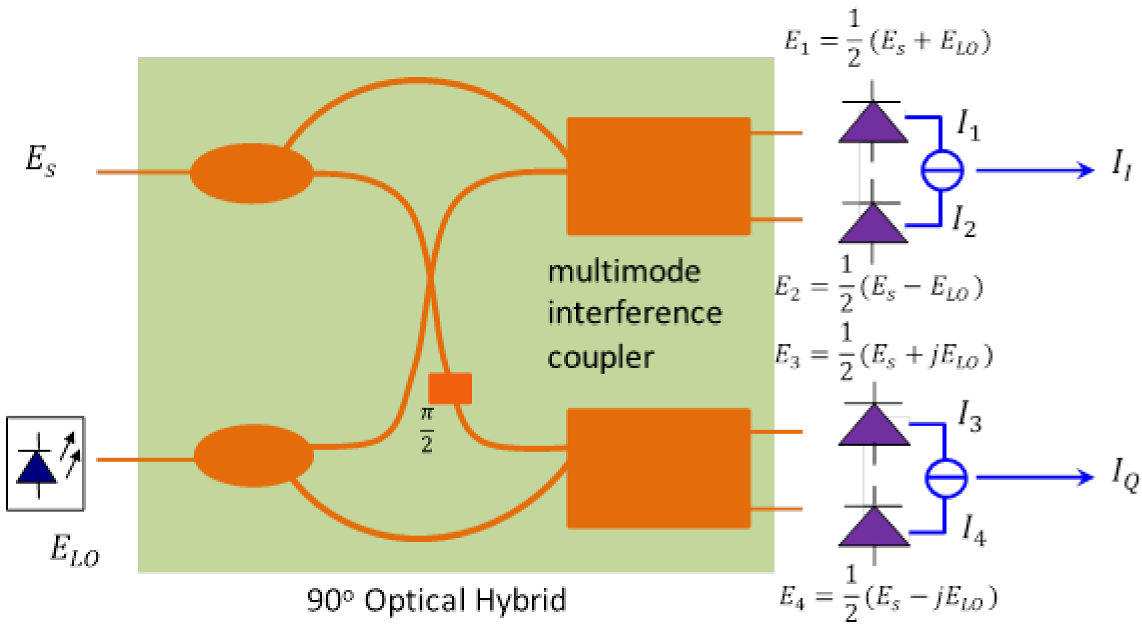


Figure 7 - Configuration of Phase-diversity Coherent Receiver

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.

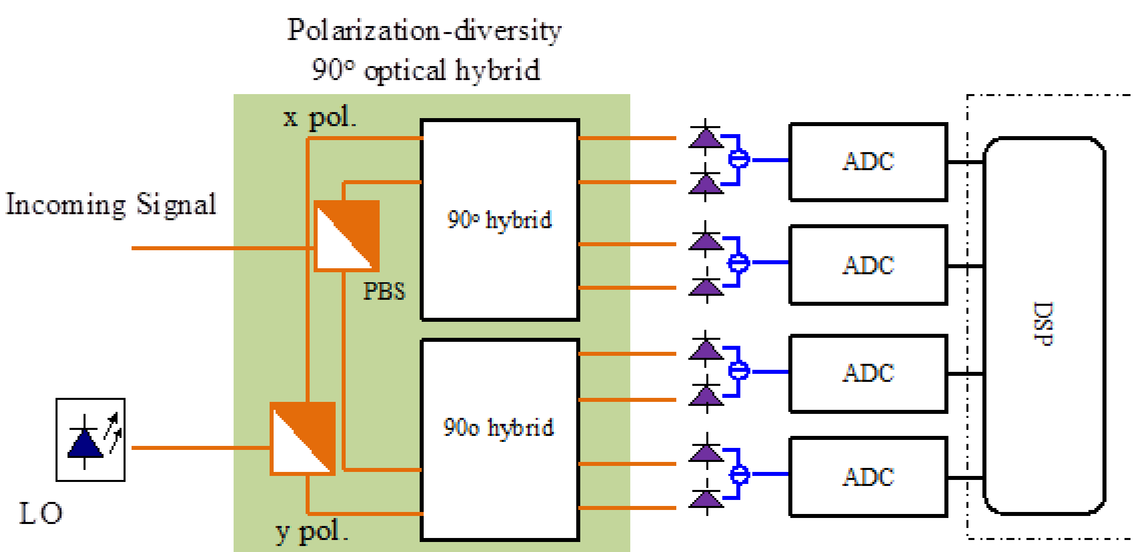


Figure 8 - Configuration of Phase and Polarization Diversity Coherent Receiver Architecture

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.

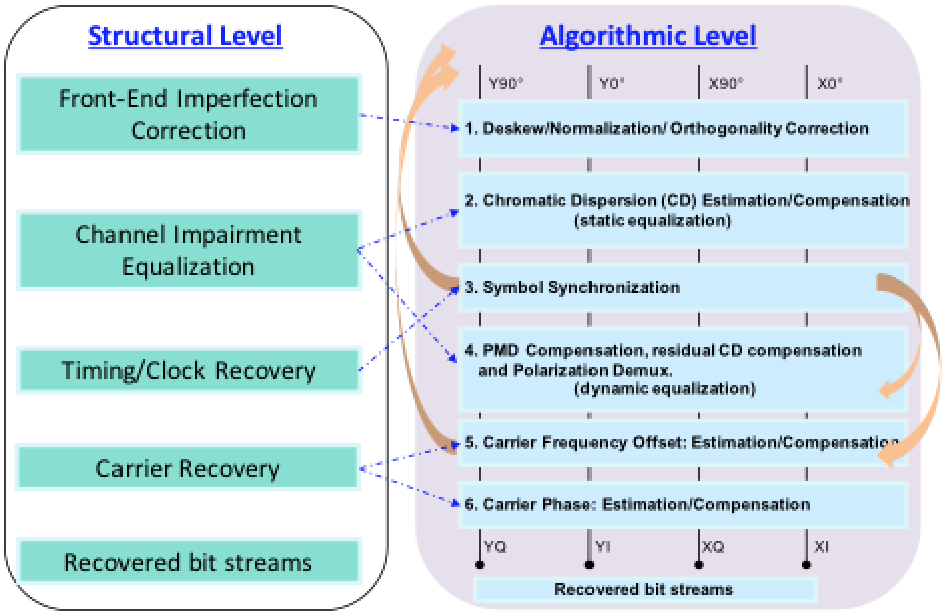


Figure 9 - DSP Flow in a Coherent Optical Receiver

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 network, 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].

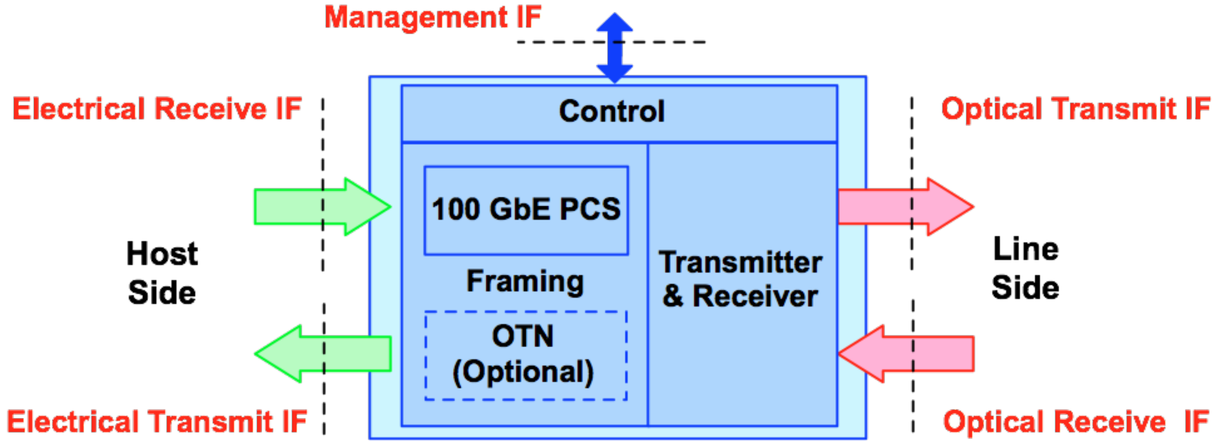


Figure 10 - Dual Optical Interface Transceiver Optical, Electrical and Management Interfaces

The dual optical interface transceiver option is the transceiver design that has historically been most common, and utilizes separate optical interfaces for transmit and receive functions.

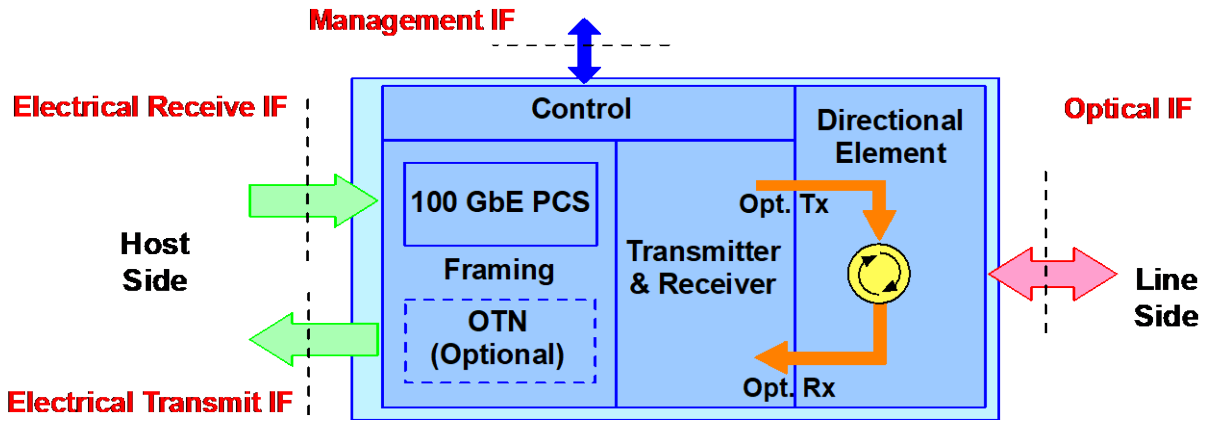


Figure 11 - Single Optical Interface Transceiver Optical, Electrical and Management Interfaces

The single optical interface transceiver option addresses the deployment scenarios identified in Section 1.2, where there is only a single fiber available from hub to node. This option incorporates a signal direction function that allows the transmitter optical signal to be directed to the single optical interface and the signal incoming through the single optical interface to be directed to the receiver with negligible performance impact and while utilizing the same frequency in both directions. The architecture implications when using the single interface transceiver option are described in section 7.6 of [OPT-P2P-ARCH].

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 12 and Figure 13. The transmitter and receiver process sequences are only provided as examples. Actual transmitter and implementations may follow different sequences and different feedback dependencies.

Figure 12 shows the example functions that take place in the transmitter from the electrical input on the host-side to the optical output on the line-side. The "Directional Element" block on the line side is only applicable to the single optical interface transceiver option.

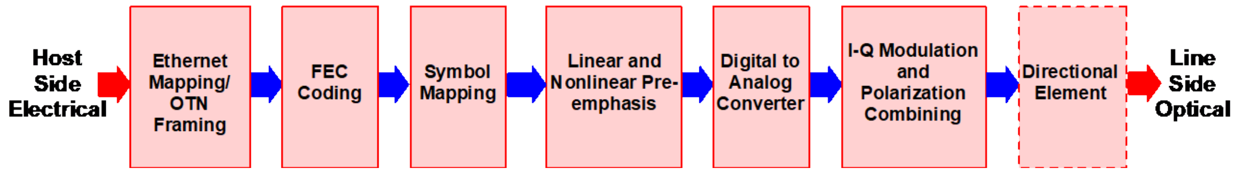


Figure 12 - Example Transmitter Functional Diagram

The transmitter processes include:

- Ethernet Mapping and OTN Framing
- FEC Coding
- Symbol Mapping
- Linear and Nonlinear 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 13 shows an example of the functions that take place in the receiver from the optical input on the line side to the electrical output on the host side. The "Directional Element" block on the line side is only applicable to the single optical interface transceiver option.

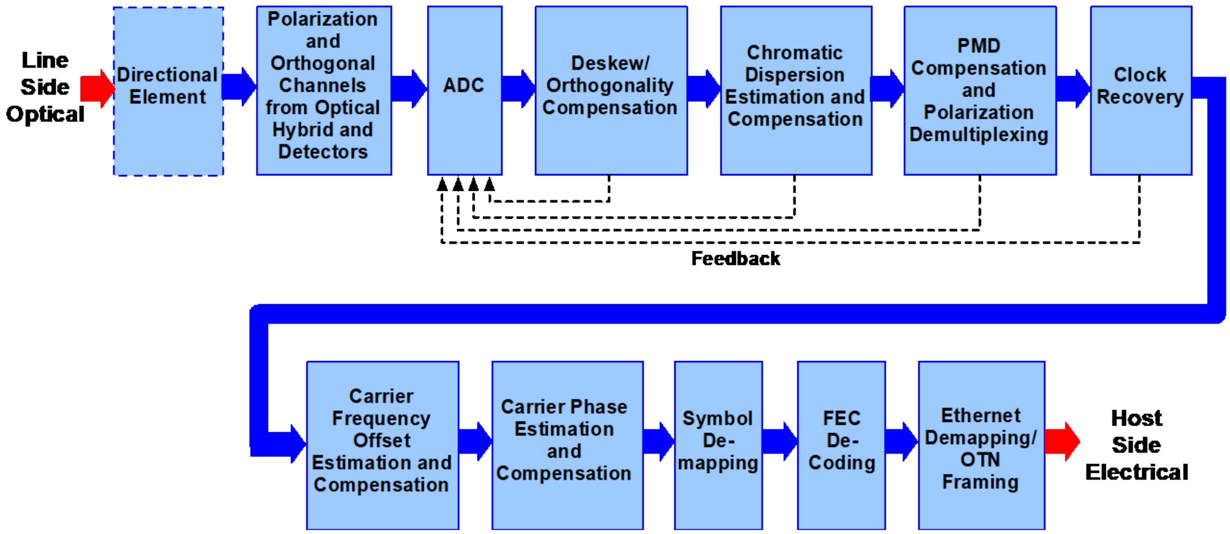


Figure 13 - Example Receiver Functional Diagram

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. For example, the end-to-end link latency consists of the transmitter and receiver latencies along with the optical channel transmission delay. Transceiver operation may be impacted by ambient temperature, which may require compensation. In the receiver, the data reacquisition 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 new 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 the range of temperatures the transceiver supports (as defined by the manufacturer), it will be expected to meet the requirements in this specification across that entire supported range.

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

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. However, it is generally expected that transceivers will support 2x100GbE on the client side to provide 200G on the optical interface. As a result, the examples given in this document illustrating various key points and requirements are generally based on this assumption.

This assumption notwithstanding, as this specification does not mandate an electrical interface consisting of 2x100GbE, other options – such as 200GbE – are permitted, as long as the transceiver supports the transport of Ethernet traffic.

The transceiver MUST support the transport of Ethernet frames.

6.3 Optical Ports and Frequencies

As discussed in Section 5.2, two different line side interface options have been defined in this specification: a dual optical interface option, and a single optical interface option. Both options can support either a single frequency for transmitting and receiving, or separate frequencies for transmitting and receiving.

This specification supports both of the line side interface options. It also requires support for using the same frequency for transmitting and receiving, but allows the option of transmitting and receiving with different frequencies.

The transceiver MUST support either dual optical interfaces or a single optical interface 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.

6.4 Backward Compatibility Requirements

Transceivers compliant with this specification can optionally support the 100G mode of operation as defined in [OPT-P2P-PHYv1.0] in addition to the 200G modes defined within the specification. If a device supports that 100G mode of operation, it is required to provide a mechanism for switching between different modes. When operating in that 100G mode it will be required to meet all of the requirements in [OPT-P2P-PHYv1.0], and when operating in a 200G mode the transceiver will be required to meet all of the requirements of this specification.

The transceiver MAY support the 100G mode as defined in [OPT-P2P-PHYv1.0].

If a 100G mode is supported, the transceiver MUST support a method of switching modes.

7 FRAMING, FEC, AND SYMBOL MAPPING

This section describes the process for adapting client-side data into coherent line-side data.

For the purposes of this section, it is assumed that the client-side interface will provide two 100GbE client signals. This section defines the process for adapting those client signals for transport over a 200G coherent DP-QPSK or DP-16-QAM optical link. This includes Framing, applying FEC, and Mapping into symbols for transmission.

The overall adaptation process is shown in Figure 14.

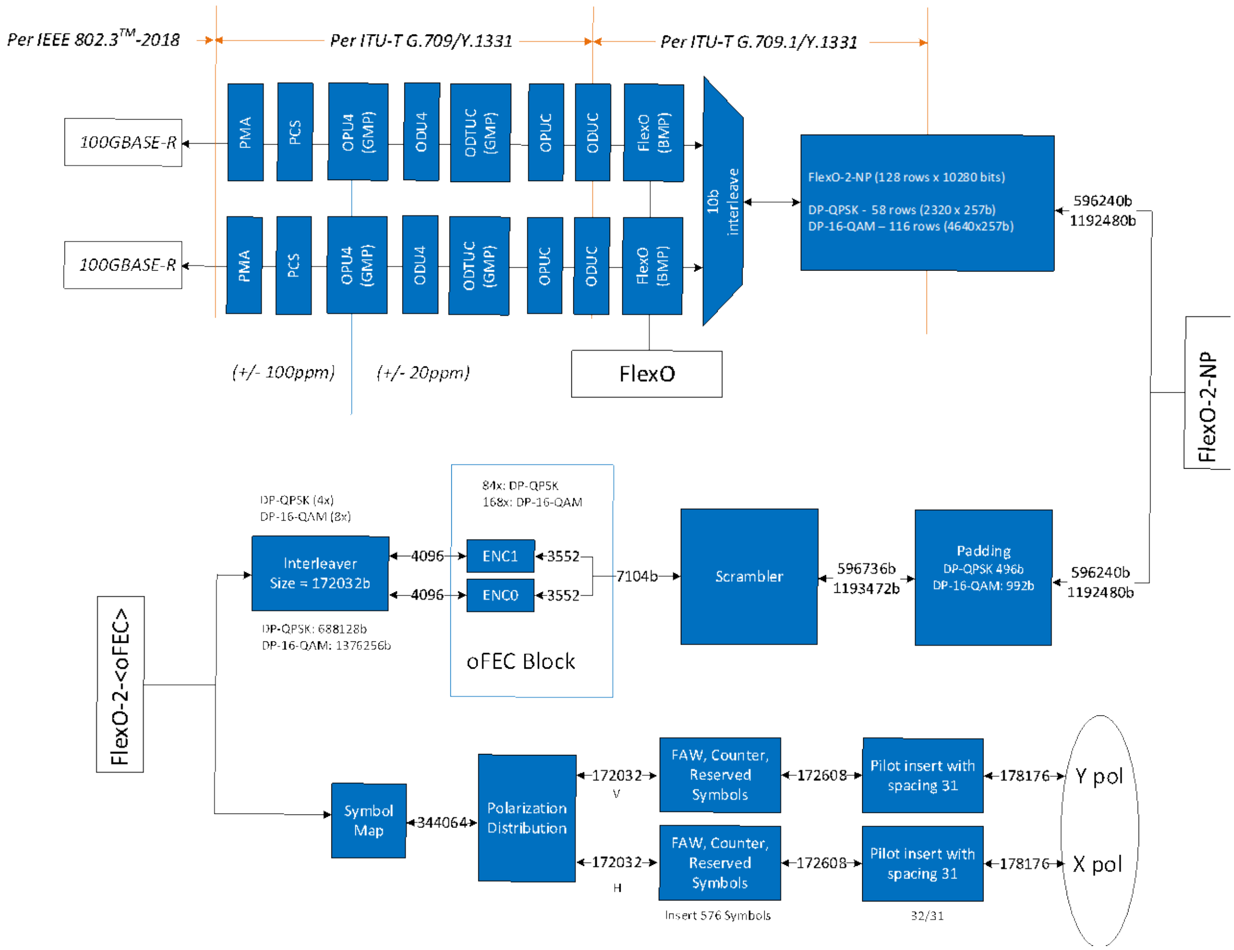


Figure 14 - Framing, FEC, and Mapping Process

Two 100GbE clients are first mapped per [ITU-T G.709] and then multiplexed per [ITU-T G.709.1] into 2 x 100G FlexO frame structures. The 2 x 100G FlexO frame/multi-frame aligned structures are then 10b multiplexed into a 200G FlexO-2-NP (200G FlexO without parity field) frame structure. The 200G FlexO-2-NP frame structure is then adapted, scrambled, and open FEC (oFEC) encoded. After FEC encoding and interleaving the frame structure is referred to as a FlexO-2-<oFEC>. The bitstream of FlexO-2-<oFEC> frames are then mapped into constellation symbols of each polarization, after which Training symbols, Super-Frame Alignment Word symbols, and Pilot symbols are added.

7.1 Framing

This section defines the requirements for taking the input from two 100GbE Ethernet Clients and generating the FlexO-2-NP frames that are adapted and scrambled before being FEC encoded. The 100GbE Ethernet Clients

(100GBASE-R) are defined by [IEEE 802.3-2018]. The client FEC, if any, is assumed to be terminated prior to mapping.

The mapping and adaptation processes are shown in Figure 15 and Figure 16.

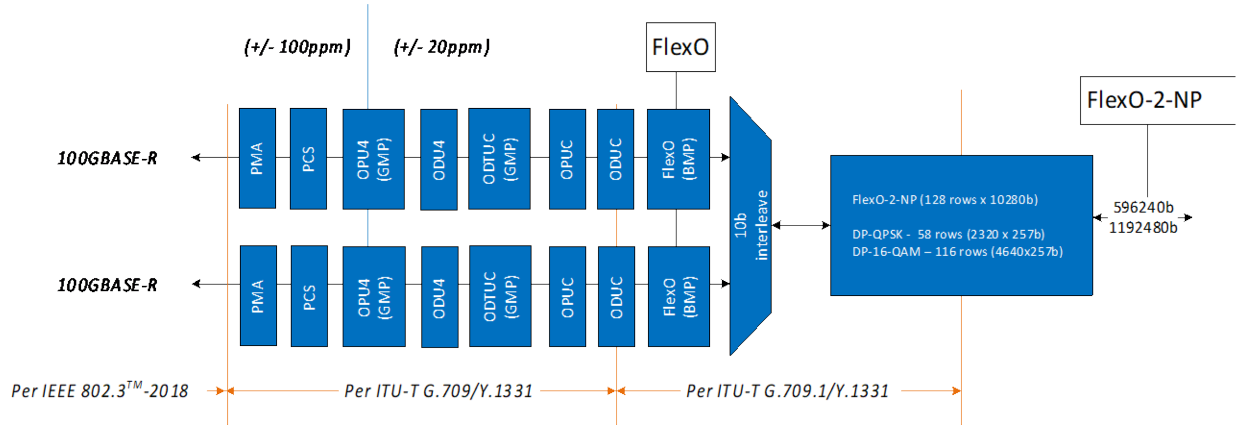


Figure 15 - 100GBASE-R framing and mapping processes to a FlexO-2-NP

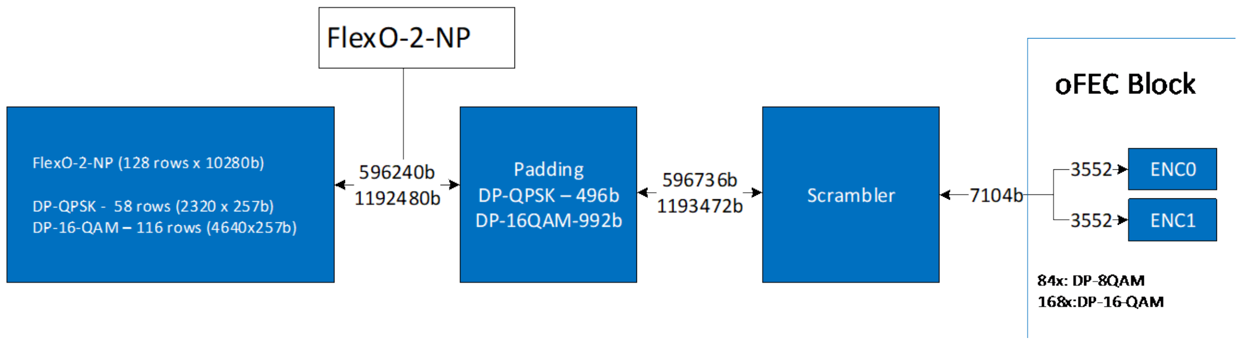


Figure 16 – FlexO-2-NP to oFEC encoding adaptation

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.

The transceiver MUST map each ODU4 signal into an ODTUC signal and the ODTUC into the OPUC tributary slots as defined in [ITU-T G.709] clause 20.

The transceiver MUST map each OTUC signal into a FlexO frame instance as defined in [ITU-T G.709.1] Clause 10.

The transceiver MUST align and deskew the OTUC instances as defined in [ITU-T G.709.1] subclause 10.4.

The transceiver MUST interleave each FlexO frame instance into a FlexO-2-NP frame structure as defined in Section 7.1.2.

The transceiver MUST adapt the FlexO-2-NP frame structure to the oFEC blocks as defined in Section 7.1.3, including padding insertion and frame synchronous scrambling.

The intermediate frame structure bit rates are defined in Table 1 below.

Table 1 - Client Types and Payload Bit Rates

Interface	Interface Nominal Bit Rate	Tolerance
100GBASE-R	103.125000000 Gbps	±100 ppm
ODU4	104.794445815 Gbps	±20 ppm
ODUC	105.258138053 Gbps	±20 ppm
FlexO	105.643510782 Gbps	±20 ppm
FlexO-2-NP	211.287021564 Gbps	±20 ppm

The frame structures, as well as the adaptation to the oFEC blocks, are defined in the following subsections.

7.1.1 FlexO Frame Structure

The FlexO (100G) frame structure is defined in [ITU-T G.709.1] and copied in Figure 17 for reference. Each 100G instance consists of block formats, 128 rows by 5,140 1-bit columns.

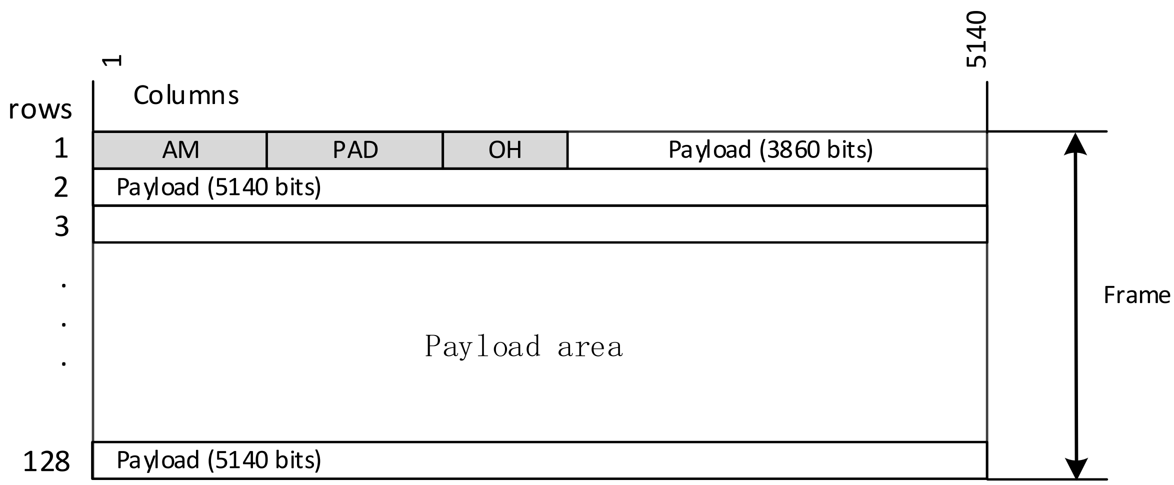


Figure 17 - FlexO Frame Structure

The 8-frame multi-frame structure, further defined in [ITU-T G.709.1], is shown in Figure 18.

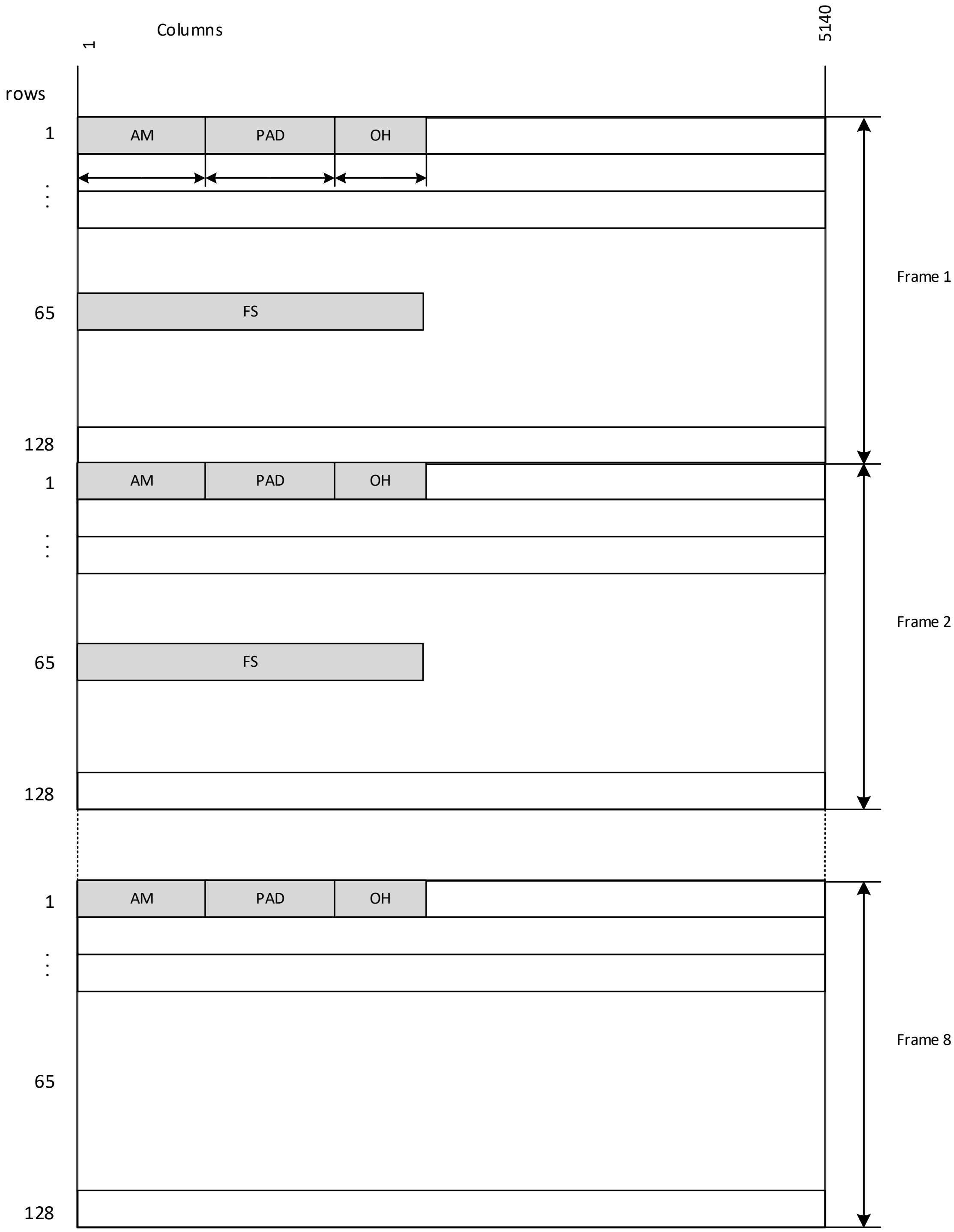


Figure 18 - FlexO Multi-Frame Format

The multi-frame contains seven fixed stuff (FS) locations in the payload area of the FlexO frames, each containing 1,280 bits. These fixed stuff locations are in row 65, columns 1 to 1,280, in the first seven frames within the multi-frame. The last frame within the multi-frame does not contain fixed stuff.

The fixed stuff bits are filled with all zeroes and not checked at the receiver sink function.

The FlexO multi-frame payload, excluding the fixed stuff (FS) locations, consists of 5,244,160 bits (655,520 bytes) out of the total 5,263,360 bits (657,920 bytes) per FlexO multi-frame.

Alignment Markers (AM), Padding (PAD) and OverHead (OH) are inserted in the first row of each FlexO frame, and are defined in [ITU-T G.709.1].

The transceiver MUST support the FlexO frame structures shown in Figure 17 and Figure 18.

7.1.2 FlexO-2-NP Frame Structure

[ITU-G.709.3] Clause 12 defines a FlexO-2-SC frame structure as 10970b × 128 rows, with FEC OH in row 1 columns 961 to 1920 and a parity area in columns 10281 to 10970 of all rows (reference [ITU-G.709.3] figure 12.1). The FlexO-2-NP frame structure is similar to the FlexO-2-SC frame structure, without the parity field. Parity is added by the oFEC block and interleaver stages downstream of the FlexO-2-NP frame structure.

The FlexO-2-NP frame structure is shown in Figure 19.

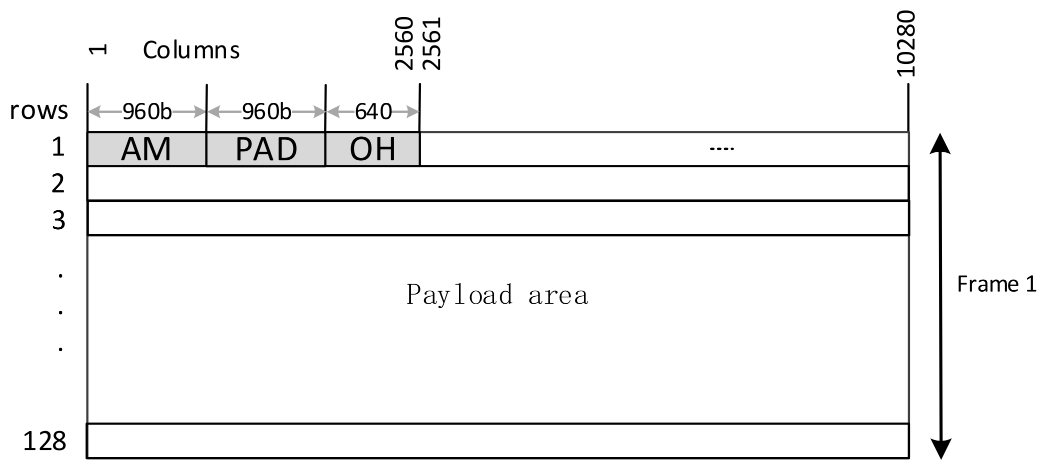


Figure 19 - FlexO-2-NP frame structure

Two frame/multi-frame aligned 100G FlexO instances are 10-bit interleaved as defined in clause 12 of [ITU-G.709.3] into a FlexO-2-NP frame structure in a similar fashion as defined by the FlexO-2-SC [ITU-G.709.3] clause 12.

This process is shown in Figure 20.

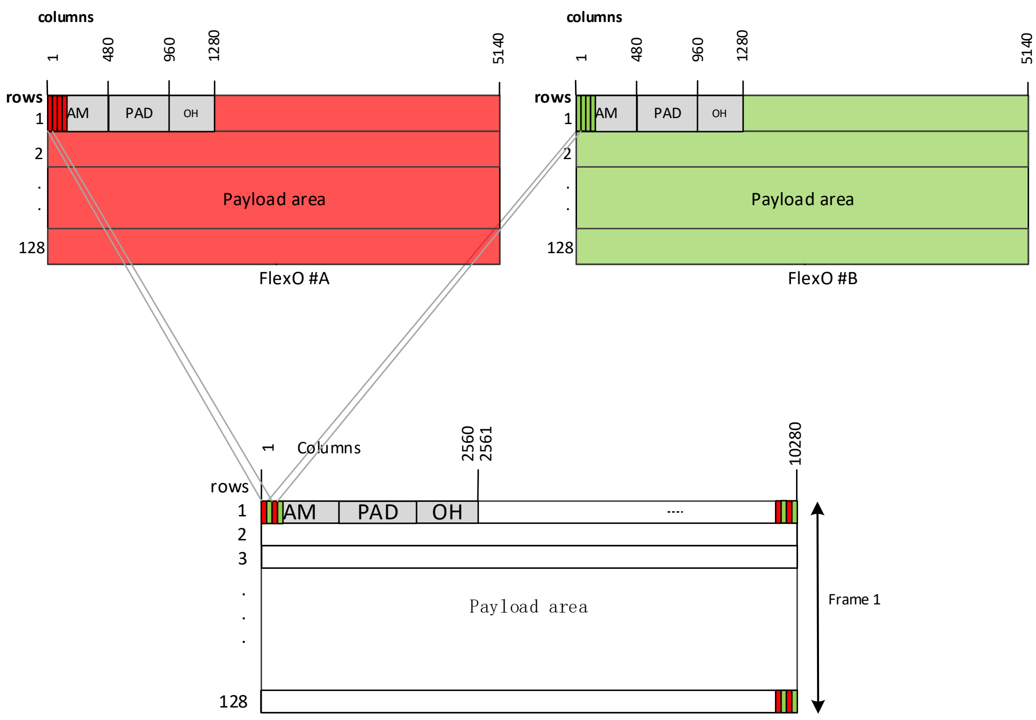


Figure 20 - Interleaved FlexO frames to FlexO-2-NP frame structure

The 120 byte FEC OH defined for FlexO-2-SC is not required for FlexO-2-NP and will be defined as reserved (RES). The FlexO-2-FlexO-2-NP AM, PAD, and OH fields are the interleaved FlexO instances AM, PAD, and OH.

The transceiver MUST support the FlexO-2-NP frame structure shown in Figure 19.

The transceiver MUST support the 10-bit interleaving process as shown in Figure 20 to create the FlexO-2-NP frame.

7.1.3 FlexO-2-NP Adaptation to FlexO-2-<oFEC>

For 200G DP-QPSK modulation, 58 FlexO-2-NP rows plus 496 bits of all-zero PAD are added then scrambled to 84 oFEC blocks. For 200G DP-16-QAM modulation, 116 FlexO-2-NP rows plus 992 bits of all zero PAD are added and then scrambled to 168 oFEC blocks. The scrambled data is then bit demultiplexed to 2 oFEC encoders, each of which operates on input blocks of 3552 bits and produces output blocks of 4096 bit. This process is summarized in Table 2. The oFEC encoder/decoder is further defined in Section 7.2.

Table 2 - oFEC Adaptation Rates

Modulation Format	FlexO-2-NP Mapped Payload Rows	oFEC Blocks	PAD (bits)	Pre FEC Encode (bits)	Post FEC Encode (bits)
200G DP-QPSK	58 rows, (2,320 x 257 bits)	84	496	596,736	688,128
200G DP-16-QAM	116 rows, (4640 x 257 bits)	168	992	1,193,472	1,376,256

Figure 21 shows the relationship of the FlexO-2-NP frame structure to the oFEC Block structure when the modulation is 200G DP-QPSK. This figure includes the additional PAD and scrambler reset location.

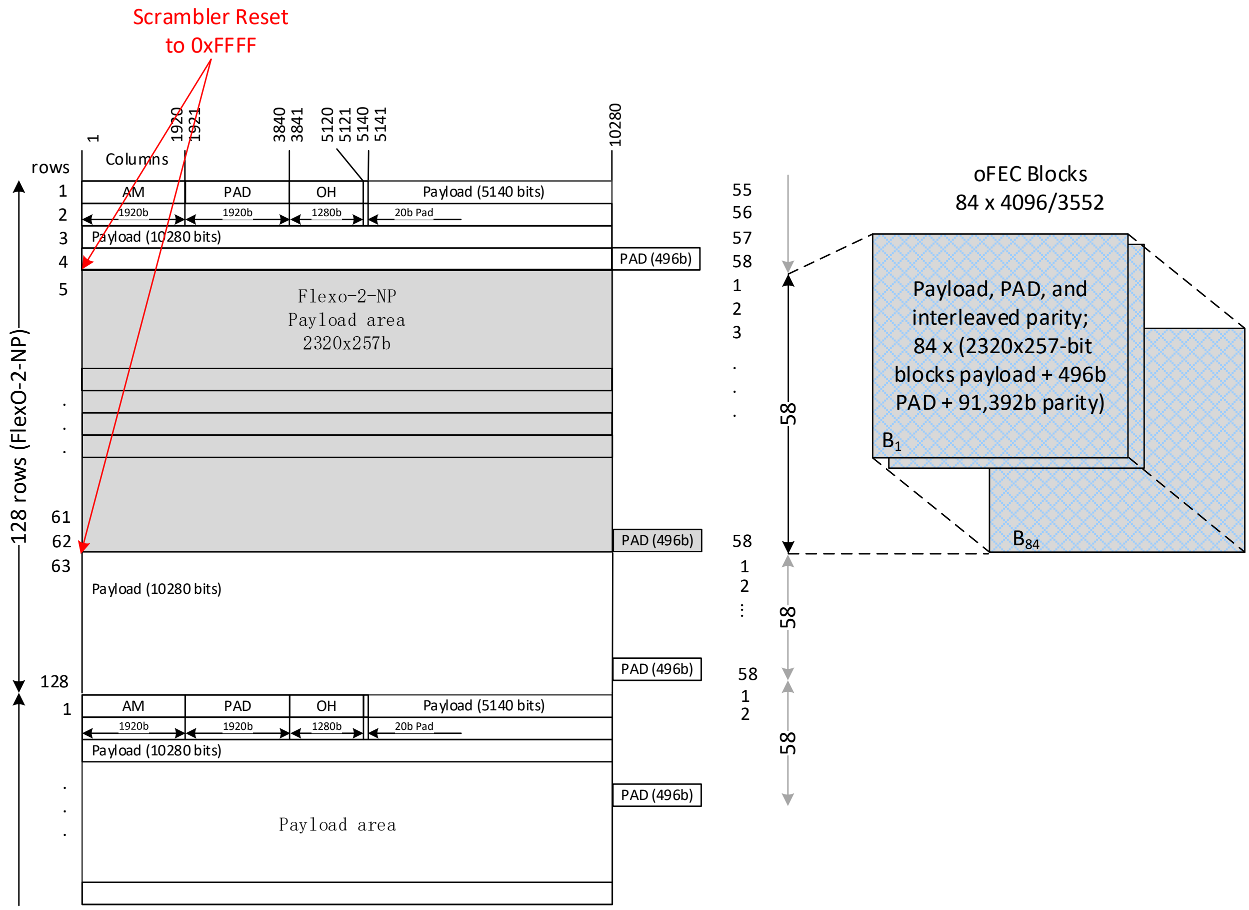


Figure 21 - FlexO-2-NP to oFEC Block Mapping for 200G DP-QPSK

Figure 22 shows the relationship of the FlexO-2-NP frame structure to the oFEC Block structure when the modulation is 200G DP-16-QAM. This figure includes the additional PAD and scrambler reset location.

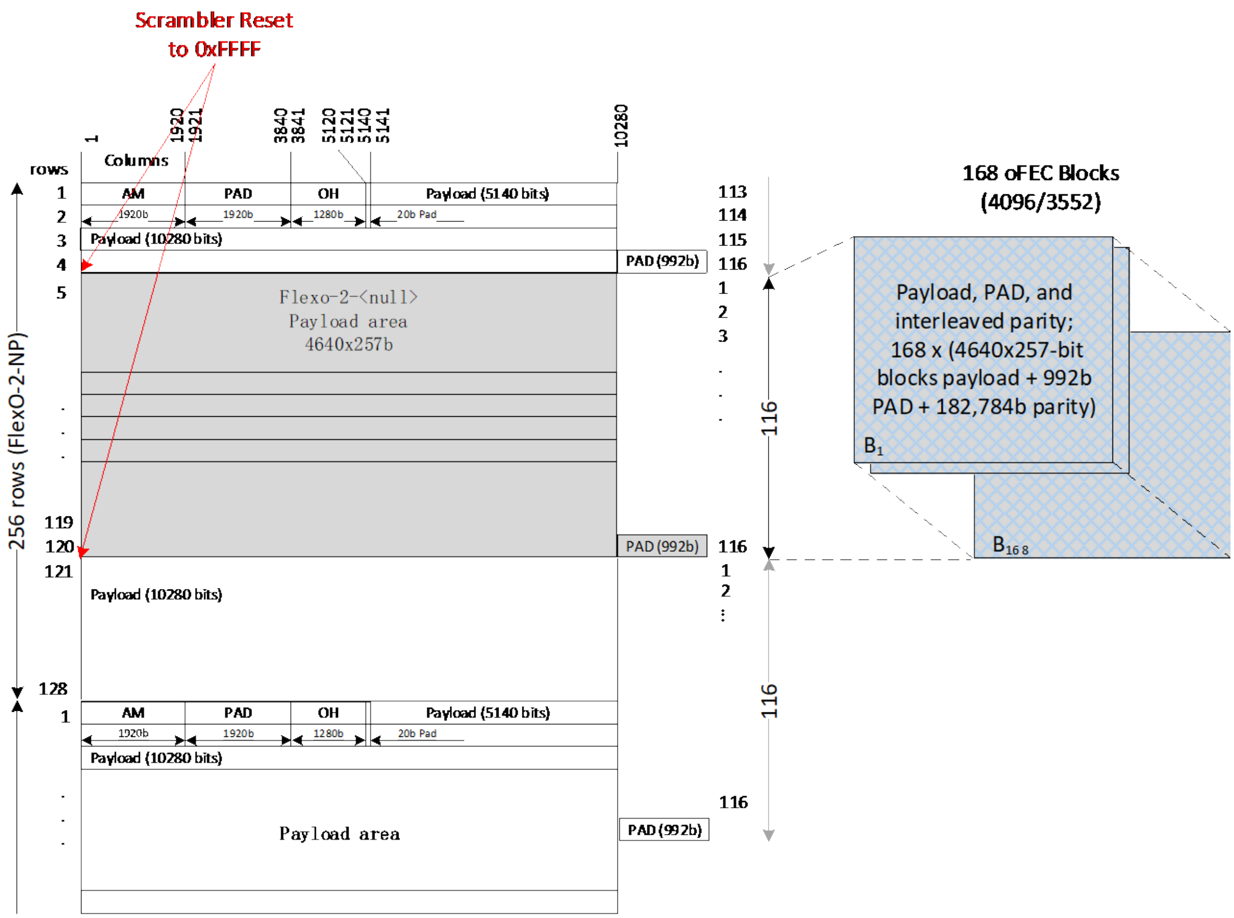


Figure 22 - FlexO-2-NP to oFEC Block Mapping for 200G DP-16-QAM

The transceiver MUST support the FlexO-2-NP to oFEC mapping as shown in Figure 21. If the transceiver supports the 200G 16-QAM mode of operation, the transceiver MUST support the FlexO-2-NP to oFEC mapping as shown in Figure 22.

7.1.3.1 Padding Insertion/Removal

For the purpose of oFEC alignment and synchronization, pad bits are prepended/removed from the FlexO payload area. The PAD is an all-zero field that gets scrambled prior to encoding and removed after decoding and descrambling.

The transceiver MUST support an all-zero field PAD where indicated by various frame structures.

7.1.3.2 Frame Synchronous Scrambling

The scrambler/descrambler is located before the oFEC encoder block on transmit and after the oFEC decoder block on receive. The operation of the scrambler will be functionally equivalent to that of a frame-synchronous scrambler of sequence 65535, and the generating polynomial will be

$$x^{16} + x^{12} + x^3 + x + 1.$$

The scrambler/descrambler resets to 0xFFFF on row 1, column 1 of each new oFEC block (i.e., on first bit of FlexO-2-NP payload mapped to the oFEC block structure or after the last bit of PAD from the previous oFEC block structure). The scrambler runs continuously over the entire FlexO-2-NP frame. Figure 23 shows a functional diagram of the frame synchronous scrambler.

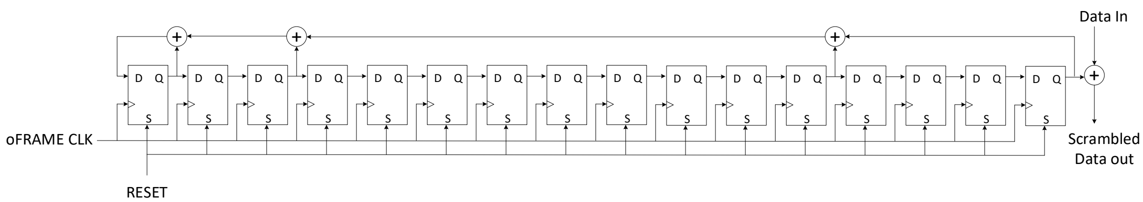


Figure 23 - Frame Synchronous Scrambler

The transceiver MUST support the scrambler implementation described in this section.

7.2 Forward Error Correction and Interleaving

NOTE: This section of the document uses base 0 for mathematical formula convenience.

This specification has adopted a Forward Error Correction (FEC) commonly referred to as Open Forward Error Correction, or openFEC (oFEC), which is defined in this section.

The oFEC encoder engine is a block-code-based encoder and iterative Soft-Decision (SD) decoder with 11.1 dB @ $10e^{-15}$ (QPSK) Net Coding Gain (NCG) and 11.6 dB @ $10e^{-15}$ (16-QAM) NCG after 3 SD iterations (correction to $\leq 10e^{-15}$ with pre-FEC BER $2.0e^{-2}$). Combined latency of the encoder and decoder is less than 3 µs.

The oFEC encoder and interleaver datapath is shown in Figure 24. The 7104 bits from the scrambler is bit demultiplexed into two (2) parallel 3552/4096 encoder engines. Even numbered bits (0 based) go to encoder 0 (ENC0) and odd numbered bits to encoder 1 (ENC1).

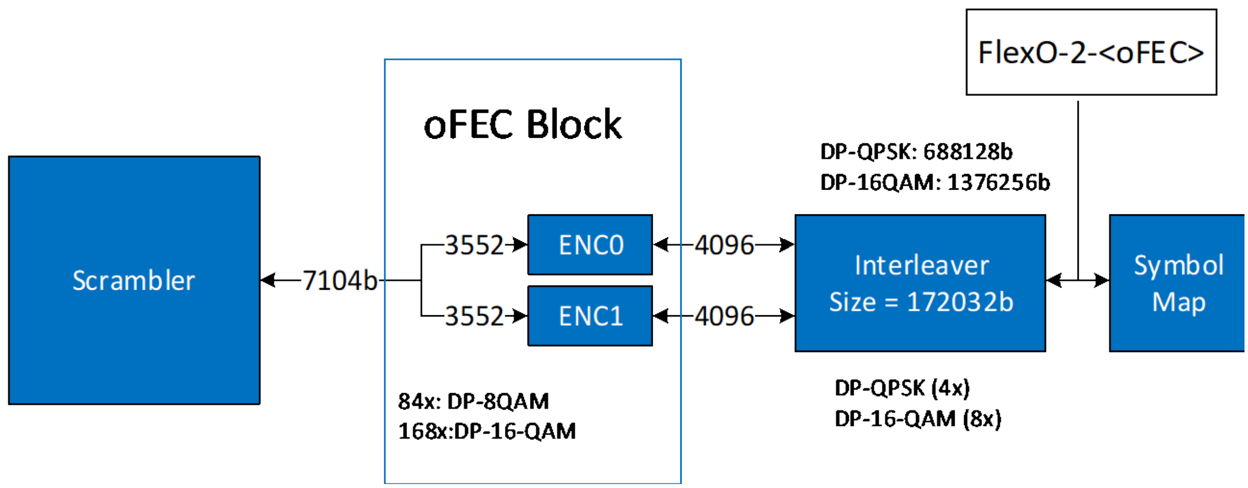


Figure 24 - oFEC Block Encoder and Interleaver

The following text describes a single instance of the oFEC encoder engine. The specification requires two encoder engines operating in parallel, with each engine producing an oFEC codeword.

An oFEC codeword is an infinite set of bits organized in a matrix with an infinite number of rows and N columns (N=128).

It has the property that each bit is part of two “constituent codewords,” in which each constituent codeword is a binary vector x of length 2N satisfying the constraint xH = 0, where H is a (2N, 2N – k) binary matrix, with 2N > k > N. Here k = 239, and each constituent code has (2N – k) = 17 parity bits. The fraction of bits that are parity bits is 17/128, the rate of the code is 111/128 = 0.867, and the overhead is 17/111 = 15.3%.

Specifically, H is the parity check matrix of an extended *BCH*(256, 239) code with minimum Hamming distance 6, using a textbook encoding; i.e., if x is a codeword satisfying xH = 0, then

1. *x* has an even parity, and
2. if the first 255 bits of *x* are seen as the coefficients of a polynomial of degree 254 (with bit 0 of *x* being the coefficient of power 254), then this polynomial is divisible by the binary polynomial $y^{16} + y^{14} + y^{13} + y^{11} + y^{10} + y^9 + y^8 + y^6 + y^5 + y + 1$.

The constituent codewords are constructed as explained below to allow high-speed parallel encoding and decoding. To define what bits are part of a given constituent code, the following structure is followed:

- The infinite matrix of bits is partitioned in blocks of B×B bits (B = 16), arranged in rows and columns as shown in Figure 25. There are N/B blocks per row (N/B = 8), and each block is identified by a block row number, R, and a block column number, C, where C = 0, 1, …, N/B – 1, appearing respectively on the left-hand side and at the top of the figure.
- Each bit inside a block is identified by its row number, r, where r = 0, 1, …, B – 1, and column number, c, where c = 0, 1, …, B – 1, where bit 0, 0 is at the upper left corner of a block. Overall, each bit in the infinite matrix is identified by a quadruple {R, C, r, c}.
- The number of guard-block rows needs to be even with a value 2G, (G = 2, or 4 rows, in Figure 25).

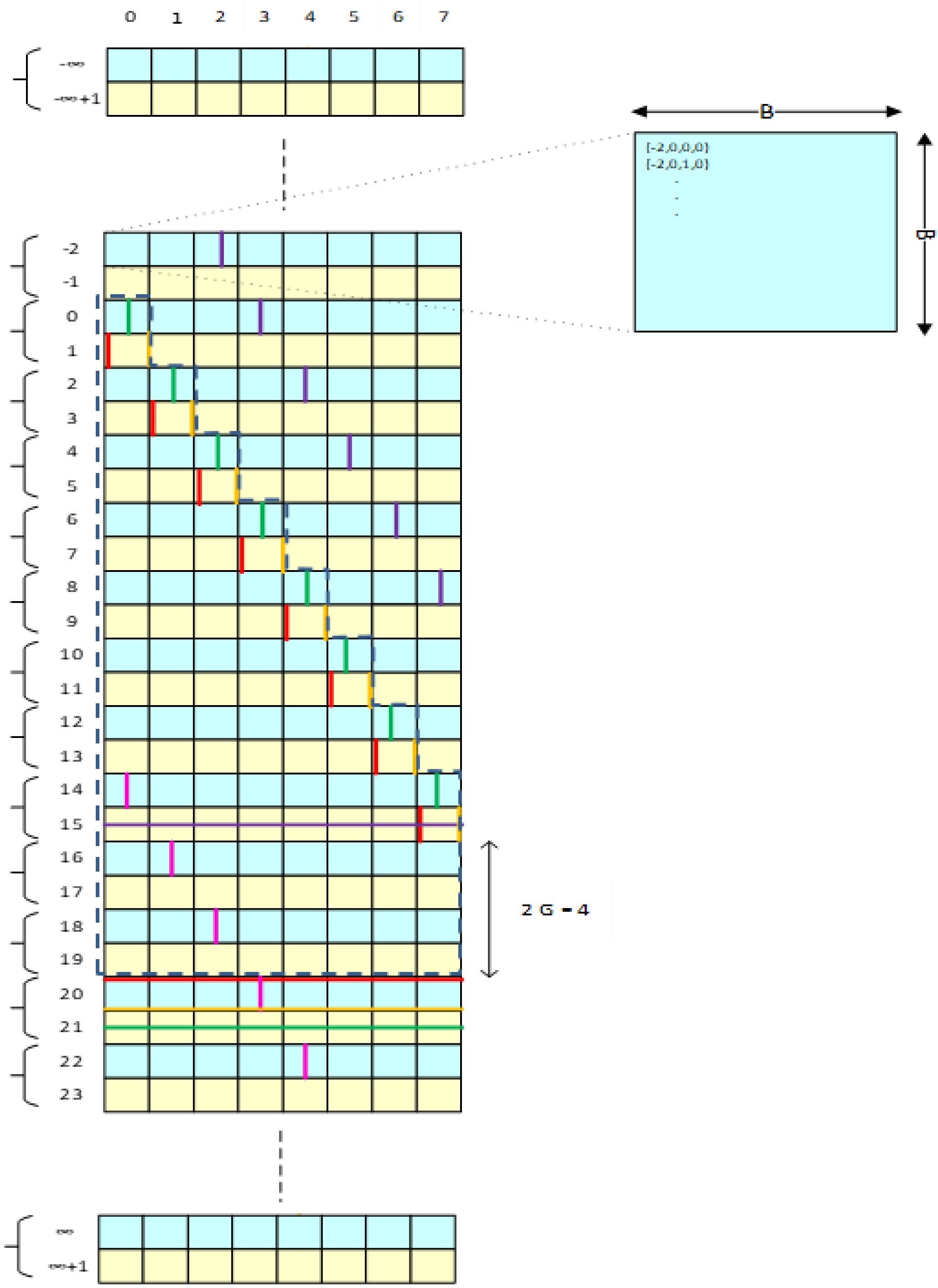


Figure 25 - oFEC Structure

A constituent codeword (R, r) is labelled by a block row number R and a bit row number r, where r = 0, 1, …, B – 1. The k^{th} bit (k = 0, 1, …, 2N – 1) of constituent code (R, r) is the bit identified with the quadruple:

- If $k < N$: $\{ (R \wedge 1) - 2G - 2\,N/B + 2\,[k/B]\,,\ [k/B]\,,\ (k \,\%\, B) \wedge r\,,\ r \}$ (1)
- If $k \geq N$: $\{ R,\ [(k - N)/B]\,,\ r\,,\ (k \,\%\, B) \wedge r \}$ (2)

where [ ] denotes the floor operator, (a % b) denotes the value of a modulo b, and (a ^ b) represents the number with a binary representation equal to the bit-wise "exclusive or" of the binary representations of the numbers a and b.

The formulas are illustrated in Figure 25. The union of line segments (both vertical or horizontal) of a given color shows the bits forming a constituent codeword.

Consider, for example, constituent code (20, 0). The position of its bits in the infinite matrix are indicated by the red line segments. Bits 0 to 15 are in column 0 of block (1, 0), bits 16 to 31 in column 0 of block (3, 1), …, and bits 112 to 127 in column 0 of block (15, 7). The bit indices go up as one descends in the columns.

Bits 128 to 255 are located in row 0 of blocks (20, 0) to (20, 7), and their indices go up as one moves to the right in a row.

Bits 0 to 127 are referred to as the "front" of a constituent code, and bits 128 to 255 as the "back." Each bit in the oFEC encoder belongs to the front of a constituent code and to the back of another one. Note that if the back of a constituent codeword is in an odd-numbered row of blocks (yellow background), then its front is in even-numbered rows of blocks (blue background).

The blocks located below the front blocks and above the back blocks are guard blocks, relative to the constituent code of interest.

The bits of constituent code (20, 15), identified by the orange line segments, are in the same blocks as the segments of constituent code (20, 0). However, because "r" is 15 instead of 0 as in the previous example, the expressions " ^ r" in formulas (1) and (2) become significant, and the bits are taken in reverse order in each block. For example, bits 0 to 15 in the front of code (20, 15) are bits 15 to 0 in column 15 of block (1, 0).

The oFEC encoder is a convolutional code, and its performances are characterized by its "error events." Without the " ^ r" permutation, there are about 625,000 possible error events of weight 36 that can start at every decoding of a constituent code. For comparison, a Product Code based on the same constituent code has more than 3.3e13 codewords of weight 36. The presence of the " ^ r" permutation can be observed to eliminate error events of weight 36. Consequently, the minimum Hamming distance of the oFEC encoder is at least 42.

The transceiver MUST comply with the oFEC encoder definition in Section 7.2.1.

The transceiver MUST comply with the oFEC interleaver definition in Section 7.2.3.

The transceiver MUST support an oFEC overhead rate of $15.\overline{315}$%.

When operating with QPSK modulation, the transceiver MUST support an oFEC decoder with a Net Coding Gain of at least 11.1 dB.

When operating with 16-QAM modulation, the transceiver MUST support an oFEC decoder with a Net Coding Gain of at least 11.6 dB.

7.2.1 Encoding

Encoding is done sequentially, in order of increasing rows. At the time when a constituent code (R, r) is being encoded, all constituent codes (R', r') with R' < R – 2G need to already be encoded.

To encode a constituent code (R, r), form a vector *x* of length 2N where the front N bits are read from previously encoded bits in the infinite matrix according to formula (1) above. In the back, the first k – N (i.e., 111) bits are fresh information bits. The last 2N – k (i.e., 17) back bits are parity bits that can be calculated to satisfy *x*H = 0. After encoding, the N back bits are placed at their positions in the infinite matrix according to formula (2) above, and bits in those positions are output to an interleaver.

Considering Figure 25, G is large enough to allow the parallel encoding of 2B (G + 1) = 96 constituent codes, assuming the pipeline delay is small. This number is considerably reduced when the pipeline delay increases, which is typically the case in the decoder.

At most, N/B (N/B + 2G + 1) = 104 blocks need to be kept in the encoder memory (excluding the current input). The blocks that need to be kept in memory in order to encode block rows 20 and 21 are indicated by the dashed lined area in Figure 25.

A large G allows for longer pipeline delays in the encoding and decoding operations and allows for more parallel execution in the encoder and decoder, at the expense of increased memory.

7.2.1.1 Encoder Interface

The encoder input consists of rectangular blocks of size (2B) × (2N – k) = 32 × 111 bits. The rectangles are numbered 0, 1, 2, …. The input bits into the encoder are sequenced. The i^{th} input bit is placed in rectangle [i / (32 × 111)] at the position indicated by the value i % (32 × 111) in Figure 26. Note that the rectangle is divided in 16 x 16 bit blocks, except along the right edge where their size is 16×15.

Bit k = 0, 1, 2, … of row p in rectangle P is placed in position N + k of constituent code (2P + [p/B], p % B).

0 1 … 15 16 17 … 31 32… . . . . 240 .. . 255	512… . . . . . . … 767	1024 … . . . . . . … 1279	1536 … . . . . . . … 1791	2048 … . . . . . . … 2303	2560 … . . . . . . … 2815	3072 3073 … 3086 3087 … 3101 3102 … 3599 . . . . 3297 … 3311
256… 271 272 . . . . 496 511	768 … . . . . . …. 1023	1280 … . . . . . … 1535	1792 .. . . … 2047	2304… . . . . . … 2559	2816.. . . . . . … 3071	3312 … 3326 3327 … . . . . 3537 … 3551

Figure 26 - Sequencing of Bits Within an Input Rectangle

The encoder output consists of rectangular blocks of size (2B) × N = 32 × 128 bits. The rectangles are numbered 0, 1, 2, …. Bit k = 0, 1, 2, … of row p in rectangle P is the bit {2P + [p/B], [p/B], k/B, p % B} of the infinite array. The bits within an output rectangular block are sequenced according to Figure 27.

0 1 … 15 16 17 … 31 32… . . . . 240 .. . 255	512… . . . . . . … 767	1024 … . . . . . . … 1279	1536 … . . . . . . … 1791	2048 … . . . . . . … 2303	2560 … . . . . . . … 2815	3072 . . . . . . … 3327	3584 . . . . . . … 3839
256… 271 272 . . . . . 496 511	768 … . . . . . . …. 1023	1280 … . . . . . . … 1535	1792 .. . . … 2047	2304… . . . . . . … 2559	2816.. . . . . . . … 3071	3328 . . . . . … 3583	3840 . . . . . … 4095

Figure 27 - Bit Numbering Within an Output Rectangle

7.2.1.2 Formal Encoder Definition

This section directly describes the encoder output bits as a function of the input bits, integrating the diverse elements that have been described in previous sections.

An oFEC encoder is an entity that produces a binary output y(i) from a binary input u(i), where i = 0, 1, 2, ….

The relationship between y and u is expressed through intermediate variables.

In particular, there is a multidimensional vector V(R, C, r, c), where R is an integer; C = 0, 1, …,7; r = 0, 1, …,15; and c = 0, 1, …, 15.

Associated with a vector V, there are constituent code vectors $W_{R,r}(i)$, where $R \geq 0$, r = 0, 1, 2….15, and i = 0, 1, …, 255.

$$\text{For } R \geq 0,\ W_{R,r}(k) = \begin{cases} V((R \wedge 1) - 20 + 2\,[k/16]\,,\ [k/16]\,,\ (k \,\%\, 16) \wedge r\,,\ r\,) & \text{for } k < 128 \\ V(R,\ [(k-128)/16]\,,\ r\,,\ (k \,\%\, 16) \wedge r\,) & \text{for } 128 \leq k < 256 \end{cases}$$

where [ ] denotes the floor function, (a % b) denotes the value of a modulo b, and (a ^ b) means the number with a binary representation equal to the bit-wise “exclusive or” of the binary representations of the numbers a and b.

The bits in the $W_{R,r}$ need to satisfy the following equalities:

For $R \geq 0$, r = 0, 1, …, 15 and k = 0, 1, …, 110

$$W_{R,r}(128 + k) = u([R/2] \times 32 \times 111 + ((R \,\%\, 2) \times 16 + r\,) \times (16 - [k/96]) + [k/16] \times 512 + k \,\%\, 16)$$

For $R \geq 20$, $W_{R,r} H = 0$, where H is the parity check matrix of an extended *BCH*(256, 239) code, using a textbook encoding; i.e., if *x* is a vector satisfying *x*H = 0, then

1. *x* has an even parity, and
2. if the first 255 bits of *x* are seen as the coefficients of a polynomial of degree 254 (with bit 0 of *x* being the coefficient of power 254), then this polynomial is divisible by the binary polynomial $y^{16} + y^{14} + y^{13} + y^{11} + y^{10} + y^9 + y^8 + y^6 + y^5 + y + 1$.

The output y satisfies the relationship

For $R \geq 0$; C = 0, 1, ..., 7; r = 0, 1, …, 15; and c = 0, 1, …, 15.

$$V(R, C, r, c) = y([R/2] \times 32 \times 128 + (R \% 2) \times 256 + C \times 16 \times 32 + r \times 16 + c)$$

It can be observed that 20 × 16 ×17 values are left undefined in $W_{R,r}$ and in V(R, C, r, c) for $0 \leq R < 20$, and thus also in the output y. This is by design; an implementation can choose any convenient values.

However, for test vectors, the output needs to be totally specified. To that end, the following additional constraints are added:

For $0 \leq R < 20$, $W_{R,r} H' = 0$, where H' is a 256 × 17 binary matrix where the first 128 rows are all zero and the last 128 rows are equal to the last 128 rows of H.

7.2.2 Decoding

Any of the iterative algorithms designed for turbo decoding of Product Codes can be adapted to decode oFEC codewords.

For use with iterative decoding, the bits in block row R will all have been decoded as front bits in later constituent codewords after 2 (N/B + G + 1) rows of blocks have been decoded. Specifically, in Figure 25, bits in row R = 0 will all have been decoded as front bits by the time block row 21 has been decoded. It then makes sense to decode the constituent codes in block row 0 again.

7.2.3 Block Interleaver

The FEC datapath is shown in Figure 24. After oFEC encoding, block interleaving of 172,032-bit blocks is done, followed by symbol mapping. The bit stream is interleaved to de-correlate the noise between consecutively received symbols, as well as to uniformly distribute the symbols. The block interleaver uses 4-block interleaving for DP-QPSK, and 8-block interleaving for DP-16-QAM signaling.

7.2.3.1 oFEC Interleaver Architecture

The oFEC interleaver buffer size is 172,032 bits. These 172,032 bits are organized as an (84, 8) array of 16 x 16 bit blocks; see Table 3, below. Note that the format is similar to the format used by the encoder and decoder. The two following mechanisms are then applied:

1. An intra-block interleaver that reorders the bits in each 16×16 block to ensure that the bits in each row and column of a block at the encoder output are remapped almost uniformly in the block for transmission on the line—that operation can be seen as happening on input to the interleaver.
2. An inter-block interleaver that attempts to have nearby symbols on the line contain bits that are widely separated in the encoder output.

The interleaver is full rate, but it is fed by two half-rate encoders, 0 and 1. Successive rows of blocks from encoder 0 will be written in even block rows of the interleaver buffer (yellowish colors in Figure 28), whereas successive rows of blocks from encoder 1 will be written in odd block rows (pinkish colors). Consequently, the content of an interleaver buffer is the row-by-row interleaving of vertical segments of the infinite matrices of encoders 0 and 1.

7.2.3.2 Intra-Block Interleaving

For the purpose of intra-block interleaving, the interleaver is considered to receive 16×16 blocks of bits from the encoders, and each such block is considered separately.

The intra-block interleaving is specified by the following table, which indicates the row and column of the source bit for each destination bit in the block. For example, bit (14, 15) [base 0] in an interleaver input block (i.e., encoder output block) is placed in row 1 of column 0 of the corresponding interleaver buffer block.

Table 3 - Source Positions (Row, Col) for Intra-Block Interleaving

0 ,0	1 ,1	2 ,2	3 ,3	4 ,4	5 ,5	6 ,6	7 ,7	8 ,8	9 ,9	10 ,10	11 ,11	12 ,12	13 ,13	14 ,14	15 ,15
14 ,15	15 ,0	0 ,1	1 ,2	2 ,3	3 ,4	4 ,5	5 ,6	6 ,7	7 ,8	8 ,9	9 ,10	10 ,11	11 ,12	12 ,13	13 ,14
12 ,14	13 ,15	14 ,0	15 ,1	0 ,2	1 ,3	2 ,4	3 ,5	4 ,6	5 ,7	6 ,8	7 ,9	8 ,10	9 ,11	10 ,12	11 ,13
10 ,13	11 ,14	12 ,15	13 ,0	14 ,1	15 ,2	0 ,3	1 ,4	2 ,5	3 ,6	4 ,7	5 ,8	6 ,9	7 ,10	8 ,11	9 ,12
8 ,12	9 ,13	10 ,14	11 ,15	12 ,0	13 ,1	14 ,2	15 ,3	0 ,4	1 ,5	2 ,6	3 ,7	4 ,8	5 ,9	6 ,10	7 ,11
6 ,11	7 ,12	8 ,13	9 ,14	10 ,15	11 ,0	12 ,1	13 ,2	14 ,3	15 ,4	0 ,5	1 ,6	2 ,7	3 ,8	4 ,9	5 ,10
4 ,10	5 ,11	6 ,12	7 ,13	8 ,14	9 ,15	10 ,0	11 ,1	12 ,2	13 ,3	14 ,4	15 ,5	0 ,6	1 ,7	2 ,8	3 ,9
2 ,9	3 ,10	4 ,11	5 ,12	6 ,13	7 ,14	8 ,15	9 ,0	10 ,1	11 ,2	12 ,3	13 ,4	14 ,5	15 ,6	0 ,7	1 ,8
15 ,7	0 ,8	1 ,9	2 ,10	3 ,11	4 ,12	5 ,13	6 ,14	7 ,15	8 ,0	9 ,1	10 ,2	11 ,3	12 ,4	13 ,5	14 ,6
13 ,6	14 ,7	15 ,8	0 ,9	1 ,10	2 ,11	3 ,12	4 ,13	5 ,14	6 ,15	7 ,0	8 ,1	9 ,2	10 ,3	11 ,4	12 ,5
11 ,5	12 ,6	13 ,7	14 ,8	15 ,9	0 ,10	1 ,11	2 ,12	3 ,13	4 ,14	5 ,15	6 ,0	7 ,1	8 ,2	9 ,3	10 ,4
9 ,4	10 ,5	11 ,6	12 ,7	13 ,8	14 ,9	15 ,10	0 ,11	1 ,12	2 ,13	3 ,14	4 ,15	5 ,0	6 ,1	7 ,2	8 ,3
7 ,3	8 ,4	9 ,5	10 ,6	11 ,7	12 ,8	13 ,9	14 ,10	15 ,11	0 ,12	1 ,13	2 ,14	3 ,15	4 ,0	5 ,1	6 ,2
5 ,2	6 ,3	7 ,4	8 ,5	9 ,6	10 ,7	11 ,8	12 ,9	13 ,10	14 ,11	15 ,12	0 ,13	1 ,14	2 ,15	3 ,0	4 ,1
3 ,1	4 ,2	5 ,3	6 ,4	7 ,5	8 ,6	9 ,7	10 ,8	11 ,9	12 ,10	13 ,11	14 ,12	15 ,13	0 ,14	1 ,15	2 ,0
1 ,0	2 ,1	3 ,2	4 ,3	5 ,4	6 ,5	7 ,6	8 ,7	9 ,8	10 ,9	11 ,10	12 ,11	13 ,12	14 ,13	15 ,14	0 ,15

Note that the left entries in this table form a Latin Square. The right entries almost form a Latin square, but they are duplicated in the first and last rows.

7.2.3.3 Inter-Block Interleaving

The intra-block permutation described in the previous section is applied to each block in the buffer as it comes in from the encoder.

In addition to partitioning the interleaver buffer as a function of the encoder, 0 or 1, it is also partitioned in an upper half of 42 block rows (light color tones) and a lower half of 42 block rows (dark color tones). Overall the buffer is then portioned in 4 subsets, each containing 21×8 blocks or 336×128 bits.

Table 4 - Interleaver Subsets

Subset Number	Row Blocks
0	0, 2, …, 40
1	1, 3, …, 41
2	42, 44, …, 82
3	43, 45, …, 83

On output, groups of 8 bits are taken in turn from each subset, reading them out of a column of bits before proceeding to the next columns of bits.

Specifically, as shown in Figure 28, the first 8 bits are read from the top of first column of subset 0, then the first 8 bits from the first column of subsets 1, 2, and 3. Those 32 bits are then followed by the taking the next 8 bits in the first column of each of the subsets 0, 1, 2, and 3. After 42 such cycles of 4×8 bits each, the first bit column of the interleaver buffer will be completely read out, and the output process continues by reading bit columns 1 to 127.

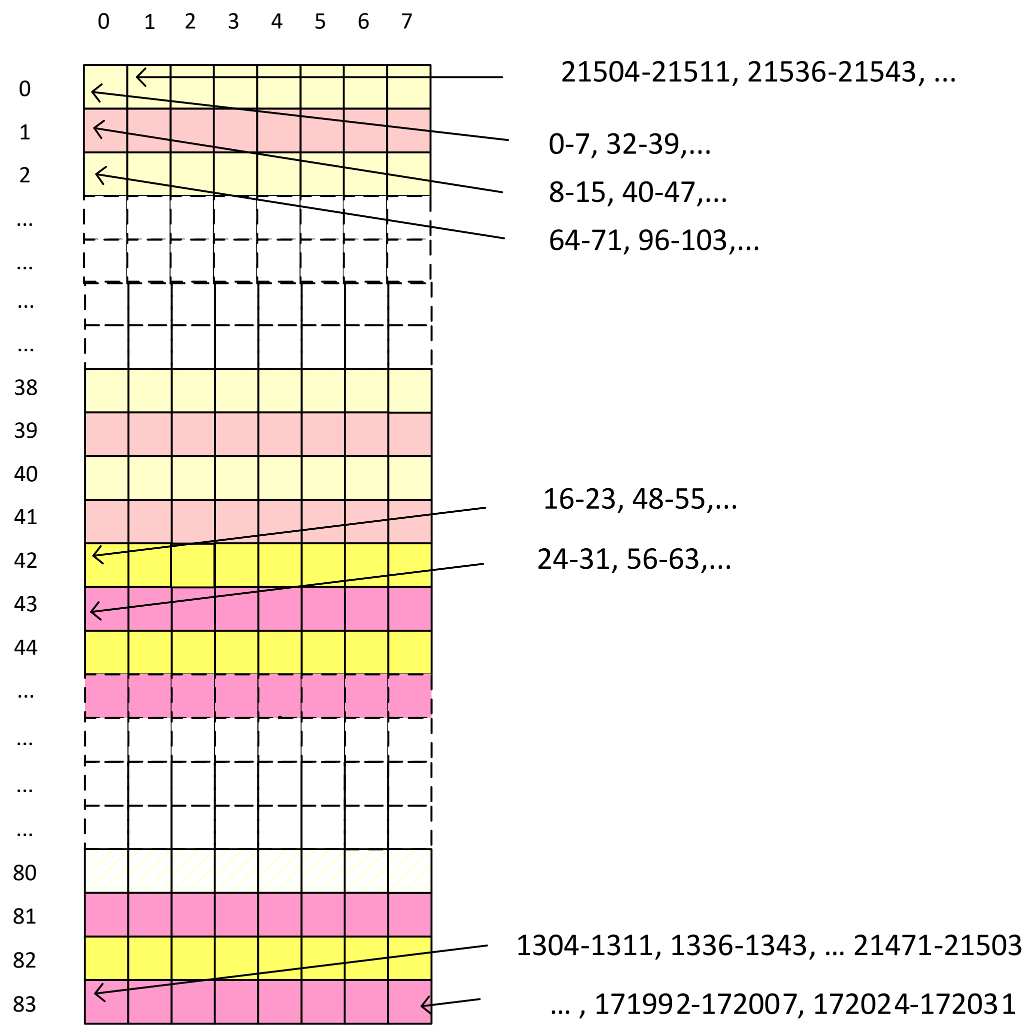


Figure 28 - Inter-Block Interleaving

Bits are read by columns, rather than rows because interleaver columns are much longer than rows, so bits in a column are spread over more constituent codes than bits in a row, which increases the tolerance to long bursts. The maximum correctable burst length, when used with a hard decoder, is a traditional measure of interleaver quality. In this case it can be shown to be 2,681 bits.

The bits read out of the interleaver are passed to the modulator, where they are used in groups of S = 4, respectively, in both the H and V polarizations.

The output bits with even indexes are used to form symbols for the H polarization, whereas those in odd positions are formed to symbols in the V polarization. This simplifies the line BER estimation in each polarization. The H and V bits will appear at fixed positions in each block in the decoder independently of the modulation.

7.3 Symbol Mapping and Transmission

This section describes the procedure for mapping encoded and interleaved oFEC Blocks onto DP-QPSK and DP-16-QAM constellation symbols of each polarization; distributing those symbols across two different polarizations; inserting Training and Super-Frame Alignment Word symbols; and adding Pilot Symbols.

7.3.1 Symbol Mapping and Polarization Distribution

Symbol mapping and polarization distribution is modulation dependent. The symbol mapping and polarization distribution for each available modulation is defined in the following two subsections, and in Figure 29.

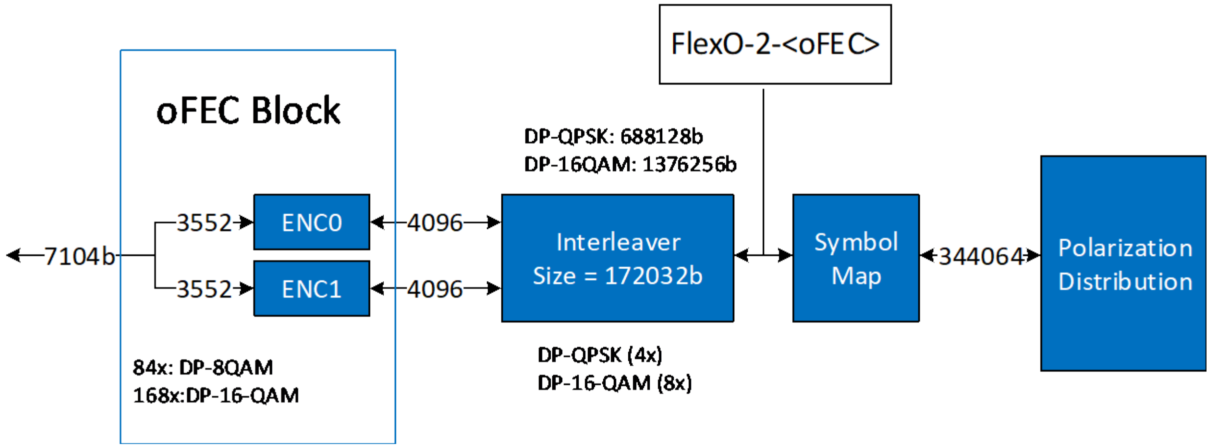


Figure 29 - Symbol mapping and polarization distribution

7.3.1.1 DP-QPSK Symbols

The FEC encoded and interleaved bit stream is 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-phase (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 5 below.

Table 5 - FAW/Training Sequence/Pilot Symbol Pattern

(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

When operating with DP-QPSK modulation, the transceiver MUST support the symbol mapping and polarization distribution defined in Section 7.3.1.1 above.

7.3.1.2 DP-16-QAM Symbols

The FEC encoded and interleaved bit stream is mapped to DP-16-QAM symbols,

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

where

- (c_{8i}, c_{8i+2}) maps to the in-phase (I) component of the X-pol of s_i,
- (c_{8i+4}, c_{8i+6}) maps to the quadrature-phase (Q) component of the X-pol of s_i,

- (c_{8i+1}, c_{8i+3}) maps to the I component of the Y-pol of s_i, and
- (c_{8i+5}, c_{8i+7}) 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 6 below.

Table 6 - FAW/Training Sequence/Pilot Symbol Pattern

(c_{8i}, c_{8i+4}, c_{8i+1}, c_{8i+5}) or (c_{8i+2}, c_{8i+6}, c_{8i+3}, c_{8i+7})	I	Q
(0,0,0,0)	-3	-3
(0,0,0,1)	-3	-1
(0,0,1,0)	-3	3
(0,0,1,1)	-3	1
(0,1,0,0)	-1	-3
(0,1,0,1)	-1	-1
(0,1,1,0)	-1	3
(0,1,1,1)	-1	1
(1,0,0,0)	3	-3
(1,0,0,1)	3	-1
(1,0,1,0)	3	3
(1,0,1,1)	3	1
(1,1,0,0)	1	-3
(1,1,0,1)	1	-1
(1,1,1,0)	1	3
(1,1,1,1)	1	1

When operating with DP-16-QAM modulation, the transceiver MUST support the symbol mapping and polarization distribution defined in Section 7.3.1.2 above.

7.3.2 DSP Framing

This section describes the DSP framing format, which is illustrated in Figure 30.

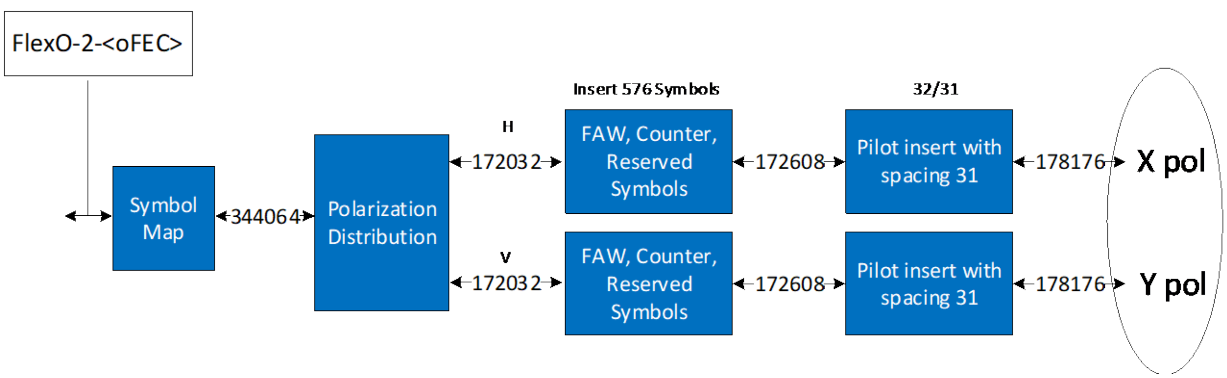


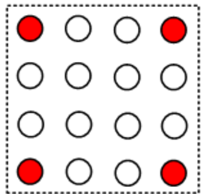
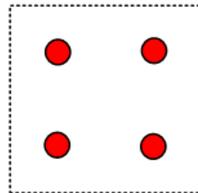
Figure 30 - DSP Framing Process

A DSP super-frame is defined as a set of 178176 symbols in each X/Y polarizations. A DSP sub-frame consists of 3712 symbols. The DSP super-frame thus consists of 48 DSP sub-frames.

Pilot Symbols (PS) are inserted every 32 symbols starting with the first symbol of the first DSP sub-frame. Each DSP sub-frame starts with an 11 symbol training sequence. The first symbol of the training sequence is a Pilot Symbol. The first DSP sub-frame of the super-frame also includes the DSP super-frame Frame Alignment Word (FAW).

As illustrated in Figure 30 above, once the datastream has been mapped into symbols and distributed onto each polarization, pilot symbols, training symbols, Frame Alignment Word (FAW), and other overhead are added to create a DSP super-frame/sub-frame structure.

Table 7 - FAW/Training Sequence/Pilot Symbol Pattern

Parameter	DP-16-QAM	DP-QPSK
Mapping		
FAW	Outer 4 points of 16-QAM 22 Symbols	QPSK 22 Symbols
Training sequence	Outer 4 points of 16-QAM 11 symbols per DSP sub-frame	QPSK 11 symbols per DSP sub-frame
Pilot symbols	Outer 4 points of 16-QAM Every 32 symbols	QPSK Every 32 symbols

The transceiver MUST support a DSP super-frame of 178,176 symbols.

7.3.2.1 DSP Super-Frame and Sub-Frame

Each DSP super-frame is divided into 48 DSP sub-frames, each consisting of 3,712 symbols.

The first DSP sub-frame includes:

- 22 symbol super-frame Frame Alignment Word (FAW) used for super-frame delineation and alignment to the oFEC block. 74 additional symbols are reserved for future use/innovation. The FAW sequence is different between X and Y polarizations.
- 74 symbols are reserved to be used for future proofing and for innovation. These symbols should be randomized to avoid strong tones.
- 11 symbols available for link training. The first Training Symbol (TS) is shared as a Pilot Symbol (PS) in each DSP sub-frame.
- 116 Pilot Symbols.

Every subsequent DSP sub-frame (sub-frames 2-48 of a DSP super-frame) include:

- 11 symbols available for link training. The first Training Symbol (TS) is shared as a Pilot Symbol (PS) in each DSP sub-frame.
- 116 Pilot Symbols

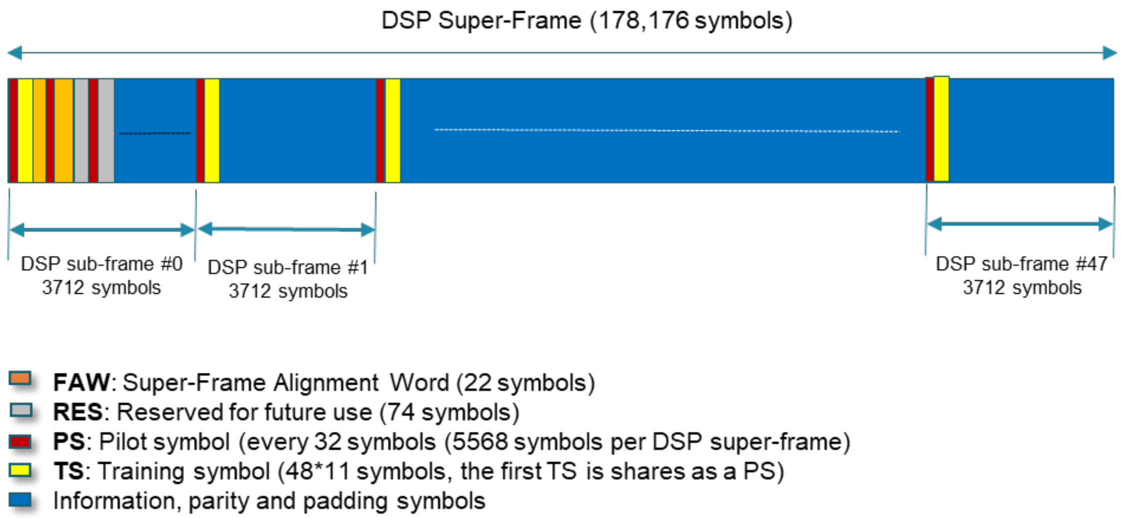


Figure 31 - DSP Super-Frame

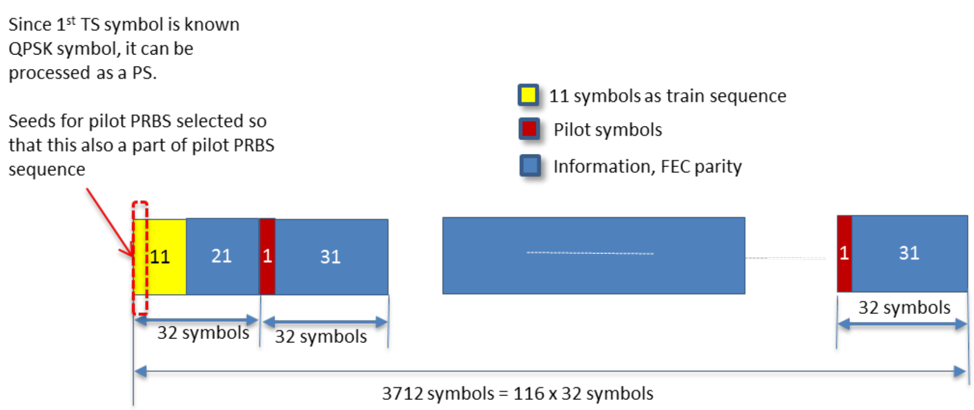


Figure 32 - DSP Sub-Frames 2 to 48 of the DSP Super-Frame

The transceiver MUST support DSP super-frames with the first DSP sub-frame as described in Figure 31.

The transceiver MUST support DSP sub-frames for sub-frames 2 through 48 of the DSP super-frame as described in Figure 32.

7.3.2.2 FAW Sequence

The required sequence for the FAW described in Section 7.3.2.1 above is shown in Table 8 below.

Table 8 - FAW Sequence

Index	FAW X	FAW 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

Index	FAW X	FAW Y
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
12	3 - 3j	-3 + 3j
13	-3 - 3j	-3 + 3j
14	-3 - 3j	3 + 3j
15	-3 + 3j	-3 - 3j
16	3 + 3j	3 + 3j
17	-3 - 3j	-3 - 3j
18	3 - 3j	-3 + 3j
19	-3 + 3j	3 - 3j
20	3 + 3j	-3 - 3j
21	-3 - 3j	3 - 3j
22	-3 + 3j	-3 + 3j

The transceiver MUST support the FAW sequence as shown in Table 8.

7.3.2.3 Training Sequence

The training sequence referred to in Section 7.3.2.1 above is defined in Table 9 below.

Table 9 - 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.

The transceiver MUST support the training symbol sequence shown in Table 9.

7.3.2.4 Pilot Sequence

Training and pilot symbols are set at the 4 points of the QPSK constellation or the outer 4 points of the DP 16-QAM constellation.

The pilot sequence is a fixed PRBS10 mapped to QPSK sequence with different seed values for each polarization.

- 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 sub-frame.

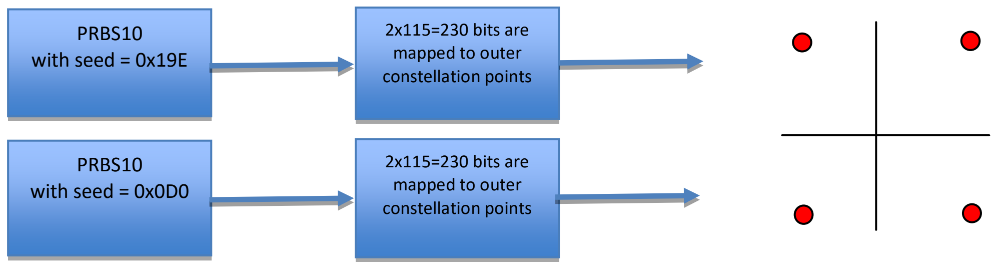


Figure 33 - QPSK Mapped Pilot Sequence (DP-16-QAM Modulation Shown)

Table 10 - Pilot Sequence

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

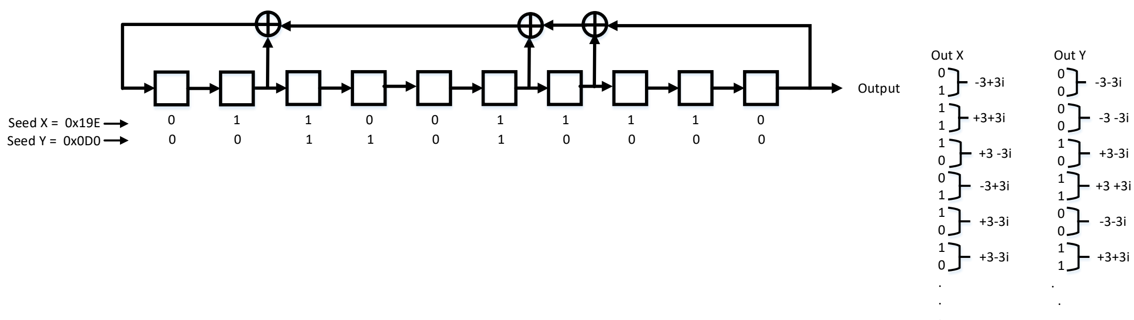


Figure 34 - Pilot Seed and Sequencing

The complete table that results is shown in Table 11 below.

Table 11 - Pilot Sequence

Index	Pilot X	Pilot Y	Index	Pilot X	Pilot Y	Index	Pilot X	Pilot Y
1	-3 + 3i	-3-3i	41	-3 - 3i	3-3i	81	3 + 3i	3-3i
2	3 + 3i	-3-3i	42	3 - 3i	3-3i	82	-3 - 3i	-3-3i
3	3 - 3i	3-3i	43	-3 + 3i	-3-3i	83	-3 - 3i	3+3i
4	-3 + 3i	3+3i	44	-3 + 3i	-3-3i	84	3 + 3i	-3-3i
5	3 - 3i	-3-3i	45	-3 - 3i	3+3i	85	3 - 3i	-3-3i
6	3 - 3i	3+3i	46	-3 + 3i	-3+3i	86	-3 + 3i	-3-3i
7	-3 - 3i	-3+3i	47	-3 - 3i	3+3i	87	3 + 3i	3-3i
8	3 + 3i	-3+3i	48	3 + 3i	-3+3i	88	3 - 3i	-3+3i
9	-3 + 3i	-3-3i	49	3 + 3i	3-3i	89	-3 - 3i	-3+3i
10	3 + 3i	3+3i	50	-3 + 3i	-3+3i	90	3 - 3i	3-3i
11	3 + 3i	3+3i	51	3 - 3i	3+3i	91	3 - 3i	3+3i
12	-3 - 3i	-3-3i	52	3 - 3i	-3+3i	92	-3 + 3i	3-3i
13	3 + 3i	3+3i	53	3 - 3i	-3+3i	93	-3 - 3i	3-3i

Index	Pilot X	Pilot Y	Index	Pilot X	Pilot Y	Index	Pilot X	Pilot Y
14	3 - 3i	3+3i	54	-3 - 3i	3+3i	94	3 + 3i	-3+3i
15	3 + 3i	3-3i	55	3 - 3i	-3+3i	95	-3 - 3i	3-3i
16	3 - 3i	3+3i	56	3 + 3i	-3+3i	96	-3 - 3i	3-3i
17	3 + 3i	3+3i	57	-3 + 3i	-3-3i	97	3 + 3i	-3+3i
18	3 - 3i	-3+3i	58	-3 - 3i	3-3i	98	-3 + 3i	3-3i
19	-3 + 3i	-3-3i	59	3 - 3i	3-3i	99	3 - 3i	-3-3i
20	-3 - 3i	3-3i	60	3 + 3i	-3+3i	100	-3 - 3i	3+3i
21	3 + 3i	3-3i	61	3 - 3i	3+3i	101	3 + 3i	-3-3i
22	-3 + 3i	3+3i	62	-3 - 3i	-3-3i	102	-3 + 3i	-3+3i
23	-3 + 3i	-3+3i	63	3 - 3i	3+3i	103	-3 - 3i	-3+3i
24	3 - 3i	3-3i	64	-3 + 3i	-3+3i	104	-3 - 3i	3+3i
25	-3 + 3i	3-3i	65	3 - 3i	3-3i	105	3 + 3i	-3+3i
26	-3 + 3i	3+3i	66	3 + 3i	3+3i	106	3 - 3i	3-3i
27	-3 + 3i	-3+3i	67	3 - 3i	-3-3i	107	3 + 3i	3+3i
28	-3 + 3i	3+3i	68	-3 + 3i	3-3i	108	-3 + 3i	-3+3i
29	-3 - 3i	3+3i	69	3 - 3i	-3+3i	109	-3 - 3i	3+3i
30	3 - 3i	3-3i	70	-3 + 3i	-3+3i	110	-3 + 3i	-3-3i
31	-3 - 3i	-3+3i	71	3 + 3i	-3+3i	111	-3 - 3i	-3+3i
32	3 + 3i	-3-3i	72	-3 - 3i	-3-3i	112	-3 + 3i	3-3i
33	-3 + 3i	3-3i	73	-3 - 3i	-3+3i	113	-3 + 3i	-3+3i
34	-3 + 3i	-3-3i	74	3 - 3i	3+3i	114	3 + 3i	3+3i
35	-3 + 3i	-3-3i	75	-3 + 3i	-3-3i	115	3 + 3i	3-3i
36	3 - 3i	3-3i	76	3 - 3i	-3-3i	116	-3 - 3i	3-3i
37	3 - 3i	3-3i	77	-3 + 3i	-3-3i			
38	-3 - 3i	-3-3i	78	-3 - 3i	3+3i			
39	-3 - 3i	3+3i	79	3 + 3i	-3-3i			
40	3 - 3i	-3-3i	80	3 + 3i	-3-3i			

The transceiver MUST support the pilot sequence shown in Table 11.

7.3.3 Frame Expansion Rate

The oFEC optical signal is ~63.139467923 GBaud. Table 12 provides detail on expansion for each functional block.

Table 12 - FlexO/oFEC Expansion Rates

Parameter	Value
FEC Payload	2×100GbE
FEC algorithm	oFEC
FEC payload size (k)	3,552
FEC block size (N)	4,096
Number of FEC blocks in super-frame	84
Total payload size	596,736 bits
PAD before FEC	496 bits
Total payload size based on 257 bits	2,320 × 257 bits 596,240 bits total
PAD after FEC	0
Total bits	688,128

Parameter	Value
Total information, parity and padding symbols per super-frame	172,032
Number of FAW/RES/training symbols	576
Total length before pilot insertion	172,608
Number of pilots	5,568
DSP sub-frame size	3,712
Number of DSP sub-frames per super-frame	48
Total symbols of super-frame	178,176
Modulation format	QPSK/16-QAM
Baud rate	63.139467923 Gbaud (QPSK) 31.5697339615 Gbaud (16-QAM)

The baud rates are calculated as follows:

- QPSK: 63.139467923 (GBaud) =
  223,618,948,892.8875 × (514/544) × (37,296/37,265) × (4,096/3,552) × (899/896) × (32/31) / 4
- 16-QAM: 31.5697339615 (GBaud) =
  223,618,948,892.8875 × (514/544) × (37,296/37,265) × (4,096/3,552) × (899/896) × (32/31) / 8

The line rate is calculated as follows:

- 252,557,871.7 (kbit/s) =
  223,618,948,892.8875 × (514/544) × (37,296/37,265) × (4,096/3,552) × (899/896) × (32/31) x 1,000,000

The transceiver MUST support the values for each parameter shown in Table 12.

8 REQUIREMENTS FOR 200G QPSK OPERATION

8.1 200G QPSK PHY Introduction

This section defines the optical physical (PHY) layer requirements for a point-to-point (P2P) coherent optics transceiver operating at 200 Gbps (200G) utilizing QPSK modulation, as well as providing some of the background for why the requirements were chosen.

200G operation is being defined in this specification based on feedback from operators that 200G will address capacity needs to an individual Aggregation Node over the anticipated lifetime of that device. 200G operation with QPSK was chosen for this specification because it allows operators to operate at 200G in almost the same plant conditions as with 100G as defined in [OPT-P2P-PHYv1.0]. As this is expected to be the primary mode of operation for 200G deployments in cable access networks, all devices that are compliant with this specification are required to support operating in a 200G QPSK mode.

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.

The transceiver MUST support the 200G QPSK mode of operation, as described in this section.

8.2 Common Transmitter/Receiver Requirements for 200G QPSK

8.2.1 Symbol Rate (200G QPSK)

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 process and 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 the baud rate.

The specific type of symbol used for the 200G PHY is defined in Section 8.2.2.

The value of 63.139467923 Gbaud was chosen for the symbol rate in order to allow 200 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 63.139467923 Gbaud with the modulation format described in Section 8.2.2.

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

8.2.2 Modulation (200G QPSK)

The mandatory modulation format for 200G transceivers is Dual Polarization Quadrature Phase Shift Keying. In addition to the mandatory QPSK, transceivers can optionally support the 16-QAM modulation specified in Section 9.2.2.

The 100G transceivers specified by the PHY v1.0 specification use dual polarization multiplexing and non-return-to-zero differential quadrature-phase shift keying modulation. Differential QPSK (DQPSK) removes the need for precise measurement of absolute phase at the receiver. The symbols are encoded by the phase differences between successive symbols. Therefore, this coding scheme is called differential QPSK, and with use of dual polarization multiplexing, the acronym DP-DQPSK is used. Employing DQPSK on each of two polarizations of the carrier allows the aggregate transmission of four data bits for each symbol period. This aligns with multiple existing specifications, such as the [ITU-T G.Sup39] and [OpenROADM] specifications.

The 200G transceivers specified here also use dual polarization multiplexing; however, the QPSK modulation is non-differential. The use of non-differential QPSK results in improved OSNR sensitivity relative to DQPSK. This non-differential scheme encodes two bits per symbol with the requirement for reference phase awareness between successive symbols. This is accomplished using pilot symbols that are inserted into the DSP FEC frames (see Section 7.3) to aid the receiver's phase recovery. Therefore, this coding scheme is called QPSK, and with use of dual polarization multiplexing, the acronym DP-QPSK is used. 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 multiple existing specifications, such as the [ITU-T G.Sup39] specification.

The 200G transceivers conformant to this specification are required to support polarization multiplexing and quadrature-phase shift keying (QPSK). On each of the two polarizations QPSK is used to encode two bits per symbol, pilot symbols (see Section 7.3.1) aid the receiver's phase recovery. The QPSK symbol constellation is illustrated in Figure 35. Data bit mapping to QPSK symbols is specified in Section 7.3.1.1.

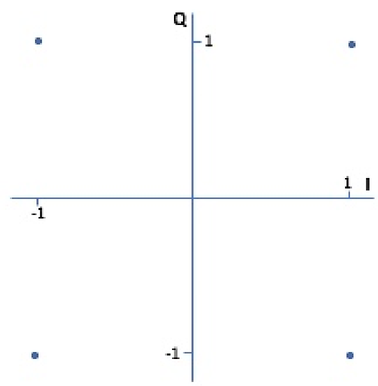


Figure 35 - 200G QPSK Symbol Constellation

The transceiver MUST support DP-QPSK modulation for the 200G signaling rate.

The transceiver MUST use the symbol constellation as illustrated in Figure 35.

The transceiver MUST use the data to symbol mapping specified in Section 7.3.1.1.

8.2.3 Line Rate (200G QPSK)

This section specifies the bit rate of the signal which is transmitted on the optical channel (= line rate). The line signal includes overhead added by the transmitter (e.g., FEC). Dual-polarization quadrature-phase shift keying (DP-QPSK) is transmitting 4 Bits per symbol. Therefore, line rate = 4x symbol rate.

Line rate details and calculation can be found in Section 7.3.3.

The transceiver MUST support a nominal signal line rate of 252,557,871.7 kbit/s.

8.2.4 DWDM Frequency Grid (200G QPSK)

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-T G.694.1] using a 100 GHz channel spacing. Specifically, Table 13 lists the specific DWDM wavelengths, frequencies, and associated channel numbers on which compliant transceivers can operate.

To transmit a line rate of 200 Gb/s using DP-QPSK modulation format, the symbol rate is approximately 63 Gbaud (see Section 8.2.1). When the light is modulated at this symbol rate, the optical signal bandwidth is at least 63 GHz.

The wavelength filters in DWDM multiplexers and demultiplexers need to have a bandwidth wide enough to pass the optical signal. In this case, the wavelength filters used in the common 100 GHz channel spacing plan have sufficient bandwidth to pass the optical signal. Wavelength filters used in a 50 GHz channel spacing plan and plans with narrower spacing do not have sufficient bandwidth to pass the optical signal.

In order to enable low-cost implementations, transceivers are only required to support one channel from Table 13. 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 13 - DWDM Frequency Grid Table for 200G QPSK Operation

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

Channel Number	Central Frequency (GHz)	Central Wavelength (nm)
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
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 13 above.

The transceiver MAY support multiple channels from Table 13 above.

The transceiver MUST report the channels from Table 13 above which it supports.

If the transceiver supports multiple channels from Table 13 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.

8.3 Transmitter Requirements for 200G QPSK

8.3.1 Transmitter Optical Output Power (200G QPSK)

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 the 1550 nm wavelength range. The minimum requirement is defined to allow for low cost options while ensuring that solutions meet minimum cable access network requirements; the maximum requirement is defined for safety purposes.

Note that all of the requirements in this section should be considered "Beginning of Life" requirements, since a device would typically be tested for compliance at the beginning of its life. Over the operational lifetime of the transceiver, it is expected that these requirements could degrade by up to as much as 0.5 dB. Therefore, operators should take this potential degradation into account as a part of their plant design.

Also note that during a transmitter power up, power down, or a change of wavelength sequence, 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. As a result, some transceivers might include the ability to do blanking, the suppressing of optical output until such time as the transceiver’s output has stabilized.

If the transceiver supports dual optical interfaces, the transceiver MUST support a transmitter optical output power of -7.5 dBm or higher. If the transceiver supports a single optical interface, then the transceiver MUST support a transmitter optical output power of -8.25 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 its transmitter optical output power with an accuracy of ±1.5 dB.

The transceiver SHOULD support adjustment of its 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.

8.3.2 Transmitter Optical Frequency Parameters (200G QPSK)

8.3.2.1 Transmitter Laser Center Frequency Accuracy (200G QPSK)

The transmitter laser center frequency accuracy is the maximum allowable offset of the actual laser frequency from the selected frequency center in Table 13. 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 carrier frequency offset (CFO) between the transmitter and local oscillator lasers.

Note that the laser carrier 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.

8.3.2.2 Transmitter Laser Linewidth (200G QPSK)

The transmitter laser linewidth is the Full-Width Half-Maximum (-3dB 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 Digital Signal Processor (DSP) to determine the phase of the symbol.

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

8.3.3 Transmitter Optical Signal-to-Noise Ratio (200G QPSK)

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. The 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 200 Gbps DP-QPSK, which operates at approximately 63 Gbaud, the resolution bandwidth of the OSA is set to 1.0 nm (approximately 125 GHz) and the optical noise floor is measured at ±200GHz 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. 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.

8.3.4 Polarization Imbalance (200G QPSK)

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. In order to balance the power for each polarization, variable optical attenuators or semiconductor amplifiers may be used on each path.

$\Delta P_{pol} = abs(10 * \log_{10} (Px / Py))$,

where Px and Py are the powers of the two nominally orthogonal polarizations carrying the two data streams.

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

8.3.5 IQ Imbalance (200G QPSK)

IQ imbalance is defined as the amplitude imbalance between the in-phase and quadrature-phase (I-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 dB.

IQ Imbalance = $10\log_{10}(AQ/AI)$,

where AI and AQ are the amplitudes of I and Q components, respectively.

In order to minimize the impact on the system, a maximum permitted IQ imbalance has been defined.

The transceiver MUST have an IQ imbalance of 1 dB or less.

8.3.6 Transmitter Skew (200G QPSK)

The transmitter modulation format uses Dual Polarization Quadrature Phase Shift Keying (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., 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.

In order 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 Transmitter Quadrature Skew (200G QPSK)

A QPSK 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 36 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 36 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.

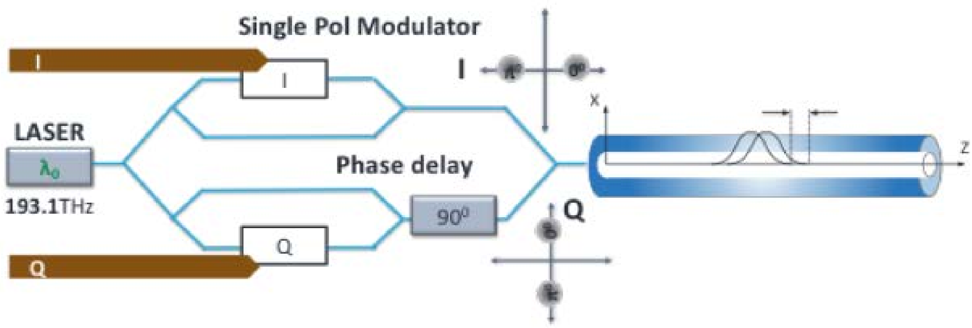


Figure 36 - QPSK Modulator with In-Phase and Quadrature Skew

The transceiver MUST have a quadrature skew of ≤ 1 ps.

8.3.6.2 Transmitter Polarization Skew (200G QPSK)

DP-QPSK signal is generated by modulating two QPSK signals in each of two orthogonal polarizations labeled X and Y and combining them before launching them into the fiber. In Figure 37 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 16 ps.

Figure 37 shows a DP-QPSK Modulator with Polarization Skew Δτ. Polarizations X and Y are each modulated at an approximate symbol rate of 63 Gbaud which equates to an approximate symbol duration time of 16 ps.

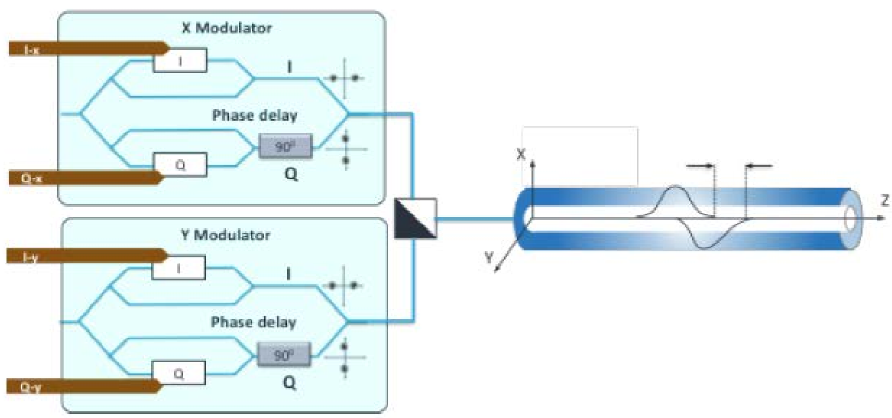


Figure 37 - DP-QPSK Modulator with Polarization Skew

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

8.3.7 Transmitter Reflectance (200G QPSK)

When optical light is inserted into the transmitter port from the direction of the network, the transmitter reflectance is the amount of light reflected back into the network. Reflections in optical systems can degrade link performance because reflected light causes noise to the desirable optical signal and reduces the system link OSNR. This specification imposes a limit on reflectance from the transmitter to limit any degradation.

Figure 38 shows the incident light on the transmitter and the reflected optical light back into the network.

The reflectance of the transmitter is defined in decibels as the ratio of light power reflected from it to the light power incident on it.

$$R = 10 \log_{10} (P_R / P_I)$$

Appendix I of [ITU-T G.957] describes two methods that can be used to measure reflectance.

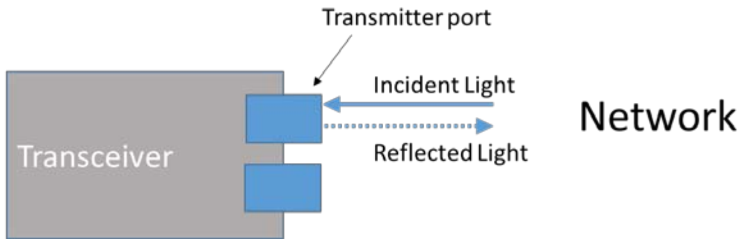


Figure 38 - Transmitter Reflectance

The transceiver MUST have an optical reflectance of ≤ -20 dB on the transmitter port.

8.3.8 Transmitter System Optical Return Tolerance (200G QPSK)

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, filters, etc. The transmitter performance cannot degrade due to the system optical return.

System optical return is defined in decibels as the ratio of light power reflected from the network to the light power emitted from the transmitter.

$$OR = 10 \log_{10} (P_R / P_E)$$

Figure 39 shows the transmitter optical signal into the network and the return optical signal.

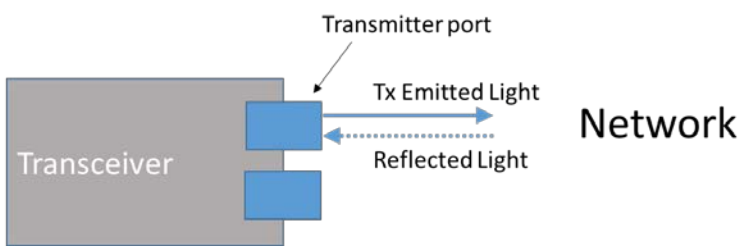


Figure 39 - System Optical Return

The transceiver MUST meet the transmitter OSNR requirements in Section 8.3.3 in the presence of a system optical return of ≤ -25 dB.

8.4 Receiver Requirements for 200G QPSK

8.4.1 Received Optical Power and OSNR (200G QPSK)

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 relaxations against these requirements can be found in Sections 8.4.2 - 8.4.5.

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.

In some scenarios, the received OSNR may be high, while the received optical power may be low. When no optical amplification is added between the transmitter and the receiver, the OSNR at the receiver will be the same as at that from 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.

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. This occurs due to the noise added by optical amplification, and because optical amplifiers boost both signal and noise power levels. In this case, the transceiver is limited by its sensitivity to OSNR rather than power. This is referred to as an "OSNR-limited case," and represents the baseline requirement for received OSNR.

In addition to the baseline received OSNR requirement that applies to the dual optical interface transceiver option, an adjustment in the receive power requirement of the single optical interface option is introduced. This adjustment accounts for the loss incurred by directional elements within the transceiver to enable the single optical interface option. Operators should also be aware that in a single optical interface transceiver option, a performance degradation in OSNR is expected due to discrete optical reflections and from back scattering caused by fiber imperfections. High-quality fiber splicing, cleanliness of fiber-optic connectors' mating surfaces and the use of angle-polished connectors, contributes to a lower back-reflection power. In an optical link using single optical interface transceivers, with an aggregate back-reflection power of -33 dBm and a receive optical power of ≥ -9.25 dBm, a 0.5 dB penalty in link OSNR is observed. In this scenario, a link OSNR ≥ 15 dB can be used to overcome this back-reflection power level.

If the transceiver supports dual optical interfaces, 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. If the transceiver supports a single optical interface, the transceiver MUST achieve a post-FEC BER of $\leq 10^{-15}$ when the link OSNR is ≥ 35 dB and the received optical power is ≥ -30.25 dBm.

The transceiver MUST report the received optical power with an accuracy of ±2.0 dB for input powers greater than or equal -20 dBm and less than or equal to 0 dBm.

The transceiver MUST report the received optical power with an accuracy of ±4.0 dB for input powers less than -20 dBm and greater than or equal to -31 dBm.

The transceiver MUST report the received optical power with an accuracy of ±4.0 dB for input powers greater than 0 dBm and less than or equal to 7 dBm.

If the transceiver supports dual optical interfaces, the transceiver MUST achieve a post-FEC 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. If the transceiver supports a single optical interface, the transceiver MUST achieve a post-FEC BER of $\leq 10^{-15}$ when the received optical power is ≥ -9.25 dBm and link OSNR is ≥ 14.5 dB.

The transceiver MAY report the received OSNR.

8.4.2 Chromatic Dispersion Compensation (200G QPSK)

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 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 CD.

In the received optical power-limited case, when the CD is 2400 ps/nm, the transceiver MUST achieve a post-FEC BER of $\leq 10^{-15}$ when the received optical power is 0.5 dB greater than the baseline optical power requirement defined in Section 8.4.1.

In the received OSNR-limited case, when the CD is 2400 ps/nm, the transceiver MUST achieve a post-FEC BER of $\leq 10^{-15}$ when the received OSNR is 0.5 dB greater than the baseline OSNR requirement defined in Section 8.4.1.

The transceiver MUST report the measured CD.

8.4.3 Polarization Mode Dispersion Compensation (200G QPSK)

A fiber optic waveguide supports two optical modes of polarization. Polarization Mode Dispersion (PMD) occurs when one of the polarizations travels faster than the other through the fiber. The delay between the two polarizations increases with distance as shown in Figure 37.

In general, PMD must be 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 PMD value is understood to stand for the mean PMD, and the DGD is a realization which can be measured by the transceiver.

In order to support standard single-mode fibers of around 100-120km in length, the transceiver will need to tolerate a PMD value of at least 10 ps.

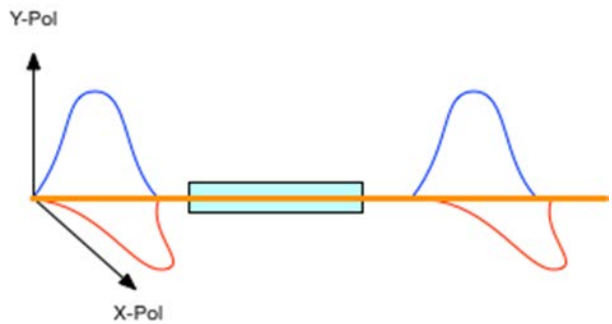


Figure 40 - DGD Diagram

The transceiver MUST support a minimum PMD of 10 ps.

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 ≤ 10-15 when the received optical power is 0.5 dB greater than the baseline optical power requirement defined in Section 8.4.1.

In the received OSNR-limited case, when the PMD is 10 ps, the transceiver MUST achieve a post-FEC bit-error ratio (BER) of ≤ 10-15 when the received OSNR is 0.5 dB greater than the baseline OSNR requirement defined in Section 8.4.1.

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

8.4.4 State of Polarization Tracking (200G QPSK)

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.). Note that faster tracking rates may result in increased power and OSNR penalties, which are beyond the scope of this specification.

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 BER of ≤ 10-15 when the received optical power is 0.5 dB greater than the baseline optical power requirement defined in Section 8.4.1.

In the received OSNR-limited case, when the SOP tracking rate is 50 krad/sec, the transceiver MUST achieve a post-FEC BER of ≤ 10-15 when the received OSNR is 0.5 dB greater than the baseline OSNR requirement defined in Section 8.4.1.

The transceiver MUST report the SOP tracking rate in use.

The transceiver MAY support multiple SOP tracking rates.

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

8.4.5 Polarization Imbalance Tolerance (200G QPSK)

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 8.3.4, 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 2.5 dB for the incoming optical signal.

In the received optical power-limited case, when the PDL is 2.5 dB, the transceiver MUST achieve a post-FEC BER of ≤ 10-15 when the received optical power is 1.5 dB greater than the baseline optical power requirement defined in Section 8.4.1.

In the received OSNR-limited case, when the PDL is 2.5 dB, the transceiver MUST achieve a post-FEC BER of ≤ 10-15 when the received OSNR is 1.5 dB greater than the baseline OSNR requirement defined in Section 8.4.1.

The transceiver MUST report the measured PDL.

8.4.6 IQ Imbalance Tolerance (200G QPSK)

As noted in Section 8.3.5, IQ imbalance is defined as the amplitude imbalance between the in-phase and quadrature-phase (I-Q) 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 dB.

It is not expected that the transmission path will introduce additional IQ imbalance, and therefore that the source of any IQ imbalance comes from the transmitter and the receiver itself. 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.

Additionally, lab testing has demonstrated that this level of IQ imbalance will not have a negative impact on system performance. Therefore, power and OSNR penalties are not necessary and have not been defined.

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

8.4.7 Received Frequency Accuracy (200G QPSK)

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 8.3.2.

The transceiver MUST be capable of successfully receiving signals with a center frequency within +/-1.8 GHz of the DWDM grid defined in Table 13 for any channel that it supports.

8.4.8 Skew Tolerance (200G QPSK)

As noted in Section 8.3.6, Skew is defined as the inter-channel delay in the I-Q or X-Y as seen by a receiver.

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

8.4.8.1 Quadrature Skew Tolerance (200G QPSK)

Quadrature skew is generated by the transmitter, as outlined in Section 8.3.6.1, 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 transceiver MUST have a minimum receiver quadrature skew tolerance of 1 ps for the incoming optical signal.

8.4.8.2 Polarization Skew Tolerance (200G QPSK)

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 8.4.2), 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 8.4.2.

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

8.4.9 Receiver Reflectance (200G QPSK)

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. Reflections can contribute to noise at the receiver and therefore need to be controlled. This specification imposes a limit on reflectance of the receiver port to do that.

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.

$$R = 10 \log_{10} (P_R / P_I)$$

Appendix I of [ITU-T G.957] describes two methods that can be used measure reflectance.

Figure 41 illustrates the incident light on the receiver and the reflected light from the receiver.

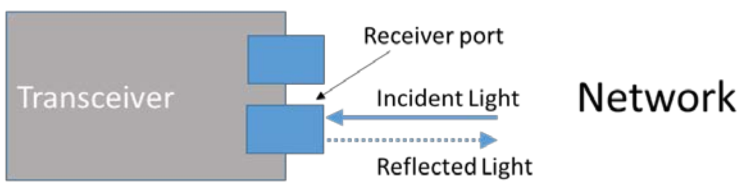


Figure 41 - Receiver Reflectance

The transceiver MUST have a maximum reflectance of ≤ -20dB or less from the receiver.

8.4.10 Data Reacquisition Time (200G QPSK)

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 reacquisition time of 250 ms or less.

9 REQUIREMENTS FOR 200G 16-QAM OPERATION

9.1 200G 16-QAM PHY Introduction

This section defines the optical physical (PHY) layer requirements for a point-to-point (P2P) coherent optics transceiver operating at 200 Gbps (200G) utilizing 16-QAM modulation, as well as providing some of the background for why the requirements were chosen.

Some cable operators are anticipating deployment of DWDM muxes operating with 50 GHz channel spacing prior to the availability of coherent optic transceivers compliant with this specification. In order to avoid the cost of replacing that equipment, some operators may therefore prefer a solution for 200G operation that can fit within a 50 GHz channel spacing. To meet this need, this specification also defines a mode for achieving 200G operation utilizing 16-QAM modulation.

As the use case for the 200G 16-QAM mode is expected to be more limited than the 200G QPSK mode, this mode is being made optional rather than mandatory. In addition, the specification only defines the basic requirements for interoperability when operating in this mode, and does not include requirements on optical performance. Instead, it is expected that an end customer that requires a 16-QAM mode of operation will define their own requirements for the optical parameters.

The requirements in this section are contained within a single category:

- Common Requirements, which apply to both the transmit and receive operation of the transceiver.

The transceiver MAY support the 200G 16-QAM mode of operation, as described in this section.

9.2 Common Transmitter/Receiver Requirements for 200G 16-QAM

9.2.1 Symbol Rate (200G 16-QAM)

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 process and 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 200G PHY is defined in Section 9.2.2.

The value of 31.5697339615 Gbaud was chosen for the symbol rate in order to allow 200 Gbps transmission of data as described in the following sections.

The symbol rate accuracy enables the successful reception of the signal.

If the transceiver supports the 200G 16-QAM mode of operation, then the transceiver MUST support a symbol rate of 31.5697339615 Gbaud with the modulation format described in Section 9.2.2.

If the transceiver supports the 200G 16-QAM mode of operation, then the transceiver MUST maintain the accuracy of the symbol rate of +/- 20 ppm.

9.2.2 Modulation (200G 16-QAM)

An optional modulation format for 200G is Dual Polarization 16Ary Quadrature Amplitude Modulation (DP-16-QAM). In each polarization (Xpol, Ypol) in-phase (I) and quadrature (Q) carriers are amplitude modulated to provide four symbols which leads to a sixteen symbol alphabet for the combined IQ system.

Each of the sixteen IQ symbols represents four bits, two of which select the amplitude of the I component while the other two determine the amplitude of the Q component. The mapping of those data bits to constellation symbols is defined in Section 7.3.2.

The symbol constellation is square i.e., type III in the terminology of [Campopiano and Glazer] The constellation points are located as shown in Figure 42, where the abscissa and ordinate represent the relative amplitudes of the modulated I and Q components of the signal, and the blue dots indicate the location in the IQ plane of the symbols.

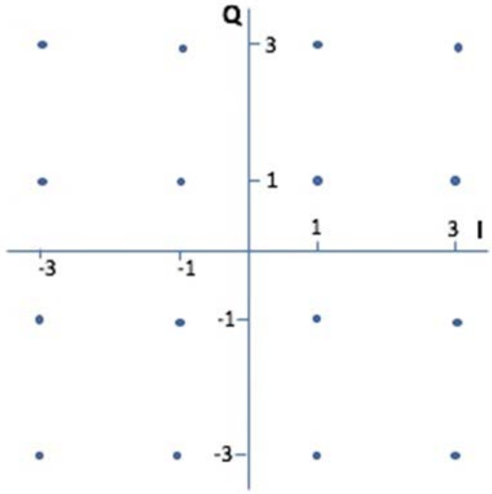


Figure 42 - 200G 16-QAM Constellation

The coordinates of the constellation points in the IQ plane are listed in Table 14.

Table 14 - Constellation Points in IQ Plane for 200G 16-QAM

-3,3	-1,3	1,3	3,3
-3,1	-1,1	1,1	3,1
-3,-1	-1,-1	1,-1	3,-1
-3,-3	-1,-3	1,-3	3,-3

If the transceiver supports the 200G 16-QAM mode of operation, then the transceiver MUST support DP-16-QAM modulation for the 200G signaling rate.

If the transceiver supports the 200G 16-QAM mode of operation, then the transceiver MUST use a square constellation with symbols located as described by Table 14 and illustrated in Figure 42.

If the transceiver supports the 200G 16-QAM mode of operation, then the transceiver MUST use the symbol mapping specified in Section 7.3.2.

9.2.3 Line Rate (200G 16-QAM)

This section specifies the bit rate of the signal which is transmitted on the optical channel (= line rate). The line signal includes overhead added by the transmitter (e.g., FEC). Dual-polarization 16 quadrature amplitude modulation (16-QAM) is transmitting 8 Bits per symbol. Therefore, line rate = 8x symbol rate.

Line rate details and calculation can be found in Section 7.3.3.

If the transceiver supports the 200G 16-QAM mode of operation, then the transceiver MUST support a nominal signal line rate of 252,557,871.7 kbit/s.

9.2.4 DWDM Frequency Grid (200G 16-QAM)

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-T G.694.1] using a 50 GHz channel spacing.

Specifically, Table 15 lists the specific DWDM wavelengths, frequencies, and associated channel numbers on which compliant transceivers can operate.

To transmit a line rate of 200 Gb/s using DP-16-QAM modulation format, the symbol rate is approximately 32 Gbaud (see Section 9.2.1). When the light is modulated at this symbol rate, the optical signal bandwidth is at least 32 GHz. The wavelength filters in DWDM multiplexers and demultiplexers need to have a bandwidth wide enough to pass the optical signal. In this case, the wavelength filters used in the 50 GHz channel spacing plan have sufficient bandwidth to pass the optical signal. Also, wavelength filters used in the 100 GHz channel spacing plan have sufficient bandwidth to pass the optical signal.

In order to enable low-cost implementations, transceivers are only required to support one channel from Table 15. 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 15 - DWDM Frequency Grid Table for 200G 16-QAM Operation

Channel Number	Central Frequency (GHz)	Central Wavelength (nm)
13.0	191300	1567.13
13.5	191350	1566.72
14.0	191400	1566.31
14.5	191450	1565.90
15.0	191500	1565.50
15.5	191550	1565.09
16.0	191600	1564.68
16.5	191650	1564.27
17.0	191700	1563.86
17.5	191750	1563.45
18.0	191800	1563.05
18.5	191850	1562.64
19.0	191900	1562.23
19.5	191950	1561.83
20.0	192000	1561.42
20.5	192050	1561.01
21.0	192100	1560.61
21.5	192150	1560.20
22.0	192200	1559.79
22.5	192250	1559.39
23.0	192300	1558.98
23.5	192350	1558.58
24.0	192400	1558.17
24.5	192450	1557.77
25.0	192500	1557.36
25.5	192550	1556.96
26.0	192600	1556.55
26.5	192650	1556.15
27.0	192700	1555.75
27.5	192750	1555.34
28.0	192800	1554.94
28.5	192850	1554.54
29.0	192900	1554.13
29.5	192950	1553.73

Channel Number	Central Frequency (GHz)	Central Wavelength (nm)
30.0	193000	1553.33
30.5	193050	1552.93
31.0	193100	1552.52
31.5	193150	1552.12
32.0	193200	1551.72
32.5	193250	1551.32
33.0	193300	1550.92
33.5	193350	1550.52
34.0	193400	1550.12
34.5	193450	1549.72
35.0	193500	1549.32
35.5	193550	1548.91
36.0	193600	1548.51
36.5	193650	1548.11
37.0	193700	1547.72
37.5	193750	1547.32
38.0	193800	1546.92
38.5	193850	1546.52
39.0	193900	1546.12
39.5	193950	1545.72
40.0	194000	1545.32
40.5	194050	1544.92
41.0	194100	1544.53
41.5	194150	1544.13
42.0	194200	1543.73
42.5	194250	1543.33
43.0	194300	1542.94
43.5	194350	1542.54
44.0	194400	1542.14
44.5	194450	1541.75
45.0	194500	1541.35
45.5	194550	1540.95
46.0	194600	1540.56
46.5	194650	1540.16
47.0	194700	1539.77
47.5	194750	1539.37
48.0	194800	1538.98
48.5	194850	1538.58
49.0	194900	1538.19
49.5	194950	1537.79
50.0	195000	1537.40
50.5	195050	1537.00
51.0	195100	1536.61
51.5	195150	1536.22
52.0	195200	1535.82
52.5	195250	1535.43

Channel Number	Central Frequency (GHz)	Central Wavelength (nm)
53.0	195300	1535.04
53.5	195350	1534.64
54.0	195400	1534.25
54.5	195450	1533.86
55.0	195500	1533.47
55.5	195550	1533.07
56.0	195600	1532.68
56.5	195650	1532.29
57.0	195700	1531.90
57.5	195750	1531.51
58.0	195800	1531.12
58.5	195850	1530.72
59.0	195900	1530.33
59.5	195950	1529.94
60.0	196000	1529.55
60.5	196050	1529.16
61.0	196100	1528.77
61.5	196150	1528.38
62.0	196200	1527.99

If the transceiver supports the 200G 16-QAM mode of operation, then the transceiver MUST support at least one channel from Table 15 above.

If the transceiver supports the 200G 16-QAM mode of operation, then the transceiver MAY support multiple channels from Table 15 above.

If the transceiver supports the 200G 16-QAM mode of operation, then the transceiver MUST report the channels from Table 15 above which it supports.

If the transceiver supports multiple channels from Table 15 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.

If the transceiver supports the 200G 16-QAM mode of operation, then the transceiver MUST report the channel from Table 15 that it is currently transmitting using the relevant management interface definition for the form factor of the transceiver module.

Appendix I Acknowledgements (Informative)

On behalf of the cable industry and our member companies, CableLabs would like to thank the following individuals for their contributions to the development of this specification. Additionally, CableLabs would like to thank the P2P Coherent Optics Working Group and the Point-to-Point Coherent Optics MSO team for their continued support in driving the specification development and the decision-making process.

Mike Pan, Tom Williams	Acacia
Nirmal Virdee, Richard Goodson	Adtran
Clark Scott, Jorg-Peter Elbers, Stephan Neidlinger	ADVA Optical
Charles Barker, LiPing Chen	ARRIS
Vasu Parthasarathy, Maged Barsoum	Broadcom
Brian Stanley, Christopher Gosnell, Eric Maniloff	Ciena
Fernando Villarruel, Matt Traverso, Gary Nicholl	Cisco Systems
Shawn Esser	Finisar
Peter Noutsios, Tooru Yamazaki	Fujitsu Optical (FOC)
Jun Zhou, Xiang Liu, Colin McKinstrie	Huawei
Paul Doolan, Avid Lemus	Infinera
Frank Chang, Ilya Lyubomirsky, Josef Berger, Martin Kuhlmann, Samuel Liu	Inphi
Andrew Smith, Terry Murray, Steven Alleston, Jeffery Maki	Juniper Networks
Daniel Tauber, David Lewis, Eugene Anoikin, Jinwoo Cho, Ernest Muhigana	Lumentum
Rajesh Radhamohan, Sridhar Ramesh, Bird Yuan	Maxlinear
Winston Way, Reggie Juluri	Neophotonics
Atul Srivastava, Hideki Nishizawa	NEL America
David Calhoun, Phillip Chang	Precision OT
Rudy Welter	Altice USA
Joel Prine, Joseph Nicksic, Peter Brown	Cable ONE
John Williams, Marek Hajduczenia, Kevin Kwasny, Richard Zhou	Charter
Robin Lavoie	Cogeco
Phil Miguelez, Phillip Chang, Robert Howald, Venk Mutalik,	Comcast
Harj Ghuman, Jeff Finkelstein, Robert Kuse	Cox
Ade Brittain, Gary Mitchinson, Jack Morrison, Mircea Damian, Phil Oakley, Seamus Gallagher	Liberty Global
Greg Kueneman, Brian Soloducha	Shaw
George Hart	Rogers
Antonio Bonici, Eric Menu, Philippe Haurie, Serge Legris, Thomas Foerster, Vincent-Gabriel Pilon Marien	Vidéotron
Tino Muders	Vodafone
Alberto Campos, Chris Stengrim, Christie Poland, Curtis Knittle, Melanie Parker, Ken Barringer, Jennifer Bane, Jing Wang, Jud Cary, Matthew Schmitt, Mu Xu, Rich Terpstra, Scott Bybee, Steve Burroughs, Steve Higgins, Steve Jia, Volker Leisse	CableLabs

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