Point-to-Point Coherent Optics

P2P Coherent Optics Architecture Specification

P2PCO-SP-ARCH-I02-190311

ISSUED

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Document Status Sheet

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Key to Document Status Codes

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

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

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

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

Trademarks

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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 provides background information regarding coherent optics technology, and how it can be used in cable access networks. More specifically, it accomplishes the following:

- Identify use cases of where operators can use P2P Coherent Optics in the access network
- Identify and document the common network requirements for the different use cases
- Identify and document through use cases the Hosts that could incorporate P2P Coherent Optics components or modules
- Identify and document where P2P Coherent Optics benefits each use case
- Communicate the architectural foundation on which the other P2P Coherent Optics specifications depend

1.2 Background

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

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

1.3 Requirements

This specification is informative in nature. As such, it does not contain any normative requirements, and none of the text in this document should be construed as requirements.

1.4 Organization of Document

The document is structured as follows:

- Discussion of cable access network architectures
- A look at access network trends
- An overview of Coherent Optics in general
- How a cable access network can leverage P2P Coherent Optics

- Use cases of how an operator can apply the P2P Coherent Optics technology to their access networks
- A discussion of operators' business needs
- A look at example link loss budgets for P2P Coherent Optics transceivers

2 REFERENCES

2.1 Informative References

This specification uses the following informative references.

[CCAP-ARCH]	Evolution of CMTS/CCAP Architectures, Karthik Sundaresan, CableLabs, 2015, https://www.nctatechnicalpapers.com/Paper/2015/2015-evolution-of-cmts-ccap-architectures
[ITU-HDB-OUT]	ITU-T Manual Optical fibres, cables, and systems, T-HB-OUT.10-2009-1, October 2009, https://www.itu.int/dms_pub/itu-t/opb/hdb/T-HDB-OUT.10-2009-1-PDF-E.pdf
[MHA-TR]	Modular Headend Architecture Technical Report, CM-TR-MHA-V02-081209, December 9, 2008, Cable Television Laboratories, Inc.
[P2PCO-OSSI]	P2P Coherent Optics Operations and Support System Interface Specification, P2PCO-SP-OSSI-D01-190311, March 11, 2019, Cable Television Laboratories, Inc.
[P2PCO-PHYv1.0]	P2P Coherent Optics Physical Layer Specification, P2PCO-SP-PHYv1.0-I02-190311, March 11, 2019, Cable Television Laboratories, Inc.
[P2PCO-PHYv2.0]	P2P Coherent Optics Physical Layer 2.0 Specification, P2PCO-SP-PHYv2.0-I01-190311, March 11, 2019, Cable Television Laboratories, Inc.
[P2PCO-PHY]	[P2PCO-PHYv1.0] and [P2PCO-PHYv2.0] collectively

2.2 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 Internet
- ITU-T: International Telecommunications Union, Telecommunication Standardization Sector, https://www.itu.int/en/ITU-T/Pages/default.aspx

3 TERMS, DEFINITIONS, AND SHAPES

3.1 Terms and Definitions

This specification uses the following terms:

Bit	The basic unit of information in computing and digital communications. A bit has one of two values either 0 or 1 that can be represented electrically and optically as "off " (0) or "on" (1)
Cable Modem (CM)	A modulator-demodulator at the subscriber premises intended for use in conveying data communications on a cable television system.
Cable Modem Termination System (CMTS)	Cable modem termination system, located at the cable television system headend or distribution hub, which provides complementary functionality to the cable modems to enable data connectivity to a wide-area network.
Coherent Optics	Coherent Optics encodes information in both in-phase (I) and quadrature (Q) amplitude components of a carrier.
Customer Premises Equipment (CPE)	Device such as a cable modem or router at the subscriber's or other end user's location. May be provided by the end user or the service provider.
Distribution Hub	A location in a cable television network which performs the functions of a head-end for customers in its immediate area, and which receives some or all of its television program material from a Master Head-end in the same metropolitan or regional area.
Downstream	In cable television, the direction of transmission from the head-end to the subscriber.
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 (FEC)	A method of error detection and correction in which redundant information is sent with a data payload to allow the receiver to reconstruct the original data if an error occurs during transmission.
Gigabit	One billion bits
Gigahertz (GHz)	One billion cycles per second.
Guard Band	Minimum time, measured in modulation symbols, allocated between bursts in the upstream referenced from the symbol center of the last symbol of a burst to the symbol center of the first symbol of the following burst. The guard band should be at least the duration of five symbols plus the maximum system timing error.
Headend (HE)	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. See also *distribution hub*.
Hybrid Fiber/Coaxial (HFC)	A broadband bidirectional shared-media transmission system or network architecture using optical fibers between the Headend and fiber nodes, and coaxial cable distribution from the fiber nodes to the subscriber locations.
Internet Protocol (IP)	The computer network protocol (analogous to written and verbal languages) that all machines on the Internet must know so that they can communicate with one another. IP is a layer 3 (network layer) protocol in the OSI model. The vast majority of IP devices today support IP version 4 (IPv4) defined in RFC-791, although support for IP version 6 (IPv6, RFC-2460) is increasing.
IQ Modulation	A method of combining two input channels into one by multiplying the "in-phase" (I) channel by the cosine and the "quadrature" (Q) channel by the sine. This way there is a phase of 90° between them, then added together the modulator sends the combined signal through the output channel.
Jitter	The fluctuation in the arrival time of a regularly scheduled event such as a clock edge or a packet in a stream of packets. Jitter is defined as fluctuations above 10 Hz.
Kilometer (km)	One thousand meters
Latency	The time taken for a signal element to pass through a device.
Layer	A subdivision of the Open System Interconnection (OSI) architecture, constituted by subsystems of the same rank.
Media Access Control (MAC)	Used to refer to the OSI Layer 2 element of the system which would include DOCSIS framing and signaling.
Multiplexer/Demultiplexer (MUX)	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
N+x	A way of conveying how many amplifiers (x) are between a fiber node and the endpoint. N+0 indicates the fiber node connects directly to the endpoint.
Orthogonal	Distinguishable from or independent such that there is no interaction or interference. Two lines that are at right angles (90°) to one another.
Physical Layer (PHY)	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. Also, called 4-QAM.
Subscriber	End user or customer connected to a provider's network.
Transceiver	A combination of transmitter and receiver in the same device or component
Ultra HD	Ultra High Definition includes two digital video formats of 4k and 8k.
Upstream	The direction from the subscriber location toward the head-end.

3.2 Shapes Legend

This specification uses the following shapes in drawings throughout this document:

Table 1 - Symbols

Shape	Meaning
λ	lambda (wavelength)

Table 2 - Cables

Shape	Meaning
	Coaxial
	Fiber
	IP

Table 3 - Components

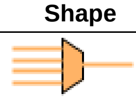
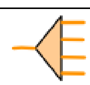
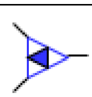
Shape	Meaning
	Optical Multiplexer/Demultiplexer
	Optical Splitter
	RF Amplifier

Table 4 - Devices

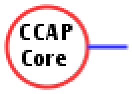
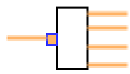
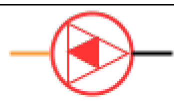
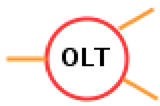
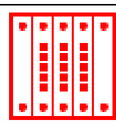
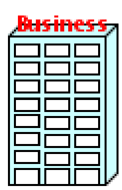
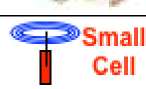
Shape	Meaning
	Converged Cable Access Platform Core
	Ethernet Switch/Muxponder
	Fiber Node
	Optical Line Terminal
	Optical Network Unit
	Remote PHY Device
	Router/Switch/Aggregation Device

Table 5 - Endpoints

Shape	Meaning
	Base Station
	Business
	Data Center
	Residential
	Small Cell

4 ABBREVIATIONS AND ACRONYMS

This specification uses the following abbreviations:

AR	Augmented Reality
BiDi	Bidirectional
CableLabs	Cable Television Laboratories, Inc.
CCAP	Converged Cable Access Platform
CD	Chromatic Dispersion
CM	Cable Modem
CMOS	Complementary Metal–Oxide–Semiconductor
CMTS	Cable Modem Termination System
CPE	Customer Premise Equipment
DAA	Distributed Access Architecture
DOCSIS	Data-Over-Cable Service Interface Specifications
DSP	Digital Signal Processing
DWDM	Dense Wavelength Division Multiplexing
EPL	Ethernet Private Line
EPON	Ethernet Passive Optical Network
EQAM	Video EdgeQAM
EVPL	Ethernet Virtual Private Line
FEC	Forward Error Correction
FTTB	Fiber-to-the-Building/Business
FTTC	Fiber-to-the-Curb/Cell
FTTH	Fiber-to-the-Home
FTTP	Fiber-to-the-Premises
FTTT	Fiber-to-the-Tower
Gbps	Gigabit per second
GHz	Gigahertz
GigE	Gigabit Ethernet
HE	Head-End
HD	High Definition (video)
HD FEC	Hard Decision Forward Error Correction
HFC	Hybrid Fiber/Coaxial
HHP	Households Passed
Hz	Hertz
IQ	In-Phase and Quadrature
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IoT	Internet of Things
IP	Internet Protocol
IPTV	Internet Protocol Television
IPv4	Internet Protocol version 4
IPv6	Internet Protocol version 6
ITU	International Telecommunication Union
km	Kilometers
LO	Local Oscillator
MAC	Media Access Control
MHz	Megahertz

MPEG	Moving Picture Experts Group
MUX	Multiplexer
ODC	Optical Distribution Center
OLT	Optical Line Terminal
ONU	Optical Network Unit
OSI	Open Systems Interconnection
OSNR	Optical Signal to Noise Ratio
OSSI	Operations Support System Interface
P2P	Point-to-Point
PHY	Physical Layer
PIC	Photonic Integrated Circuits
PM	Polarization Multiplexing
PON	Passive Optical Network
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase-Shift Keying
R-MACPHY	Remote MAC-PHY
R-PHY	Remote PHY
R-OLT	Remote Optical Line Terminal (OLT)
RF	Radio Frequency
RFC	Request for comment
RMD	Remote MAC-PHY Device
ROI	Return on Investment
RPD	Remote PHY Device
RX, Rx	1) Receive; 2) Receiver
SCTE	Society of Cable Telecommunications Engineers
SD	Soft Decision (FEC)
SNR	Signal-to-Noise Ratio
Tbps	Terabits per second
TV	Television
TX, Tx	1) Transmit; 2) Transmitter
VOD	Video-on-demand
VR	Virtual Reality
WDM	Wavelength Division Multiplexing

5 OVERVIEW

5.1 Cable Access Network Architectures

5.1.1 Currently Deployed Cable Networks

A typical cable operator's network, as depicted in Figure 1, consists of the following:

- Long-haul or backbone network that interconnects the different metropolitan areas or regions in which a cable operator provides services.
- Metro or regional network that provides interconnection to the HE/Hubs/Regional Network Centers the cable operator has deployed in a contiguous geographic area, such as an entire metropolitan area or state, or portions of either.
- Access network that provides connections to end users, such as residential customers, business customers, or backhaul/front-haul of small cells/base stations. The access network contains the fiber nodes, amplifiers, taps, etc. that are interconnected with fiber or coaxial cables to provide services to endpoints.

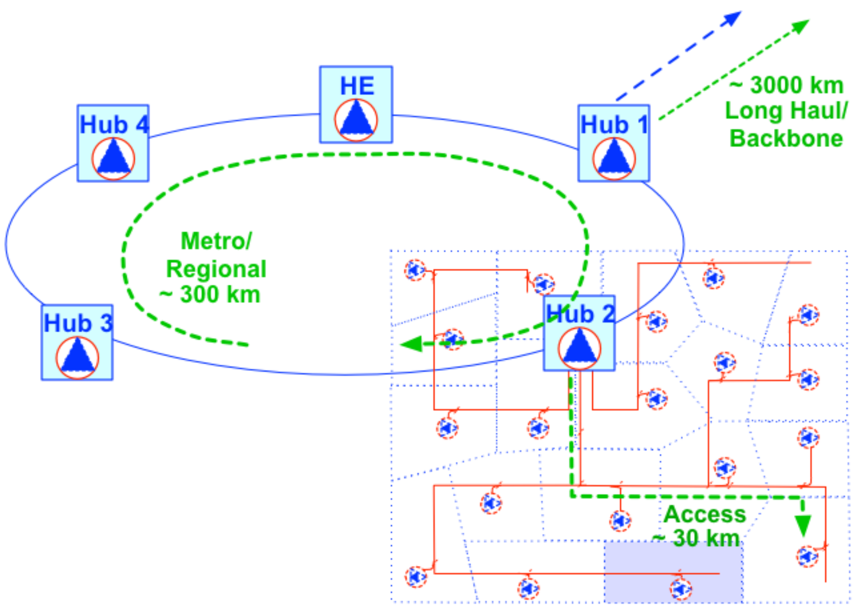


Figure 1 - Cable Network Architecture

In this architecture, the equipment at the HE/Hub generates Radio Frequency (RF) signals that are converted to optical signals that the HE/Hub transmits over fiber to the fiber node utilizing analog optics. The fiber node converts the optical signals back to RF/electrical signals that the fiber node transmits over coaxial cable to the end customer. In most cases, that RF signal will need to be amplified several times using RF amplifiers to reach all end customers, as shown in Figure 2.

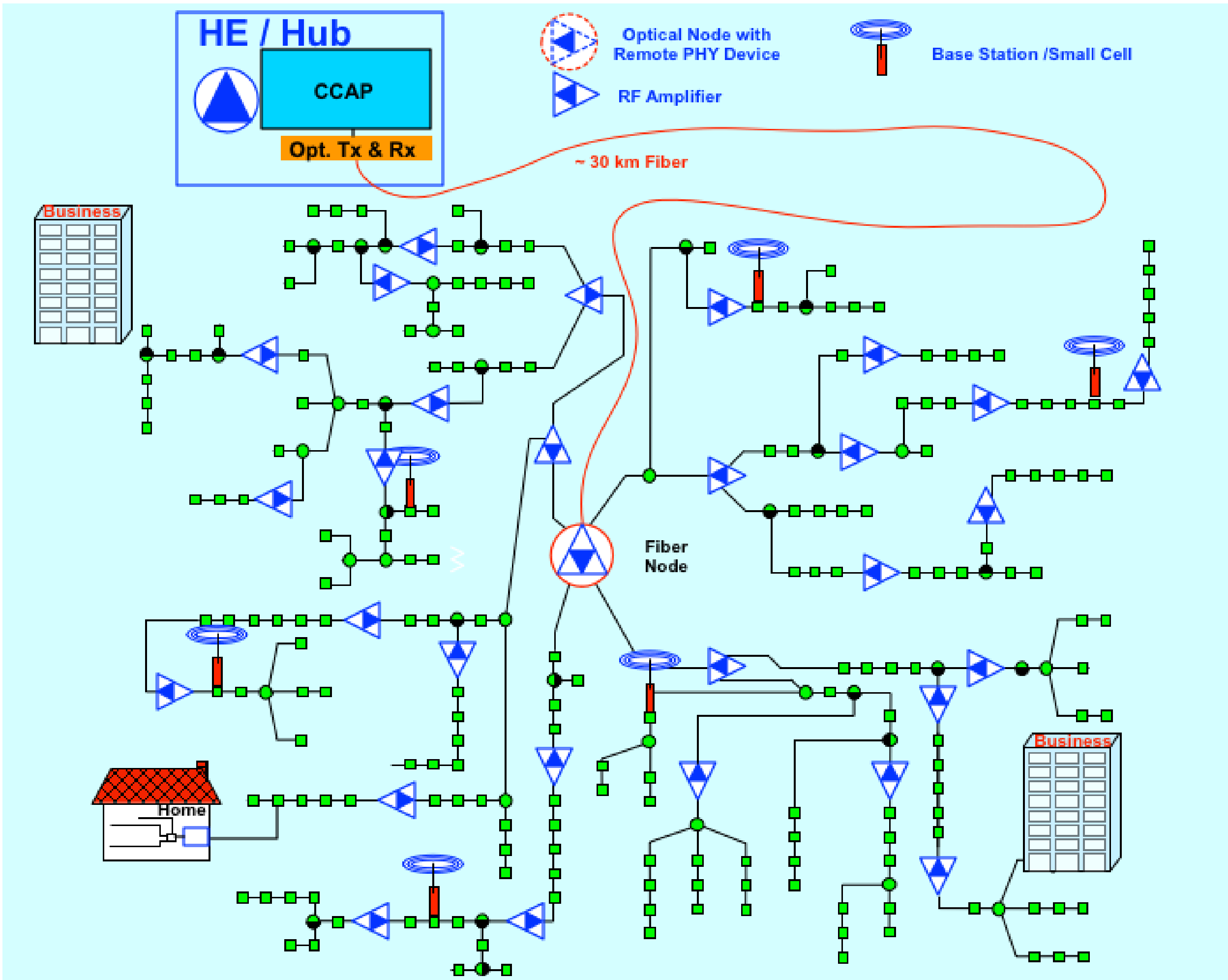


Figure 2 - Example Centralized Access Architecture Network

5.1.2 Centralized Architecture

Most cable operators run a Centralized Network that consists of HEs/Hubs and fiber nodes. The architecture initially provided downstream video to cable subscribers. It then evolved into a data over cable network as defined by DOCSIS specifications that introduced the Cable Modem Termination System (CMTS) in the HE and the Cable Modem (CM) at the premise. This architecture provides internet access and video delivery on the same coaxial cable. The Video EdgeQAM (EQAM) was introduced into the HE/Hub to enable digital video, video-on-demand (VOD), and switched-digital-video. EQAMs evolved to support the modulation of both MPEG video and DOCSIS data onto the wire using a Modular Headend Architecture [MHA-TR]. The CMTS and EQAM evolved into the Converged Cable Access Platform (CCAP) to provide higher densities of EQAM and CMTS combined together into the same chassis; other technologies like Ethernet optics and Ethernet Passive Optical Network (EPON) could theoretically share the same chassis as well. As a result, the CCAP enables data, voice, and video to be handled over Internet Protocol (IP) before being converted to RF or optical signals [CCAP-ARCH].

Figure 3 depicts an example of a Centralized CCAP architecture. The CCAP at the HE/Hub generates RF signals and transmits them to fiber nodes over analog optics. From these fiber nodes, there are one or more amplifiers in cascade. Hybrid Fiber-Coax (HFC) Networks have been designed with a small number (6-8) of fiber strands dedicated to each fiber node. However, some of these fibers have been repurposed for other services or node splitting, which usually leaves 1-2 strands available for the Original Fiber Node to support video and data services. This traditional architecture usually supports 400-500 households passed (HHP) per fiber node.

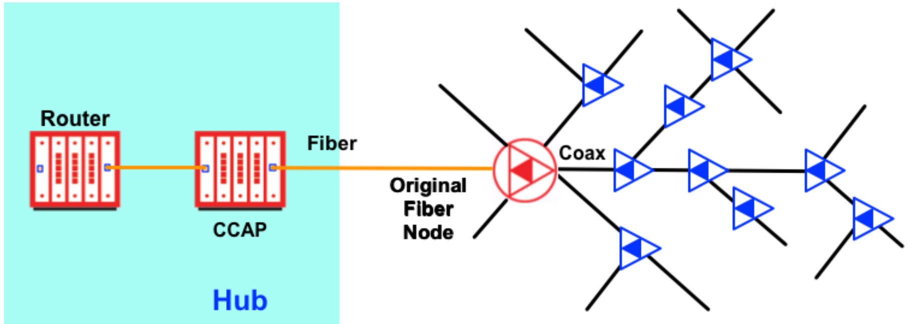


Figure 3 - Example Centralized CCAP Architecture

5.1.3 Centralized Architecture with Fiber Deep Nodes

As bandwidth demands increased, one approach utilized by cable operators to increase capacity is to split each fiber node into multiple nodes, referred to as a node split. With each node split, the number of amplifiers between the fiber node and the end of the coaxial plant typically decreases. Eventually operators can reach a point where there is only a single amplifier between the fiber node and the end of the plant (known as N+1), or there are no amplifiers at all (known as N+0 or Passive Coax). This both reduces the number of customers sharing the capacity available from that fiber node, and also reduces the noise introduced by RF amplifiers.

Collectively, when a node reaches N+1 or N+0, it is referred to as a Fiber-Deep Node. The reason for this is that while some node splits can be made at the existing fiber node location by segmenting the existing coaxial plant, eventually it becomes necessary to push those fiber nodes – and the fiber that supports them – deeper into the network.

In cases where there are extra strands of fiber at the Original Fiber Node that are not being used, these strands can be repurposed and extended out to the Fiber-Deep Nodes. As shown in Figure 4, the thick line from the HE/Hub to the Fiber-Deep Nodes gets thinner as it adds each Fiber-Deep Node to represent multiple fibers from the HE/Hub being extended to each fiber node. By extending the fiber(s) to the Fiber-Deep Node, it increases capacity deeper in the access network. Since each Fiber-Deep Node has fewer homes to serve, there is more capacity available per home. In these instances, the capacity becomes limited by that of the fiber(s) at the Fiber-Deep Node.

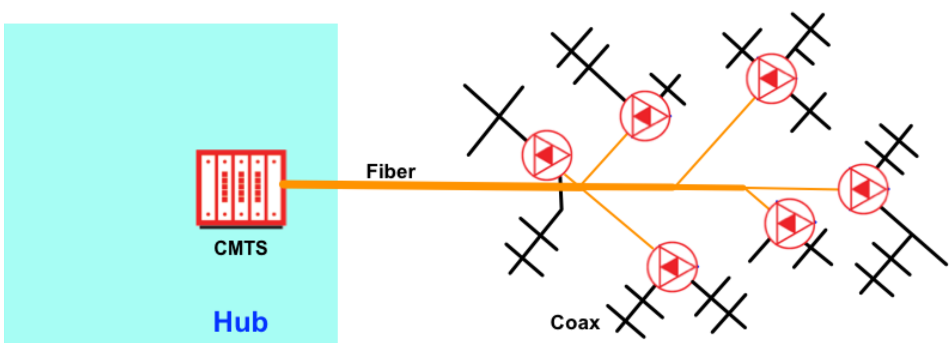


Figure 4 - Example Fiber Deep Node Architecture

However, there is often very few fiber strands available between the Original Fiber Node location and the headend/hub. Therefore, in order to support multiple fiber nodes when there aren't additional fiber strands available, it is often necessary to use Wavelength Division Multiplexing (WDM) technology to support multiple wavelengths, one for each of the new fiber nodes. As shown in Figure 5, a Multiplexer (MUX) can be used to aggregate multiple wavelengths onto a single fiber or fiber pair, allowing multiple fiber nodes to share the same fiber connecting to the HE/Hub. It should be noted that with Analog Optics, usually there are four wavelengths supported between the HE/Hub and Original Fiber Node location, although there could be up to 16 wavelengths for shorter distances. This limited number of wavelengths is due to the noise generated by the analog signals, which requires larger spacing between neighboring wavelengths to prevent inter-channel interference. Therefore, in a practical system implementation, the maximum number of analog wavelengths from the HE/Hub to Original Fiber Node location without adding additional fiber is 16.

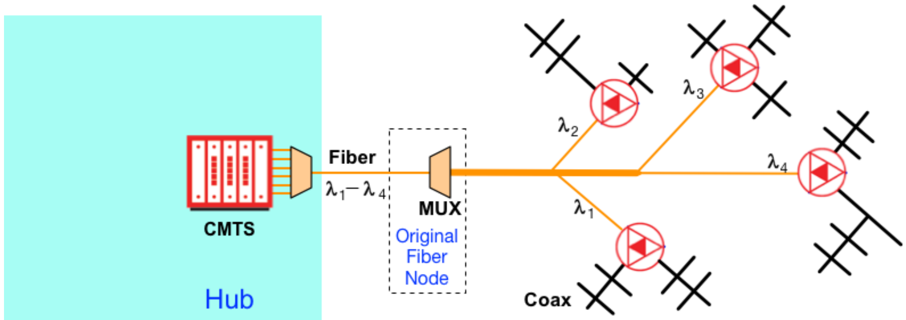


Figure 5 - Example Wavelength Multiplexing for Fiber Deep Node Architecture

5.1.4 Distributed Architecture

The next evolution of the cable access network is to distribute some functions of the HE/Hub down to remote locations like the fiber node. This is generally referred as a Distributed Architecture; when some or all CCAP functions are distributed into the network, it's referred to as a Distributed Access Architecture (DAA). Distributed Access Architectures extend the reach of the digital transmissions, which facilitate the support of higher order modulation of DOCSIS signals [CCAP-ARCH].

There are three distributed architectures that have been defined so far: Remote-PHY, Remote-MACPHY, and Split-MAC. Remote MAC-PHY moves the entire CMTS/CCAP into a device that sits at the Remote Node, referred to as a Remote-MACPHY Device (or RMD). Remote PHY splits the CMTS between the MAC and PHY layers and moves the PHY layer to the Remote Node; the device at the headend/hub that retains the MAC layer is referred to as a CCAP-Core, and the device that sits at the Remote Node location is referred to as Remote PHY Device (or RPD). Split-MAC splits the MAC layer and moves some of the MAC layer functions and all the PHY layer functions to the Remote Node.

The role of the RPD/RMD is to convert digital signals like Ethernet or a form of Passive Optical Network (PON) to analog for transmission over coax using RF in the downstream and upstream directions. Figure 6 is an example R-PHY architecture. In this example, the Original Fiber Node location now contains an Ethernet switch that takes the inbound Ethernet signal from the CCAP (or a collection of devices serving the functions of a CCAP) at the HE/Hub and routes the Ethernet signal to the intended RPD. The RPD terminates the Ethernet signal and converts it into RF signals that it sends to the CM at the Customer premise. The R-MACPHY architecture is similar, but has RMD instead of RPD as the Remote Nodes. Note that other similar architectures are also possible; for example, colored 10G optics and a passive Mux/Demux could also be used to connect to the RPDs.

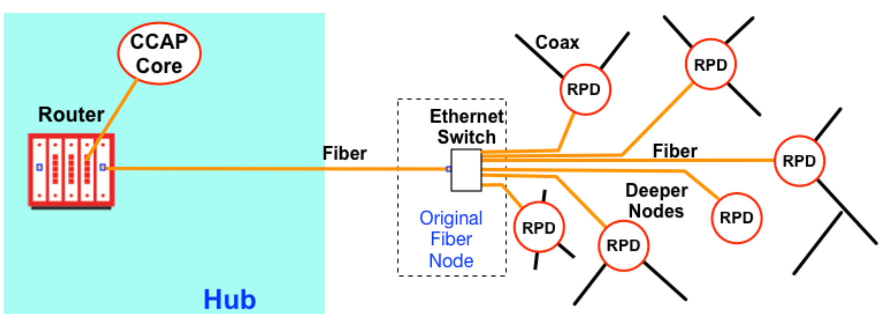


Figure 6 - Example R-PHY Architecture

5.1.5 Passive Optical Network (PON) Architecture

In some cases, such as areas with new construction, cable operators may use Passive Optical Network (PON) technologies to build fiber networks rather than Hybrid Fiber Coax (HFC) networks. A Passive Optical Network (PON) architecture supports fiber to the X, where X could be Home (FTTH), Business (FTTB), Curb/small cell (FTTC), or base station/Tower (FTTT). The architecture consists of an Optical Line Terminal (OLT) at the HE/Hub, optical splitters, and Optical Network Units (ONUs) at the premise of the endpoint or very near the premise (Fiber to the Curb – FTTC). PON architectures typically service 16 to 32 ONUs per OLT port (although in some cases can support up to 64 ONUs). Figure 7 gives an example of a basic PON architecture.

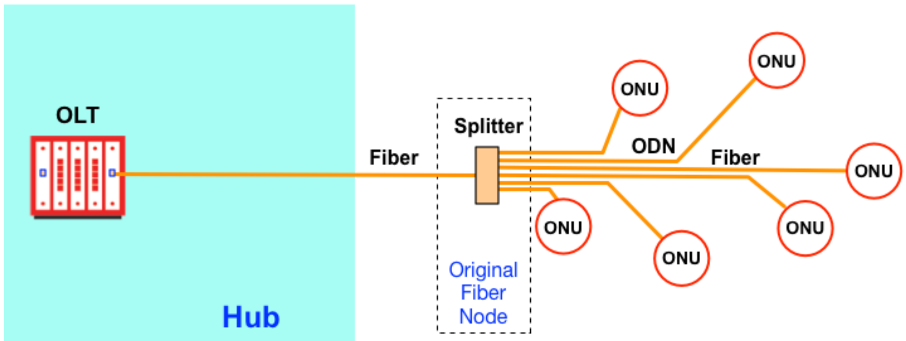


Figure 7 - Example PON Architecture

PON typically supports distances of 20 kilometers (km) or less between the OLT and ONUs, due to fiber attenuation and the insertion loss of passive devices. To overcome this limitation, operators can deploy Remote OLTs (R-OLT). R-OLT moves the OLT out of the HE/Hub to a cabinet within a Virtual Hub location that is located less than 20 km from the ONUs. By exploiting WDM technology between HE/Hub and Virtual Hub, each Virtual Hub can contain multiple OLTs, each supported by one wavelength. In Figure 8, the Virtual Hub contains the Remote OLT as well as an element that decomposes and separates the wavelengths, and delivers each wavelength to a remote OLT. If the Remote OLT happens to reside in the same cabinet or chassis as the Ethernet switch, there could be an electrical interface from the switch to the Remote OLT instead of fiber. The Remote OLT will usually be in the Virtual Hub, but the Remote OLT could be deeper in the access network to maintain the maximum 20 km distance between OLT and ONU. Like traditional PON, each Remote OLT can service 16 to 32 ONU.

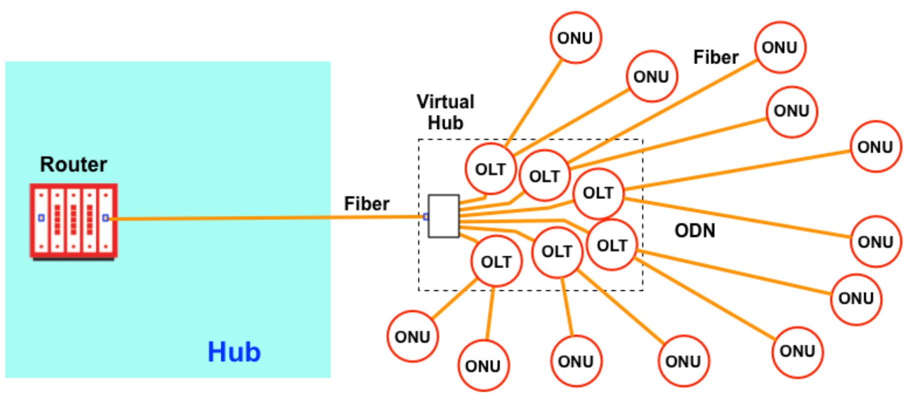


Figure 8 - Example R-OLT Architecture

5.1.6 P2P Ethernet over Fiber

As noted above, HFC networks have been designed with a small number (6-8) of fiber strands dedicated to each fiber node. Some of these fibers have since been re-purposed for business services, such as Ethernet Private Line (EPL) or Ethernet Virtual Private Line (EVPL), while others were sold as dark fiber for the business that has total control of the fiber. In the Ethernet service architecture, the HE/Hub connects directly to the premise over fiber by using spare fibers or by re-purposing and extending a fiber that was deployed to a fiber node as shown in Figure 9.

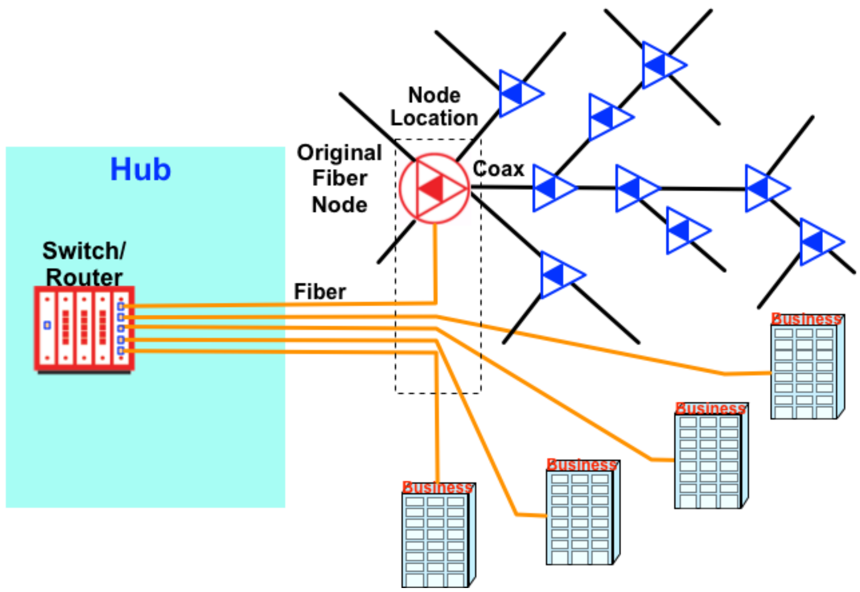


Figure 9 - Example EPL Architecture

5.2 Access Network Trends

As Figure 10 shows, service demand in the access network is increasing exponentially, driven by a variety of factors. As the demand for service bandwidth increases, access network capacity needs to increase with it.

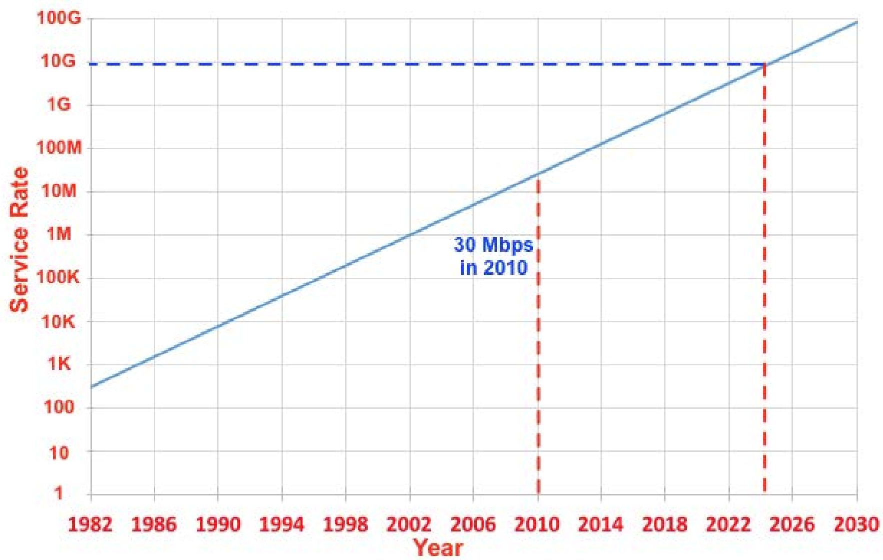


Figure 10 - Peak Service Offering Growth Projection

This growth has continued at this pace for many years, driven by an ever-changing mix of different applications and services. Some that are expected to drive increasing service and capacity demands in the near future include:

- **Internet of Things (IoT)**: As more and more devices become connected to the internet, the huge number of devices will drive the need for more bandwidth. Additionally, some devices -- such as video doorbells or security cameras -- will require large amounts of bandwidth on a periodic basis.

- **Healthcare**: An offshoot of IoT, as more home healthcare devices become connected to the internet, the volume of devices will drive bandwidth needs, some of which may demand high capacity and high reliability. In addition, video conferencing with patients and between doctors will drive service needs.
- **Virtual Reality (VR) and Augmented Reality (AR)**: Devices that create virtual worlds or overlay information or images onto the real world already consume large amounts of bandwidth. Over time, these devices will become more mainstream and interactive, driving the demand for more capacity and lower latency.
- **IPTV**: More and more video content is being delivered using IP, and the resolution of that content continues to grow, progressing from High Definition (HD) to Ultra High Definition (UHD) at 4k and 8k resolutions; greater resolution requires greater bandwidth to carry it.
- **Fog and Cloud Computing**: As more and more applications and data processing moves into the cloud, greater bandwidth with low latency will be required.
- **Mobile**: With the push toward smaller and smaller cells, cable operator networks are well placed to provide mobile backhaul/front-haul services, adding additional capacity demands to the network.

While each of these on their own can drive bandwidth growth and a need for lower latency, combinations of them together will do so to an even greater extent, such as streaming UHD VR content from the Cloud.

For all of these reasons, and for others not yet known, capacity demand in the access network will continue to increase, and cable operators will need cost effective solutions to address bandwidth growth. As noted, cable operators are addressing this by splitting nodes and pushing fiber deeper into the network, as well as deploying Distributed Access Architectures. However, with the limited fiber available between the headend/hub and the existing fiber node location, the current technology of choice – 10Gbps direct detect combined with DWDM – can quickly become cost prohibitive, and provides a long-term limit on network capacity; trenching new fiber is even more expensive, and therefore even less desirable.

A technology that would address these issues -- and may be capable of doing so cost effectively -- is known as Coherent Optics.

5.3 What is Coherent Optics

Coherent Optics is a technique for using amplitude and phase of light, as well as two orthogonal polarizations, to transmit multiple bits per symbol across fiber. There are several efficient modulation formats such as M-ary phase shift keying (such as Quadrature Phase-Shift Keying (QPSK)) and quadrature-amplitude-modulation (QAM). The modulation formats have an in-phase (I) component and a quadrature phase (Q) component. Additionally, the modulation format can be carried by two orthogonal polarizations, represented as X polarization and Y polarization. This is known as polarization multiplexing as shown in Figure 11.

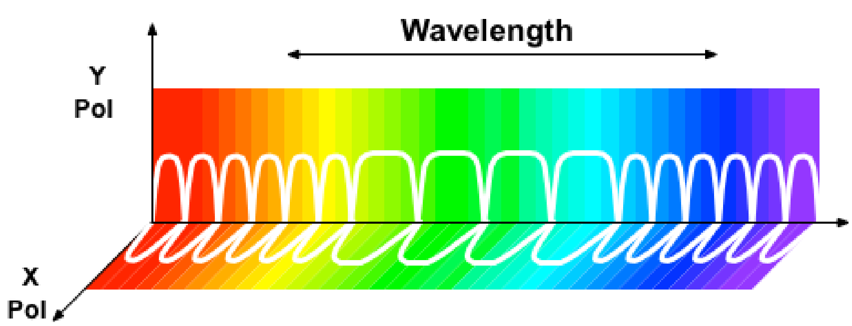


Figure 11 - Polarization Multiplexing

The Coherent Optic link consists of the transmitter, receiver, and the fiber in between. The Coherent Optic link is bidirectional in that it can use the same wavelength for sending that it does for receiving as long as the link is over 2 fibers. In this case, the Coherent Optic Transceiver uses the same laser for transmitting as it does for receiving (Local Oscillator). In the case of a single fiber, the Coherent Optic link typically uses a different wavelength for sending than it does for receiving, in which case the Coherent Optic Transceiver needs 2 different lasers, one for each direction. The following paragraphs provide a high-level description of the transmitter and receiver functions as well as a description of how the data streams across the fiber.

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

NOTE: For example, using 16-QAM modulation format with 4 bits per symbol and multiplexing two polarizations at a 32G baud (symbol rate), a single wavelength can achieve 256 Gbps per channel.

$$\frac{\text{4 bits}}{\text{symbol}} * \frac{\text{32G symbols}}{\text{sec}} * \text{2 polarizations} = \frac{\text{256G bits}}{\text{sec}}$$

Figure 12 - Bits per Second Formula

NOTE: As another example, by using a WDM configuration with eight wavelengths carrying 256 Gbps each, the raw bit rate across the fiber can reach 2048 Gbps (2.048 Terabits per second - Tbps).

Each data channel contains two polarization tributaries. Each polarization contains In-Phase and Quadrature components. Each symbol has a defined duration determined by the symbol rate. The number of bits per symbol period ranges from two bits (QPSK with single polarization) up to eight bits (16-QAM with two polarizations). Figure 13 is a visualization of these relationships for 16-QAM with two polarizations.

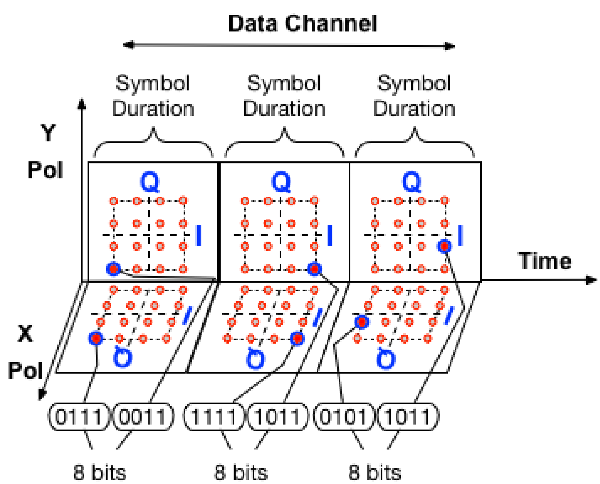


Figure 13 - Data Channel Visualization

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

Figure 14 shows a high-level functional view of the Coherent Optic Transmitter and Receiver. The transmitter takes in bits and maps them into symbols with four degrees of freedom (XI, XQ, YI, YQ). The receiver demultiplexes the two orthogonal polarizations and demodulates the symbols to retrieve the transmitted bits. There are additional components and processes not shown here that are covered in [P2PCO-PHY].

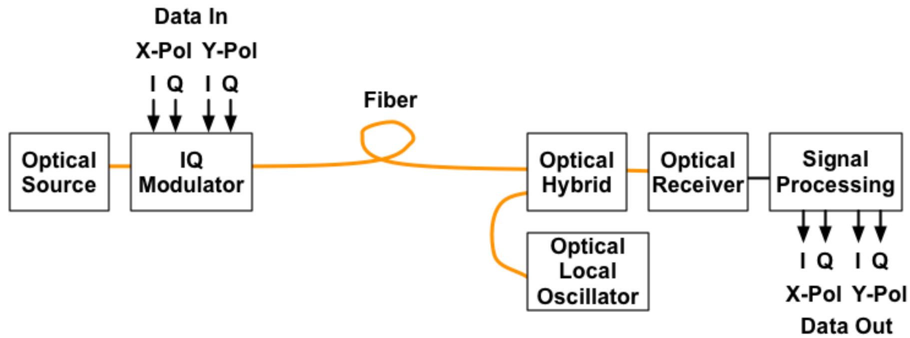


Figure 14 - Coherent Transmitter and Receiver High-Level Functions

5.4 P2P Coherent Optics in Access Networks

The optical technologies currently used in the access network have limitations on how much capacity a single fiber can support (usually 10 Gbps or less per wavelength). To achieve greater capacity requires more wavelengths and eventually more fiber strands. In many cases, it requires retrenching to add more fiber strands. As an alternative, Coherent Optics Point-to-Point (P2P) links can deliver higher capacity over the existing fiber, thereby avoiding retrenching. In most cable access networks, the distance between the HE/Hub and fiber node is less than 100 km, and in a substantial majority of cases is less than 40 km. Therefore, the access network does not need some of the components needed for long-haul and metro coherent networks. These other coherent networks require EDFAs to amplify the signal between transceivers and use more expensive components to deal with impairments of the signal, such as Chromatic Dispersion (CD) and Polarization Mode Dispersion (PMD) that worsen with distance. With shorter distances to fiber nodes that are in tens of km instead of hundreds or thousands of km, P2P Coherent Optics for access networks are less complex than metro and long-haul, so they can use less complex components including less expensive DSPs. Common interface definitions will enable interoperability between vendors, which in turn allows for greater scale and competition, greatly reducing cost. Therefore, P2P Coherent Optics designed for the access network can deliver a lower cost per bit than counterparts in long-haul and metro networks, while leveraging similar technology.

The shorter distances result in fewer signal impairments, especially when using unamplified links. For instance, there is almost no Chromatic Dispersion for distances less than 100 km, and what there is can easily be corrected for with a DSP or inexpensive filter. With less severe distortions, P2P Coherent Optics for access networks has better Signal to Noise Ratio (SNR) that allows for higher modulation orders than the other networks, which leads to more efficient use of the fiber. The simpler design results in a more scalable network. For instance, the P2P Coherent Optics Transceiver will be able to provide 100, 200, or even 400 Gbps per wavelength. Because of the higher spectral efficiency, P2P Coherent Optics in the access network provides increased data capacity over the existing fiber infrastructure between the HE/Hub and the Original Fiber Node locations, which avoids the cost of retrenching. By using WDM technology, P2P Coherent Optics future-proofs the access network by supporting multiple 100-200 Gbps (or higher) wavelengths on a single fiber at a higher density than competing technologies. WDM technology also allows P2P Coherent Optics to coexist with Analog, IM-DD, and PON technologies to enable a smooth transition for an operator.

Introducing P2P Coherent Optics into the access network is a natural progression of optical and electronics technologies that are moving to Photonic Integrated Circuits (PIC) and Complementary Metal–Oxide–Semiconductor (CMOS) implementations that add greater functionality to the transceiver. Section 6 shows how P2P Coherent Optics can augment the proposed future Point-to-Point (P2P) architectures to provide the high capacity at the lower cost. Additionally, Section 6 will show how many of the proposed P2P architectures can use muxponders instead of more expensive Ethernet switches at the Original Fiber Node location, which could lower costs even more.

The P2P Coherent Optics solution targets the C-Band spectrum. However, other services are already using portions of the C-Band, so not all wavelengths will be available to the P2P Coherent Optics solution when it coexists with other technologies on the same fiber. Figure 15 shows a high-level diagram of what wavelengths make up the C-Band as defined by ITU in [ITU-HDB-OUT]. For the initial deployment, operators would like to reuse existing

WDM equipment that uses 100 Gigahertz (GHz) spacing between channels within the C-Band. Although the C-Band is the initially targeted spectrum, it may be possible in the future to expand P2P Coherent Optics for the access network into part of the L-Band to further increase the capacity a single fiber could support.

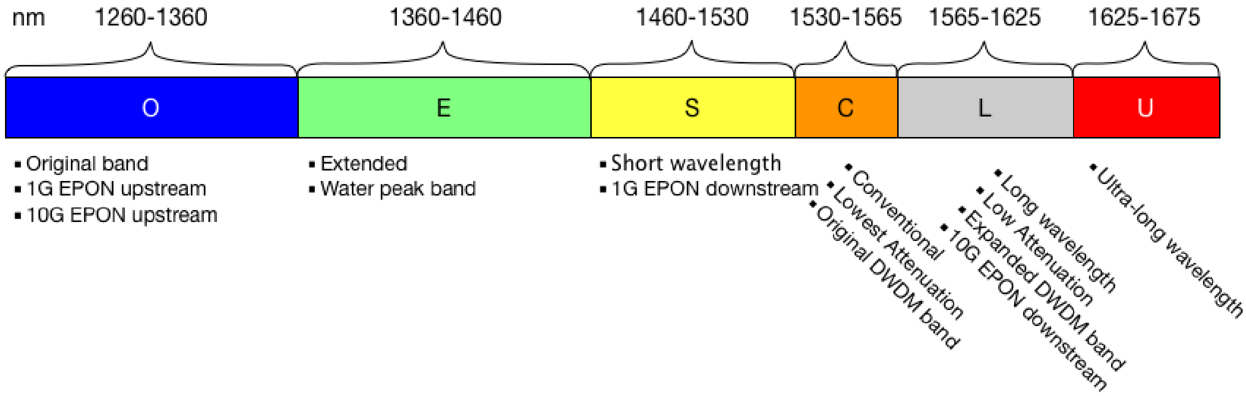


Figure 15 - Spectral Bands Diagram

Coherent Optics in the access network enables increased bandwidth by reusing Coherent Optics technology developed for metro and long-haul networks. Due to the shorter distances it needs to support, combined with common specifications that enable scale and competition through interoperability, Coherent Optics for the access network can be less expensive and less complex than for metro or long-haul networks.

6 POINT-TO-POINT (P2P) COHERENT OPTICS

There are two main use cases for P2P Coherent Optics that operators can use to provide services. The first is an aggregation use case as shown in Figure 18, where the Coherent link is terminated at an aggregation point and other links are used to reach the end customer. The second is an Edge-to-Edge (E2E) use case as shown in Figure 19, where each P2P Coherent Optic link is terminated at the end customer location. The aggregation use case is the most likely first use of the P2P Coherent Optic link. The aggregation use case supports any Distributed Access Architecture, including Remote PHY, Remote MAC-PHY, and Remote OLT architectures.

6.1 Aggregation Use Case

In the aggregation use case, a host at device called the Optical Distribution Center (ODC) – which sits at the Virtual Hub or Original Fiber Node location – terminates the downstream P2P Coherent Optic link that originated at the HE/Hub, and outputs multiple optical or electrical Ethernet interfaces operating at lower data rates to connect devices that are either co-located with the ODC and/or exist deeper in the network. This could be done by an Ethernet switch or muxponder. The Ethernet switch (Figure 16) can support output to optical or electrical links using Ethernet at various data rates depending on the needs of the end device or user. The muxponder (Figure 17) outputs links at the same data rates that originated at the HE/Hub; therefore, the capacity out must equal the capacity in. The following diagrams are examples only, as a variety of data rates are possible both for the Coherent link and for the outputs from the Ethernet switch or the muxponder.

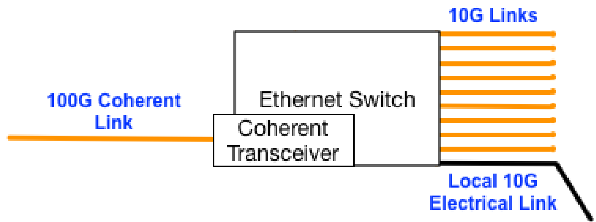


Figure 16 - Example P2P Coherent Optic Link to Ethernet Switch

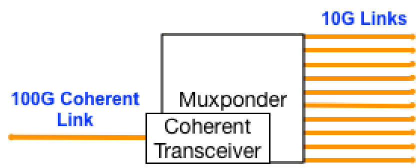


Figure 17 - Example P2P Coherent Optic Link to Muxponder

The following figure (Figure 18) shows the entire system, with a variety of possible different devices connected to the other side of the Ethernet switch or muxponder (such as remote OLTs or RPDs). The P2P Coherent Optic link will go from the HE/Hub device with a P2P Coherent Optic Transmitter to the Ethernet switch or muxponder with a P2P Coherent Optic Receiver. The Ethernet switch or muxponder will terminate the P2P Coherent Optic link and perform an optical/electrical/optical process to convert the P2P Coherent Optic link into several Ethernet links. The Ethernet link is usually (but not always) 10 Gbps.

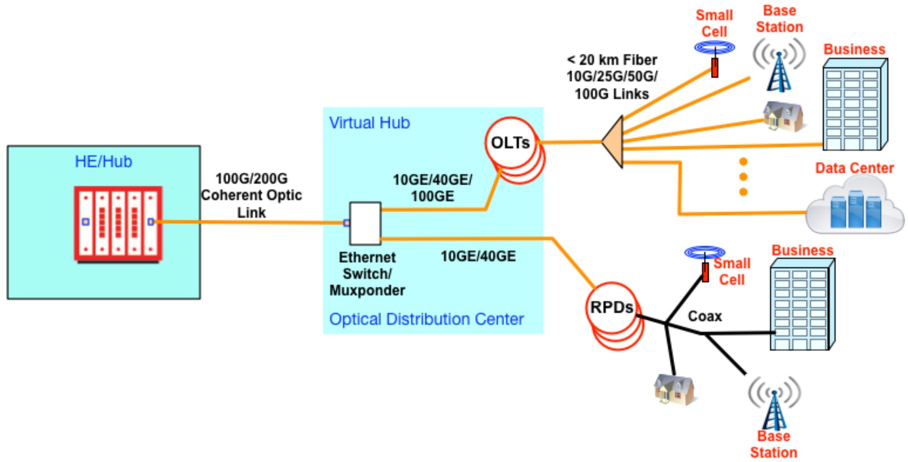


Figure 18 - Aggregation Use Case with P2P Coherent Link

6.2 Edge-to-Edge (E2E) Use Case

The second use case is for Edge-to-Edge (E2E) services. In this use case, the Coherent Optic links are terminated at the edge customer, whereas in the aggregation use case the Coherent Optic links were terminated at an ODC. In this use case, there is a WDM multiplexer/demultiplexer at the HE/Hub that combines multiple P2P Coherent Optic links onto a fiber. At the Optical Distribution Center, another WDM multiplexer/demultiplexer will split the wavelengths and put each on its own fiber strand. As shown in Figure 19, the demultiplexed P2P Coherent Optic links will connect directly to the endpoint. The P2P Coherent Optic links from the HE/Hub could be a mix of different link rates.

As shown in Figure 19, there could still be a mix of aggregation links with the edge-to-edge links.

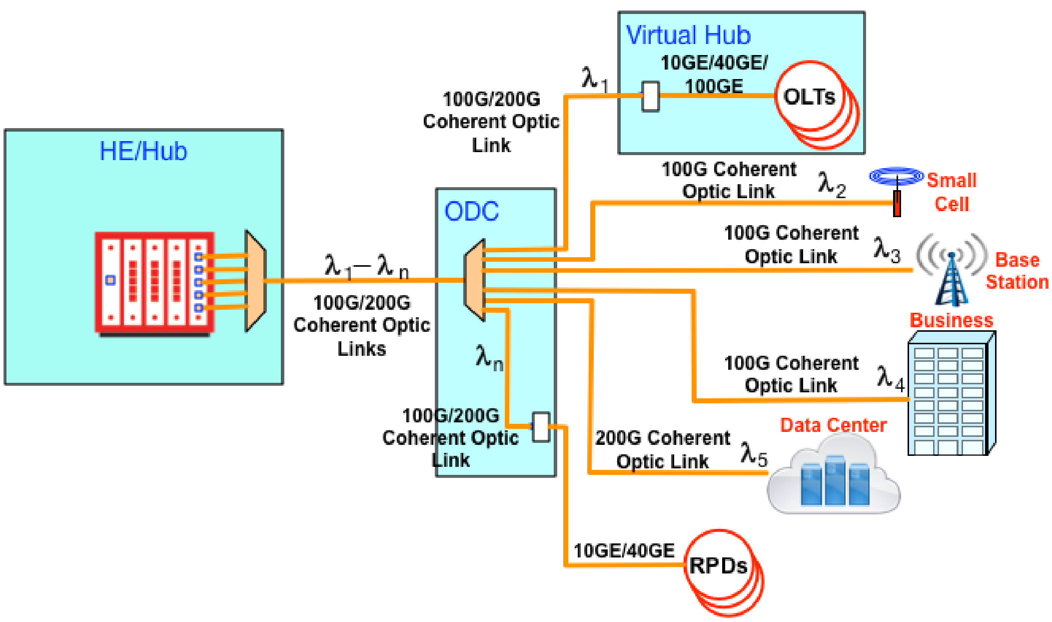


Figure 19 - Edge-to-Edge Use Case with P2P Coherent Optic Links

7 OPERATOR BUSINESS NEEDS

7.1 Targeted Link Rates for P2P Coherent Optics

A Coherent Optic Transceiver for the access network will support one or more of the following data rates on a single wavelength:

- 100 Gbps
- 200 Gbps
- 400 Gbps

While higher data rates provide more capacity per wavelength, they also generally need higher signal to noise; by defining multiple data rates, operators will have multiple solutions from which to choose to support different use cases and scenarios.

A Coherent Optic solution for the access network will also support the use of multiple wavelengths through WDM technology, which will allow cable operators to flexibly increase their capacity over time based on business needs.

7.2 Distance Considerations for P2P Coherent Optics

The fiber network over which a P2P Coherent Optics solution for the access network will need to operate will vary greatly in terms of optical attenuation. For example, distance, the use of a mux/demux, band splitters, and/or EDFAs can all impact the amount of optical attenuation a Coherent Optic signal will need to overcome.

For the purposes of simplification, the analysis provided in this specification examined three distance ranges:

- 0 km to 40 km
- 40 km to 80 km
- 80 km to 120 km

The first range (up to 40 km) covers approximately 90% of all operator use cases, and so is a primary target for this solution; it should be designed to support operation at this distance with most data rates and without optical amplification. The second range (from 40 km to 80 km) covers the majority of all remaining use cases, and so needs to be supported as well, although with tradeoffs (such as the need for greater power or optical amplification). Support for operation at the third range may be possible as well, depending on network design and other factors, but is not a primary design objective.

7.3 Environmental Conditions Considerations for P2P Coherent Optics

A P2P Coherent Optic Transceiver in the HE/Hub will be within an enclosure that is environmentally controlled, so it would be expected to operate within normal specifications for that type of environment.

The P2P Coherent Optic Transceiver in the field, however, may or may not be in a controlled environment. The remote P2P Coherent Optic Transceiver could exist on a pedestal, pole, or other enclosure that is exposed to adverse environmental conditions. Therefore, the environmental requirements will vary drastically depending on where a P2P Coherent Optic Transceiver is deployed.

These temperatures may range from as low as -40C to as high as +85C. However, it is not expected that a single device will need to operate over that entire range; rather, they will be expected to operate over a subset of that range, driven by operator needs.

7.4 Transceiver Power Consumption

P2P Coherent Optic Transceiver needs to work with the power available at the current fiber node location, sharing it with any other devices that may be present. Therefore, P2P Coherent Optics Transceiver implementations should target 10 to 20 Watts of power consumption for the P2P Coherent Optic Transceiver, including the power consumption for both optics and DSP components.

7.5 Migration Considerations for P2P Coherent Optics

During the transition from a current architecture to a P2P Coherent Optic architecture, there could be a time when P2P Coherent Optic links need to coexist with other analog or digital IM-DD links on the same fiber using WDM technology.

When operators are already using wavelength multiplexing for existing services, adding a P2P Coherent Optic link on a different wavelength could be relatively easy. However, the P2P Coherent Optic link would need to match the wavelength grid of the WDM multiplexer. Additionally, operators would need to do wavelength management to ensure there is no interference between the channels they assign (as with any other WDM wavelength). Another consideration is that the different power levels of analog and Coherent Optic links may pose difficulties for existing optical amplifiers, which operators would need to account for.

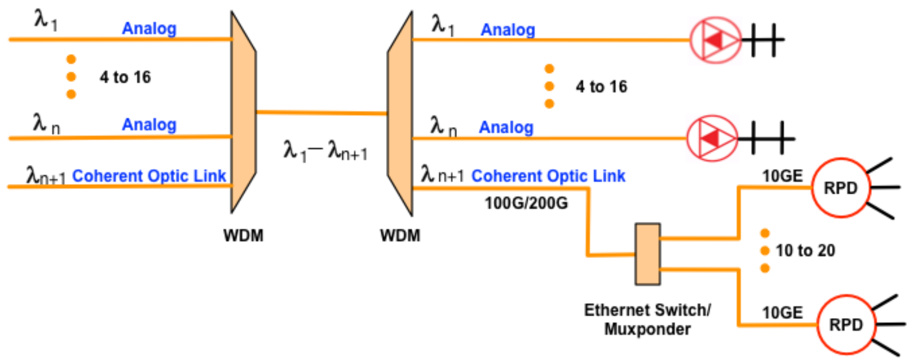


Figure 20 - Migration of Analog to P2P Coherent Optic Link

To support the longer distances, operators may apply more power at the P2P Coherent Optic Transmitter or add an optical amplifier to increase the power of the P2P Coherent Optic link. However, when applying more power on the P2P Coherent Optic link, the more likely it could interfere with neighboring channels. Since the output power of any analog links are higher than the P2P Coherent Optic link, it is more likely that the analog signal will interfere with the P2P Coherent Optic link than vice versa. Therefore, when mixing the P2P Coherent Optic link with analog signals, the operator must find a wavelength with which the analog signal will not cause interference. As the number of analog signals decreases, the chance for interference will decrease as well.

Each analog channel serves a different fiber node. However, a P2P Coherent Optic link will terminate at an Ethernet switch or muxponder to convert to Ethernet distribution. Since an existing fiber node works with analog signals, the conversion to Coherent Optics will be done in conjunction with a migration to some type of Distributed Access Architecture (which requires a conversion to digital optics).

Once everything converts to a single P2P Coherent Optic link between the HE/Hub and ODC/Virtual Hub, the WDM multiplexer/demultiplexer is no longer needed. However, if the operator plans to add more P2P Coherent Optic links in the future, it may make sense to leave the WDM multiplexer/demultiplexer in place. Additionally, the operator could remain in the hybrid mode indefinitely, if some of the existing analog channels are adequate for the traffic they are carrying.

The P2P Coherent Optic Transceiver could use tunable lasers or fixed lasers. To optimize the P2P Coherent Optic Transceiver for cost, a set of fixed lasers may be the most cost effective. There is an option to use tunable lasers that only support 4 to 8 wavelengths. Managing fixed lasers over the entire C-band could become cumbersome, and could make tunable lasers attractive. However, for initial implementations that use the defined P2P Coherent Optic link(s), a fixed laser seems reasonable.

7.6 Single Fiber Connection

According to a recent operators' survey, approximately 20 percent of existing cable access networks use a single-fiber topology, meaning that downstream and upstream transmission to and from fiber nodes takes place on a single strand of fiber. The same survey estimated that this number is likely to grow larger in the future, for example to provide for redundant optical links and new business opportunities. Therefore, a cost-effective mechanism to support bidirectional transmission over a single fiber is needed for coherent signals in access networks.

In a typical pluggable coherent transceiver, to minimize cost and power consumption, coherent optic transceivers have been built with just a single laser. That single laser performs two functions:

As the optical signal source in the transmitter; and

As the reference local oscillator signal in the receiver.

Because a single laser is used, the transceiver transmits and receives using the same wavelength. This has necessitated the use of two fibers: one fiber for downstream and a second fiber for upstream.

In order to operate on a single fiber, the typical approach has been to use two separate lasers in a single transceiver, allowing it to transmit and receive on different wavelengths. However, adding a second laser adds significant cost, as well as increasing power consumption, operational complexity, and transceiver footprint.

To achieve the objective of keeping cost down while using a single fiber, an alternative method is to employ full duplex coherent optics. In this approach, an optical circulator is added to each end of the coherent link in a special configuration. The circulator is a low-cost, passive, directional device: much like a traffic roundabout for cars, but for rerouting the optical path in different directions. This permits the coherent transceiver to transmit and receive using the same wavelength (and therefore using a single laser) over a single fiber in both directions simultaneously. Figure 21 shows one embodiment of this method with the circulator outside of the coherent transceiver for single wavelength connection in an unamplified single fiber system.

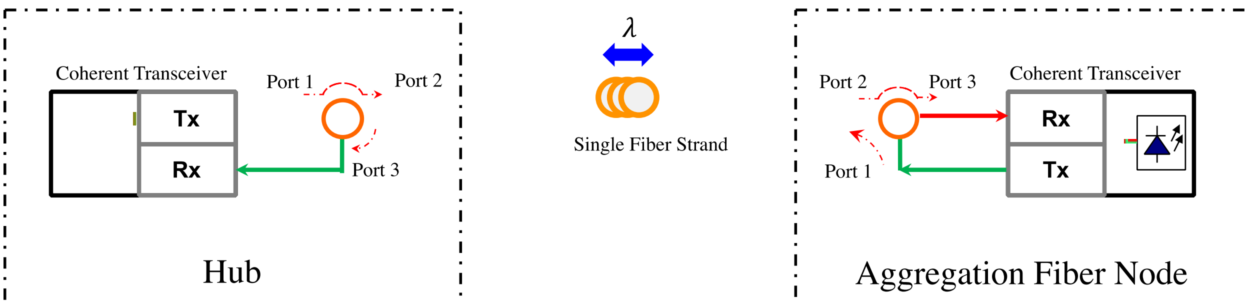


Figure 21 - Full-Duplex Single-Fiber Approach (single wavelength)

A more complex configuration example is shown in Figure 22, which includes the use of Wavelength Division Multiplexing (WDM) to support operation with other transceivers simultaneously. It also demonstrates where optical amplification could optionally be incorporated into this architecture (inside the dashed boxes). Another alternative would be to incorporate a bidirectional optical amplifier in the common part of the single fiber. It is noted that the circulator or other optical directional element could also be integrated with coherent transceiver, in which case each wavelength will need an independent directional element before optical mux or after optical demux.

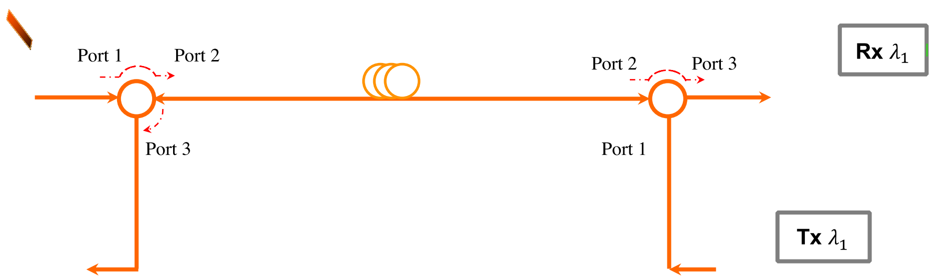


Figure 22 - Full-Duplex Single-Fiber Approach (WDM)

A variety of unique aspects of cable access networks, taken together, enable the use of this approach. Many scenarios in cable focus on the access environment with limited transmission distances. Unlike backbone and metropolitan coherent optical networks, access networks don't require multiple directional optical amplifiers in a cascade optical link. When dealing with coherent signals, we have a much higher Optical Signal to Noise Ratio (OSNR) sensitivity and higher tolerance to impairments from the spontaneous Rayleigh backscattering (continuous reflection) and Fresnel reflection (discrete reflections), than intensity-modulated systems. In addition, the majority of existing analog optics systems employ angle-polished connectors (APC), which provides excellent mitigation for return loss from Multiple-Path Interference (MPI), jumper cable/optical distribution panels/fusion, or mechanical splices. In addition, the threshold of the stimulated Brillouin scattering (SBS) nonlinear effect is much suppressed because of the nature of phase-modulated signals on the reduction of optical carrier power and the increase of effective linewidth.

With this new dimension of direction-division multiplexing (DDM) in the optical domain, any coherent wavelength can be used twice, once in each direction, thus doubling the whole fiber system capacity. This full-duplex implementation is not wavelength-selective. It works for both short and long wavelengths, and it can cover not only the entire C-Band, but with different optical sources, the entire fiber spectrum.

8 LINK BUDGET EXAMPLES

8.1 Link Budget Introduction

While some high-level goals were stated regarding the distances that a P2P Coherent Optics link will need to support, in the end what determines distance will be the link budget: how much loss the system can tolerate, vs. how much loss is actually present. This in turn results in a calculated reach: an estimate of how far apart two transceivers can be while still operating as expected.

While the amount of loss a minimally compliant device can tolerate is easy to determine from the specifications, due to the great variety of different network configurations that exist, the amount of loss in the network can vary widely. Further, compliant transceivers can exceed the minimum requirements in the specifications, which adds yet another layer of variability.

This section looks at some example scenarios in which a P2P Coherent Optics link could be used, and the anticipated reach of a minimally compliant device in each of those scenarios.

8.2 Sources of Loss

Loss can occur within the fiber as well as traversing each component in the path. There are a number of variables that affect the loss budget:

- Fiber Loss (including fiber attenuation, splices, etc.)
- WDM Loss (from multiplexers/demultiplexers)
- Insertion Loss (including connectors, splitters, failover switches, band splitters, etc.)
- Link impairments
- Safety Margin for other unaccounted for factors that could occur between the transmitter and receiver, including aging

Increasing the launch power from the transceiver into the fiber can overcome some loss, but at the expense of more consumed power and potentially increasing the cost of the transceiver. Inline optical amplifiers (such as EDFAs) can help to overcome loss by amplifying the power, but also generate and amplify noise. The ability of the receiver to successfully receive the signal will be determined by a combination of receiver sensitivity and the OSNR of the signal.

The following examples calculated the anticipated reach for a minimally compliant transceiver given several assumptions regarding link loss in the network. The examples are not exhaustive, but examine some variations that operators might deploy to determine their viability.

The numbers for the launch power and receiver sensitivity are taken directly from the specification, and as such are not based on one specific vendor. The following modulation formats were used to calculate the link loss:

- 100G: DP-QPSK at 28 GBaud with Staircase HD FEC (as defined in [P2PCO-PHYv1.0])
- 200G: DP-QPSK at 64 GBaud with oFEC (as defined in [P2PCO-PHYv2.0])

The example link budget calculation tables in the following sections use two different transceiver design options: a dual optical interface design, and a single optical interface design. The single optical interface design is for transceivers designed to operate on a single bi-directional fiber, the architecture of which results in some differences in mandatory transmit and receive power levels (and therefore impacts reach and link budget), but enables the use of a single laser in the transceiver, which in turn reduces cost and power requirements as compared to a dual laser solution. To calculate a reasonable level of impairments, a squared-sum of the maximum impairment levels that a compliant device is required to support was used. In addition, to account for aging, some additional margin was added.

8.3 Calculated Reach Examples

8.3.1 Single Channel Power Limited Case (no amplifier)

This example is the simplest architecture for P2P Coherent Optic link. In this example, there is only a single channel, so a WDM mux/demux is not used. For a dual optical interface transceiver, the P2P Coherent Optic link uses two fibers between the HE/Hub and the ODC as shown in Figure 23. The two fibers require a pair of P2P Coherent Optic Transceivers to support the bi-directional traffic. For the single optical interface example, the basic example is the same, although there is only a single fiber connecting two single interface transceivers.

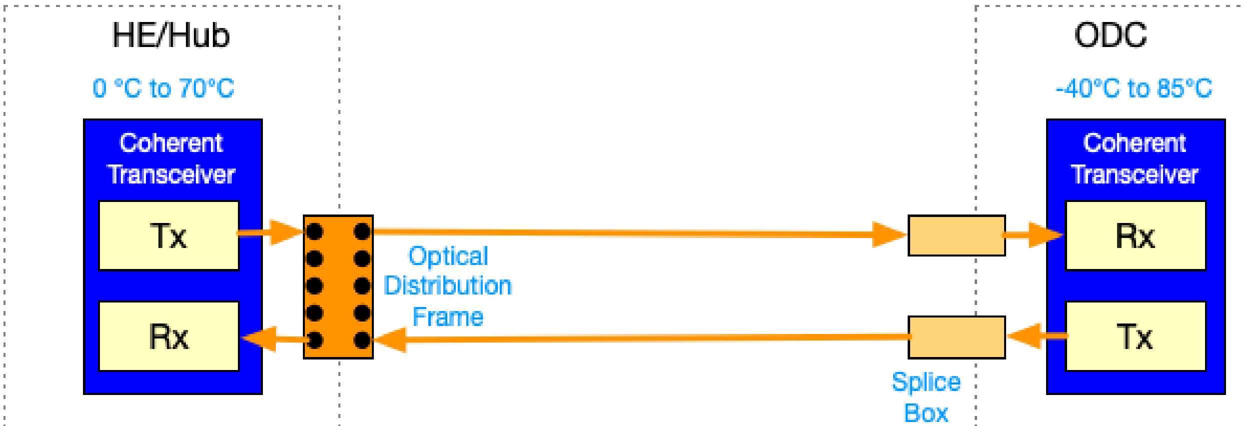


Figure 23 - Example Dual-Fiber Single-Channel Architecture

In Table 6 we show the calculated reach for each option in a single channel scenario (in other words, without a WDM mux and de-mux), and without amplification. The optical equipment loss (1 dB) is introduced by the optical distribution frame.

Table 6 - Calculated Reach in Single Channel Power Limited Case (no amplifier)

	Dual Optical Interface		Single Optical Interface	
	100G DP-QPSK28	200G DP-QPSK64	100G DP-QPSK28	200G DP-QPSK64
Tx Output Power (dBm)	-6	-7.5	-6.75	-8.25
Tx OSNR (dB)	35	35	35	35
Rx power baseline (dBm)	-31	-31	-30.25	-30.25
Link Impairment (squared sum) (dB)	+1.7	+1.7	+1.7	+1.7
Rx Power w/ impairment (dBm)	-29.3	-29.3	-28.55	-28.55
Optical Equipment Loss (dB)	1	1	1	1
Margin (aging) (dB)	1.5	1.5	1.5	1.5
Link Budget (dB)	20.8	19.3	19.3	17.8
Fiber Loss (dB/km)	0.25	0.25	0.25	0.25
Reach (km)	83.2	77.2	77.2	71.2

As can be seen from these calculations, in this simplest case a reach of around 80 km is feasible.

8.3.2 Multi-Channel (WDM) Power Limited Case (no amplifier)

Although the example architecture shown in Figure 24 is possible, based on operator survey feedback ~70% of the time operators will add a P2P Coherent Optic link to an existing HE/Hub that uses analog channels to the ODC. In this case, the P2P Coherent Optic link will go through a WDM multiplexer/demultiplexer (denoted WDM in the figure) and co-exist with the analog channels as is shown in Figure 24.

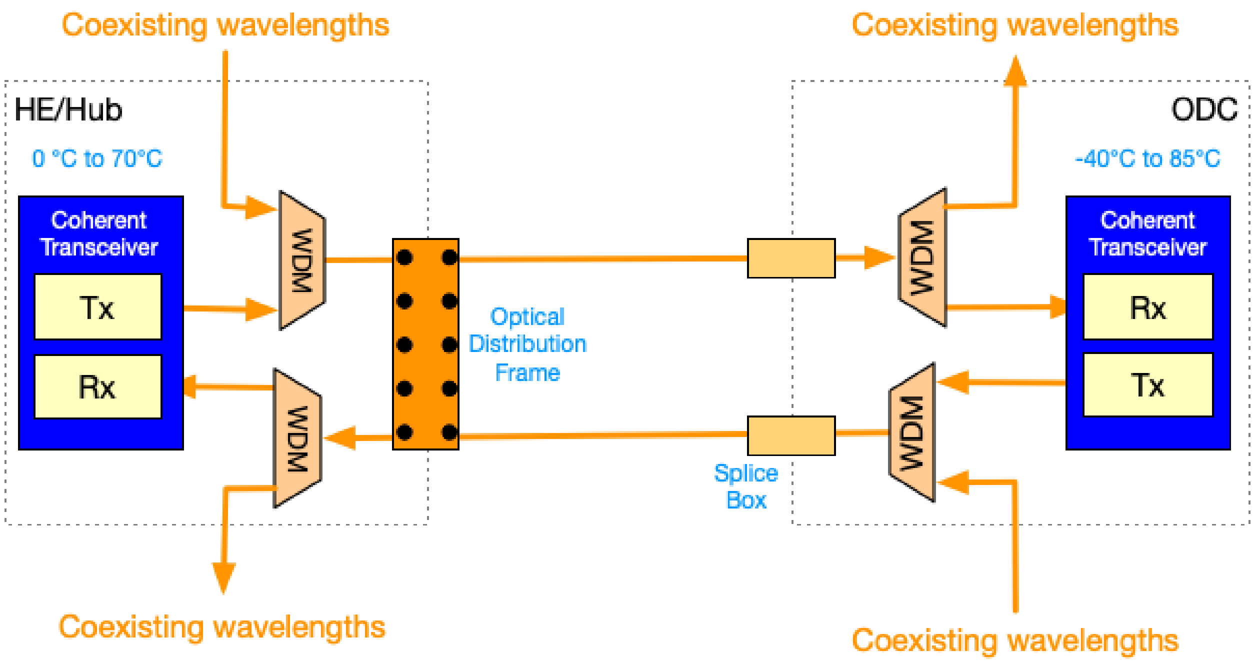


Figure 24 - Example Dual-Fiber Multi-Channel Architecture

In Table 7 we show the calculated reach for each option with the WDM multiplexer/demultiplexers, but without the presence of an optical amplifier. For the purposes of these calculations, we are assuming a 40 channel mux, each of which adds 5 dB of attenuation to the system (for a total of 10 dB of attenuation in addition to the loss of the optical distribution frame).

Table 7 - Calculated Reach in WDM Power Limited Case (no amplifier)

	Dual Optical Interface		**Single Optical Interface**	
	100G DP-QPSK28	**200G DP-QPSK64**	**100G DP-QPSK28**	**200G DP-QPSK64**
Tx Output Power (dBm)	-6	-7.5	-6.75	-8.25
Tx OSNR (dB)	35	35	35	35
Rx power baseline (dBm)	-31	-31	-30.25	-30.25
Link Impairment (squared sum) (dB)	+1.7	+1.7	+1.7	+1.7
Rx Power w/ impairment (dBm)	-29.3	-29.3	-28.55	-28.55
Optical Equipment Loss (including WDM) (dB)	11	11	11	11
Margin (aging) (dB)	1.5	1.5	1.5	1.5
Link Budget (dB)	10.8	9.3	9.3	7.8
Fiber Loss (dB/km)	0.25	0.25	0.25	0.25
Reach (km)	43.2	37.2	37.2	31.2

As can be seen, the additional 10 dB of attenuation reduces the reach by 40 km, resulting in a reach of around 40 km in most cases. This is sufficient for the vast majority of cable operator applications. If additional reach is needed, operators could deploy higher power transceivers, reduce attenuation in their plant (such as by using a mux with fewer channels and lower attenuation), or by employing optical amplifiers to extend the reach of the system.

8.3.3 Multi-Channel (WDM) OSNR Limited Case (with amplifier)

As noted in the previous section, for longer distances operators will often employ optical amplifiers as shown in Figure 25 (note that a network design with a single optical interface device would be somewhat different from the one depicted below). Operators generally prefer to only deploy the optical amplifiers in the HE/Hub, so for the downstream direction the optical amplifier will boost the signal before it leaves the HE/Hub. For the upstream direction, the optical amplifier will act as a pre-amplifier to amplify the signal as it enters the HE/Hub. In the upstream case, the optical amplifier may be receiving a relatively weak signal. When it amplifies the signal, it adds noise and lowers OSNR.

Depending on the type of optical amplifier, the amount of gain can vary; some optical amplifiers allow the operator to adjust the amount of gain. This allows the operator to optimize the OSNR at the receiver. Based on a survey of operations in 2017, approximately 20% of current optical links use amplification to overcome transmission loss between the transmitter and the receiver.

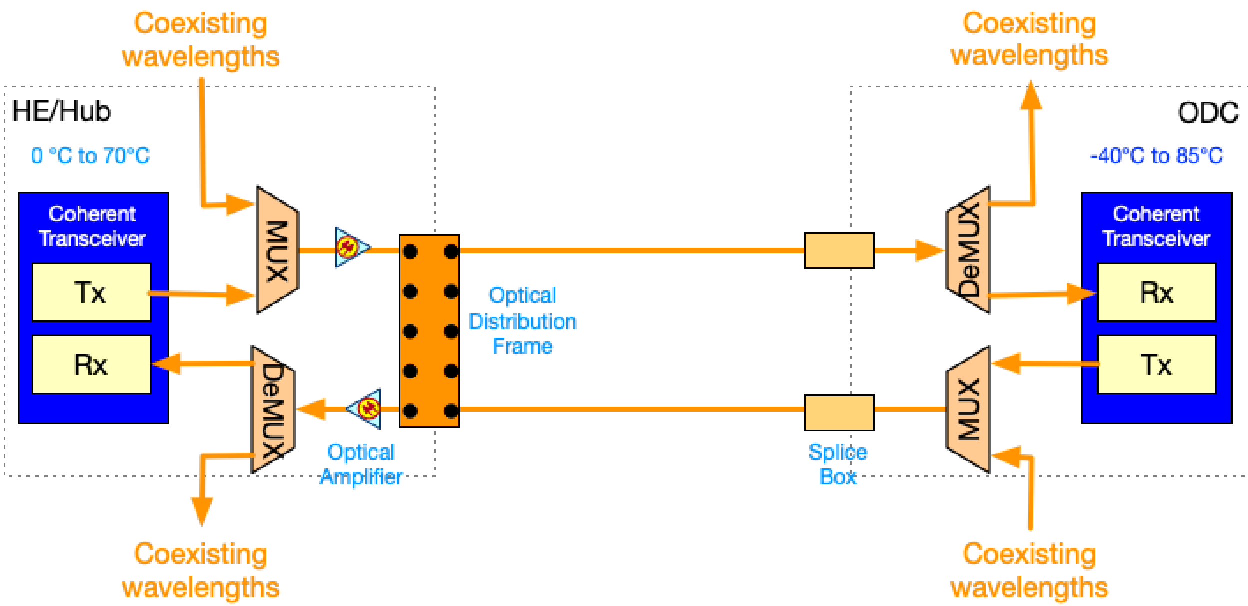


Figure 25 - Example Dual-Fiber Multi-Channel with Optical Amplifier Architecture

In this scenario, due to the fact that in the upstream direction power may be high but OSNR may be low, the OSNR in the upstream now becomes the limiting factor in determining the reach for the link. In Table 8, we show the estimated reach when the optical amplifier acts as a pre-amplifier, which is the upstream case.

Table 8 - Calculated Reach in WDM OSNR Limited Case (w/pre-amplifier)

	Dual Optical Interface		Single Optical Interface	
	100G DP-QPSK28	**200G DP-QPSK64**	**100G DP-QPSK28**	**200G DP-QPSK64**
Tx Output Power (dBm)	-6	-7.5	-6.75	-8.25
Tx OSNR (dB)	35	35	35	35
Rx OSNR baseline (dB)	14.5	14.5	14.5	14.5
Post-amplifier Rx Power (dBm)	-10	-10	-9.25	-9.25
Link Impairment (squared sum) (dB)	+1.7	+1.7	+1.7	+1.7
Rx OSNR w/ impairment (dB)	16.2	16.2	16.2	16.2
Reach (km)	80+	80+	80+	80+
Rx OSNR @ 80km (dB)	19.3	17.9	18.6	17.1

	Dual Optical Interface		Single Optical Interface	
	100G DP-QPSK28	**200G DP-QPSK64**	**100G DP-QPSK28**	**200G DP-QPSK64**
Available Aging Margin @ 80km (dB)	3.1	1.7	2.4	0.9

As can be seen, the system can reach to at least 80km in all cases (with varying degrees of margin), satisfying operator requirements. If additional reach is needed, an operator would need to either use higher power transceivers, reduce attenuation in the system, or employ amplifiers at both ends of the link.

Appendix I Acknowledgements

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Appendix II Revision History

Engineering Changes incorporated into P2PCO-SP-ARCH-I02-190311:

ECN Identifier	Accepted Date	Title of EC	Author
ARCH-N-18.0001-1	12/12/18	Full Duplex Coherent Optics (ARCH)	Jia
ARCH-N-19.0004-3	3/7/19	Link Budget Updates	Schmitt

* * *