Impact of Access Environment in Cable's Digital Coherent System – Coexistence and Full Duplex Coherent Optics

A Technical Paper prepared for SCTE•ISBE by

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Introduction

Cable access networks have been undergoing significant technology and architecture changes driven by the ever-increasing residential data service growth rate and an increasing number of services types being supported, such as business services and cellular connectivity. Digital fiber technologies and distributed access architecture for fiber deep strategies offer an infrastructure foundation for cable operators to deliver the best service quality to the end users in the years ahead. The combination of the natural evolution of coherent optics technology, along with this increasing demand for capacity and the unique features of a cable-specific fiber access environment with only a few fibers available for a 500-household passed serving area, prompted the evaluation of coherent optics as an alternative for a long-term fiber access connectivity solution in next-generation cable access networks.

During its 2017 Winter Conference, CableLabs® announced the launch of the point-to-point (P2P) Coherent Optics specification project. The project looks into the evolution of cable’s optical access network, addresses its fiber shortage challenge, and re-designs digital coherent system from long-haul and metro solutions to the access network applications. This specification allows operators to best leverage the existing fiber infrastructure to withstand the exponential growth in capacity and services for residential and business subscribers while keeping cost down as much as possible.

When cable operators look to deploy coherent optics into their access networks, they are typically faced with two options: deploy coherent optics on the existing 10G system or build a new coherent-only connection. The ideal network for deploying such coherent systems would be a green field deployment on fibers without any compensation devices such as dispersion compensation modules (DCM) and other wavelength channels. However, in practice, to make the upgrade cost-effective, only one or a few channels may be upgraded in many brown field installations, depending on capacity demand. That means many of these networks that are deployed already with WDM analog DOCSIS technology and/or 10G on-off keying (OOK) services will coexist with a coherent system to support a hybrid scenario over the same fiber transmission. Such a hybrid configuration needs to be studied, especially the cross-phase modulation (XPM) impairment in the fiber nonlinear regime, to provide this option for operators to effectively support 100G on their existing networks. In this work, we fill the gap by presenting extensive experimental verifications under various coexistence scenarios and provide operational and deployment guidance for such use cases.

Additionally, according to a recent operators’ survey, 20 percent of existing cable access networks use a single-fiber topology. This means that downstream and upstream transmission to nodes takes place on a single strand of fiber. This number is expected to grow further in the near future. Therefore, bidirectional transmission is needed for coherent signals to support single-fiber topologies and to facilitate the business use and redundancy of optical links. CableLabs’ Full Duplex Coherent Optics (FDCO) proposal and the experiments that demonstrate simultaneous bi-directional transmission over single fiber and single wavelength are described. This paper shows how FDCO effectively doubles fiber capacity in a coherent optics-based fiber distribution network. The major impairment in the FDCO system is optical return loss (ORL) or optical reflections including all discrete reflections (Fresnel) and continuous reflections (backscatter). In this paper, the impact of ORL for FDCO is also analyzed and quantified for various configurations.

Content

1. Coherent Optics for Access Applications

Coherent optics initially received significant research interest in the 1980s because of high receiver sensitivity through coherent amplification by a local oscillator, but its use in commercial systems has been hindered by the additional complexity of active phase and polarization tracking. In the meantime, the emergence of a cost-effective erbium-doped fiber amplifier (EDFA) as an optical pre-amplifier reduced the urgency to commercialize coherent detection, because EDFAs and wavelength-division multiplexing (WDM) extended the reach and capacity as shown in Figure 1. Traffic demand, combined with the requirement to reduce cost per bit per Hz, or spectral efficiency increases, as well as advancements in CMOS processing nodes and powerful digital signal processing (DSP), led to the renaissance of coherent optics technology. 2018 is the 10th anniversary that digital coherent optical technology was officially reintroduced to the world.

Commercial coherent optical technology was first introduced in long haul applications to overcome fiber impairments that required complex compensation techniques when using direct detection receivers. The first-generation coherent optical systems are based on single-carrier polarization division multiplexed quadrature phase shift keying (PDM-QPSK) modulation format and the achieved spectral efficiency (SE) is 2 bit/s/Hz over conventional 50-GHz optical grid, thus the system capacity has been increased to around 10 Tb/s in the fiber C-band transmission window. Leveraging further development of CMOS processing, reduction in design complexity, and price decreases on opto-electro components, coherent solutions have moved from long haul to metro and access networks. This migration model has been demonstrated in the optical industry before: the DWDM system technology started in the long haul and then migrated to metro and edge access; forward error correction (FEC) encoding and decoding follows the same pattern. Benefiting from initial long-haul technology development, coherent optics for access networks will be the next natural progression. Current development of application-specific integrated circuits (ASICs) for DSP chips, and corresponding optical modules head in the two directions shown in Figure 1. One path is to have a programmable and comprehensive coherent DSP which is capable of processing data rates from 100G to 600G per single wavelength, with the support of higher modulation formats like 32/64-QAM and high net coding gain (NCE) FEC. The second path is the development of reducing the power consumption and thereby meeting the size and cost requirements for access applications, which is the focus of this work.

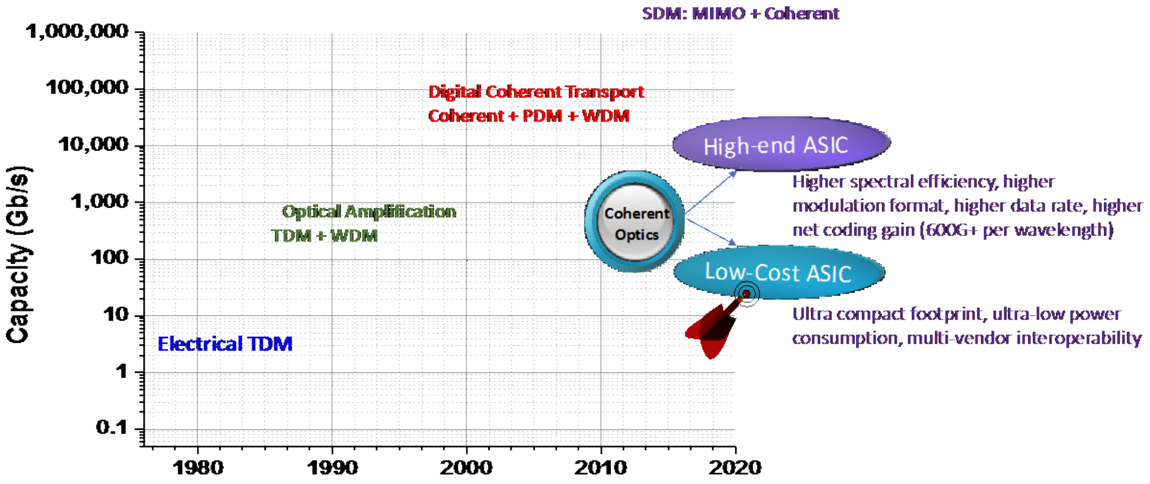

Figure 1 – Optical Technology Evolution

Coherent detection for access networks enables the superior receiver sensitivity that allows for extended power budget, and the high spectral efficiency enables dense WDM (DWDM). Moreover, the use of high-order modulation formats enables efficiently utilizing the spectral resource and benefiting future-proof network upgrades. In the cable access environment, coherent optics allows operators to best leverage the existing fiber infrastructure to deliver vastly increased capacity with even longer distances. However, the coherent technology in a long-haul optical system utilizes best-in-class discrete photonic and electronic components, the latest DAC/ADC and DSP ASIC based on the most recent CMOS processing node. The coherent pluggable modules for metro solution have evolved from CFP to CFP2 form factor for smaller footprint, lower cost, and lower power dissipation. However, it is still over-engineered, too expensive, too power hungry, and not interoperable. The access network is a totally different environment as compared to long haul and metro. It may need hardened solution for remote site locations, where temperature is not controlled. Another important factor to consider is standardization and interoperability. Standardization in the optical community is driven mainly by short-reach metro/aggregation applications, where optical performance is not a differentiator. Interoperability and a robust vendor ecosystem are therefore keys to providing a low-cost solution using coherent optics.

In 2017, CableLabs recognized the benefit of coherent optics and announced the launch of the point-to-point (P2P) Coherent Optics that allows the cable industry to support the growing requirements of broadband access as the industry evolves toward Node+0 architectures, and the volume of optical connections to intelligent nodes increases substantially. On June 29th, 2018, CableLabs publicly unveiled for the first time two new specifications: P2P Coherent Optics Architecture Specification and P2P Coherent Optics Physical Layer v1.0 Specification. These two new specifications are the result of a focused effort by CableLabs, its members, and the manufacturer partners to develop Coherent Optics technology for the access network and bring it to market quickly [3] [4].

Industry organization bodies such as the Optical Internetworking Forum (OIF) and IEEE are working on short-reach coherent optical standardizations. The OIF is defining a coherent standard for DWDM interfaces in DCI applications with reaches up to 120 km with multi-vendor interoperability, and IEEE is considering coherent optics for unamplified applications beyond 10 km distances. All of this standardization activity reinforces the view of coherent optics moving to shorter reach and high-volume applications.

2. Deployment Scenarios of Coherent Optics in Cable

Coherent optics technology can be leveraged in cable following two general approaches. First is when used as a means of multi-link aggregation, and the second is through direct edge-to-edge connectivity to the desired end-point as shown in Figure 2. Following capacity growth trends, it is obvious that initially the aggregation use cases are going to outnumber the direct edge-to-edge connectivity use cases. The aggregation use case supports any Distributed Access Architecture (DAA), including Remote PHY, Remote MAC-PHY, and Remote optical line terminal (OLT) architectures.

In the aggregation use case, a device host called the Optical Distribution Center (ODC) or Aggregation Node terminates the downstream P2P coherent optic link that originated at the Headend or Hub, and outputs multiple optical or electrical Ethernet interfaces operating at lower data rates to connect devices that are either colocated with the ODC and/or exist deeper in a secondary Hub in the network. This aggregation or disaggregation function can be done by a router, an Ethernet switch, or a Muxponder, depending on the DOCSIS/PON/business traffic demand, cost, scalability/flexibility/reliability, and other operational considerations. The distance between the Hub and Aggregation Node ranges from 20 to 80 km, and the distance from the Aggregation Node to each end point is less than 3 km. Each primary Hub can support multiple (~60) Aggregation Nodes for different services.

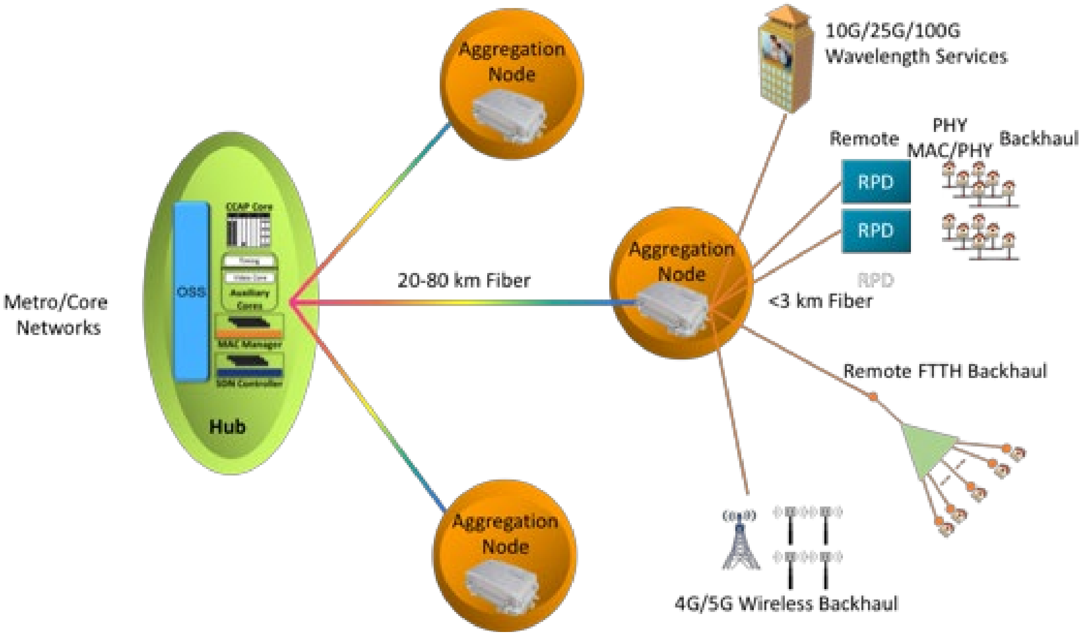

Figure 2 – Coherent Optics for Cable Access Applications

Commercial services have been a rapidly growing and high revenue segment in cable. Business connectivity, cellular backhaul and wireless access point connectivity, including 5G connectivity, are expected to play a bigger role in cable's future service portfolio [1]. These services demand very high bandwidth as well as robustness and flexibility for supporting a diversity of service levels. Coherent optics is a technology that can easily address the service requirements of this market segment, which is also shown in Figure 2. Direct wavelength services can overlay aggregation connections with 10G/25G intensity modulated signals or 100G coherent signals. This is lambda/wavelength deep for edge to edge services. In this use case, the coherent optic links are terminated at the edge customer and WDM multiplexer/demultiplexer at the HE/Hub is used for aggregating multiple P2P optical links onto a fiber. The WDM systems can be a hybrid system with a mix of data rate and modulation formats [2].

3. Coexistence Testing with Legacy Optical Channels

The commercial coherent 100G transmission systems are showing excellent receiver sensitivity, robustness, and tolerance for channel impairments such as CD and PMD. Therefore, the ideal network for deploying such coherent systems would be a green field deployment on fibers without any compensation devices such as dispersion compensation modules (DCM) and other wavelength channels, which is called a coherent-only implementation. However, in practice there are many brown field installations, meaning many of these networks are deployed and have several WDM analog DOCSIS and/or 10G OOK (Ethernet over fiber or PON) services running over the existing fiber already. The expectation from cable operators has been that adding additional 100G coherent services by using free channels in the WDM grid is preferred without impacting the existing services. This will essentially create a hybrid 10G/100G network with multiple services coexistence. But the fact is that 10G signals based on analog amplitude modulation (AM) or OOK have a much higher power density than coherent 100G, causing them to have a much greater impact on the refractive index for nonlinear effects such as cross phase modulation (XPM) and four-wave mixing (FWM). Additionally, crosstalk penalties in ITU-T grid networks with mixed rates lead to system degradation due to optical Mux/DeMux in-band residual power or non-uniform channel grid allocation in DWDM systems.

To provide an option that enables network operators to effectively support 100G on their existing networks infrastructure, such as optical amplifier and Mux/DeMux, CableLabs took the initiative and has done experimental verification to quantitatively explore the performance challenges in such coexistence applications. In the previous effort [5], because of the limited availability of analog optical channels, three copropagating analog DOCSIS channels were tested along with single coherent channels. The experimental results show that coherent optics transmissions are robust, even in close proximity to much stronger analog optical carriers, and coherent optical carriers impose negligible impact on analog optical carriers. To further test the transmission performance of full-loading coexisting systems, the following experiments have been conducted with longer transmission distances.

3.1. DWDM Components

Three different kinds of optical multiplexors/demultiplexors have been evaluated in the testing. Figure 3 shows their optical spectra for two wavelength channels; they are 8-port thin-film filters (TFFs), and 40-48-port array waveguide grating (AWG) based optical multiplexors/de-multiplexors. TFFs use concatenated interference filters, each of which is fabricated with a different set of dielectric coatings designed to pass a single wavelength. As shown in Figure 3, TFFs have a better optical performance in terms of flatter passband ripple and higher isolation in neighboring channels. They work well for low channel counts, especially for analog WDM systems, but have challenges at higher channel counts and narrower spacing because they need several hundred layers of coating, which requires stricter error control. In contrast to TFFs, AWG devices use a parallel multiplexing approach that is based on planar waveguide technology. The key advantage of AWGs over TFFs is that their cost is not dependent on wavelength count making them extremely cost-effective for high channel count applications. The existing long-haul coherent DWDM systems are typically using AWG for Mux and Demux. In our experimental setup, the insertion loss is ~1.5 dB for TFFs and ~3.5 dB for 40-port AWG.

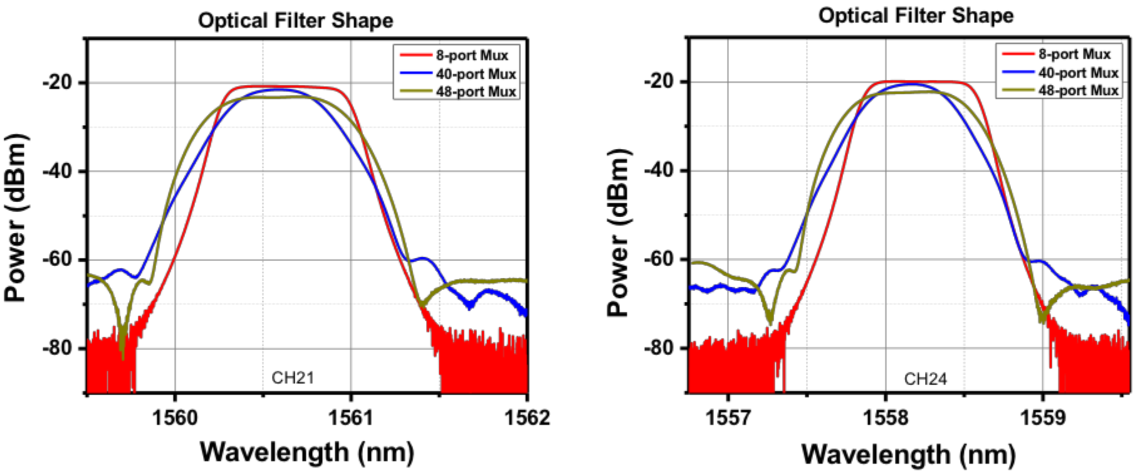

Figure 3 – Optical Spectra of Mux and Demux

3.2. Coexistence Using 8-port Mux (Analog + Coherent)

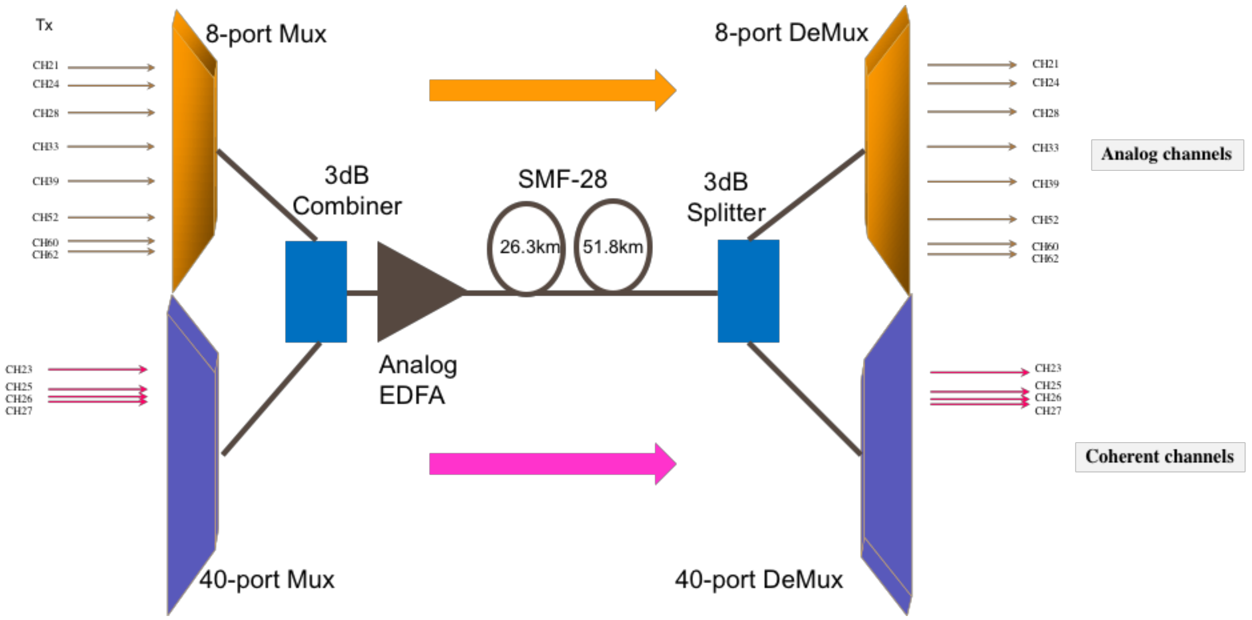

Figure 4 - Experimental Setup for Coexistence Evaluation Using 8-port Mux/DeMux

Figure 4 shows the experimental setup of the first case. All eight analog DOCSIS channels (up to 1.2 GHz) are multiplexed through a TFF based 8-port Mux, while four coherent channels are multiplexed via the 40-port AWG based Mux with 100-GHz optical grid spacing. The analog channels are selected in order to minimize nonlinear interference with each other, and the selection of coherent signals is expected to exhibit the worst coexistence condition. These two kinds of signals are combined via an optical combiner. The channel labels in the diagram correspond to the standard ITU-T wavelength grid. The purpose of selecting a nonuniform analog wavelength plan is to mitigate fiber nonlinear impairments, especially four-wave mixing (FWM). In the meantime, creating the worst nonlinear crosstalk impairments is the criteria for selecting coherent wavelength plans. The combined signals are then amplified by an EDFA that is designed for long-distance analog signal amplification. The maximum output power is about 18 dBm. These amplified signals then transmitted over 80 km single mode fiber (SMF) and are split to reach the corresponding optical DeMux for analog and coherent channels respectively. The launched power of two kinds of channels and the gain/attenuation of optical devices along the optical links are shown in Table 1. Around 10 dB power difference is set between coherent and analog channels.

Table 1 – Launched & Received Power, and Gain/Attenuation of Optical Devices

Signal Type	Tx Output Power (dBm)	Mux Loss (dB)	Coupler Loss (dB)	EDFA Gain (dB)	Fiber Attenuation (dB)	Splitter Loss (dB)	DeMux Loss (dB)	Received Power (dBm)
Analog	9.5	-1.5	-3	+2.5	-5.5 for 26.1 km; -9.5 for 51.8 km	-3	-1.5	-2.5 for 26.1 km; -6.5 for 51.8 km
Coherent	-1	-3.5	-3	+5		-3	-3.5	-14.4 for 26.1 km; -18.4 for 51.8 km

Figure 5 shows the optical spectra of all signals before and after optical amplification (a) and before and after optical fiber transmission (b). CH 23, 25, 26, and 27 are coherent channels with wider spectra and much lower power compared to eight analog channels.

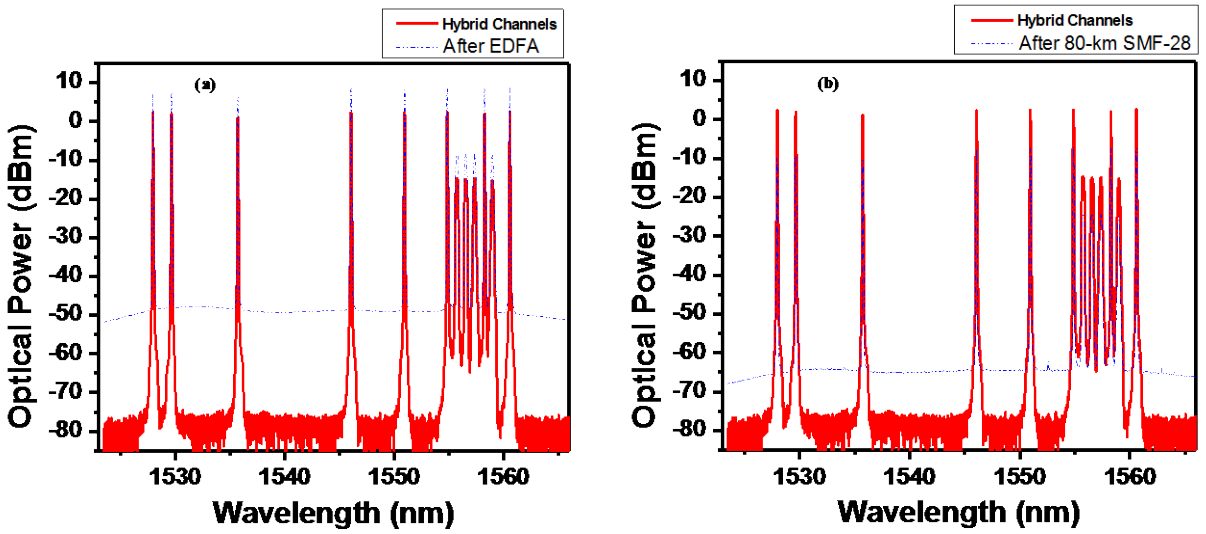

Figure 5 – Optical Spectra for both Analog and Coherent Signals

In this system setup, the transmission performance of both analog and coherent channels is shown in Figure 6. Negligible penalty is observed after 26.3 km or 51.8 km fiber transmission with the impact of coherent signals on analog channel CH 52 as shown in Figure 6 (a) with 26.3 km transmission. Other analog channels show similar performance when we compare the transmission condition (with or without a coherent channel over the same fiber). In the case of the impact of analog channels on coherent channels, minor BER difference is observed for 8-QAM and 16-QAM based 200 Gbps channels with 0 dBm transmitter output power. When compared with back to back coherent signal sensitivity, less than 0.5dB power penalty is found for the transmission and analog overlay using analog EDFA amplification and the same fiber.

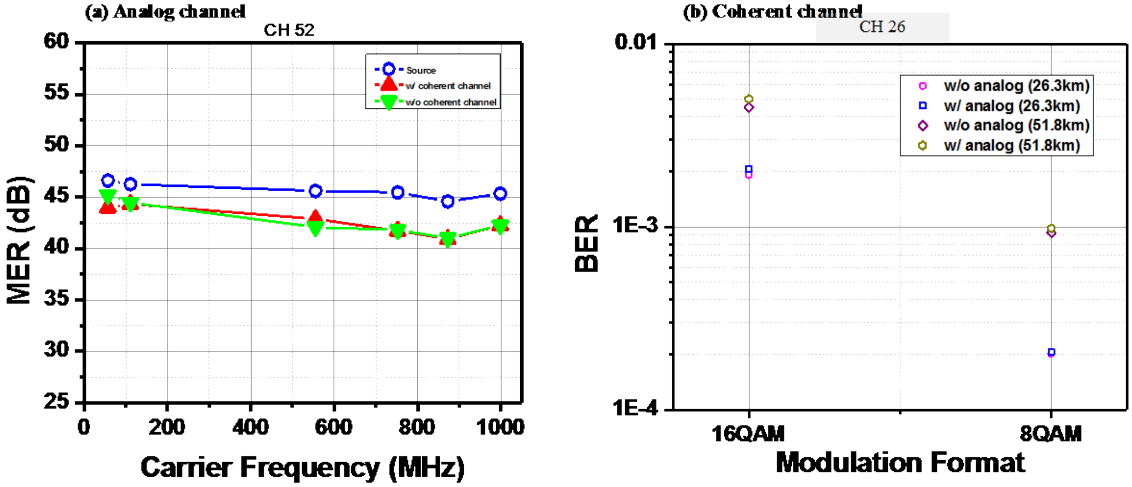

Figure 6 – Experimental Results of Coexistence with 8-port Mux/DeMux

3.3. Coexistence Using 16-port Mux (Analog + OOK + Coherent)

Next, the more complex coexisting setup was established with eight analog channels, two coherent 100G PM-QPSK channels (CFP2-DCO form factor), two coherent 400G channels, and two 10G NRZ channels. This coexistence hybrid scheme includes all the major modulation formats, and services under different data rates/baud rates. A pair of 16-channel TFT based wavelength division multiplexers are used for channel multiplexing and demultiplexing. The optical spectra of these multi-channel coexistences are shown in Figure 7, with analog, coherent 100G, coherent 400G, and 10G NRZ marked with red, blue, green, and purple respectively.

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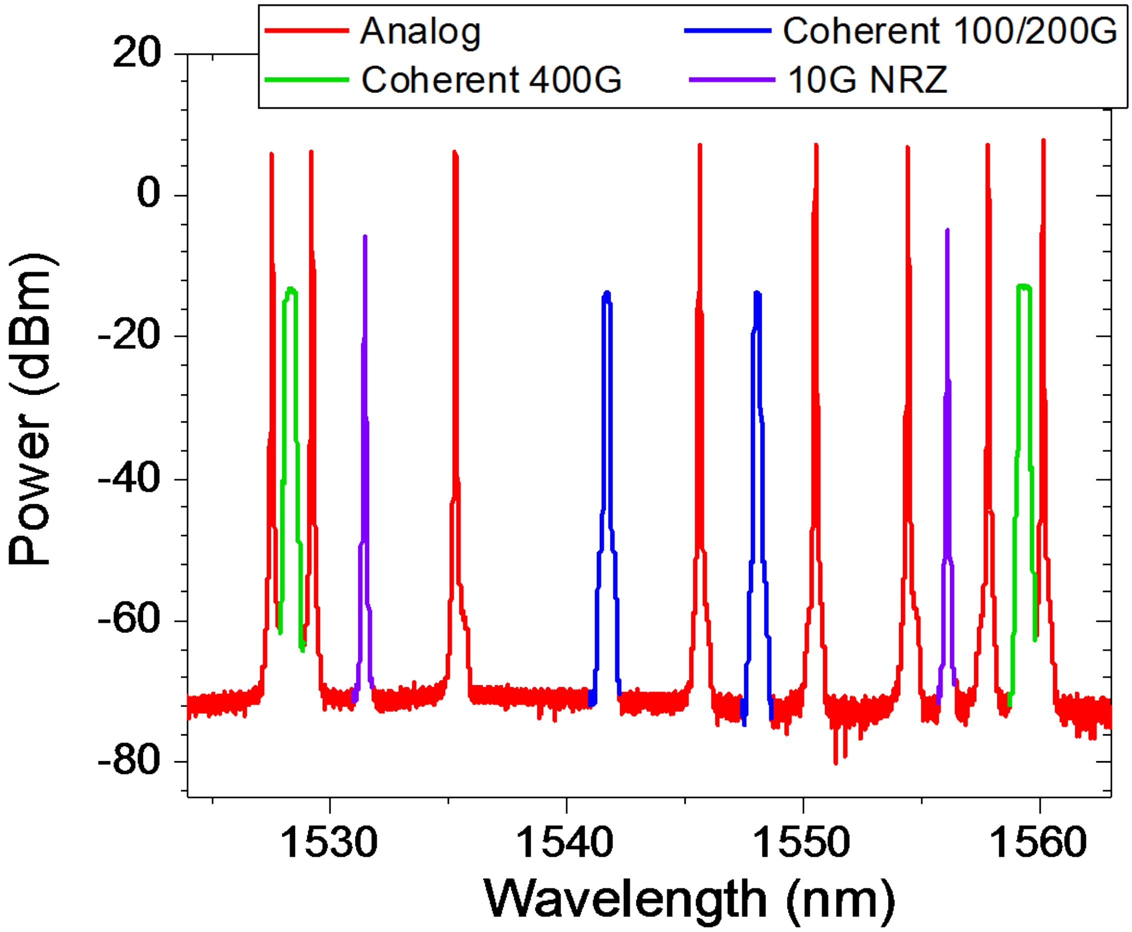

Figure 7 – Optical Spectra for Analog, NRZ, and Coherent Signals

The corresponding input power level (right after the transmitter) is shown in Table 2, based on typical operational conditions for different detection schemes. The power levels are measured at the output port of each transmitter before entering the WDM Mux. Among them, the powers of the analog channels are set to around 9.5 dBm while 56GBaud 400G coherent channels have the power set to ~3 dBm. To improve the spectral efficiency and confine the optical power within each WDM channel, the coherent signals are shaped by square root raised cosine filters.

Table 2 – Optical Transmitted Power for Analog, OOK, and Coherent Signals

Application Scenarios	Channel Index	Input Power (dBm)
DOCSIS Analog	21	9.64
	24	9.48
	28	9.43
	33	9.64
	39	9.48
	52	9.11
	60	9.01
	62	8.92
400G Coherent	22	2.68
	61	3.15
CFP2 Coherent	36	0.08
	44	-0.14
10G NRZ	26	-0.89
	57	-0.75

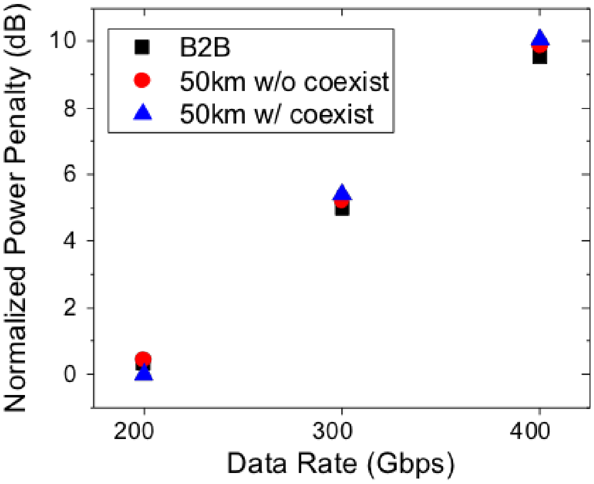

Figure 8 – Experimental Results

The performance difference is insignificant for analog channels compared to coexistence using the 8-port Mux. In the case of the coherent channels, Figure 8 shows the normalized power requirements for 200G, 300G, and 400G data rates, at back-to-back and 50 km transmission, with and without analog plus NRZ channels. Less than 0.6 dB power penalty is observed in the coexistence scenarios compared to the non-coexistence case.

In summary, three main observations were found in the coexistence measurement experiments:

- Both coherent and analog/NRZ signals work well in the coexistence application with ~0.6 dB maximum power penalty in the case of 100 GHz channel spacing and 50/80 km fiber transmission distances for different nonlinearity tolerance scenarios.

- The legacy components/devices for analog systems are working well for coherent signals multiplexing and amplification, including analog EDFA, optical Mux and DeMux. Coherent signals show strong robustness when they are deployed in traditional analog DWDM systems.
- However, the conventional AWG-based optical Mux and DeMux configuration, which is typically used for coherent channels, is not good for conventional analog channels.

4. Full Duplex Coherent Optics

4.1. The Need for Single Fiber Connections

According to a recent operators' survey, 20 percent of existing cable access networks use a single-fiber topology as shown in Figure 9. This means that downstream and upstream transmission to nodes takes place over a single strand of fiber. It is estimated that over the next several years, this number will grow further. Therefore, to control the cost and fully utilize the existing infrastructure, bidirectional transmission over a single fiber is needed for coherent signals to support single-fiber topologies and to facilitate the redundancy of optical links.

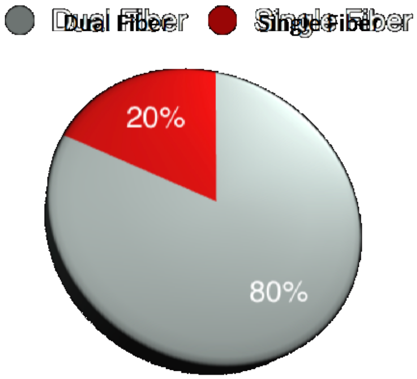

Figure 9 – Today's Single Fiber Use Percentage

4.2. The Existing Approach

Today, achieving bidirectional transmission in an optical domain with a single laser requires two fibers. This is the standard practice using today's coherent optical technology. One laser in a transceiver performs two functions:

- as the optical signal source in the transmitter
- as the reference local oscillator signal in the receiver

Because of the use of the same wavelength from the same laser, a second fiber must be available for the other direction—one fiber for downstream and a second fiber for upstream as shown in Figure 10.

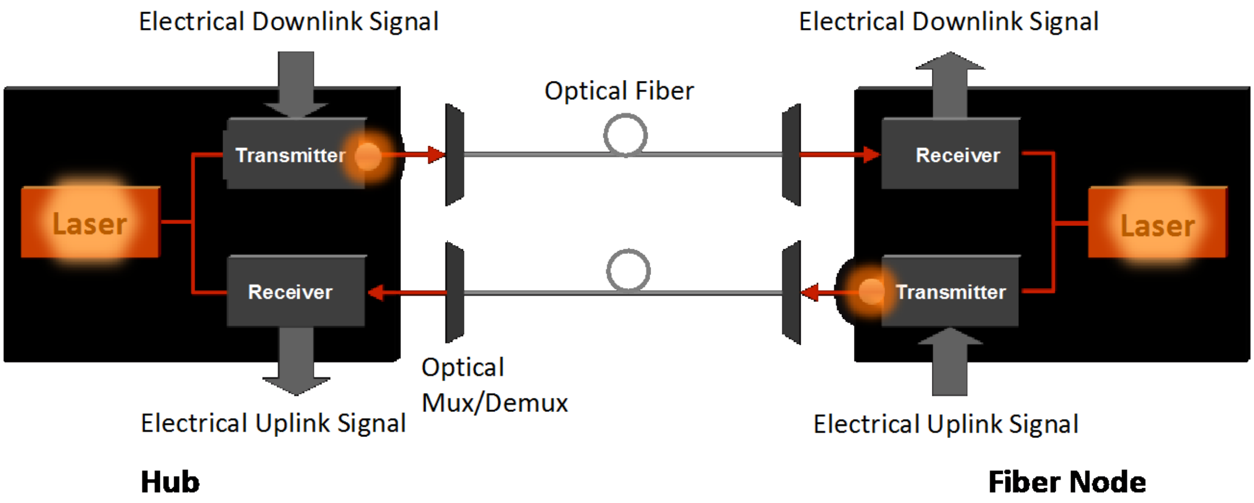

Figure 10 – Dual-Fiber Approach

The second typical approach is to use a single fiber but transmit at different frequencies or wavelengths, similar to the upstream and downstream spectrum split that we implement in our HFC networks. To accomplish this frequency/wavelength multiplexing approach, two lasers operating at different wavelengths are needed, as shown in Figure 11. Wavelength multiplexers and demultiplexers following a wavelength management and allocation strategy are needed to combine these different wavelengths over the same fiber. The second laser ends up costing a lot more than money—increasing power consumption, operational complexity, and transceiver footprint.

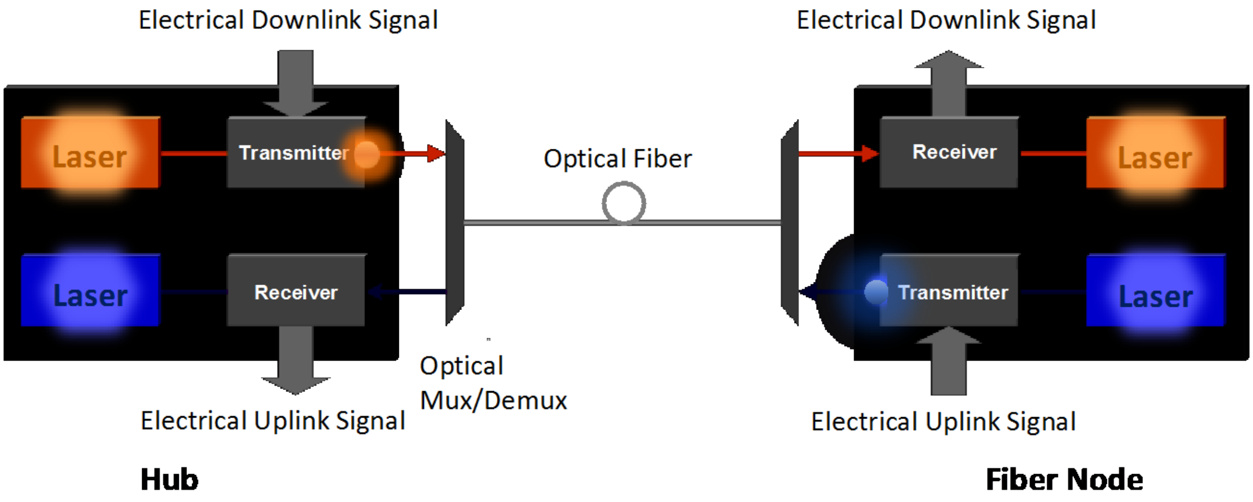

Figure 11 – Single-Fiber Approach with Two Lasers

4.3. Full Duplex Coherent Optics Approach

CableLabs proposes an alternative method achieving full duplex coherent optics. We leverage two optical circulators on each end in a special configuration. The circulator is a low-cost, passive, but directional device—much like a traffic roundabout for cars, however this device is used for rerouting the optical path in different directions. Instead of using two fibers, a single fiber is connected for bidirectional transmission; most importantly, instead of using two lasers, a single laser is employed for single-fiber coherent systems. The scheme is shown in Figure 12.

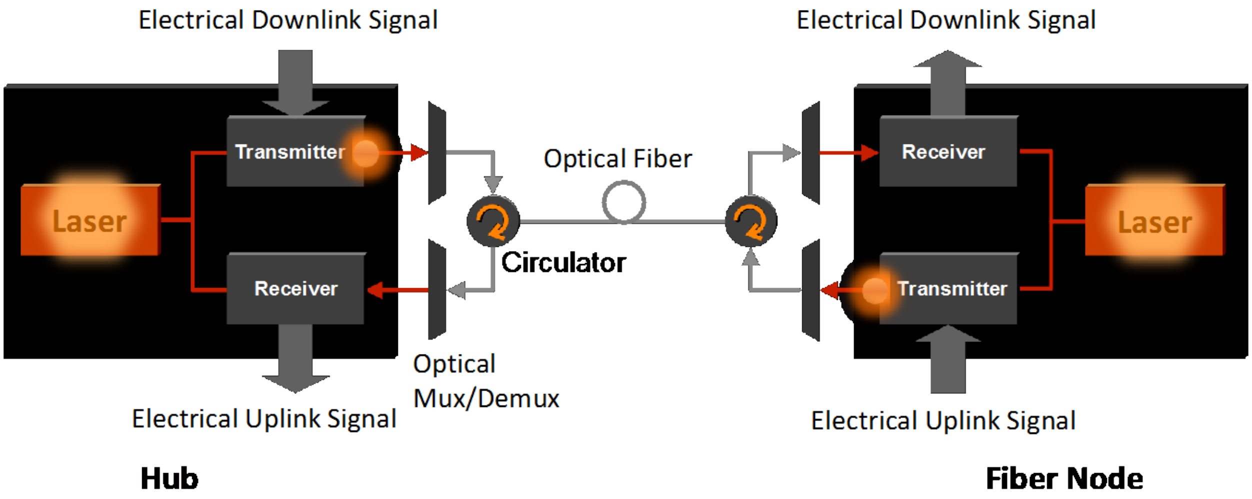

Figure 12 – Full-Duplex Single-Fiber Approach

4.4. How Does It Work in a Cable?

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 cascade. When dealing with coherent signals, we have much higher Optical Signal to Noise Ratio (OSNR) sensitivity and higher tolerance to the impairments from the spontaneous Rayleigh backscattering (continuous reflection) and Fresnel reflection (discrete reflections), than intensity-modulated systems. The majority of existing analog optics employs angle-polished connector (APC), which provides excellent mitigation for return loss from Multiple-Path Interference (MPI) or jumper cable/optical distribution panels/fusion or mechanical splices. In addition, the threshold of the Stimulated Brillouin scattering (SBS) nonlinear effect is suppressed because of the nature of phase-modulated signals on reducing optical carrier power and increasing the 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 would cover not only the entire C-Band but, with different optical sources, the entire fiber spectrum.

4.5. Testing Setup and Results

Figure 13 shows the first test setup with the variable attenuator on the receiver side in each direction. This is the typical operational case to measure the power penalty with and without full duplex operation, where the power of both received signal and returned impairment is attenuated. The penalty comes from the Rayleigh backscattering and Fresnel reflection along the whole link.

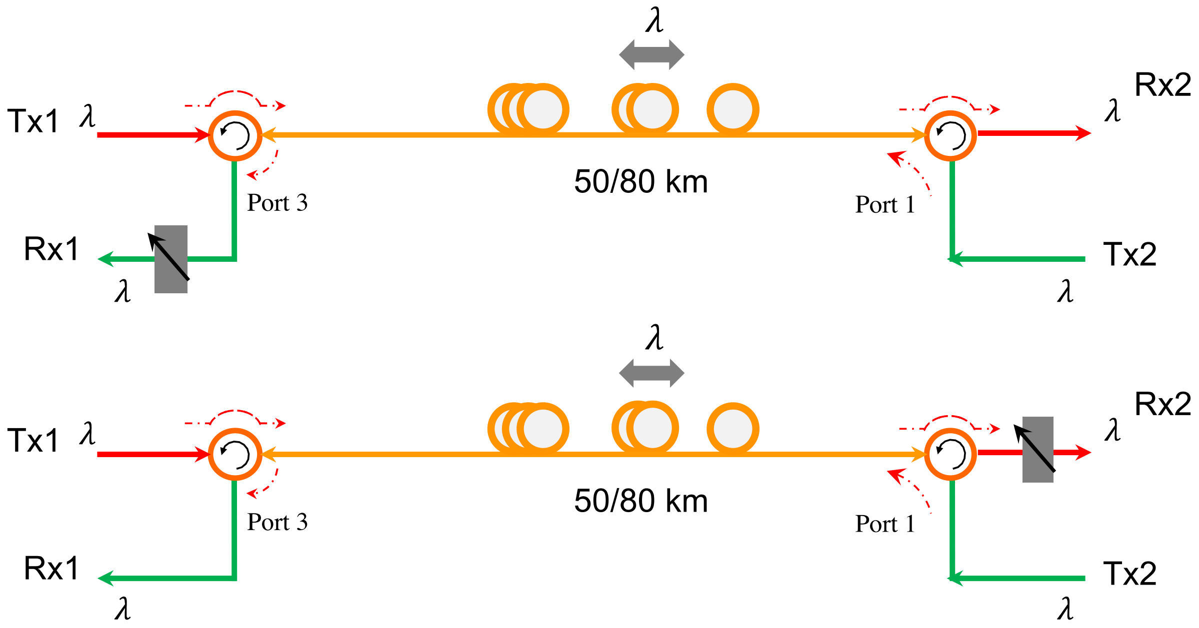

Figure 13 – Testing Case I: 50km, 80km, Attunator at Rx Sides

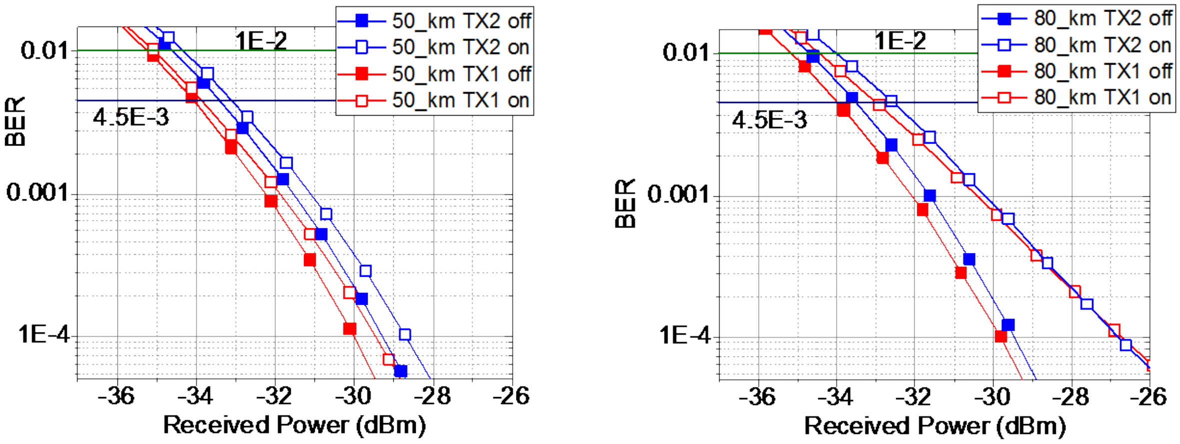

Figure 14 – Testing Case I: Results

The reflected power is measured as -34.7 dBm, as the output power of the transmitter (TX1 or TX2) is set to 0 dBm. Figure 14 shows the results for 50 and 80 km transmission distances. Around 0.5 dB and 1 dB power penalties are observed for 50 km and 80 km transmission, respectively, when compared with full duplex operation with single direction operation.

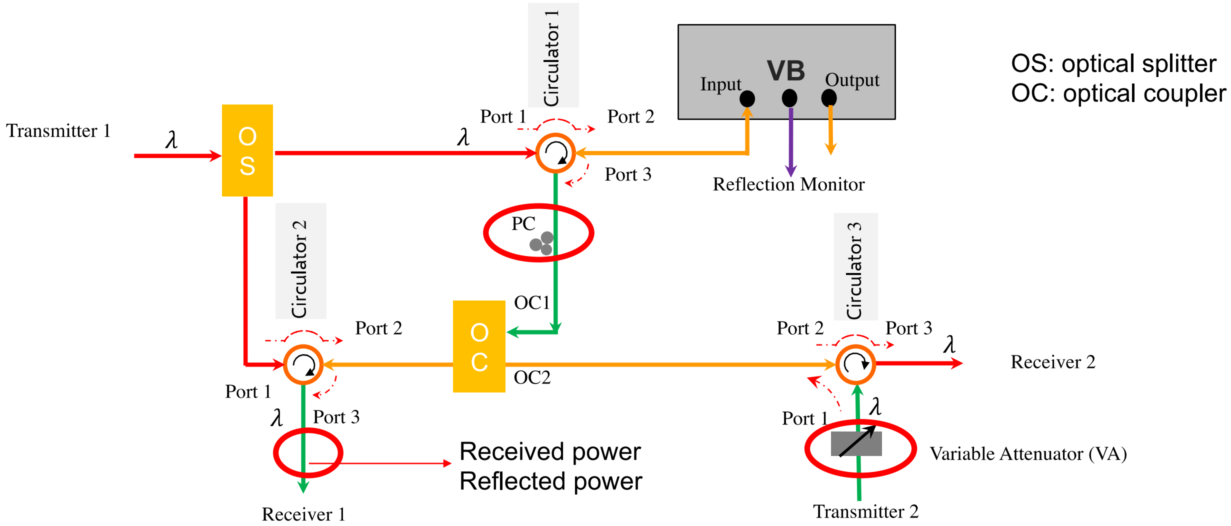

Figure 15 – Testing Case II: Variable Backreflector

Figure 15 shows the second test setup with the variable backreflector to measure the robustness of coherent signals at different return loss levels. Instead of a fixed reflection impairment used in the previous setup, we use a backreflector to purposely control the reflected power to the desired signal detection level. To achieve full duplex operation, there are two conditions that need to be satisfied at the receiver:

- The received power (the transmitted power – link loss) has to be larger than the power sensitivity requirement;
- The optical signal to noise ratio (from reflection power) has to be better than the OSNR sensitivity requirement.

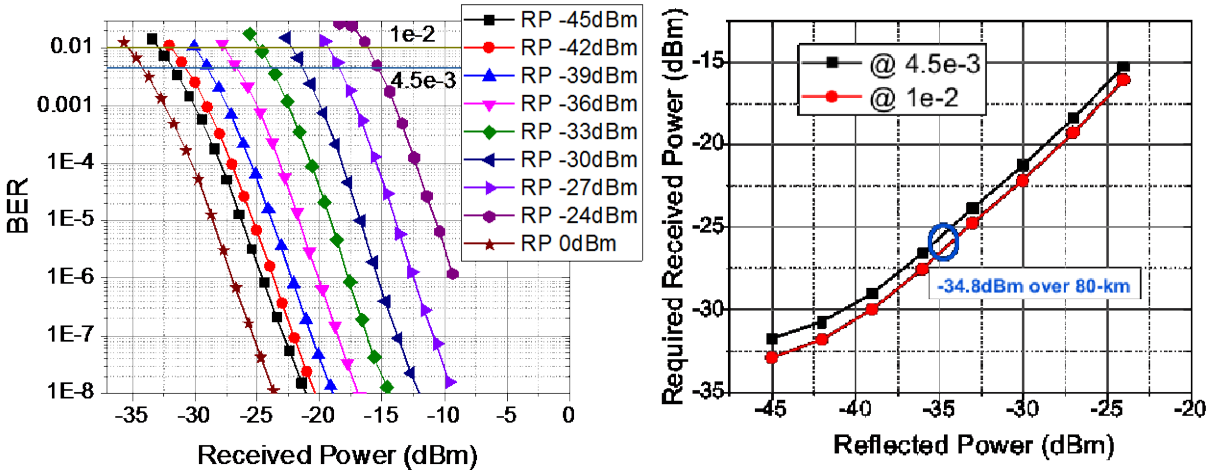

Figure 16 – Testing Case II: Results (RP: Reflected Power)

Figure 16 shows the BER vs. power curves under different reflected power levels for 100G PM-QPSK signals. The reflected power is measured before RX1 and the transmitter output power is set to 0 dBm. It is also noted that the polarization controller is inserted in the setup to emulate the worst case of polarization alignment. The required receive power almost linearly increases as the reflected power becomes larger. For example, for the 80 km transmission case with -34.8 dBm reflected power in Test Case I, the required received power would be ~-26 dBm to maintain the required OSNR level. It is also noted that there is no error floor observed even if the reflected power is measured at -24 dBm.

Conclusion

As the industry evolves toward Node+0 architectures, the volume of optical connections to intelligent nodes will increase substantially compared to traditional architectures. Coherent optics technology offers a future-proofing solution for cable operators to meet bandwidth demand without the need for retrenching new fibers.

In this paper, we presented extensive experimental verification under different coexistence scenarios and provided operational and deployment guidance for such use cases. Less than 0.6 dB power penalty is observed with complexed hybrid scenarios. The results show coherent optics transmissions are robust, even in close proximity to much stronger analog and intensity modulated optical carriers. This means that the cable operators can effectively support 100G or higher coherent channels on their existing networks without the concerns of significant performance degradation.

Additionally, CableLabs' full duplex coherent optics proposal and the experiments that demonstrate simultaneous bi-directional transmission over single fiber and single wavelength are also discussed in this paper. The major impairment in the full duplex coherent optics system is ORL including all discrete reflections (Fresnel) and continuous reflections (backscatter). The impact of ORL for FDCO is also analyzed and quantified for various configurations. The quantitative results provide the cable operators an elegant solution to their single-fiber use cases with coherent optical systems.

Acknowledgement

The authors of this paper would like to extend their gratitude to Acacia, ARRIS and Ciena for providing analog optics and coherent optical transceiver components, in addition to their technical support for setup and operation.

Abbreviations

ADC	analog to digital converter
ASIC	application-specific integrated circuit
BER	bit error rate
bps	bits per second
CD	chromatic dispersion
CMA	constant modulus algorithm
CMOS	complementary metal–oxide–semiconductor
CMTS	cable modem termination system
DAC	digital to analog converter
dB	decibel

dBm	dB milliwatt
DCF	dispersion compensation fiber
DFB	distributed feedback (laser)
DMF	dispersion managed fiber
DSP	digital signal processing
DWDM	dense wavelength division multiplexing
ECL	external cavity laser
EDFA	erbium-doped fiber amplifier
EPON	ethernet passive optical network
ETDM	electrical time division multiplexing
EVM	error vector magnitude
FDCO	Full Duplex Coherent Optics
FEC	forward error correction
FWM	four-wave-mixing
Gbps	gigabit per second
GHz	gigahertz
HD	high definition
HFC	hybrid fiber-coax
HHP	household pass
Hz	hertz
I	in-phase
ISBE	International Society of Broadband Experts
km	kilometer
LD	laser diode
LO	local oscillator
LPF	low-pass filter
MHz	megahertz
MIMO	multi-input multi-output
MMI	multi-mode interference
MSA	multi-source agreement
MZM	Mach-Zehnder modulator
NRZ	non-return zero
NZDSF	non-zero dispersion shifted fiber
OIF	Optical Internetworking Forum
OLT	optical line terminal
OOK	on-off keying
OPLL	optical phase locked loop
PAM	pulse amplitude modulation
PBS	polarization beam splitter
PHY	physical layer
PM	polarization multiplexing
PMD	polarization mode dispersion
PON	passive optical network
Q	in-quadrature
QAM	quadrature amplitude modulation
QPSK	quadrature phase shift keying
R-PHY	remote PHY
RF	radio frequency

RFoG	RF over glass
RIN	relative intensity noise
RPD	remote PHY device
SBS	Stimulated Brillouin scattering
SCTE	Society of Cable Telecommunications Engineers
SD-FEC	soft decision forward error correction
SMF	single mode fiber
SNR	signal to noise ratio
SOP	state of polarization
SPM	self-phase modulation
ULA	ultra-large area
ULLF	ultra-low loss
XPM	cross-phase modulation

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