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Coherent Access Applications for MSOs

A Technical Paper prepared for SCTE•ISBE by

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1. Introduction

While Coherent optics are ubiquitous in the MSO metro core and backbone optical networks, initial planning and use cases are now being investigated for Coherent technology in the Access domain. Cable HFC optical networks are rapidly evolving from traditional analog to digital DWDM infrastructures that enable the adoption of Distributed Access Architectures (DAA) such as Remote-PHY and Remote MAC, which provide higher performance, lower overall optical costs and simplified network designs.

The available digital DWDM infrastructure within the Access network will accommodate the pervasive 10G NRZ DWDM connections associated with DAAs as well as the introduction of Coherent technology to address high bandwidth applications (i.e. MDU service delivery and Enterprise Business services.) In that regard we detail proof of concept testing over 40 and 60 km distances with bi-directional Coherent 100G/200G and 10G NRZ DWDM wavelengths placed adjacent to each other on the same fiber, using our Cox designed Optical Communications Module Link extender (OCML) and a Mux/DeMux. Use cases of a converged Access network consisting of 100G/200G Coherent, 10G DWDM and PON are presented, allowing operators to deploy a solution which is technology agnostic and able to support a multitude of services over the same network, while fully utilizing existing fiber assets.

2. What is Coherent Optics?

Coherent was first unveiled at OFC 2008 and began to be deployed in long-haul optical networks around the world in 2010. Coherent-based technology today is the de-facto standard for high-speed long-haul optical transport networks at 100G and beyond. Most long haul networks have already been deployed at 200G, with 400G emerging. Eighty eight wavelengths at 200G equate to an enormous capacity of 18 terabits per second which can be transported over distances of up to 2000 km.

Coherent optics were developed to overcome two fundamental limitations as you go beyond 10G: chromatic dispersion (CD) and polarization mode dispersion (PMD). Network capacities are increasing by a 25 to 50 percent Compound Annual Growth Rate (CAGR) every year, and systems running at 10 Gb/s cannot keep up with this kind of growth. At its most basic level, Coherent optical transmission is a technique that uses modulation of both the light amplitude and phase, as well as transmission across two polarizations to transport considerably more information through a fiber optic cable. At the receiver, a local oscillator (LO) measures the phase and amplitude, while a digital signal processor (DSP) recovers and demodulates the phase information. Phase modulation also reduces susceptibility to optical impairments, thus Coherent systems have improved OSNR tolerance, and better reach with multiple advanced modulation formats such as DP-QPSK, DP-8QAM and DP-16QAM being utilized.

Advanced Coherent optical technology has a number of key attributes, including:

- High-gain soft-decision Forward Error Correction (FEC), which enables signals to traverse longer distances while requiring fewer regenerator points which also provides more margin, allowing higher bit-rate signals to traverse farther distances.
- Coherent Digital Signal Processors (DSPs) account for dispersion effects after the signal has been transmitted across the fiber, including compensating for both CD and PMD and also improved tolerances for Polarization-Dependent Loss (PDL). The use of Dual Polarity (DP) modulation in the optical domain also doubles the effective bit rate for many Coherent systems.

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2.1. Coherent Time Line

As shown in Figure 1, the introduction of Coherent Optics enabled the "10G Speed Limit" to be broken, initially for 40G and soon after for 100G long-haul transmission. Figure 1 represents the commercial deployment of products. By 2010 to 2011, the technologies had reached a point of market maturity at which they could genuinely allow 100G Coherent signals to be sent over the same (and sometimes greater) distances as 10G, with mass market deployments beginning in 2012. Today 200G systems are common in metro and long haul networks, 400G is emerging, 600G is on the horizon, and one Tbps per wavelength has already been demonstrated in the lab. The development of optical Coherent technologies has been an incredible technical achievement allowing for an enormous increase in capacity.

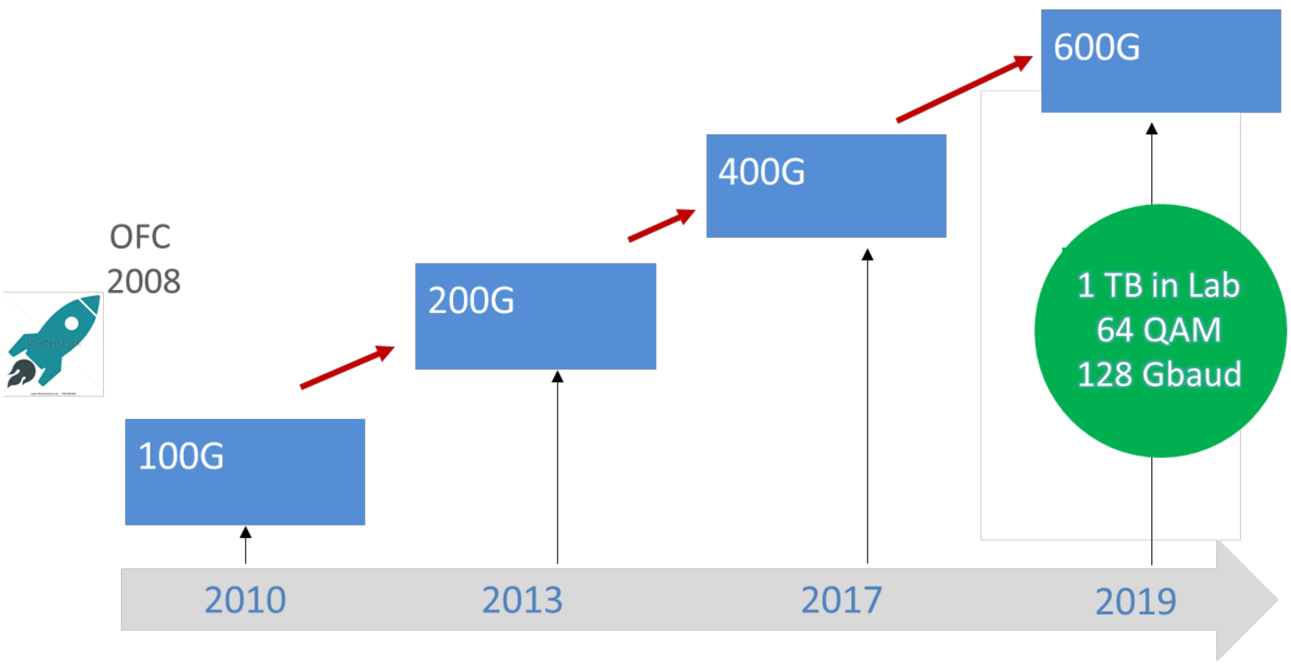

Figure 1 - Coherent Deployment Timeline

2.2. Modulation In Coherent Systems

Various types of modulation techniques are used in Coherent systems, depending on system requirements like reach and also existing fiber deployments which need to be upgraded to Coherent. DP-QPSK is one form of modulation used in Coherent 100G networks as this provides a robust system with long reach. In addition, the transmitter complexity is low and the DSP algorithms can be performed more simply. The sensitivity of QPSK is suitable for long-haul distances such as transoceanic links. However as the capacity increases to 200G and beyond, the common modulation format is DP - 8,16 or 64 QAM with its associated baud rates. Since Access distances are usually less than 100km, the most common modulation format planned for Coherent systems is 100G QPSK while 200G can utilize QPSK, 8-QAM, or 16-QAM formats. Figure 2 shows the various modulation formats as a function of distance.

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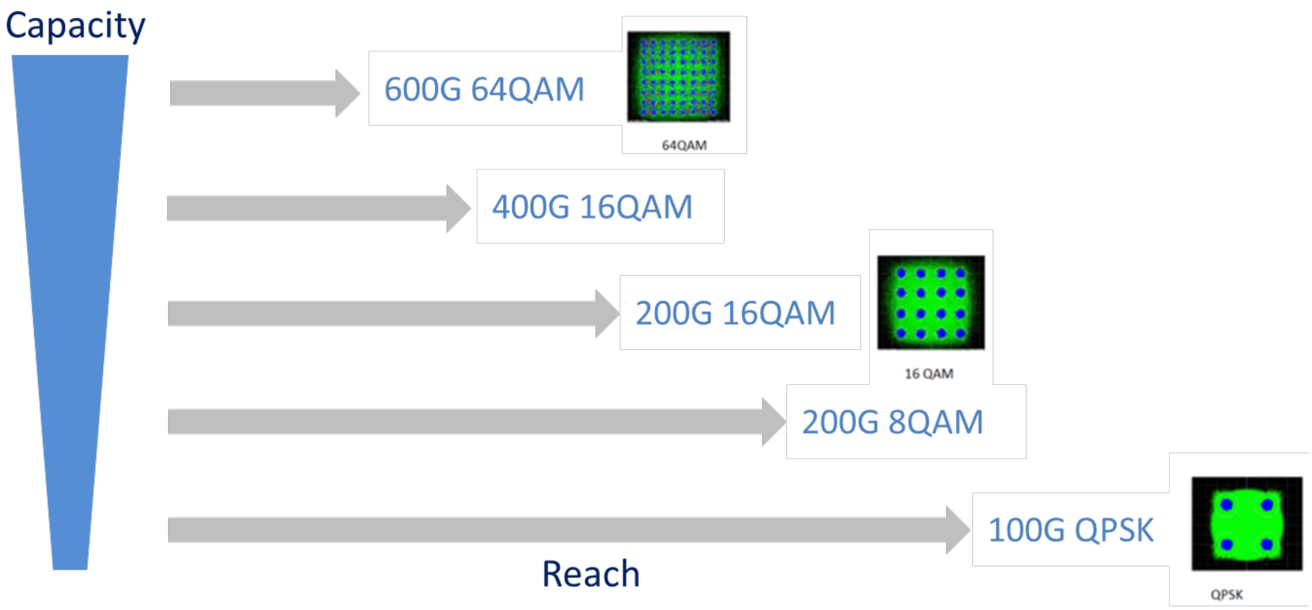

Figure 2 - Coherent Modulation and Reach

2.3. FEC in Coherent Systems

As data rates increase, chromatic dispersion increases which reduces the optical signal-to-noise ratio (OSNR) of a given system. Coherent technologies can digitally compensate for degradation caused by chromatic dispersion and polarization mode dispersion using DSPs. In addition, Coherent systems also employ forward error correction (FEC) codes that allow very significant levels of errored bits to be recovered to deliver an error free digital signal. The latest generation of FEC uses a soft-decision algorithm that significantly improves the net coding gain (NCG) of previous FEC schemes.

Figure 3 shows the basic principle of FEC in optical transport network (OTN) systems. The optical transport unit (OTU) has pre-FEC bit errors (shown by the red lines). The FEC decoder corrects certain level of error, producing a post-FEC, error-free optical data unit (ODU). Powerful electronic processing is required in the receiver to process FEC, and as the complexity of FEC algorithms has increased, the electronics have had to evolve to keep up.

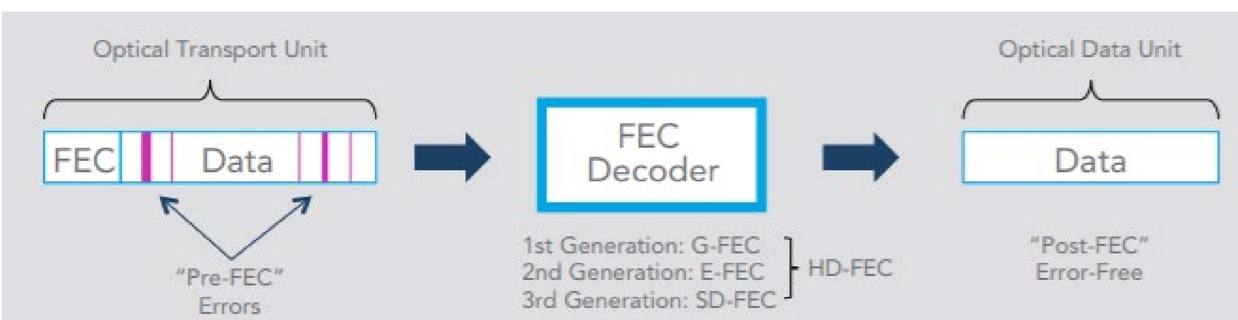

Figure 3- Pre-FEC and Post-FEC Operational Schematic

FEC evolution is generally regarded as having three distinct generations:

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First generation: A generic FEC (G-FEC) which uses hard-decision decoding defined in ITU-T G.709 which allows interoperability between vendors but only delivers around 6 dB of NCG with a 6.69 percent overhead.

Second generation: An enhanced FEC (E-FEC), uses hard-decision decoding defined in ITU-T G.975.1., but no interoperability between multi-vendor E-FEC systems. It delivers between 8 dB and 9.5 dB of NCG with overhead between 6.69 and 10 percent. G-FEC and E-FEC can be used with both non-Coherent and Coherent transmission systems. Second-generation E-FEC implementations for submarine networks typically have overhead as high as 25 percent.

Third generation: Uses soft-decision decoding (SD-FEC), enabled by advances in electronic signal processing for Coherent systems at 100G and beyond. It can deliver a NCG of 11 dB or more with an overhead of 15 to 35 percent, depending on the implementation. Newer techniques to further enhance SD-FEC performance continue to be developed.

Three generations of FEC technologies have been spanned in a very short time since the introduction of Coherent systems. FEC is of key importance in achieving the necessary system margin to offer high Quality of Service (QoS) networks.

2.4. Coherent DWDM Grid and OSNR Requirements

Since operators may have existing DWDM filters deployed and wish to run Coherent through them, it is important to understand filter bandwidths and associated channel spacings required for Coherent transmission. The filter bandwidth/channel spacing requirements are determined from the modulation and its accompanying baud rate. Table 1 gives the channel spacing (grid) requirements for different Coherent modulations, as well as the OSNR requirements for typical CFP2-DCOs most likely used in Access networks. If CFP2-ACO or discrete optics are used with external (and higher power DSPs), the FEC NCG or threshold will be different and the OSNR tolerance will be different/better, assuming the same modulation schemes. The actual filter bandwidth is directly proportional to the baud rate utilized and also depends on the FEC used, in particular the % overhead employed.

Table 1 - Coherent Optical Characteristics For Typical CFP2 – DCOs

Data Rate (Gbps)	Modulation	Baud Symbol Rate (Gbaud)	Minimum Grid GHz	OSNR (dB) 10^{-15} Post FEC
100G	DP-QPSK	32	50	12
200G	DP-QPSK	64	100	16
200G	DP-8QAM	42	50	18
200G	DP-16QAM	32	50	20
400G	DP-16QAM	64	100	25
Assumes Soft decision FEC, 10.8 - 11.3 dB NCG, BOL measurements				

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2.5. Coherent Equipment Type

There are various types of Coherent equipment manufactured by vendors, depending on cost and system requirements. For Access networks, transmission distances are normally less than 100km , but for long haul > 2000km transmission systems, a heavy focus on reach and performance is required.

Access applications require compact, scalable, cost-efficient, and easy-to-use Coherent transport solutions, which are met by pluggable transceiver modules such as CFP2-ACO (Analog Coherent Optics) or CFP2-DCO (Digital Coherent Optics) that include all optics and the associated digital signal processing.

The key differentiator between the two types of modules is that in the CFP2-ACO, the DSP is located outside the module with the rest of the electronics. This is a more complex solution that requires the user to interface the optical module with the DSP, but users can choose their own DSP, which makes the ACO a good fit for network equipment manufacturers who want to incorporate their own proprietary DSPs. In the CFP2-DCO the DSP is located within the module, making it a plug-and-play, simple to-deploy and operate solution for enterprise connectivity and data center interconnect (DCI).

In order to achieve the capacity and cost-per-bit targets of Access and Metro/Regional systems, it is desirable to be able to increase the data rates from 100Gb/s to 200Gb/s while maintaining sufficient signal robustness in narrower optical filtering (50GHz grid) applications. Thus it is desirable that 200Gb/s CFP2-DCO/CFP2-ACO support higher modulation formats like 8QAM and 16QAM. Higher modulations do however, have increased susceptibility to distortions, requiring higher OSNR values.

Higher performance Coherent equipment designed for regional, long haul and submarine applications, typically have discrete optical front ends with flexibility to add EDFAs, tuneable filters and high end modulators (LiNbO3 Mach Zender for example). The actual transmitted power could be much higher in discrete implementation (up to 5dB higher launch power) than typical CFP2-ACO/DCOs. Similarly, Rx sensitivity can be a lot lower.

As described in the previous sections, Coherent system performance and reach also depends on many factors such as FEC and modulation schemes employed in addition to the optical front end used. To summarize, Coherent system performance depends on:

- DSP FEC and Gain (NCG) with Soft decision Forward Error Correction.
- Optical front end: Transmit output power, fixed or adjustable (built in EDFA), type of modulator, e.g (LiNbO3 MZM), laser linewidth
- Receiver sensitivity

In this paper we will present proof of concept test results of bi-directional, mixed 10G and Coherent 100G/200G using two very different types of equipment. We will designate them as equipment A (used in long haul/submarine deployments) and equipment B (Metro/Access platform with pluggable CFP2-ACOs designed for enterprise and data center interconnect (DCI) connectivity).

2.6. Coherent Bi-directional Transmission Capability

An important requirement for Cox networks is the ability to have bi-directional transmission, where both downstream and upstream signals are transported over the same fiber in opposite directions. This is important for applications where fiber resources are limited or where there is a requirement for fiber

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redundancy. Other operators may have "unidirectional" transmission (uni) that utilize two fibers, one for each direction.

Figure 4 below shows a high-level block diagram of the uni and bi-directional transmission Coherent equipment. The receiver uses a reference light signal (local oscillator or LO) as a comparison to measure the phase and amplitude of the incoming light wave. In unidirectional transmission, the same laser is used for both the transmitted wavelength and as an LO for the receive signal, so the downstream and upstream must be the same wavelength. This is the normal case where two separate fibers are utilized for the downstream and upstream directions. In bi-directional Coherent transmission, the optical front end contains two lasers so the transmitted and receive signals can be at different wavelengths.

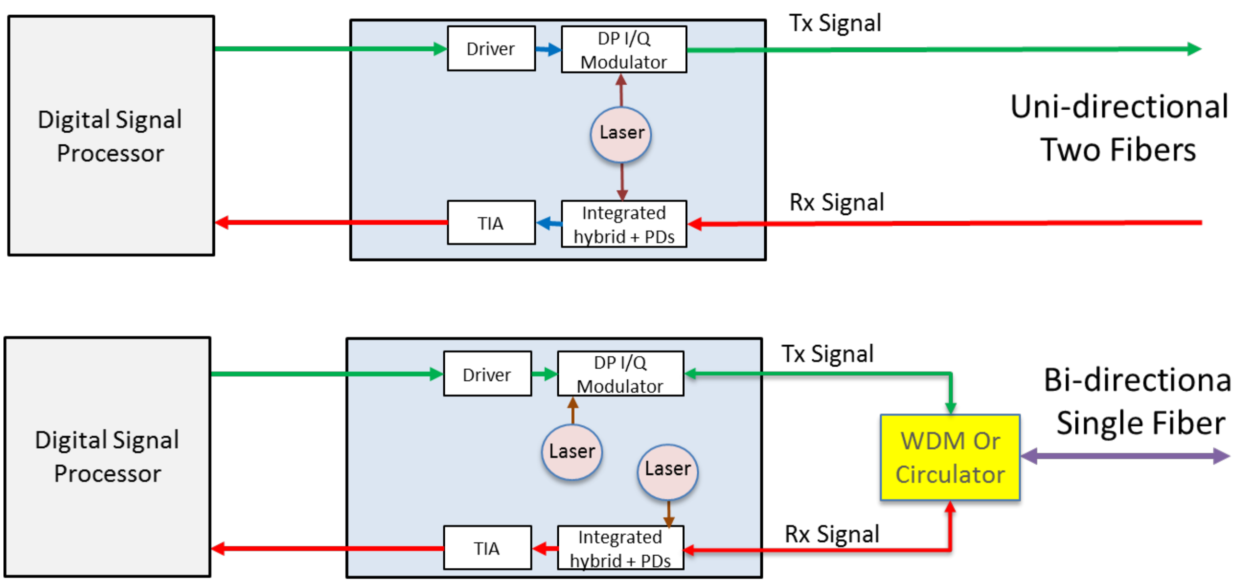

Figure 4– Uni and Bi-directional Coherent Transceivers

3. OCML – MDM Network

Cox Communications Access networks are unique in the sense that most of its primary HFC nodes are protected by a secondary back-up fiber, providing optical path redundancy which significantly increases reliability. Additionally, we have bi-directional traffic flow on the same fiber. To maintain this architecture in the transition to DAA networks, we had to solve the problem of how to effectively transport optical signals over these bi-directional dual fiber rings.We had the additional requirement to carry GPON/10GEPON plus 10G DWDM Remote-PHY signals. It was also desirable to be able to carry Coherent 100G/200G over the same network.

To meet these exacting requirements, we developed the Optical Communications Module Link Extender (OCML)[1] and the MDM. The OCML supports next-generation fiber deep DWDM Access networks and may transport up to 20 X 10G bi-directional wavelengths, plus future Coherent 100G/200G over variable 5 to 60 km path redundant fiber links. PON/10GEPON signals may also be transported in the platform through an innovative WDM filter mechanism which passes through all wavelengths and blocks the 10G C band. As the industry begins to implement DAA rollouts, the OCML allows use of available 10G NRZ

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DWDM technology, but the underlying infrastructure is based on ITU standard wavelength plans in anticipation of the requirement to deploy Coherent 100G (and beyond) wavelengths. The MDM is a field-based passive Mux/DeMux filter incorporating a 3 dB splitter for connection to the primary and backup secondary fiber. The basic OCML – MDM network shown in figure 5 below allows active components of a DWDM Access network to be integrated into one module which can then be placed in the central office/headend/hub, while the outside plant aggregation point can be a simple Mux/Demux (MDM).

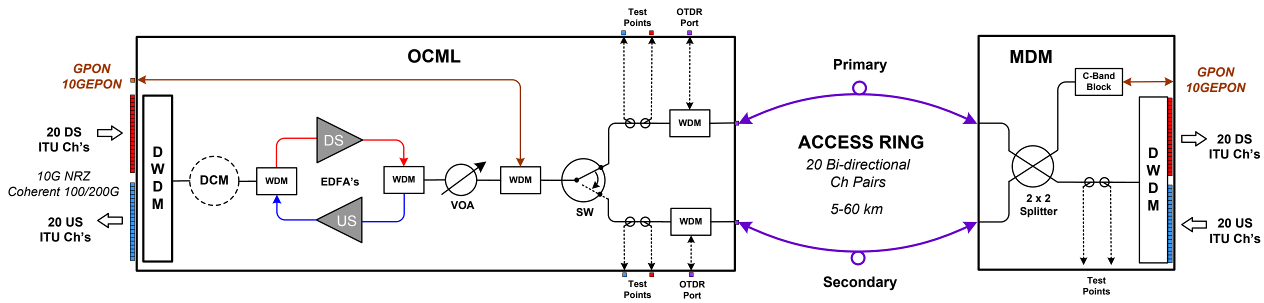

Figure 5- OCML - MDM Network

A high level remote-PHY architecture showing the OCML - MDM is shown in Figure 6 below. This basically shows how a 10G DWDM optical trunk can be used to effectively feed a large number of Remote-PHY nodes. While ten RPD nodes are shown, the OCML – MDM can support up to twenty RPD's.

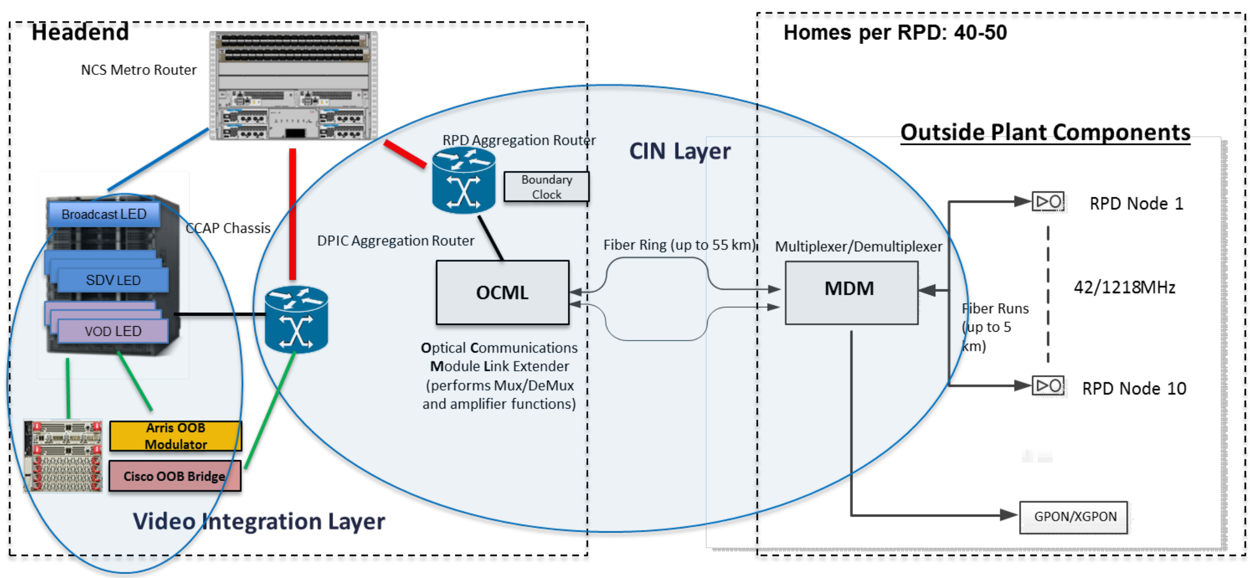

Figure 6 - Remote-PHY High Level Solutions Architecture

3.1. 10G and Coherent Coexistence

One of the key advantages which DAA networks provide is the ability to transport various types of signals across MSO Access networks. Up to now, MSO HFC networks have utilized very restrictive analog signals which normally have high power levels. The analog optical signals typically required

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elaborate wavelength plans to mitigate fiber non-linearities such as Four wave Mixing (FWM). Cox is planning to roll out Remote-PHY networks utilizing a 10G DWDM bi-directional network via the OCML-MDM. Our challenge was to utilize this same network to also transport Coherent 100G and 200G signals plus GPON and 10GEPON. In addition, the network had to carry bi-directional wavelengths over a primary and backup secondary fiber. We will discuss some of the technical considerations to be taken into account in deploying mixed 10G and Coherent opticval signals over fiber networks.

3.2. Impact of 10G and DCMs on Coherent 100G/200G

Existing 10G networks pose two performance challenges to Coherent 100G/200G. The first is the 10G DWDM signals themselves, while the second is due to the dispersion compensation modules (DCMs) typically found in 10G networks. Since one of the OCML variants utilizes a DCM, we needed to ensure that Coherent signals can be transported through the OCML, both with and without dispersion compensation.

3.2.1. Cross Phase Modulation (XPM) In Mixed 10G/Coherent Signals

10G systems use amplitude (or power) based On-Off Keying (OOK) modulation, while Coherent 100G/200G transmission most commonly uses DP-QPSK or DP-8/16QAM modulation formats. These modulation schemes alter the phase of the transmitted signal in addition to the amplitude. 10G signals have a much higher power spectral density (large amount of power in a very small spectral range) than Coherent 100G/200G, as shown in figure 7 below. This has a greater impact on the refractive index than Coherent signals. Since Coherent signals make use of phase modulation, they are more severely impacted by effects that alter the signals phase. For these reasons, cross phase modulation (XPM) from 10G wavelengths can have a significant impact on the reach of Coherent 100G/200 wavelengths in a mixed 10G/100G network. Fortunately, since Access networks are typically less than 80km, XPM impacts induced by 10G signals should not be too severe, but still ought to be evaluated in mixed 10G/Coherent 100G or 200G networks.

10G DWDM receivers based on OOK can typically tolerate 80km~100km of chromatic dispersion. For this reason, dispersion compensation modules (DCMs) are typically deployed in 10G networks. Since the performance of 10G DWDM systems with EDFAs depend on various facators such as OSNR, fiber dispersion and optical receive power, DCMs are also used to help offset the effects of low OSNR, as can be the case in Cox OCML - MDM networks. However, low chromatic dispersion is actually a disadvantage for Coherent transmission. In the absence of chromatic dispersion, the symbols of each channel could all alter the refractive index of the fiber at the same time, thus maximizing the impact on the fiber's refractive index and thereby increasing XPM. By causing the channels to travel at slightly different speeds, chromatic dispersion reduces the time correlation between the symbols, thus reducing the buildup of nonlinear penalties including XPM and Self Phase modulation (SPM). Given the above, we investigated the impact of 10G signals and DCMs on Coherent 100G/200G signals through the OCML – MDM network.

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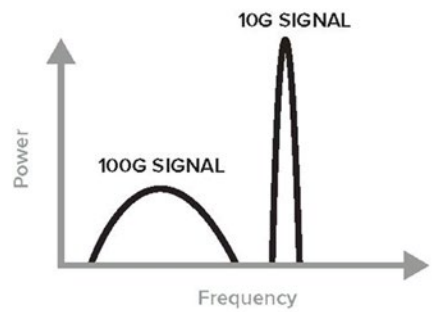

Figure 7 - Signal Power Density 10G and 100G

3.2.2. Guard Bands In Mixed 10G and Coherent 100G/200G

Guard bands (not using one or more channels between the 100G and the 10G channels) can be employed to mitigate XPM in mixed 10G and Coherent signal networks as shown in Figure 8. For example, if a 100G wavelength is deployed on channel 25, then channel 24 and channel 26 are left empty to accommodate 10G wavelengths on channels 23 and 27. Alternatively, 10G channels can use one end of the C- band and Coherent signals deployed from the other end. However, guard bands cause reduced spectral efficiency and planning challenges since they do not use certain wavelengths. Guard bands are typically deployed on very long (>1000km) links where 10G and Coherent coexist. We evaluated whether guard bands would be needed in short (< 80km) links for mixed 10G and Coherent signals.

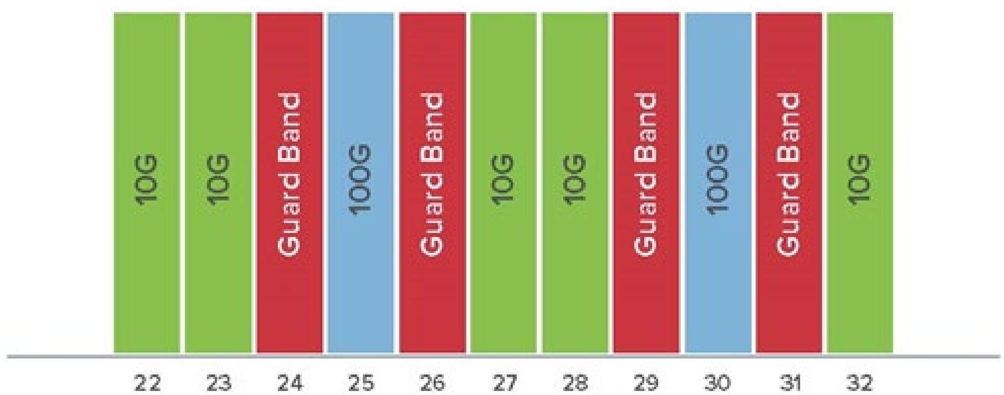

Figure 8 - Guard Band Example

4. Testing of Coherent and 10G Coexistence in OCML

The performance of Coherent systems depends on various factors as explained in section 2.0.

In this section we present proof of concept test results for mixed bidirectional 10G and Coherent 100G/200G through the OCML using two types of equipment.

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Equipment A: High performance Coherent equipment designed for regional, long haul and submarine applications. Typically this type of equipment has a discrete optical front-end with added flexibility to add EDFAs, tuneable filters and high end modulators (LiNbO3 Mach Zender for example). This allows for links to be optimized for performance and reach.

Equipment B: Lower cost and lower performance Coherent equipment designed for shorter, Metro/Access applications. Typically this type of equipment utilizes off-the-shelf 200G 16QAM pluggable CFP2-ACO optics. Since this is most likely the type of equipment which cable operators will use for Access, we wanted to evaluate its performance against the high performance long haul equipment.

In addition both the Coherent platforms we tested had bi-directional capability in that they could transmit and receive at different wavelengths to allow transmission over a common fiber. This was a major requirement for the Cox Access network.

4.1. Test Set-Up

Figure 9 below shows the test set-up used to evaluate the performance of a network supporting bi-directional multi-channel 10G and Coherent 100G/200G through the OCML – MDM network over 40 and 60 kilometers of fiber. The 60km setup used a version of OCML that has an integrated Dispersion Compensation Module (DCM). The 40km setup used a lower cost version of OCML without DCM. We also used two types of Coherent equipment (A and B) as described above. The OCML – MDM equipment supports twenty bi-directional DWDM channel pairs. Seventeen were used to carry 10G NRZ signals and the remaining three transported Coherent 100G/200G.

The high-capacity Ethernet traffic generators shown in the diagram were used to compare transmitted packets to received packets to determine whether any uncorrected data errors occurred on any of the bi-directional channel pairs during the testing. In the case of the Coherent optical signals, any errors detected by the traffic generator/packet analyzer indicated the presence of uncorrectable (post-FEC) errors. There was no FEC in the 10G NRZ SFP+ optics, nor the host switches they were installed in.

Two different channel loadings were used in the 60km testing (1 and 2). Only channel loading 1 was used in the 40km testing. Figure 10 shows the ITU channels, associated equipment types, modulation types, and data ratings used for both channel loadings. Note that no guard bands were used to separate the 10G and the 100/200G Coherent signals.

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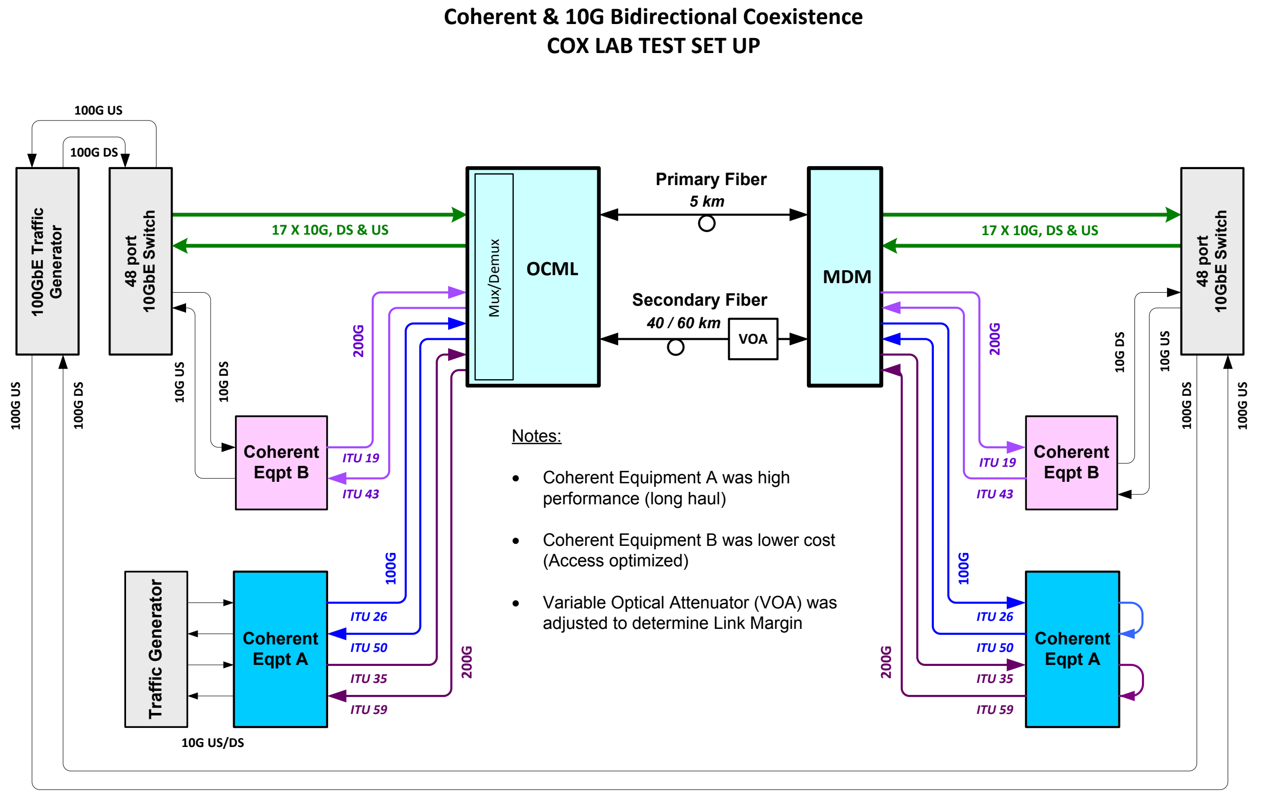

Figure 9 - Test Set up for 10G and Coherent 100G/200G Coexistence

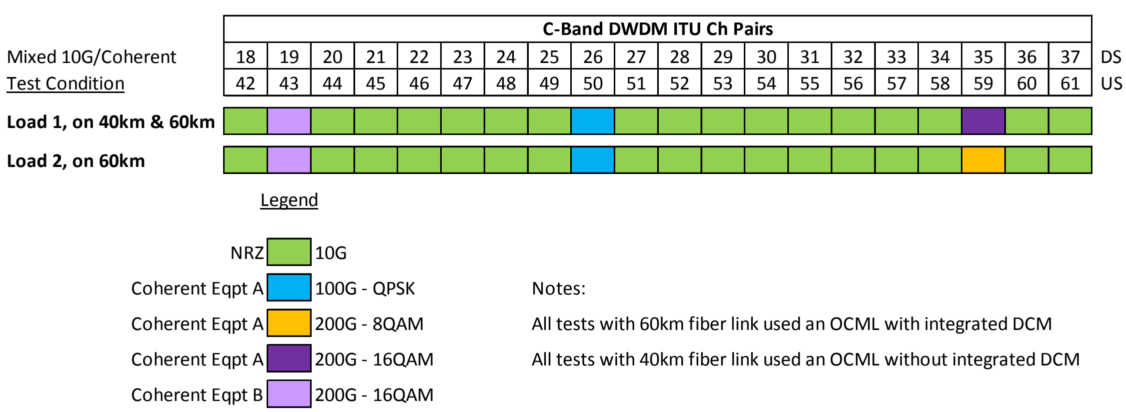

Figure 10 - Test Wavelengths (ITU Ch Pairs) and Optical Signal Types

4.2. Tests Performed

We first performed baseline tests with only the seventeen 10G signals present on the fiber link, and then with only the three 100G/200G Coherent signals present. With the 60km and the 40km fiber link and an additional 2.7 dB of optical attenuation inserted in the link, no uncorrectable errors occurred on any of the

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signal paths. Next, we combined the 10G and 100/200G Coherent signals on the fiber with the same link condition and again had no uncorrectable errors on any of the signal paths with either of the channel loadings.

After we established error free performance in the initial coexistence tests, we performed what we called Link Margin tests. In these tests we adjusted the variable optical attenuator (VOA) in the 60km and the 40km fiber link to determine the maximum amount of attenuation that could be inserted prior to the onset of uncorrectable errors for each equipment and modulation type. To do so, we first increased the optical attenuation in the link until we found the onset of uncorrectable errors. We then reduced the optical attenuation slowly in 0.5 dB increments to determine the maximum amount of attenuation that could be added without inducing errors. The Link Margin in dB was recorded in the test results for the various types of optical signals used in the test.

Lastly, we turned the 10G optical signals adjacent to the 100G/200G Coherent optical signals off to determine if it made any difference to Link Margin - which might occur if the Coherent signals were negatively impacted by Cross Phase Modulation (XPM).

4.3. Test Results

The Link Margin Test Results are presented in figure 11 below. Note that there were seventeen 10G NRZ channel pairs used in the test. We monitored all seventeen and recorded the worst case Link Margin in the results. The OCML's used in the testing make use of both downstream and upstream optical amplification, but the optical input power to the upstream EDFA gets lower on longer optical links, which in turn causes the upstream OSNR to be lower than the downstream OSNR. As expected, when we performed the Link Margin tests the upstream was the first to start taking errors, due to the combination of lower OSNR and low optical receive power.

Additionally, when we turned the 10G signals adjacent to the 100G/200G Coherent signals off and on, we found no difference to the measured Link Margin for the Coherent signals, indicating that there was no measurable XPM impact on the Coherent signals.

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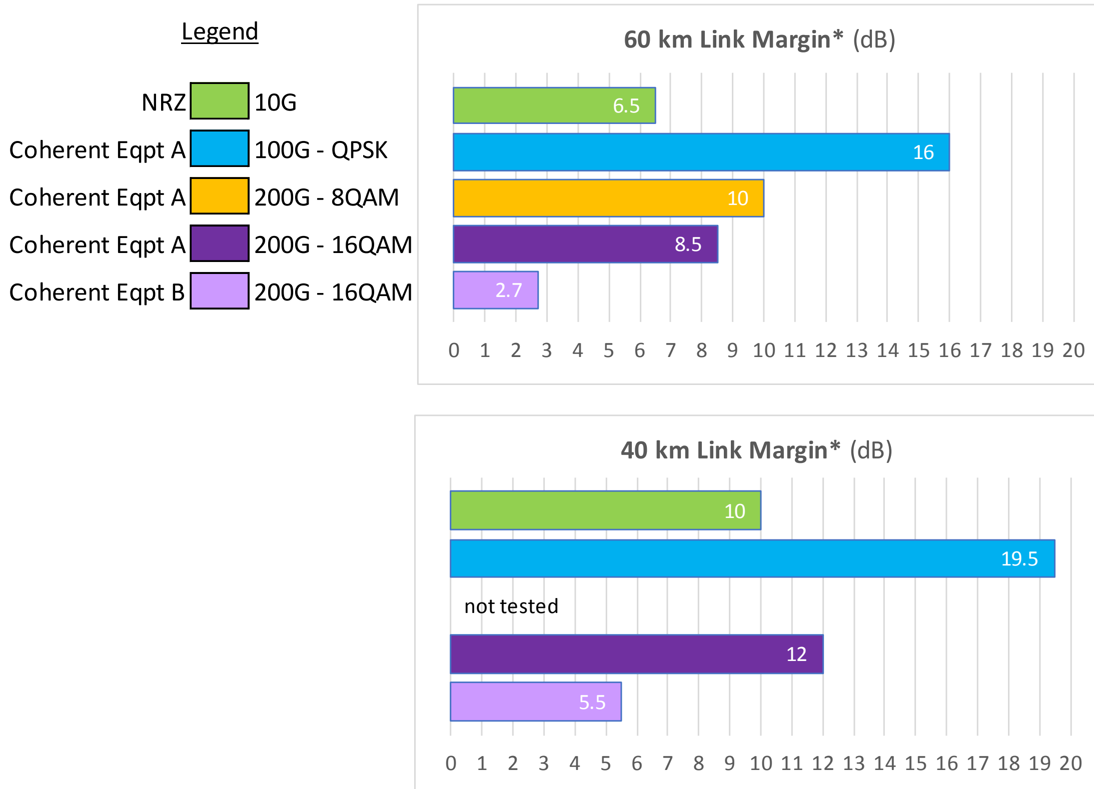

*__Link Margin__ = Maximum optical attenuation that could be added to the 40/60km link before onset of uncorrectable errors

Figure 11 - Link Margin Test Results

4.4. Test Conclusions

We proved that 10G NRZ and 100G/200G Coherent signals can coexist and perform well across 40 and 60km bi-directional optical links using the OCML/MDM. As expected, the amount of headroom (link margin) available depended on the type of Coherent equipment used and the modulation type. While the margin for the lower cost Equipment B Coherent type that we expect operators to use in Access applications was somewhat lower than with the tradtional 10G NRZ pluggable optics, it was the 200G equipment with higher order 16QAM modulation which had the highest OSNR requirements of the types tested. While we did not have any 200G 8QAM or 100G QPSK equipment available for testing in the lower cost Equipment B type, we anticipate such equipment will provide additional margin of roughly 2-7 dB, depending on type.

Link Margin (headroom) can be thought of in two ways. One is that each dB of margin might allow an additional dB of optical reach. The other is that each dB of margin affords additional protection from service interruption in the event of inadvertant conditions in the plant that create additional optical loss. When determining optical design guidelines it is best to consider both aspects and first apply an agreed upon minimum amount of margin to absorb undesired optical losses and account for equipment performance variation, and then consider the rest of the margin available for additional optical reach if

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needed. We recommend working with your selected equipment vendor on any designs incorporating Coherent equipment.

5. Coherent Access Applications

Long-haul and metro network systems have been utilizing the tremendous capabilities of optical Coherent transport for many years. Coherent transport is now being investigated for Access optical networks. In this section we will present some of the applications which can be supported by Coherent technologies.

5.1. Converged Cable Access Network

Figure 12 shows how several optical technologies may coexist on the same fiber using the Optical Communications Module Link Extender (OCML) and MDM network. This network supports several optical technologies and applications, resulting in a powerful, scalable and technology agnostic solution. It can provide 10G for cable RPDs (Remote-PHY Devices) and RMDs (Remote-MAC Devices),as well as 100G/200G Coherent for high capacity applications such as businesses, hotels, hospitals and MDUs. A Coherent optical trunk can also support Remote-PHY nodes but would need an outside plant aggregation node device to provide dedicated 10G fiber links to the RPD nodes.

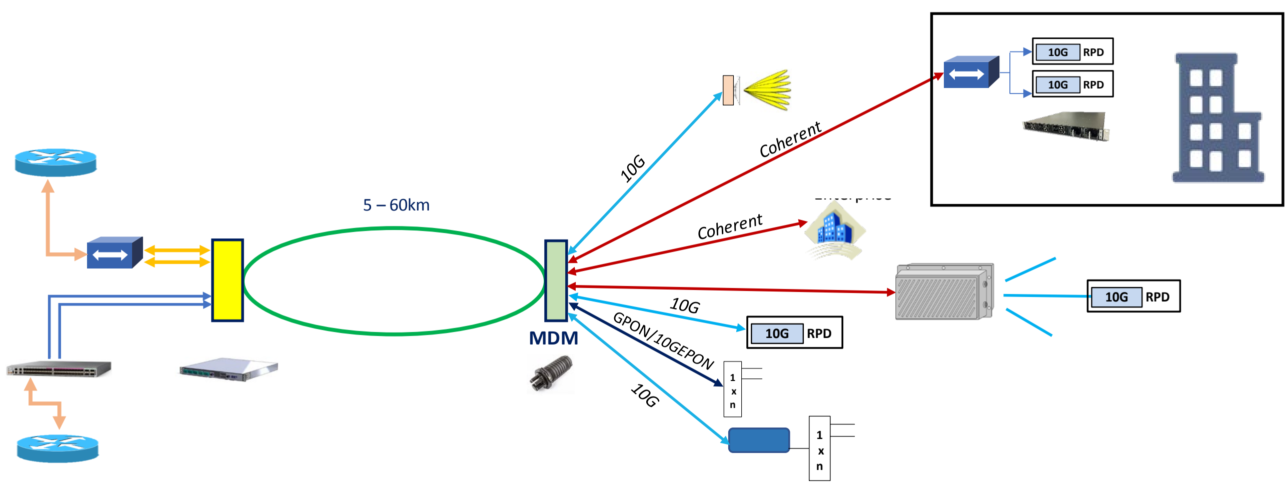

Figure 12 - Converged Cable Access Network

5.2. Remote-PHY Coherent Optical Trunk

Figure 13 shows how a Remote-PHY architecture utilizing a Coherent link can be realized with a high capacity Coherent optical trunk. Essentially a 100G/200G Coherent link would feed an outside plant, hardened aggregating device to provide up to 10G data links to individual Remote-PHY Nodes. These 10G links can be lower cost grey (1310nm) optics, with each RPD supported by a dedicated fiber pair for downstream and upstream.

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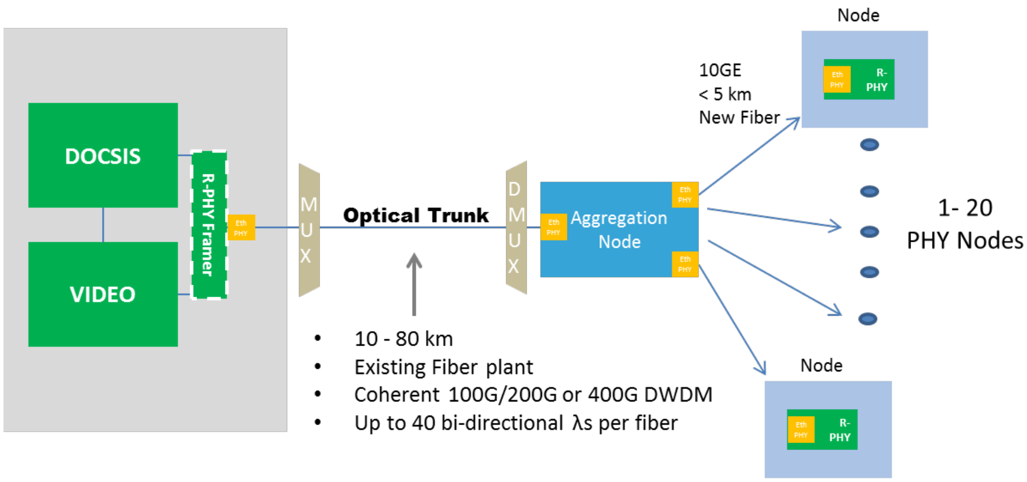

Figure 13 - Remote-PHY Physical Distribution

This hardened (I – Temp) aggregation node can be a Muxponder, Ethernet Switch or Router, depending on operator architectures and preferences. The main features of the various types of aggregation devices are given below.

5.2.1. *Muxponder*

A Muxponder operates at Layer 1. It is a simple, low-cost device which provides dedicated bandwidth or capacity with 100% mapping, essentially the same inputs as outputs. A Muxponder does not support statistical multiplexing nor over-subscription. The total backhaul capacity is shared equally between the output ports, so a 200Gbps optical link can provide 20 x 10G ports, each with dedicated 10G to RPDs. The muxponder is the easiest and lowest cost option to support DAA architectures.

5.2.2. *Ethernet Switch*

An Ethernet switch operates at layer 2 and allows both statistical multiplexing and oversubscription. The inputs and outputs need not match, so a 100G optical link can provide 20 x 5G ports to provide 5G links to RPDs. An Ethernet switch can technically operate with less backhaul capacity than a muxponder. An Ethernet switch is a relatively simple device, but more complex than a muxponder. It will also cost more and have a higher power consumption than a Muxponder. It requires a backplane with switching capacity to handle all inputs and outputs. An Ethernet switch is perhaps a good compromise between a muxponder and a full-fledged router as described in section 5.2.3 below.

5.2.3. *Router*

A Router operates at Layer 3 and can do all the same things as an Ethernet switch. It natively supports multicast replication and for Remote-PHY permits lower backhaul capacity requirements until the service group to RPD ratio becomes 1:1. It is moderately more complex than an Ethernet switch and likely costs more and consumes more power. From the various aggregation node types described in this section, the router affords the most flexibility, but comes with a higher degree of complexity, power consumption and cost.

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5.3. RPhy 10G DWDM Optical Trunk Transition to Coherent

Figure 14 shows a typical spine and leaf network where the CCAP aggregation switch is connected to the OCML with multiple 10G signals. The OCML is connected to an MDM through a primary and backup secondary fiber. The MDM provides 10G dedicated links to Remote-PHY devices. In transitioning to a Coherent optical trunk, the Spine Aggregation router could be directly connected to a Coherent transport system and input to the OCML. The "leaf" CCAP Agg switch could then be moved to an outside plant location, but would need to be housed in a temperature hardened device (aggregation node). This type of aggregation node would also need to contain the necessary hardened Coherent transceivers plus the switching fabric to provided lower capacity 5G to 10G connections to Remote-PHY Devices.

We could replace a 10G DWDM ring with a Coherent 100G or 200G optical trunk. This would reduce the number of 10G ports at the headend but we would then need a more complex, active hardened device in the outside plant. The advantage of a Coherent optical trunk is that we would only need a single Coherent wavelength to feed all the RPD devices in a typical node serving area, thus freeing other wavelengths to support higher bandwidth applications like business services, hospitals, schools, etc.

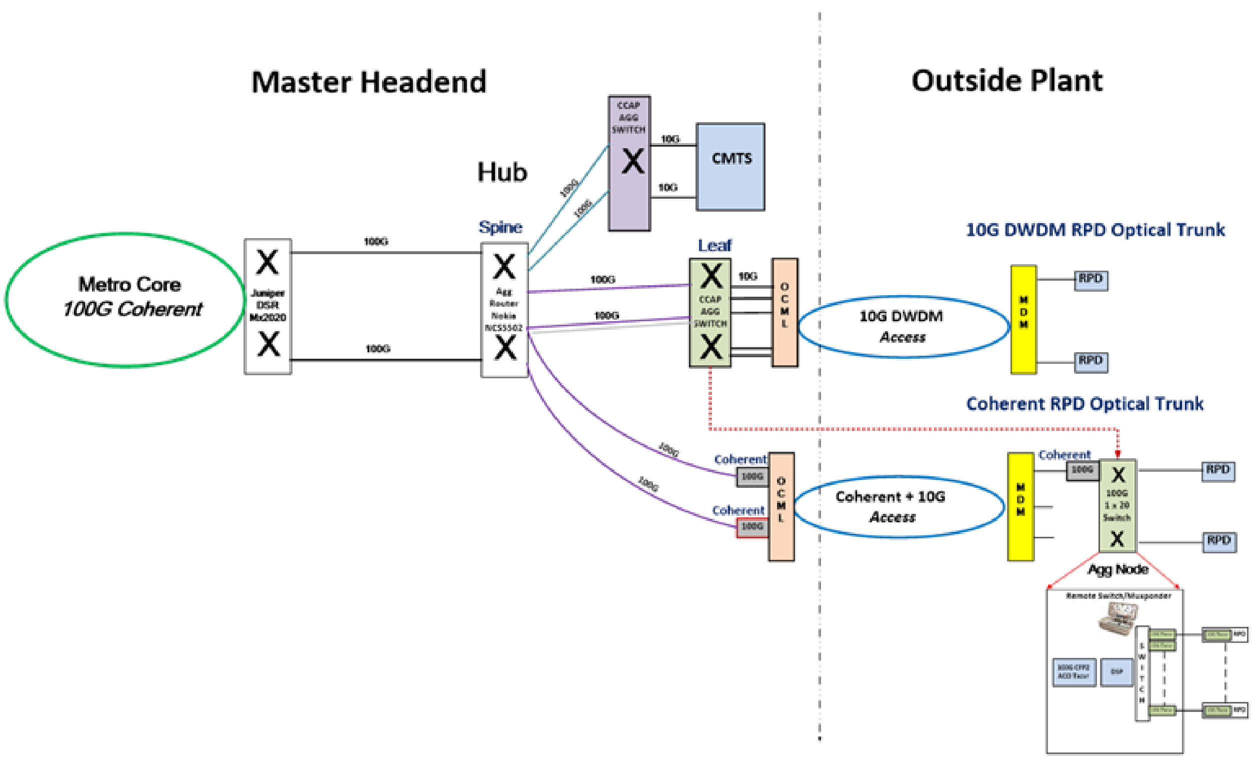

Figure 14 - 10G DWDM Optical Trunk Transition to Coherent

5.4. Coherent Business Service Applications

Figure 15 shows a Coherent 100G/200G DWDM Access network which can support business services and other high capacity applications such as Airports, Conference centers, hospitals, etc. The OCML would be located at the headend while the MDM would be physically located near an existing HFC node

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and provide multiple Coherent 100G or 200G outputs. Applications requiring high capacity bandwidths can be provided with a dedicated Coherent 100G/200G link.

Figure 14 also shows how a Coherent 100G link could be provided to existing cabinets where muxponders, switches or routers could be used to provide lower capacity such as 1G and 10G services. This architecture fully utilizes the capacity of Coherent technology to provide ever increasing bandwidth to customers.

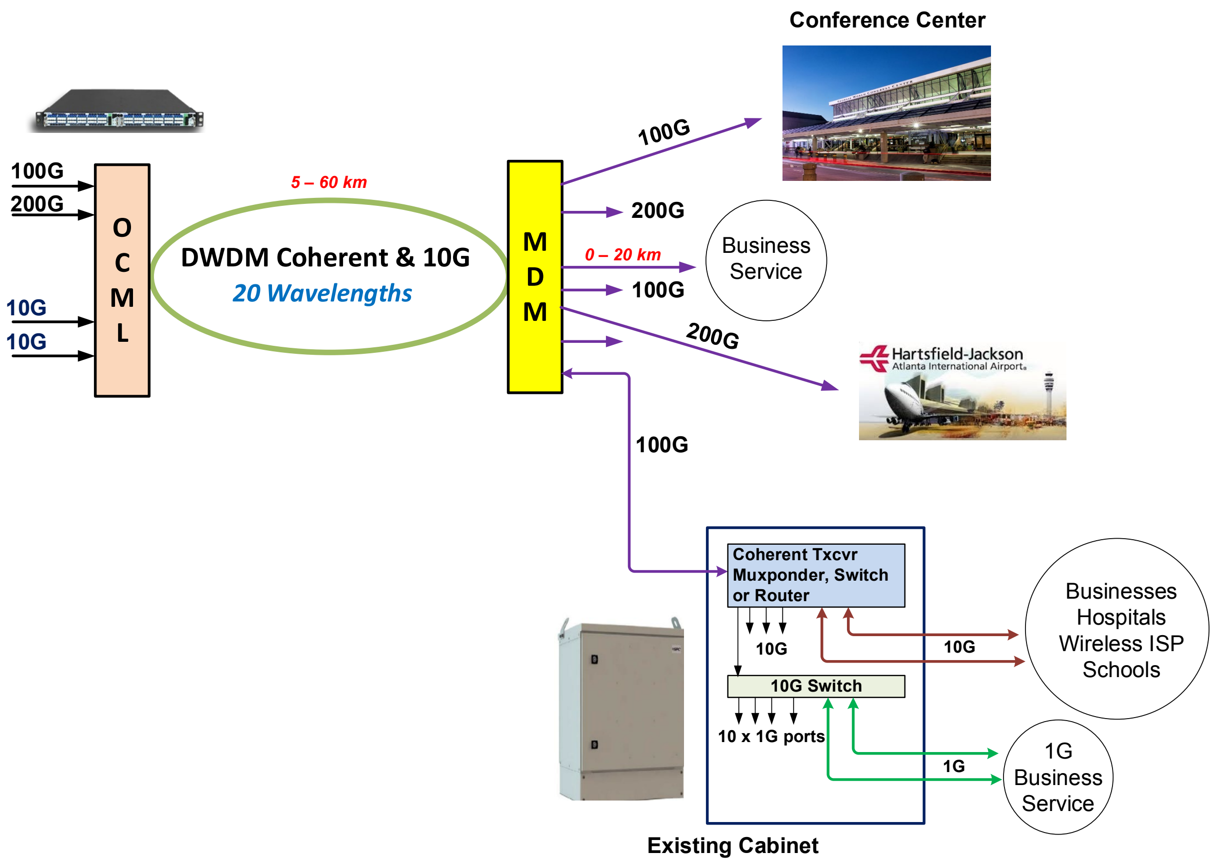

Figure 15 - Coherent Business Services

5.5. Coherent Hub Consolidation

With its high capacity DWDM capability, Coherent transport could also be used for Hub consolidation or collapsing the hubs to smaller sizes. Figure 16 shows a typical metro MSO fiber optical ring where several hub sites are connected. If we have multiple 10G DWDM links feeding Remote-PHY devices at hub A, these could be aggregated via muxponders onto a 200G DWDM ring and transported back to the master headend. This would considerably reduce equipment required at Hub A which could be collapsed into a much smaller footprint, potentially in a hut or hardened cabinet.

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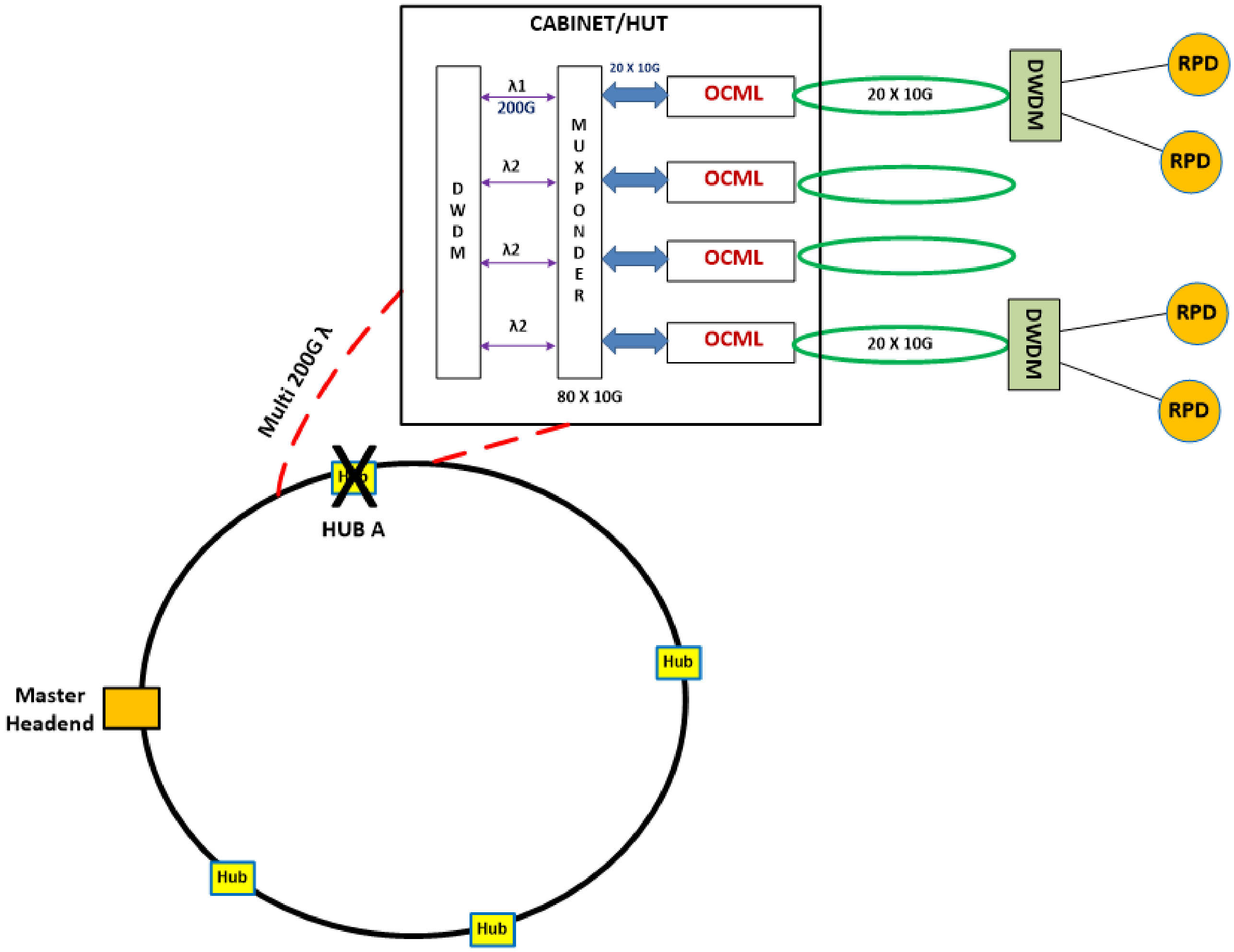

Figure 16 - Coherent Hub Consolidation

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6. Conclusion

A high-performance Access network is key to the commercial success of delivering broadband services to the customer. In addition, Access networks should be scalable and technology agnostic. 10G NRZ and 100G/200 Coherent coexistence on a single fiber through an integrated platform (OCML) has been successfully demonstrated over 60km with dispersion compensation and 40km without dispersion compensation. We tested two types of Coherent equipment, a high performance, long-haul (A) and a lower cost, lower performance Access/Edge Coherent device (B). We established that both Coherent 100G QPSK and 200G 8 QAM and 16 QAM could easily be transported through the OCML – MDM infrastructure, and as expected, the Coherent 100G had greater reach (link margin) than the Coherent 200G. Several Access applications using Coherent 100G/200G have also been presented. In conclusion, with data rate requirements increasing every year, the huge capacity capability of Coherent can be used effectively to supplement or transplant 10G OOK signals in the Access region of MSO networks.

Abbreviations

OCML	Optical Communications Module Link Extender
MDM	Mux DeMux
MTC	Master Terminal Center
STC	Secondary Terminal Center
10G	10Gbps
DSP	Digital Signal Processing
LO	Local Oscillator
Bps	bits per second
FEC	Forward error correction
HFC	Hybrid fiber-coax
SCTE	Society of Cable Telecommunications Engineers
OIF	The Optical Internetworking Forum
DCM	Dispersion Compensation Module
NRZ	Non-Return-to-Zero
DWDM	Dense Wavelength Division Multiplexing
RPD	Remote-PHY Device
FTTH	Fiber to the Home
PON	Passive Optical Network
GPON	Gigabit-capable Passive Optical Network
PIN	**PIN diode** has a wide, undoped intrinsic semiconductor region between a p-type semiconductor and an n-type semiconductor region.
APD	Avalanche photo diode
OSNR	Optical to Signal Noise Ratio
OOK	On-Off keying
NCG	Net Coding Gain
DCI	Data Center Interconnect (DCI)
BOL	Beginning of Life

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Bibliography & References

1. DWDM Access For Remote-PHY Networks Integrated Optical Communications Module (OCML), Harj Ghuman SCTE 2017.
2. Optimizing the Performance of Coherent 100G in 10G Dispersion-Managed Networks,
3. Coriant White Paper.
4. Coherent WDM technologies, Infinera White Paper.
5. Soft-decision Forward Error Correction for Coherent Super-channels, Infinera White Paper.
6. Backhaul Capacity for Optics in Remote-PHY, IEEE 802.3 Interim March presentation, Fernando Villarruel, Harj Ghuman, Michael Eggert, Marek Hajduczenia.
7. FEC in Optical Communicatios, A.Tychopoulos, O. Koufopavlou, I. tomkos, IEEE Circuits & Devices, 2006.
8. Evaluating 200G/400G solutions for practical deployments in long-haul network, Electronic Letters, Sep. 2016, Y. Ma, S. Makovejs, Q.Wang, W.Wood, N. Kaliteevskiy, J. Li, C. Zhang
9. Real-time transmission of 16 Tb/s over 1020km using 200Gb/s CFP2-DCO, H. zhang, B. Zhu, S. Park, C. Doerr, M. Aydinlik, J. Geyer, T. Pfau, G. Pendock, R. Aroca, F. Liu, C. Rasmussen, B. Mikkelsen, P. I. Borel, T. Geisler, R. Jensen, D. W. Peckham, R. Lingle , D. Vaidya,. F. Yan, P. Wisk, D. Digiovanni, Optics Express, 2018

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