Digital Coherent Transmission for Next-Generation Cable Operators' Optical Access Networks

A Technical Paper prepared for SCTE/ISBE by

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Introduction

Cable operators' residential offerings of Gigabit per second service are occurring on a regular basis now, and access bandwidth requirements are expected to grow to multi-Gigabit per second speeds driven by increasing 4K/8K video streaming, proliferation of cloud computing, big data, social media, Internet of Things, and mobile data delivery. Existing Hybrid Fiber Coax (HFC) networks have typically been designed with 6 to 8 fibers connecting the hub to the fiber node; however, many of these fibers have been repurposed for business services, node splits and backhaul services. In many instances, only the two primary fibers remain available for access network transport. This fiber shortage will only intensify as fiber demand for business and wireless backhaul increases and fiber deep architectures become prevalent. Efficient use of optical fiber infrastructure and adoption of innovative technology becomes critical in the evolution towards next-generation cable access networks.

The current analog or direct detection optical schemes face huge challenges because of their low receiver sensitivity and limited options for long-term upgrading, especially in the legacy fiber environment, where operators continue to take advantage of the existing infrastructure to avoid costly fiber re-trenching. Coherent technologies have been recently considered as the most effective future-proof approach for both brown and green field optical access deployments. Thanks to the advancements in digital signal processing (DSP), digital coherent detection enables superior receiver sensitivity that allows an extended power budget and high frequency selectivity enabling dense wave division multiplexing (DWDM) without the need of narrow-band optical filters. Moreover, the multi-dimensional recovered optical signal provides additional benefits to compensate linear transmission impairments such as chromatic dispersion (CD) and polarization mode dispersion (PMD). In the cable access environment, coherent optics allows operators to best leverage the existing fiber infrastructure to withstand the exponential growth in capacity and services. However, there are several engineering challenges of introducing digital coherent technologies into optical access networks. To reduce the power consumption and thereby meet the size and cost requirements for access applications, development of both low-complexity application-specific integrated circuits (ASICs) and optics is essential. In particular, co-design of a DSP ASIC and optics to trade performance against complexity, cost and power consumption is imperative.

In this paper, use cases are explored for near-term and long-term applications, including the deployment for aggregation points in distributed HFC architecture (Remote PHY or Remote MAC and PHY, abreviated R-PHY/ R-MAC-PHY), remote Passive Optical Network (PON) systems, and eventually coherent optics to the premises. The corresponding economic model for near-term aggregation transmission system will be presented for the comparison with WDM direct detection system. This paper provides an in-depth analysis describing a typical digital coherent optical system, including basic elements of multi-dimensional modulation scheme and a digital coherent receiver structure with fundamental DSP building blocks for both optical transmitter and receiver. The current evolution of coherent optical modules is also introduced.

This paper highlights the motivation for coherent optics in access and potential approaches to re-design and re-engineer the digital coherent concept from long-haul and metro solutions to the access network, leveraging reduction in complexity and cost as well as the benefits of capacity increases and operational improvements. Proof-of-concept experimental results demonstrating multi-wavelength multi-terabit per second within an access environment and the evaluation of coexistence between legacy analog and coherent system are also shown here.

Content

1. Increasing Demand for Higher Bandwidth

Video intensive technologies require the most bandwidth, and currently out of all the video-related applications, Virtual Reality/Augmented Reality (VR/AR) are the most demanding. Current VR applications are little more than 360º video/panoramas. A low quality 360º video requires at least a 30 Mbps connection, HD quality streams easily surpass 100 Mbps, and retina quality(4k+) streams approach Gbps territory. However, there are still many things holding back its use beyond showrooms and proof of concepts, the most glaring problem being our network's capacity.

These days it seems that just about everything is getting smarter, from thermostats to refrigerators, and becoming ever-more connected. Each of these devices -- physical objects with data sensing, analyzing, and recording functions plus the ability to communicate remotely -- collectively form the "Internet of Things" (IoT). Clearly, expansion in the use of smart devices is an unstoppable force, but one thing could hamper this growth -- inadequate bandwidth. While most of the devices that comprise the IoT communicate wirelessly with the world, all the data that they send must be transmitted over a physical wireline network between wireless access points. High throughput, low latency and high reliability networks will be needed for applications such as video analytics in public safety and to support self-driving cars. [1].

In the upcoming 5G era, massive MIMO (Multiple-Input Multiple-Output), Carrier Aggregation, Multi-band support, and radio cell densification are impacting the bandwidth requirements, while the coexistence between macro, micro, pico, and small cells along with a centralized/virtualized processing environment are impacting the flexibility requirements. Fiber and optical access technologies are expected to play more and more important roles in the fronthaul and backhaul services to meet the aggressive performance goals of 5G.

Cable has been undergoing significant changes impacting network speeds which are not only caused by the ever-increasing residential data service tier growth rate but also due to an increasing number of services types being supported, such as business services and architectural changes in the HFC network. With the advent of network function virtualization and more and more applications running from the cloud, cloud computing related capacity is bound to make an impact. Therefore, it is safe to say that not one application or service is driving the increases in capacity but that the aggregate of multiple services has steadily maintained the exponential growth observed in broadband networks. Figure 1 depicts the historical growth of broadband service offerings including a constant growth rate extrapolation up to the year 2030.

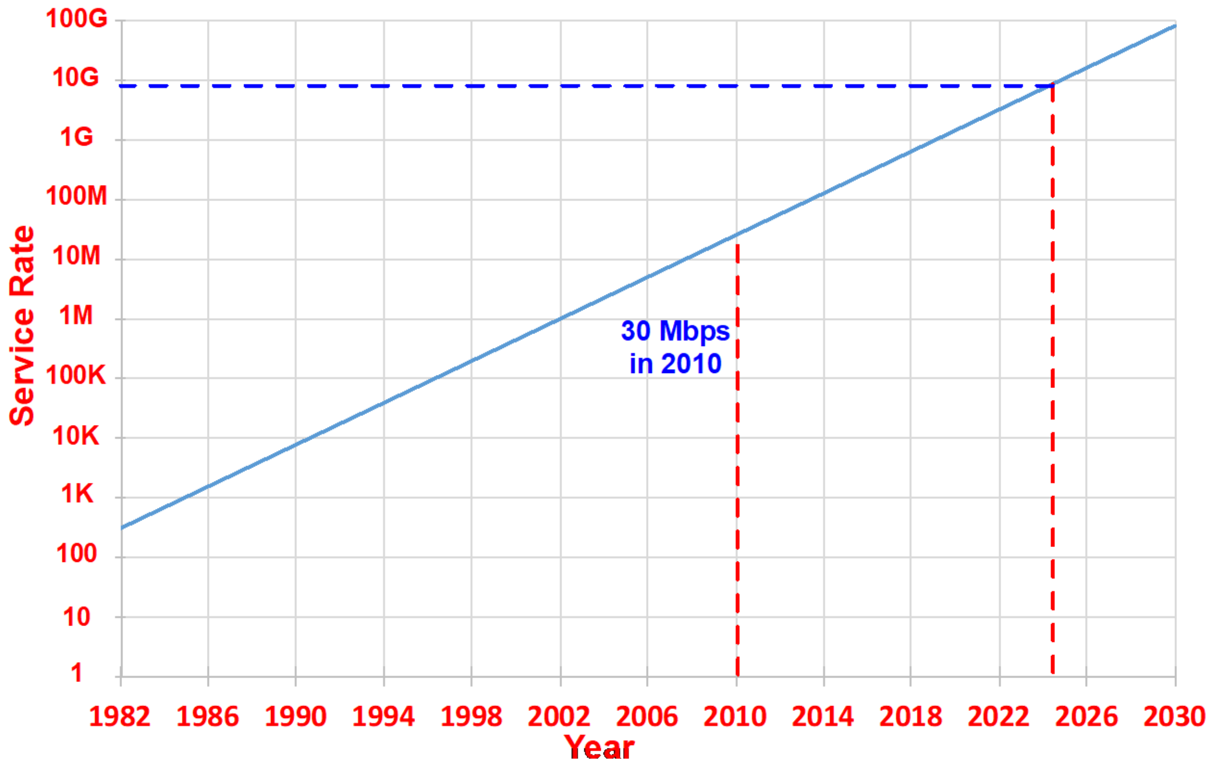

Figure 1 - Exponential Growth of Broadband Service Offerings

2. Fiber Shortage Challenge in Cable HFC Network

In cable, the fiber access networks extend from the hub or headend to the fiber node. These fiber links are typically laid out by running a fiber bundle that passes by different nodes. From a splice point near a fiber node, a fiber cable with fewer fiber strands is trenched or strung to the node. In this initial HFC build-out, 6 to 8 fiber strands were typically dedicated to a node. This was ample at the time because cable companies primarily were offering broadcast services. Most fiber distances from node to hub are less than 25 miles, although in a few areas where hubs may have been consolidated, distances may be as long as 100 miles, leveraging the maximum distances allowed in DOCSIS 3.0 (Data Over Cable Service Interface Specification 3.0) and earlier versions. Figure 2 shows a representation of the fiber access network that extends from a hub.

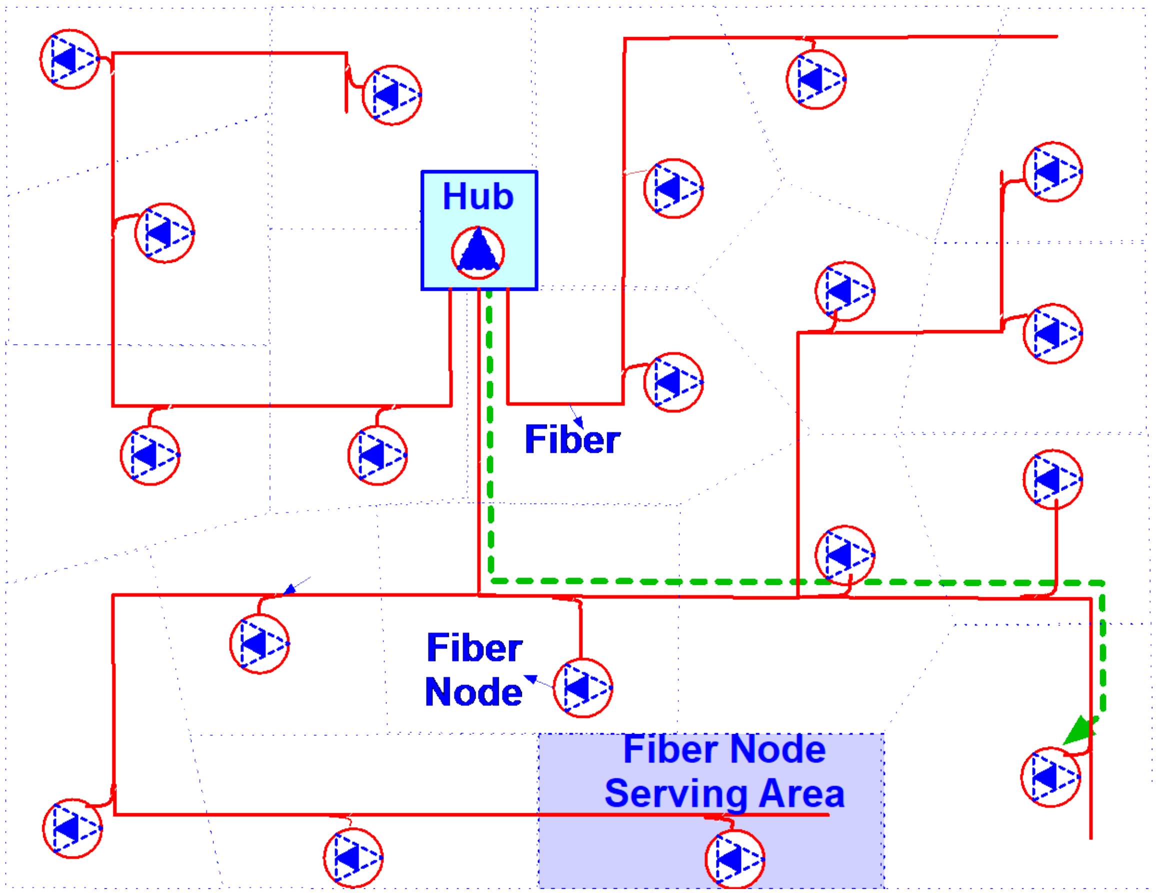

Figure 2 - Fiber Distribution in Access Network

When these HFC networks were built in the mid 1990s, this capacity expansion has been addressed through RF spectrum expansion from 750 MHz to 860 MHz and 1 GHz as well as through node splits, meaning that the original fiber node serving area size of 500 households passed would be split or segmented into smaller portions. These newer smaller nodes consumed some of the spare fibers available.

In addition to spectrum expansion, capacity needs have also been addressed by improvements in transport efficiency. For the past 20 years, DOCSIS technology has been the main transport technology of cable data. After many protocol iterations, in DOCSIS 3.1 today, 4096 QAM (Quadrature Amplitude Modulation) upstream modulation and 16384 QAM downstream modulation are possible. To support these much higher fidelity RF signals, the traditional intensity modulation requires a very high signal to noise ratio (SNR). This SNR, > 47 dB for 16384-QAM and >43 dB for 4096-QAM, requires very high optical power levels. A side effect of using very high optical power levels is that they drive fiber into nonlinear operation and distort the signals within this fiber transmission. WDM is a technique leveraged to make efficient use of fiber resources, however, the nonlinear distortion in fiber at high optical power levels, makes wavelength multiplexing of analog carriers challenging. The end-result is that a single fiber cannot handle many analog optics carriers with high fidelity RF signals.

While the demand for residential data service rates has been steadily increasing, operators also expanded their services portfolio to include business and wireless base station connectivity. As a result of these new services, some fiber strands in the access were re-purposed to address that need. In high demand business areas as few as 2 fibers per node may be available. Demand for higher upstream rates has been a key driver for a technology called Full Duplex DOCSIS, which requires passive N+0 topology implemented in what is called Distributed Architectures. In a distributed architecture, at least the PHY portion of the CMTS (Cable Modem Termination System) resides at the node. At the remote PHY device at the node, through RF and digital cancellation mechanisms, the strong downstream transmit signal impact on the weak upstream receive signal is cancelled. Figure 3 shows a traditional node serving area of about 500 HHP while Figure 4 shows the N+0 upgrade of that same serving area which could support Full Duplex DOCSIS systems.

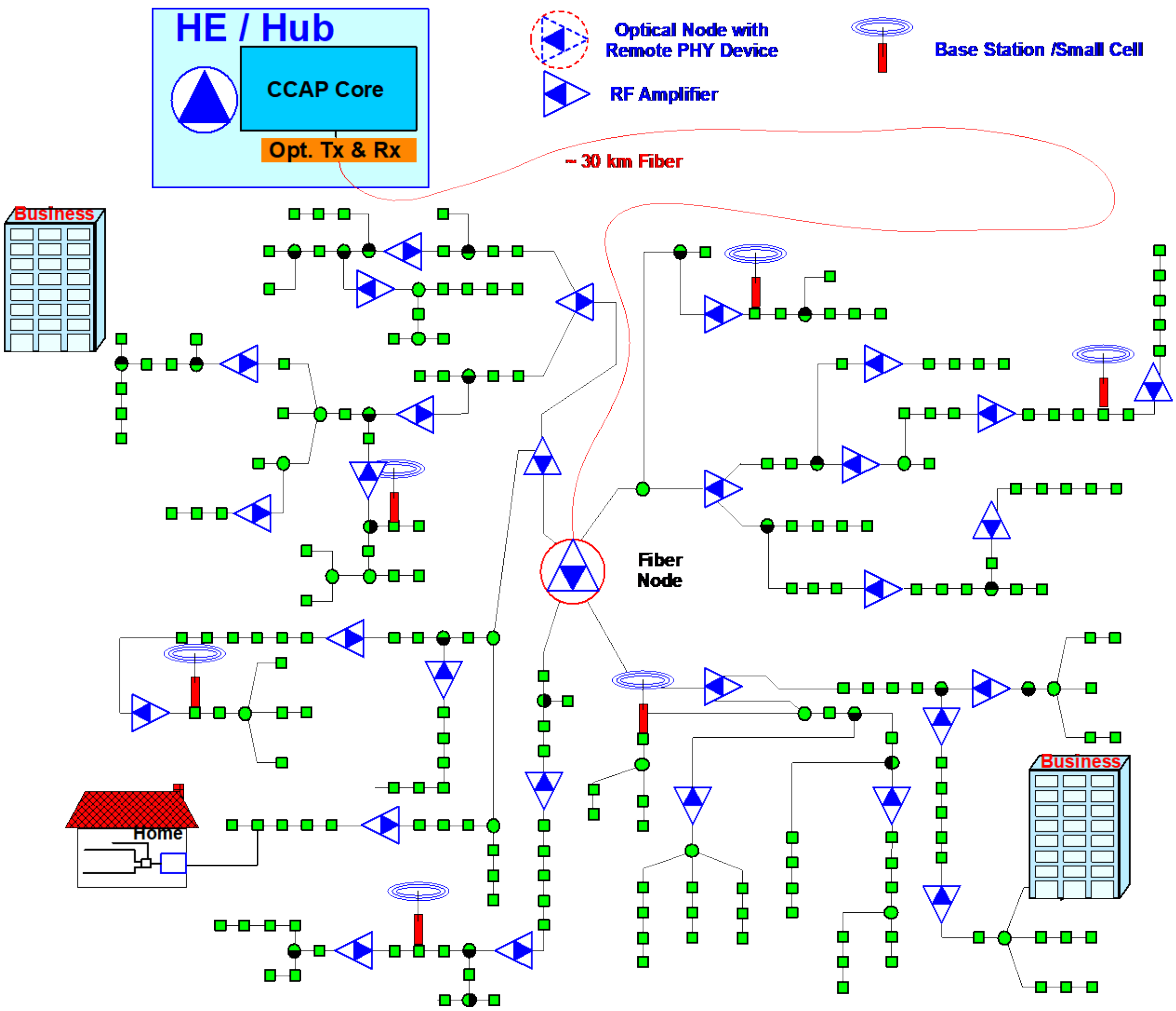

Figure 3 - Traditional Node Serving Area

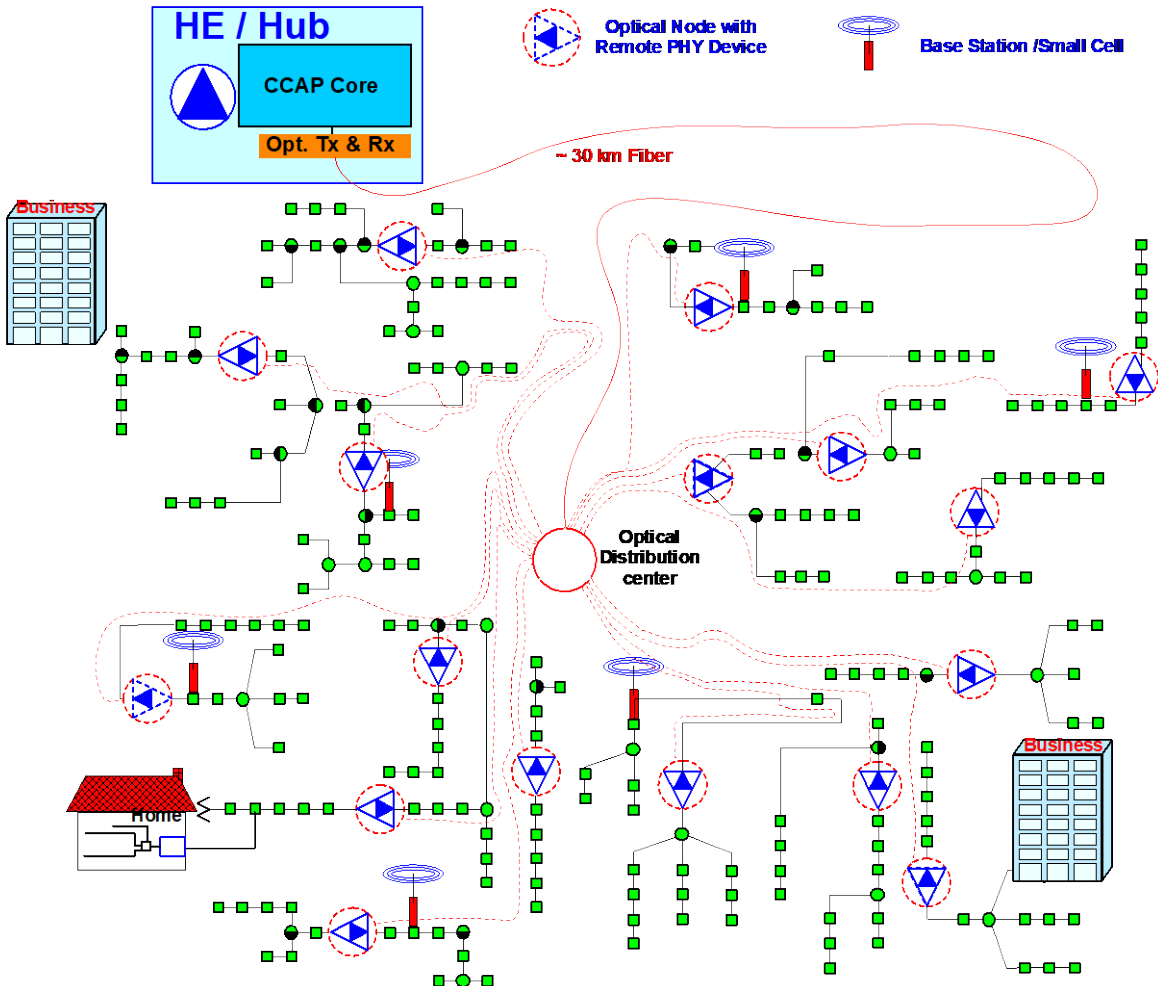

Figure 4 - Original Node Serving Area upgraded to N+0

In Figure 4, some of the amplifiers observed in Figure 3 are not used, while the rest of the amplifiers have been replaced by optical nodes. In N+0 networks like the ones shown in Figure 4, the distance between the node and the subscriber is probably less than 1000 feet [2], [11] through [15].

The cable fiber environment can thus be considered as sparse from a fiber strand count perspective but deep as the fiber is quite close to any potential subscriber. Just driven by the fiber network characteristics and topology, the technologies that the cable industry may consider and select, may not be the appropriate solution for other industries that don't share the same fiber environment characteristics as cable.

The key difference between Figure 3 and Figure 4 is the increase number of optical endpoints in Figure 4. As indicated earlier, transitioning to the architecture in Figure 4, also implies a transition to a Distributed Architecture. This means that it is no longer a centralized architecture, where the CMTS remains at the hub and analog optics carries RF signals to the nodes, but in a Distributed Architecture at least the PHY portion of the CMTS is remotely located in the node. Figure 5 shows the traditional centralized architecture with the CMTS located at the hub.

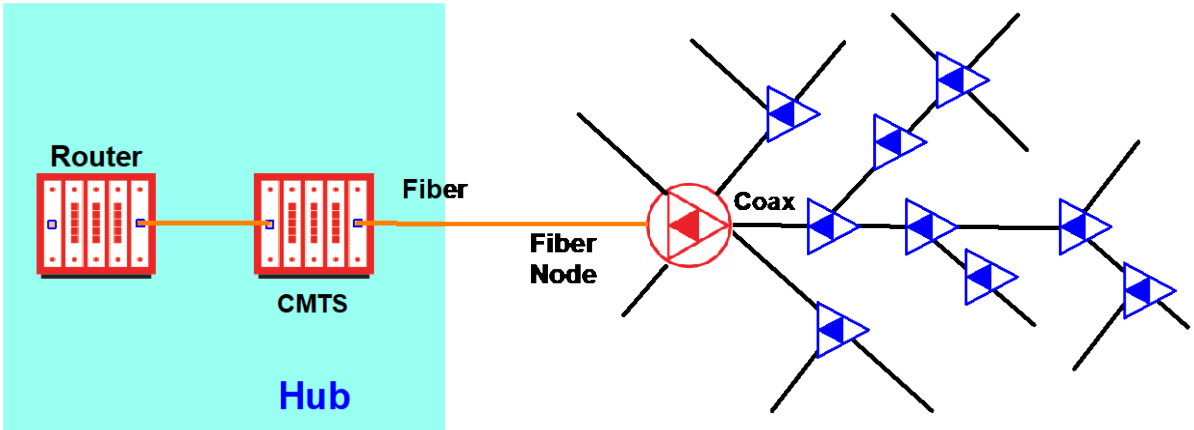

Figure 5 - Traditional Centralized Architecture

3. Coherent Optics Use Cases in Cable

The combination of the natural evolution of coherent optics technology, along with the 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 strategy.

This demand is not just for residential connectivity but also for business and cellular connectivity. A short-term strategy would not only result in an inefficient use of resources but also in having operators upgrading technology within a few years.

Coherent optics technology can be leveraged in cable following two general approaches. One is when used as a mean of multi-link aggregation and a second one is through direct edge-to-edge connectivity to the desire end-point. Following capacity growth trends, it is obvious that initially the aggregation use cases are going to out-number the direct edge-to-edge connectivity use cases. Within these broad categories, one can identify finer granularity sub-categories of these use cases.

3.1. Aggregation Use Case Scenarios

There are two-dominant aggregation use case scenarios, the first one being the use case of aggregation of multiple remote PHY or remote MAC/PHY devices. Figure 6 shows the distributed architecture example where the CMTS is split between a remote PHY device located at the fiber node and the MAC portion of the CMTS also known as CCAP core, is located at the hub. The hub and the aggregation node is connected through 100G or 200G per wavelength coherent optical transmission system.

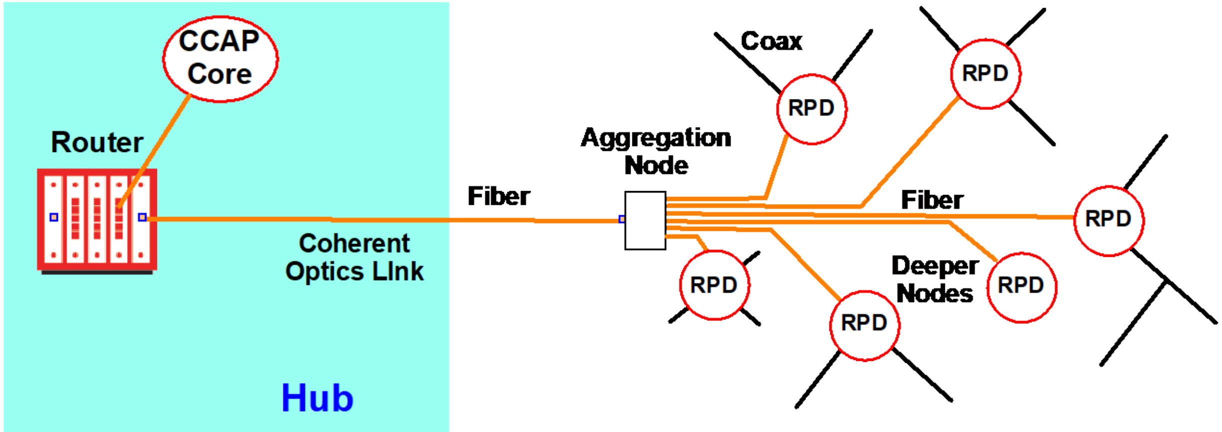

Figure 6 - Distributed Architecture with Traffic Aggregation at Original Node Location

In this distributed architecture, the optical transport is baseband digital optical transport and the DOCSIS RF is generated at the node by the remote PHY or remote MAC/PHY device. The downstream .DOCSIS 3.1 RF spectrum is capable of carrying about 10 Gbps worth of data.

While wavelength multiplexing could have been used to carry traffic to and from RPDs or to carry the aggregate traffic from RPDs within a node serving area to the hub, cost and operation complexity of managing a large number of ports and managing wavelengths are important considerations. Section 3.3 covers scenario cost comparisons including some of these considerations.

The second use case is aggregation of PON networks through the connection of multiple optical line terminals (OLTs) (Figure 7).

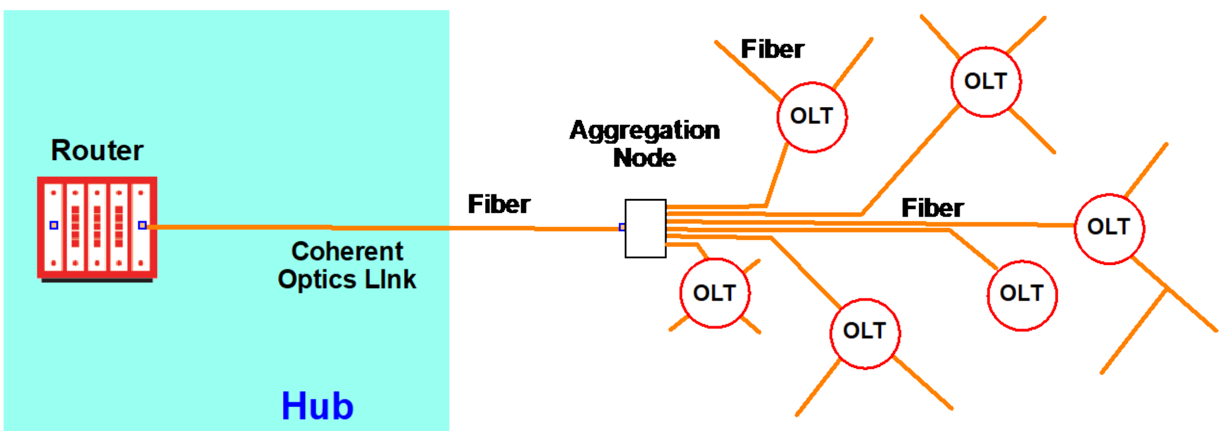

Figure 7 - PON Aggregation, OLTs may be Collocated with Aggregation Node

In addition, although at a lower scale, there could be aggregation of business service traffic and/or aggregation of traffic from base stations. Cable operators' public announcements towards N+0 architectures over the next decade in part of their footprint make the aggregation of multiple nodes, the most likely aggregation use case where coherent optics will play a role. The advent of Full-Duplex-DOCSIS technology drives the evolution towards N+0 architectures. Cable fiber nodes were designed with 6 to 8 fibers dedicated to an individual fiber node covering around 500 HHP. Since some of these fibers may have been re-purposed to provide business connectivity or for node splitting, a cable service provider can safely rely on having just two fibers available.

Based on traffic demand and traffic growth particularly in the upstream, node demographics and topology, proximity to businesses and other criteria, we could assume that over the next decade a portion of these nodes will gradually migrate to N+0.

In these scenarios, a sustained market size of approaching 100,000 transceiver units after four years has been estimated. Since the need for coherent transceivers supporting N+0 migration is expected to dominate the market, wireless backhaul and Business link aggregation use cases were not included in this estimate.

3.2. Direct Edge-to-Edge Connectivity Use Case Scenarios

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. 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.

As demand for capacity further increases, the capacity required by each RPD will surpass 10 Gbps and operators will likely be required to split that N+0 node and/or extend the RF coaxial spectrum. Such an environment, urges a review of the optical transport approach. This implies that the deeper node instead of requiring 10 Gbps, could require 40 Gbps or higher capacity. At these capacity levels, one has to explore the advantages of an aggregation strategy versus a direct edge-to-edge connectivity strategy. Today a multi sector, multi carrier cellular system requires a 40 Gbps feed. With a capacity compound annual growth rate in cellular greater than 50% [1] and the expected proliferation of 5G access points in the near future, direct edge-to-edge connectivity using coherent optics is quite appropriate.

As is described in the next section, coherent technology, because it operates at the lowest optical power and more efficiently uses the fiber wavelength spectrum, is the best neighbor to other optical transport technologies.

3.3. Economics of Coherent Optics in the Aggregation Use Case Scenario

For the Aggregation Use Case depicted in Section 3.1, other digital optics solutions can achieve similar results in meeting bandwidth demand. Dense wavelength division multiplexing (DWDM) + Direct Detection (DD) allows the combination of incremental 10 Gbps wavelengths to meet the capacity demand of aggregating traffic from multiple end points at a single location (such as shown in Figure 6 and Figure 7). However, DWDM + DD depletes a scarce spectral resource when scaling to meet bandwidth demand, whereas coherent optics can provide sufficient bandwidth on a single wavelength with very high spectral efficiency. The opportunity cost of a wavelength can be quantified in many ways, such as the missed revenue opportunity for leasing high-bandwidth wavelength services to enterprise customers.

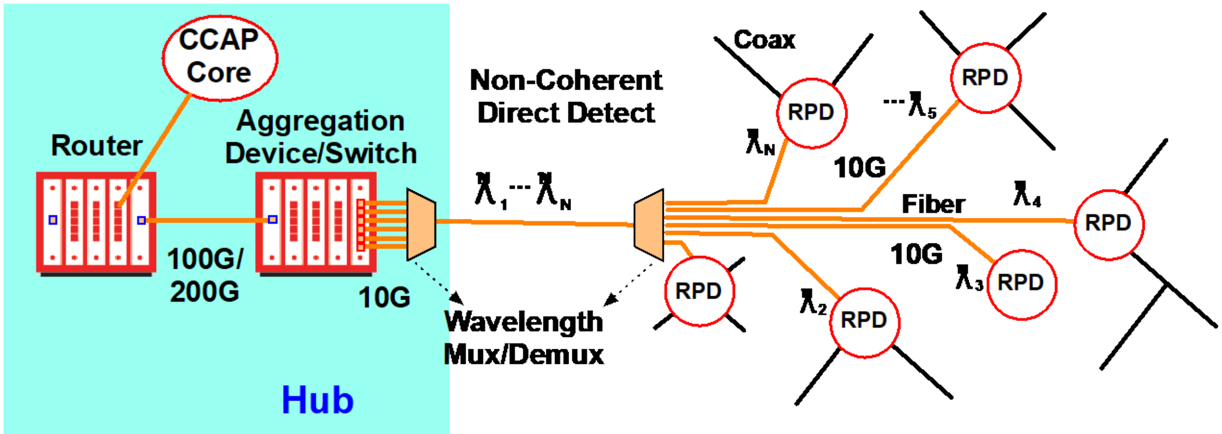

Figure 8 - DWDM + Direct Detection for Aggregation Node

The real economic value of coherent optics versus DWDM direct detection (DD) scheme (see Figure 8) can be shown in the scale provided when aggregating multiple end points, whether for Remote PHY Devices or for OLT's. A passive edge-to-edge DWDM + DD solution requires more expensive Fixed DWDM 10 Gbps optical transceivers from the aggregation point to the end points because of longer transmission distance. A coherent optics solution can use less expensive 1310 nm 10 Gbps optical transceivers to connect the aggregation point to the end points with a couple thousand feet distance. According to IHS, the 1310 nm transceiver are 1/3 the cost of Fixed DWDM transceivers today [15], [16], [17]. Further, the Multi-line gearbox (MLG) in the coherent optical transceiver provides flexible bandwidth allocation to end points.

Assuming current coherent optical transceiver (CFP2-DCO) costs for metro networks, coherent optics becomes a more cost-effective solution than wavelength multiplexing when aggregating 14 or more end points as shown in Figure 9. This breakeven point may not seem too impressive until considering the following factors: 1) most Node+0 architecture call for aggregation of 12-18 mini-nodes or Remote PHY Devices; 2) Coherent optics can reach up to 80 km without the need for dispersion compensation; 3) Coherent optics uses a single wavelength up to 200 Gbps, directly connected to the CMTS at a hub without the need for demultiplexing; and 4) the Coherent optics transceivers are not optimized for the Cable Access Network today.

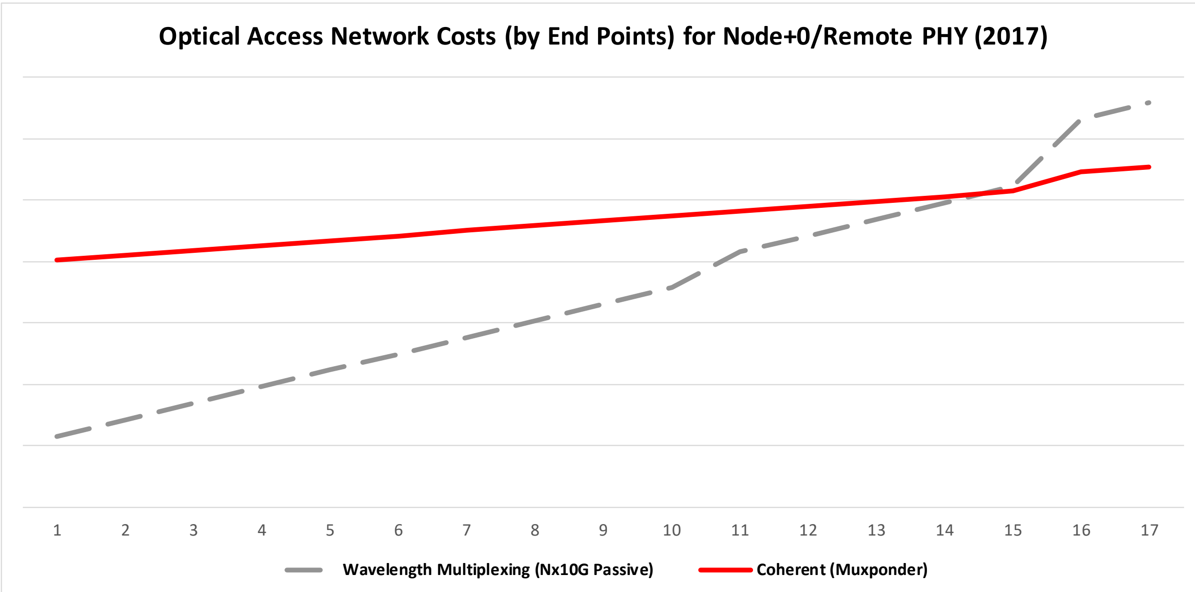

Figure 9 - Breakeven End Points for Coherent Optics vs. Wavelength Multiplexing (2017)

The economics of coherent optics will improve substantially in the coming years. A recent IHS Report [17] projects mature DWDM + DD technology costs will decrease up to 3% annually while coherent optics costs will decrease up to 15% annually. Assuming the 15% annual cost decrease for the coherent Optics transceiver and a 3% annual cost decrease for other optical components, the breakeven shifts to ten end points in the year 2020 as shown in Figure 10. That is, 100 Gbps aggregation will have similar costs whether using wavelength multiplexing or Coherent Optics. This Coherent Optics cost improvement could accelerate with a solution optimized for the Cable Access Network with more benefits from operation.

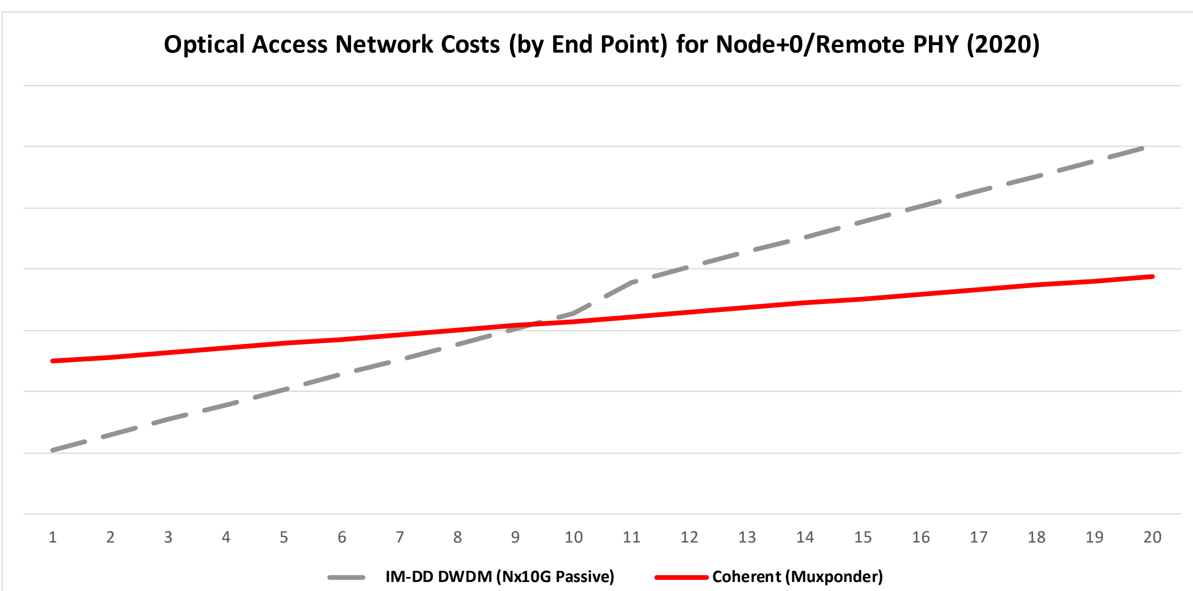

Figure 10 - Breakeven End Points for Cohernet Optics vs. Wavelength Multiplexing (2020)

4. Digital Coherent Optical Transmission Technology

4.1. Optical Transmission Technology Evolution

As shown in Figure 11, optical transmission technologies have evolved over multiple generations. The inventions of semiconductor lasers and low-loss single-mode fiber (SMF) were the major breakthroughs in the 1970s. From the 1980s to early 1990s, electrical time-division multiplexing (ETDM) was the core technology. The invention of the Erbium-doped fiber amplifier (EDFA) in the 1990s and the first commercial use of 8 × 2.5-Gbit/s WDM in 1996 were important milestones. The next technological leap occurred during the mid 2000s. The rapid development of silicon-based electronic chips and maturing of DSP technologies reinvigorated coherent detection. This has increased the spectral efficiency of optical signals to 2 bits/s/Hz, and optical transmission has entered the stage of digital coherent transmission with the use of four-dimensional orthogonal signals.

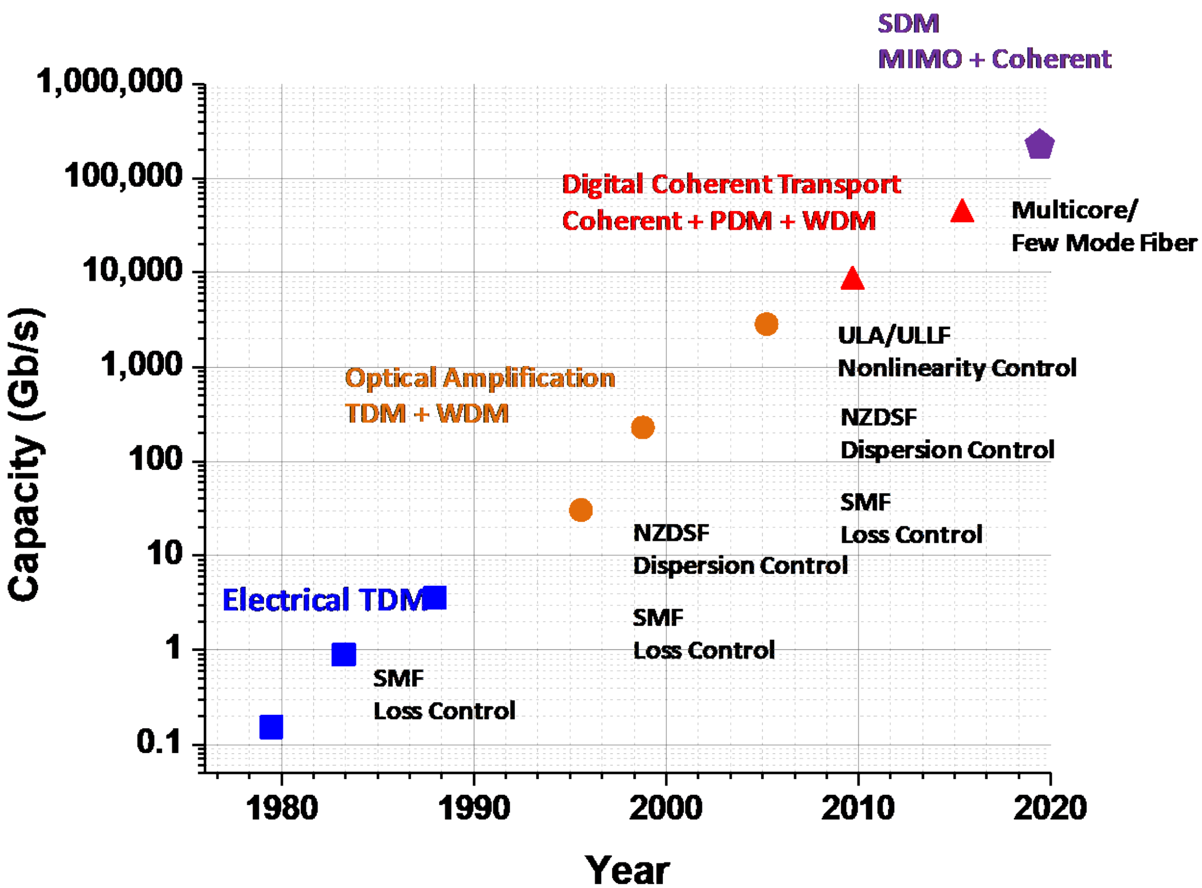

Figure 11 - The Evolution of Optical Transmission Technologies

Besides the optical terminal system evolution, optical fiber media has evolved from early loss-reduction dispersion-managed fiber (DMF), to increased effective area fiber and fiber with further reduced propagation loss. These developments have greatly helped overcome linear and nonlinear impairments in optical fibers. In the future, space division multiplexing (SDM) is likely to become a technological turning point for addressing optical capacity crunch challenge.

It is noted that the new generation of technology can take full advantage of the technology that has been developed, for example, coherent technology along with polarization multiplexing can easily integrate into existing DWDM systems with much improved SE. In the meantime, new technologies can continue to use the existing deployed optical fiber links. Actually, a standard SMF is more tolerant than non-zero dispersion shifted fiber to nonlinear effects especially for coherent optical systems because of nonlinear phase-matching conditions.

4.2. Rebirth of Coherent Optics

Coherent optical receivers have initially received significant research interest in the 1980s. At that time, no optical pre-amplification was used in front of the receiver. As the local oscillator (LO) signal typically has a much higher power than the received signal, it can be used for coherent amplification gain. This can potentially increase the receiver sensitivity with up to 20 dB in comparison to optically unamplified direct detection.

However, the invention of EDFAs made the shot-noise limited receiver sensitivity of the coherent receiver less significant. This is because the Optical Signal-To-Noise Ratio (OSNR) of the signal transmitted through the amplifier chain is determined from the accumulated amplified spontaneous emission (ASE) rather than the shot noise. Both the surge in EDFA based optical communication solutions as well as the challenges with coherent detection interrupted research and development activities in coherent communications for nearly 20 years. Even though the increase in capacity enabled by EDFAs and WDM has scaled well in the past, a hard limit on capacity exists while non-coherent On/Off Key (OOK) modulation is used. Due to these pressures, advanced modulation formats, capable of transmitting more than one bit per symbol, became a highly desirable technical advancement.

On the other hand, the development and maturity of high-speed digital integrated circuits has offered the possibility of using DSP capability of providing us with simple and efficient means for equalizing fiber transmission impairments, demultiplexing two polarizations, and estimating the carrier phase. Through the adoption of high-order modulation formats, higher spectral efficiencies can be reached through the reduced symbol. Furthermore, only coherent detection permits convergence to the ultimate Shannon limits of spectral efficiency in theory.

4.3. Advanced Modulation Format

As described earlier, the use of coherent detection and DSP enabled system fully leveraged the benefits of advanced modulation formats and provided previously unavailable functionality in systems with direct detection, such as the use phase and the state of polarization as means to convey information. The migration from traditionally used OOK modulation formats to formats with more bits per symbol leads to a reduction of the symbol rate and narrowed spectral widths. Therefore, higher spectral efficiencies, per fiber capacities, and then cost per bit can be realized. This is the main motivation for a system upgrade to higher-order modulation. The constellation diagrams of currently most popular modulation formats are shown in Figure 12, [3] through [7].

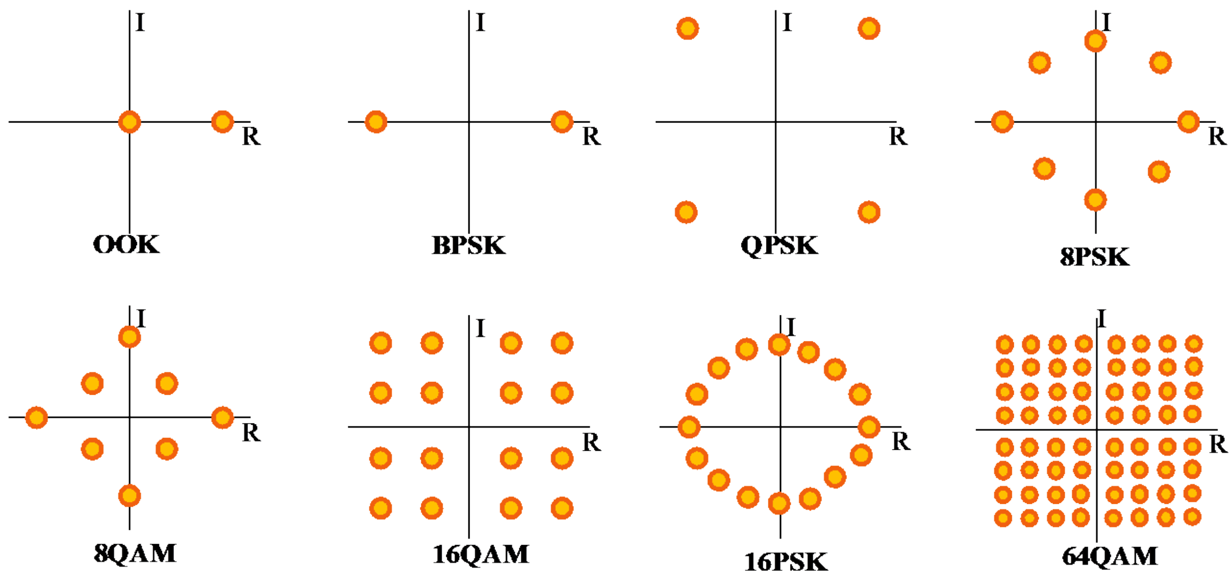

Figure 12 - Constellation Diagrams of Various Modulation Formats

From a system perspective, there are multiple optimization parameters when making a decision on these modulation formats, metro access systems generally emphasize the cost, complexity, and receiver sensitivity since the impact of transmission impairments are small compared to long haul systems.

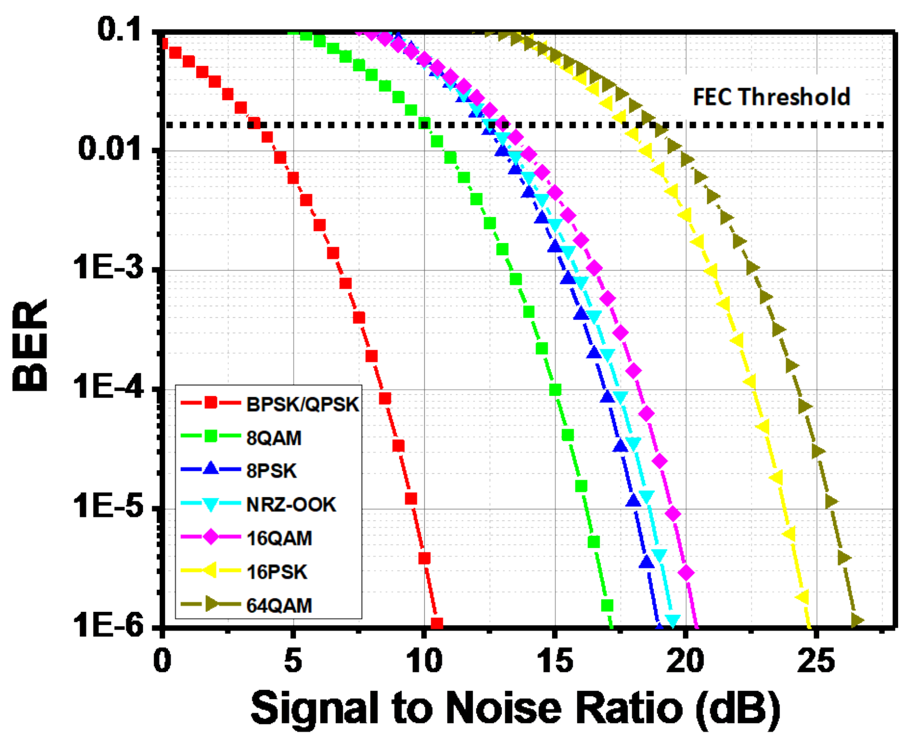

Figure 13 - Theoretical BER Curves for Various Modulation Formats.

It is possible to derive theoretical limits on the performance of different modulation formats and performance being purely impaired by additive white Gaussian noise. The transmitter and receiver are assumed to have ideal matched filters. The noise level is described here using the signal processing convention of E_b/N_0, where E_b is the mean energy per transmitted bit and N_0 is the mean noise energy per symbol. This metric enables comparison between modulation formats with differing parameters but at identical bit rates, as the SNR is normalized to the number of bits per symbol of the modulation format (unlike, for example, Es/N0).

As a result of an increasing number of bits per symbol, noise performance degrades as the Euclidean distances between the symbols become smaller as shown in Figure 12. High-order QAM formats exhibit a significantly better noise performance than high-order phase modulation formats for a certain number of bits per symbol, Square QAM formats in particular, due to the more optimum allocation of symbols on the complex plane. In comparison with 16 PSK as shown in Figure 13, Square 16-QAM has an OSNR performance gain of about 4 dB, for instance. High-order modulation formats offer a way of relaxing the requirements on PMD since a certain group delay difference has a smaller impact on neighboring pulses for reduced symbol rates and longer pulse durations.

4.4. Polarization-Multiplexed (PM) QAM Optical Transmitter

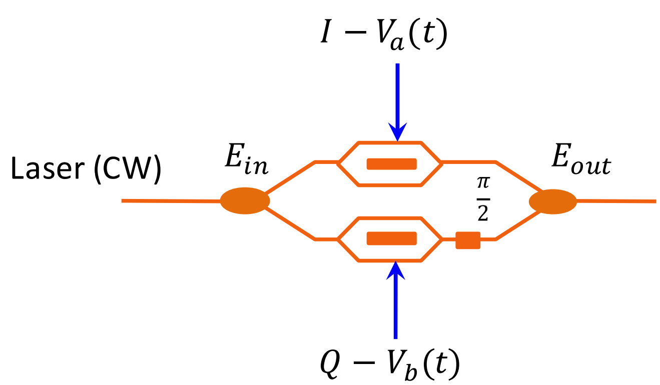

Figure 14 - Architecture of a Standard Mach-Zehnder Modulator

In this section, a most commonly used transmitter architecture is presented and is compatible to arbitrary QAM constellations. As an example, Figure 14 presents an optical nested IQ modulator with dual Mach-Zehnder modulators (MZM) for Quadrature Phase Shift Keying (QPSK) modulation format. It can be composed of a phase modulator and two MZMs, and is commercially available in an integrated form. The incoming light is equally split into two arms, the in-phase (I) and the quadrature (Q) arm. In both paths, a field modulation is performed by operating the MZMs in the push-pull mode at the minimum transmission point. Moreover, a relative phase shift of π/2 is adjusted in one arm, for instance by an additional phase modulator. This way, any constellation point can be reached in the complex IQ-plane after recombining the light of both branches.

As illustrated in Figure 15 (a), the recombination of the two Binary Phase-Shift Keying (BPSK) signals with π/2 phase difference yields a QPSK signal. In a similar way as in QPSK generation, the mechanism for 16-QAM can be considered as two Pulse Amplitude Modulation 4 (PAM-4) signals inference with the phase shifted by π/2 (see Figure 15 (b)). It is a superposition of vectors on a complex plane. This BPSK or 4-level PAM-4 signals can be obtained by DACs in commercial implementations. One of the most

important parameters of the QAM signal modulation is the modulation loss, which depends on the following factors:
– Insertion loss and bias points of modulator
– Driver swing and driver rise/fall times
– Modulation format
– Linearity of modulator
– Spectral shaping and pre-compensation

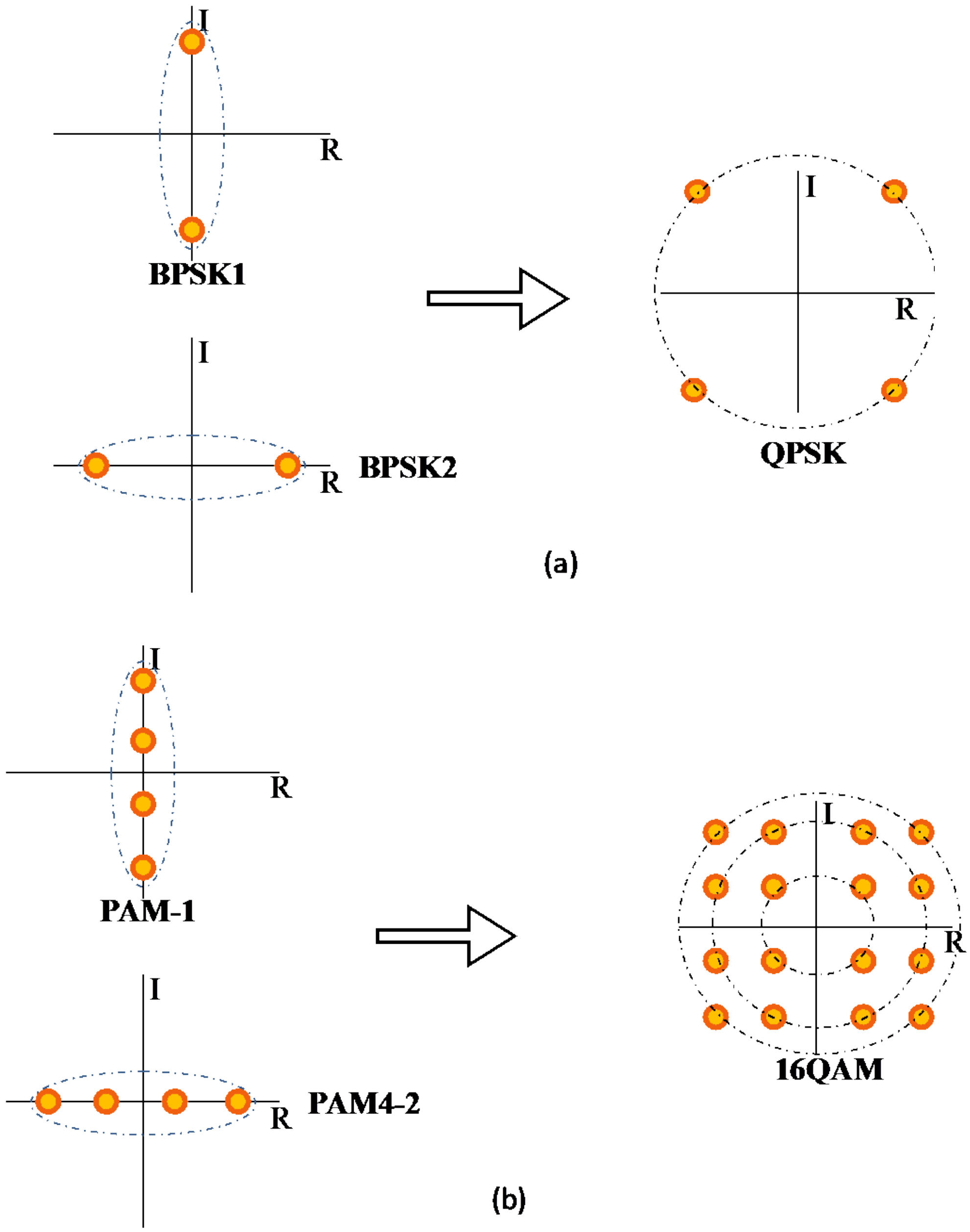

Figure 15 - Illustration of QPSK (a) and 16QM (b) Signal Generation.

Back to the QPSK example, the transfer function of a single MZM is given by

$$E_{out} = E_{in}\cos(\pi V(t)/V_{\pi})$$

where E_{in} is the input optical signal, E_{out} is the output optical signal of the MZM, V(t) is the driving signal, and V_{π} is a characteristic of the MZM and determines the amplitude required for the driving signal. Thus, the transfer function of this IQ modulator is given by

$$E_{out} = E_{in}\sqrt{cos^2\,(\pi V_a(t)/V_{\pi}) + cos^2\,(\pi V_b(t)/V_{\pi})} * e^{jtan^{-1}\frac{cos(\pi V_b(t)/V_{\pi})}{cos(\pi V_a(t)/V_{\pi})})}$$

If $V_a(t)$ and $V_b(t)$ take on one of two values $\{0, V_{\pi}\}$, then the phase shift induced on the IQ modulator is one of four values as shown in Table 1 - Phase Shifts in an IQ QPSK Modulator below.

Table 1 - Phase Shifts in an IQ QPSK Modulator

$V_a(t)$	$V_b(t)$	$cos\,(\pi V_a(t)/V_{\pi})$	$cos\,(\pi V_b(t)/V_{\pi})$	$tan^{-1}\frac{cos(\pi V_b(t)/V_{\pi})}{cos\,(\pi V_a(t)/V_{\pi})})$
0	0	1	1	$\pi/4$
0	V_{π}	1	-1	$-\pi/4$
V_{π}	0	-1	1	$3\pi/4$
V_{π}	V_{π}	-1	-1	$5\pi/4$

For generating dual-polarization modulation formats, typically two triple MZMs are used in parallel, each modulating an orthogonal polarization (see Figure 16). The two unmodulated carriers come from the same laser and are split into orthogonal linear polarizations with a polarization beam splitter (PBS), before the two-independent polarization modulated signals are multiplexed together with a polarization beam combiner (PBC).

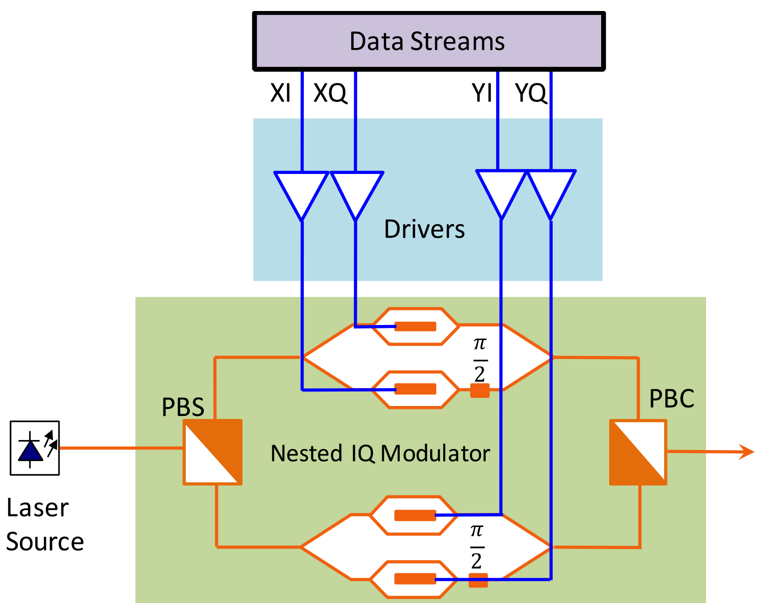

Figure 16 - Optical Transmitter for PM-QAM Modulation Formats

4.5. Digital Coherent Receiver

4.5.1. Homodyne/Intradyne/Heterodyne

In a coherent receiver, an LO is used to down-convert its signal with the incoming signal lightwave for demodulation. Depending on the intermediate frequency f_{IF} defined as $f_{IF} = f_s - f_{LO}$, coherent detection can be realized using a homodyne, intradyne or heterodyne receiver as illustrated in Figure 17, where $Bandwidth_s$ is optical signal bandwidth [8], [9], and [10].

In a homodyne receiver, the LO and transmitter laser have the same frequency and the phase difference should be zero (or a multiple of 2π). Intra-dyne detection is similar to homodyne detection, with the exception that a frequency offset between the LO and transmitter laser exists, but the $f_{IF}$is chosen to fall within the signal band by roughly aligning the f_{LO} with f_s. In heterodyne detection, the difference between the LO and transmitter laser frequency is chosen higher than the electrical signal bandwidth, the entire optical signal spectrum is directly translated to an electrical bandpass signal centered at the f_{IF} for further electronic processing.

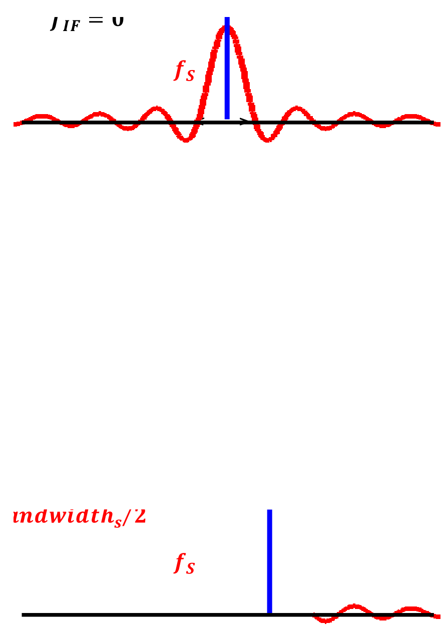

Figure 17 - Three Coherent Detection Schemes: (a)Homodyne, (b)Intradyne, (c)Heterodyne

Compared with heterodyne and homodyne detection, intradyne detection has the advantage that the processing bandwidth is relaxed for the optical and electrical components. It is also noted that both heterodyne and intradyne detection that uses single-ended detection is vulnerable to RIN from LO. This can be solved through balanced detection, which requires a total of 4 photo-diodes and an optical hybrid with 4 outputs, each shifted by 90º degrees.

4.5.2. Coherent Receiver Architecture

The fundamental concept behind coherent detection is to take the beating product of electric fields of the modulated signal light and the continuous-wave LO. To detect both IQ components of the signal light, A 90° optical hybrid is utilized. A key building block of such a hybrid is an 2x2 optical coupler with its property of a 90° phase shift between its direct-pass and cross-coupling outputs via multimode interference (MMI) coupler. By combining such optical couplers into the configuration shown in Figure 18, together with an additional 90° phase shift in one arm, a detection of real and imaginary parts can be achieved. Balanced detection is usually introduced into the coherent receiver as a mean to suppress the DC component and maximize the signal photocurrent.

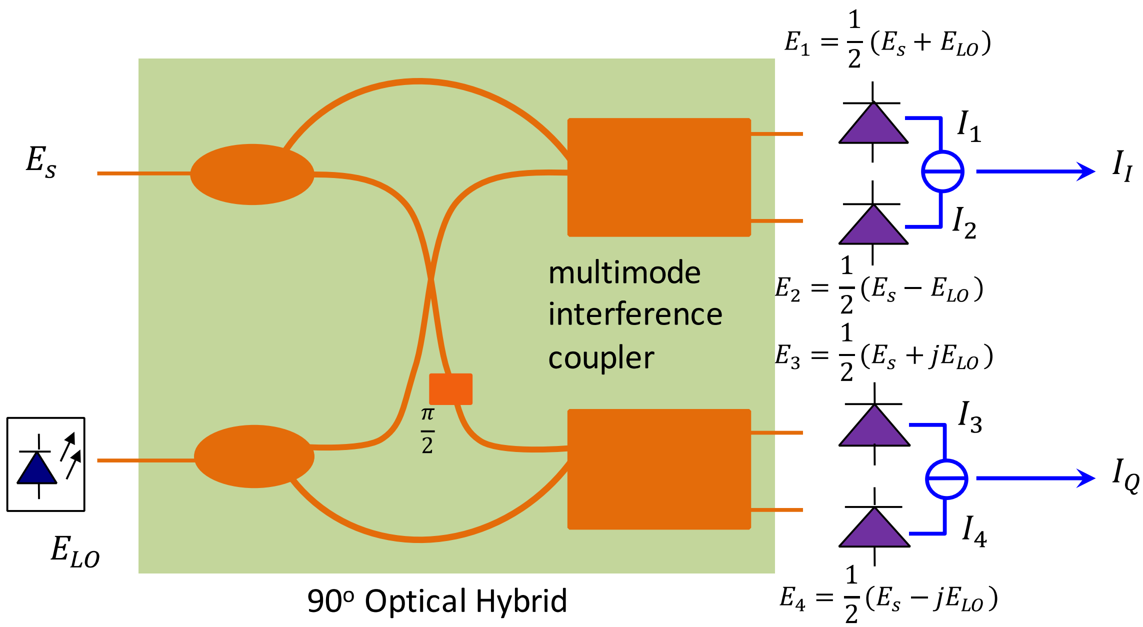

Figure 18 - Configuration of Phase-diversity Coherent Receiver

Output photocurrents from balanced photodetectors are then given as

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

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

where R is the responsitivity of the photodiode, P_s and $P_{LO}$are the power of the optical fields for incoming and LO signal, respectively. It is possible to estimate the phase noise $\theta_{LO}(t)$ varying with time and restore the phase information $\varphi_s(t)$ through the following DSP on the intradyne detected signal.

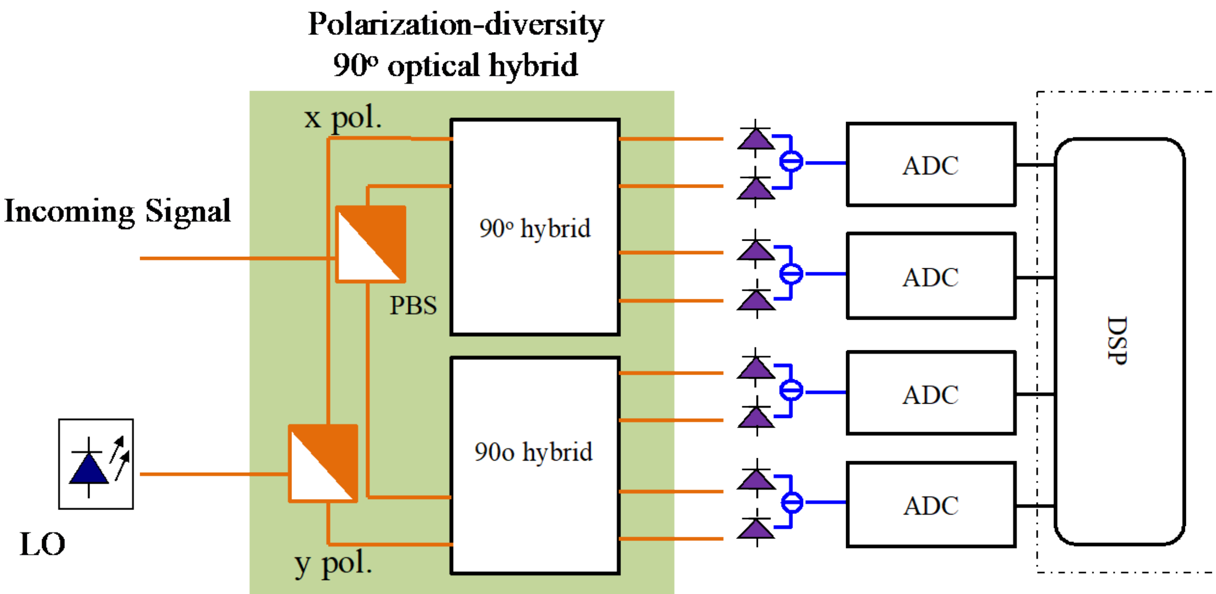

Figure 19 - Configuration of Phase and Polarization Diversity Coherent Receiver Architecture

The schematic diagram of a polarization multiplexed coherent receiver is shown in Figure 19. Both the incoming PM signal and LO are split into two orthogonal polarizations using a PBS, after which the co-polarized signal and the LO are mixed in two 90° optical hybrids to produce an in-phase and quadrature components for each polarization. The four signals are then digitized by four ADCs after which DSP can be performed for signal demodulation.

4.5.3. Digital Equalization Algorithms

Current coherent optical transceivers now utilize DSP with the transmitter being responsible for modulation, pulse shaping and pre-equalization and the receiver responsible for equalization, synchronization and demodulation.

At the transmitter, the DSP in conjunction with the DACs and FEC, convert the incoming data bits into a set of analog signals. As shown in Figure 20 in detail, transmitter DSP functions include symbol mapping and signal timing deskew adjustment, optional pre-distortion for dispersion or self-phase modulation, and software-programmable capability of supporting multiple modulation formats and encoding schemes. Transmitter DSP also allows compensating nonlinearities induced by the electrical driver and the optical modulator.

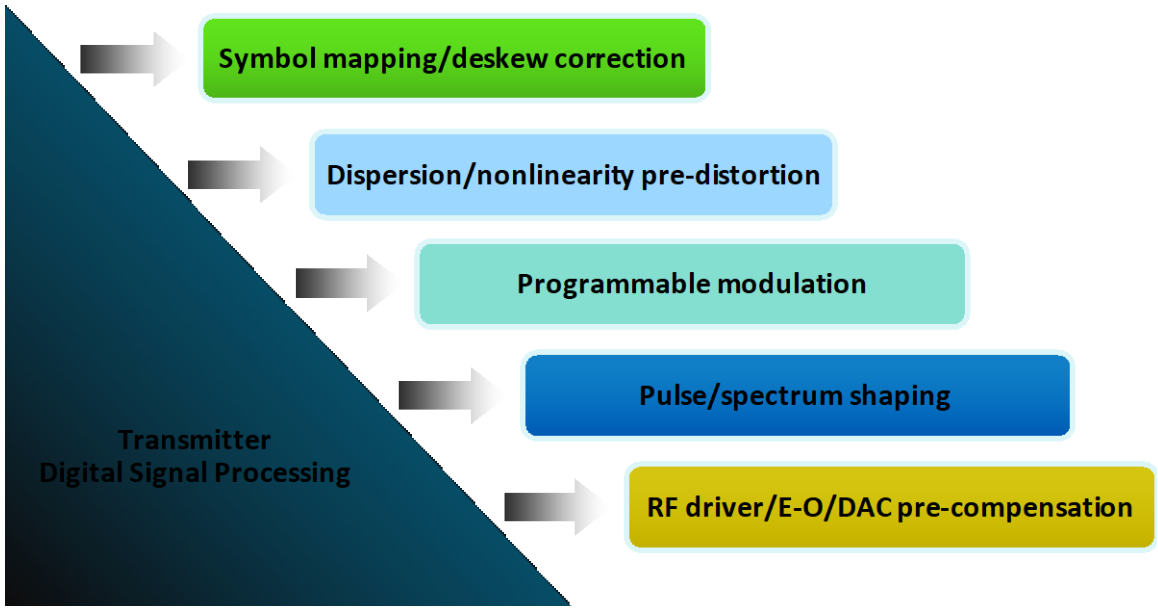

Figure 20 - Transmitter Side DSP Functions

The major benefit of the transmitter DSP is to perform pulse shaping and thus engineer the spectrum of signal, such as generating Nyquist pulse. Pulse shaping controls the spectrum to increase the spectral efficiency or reduce the nonlinear impairments. Basically, there are three types of pulse shaping filters, sinc, raised-cosine, and Gaussian filters. Table 2 summarizes their corresponding transfer function, spectral and pulse shapes, and eye diagrams of QPSK filtered driving signals.

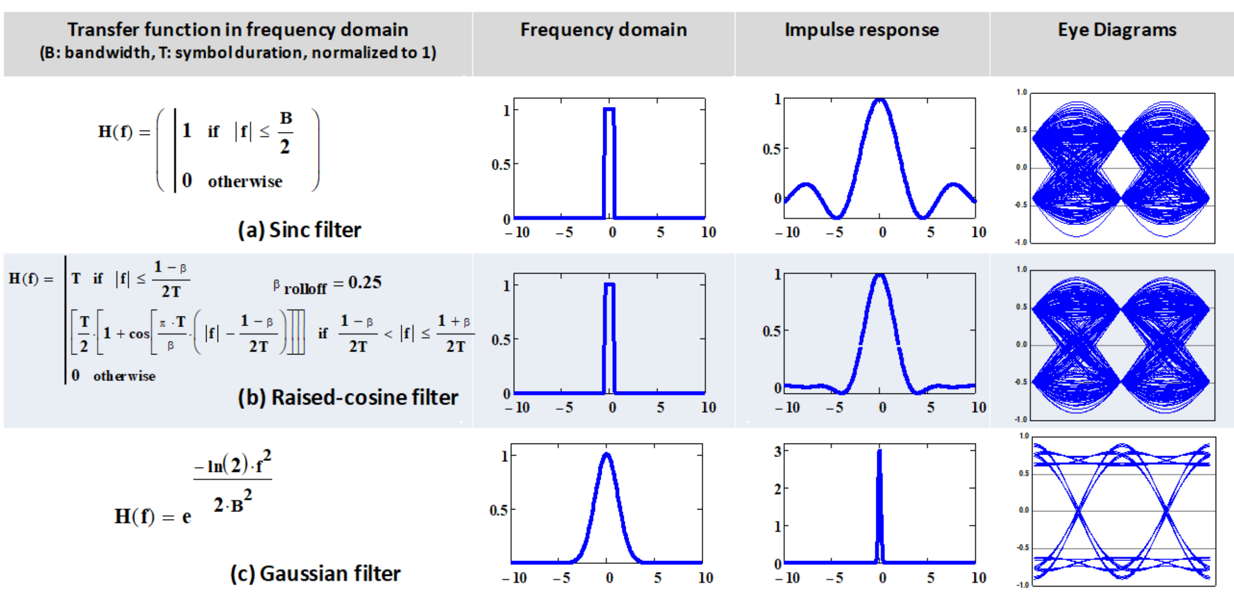

Figure 21 - Three Pulse Shaping Filters with Different Transfer Functions

Transmitter-side DSP enables more flexibility not only in channel impairment pre-compensation but software configuration for elastic optical networks. In correspondence to the operation of the transmitter, the major advantage of receiver-side DSP stems from the ability to arbitrarily manipulate the electrical field after the ADC enables the sampling of the signal into digital domain. As shown in Figure 22, the fundamental DSP functionality in a digital coherent receiver for PM-QAM signals can be illustrated by the following flow of steps and their correlations from structural and algorithmic level of details.

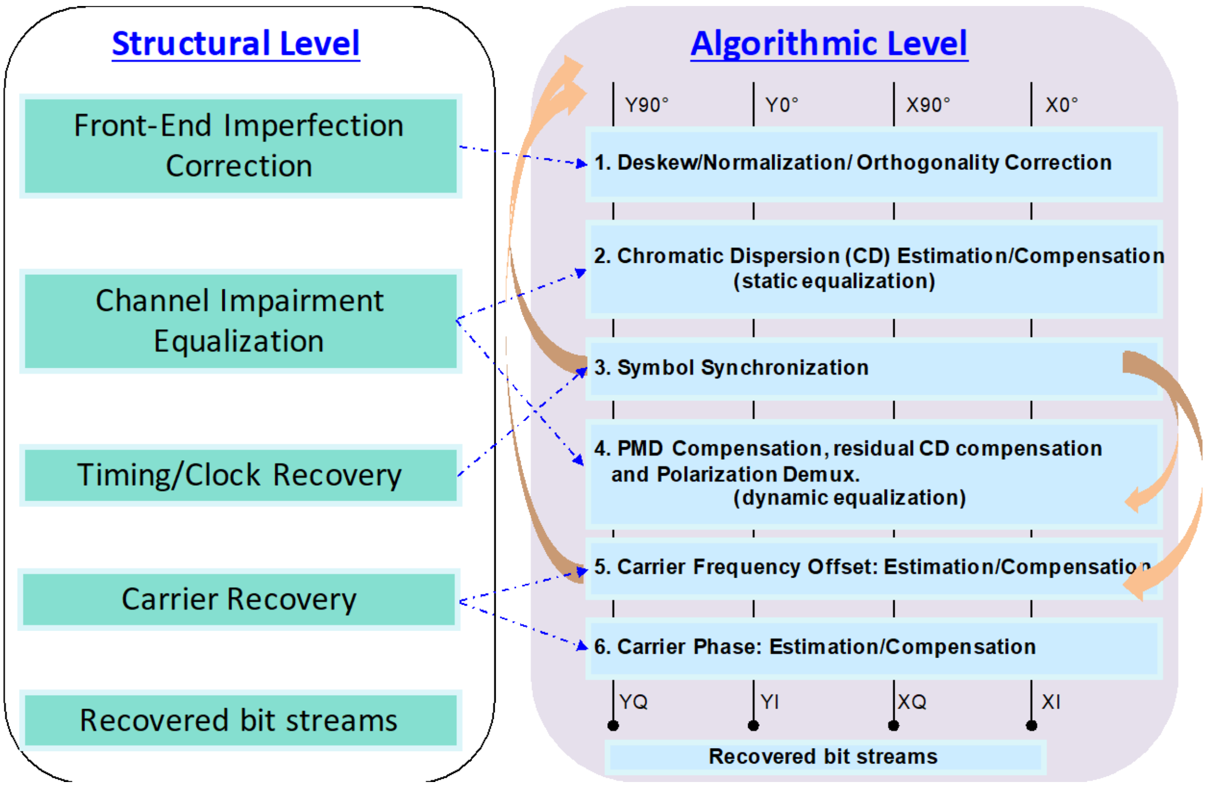

Figure 22 - DSP Flow in a Digital Optical Coherent Receiver

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

Second, the major channel transmission impairments are compensated through digital filters, in particular, CD and PMD. The static equalization for CD compensation is performed first because of its independence of SOP and modulation format and the impact on the subsequent blocks before the CD estimation is needed to achieve accurate compensation. Then the clock recovery can be processed to track the timing information of incoming samples. Note that it is possible to perform joint process between the blocks of clock recovery and polarization demultiplexing for achieving the symbol synchronization (see arrows in Figure 22). A fast-adaptive equalization is carried out jointly for two polarizations through a butterfly structure. Then the frequency offset between the source laser and the LO is estimated and removed to prevent the constellation rotation at the intradyne frequency.

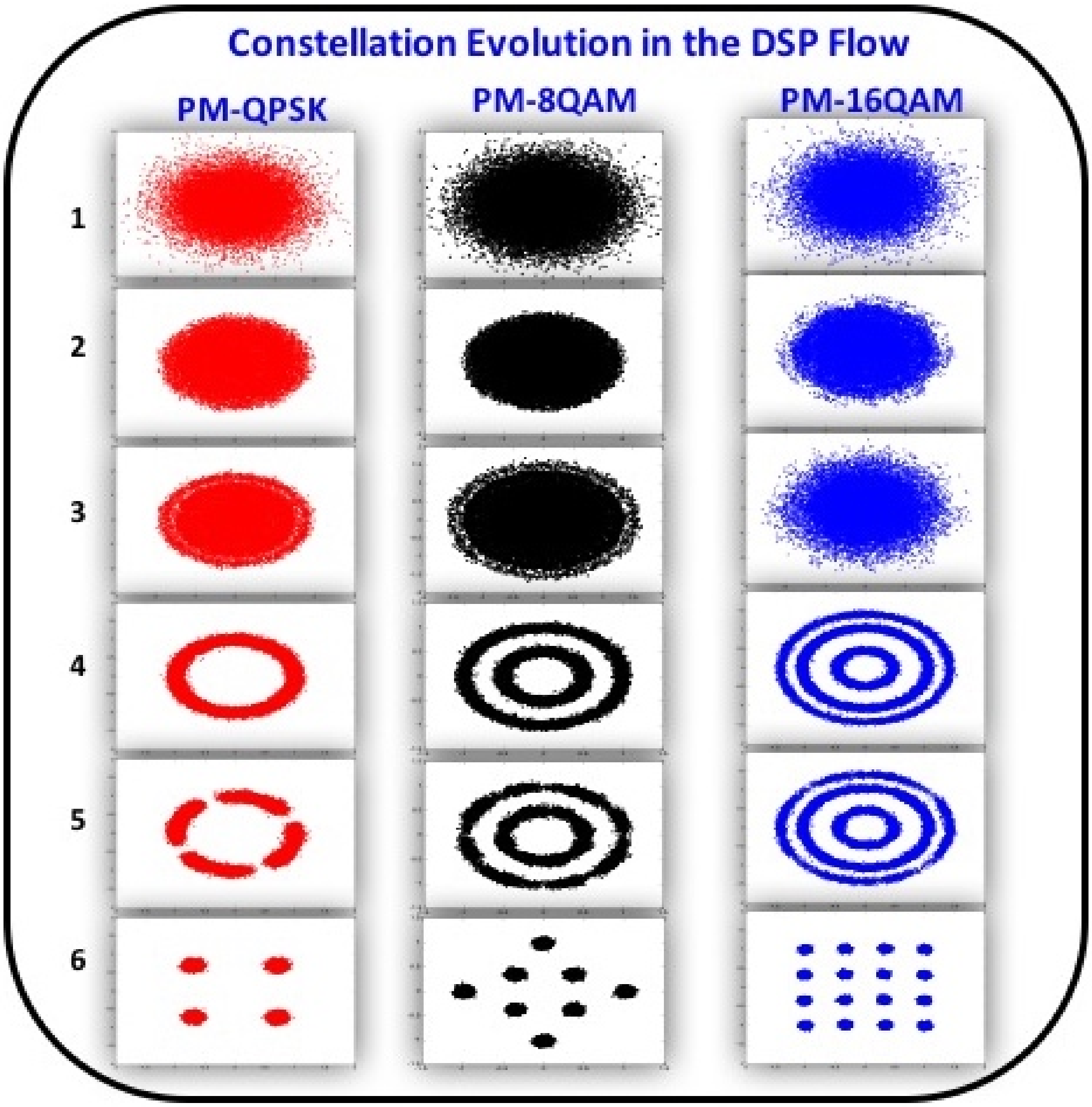

Figure 23 - Constellation Evolutions for QPSK/8QAM/16QAM Signals

Finally, the carrier phase noise is estimated and removed from the modulated signal, which is then followed by symbol estimation and hard or soft-decision FEC for channel decoding. Note that for a particular digital coherent receiver, the ordering of DSP flow may differ slightly from those detailed in Figure 22 because of different design choices. Besides feed-forward process, it is possible to perform joint process and feedback among different process blocks such as clock recovery and polarization demultiplexing as mentioned above.

The constellation evolutions show examples (Figure 23) of the received signal after linear transmission over uncompensated SMF link with EDFAs only. Note that the results in this proposal are based on 32-GBaud rate. It is also noted that the impairments of frequency offset of 0.1 GHz, 100-kHz linewidth of Transmitter laser and LO are induced with 20000 ps/nm accumulated CD.

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

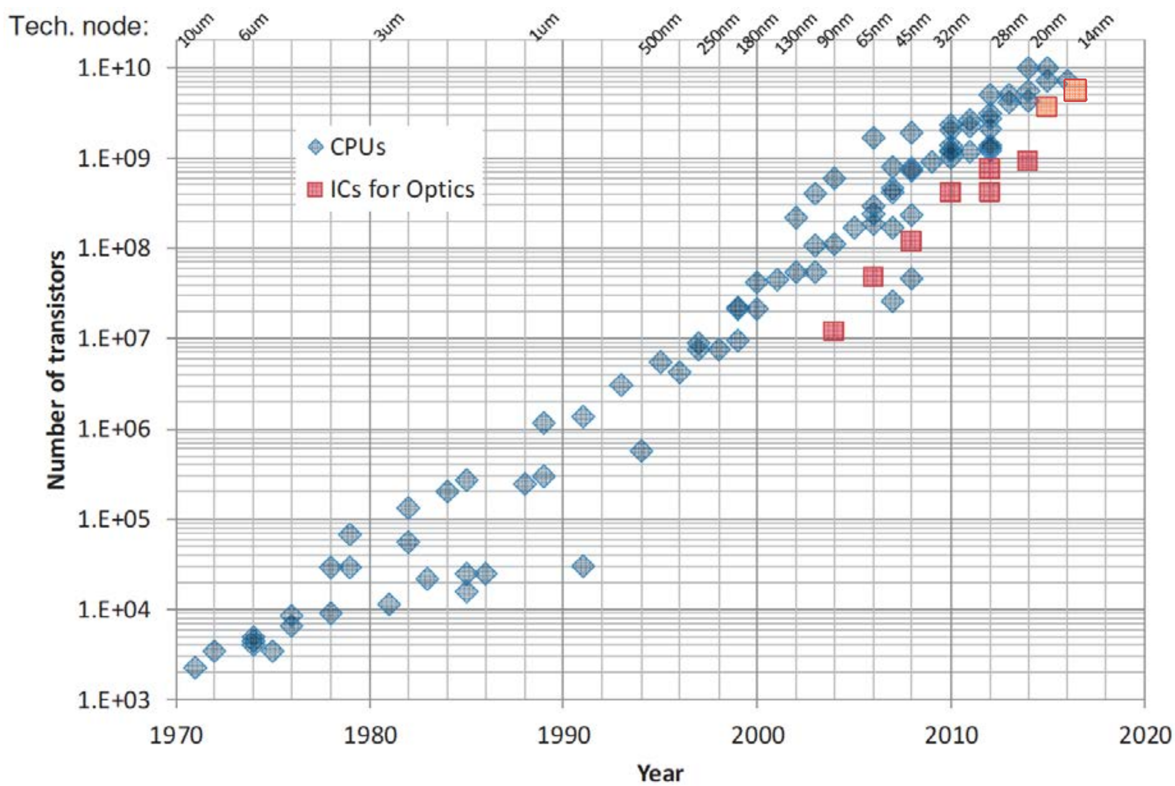

Figure 24 - Transistor Counts for Both CPUs and ASICs in Optical Communication

Key to advancing the use of DSP in optical communications is the consistent improvement in complementary metal–oxide–semiconductor (CMOS) technology. As shown in Figure 24, DSP ASICs for coherent optics are following the complexity trend with approximately ~1 order of magnitude difference between CPUs. As feature node sizes have shrunk and design tools improved over the years, the maximum complexity (and hence functionality) possible in an ASIC has grown from thousands to several hundred million gates. Today's coherent DSPs use 16/14 nm and tomorrow's will use 10/7 nm [10].

Not only is the feature size in a coherent ASIC decreasing exponentially but the sampling rates of CMOS data converters are also exponentially increasing to support higher symbol rates and hence bit rates. In the meantime, the advancement of high ENoB is very important for higher-order modulation formats. Today's coherent ADC/DACs use 56-64GSamples/s and tomorrow's will use 90-128GSamples/s, as shown in Figure 25, [10].

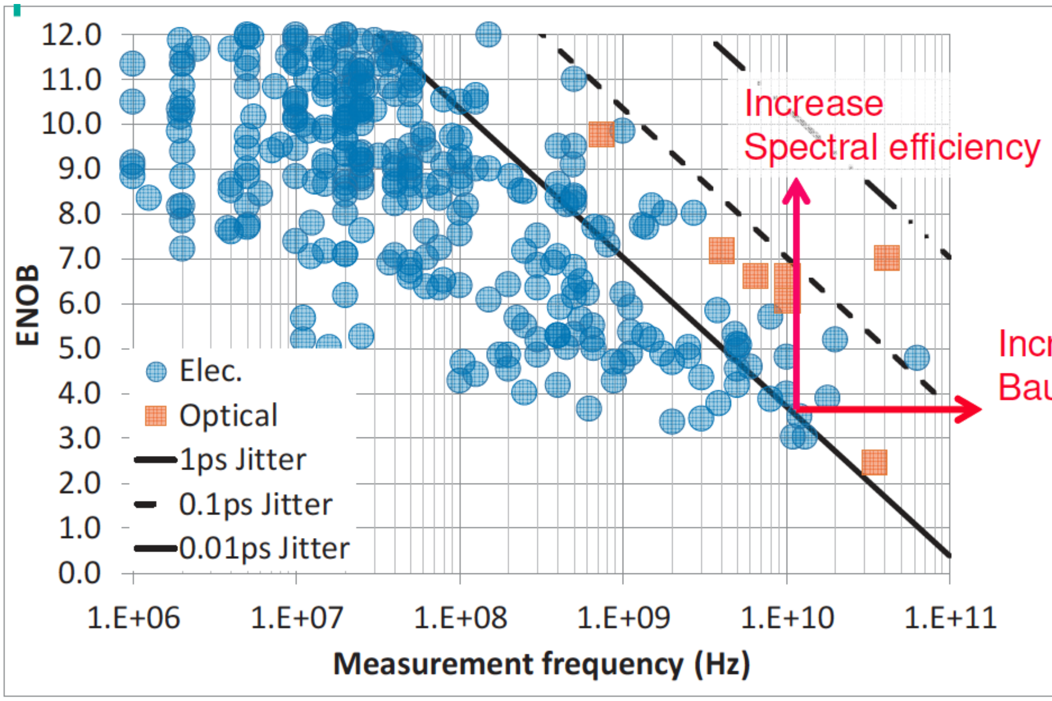

Figure 25 - ADC/DAC Development in Optical Communication

4.5.4. Coherent Transceiver Module Evolution

First coherent 100 Gb/s interfaces were built using a discrete line card architecture by large network equipment manufacturers. Next to custom line cards, 100G was also defined in a standard line interface module with a total power of less than 80W in 5”x7” OIF compliant Multi-Source Agreement (MSA) modules for QPSK modulation signals. The intention of the 100G MSA module is to support long-haul applications beyond 2,000 km. The second non-pluggable MSA module is 4”x5” with less than 40W of power as shown in Figure 26. To provide high density and low-cost coherent transceivers, hot pluggable modules are being implemented with small form factors. The power consumption for a coherent transceiver mainly includes the power consumed by the ASICs (DACs, ADCs, DSPs), lasers, modulator drivers, and TIAs. In order to pack all the components in a small form factor, the power dissipation need to be reduced significantly.

There are two classes of pluggable transceivers for the optical transmission nodes: one is the line-side transceivers the other one is the client-side transceivers. Most of today’s development of client-side transceivers are focusing on CFP2, CSP, and QSFP+ formats without coherent optics. For the line-side transceiver with coherent optics, there are initial emerging CFP modules available and moving to CPAK and CFP2 format. The power requirement for a CFP is <28-32W, while a CFP2 has to fulfill a maximum of <9-12W. CFP2 can be implemented with analog host interfaces and the ASIC on an external board or digital CFP2 includes all optics and ASIC.

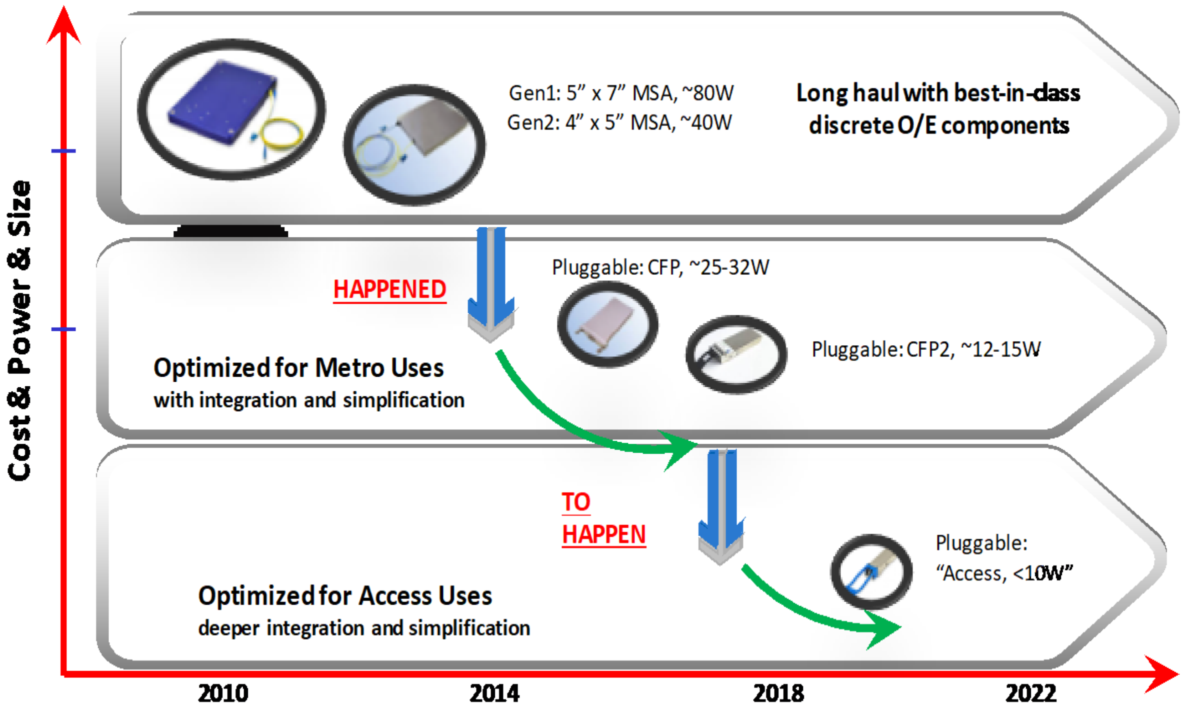

Figure 26 - Evolution of Digital Coherent Optical Module

Photonic integration circuit appears to be a must for CFPx modules instead of separate $LiNbO_3$ modulators and InP/PLC receivers. To achieve the cost targets, the use of electronic integration and photonic integration needs to be implemented to reduce component count and improve manufacturability. Another dominant cost for the DSP and optics is the packaging, one can further reduce cost, power, and footprint by co-packaging the DSP and optics.

Recent technology advances and ongoing price drop further open the window of opportunity for the application of coherent optics in access networks. It is envisioned that the migration of coherent optics from long haul and metro to access domain will need to further optimization and deeper integration to lower the cost and complexity.

4.6. Coherent Optics for Access

Coherent detection for access networks enables the superior receiver sensitivity that allows for extended power budget, and the high frequency selectivity enabling dense WDM. Moreover, the linearly recovered signal provides additional benefits to compensate for the linear transmission impairments such as CD and PMD, and efficiently utilize the spectral resource and benefiting future network upgrades. In the cable access environment, coherent optics allows operators to best leverage the existing fiber infrastructure to withstand the exponential growth in capacity and services. However, there are several engineering challenges. The coherent technology in 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 process. The coherent pluggable modules for metro solution has gone through CFP to CFP2 via MSA standardization for smaller footprint, lower cost, and lower power dissipation. However, it is still overengineered, too expensive, and too power hungry. Therefore, it is not efficient and practical for access applications.

Access network is totally different environment as compared to long haul and metro. To reduce the power consumption and thereby meet the size and cost requirements for access applications, development of both low-complexity ASIC and optics is essential. In particular, co-design of a DSP ASIC and optics to trade performance against complexity, cost and power consumption is imperative.

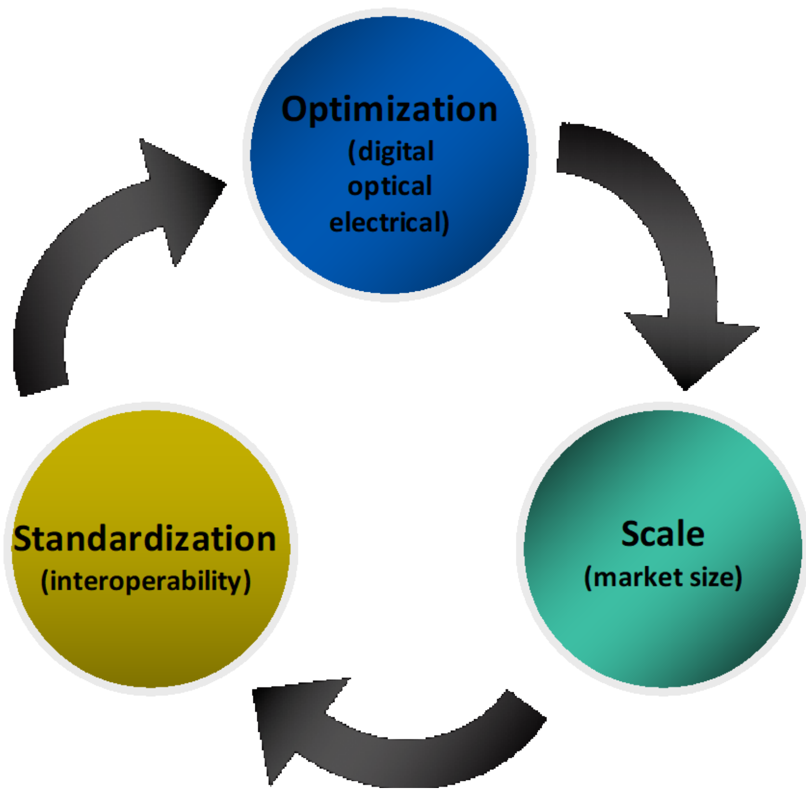

Figure 27 - Three Major Factors for Impacting Coherent Optics in Access Networks

Besides the natural technology advancement of coherent optics and reuse of existing fiber infrastructure, there are three major factors that impact on the cost and power reduction and eventually lead to successful deployment in access networks. As shown in Figure 27, We know that the access network is the largest component of the network in terms of physical/geographic size and amount invested. Increasing shipment volume for both long haul, metro, and access will drive component and equipment pricing down quickly. The following subsections will illustrate the details on optimization of the digital, optical, and electrical complexity and standardization and interoperability.

4.6.1. DSP Optimization

Naturally, the shorter transmission reach means less distance-dependent signal degradation, requiring less link equalization (i.e., fewer digital filter taps) and less processing in the DSP ASIC for impairment compensation, such as CD compensation, PMD compensation, and tracking the signal state of polarization. A reduction in OSNR performance is acceptable for shorter-reach access applications, which allows for a lower sampling rate and resolution of ADCs/DACs and fewer bits to be carried through the

DSP. Because of shorter distance and less demand on the link budget, soft-decision FEC (SD FEC) encoder and decoder, the major blocks in terms of power dissipation of ASIC, can also be significantly reduced on the complexity by either using hard-decision FEC, less overhead SD FEC, and/or decreasing the number of iterations. Figure 28 shows our analysis on power consumption of typical ASIC from long haul, metro, to access applications. In addition to the percentage change of each constituent element, the total energy consumption is significantly reduced.

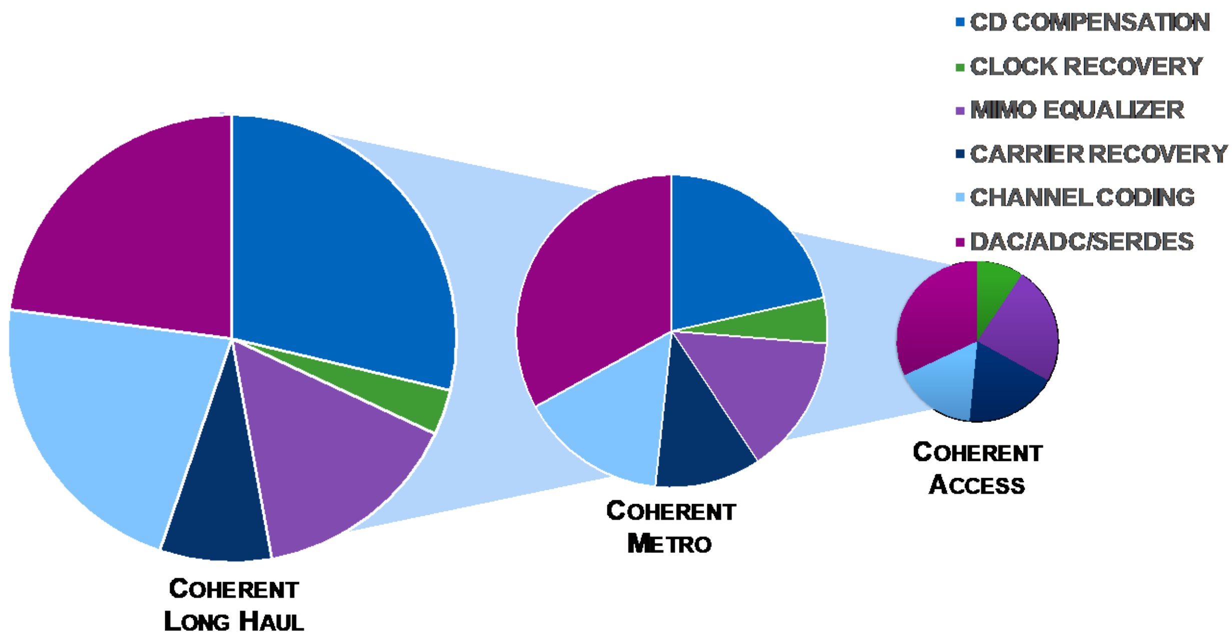

Figure 28 - Analysis on Power Consumption of Typical ASICs.

4.6.2. Optical and Electrical Components Simplification

Both optical sources, usually lasers as transmitter and LO, are crucial building blocks to optimize the system cost and performance. Low-cost, small-footprint lasers with relatively large linewidth are preferred over the costly narrow linewidth external cavity lasers in such context, provided acceptable degradation in system performance. As shown in Figure 29, the analysis shows little impact on 16-QAM signals when the linewidth is increased from 100kHz to 1MHz. This will allow the use of cheap laser sources for access coherent systems. It is worth mentioning that higher order modulation formats such as 32/64-QAM are more sensitive to phase noise.

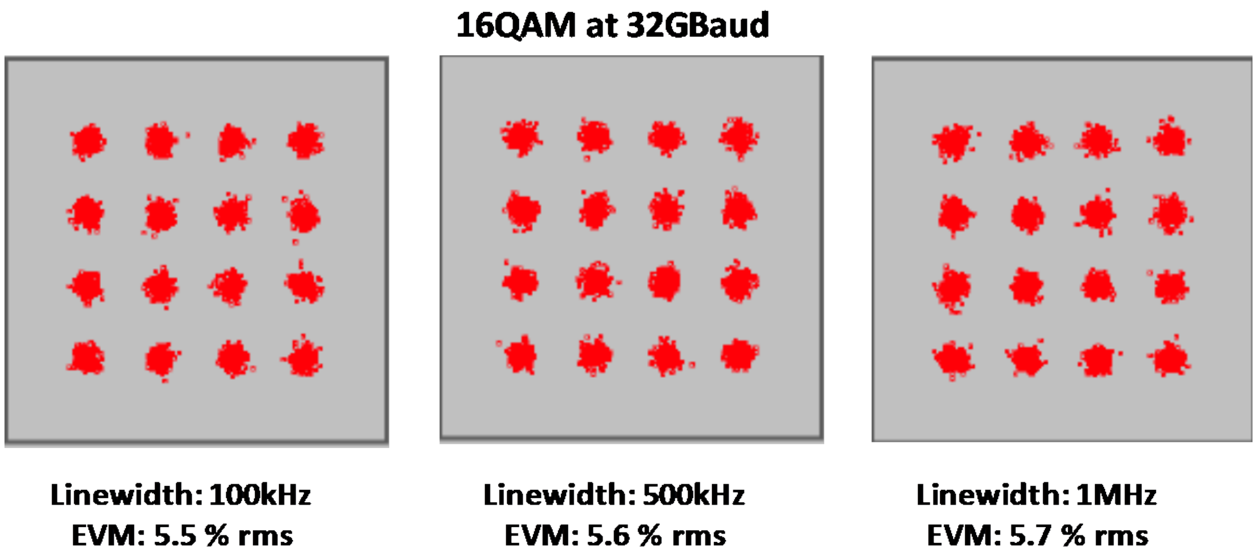

Figure 29 - Impact of Linewidth (Phase Noise) on 16QAM Signal Performance

A miniaturized optical IQ modulator is another key component for coherent optical transceiver. Currently, there are three materials for IQ modulators, i.e., LiNbO3, Indium-phosphide (InP), and silicon photonics (SiPh). To fit inside a pluggable module like CFP2-ACO/DCO, only InP and SiPh based modulator can be applicable for such small optical modules. A booster optical amplifier, either SOA or EDFA, is often required to compensate coupling and modulation loss in order to meet the power budget of long haul or metro applications. However, this optical amplifier can be avoided to reduce the cost because of the access environment with a less demanding optical link power budget.

Using low-bandwidth, low-cost electrical and opto-electronic components such as driver, modulator, photodetector, TIA, is another consideration to reduce the overall cost for access networks. These components operate beyond their specified bandwidth, the introduced impairments can be equalized in the DSP section to balance the cost of components and the DSP complexity. As shown in Figure 30, two pre-comp schemes at DAC are presented here, including least mean square and constant modulus algorithm (CMA) algorithms. The criterion is to minimize the difference between the received data and convolution result of estimated channel coefficients.

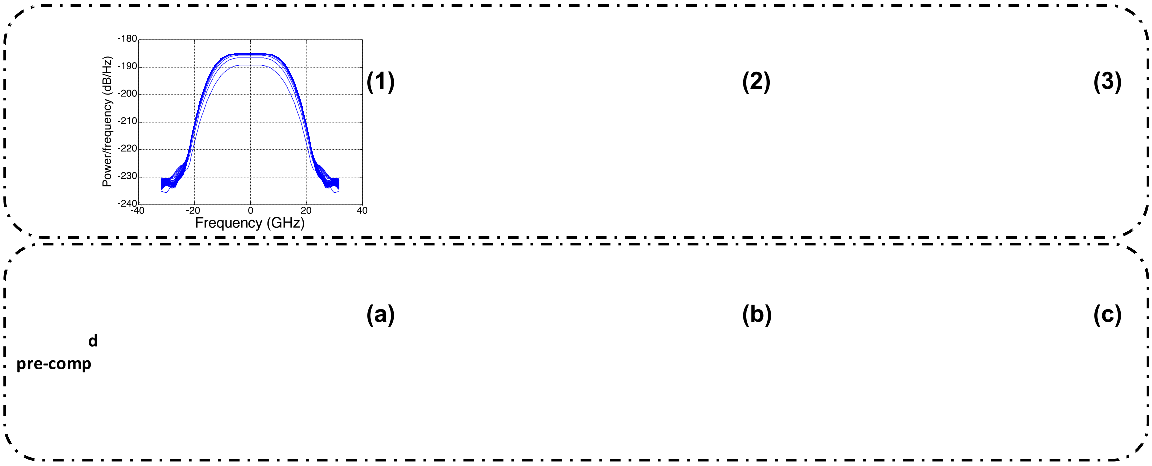

Figure 30 - Pre-Compensation Algorithms for 32-GBaud Signals with 22-GHz System Bandwidth

Figure 31 shows the results of 80-km SMF transmission of PM-QPSK/16-QAM in our proof-of-concept testbed, where error vector magnitude (EVM) is plotted as a function of baud rate. Due to the limited bandwidth of low-cost RF amplifiers (10 GHz RF drivers from Picosecond Pulse Labs 5822B) and the optical IQ MZM (14 GHz IQ-MZM from Covega LN86S-FC), EVM increases with baud rate.

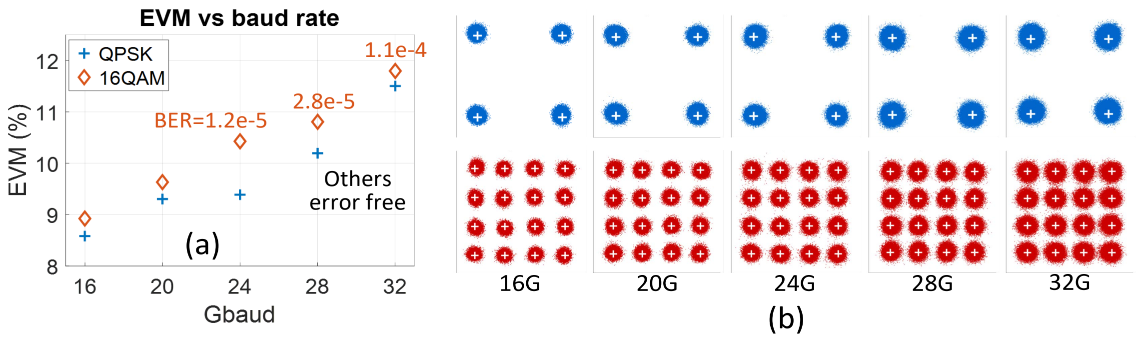

Figure 31 - Transmission Results of Low-Cost PM-QPSK and PM-16QAM Signals.

4.6.3. Standarization and Interoperability

Another important factor to consider is standardization and interoperability. Standardization is driven mainly by short-reach metro/aggregation applications, where optical performance is not a differentiator. Today, around seven DSP solutions from different companies are offered. The standardization will eventually lead to improved interoperability and predictable performance and allow operators to utilize the optical fiber infrastructure more efficiently to meet future bandwidth demand.

In 2016, The Optical Internetworking Forum (OIF) launched a new project related to coherent transmission technology: 400G ZR Interoperability. The OIF expects to develop an implementation agreement (IA) for 400G ZR and short-reach DWDM multi-vendor interoperability. The IA will support single-carrier 400G transmission using coherent detection and advanced DSP/FEC algorithms.

To make the coherent transceiver interoperable to each other, the following main parameters need to be considered:

1. Modulation format.
2. Framing format.
3. DSP algorithms.
4. Symbol mapping.
5. Optical properties.
6. Equalization parameters.

It is believed that the industry as a whole would benefit from a successful standardization of coherent transceiver including both optical performance and DSP functions and capabilities.

4.7. Experimental Results

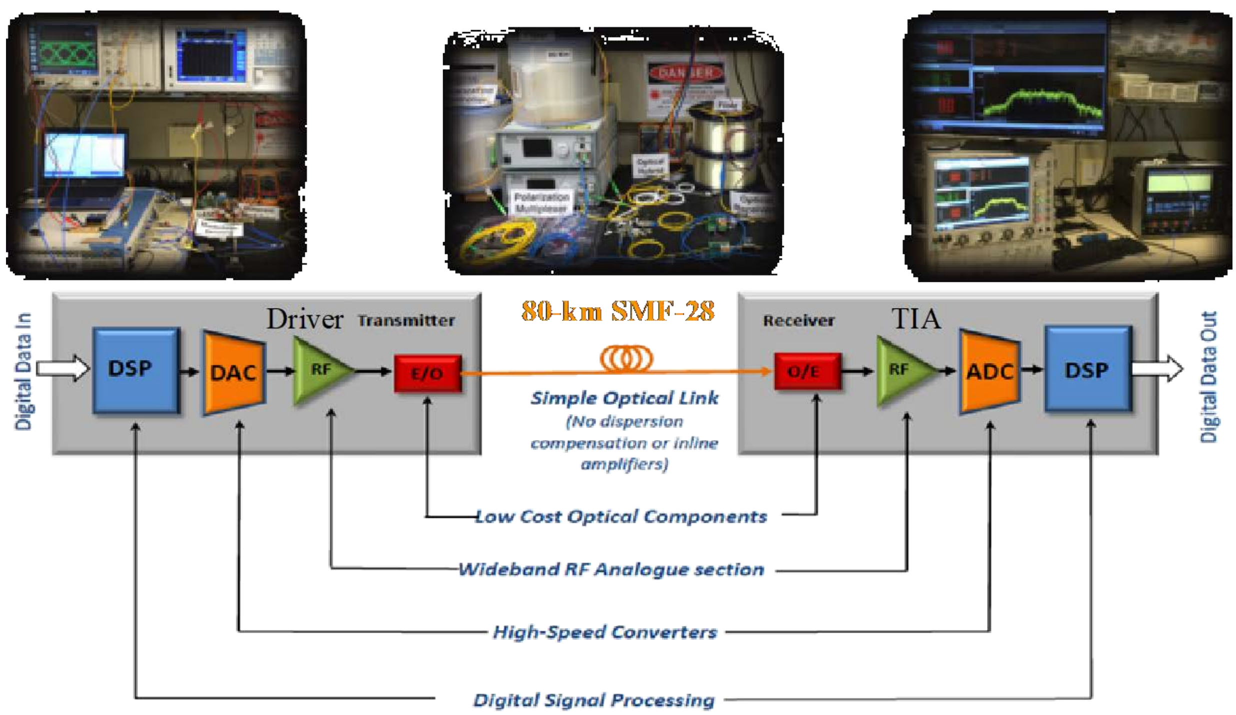

Figure 32 - End to End Coherent Optical Link in the Lab

To demonstrate the feasibility of coherent optics in access networks and verify methods and ideas that have practical potential, CableLabs has established a coherent optical transmission system in an optical laboratory. Figure 32 shows the end-to-end coherent optical link with in-house developed DSP algorithms at both the transmitter and receiver sides. The DAC function is achieved via Keysight M8196A arbitrary waveform generator with up to 92 GSa/s and 32-GHz analog bandwidth. The real-time sampling scope with up to 80 GSa/s and 33-GHz analog bandwidth performs the function of ADC. Different types of off-the-shelf electrical and optical components are acquired to emulate different implementation scenarios, such as low-bandwidth scheme or high-performance solution.

4.7.1. Single Wavelength

In the laboratory, we have achieved 256 Gbps over 80 km on a single wavelength with low-bandwidth optical components and simplified DSP algorithms. That is ~26 times the capacity of what can be achieved over an analog optical carrier fully loaded with 1.2 GHz worth of DOCSIS 3.1 signals. We have achieved that using a symbol rate of 32 GBaud, using 16-QAM modulation over 2 polarizations.

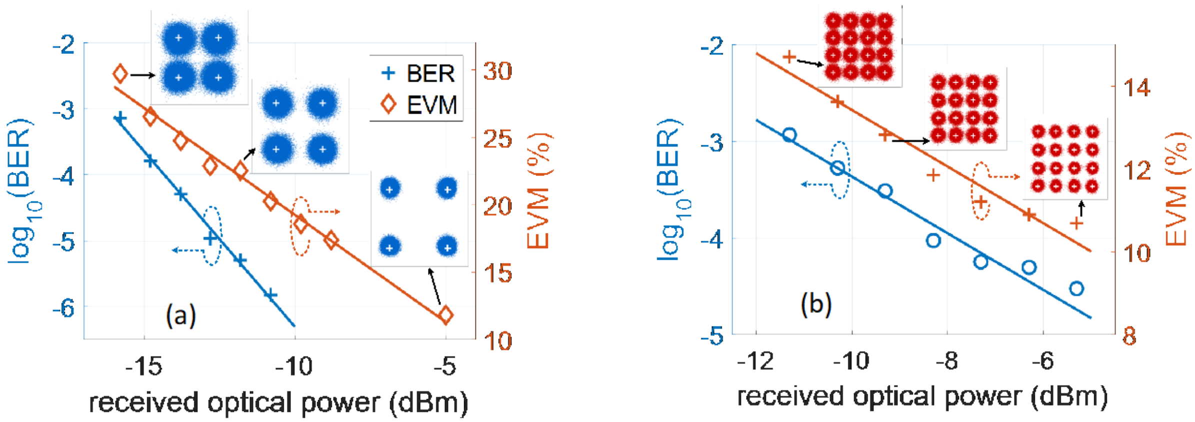

Figure 33 - BER and EVM Performance of Low-Bandwidth Coherent Scheme

BER and EVM performance of coherent 32-Gbaud PM-QPSK transmission are presented in Figure 33 (a), with constellations plotted in the insets. Due to the limited memory of our AWG, minimum measurable BER is 1×10-6, and error free transmission is achieved for received optical power larger than -10 dBm. BER and EVM of 32-Gbaud PM-16-QAM transmission is presented in Figure 33 (b), and the minimum achievable BER is 3×10-5. As shown in Figure 34, high baud rate and high-order modulation formats are also tested based on the high-performance setup.

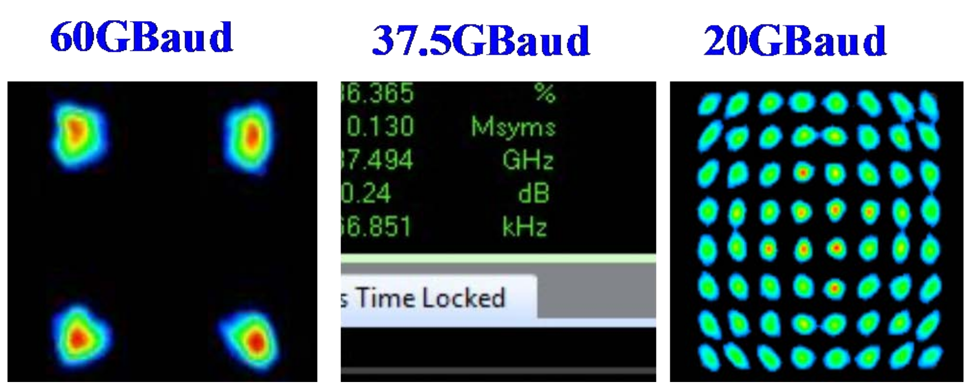

Figure 34 - Constellations of High Baud Rate and High-Order Modulation Formats

4.7.2. DWDM System

In addition, we have multiplexed eight of these wavelengths to achieve 2048 Gbps. That is 50 times more than what can be achieved over 4 analog optical carriers each with 10 Gbps of DOCSIS 3.1 payload. Each wavelength carries 256 Gbps based on 32GBaud PM16-QAM signals using low-cost components. The optical spectra of unmodulated CW and modulated coherent signals are shown in the following figure. These eight wavelengths only occupy a very small portion of C-band transmission window, which is shown in (b) of the following figure. In this system, the net SE is 4bits/s/Hz, which is 40 times better than DWDM direct detection scheme.

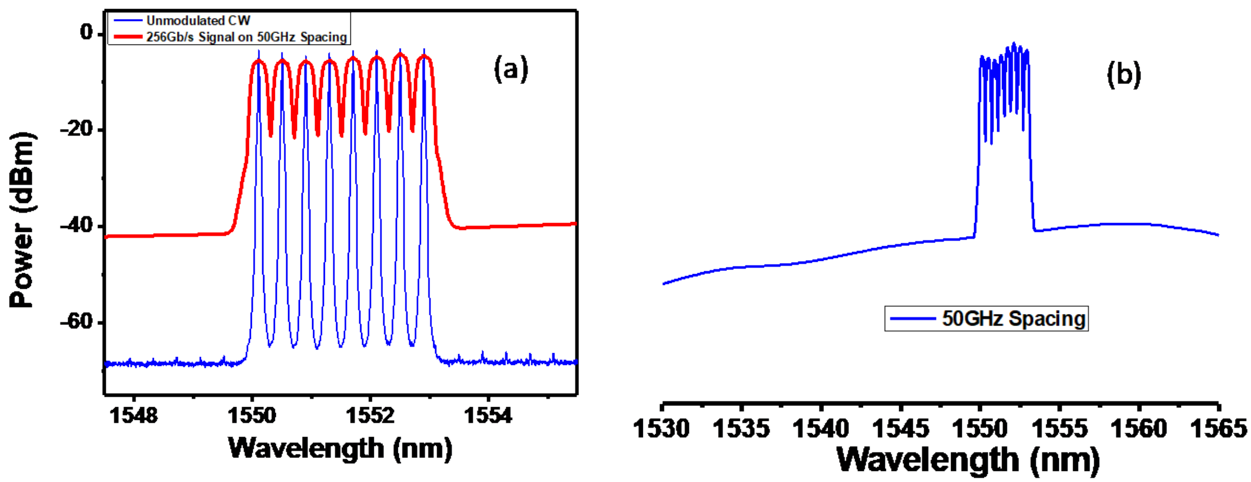

Figure 35 - Optical Spectra of Eight DWDM Coherent Signals

4.7.3. Coexistence Evaluations (Preliminary Results)

The ideal network for deploying such coherent systems would be a green field deployment on fibers, which is called coherent-only implementation. However, in practice there are many brown field installations, meaning many of these networks are deployed already and have several DOCSIS and or 10G OOK 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 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 in WDM systems.

To provide an option that enables network operators to effectively support 100G on their existing networks, CableLabs has done some preliminary experimental verifications to explore the performance challenges in such coexistence applications.

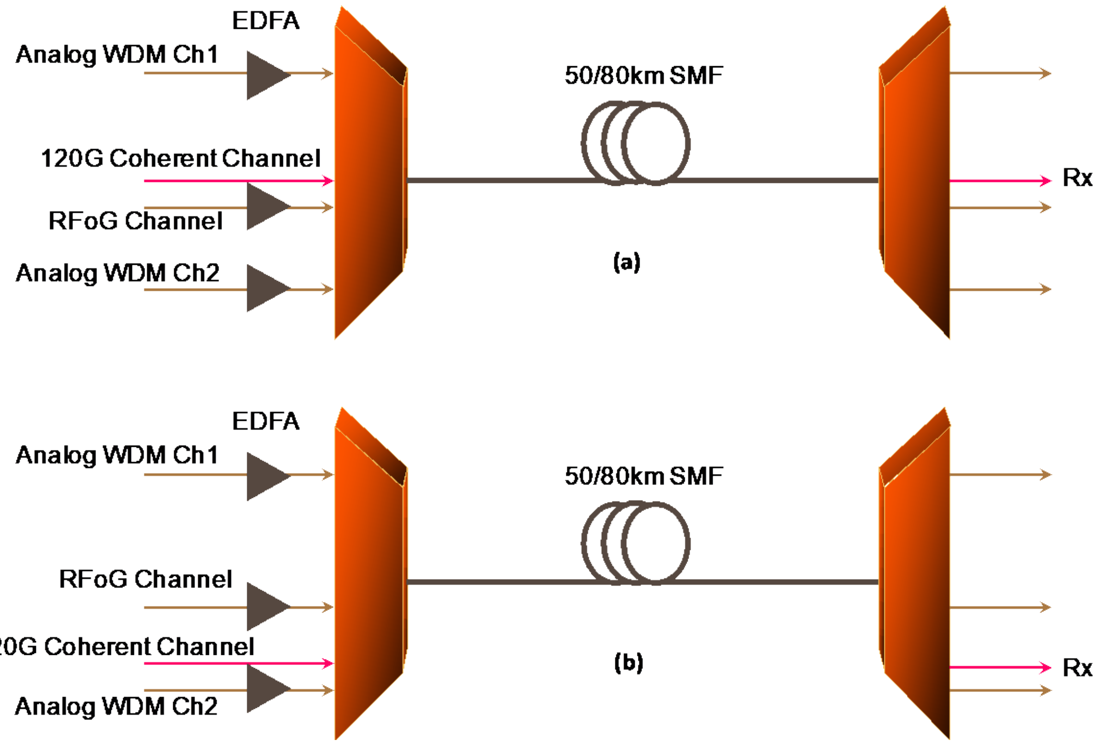

Figure 36 - Experimental Setup for Coexistence Evaluation, (a) Case I and (b) Case II

Because of the limited availability of the number of analog optical channels, two cases are selected for coexistence testing between coherent and analog channels as shown in Figure 36 (a) and (b) for case I and II, respectively. Our experimental work includes a single 120-Gb/s coherent PM-QPSK channel with three co-propagating analog DOCSIS3.1 channels through 50 or 80-km SMF. A CFP module is used to generate the PM-QPSK coherent signal, the two neighboring channels on the 100 GHz ITU-T grid CH28 and CH40 at each side of the test channel are generated by independently modulated commercial 1-GHz DOCSIS 3.1 transmitters. The other channel is based on radio-frequency over glass (RFoG) channel at CH33. The wavelength allocation and launched power of each channel are shown in Table 2. Around 15-dB power difference is set between coherent channel and analog channels.

Table 2 - Wavelength Allocation on ITU-Grid

Channel	ITU-T Grid	Carrier Frequency (THz)	Wavelength (nm)	Input Power (dBm)
Acacia 120G Coherent CFP	CH 34	193.400	1550.097	-1.67
Arris RFoG	CH 33	193.300	1550.967	13.78
Cisco Prisma II	CH28	192.800	1554.92	13.11
Cisco Prisma II	CH40	194.000	1545.309	12.75

Figure 37 shows the optical spectra of all signals before optical transmission, where the coherent wavelength is tuned to CH29.

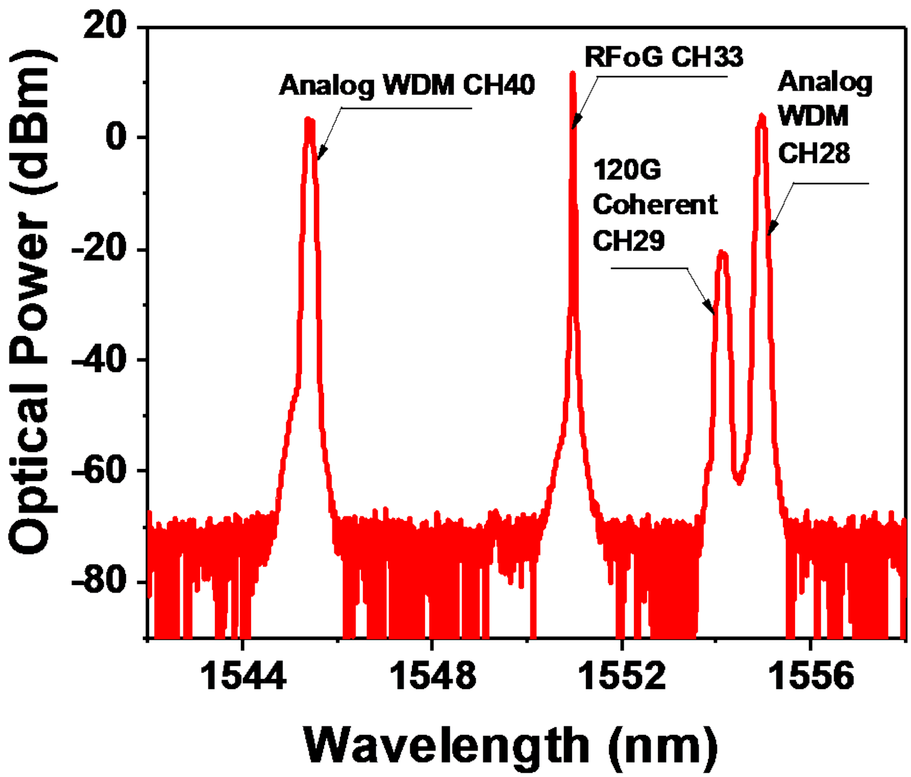

Figure 37 - Optical Spectra before Fiber Transmission

In this testing condition, the transmission performance of coherent channel with and without neighboring analog channels are shown in Figure 38 (a) and (b). Negligible penalty is observed after 50 or 80-km fiber transmission both testing cases.

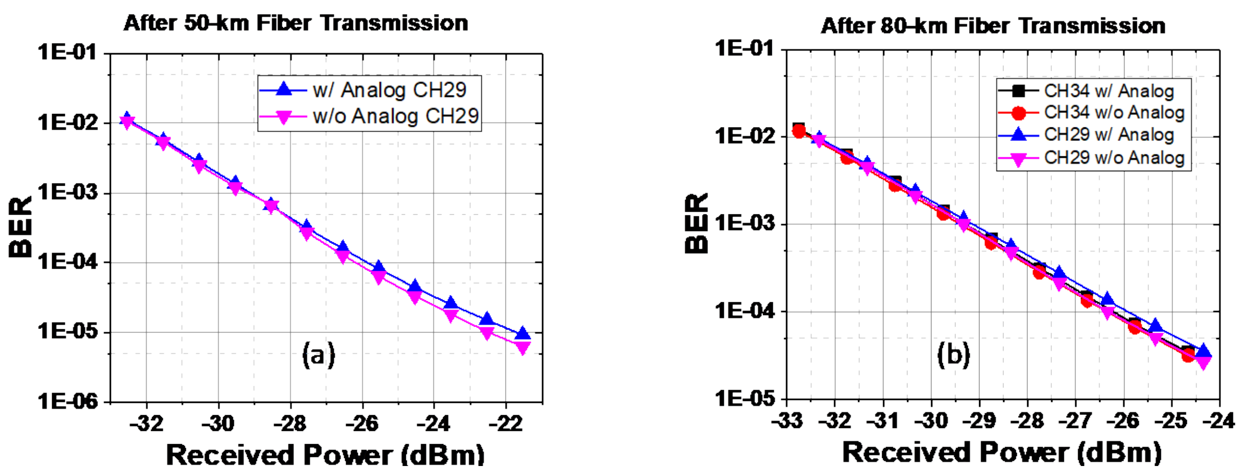

Figure 38 - Transmission Performance w/ & w/o Analog Channels

Towards the highly nonlinear regime, a penalty in BER can be observed with the increase launch power of analog channel power (CH 28). As shown in Figure 39, negligible impairment is observed if the analog power is less than 14 dBm in this testing scenario.

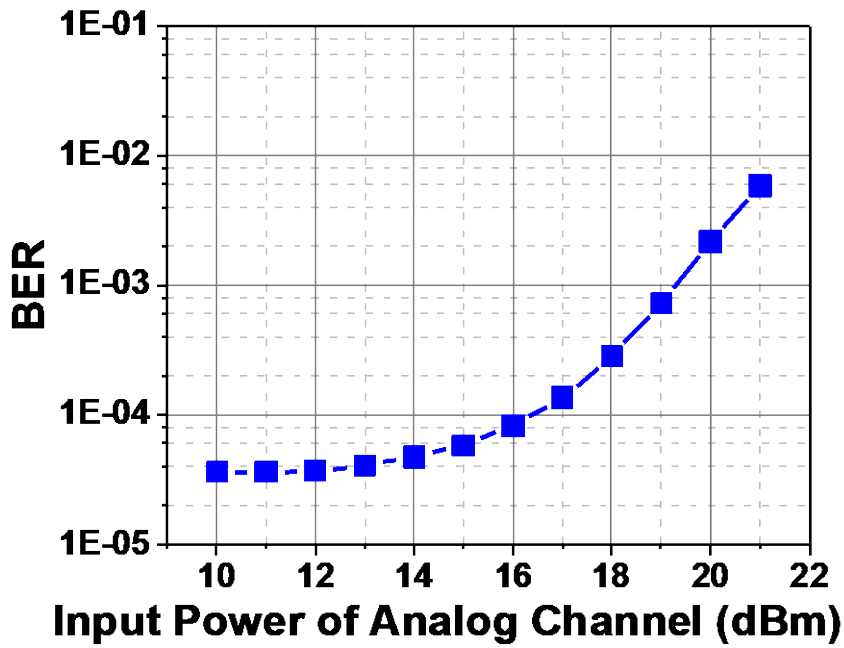

Figure 39 - Transmission Performance w/ Different Input Power of Neighboring Analog Channel

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 discussed use cases for near-term and long-term applications, including the deployment for aggregation points in distributed HFC architecture, remote PON systems and eventually coherent optics to the premises. Economics of coherent optics in the aggregation use case scenarios have been analyzed. This economic analysis show that 100 Gbps aggregation by 2020 will have similar link costs using either wavelength multiplexing direct detection or coherent optics, and the breakeven link cost point will occur earlier for a greater capacity demand. In addition, coherent optics systems are advantageous operationally as they consume lower power and require much lower number of ports at the hub than wavelength multiplexed direct-detection alternatives. This coherent optics cost improvement could accelerate further with a solution optimized for the Cable access network.

This paper introduces digital coherent optical system in detail, including advanced modulation formats, architecture of modulation and detection, and DSP flow for both transmitter and receiver. The paper highlights the motivation for coherent optics in access and potential approaches to re-design and re-engineer the digital coherent concept from long-haul and metro solutions to the access network, leveraging reduction in complexity and cost of electrical and optical components as well as DSP ASIC. While coexistence between coherent signals and analog signals was simulated [2] in a previous paper, in this paper coexistence between these two systems was experimentally demonstrated showing 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.

Standardization and interoperability will play a key role for low-cost implementation for access. Proof-of-concept experimental results demonstrating multi-wavelength multi-terabit per second within an access environment are shown in the laboratory. This also demonstrates coherent optics technology long term scalability leveraging the fiber from hub to node already deployed.

Abbreviations

ADC	analog to digital converter
ASIC	application-specific integrated circuit
BER	bit error rate
BPSK	binary phase-shift keying
CD	chromatic dispersion
CMA	constant modulus algorithm
CMOS	complementary metal–oxide–semiconductor
CMTS	cable modem termination system
DAC	digital to analog converter
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
FEC	forward error correction
FWM	four-wave-mixing
Gbps	gigabit per second
GHz	gigahertz
HD	high definition
HFC	hybrid fiber-coax
HHP	household pass
ISBE	International Society of Broadband Experts
km	kilometer
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
OSNR	optical signal-to-noise ratio
PAM	pulse amplitude modulation
PBS	polarization beam splitter
PHY	physical layer
PM	polarization multiplexing
PMD	polarization mode dispersion
PON	passive optical network
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
SMF	single mode fiber
SNR	signal to noise ratio
SOP	state of polarization
SPM	self-phase modulation
XPM	cross-phase modulation

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