Amphenol NETWORK SOLUTIONS™

Coherent Optics Technologies and Applications for Next-Generation Optical Networks

White Paper

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1. Executive Summary

This white paper provides an overview of coherent optics technologies and their applications in the next-generation optical networks. As the demand for higher bandwidth, longer reach, and more efficient optical communication systems continues to grow, coherent optics has emerged as a key enabling technology. This paper explores the basics of coherent optics, highlights recent advancements in the field, and discusses the various applications and benefits of coherent optics in shaping the future of optical networking.

2. Introduction

The increasing demand for bandwidth-intensive applications, such as cloud computing, streaming services, and Internet of Things (IoT) connectivity, has driven the need for faster and more reliable optical networks. Coherent optics technology has played a pivotal role in meeting these demands by revolutionizing the way optical signals are transmitted, received, and processed.

Coherent optics leverages advanced modulation schemes, digital signal processing (DSP), and coherent detection techniques to enable high-capacity, long-haul transmission over optical fiber networks. This section provides an overview of the challenges faced by existing optical networks and the role of coherent optics in addressing these challenges.

History Review:

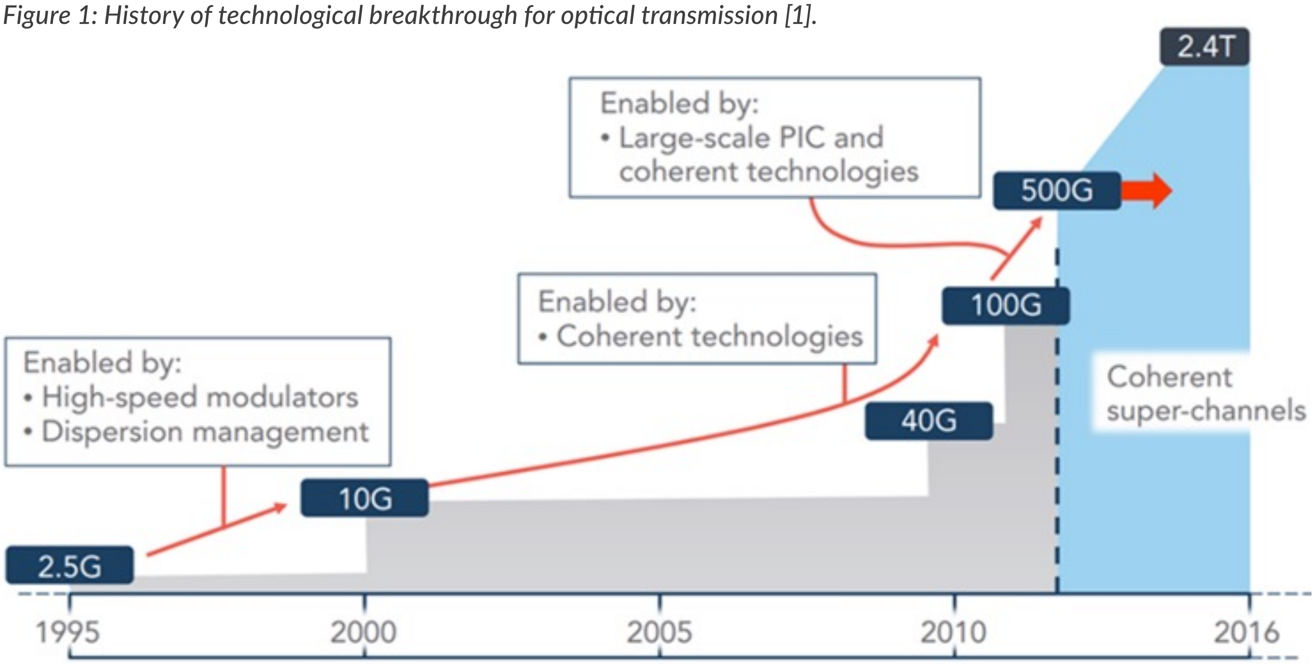
In the mid-1990s, wavelength-division multiplexing (WDM) was introduced with a typical data rate of 2.5Gb/s per wavelength. To increase fiber capacity, the channel count on the fiber was increased using wavelength multiplexing (Mux) and demultiplexing (Demux) components. The transition to 10G wavelengths became possible due to advancements in optical modulators, better understanding of chromatic dispersion management, and the availability of dispersion compensating fibers.

However, both 2.5Gb/s and 10Gb/s data rates used a simple modulation format called intensity modulation with direct detection (IM-DD), also known as on/off keying (OOK) and non-return to zero (NRZ). While this modulation technique served the industry well, it became less efficient in terms of spectrum utilization as the data rate increased beyond 10Gb/s. It was also susceptible to fiber impairments such as chromatic dispersion (CD) and polarization mode dispersion (PMD).

Initial attempts to achieve higher data rates beyond 10Gb/s resulted in 40Gb/s transponders using slightly more complex modulation schemes like optical duobinary (ODB) and differential phase shift keying (DPSK). However, these implementations were commercially unsuccessful because they had inadequate optical reach for long-haul deployments. Additionally, the presence of polarization-mode dispersion (PMD) became a significant problem at data rates above 10Gb/s, requiring expensive and power-hungry external PMD compensation systems.

Furthermore, the cost of 10Gb/s IM-DD systems continued to decrease significantly, making it difficult to economically justify switching to 40Gb/s technology. These factors contributed to

Figure 1: History of technological breakthrough for optical transmission [1].

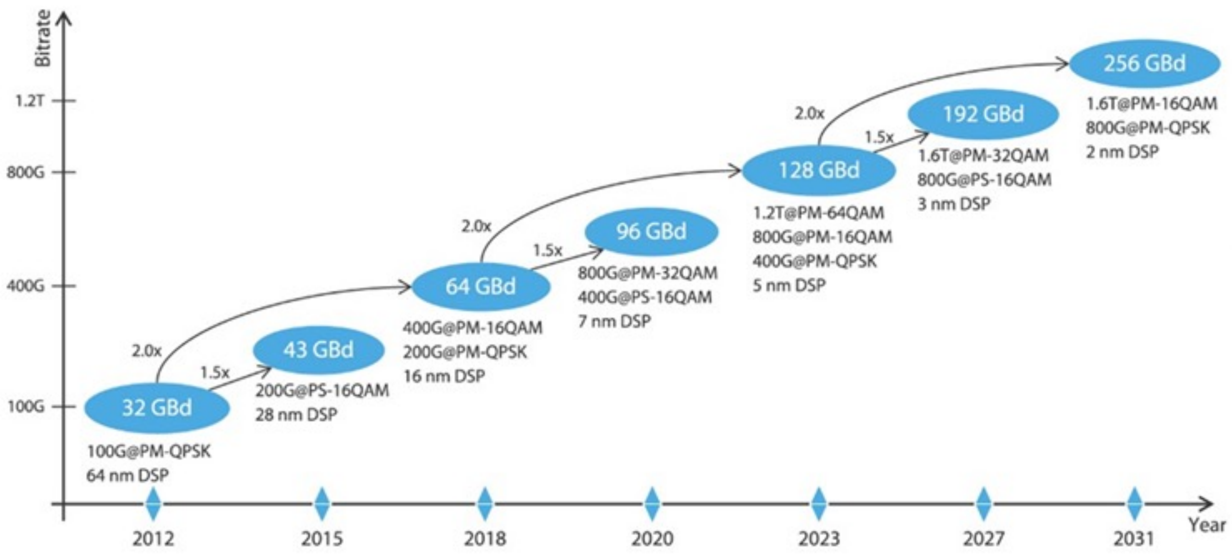


The breakthrough that allowed the "10G Speed Limit" to be surpassed was the introduction of coherent optical technologies. These technologies were initially developed for 40Gb/s transmission and later for 100Gb/s long-haul transmission. By around 2010 to 2011, these coherent technologies had matured enough to enable the transmission of 100Gb/s coherent signals over similar or even longer distances compared to 10Gb/s IM-DD.

During this time, the increasing demand for internet services driven by factors such as increased video traffic, mobile devices with high-resolution displays, and the use of cloud-based storage contributed to a significant growth in internet demand. This growth was estimated to be between 35% and 50% per year.

As a result, there emerged a need for additional capacity, improved spectral efficiency, and better cost per bit to meet the increasing demand for internet services. Coherent 100Gb/s technologies proved to be a viable solution, offering the required capacity, spectral efficiency, and cost-effectiveness. This created a favorable environment for the mass-market adoption of coherent 100G technology, which began around 2012.

Figure 2: Coherent optical transmission technology advancement [2].



The development of optical coherent technologies has been a remarkable technical achievement. As indicated in Fig. 2, there has been a trend of introducing a new generation of coherent optical modules approximately every three years. This timeline is based on advancements in digital signal processor (DSP) technologies and the evolution of baud rates.

Looking ahead, the next expected milestone is the entrance of coherent 128 GBaud technology into the market in 2023. This upcoming technology is anticipated to bring further progress and improvements in coherent optical transmission capabilities.

The continuous development and deployment of higher baud rates and modulation schemes in coherent optical technologies have been instrumental in meeting the growing demands for higher capacity and improved transmission performance in optical networks.

3. Modulation Format and Spectrum Efficiency

3.1 Quadrature Phase Shift Keying (QPSK) Modulation

In a bandwidth-limited transmission system, it is crucial to employ more efficient and advanced signal modulation and transmission techniques to effectively transfer a higher number of bits over the existing fiber infrastructure. This is particularly important in the context of the cloud revolution and the immense growth of data traffic.

Traditional on/off keying (OOK) transmission, which uses a simple approach of interpreting the laser source being turned on as a "one" and turned off as a "zero," has limitations in terms of utilizing the full potential of light waves. In OOK, the information is encoded solely based on the amplitude of the light signal.

However, a light wave comprises more parameters than just amplitude, including phase, polarization, and frequency. By leveraging all these degrees of freedom, there are more possibilities to encode and transmit information efficiently.

Advanced modulation techniques, such as phase modulation, frequency modulation, polarization modulation, and combinations thereof, can be employed to encode multiple bits per symbol or to enable the transmission of higher-order modulation schemes. These techniques allow for the simultaneous manipulation of multiple parameters of the light wave to represent more information within each symbol.

By using more efficient complex signal modulation and transmission techniques, it becomes possible to increase the data rate and spectral efficiency of the fiber infrastructure. This is crucial to meet the challenges posed by the increasing data demands of the cloud revolution and the

Figure 3: The model of the electric field of optical wave with two polarizations [3].

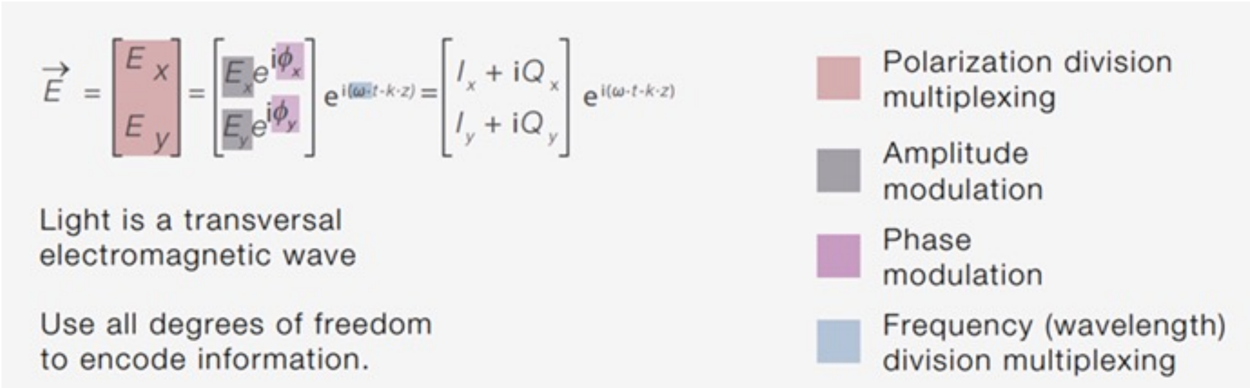


Figure 3 illustrates the mathematical description of an electromagnetic wave's electric field, which consists of two orthogonal polarization components, Ex and Ey. These two components can be utilized as independent channels to transfer separate signals. In wavelength-division multiplexing (WDM), different frequencies (or wavelengths), represented by ω, are assigned as distinct channels for transmitting independent data at those specific frequencies.

In complex modulation schemes, in addition to modulating the amplitude (E) of the light wave, the phase (ϕ) is also modulated to carry information. This allows for a more efficient utilization of the available degrees of freedom in the light wave.

The electric field of the modulated light wave can be described in the complex plane using an I/Q (in-phase/quadrature) diagram. In this diagram, the I component represents the real part, and the Q component represents the imaginary part of the complex electric field. The I/Q diagram is a useful representation for understanding and analyzing the modulation and demodulation processes in complex modulation schemes. It provides a visual representation of how the modulation manipulates the amplitude and phase of the light wave to encode and carry information.

Figure 4: 4 Four symbols / constellation points for 2 bits encoded in one symbol (quadrature phase shift keying, QPSK) [3].

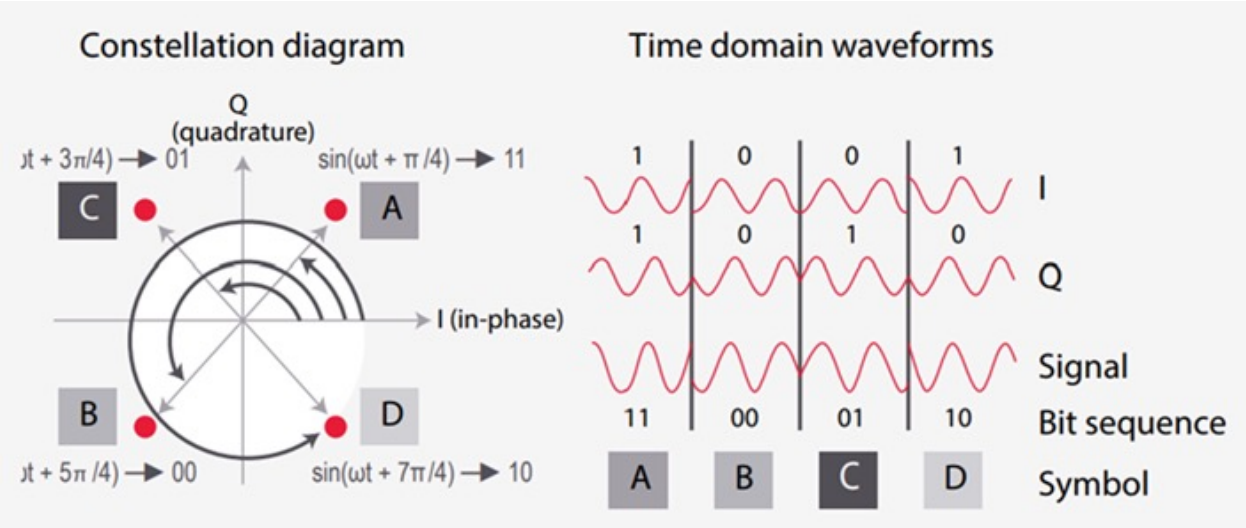


Figure 4 illustrates the constellation points for quadrature phase-shift keying (QPSK), which is a complex modulation scheme. In QPSK, each symbol represents 2 bits of information. The four constellation points are positioned on a circle with a radius of E, indicating that the symbols differ only in phase, not in amplitude. The phase difference between neighboring points is always π/2.

In the time domain, the four symbols of QPSK are represented by a combination of two waves with the same amplitude but different phases. By manipulating the phase of these waves, the desired symbol is transmitted.

One important aspect to note is that the bandwidth required by complex modulated signals is determined by the symbol rate rather than the data rate. This means that increasing the number of bits encoded into a single symbol while keeping the symbol rate constant can lead to a reduction in the occupied optical bandwidth. In other words, if the symbol rate remains unchanged, increasing the number of bits per symbol allows for a higher data rate while maintaining the same occupied optical bandwidth. This highlights the advantage of increasing the *bits per symbol* in terms of achieving higher data rates without expanding the optical bandwidth.

3.2 Tim Domain Pulse Shaping

It must be aware that the complex modulated signal spreads in time and that consecutive symbols may overlap, which is referred to as inter-symbol interference (ISI), leading to errors in signal interpretation at the receiver side.

In the frequency domain, it is also crucial to prevent interference between adjacent channels crosstalk to maintain signal integrity. This becomes especially important for high data rate transmissions such as 400 Gb/s and 1 Tb/s.

To address these issues, digital signal processing techniques play a significant role. One commonly used technique is the implementation of a Raised-Cosine Filter. This filter provides effective out-of-band spectrum suppression and ensures that only the sampled symbol contributes to the signal, while all other symbols are zero at the sampling points in time domain.

The use of a Raised-Cosine Filter helps meet the Nyquist inter-symbol interference criterion, which states that the received signal should have no interference from neighboring symbols at the sampling instants. By carefully designing the filter, it is possible to mitigate inter-symbol interference and maintain signal quality, thus improving the overall performance of high-speed digital communications systems.

Applying appropriate digital signal processing techniques, including the use of filters like the Raised-Cosine Filter, is crucial in achieving reliable and efficient transmission of complex modulated

Figure 5: Normalized Raised-cosine filter with different roll-off factors (left: time domain, right: frequency domain) [3].

$$h[t] = sinc\left(\frac{t}{T}\right) \frac{\cos \frac{\pi \alpha t}{T}}{1 - \frac{4\alpha^2 t^2}{T^2}}$$

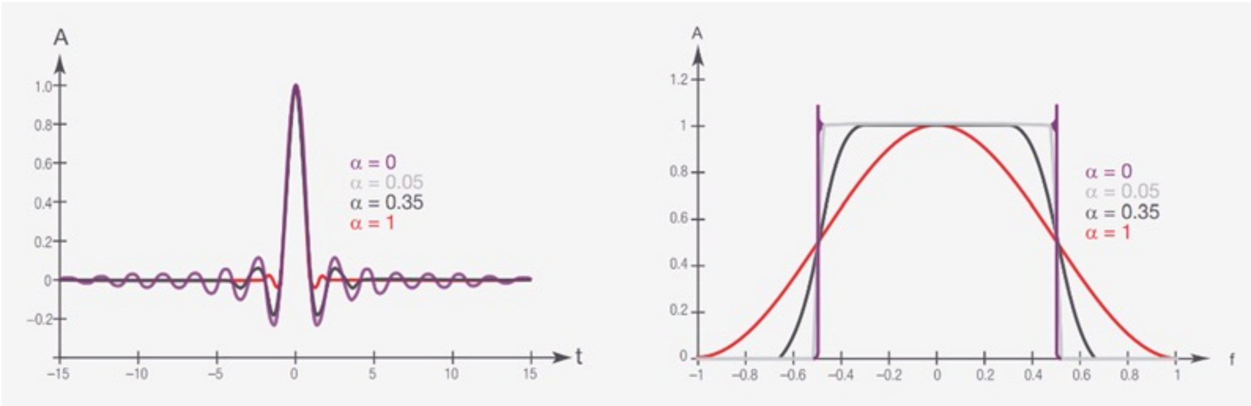
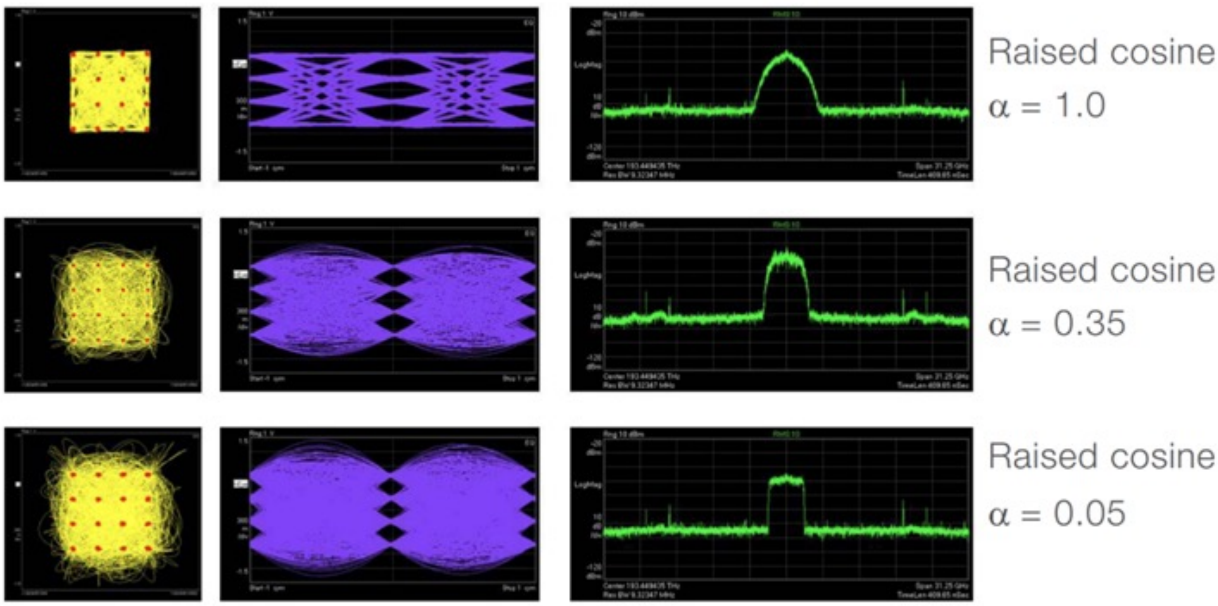


Fig. 5 is the mathematical model of Raised-Cosine Filter and its pulse response in time domain and frequency domain with different roll-off factors. In the time domain, with a roll-off factor **α** = 1, we see less ring of the impulse response, but more passband required in the frequency domain. When **α** = 0, it is opposite.

Figure 6: Raised-cosine filter on the 16-QAM signal with different roll-off factor: constellation, eye-diagram and frequency spectrum.



In Fig. 6, with a roll-off factor **α** = 1, the eye diagram shows wide-open eyes. The constellation points are smaller. This is typical for a system with reduced bandwidth. The detection bandwidth on the receiver side is, by implication, also reduced, which lowers noise.

At a roll-off factor **α** = 0.35, the frequency width has further decreased, and with it the size of the constellation points. The transitions between the constellation points start to show much overshot. This is because when reducing bandwidth, the transitions between the symbols get extended in time, which is reflected in the constellation diagram by the long, curved transitions between the points. The eyes are closing and therefore the sampling timing gets more critical.

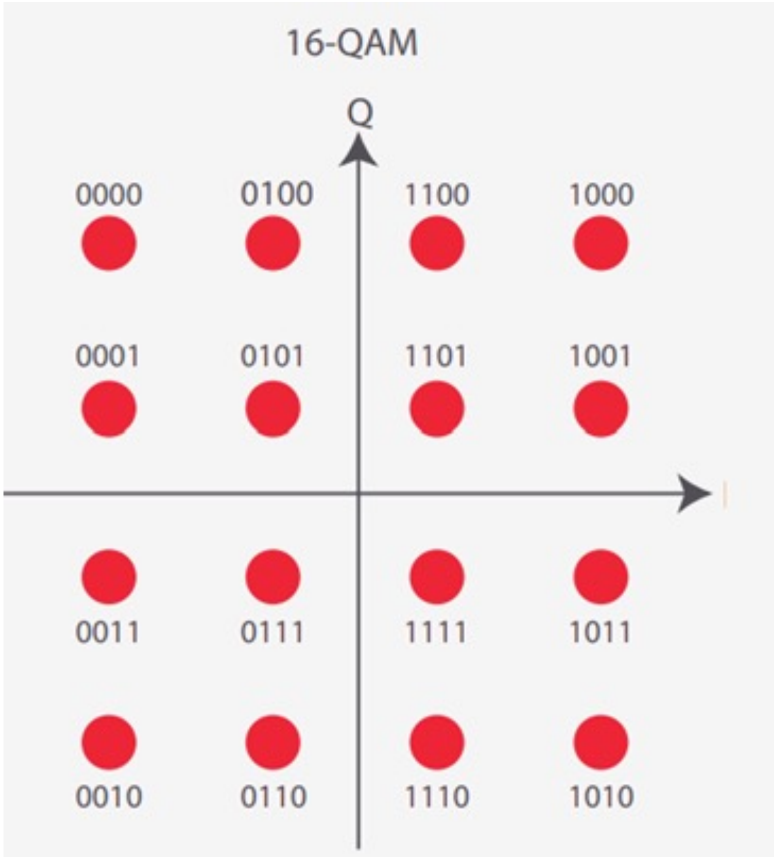
An almost perfect rectangular spectrum is reached at **α** = 0.05. The transitions between the little constellation points show large overshoot. The completely closed eyes indicate that to avoid errors, the sampling point must be adjusted precisely.

For the complex modulation with improved spectrum efficiency transmission system, an optimized roll-off factor has been chosen to balance the signal quality as well as signal bandwidth requirements.

3.3 Forward Error Correction (FEC)

For higher data rate transmission, 16-QAM is one of the most popular modulation schemes. In this scheme, 4 bits are represented by one symbol. The 16 constellation points are distributed in a square lattice (see Figure 7). Typically, they are Gray coded; from one constellation point to every neighboring point, only one bit value changes. This way, if due to noise, a measured point is wrongly assigned to a neighboring point, the resulting bit error is kept to a minimum: 1 wrong bit.

Figure 7: 16-QAM with Gray-coded



4. Coherent Optics Technologies

4.1 What is Coherent Optics

Coherent optics are extensively used in ultra-high bandwidth applications, ranging from 100 Gigabit to 1 Terabit per second. These systems employ powerful digital signal processing chips (DSPs) to mitigate the impact of fiber impairments, such as chromatic dispersion and polarization mode dispersion, which can degrade signal quality.

A coherent optical fiber communication system takes advantage of various properties of light waves, including amplitude, phase, and polarization, to optimize the capacity and performance of a fiber optic link. Unlike traditional on/off keying (OOK) modulation, coherent optical transmission utilizes tunable lasers and sophisticated digital signal processing techniques at both the transmitter and receiver ends of the link.

At the transmitter, the light wave's amplitude, phase, and polarization are precisely modulated to encode the information being transmitted. This modulation can involve complex schemes such as quadrature amplitude modulation (QAM) or phase shift keying (PSK) with multiple levels. The DSP in the transmitter prepares the signal for transmission by compensating for impairments and optimizing its performance.

At the receiver, the received signal is processed using digital signal processing techniques to demodulate and extract the transmitted information. The DSP in the receiver performs various tasks such as signal equalization, chromatic dispersion compensation, polarization demultiplexing, and error correction. By employing sophisticated algorithms and processing techniques, the DSP mitigates the impact of fiber impairments and enhances the overall system performance.

Coherent fiber optics excel in high-bandwidth dense wavelength division multiplexing (DWDM) applications. The high spectral efficiency offered by coherent transmission allows for the transfer of a significant number of bits in the optical spectrum. This means that multiple wavelengths or channels can be densely packed together, maximizing the utilization of the available optical bandwidth.

By leveraging the high spectral efficiency of coherent optics, dense wave division multiplexing (DWDM) systems can support the transmission of multiple channels or wavelengths over a single optical fiber simultaneously. This enables the transmission of a large amount of data over long distances without the need for extensive amplification or regeneration.

The reduced amplification requirements in coherent fiber optics are particularly advantageous for high-bandwidth DWDM applications. Since the signals are processed and amplified in the digital domain, the need for optical-to-electrical conversion and subsequent re-amplification is minimized, leading to improved efficiency and cost-effectiveness.

In summary, advanced coherent optical technology has several key attributes, including:

- High-gain soft-decision Forward Error Correction (FEC), which enables signals to traverse longer distances while requiring fewer regenerator points. It provides more margin, allowing higher bit-rate signals to traverse farther distances. This results in simpler photonic lines, less equipment, and lower costs—while, of course, increasing bandwidth significantly.
- Spectral shaping, which provides greater capacity across cascaded Reconfigurable Optical Add-Drop Multiplexers (ROADMs), resulting in increased spectral efficiency for super channels. Spectral shaping is critical in flexible grid systems because it allows carriers to be squeezed closer together to maximize capacity.
- Programmability, which means the technology can be tailored for a wide variety of networks and applications and the same card can support multiple modulation formats and/or different baud rates, enabling operators to choose from a variety of line rates. Fully programmable coherent transceivers provide a wide range of tunability options with fine granularity between incremental capacities, enabling network operators to make use of all available capacity and convert excess margin into revenue-generating services.
- Strong mitigation to dispersion, which offers better optical performance at higher bit-rates. Coherent processors must account for dispersion effects after the signal has been transmitted across the fiber, including compensating for CD and PMD. The advanced digital signal processors in coherent optics take away the headaches of planning dispersion maps and budgeting for PMD by mitigating these effects. Additionally, coherent processors improve tolerances for Polarization-Dependent Loss (PDL) and must rapidly track the State of Polarization (SOP) to avoid bit-errors due to cycle slips that would otherwise affect optical performance. As a result, operators can deploy line rates up to 400G per carrier across longer distances than ever; high bit-rate signals can even be deployed on old fiber that previously couldn't support 10G.

4.2 Coherent Optics in DWDM System

WDM enables the transmission of multiple wavelengths or colors of light over the same fiber simultaneously, with each wavelength carrying a separate and discrete signal. This allows for increased capacity and efficient utilization of the fiber's bandwidth. DWDM takes WDM to a higher level by employing tighter wavelength spacing, accommodating a larger number of channels (up to 96 or more) on a single fiber. When combined with coherent modulation, individual channel bandwidth can expand to higher capacities, such as 400 or 800 Gigabits.

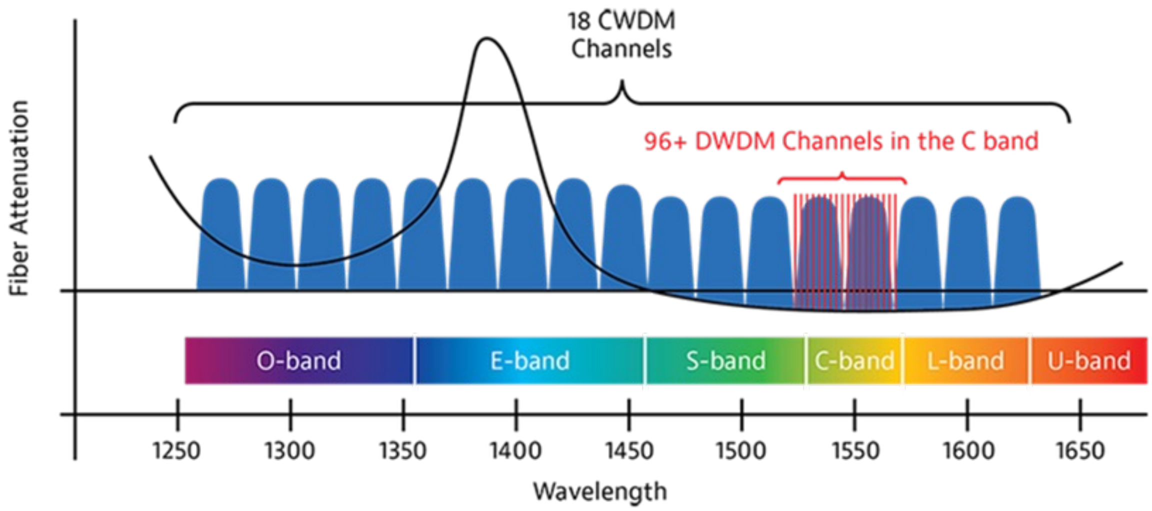
It's worth noting that DWDM is a transmission technology that can support both coherent optics and traditional on/off keying (OOK) modulation. Coherent optics, when deployed in DWDM systems, provide advanced modulation schemes and powerful digital signal processing (DSP) capabilities. These technologies allow for higher data rates and improved signal quality.

For coherent transmission, in DWDM systems, the channel width may need to be adapted based on the spectral width requirements. The flexible grid architecture and dynamic channel spacing in DWDM systems allow each channel to have a different passband, accommodating different bandwidth requirements and spectral characteristics.

One significant advantage of coherent optical fiber communication is the elimination of the need for dispersion compensation modules (DCMs) in DWDM systems. Coherent transmission, through the use of advanced DSP algorithms, compensates for chromatic dispersion and other impairments, ensuring high-quality signal transmission without the need for additional hardware.

By combining coherent modulation, DWDM, and advanced DSP techniques, optical fiber communication systems can achieve high capacities, improved spectral efficiency, and enhanced transmission performance, making them vital for meeting the increasing demand for high-bandwidth applications.

Figure 8: Fiber optical spectrum with CWDM and DWDM.



Traditional IM-DD transmission is typically limited to lower data rates, such as 10 Gb/s. In this method, only 1 bit of information is encoded per symbol, leading to a limited capacity for data transmission.

In contrast, coherent optics enables the encoding of multiple bits per symbol, significantly increasing the potential data capacity. By leveraging the adaptable properties of light, including amplitude, phase, and polarization, coherent optical systems can achieve higher-order modulation formats. These formats allow for the encoding of multiple bits per symbol, such as 4, 8, 16, or 32 bits per symbol, depending on the modulation scheme employed.

Overall, coherent optical technology offers the means to maximize data capacity through the use of advanced modulation formats and the exploitation of multiple degrees of freedom in light, providing a significant advantage over traditional IM-DD transmission.

4.3 Modulation of Coherent Optics

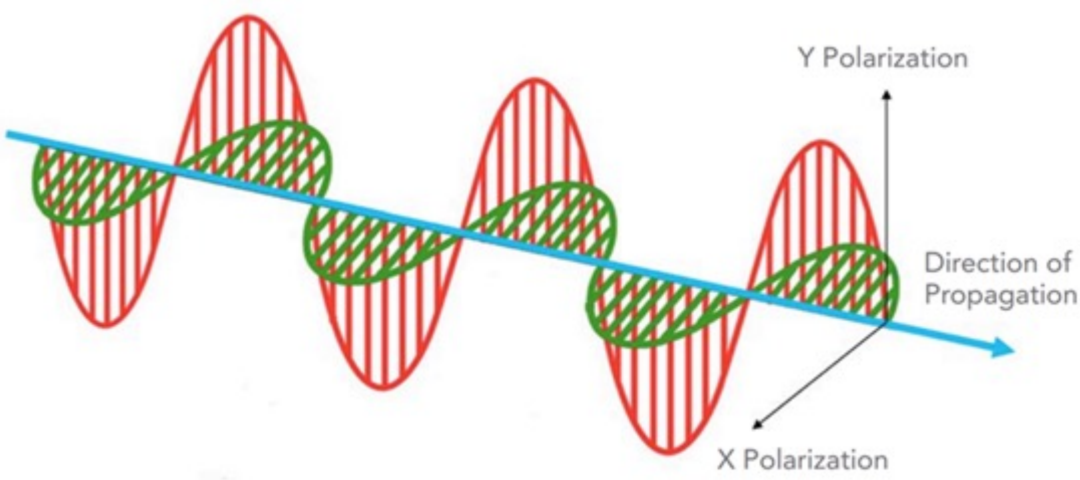
Before we go into the details of coherent optical transmitter, let's explain some technical terms below:

Amplitude Modulation: amplitude modulation is a method used to encode data based on the amplitude (intensity) of light. While OOK modulation employs intensity modulation in a binary (on-off) fashion, coherent optics utilize amplitude shift keying (ASK) to increase the available symbols.

Phase Modulation: The frequency of light at a given wavelength is highly predictable in an unmodified state. Modulating the phase creates a change in this pattern that is decoded by the demodulator at the receive end. For coherent optics, this process is known as phase shift keying (PSK).

Polarization: As a form of electromagnetic energy, polarized light waves produce an electric field which oscillates perpendicular to the direction of travel. The horizontal and/or vertical orientation of this electric field can be induced to provide an additional vehicle for data encoding.

Figure 9: Polarization of electrical field of optical signal.



QPSK: Quadrature Phase Shift Keying (QPSK) is a phase modulation technique which allows multiple symbols per bit to be encoded based on four phase shift orientations (e.g., 0°, 90°, 180°, and 270°). Dual Polarization Quadrature Phase Shift Keying (PM QPSK) uses horizontal and vertical polarization along with QPSK to represent twice as many bits.

Figure 10: Constellation diagrams of high-order modulation.

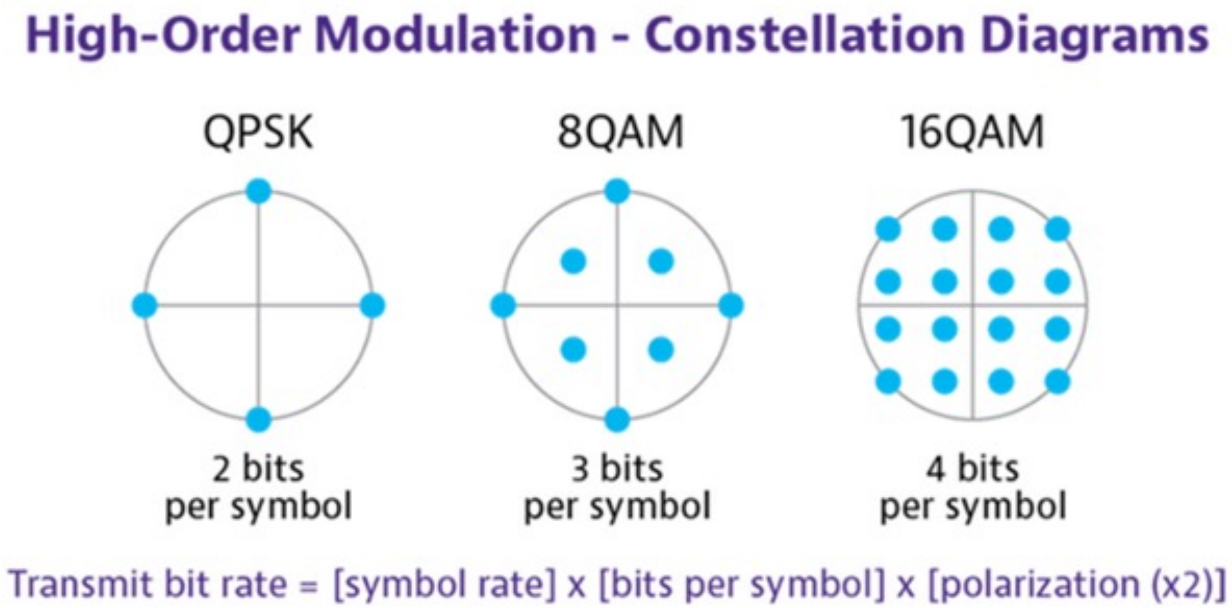
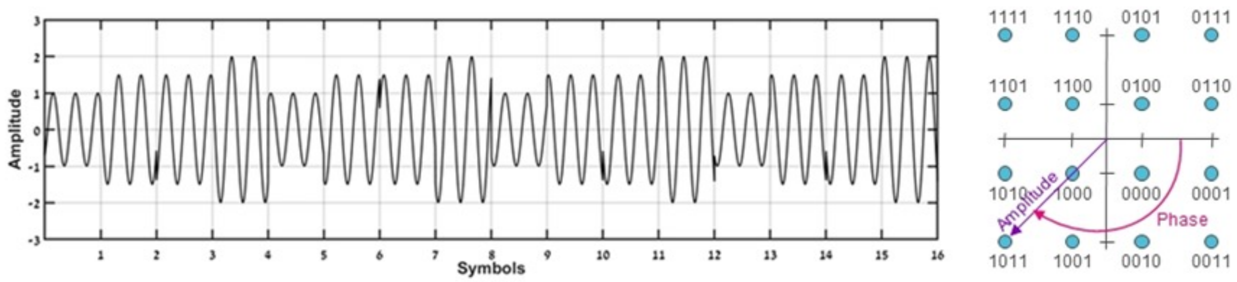


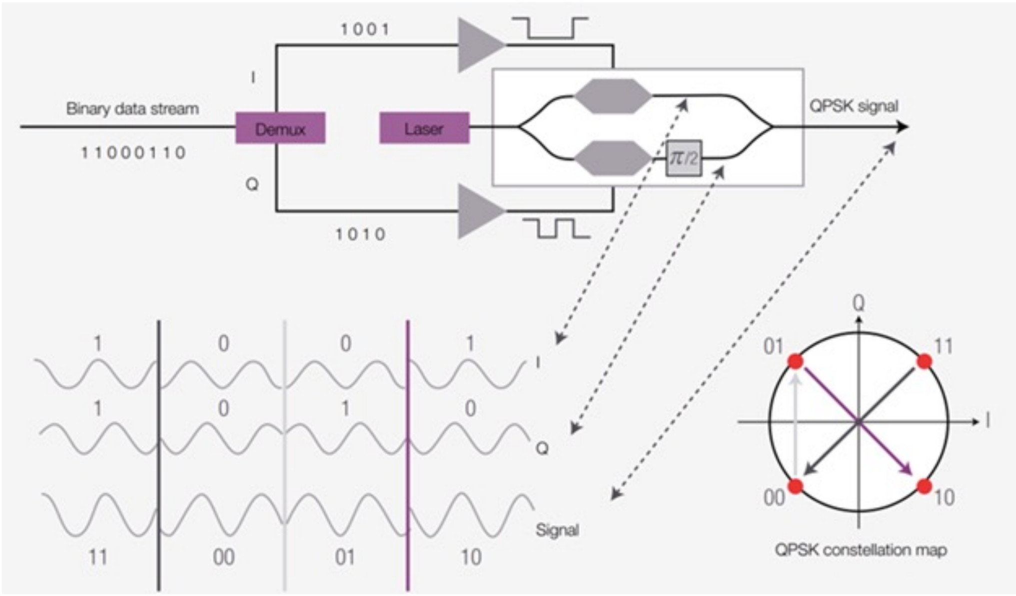
Figure 11: An illustration of 16-QAM modulated coherent optical wave electrical field.



4.4 Coherent Optical Transmitter

In QPSK modulation, the transmission rate relative to OOK is doubled by encoding 2 bits into one symbol. The four possible symbols are in the IQ diagram's four constellation points, which are all situated on the same circle. That means operating with one amplitude only. The points are separated by $\pi/2$.

Figure 12: QPSK modulation with MZ modulator.



In the transmitter, the electrical bit stream is split by a demultiplexer into the I (in-phase) and Q (Quadrature phase) part of the signal. Each of the two parts directly modulates the phase of the laser signal on one arm of a Mach-Zehnder modulator. An additional Mach-Zehnder element shifts the phase of the lower branch, the Q branch, by $\pi/2$. After recombination of the two branches, the result is a QPSK signal as shown at the bottom of Figure 12.

When it comes to higher-order modulation schemes like 8-QAM and 16-QAM, the transmitter setup must be able to provide more amplitude levels and phases, which means higher complexity. Figure 10 shows the constellation of high order modulation. We keep the MZ IQ optical modulator the same as QPSK but adding amplitude modulation for 8-QAM and 16-QAM. In practice this is the typically used transmitter implementation. The signal is modulated for example with an arbitrary waveform generator, which then drives a Mach-Zehnder interferometer. With this approach it is no

As fiber is a circular waveguide and it supports two orthogonal polarizations, shown in Figure 9. By selectively transmitting modulated signals using polarization multiplexed (PM) carriers, we can effectively double the spectral efficiency of a given modulation technique while using the same PM receiver.

So, compared to the single polarization signals in Figures 12, PM-QPSK, PM-8QAM and PM-16QAM modulation techniques in Fig. 13 offer two, four, six and eight bits per "symbol" respectively. In this case a symbol is the combination of amplitude/phase states and polarization states, which can be referred

Figure 13: PM-QPSK, single carrier, coherent optical transmitter.

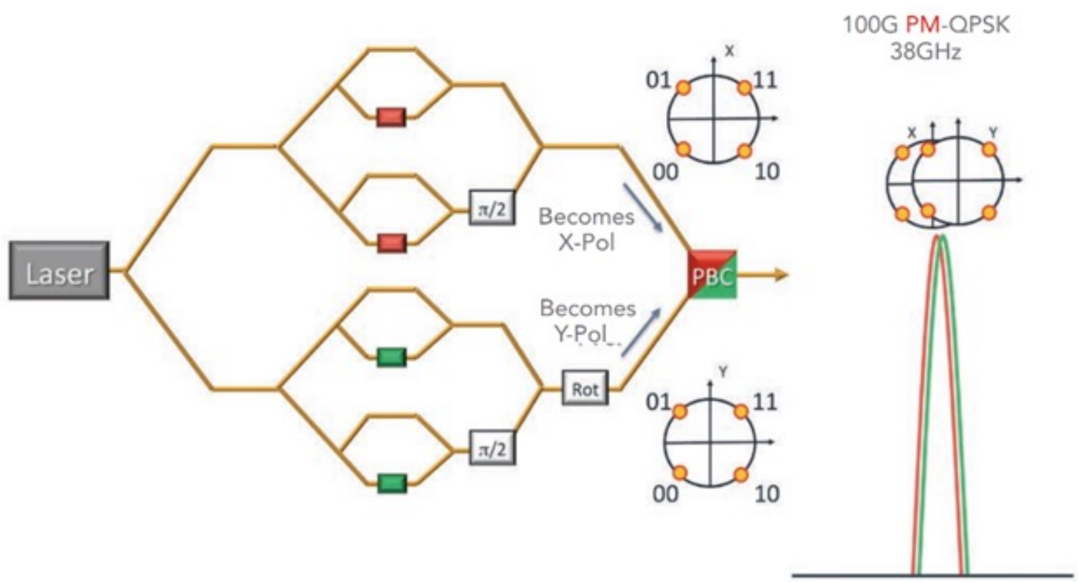


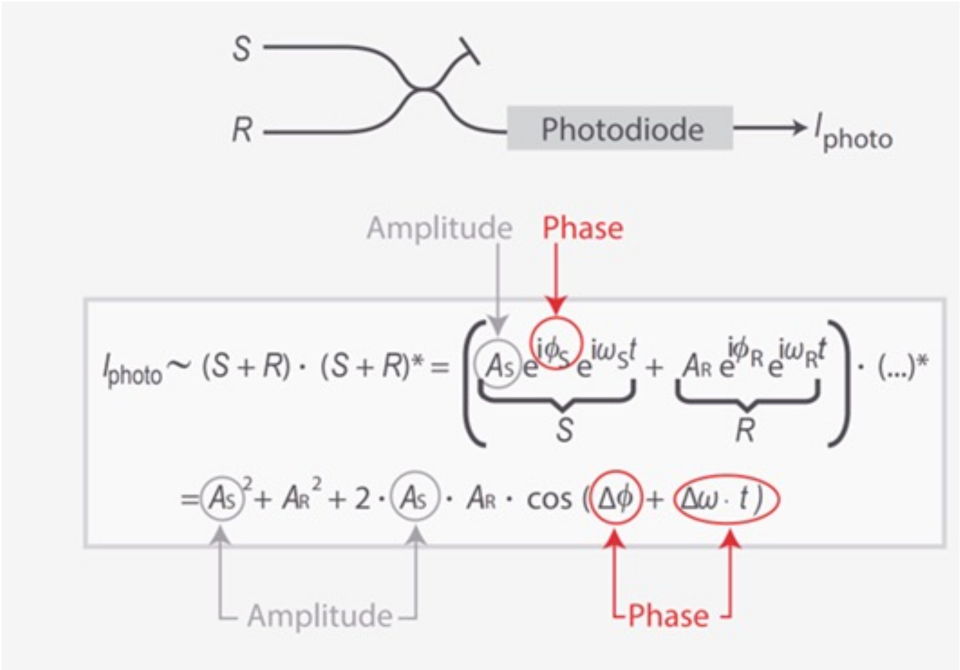
Figure 13 shows a schematic of a transmitter that would be required to generate, for example, a 100G single carrier PM-QPSK modulation constellation. Notice that the light from a single laser signal is split and sent into four separate Mach-Zehnder modulators. The upper and lower portions of this super Mach Zehnder structure each generate a QPSK signal. The signals are then sent into a polarization beam combiner so that the signal from the upper half of the circuit becomes X-polarized, while the signal from the lower half of the circuit becomes Y-polarized.

The resulting 100G PM-QPSK signal is shown on the right-hand side of Figure 13. Note that the red and green colors of the peaks are used to illustrate the two different polarization states. The signals

4.5 Coherent Optical Receiver

For QPSK modulation, to detect information on the angular frequency ωs and the phase Φs, a local reference oscillator is needed to mix with received signal, this is the essential for the coherent detection.

Figure 14: Mixing the received signal with reference signal to measure the phase difference [3].



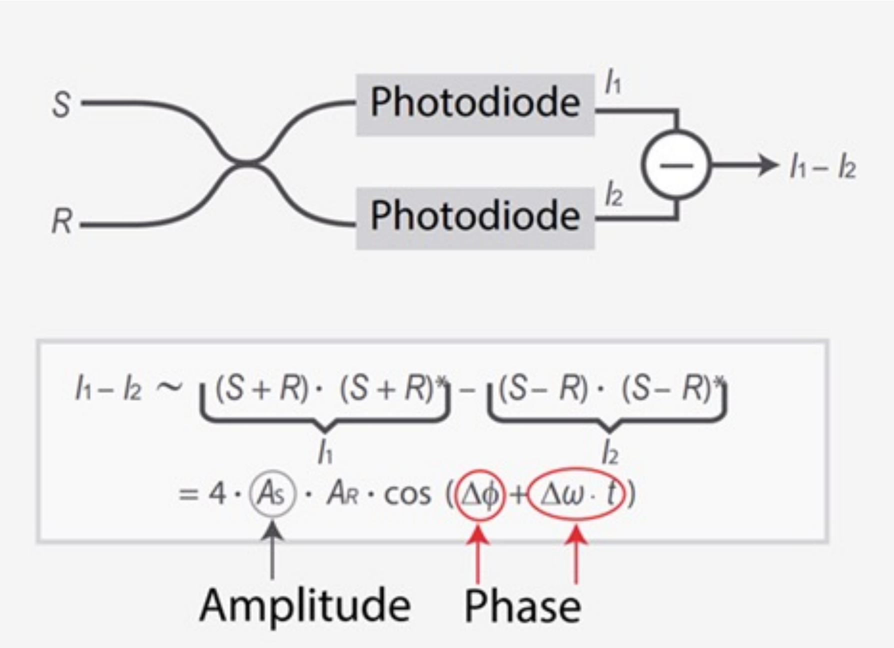
The signal of interest S and the reference signal R are superimposed in an optical combiner and detected with a photodiode. IPhoto is then proportional to the product of the sum of both signals (R+S) and its complex conjugate (R+S)*. The equation in Figure 14 reveals that the result holds the phase difference ΔΦ = ΦS – ΦR and the frequency difference Δω = ωS – ωR. From ΔΦ, now the evolution of ΦS over time can be deduced.

The reference frequency ωR is chosen close to ωS so that Δω is now small enough to be electronically processable. The phase-dependent term is called the heterodyne term or beat term, because it results from mixing or “beating” the two signals.

Balanced Receiver: The beat term is what we need for signal detection. The balanced receiver in Figure 15 shows that all other phase-independent terms can be suppressed with a differential receiver.

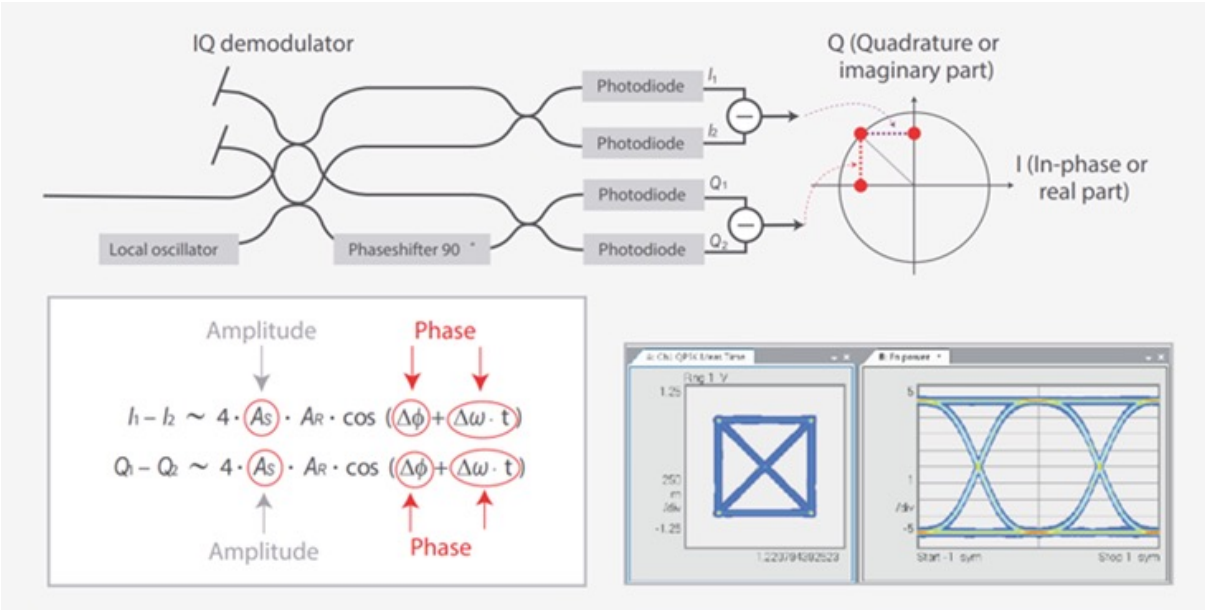
Here, the signal to be detected S and the reference signal R are summed on one branch and subtracted on the second branch of a 2x2 optical combiner (which could be a fiber optical or free-space optical coupler). Each of the resulting signals is detected by one photodiode. The difference between the two photocurrents is then used. In Figure 15, all other terms have cancelled out, and only the beat term remains.

Figure 15: Using balanced receiver, only the beat term remains.



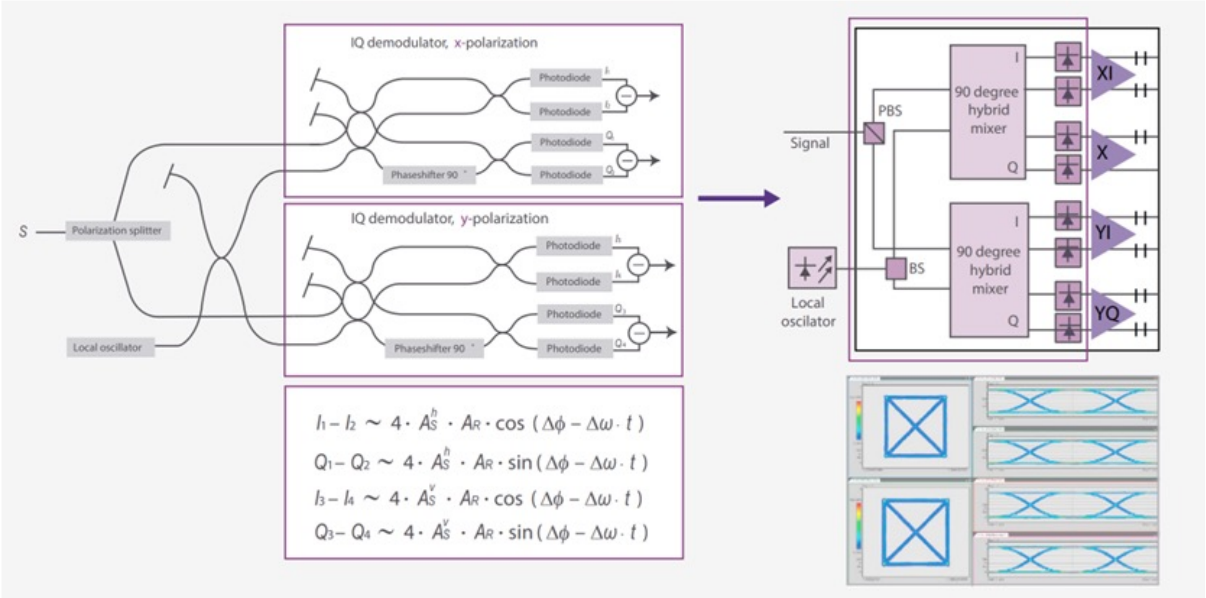
QPSK Receiver: To recover both amplitude and phase, a coherent receiver should provide the in-phase (I) component and the quadrature (Q) component as two separate output signals. For this purpose, a second balanced detector is needed. A single local oscillator provides the reference signal for both of them, but the phase must be shifted by π/2 to obtain the Q part. Figure 16 gives, for the case of a QPSK signal, an idea of the whole setup, which is called an "IQ demodulator."

Figure 16: IQ Demodulator for the detection of QPSK.



For the case of PM-QPSK coherent transmission, the full block diagram of coherent receiver is shown in Figure 17. There are four output signals to resolve I and Q-coordinates, one for each polarization direction respectively. In the equations, the upper indices h and v reflect the horizontal and vertical polarization state of the signal with respect to the polarization reference frame of the receiver. This polarization diversity architecture also assures that all of the signal is mixed with the local oscillator, regardless of the input state

Figure 17: IQ demodulator for PM-QPSK

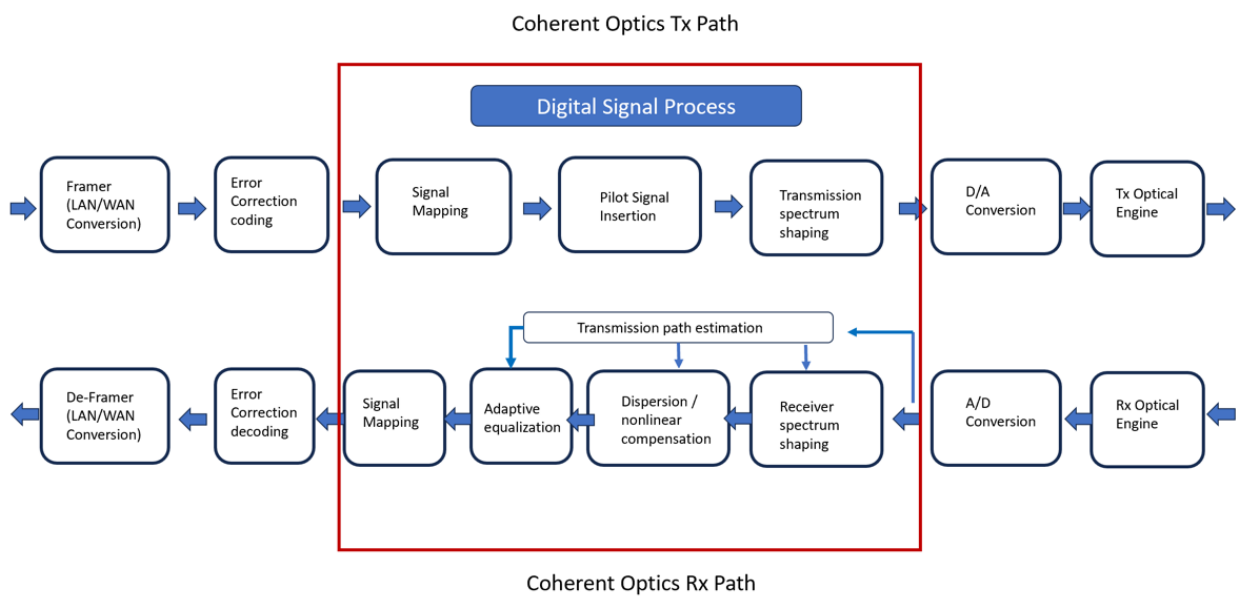


Note that the phase and frequency of the LO does not have to be actively controlled, which would be necessary in a conventional phase lock loop implementation. In fact, the LO frequency only needs to be within approximately 1 GHz of the incoming signal, and the speed of frequency adjustment can be relatively slow. In order to recover the transmitted bits, carrier phase synchronization is performed in the digital signal processor (DSP), and this mode of coherent detection without active optical phase lock loop is known as intradyne coherent detection. In addition to a huge increase in detector sensitivity, a coherent detector can be tuned to receive only a specific wavelength, allowing for a high level of signal rejection from neighboring WDM channels.

4.6 Digital Signal Process (DSP)

The digital signal processor (DSP) plays a crucial role in coherent optical transmission systems, performing various functions to encode, decode, and enhance the optical signal.

Figure 18: Function block of DSP in coherent optics transmission.



Here is a breakdown of the functions performed by the DSP in coherent optics transmission:

- **Signal Mapping:** The DSP maps the digital data into different phases, amplitudes, and polarizations of the light signal. This process is known as quadrature modulation. When receiving the signal, the DSP performs the inverse process, mapping the phase and polarization information back into a stream of bits.
- **Pilot Signal Insertion:** The DSP inserts a pilot signal into the transmitted signal to estimate the status of the transmission path. This pilot signal aids in the decoding of data from the phase and polarization of the light signal at the receiver end, making it more energy efficient.
- **Adaptive Equalization:** This function occurs during signal reception. The fiber channel introduces distortions that change the signal's frequency spectrum. The DSP employs an equalizer to compensate for these distortions, adjusting specific frequencies of the signal to restore the intended spectrum.
- **Dispersion and Nonlinear Compensation:** Also performed during signal reception, the DSP addresses the degradation caused by dispersion and nonlinear optical effects in the fiber. It applies various operations to offset these distortions, improving the quality of the received light signal.
- **Spectrum Shaping:** Spectrum shaping is a digital filtering process used to narrow down the signal's frequency bandwidth, maximizing efficiency and transmitting as much signal as possible within limited frequencies.
- **Carrier Recovery:** In coherent detection, intradyne detection is commonly used, where a free-running local oscillator is employed. The DSP performs carrier recovery digitally, tracking the phase noise and offset frequency between the received signal and the local oscillator. This process ensures accurate demodulation of the signal.
- **Digital-to-Analog (D/A) and Analog-to-Digital (A/D) Conversion:** When transmitting, the DSP performs digital-to-analog conversion to convert the processed digital signal back to an analog optical signal. When receiving the signal, the inverse process occurs, where the analog signal is converted to a digital format through analog-to-digital conversion before undergoing further DSP operations.

The DSP in coherent optics systems acts as the central processing unit, handling encoding, decoding, compensation, and various signal processing tasks. Its capabilities enable efficient and reliable transmission over optical fibers, mitigating impairments and maximizing the utilization of the fiber's capacity.

5. Coherent Optics in Next Generation Optical Networks

Coherent optical technology has evolved from its initial deployment in long-haul applications to encompass a wide range of markets and distances. Here are some key points about the adoption and deployment of coherent technology:

- **Migration from Long Haul to Metro and Access:** Coherent technology was initially introduced in long-haul applications to overcome fiber impairments. With the progress in digital signal processing (DSP) and design simplification, coherent solutions have extended to metro and access networks.
- **Coherent Pluggable Module:** The introduction of the CFP-DCO (Digital Coherent Optics) module in 2014 brought the benefits of coherent technology to metro and data center interconnect (DCI) applications. The pluggable modules enable scalability and pay-as-you-grow capabilities, making coherent technology more attractive for these markets.
- **Standardization Efforts:** Industry organizations such as the Optical Internetworking Forum (OIF), IEEE, and Cable Labs have initiated standardization activities to address the use of coherent technology in various applications. This recognition of the trend toward using coherent optics reinforces the expectation that coherent technology will continue to expand into high-volume demands.
- **Coherent Technology in Various Markets:** Coherent technology is already being deployed in a wide array of applications, each with its own unique requirements. Some key market applications include:

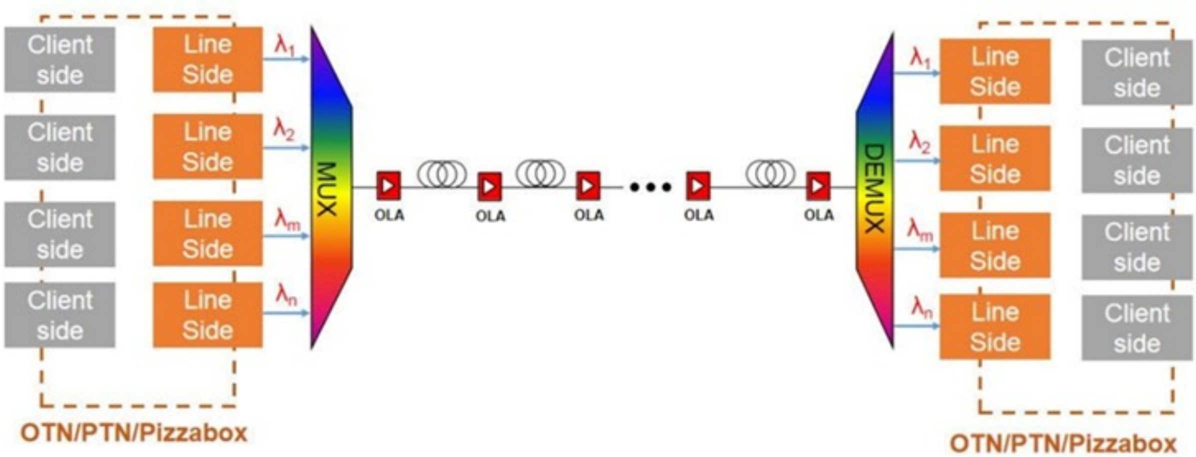
    1. **Long Haul:** Coherent technology enables high-capacity, long-distance transmission in traditional long-haul networks.
    2. **Metro:** Coherent solutions are increasingly used in metro networks to overcome impairments and achieve higher capacity.
    3. **DCI:** Data center interconnects benefit from the scalability and flexibility offered by coherent technology.
    4. **Remote PHY Cable Access:** Coherent technology can enhance the performance and capacity of cable access networks.
    5. **5G:** Coherent optics play a role in supporting the high-speed and low-latency requirements of 5G networks.
    6. **Unamplified Interfaces:** Coherent solutions are being considered for applications beyond 10km without the use of amplifiers.

As the demand for higher data rates and increased capacity continues to grow, coherent technology is expected to be used in many communication interfaces, driving further innovation and standardization efforts in the industry.

5.1 Coherent optics for Long-haul and Metro Network

In the long-haul market, where coherent technology has gained significant traction, the majority of coherent ports are shipped each year. Long-haul transmission involves multiple fiber spans with optical amplifiers, and optical performance is crucial in this market as it eliminates the need for costly regeneration. QPSK modulation has been widely adopted in long-haul networks due to its exceptional performance in terms of achievable optical signal-to-noise ratio (OSNR) margins and the maturity of the technology.

Figure 19: An example of multi-span DWDM long-haul system.



In optical transmission engineering, there are two widely recognized modulations as the standards for specific transport distances:

- QPSK (Quadrature Phase-Shift Keying): QPSK modulation, with 2 bits per symbol, is typically used for long-haul transport spanning approximately 2,000 miles. The use of QPSK modulation allows for efficient and reliable transmission over long distances, taking into account the optical impairments and the desired OSNR.
- 16-QAM (16 Quadrature Amplitude Modulation): 16-QAM modulation, with 4 bits per symbol, is commonly employed in metro transport networks for distances of up to approximately 500 miles. This modulation format offers higher spectral efficiency compared to QPSK, enabling greater data rates within the limited optical bandwidth of metro networks.

By utilizing QPSK for long-haul and 16-QAM for metro transport, network operators can effectively address a wide range of applications within these two transport domains while considering the specific requirements and transmission distances involved.

There is a trade-off among baud rate, modulation order, required optical signal-to-noise ratio (OSNR), and channel spacing in coherent optical transmission systems. Here's a breakdown of the options and their implications:

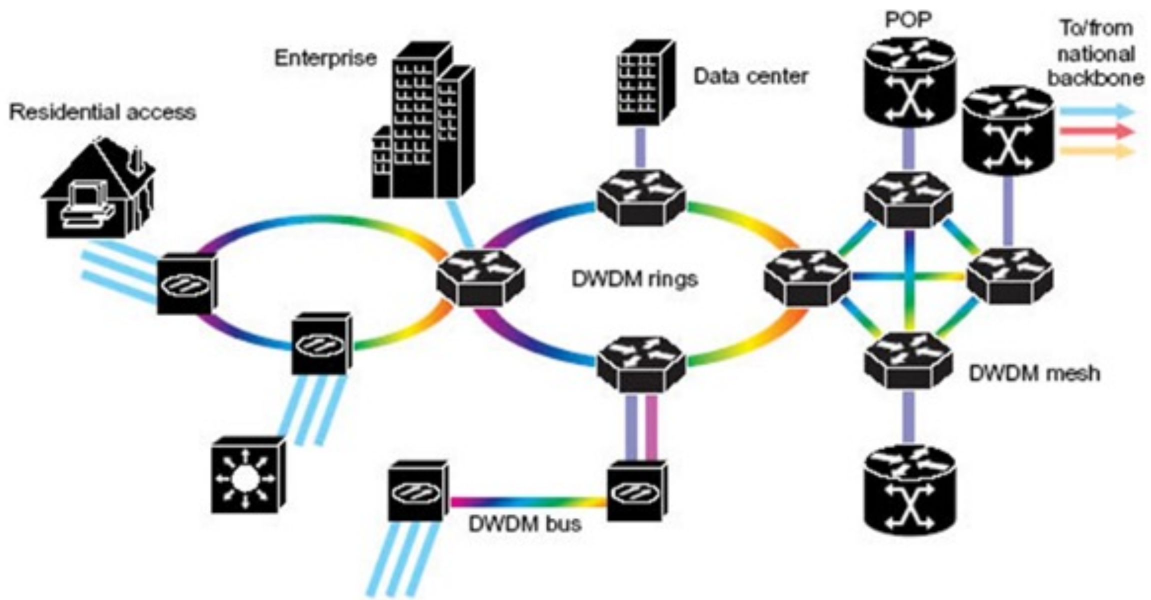
1. Increasing the baud rate without changing the modulation order: By increasing the baud rate, more symbols can be transmitted per second, thereby increasing the data capacity. However, this approach requires wider channel spacing to accommodate the higher baud rate, which may not be feasible in some cases due to limitations in the available optical spectrum.

2. Holding the baud rate constant while moving to a higher modulation order: This option involves encoding more bits per symbol by increasing the modulation order (e.g., moving from QPSK to 16-QAM). While it allows for higher data rates with the same channel spacing. The higher order modulation likely requires a higher OSNR margin to maintain acceptable performance.

3. Increasing the baud rate as well as moving to a higher modulation order: This option combines the benefits of both options 1 and 2. It allows for an increase in data capacity by transmitting more symbols per second (higher baud rate) and encoding more bits per symbol (higher modulation order). Importantly, this option assumes that there is sufficient OSNR margin available when moving to the higher modulation order. If the OSNR margin is not adequate, it could result in degraded performance and increased error rates.

Choosing the most suitable option depends on various factors, including the available optical spectrum, system design constraints, and the desired balance between data capacity and performance. Option 3 offers the advantage of maximizing capacity with minimal changes to the channel spacing, but careful consideration of the OSNR margin is essential to ensure reliable operation at

Figure 20: An example of optical DWDM Metro-network.



Metro networks, which typically consist of reconfigurable optical add-drop multiplexer (ROADM) nodes and wavelength selective switches (WSS), have specific considerations compared to long haul networks. Here are the key points:

Reconfigurable Optical Add-Drop Multiplexer (ROADM) Nodes: Metro core networks utilize ROADM nodes to drop, add, or route wavelengths to different destinations. These nodes incorporate WSS, which act as optical filters to narrow the bandwidth of the channels. Passing through multiple ROADM nodes can lead to significant spectrum narrowing along the optical path, potentially introducing impairments such as polarization dependent loss. Managing these impairments and maintaining optical performance is crucial in metro networks.

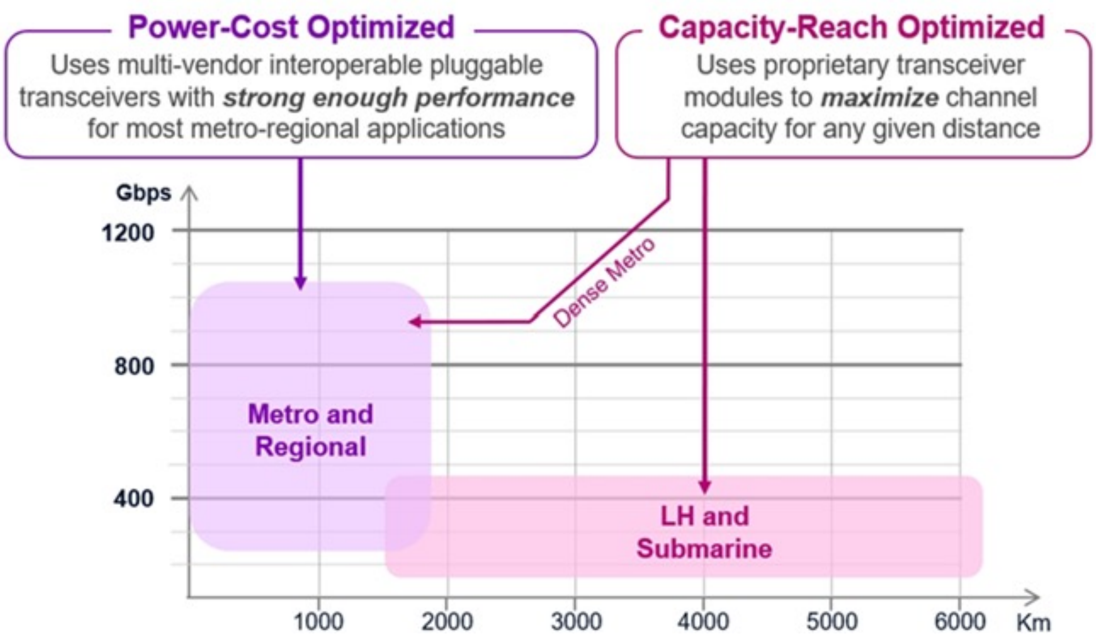
Power Efficiency and High Density: Metro networks often operate within power-limited environments, such as crowded central offices. Therefore, power-efficient and high-density solutions are highly valued in these applications. Optimal use of power resources and compact form factors are essential to maximize capacity while minimizing power consumption and space requirements.

Wide Range of Traffic and Complexity: Metro networks handle diverse types of traffic, including voice, data, video, and more. This diversity results in complex network management and the need for different equipment to meet specific traffic requirements. Having common solutions that can be leveraged across

These solutions allow for scalability and cost-effectiveness while effectively managing operational costs.

In summary, metro core networks require high-performance solutions that address impairments caused by ROADM nodes and WSSs, while also offering power efficiency, high density, and flexibility to handle diverse traffic types. By leveraging common solutions and scalable architectures, network operators can efficiently manage their networks and provide reliable and cost-effective services in metro environments.

Figure 21: Optical transport optimization for Metro and Long-Haul.



The optical transport solutions for long-haul and metro networks differ in their optimization goals and the types of transceiver technologies employed. For Long-Haul applications, Capacity-Reach Optimized is the goal, whereas in Metro, Power-Cost Optimized is the target. Here is a breakdown of the two types of coherent optical transport solutions:

1. **Long-Haul Capacity-Reach Optimized:** These solutions prioritize maximizing spectral efficiency for any distance and fiber condition. They are commonly used in long-haul applications where the goal is to extract the highest possible capacity from each channel. These solutions employ proprietary transceiver technologies that programmatically determine the optimal mix of baud rate, modulation scheme, and channel width to achieve maximum bit rate.

These proprietary transceivers are not constrained by size or electrical power limitations, allowing them to deliver higher performance.

2. **Metro Power-Cost Optimized:** These solutions focus on minimizing electrical power consumption and cost while still providing sufficient performance for most metro applications. As technology evolves, these solutions are also suitable for regional transport. They rely on multisource pluggable transceivers that adhere to industry agreements, such as the Open ROADM Multi-Source Agreement (MSA) [4], which promotes multivendor interoperability. Additionally, standards like OpenZR+ [5] and the Optical Internetworking Forum (OIF) [6] play a role in defining the specifications for these transceivers.

The choice between the two types of solutions depends on the specific requirements and priorities of the network deployment. Long-haul capacity-reach optimized solutions are commonly used in long-haul scenarios where maximizing capacity is paramount, while metro power-cost optimized solutions provide a more power-efficient and cost-effective approach suitable for metro and regional transport applications.

Figure 22: 400G+ Coherent optics development for long-haul and Metro system.

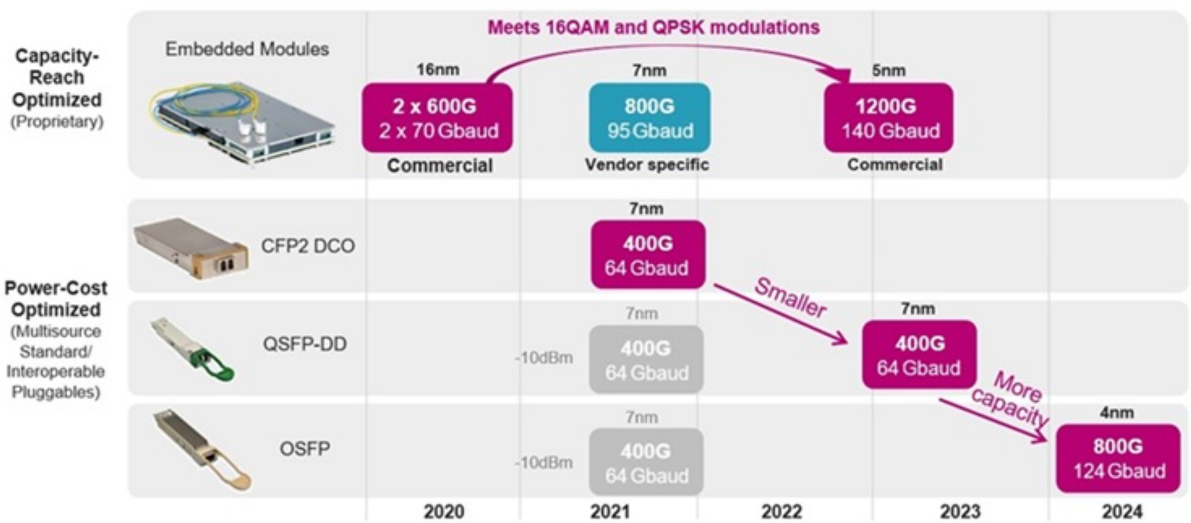


Figure 22 illustrates the industry development of coherent transceiver technologies for long-haul and metro applications. Here are the key points highlighted in the description:

1. **Initial Commercial Capacity-Reach Optimized Transceiver:** In 2020, the commercial transceiver for capacity-reach optimization used dual wavelengths operating at 70 Gbaud. This transceiver allowed the combination of two 400G wavelengths using 16QAM modulation for metro applications, resulting in an equivalent 800G line rate. For long-haul applications, it utilized two 200G wavelengths with QPSK modulation, providing an equivalent 400G line rate.

2. **Upgraded Commercial Technology:** The same commercial technology is being updated with the latest 5 nm digital signal processor (DSP) to operate at 140 Gbaud. This updated transceiver, available in early 2023, will maintain the metro-16QAM and long haul-QPSK functionality but with a more economical single wavelength.

3. **Proprietary Capacity-Reach Optimized Transceivers:** Optical equipment vendors have developed proprietary transceivers for their specific use, operating at 95 Gbaud. These transceivers are designed to support 800G capacity but require higher order modulation schemes than 16QAM.

It is noteworthy that the higher-performing proprietary transceivers are introduced before similar pluggable varieties that are more cost-effective. This is because there is always a demand for the best transceiver technology in long-haul applications, and proprietary form factors are not limited by size and power constraints. Subsequently, the technology is optimized to fit into pluggable form factors while preserving as much performance as possible.

This observation reflects the iterative nature of technology development, where advancements initially occur in specialized, non-pluggable implementations and are later adapted

Figure 23: 75/150GHz DWDM channel spacing for 400G+ transmission.

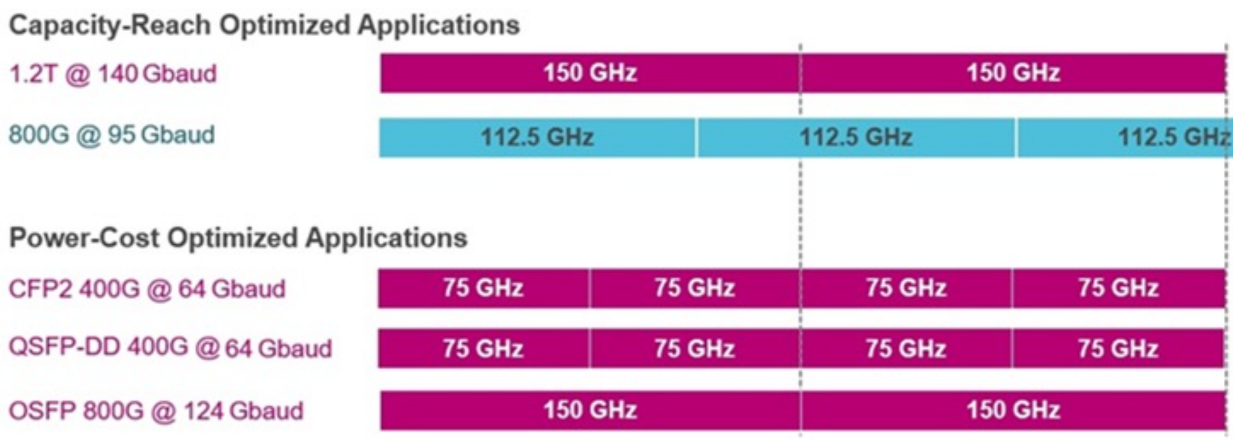
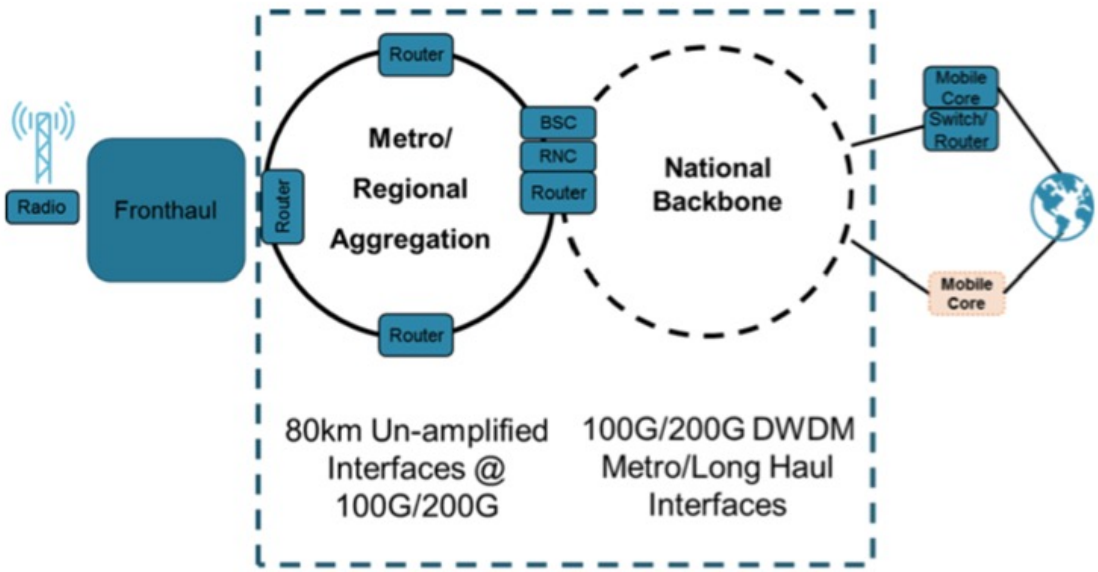


Figure 23 illustrates the spectrum requirements for 400G+ coherent optical transceiver technologies. It highlights the importance of utilizing DWDM flex-grid technology with channel spacing of 75 GHz/150 GHz to efficiently utilize the optical bandwidth in the C-band (5THz) of single-mode fiber. This flexibility in channel spacing allows for efficient utilization of the available spectrum for high-capacity transmission. The figure also suggests that both capacity-reach and power-cost optimized transmission technologies can coexist in metro and long-haul applications, with the ability to transition between them as the technologies evolve, ensuring a smooth progression without creating spectral gaps.

5.2 Coherent Optics for Wireless Backhaul Network

Figure 24: 5G wireless backhaul network.



Coherent optics technology is becoming increasingly relevant in wireless backhaul networks due to its ability to meet the growing capacity demands of 5G and other wireless technologies. Here are some key points about coherent optics in wireless backhaul:

- **Increased Capacity:** Coherent optics enables high-capacity transmission over long distances, allowing wireless backhaul networks to handle the substantial increase in data traffic generated by 5G networks. Coherent systems can achieve multi-gigabit or even terabit-level capacities, providing the necessary bandwidth to support high-speed wireless connections.

- **Longer Reach:** Coherent optical systems can transmit signals over longer distances without the need for costly intermediate regeneration. This extended reach is crucial for wireless backhaul networks, as they often require connectivity over considerable distances to connect remote cell sites to the core network.
- **Spectrum Efficiency:** Coherent optics can efficiently utilize the available optical spectrum by leveraging flexible grid (flex-grid) technologies. With the use of narrow channel spacing, such as 75 GHz or 150 GHz in DWDM systems, coherent optics can maximize the utilization of the C-band optical spectrum in single-mode fiber, enabling the transport of multiple high-capacity wavelengths.
- **Interference Mitigation:** Coherent optical systems employ advanced modulation schemes and sophisticated digital signal processing (DSP) techniques that enable robust signal transmission even in the presence of impairments such as optical noise and dispersion. These techniques help mitigate interference and improve the overall reliability and performance of wireless backhaul networks.
- **Scalability and Future-Proofing:** Coherent optics provides scalability for wireless backhaul networks by supporting higher data rates and the ability to add additional wavelengths or increase capacity as network demands evolve. This future-proofing capability ensures that network operators can easily accommodate the growing data requirements of wireless networks without significant infrastructure upgrades.
- **Operational Efficiencies:** Coherent optics can offer operational benefits in wireless backhaul networks. The use of tunable laser technology allows for simplified network planning and inventory management, as a single transceiver can cover a wide range of frequencies. Additionally, the convergence of multiple network interfaces onto a single coherent solution can streamline procurement, deployment, and maintenance processes, leading to operational efficiencies for network operators.

Coherent optics technology brings significant advantages to wireless backhaul networks, including increased capacity, longer reach, spectrum efficiency, interference mitigation, scalability, and operational efficiencies. As the demand for high-speed wireless connectivity continues to grow, coherent optics is playing a crucial role in enabling the reliable and high-capacity transmission required for wireless backhaul infrastructure.

5.3 Coherent optics for Data Center Applications

Coherent optics technology is increasingly being adopted in data center applications to address the growing demand for higher bandwidth, longer reach, and improved performance.

High-Speed Connectivity: Coherent optics enables data centers to achieve high-speed connectivity between geographically distributed sites. It allows for the transmission of data at multi-terabit or even petabit-per-second rates, supporting the rapid exchange of large volumes of data between data centers.

Extended Reach: Coherent optical systems provide the capability to transmit data over longer distances, eliminating the need for costly signal regeneration in data center interconnect (DCI) applications. This extended reach enables data centers to connect to remote locations and leverage geographically dispersed resources efficiently.

Dense Wavelength Division Multiplexing (DWDM): Coherent optics leverages DWDM technology to maximize the utilization of optical fiber capacity within data center networks. DWDM allows for the simultaneous transmission of multiple wavelengths of light over a single fiber, significantly increasing the overall capacity of the network.

Flexibility and Scalability: Coherent optics provides flexibility and scalability to data center networks. The use of advanced modulation schemes and programmable DSP algorithms allows for adaptive transmission parameters, enabling optimal performance based on the specific network conditions. This flexibility also enables data centers to scale their capacity by adding more wavelengths or increasing data rates as needed.

Optical Performance and Reliability: Coherent optical systems employ advanced error correction techniques and adaptive modulation schemes to mitigate impairments such as optical noise and dispersion, ensuring reliable and high-quality transmission of data. These technologies enhance the overall optical performance of the network, minimizing errors and maximizing data integrity.

Cost Efficiency: Coherent optics can offer cost advantages in data center applications. By enabling longer reach and higher capacity transmission, coherent systems reduce the need for costly optical regeneration and parallel optical interfaces. This can lead to cost savings in terms of infrastructure, equipment, and operational expenses.

Interoperability and Standardization: The industry has been working on standardization efforts for coherent optics in data center applications. The adoption of common interfaces, such as CFP2-DCO and QSFP-DD, ensures interoperability between different vendors' equipment and facilitates seamless integration into existing data center architectures.

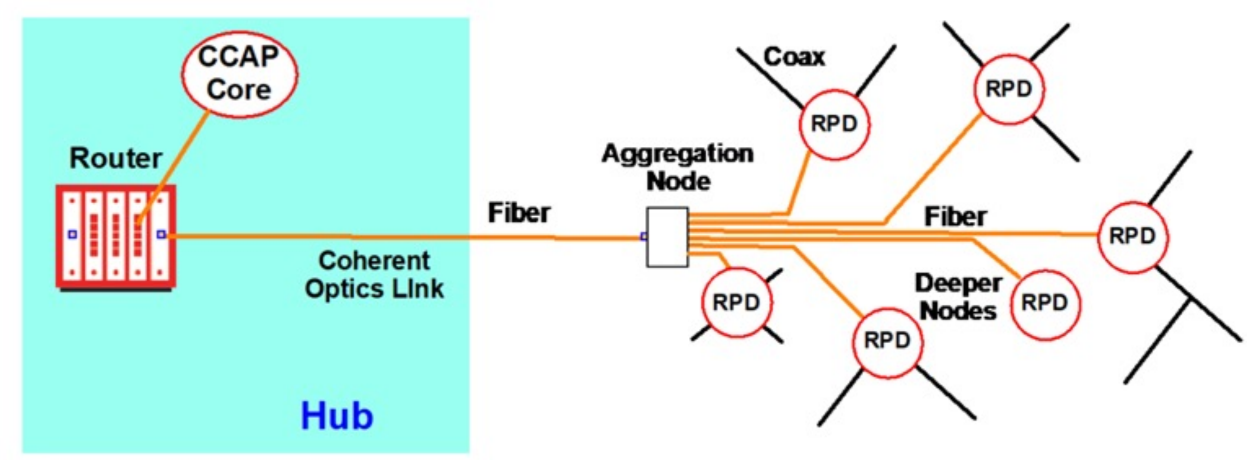
In summary, coherent optics technology brings significant benefits to data center applications, including high-speed connectivity, extended reach, DWDM capability, flexibility, scalability, optical performance, cost efficiency, and interoperability. As data centers continue to grow in size and complexity, coherent optics plays a crucial role in enabling reliable and high-capacity connectivity between data centers, supporting the increasing demands of modern data-intensive applications.

5.4 Coherent Optics for Cable Access Network

Access networks are an emerging opportunity for coherent interconnections. The cable industry is taking the lead in this segment by driving standardization of coherent for access aggregation.

As the hybrid fiber-coax (HFC) networks evolve toward remote PHY architectures, fiber is being deployed deeper in the network as shown in Figure 25, resulting in increased available bandwidth to residential end-user customers, while eliminating bottlenecks in the HFC network. 10G optical interfaces are pushed closer to the end users resulting in aggregation points in the network

Figure 25: Coherent optics in MSO Distributed Architecture [7].

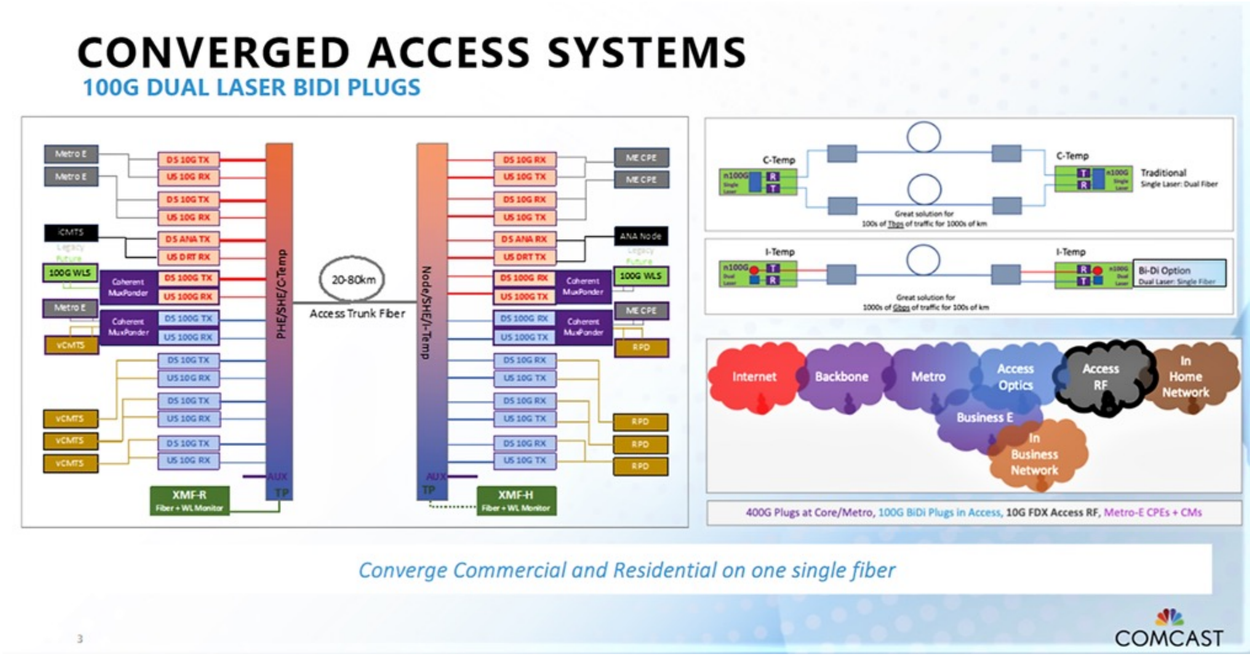


Coherent can be an effective way to transport these aggregated signals back to the hub. In some cases, it may only be necessary to transport a single coherent wavelength back to the hub, but since coherent is inherently a DWDM technology, this approach provides the capability to expand capacity by up to two orders of magnitude in the future.

Cable Labs is the standards organization of the cable industry and has recognized the need for this solution in the market. In 2017, they kicked off a project to define coherent standards for cable access aggregation applications [7]. The latest coherent optics P2P PHY spec released in 2019 [8].

Comcast has a very large core metro footprint, their access network has 3x the fiber mileage compared to the core, making it a very rich fiber environment. During a Lightwave on-line meeting in 2022, Comcast stated that coherent 400G pluggable are now in the core and the metro and they expect them to become even more important in the future. For Comcast's access network, they viewed that converged platform in Figure 26 that can handle both business and residential services. It is the 100G Bi-Directional CFP-2 DCO pluggable module that enables Comcast to use the access footprint to provide these combined services on one single fiber.

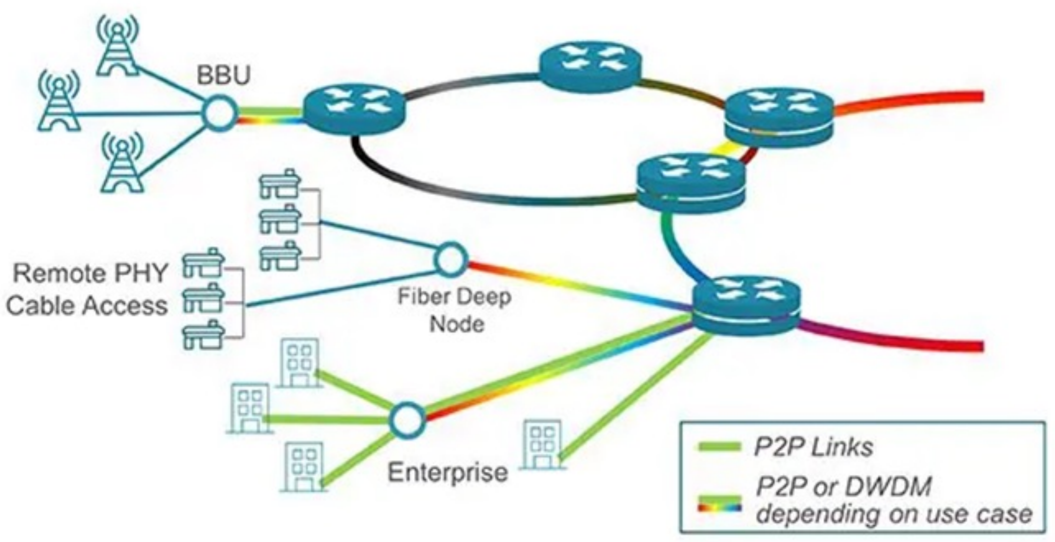
Figure 26: Converged Access System.



5.5 Coherent Optics for Point-to-Point Applications

For optical access networks, the demand for increased bandwidth is driving the need for higher data rates and more efficient solutions. Legacy optical transmission technologies may not be capable of supporting the required data rates beyond a certain speed for a given distance. As a result, there is a growing requirement to evolve directly from legacy 10Gb/s to 100Gb/s optical links in order to meet the bandwidth demands efficiently.

Figure 27: Optical Access Network.



The use of unamplified point-to-point interfaces, also known as client optical interfaces, is common in optical access networks. These interfaces connect buildings or locations within relatively short distances. As data rates have increased, it has become increasingly challenging for direct detect solutions (non-coherent) to meet the performance requirements of these applications.

Proprietary coherent solutions are already being used for links in the 40-80km range at data rates of 100Gb/s and 200Gb/s. Coherent detection offers improved performance for power-limited sensitivity, making it suitable for these power-constrained applications. The usable link budget in such cases is defined by transmitter power and receiver sensitivity rather than the optical signal-to-noise ratio (OSNR).

Coherent implementations for optical

access networks need to be cost-effective and highly power-efficient, considering that the volumes for these applications can be larger than those for transport applications. Optimizing power efficiency is crucial to meet the requirements of power-limited environments such as edge/access aggregation terminal equipment and other points in the network closer to the end user.

By adopting coherent solutions in optical access networks, service providers can achieve higher data rates, extend the reach of their networks, and effectively address the increasing bandwidth demands driven by applications such as gaming, telemedicine, autonomous vehicles, and enterprise services. Coherent technology enables efficient and reliable transmission over dedicated fiber pairs, supporting the seamless delivery of high-capacity services to the

6. Conclusion

In conclusion, coherent optics technologies have become indispensable for next-generation optical networks, providing enhanced performance, flexibility, and scalability. The advancements in digital signal processing, modulation formats, and high-baud-rate coherent systems have enabled significant improvements in capacity, reach, and spectral efficiency.

Amphenol Network Solutions has been co-developing with customers of various products to fit into the existing coherent optic transmission systems. In the next step, Amphenol Network Solutions [9] will work on the low insertion loss C/L band 150GHz spacing DWDM optical passive modules, which target for the applications of next generation 800G/s and 1.6Tb/s coherent optical networks.

Amphenol Network Solutions believes coherent optics plays a critical role in meeting the growing demands of emerging technologies. The continuous innovation and research in coherent optics will shape the future of optical networking, unlocking new opportunities and applications for high-speed and reliable data transmission.

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Charles Su, PhD, is a seasoned Senior Optical Engineer with over 20 years of experience in the telecom industry. Specializing in optical fiber components and systems, he has demonstrated strong leadership capabilities, successfully leading teams and delivering impactful solutions to address complex challenges. With a deep understanding of fiber optics technologies, Charles Su is renowned for his forward-thinking approach to next-generation product development. He has a passion for understanding and meeting customer needs, consistently developing innovative solutions that exceed expectations. Committed to driving customer success, Charles Su leverages his extensive industry knowledge and dedication to continuous improvement to deliver exceptional

About Amphenol Network Solutions

At Amphenol Network Solutions, we are driven by a passion for innovation and a relentless commitment to creating customized solutions that seamlessly integrate with your unique requirements. With our deep understanding of fiber optic technology, we specialize in creating tailored solutions that anticipate and adapt to the rapidly evolving demands of your network. Through our responsive support, unwavering commitment, and ongoing collaboration, we ensure that our solutions are ready to deliver superior performance and reliability.

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