White Paper

Coherent for Service Provider Edge and Access Network Applications

Meeting Bandwidth Demands in a Cost Effective and Operationally Simplistic Way

March 2021

Abstract

Service provider edge and access networks are continuing to evolve. With bandwidth demands increasing exponentially due to exciting new applications being offered to consumers and enterprise customers, their legacy network infrastructures, based on older optical transmission technology, can’t scale to the bandwidth that will be needed to handle these demands in the future. New technologies and strategies are needed to upgrade both the wired and wireless network infrastructure in the segments currently supporting 10G links so that it can support optical links at 100G and beyond, while also accommodating the many different fiber types that exist such as point to point, DWDM, and BiDi links. This paper discusses how advancements in coherent optical technology are paving the way to meet these challenges, providing service providers with the path they need to meet growing bandwidth demands today and in the future.

Service Provider Edge and Access Demand Continues to Grow

Applications are driving the need for increased bandwidth towards the edges of the network that are closer to the end user. New and next-generation applications serving the consumer and enterprise customers are primarily responsible for the growth in edge and access bandwidth requirements. According to Cisco's Annual Internet Report[1], ultra-high-definition internet-connected 4K TVs are globally forecasted to account for 66% of flat-panel TVs (891 million) by 2023. Connected home applications such as home automation, home security, and video surveillance are forecasted to represent nearly half of all machine-to-machine connections by 2023 (estimated 14.7 billion total machine-to-machine connections). In addition, according to CableLabs[2], by December 2019, cable gigabit had reached 93% of all US housing units passed by cable broadband providers, with available downstream speeds growing by approximately 50% per year (CAGR).

Applications outside of the home, such as vehicle navigation/diagnostics/entertainment and fleet management, are forecasted to represent the fastest growing machine-to-machine segment with growth at 30% CAGR through 2023, according to the Annual Internet Report. By 2023, Internet of Things (IoT) devices used in multiple industry segments are forecasted to account for 50% (14.7 billion) of all global networked devices.

In addition to the aforementioned bandwidth growth drivers, other applications such as gaming, telemedicine, and autonomous vehicles, as well as high-capacity enterprise services for hybrid cloud connections to centralized cloud networks are also expected to drive up the demand for bandwidth in service provider edge and access networks..

The wired and wireless network infrastructure being deployed to support aggregated residential customer traffic and enterprise business services is driving bandwidth capacity higher than legacy infrastructure can support based on traditional optical transmission technology. For example, 5G wireless connections are forecasted to generate approximately 3 times more traffic than 4G connections. All of these bandwidth growth drivers are creating a challenge for legacy optical service provider edge and access infrastructure to support this traffic.

Wide Range of Access Challenges with a Coherent Theme

A common theme among access network architectures is a desire by the network operator to stay ahead of the curve when it comes to ensuring sufficient network capacity to accommodate rising bandwidth demand. To achieve this, many access architectures require capacity upgrades and they may include at least one of the following link designs, each with its own set of challenges:

- Dedicated point-to-point (P2P) fiber links,
- Higher-capacity dense wave-division-multiplexed (DWDM) links, or
- Fiber-constrained routes requiring single-fiber bidirectional (BiDi) P2P or DWDM links.

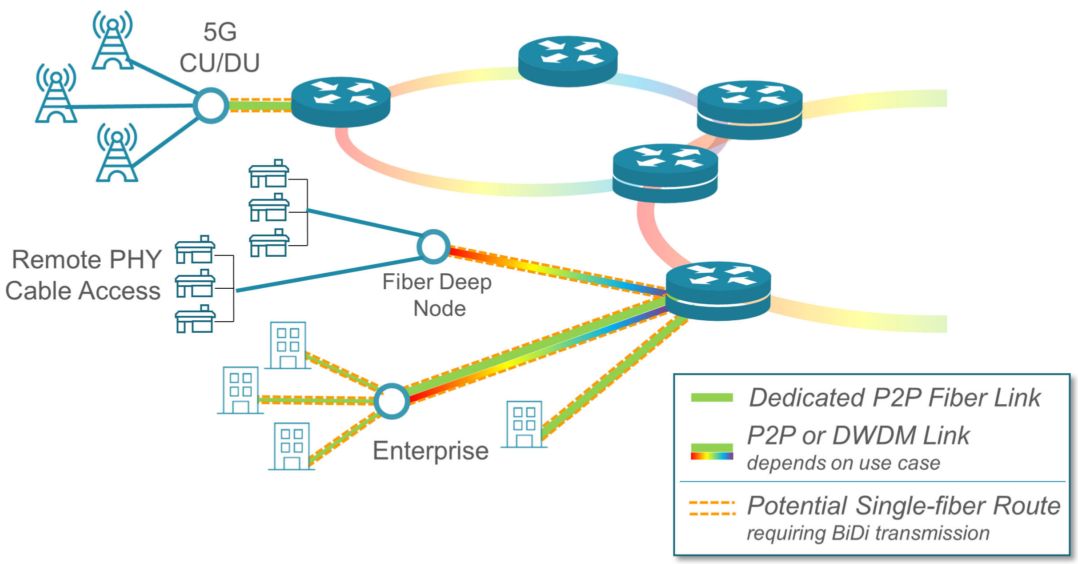


Figure 1. Examples of different connectivity solutions in the service provider edge/access portion of the network.

This paper examines the different challenges of increasing bandwidth in these types of access network topologies, and discusses how coherent optical technology can provide a scalable solution to address high-bandwidth demands, and operational and scalability benefits in these networks when increasing bandwidth to 100Gbps and beyond.

Dedicated Point-to-Point Fiber

Optical fiber deployments that do not require optical amplification or DWDM to reach the service provider edge/access terminal equipment rely on economically optimized dedicated P2P fiber links in which a fiber pair is used between the metro core and edge/access aggregation terminal equipment or enterprise site. Here we use the term **dedicated P2P fiber** to denote a data path between endpoints of a fiber link for a single application or customer service. As described later in this paper, in some optical implementations the optical link may utilize multiple widely spaced wavelengths constituting a single data path over a dedicated P2P fiber link.

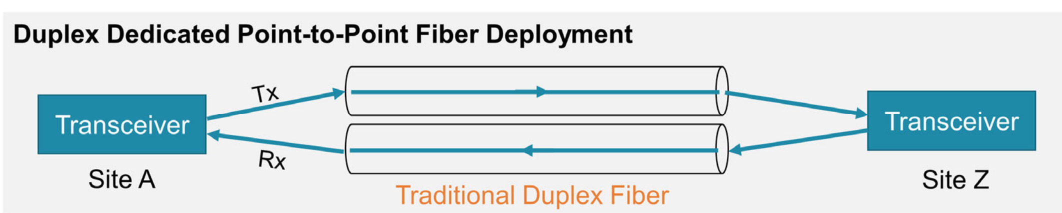


Figure 2. Typical dedicated point-to-point fiber link.

As bandwidth demand in these types of networks increases, limitations are encountered because legacy optical transmission technology have distance limitations when scaling to 100Gbps and beyond. For service provider edge and access networks, there is an emerging requirement to evolve directly from legacy 10Gbps to 100Gbps optical links as a preferred means to increase bandwidth. An attractive solution would be one that can provide a 10x increase in bandwidth capacity without requiring a change to the network architecture, thus minimizing the total cost of ownership.

Higher data rates pushing the limits of legacy dedicated P2P fiber solutions

Traditional direct-detect optical transmission technology used in pluggable optical transceiver module solutions over single mode fiber have served the industry well in providing reliable dedicated P2P fiber at 10Gbps over service provider edge/access networks. However, beyond 10Gbps, the ease of use becomes more challenging. Increasing the bandwidth of a dedicated P2P fiber link from 10Gbps to 100Gbps using direct-detect relies on transmitting over multiple optical lanes at sub-multiples of 100Gbps (see *Direct-Detect and Coherent Comparison for 100Gbps Edge/Access* inset), such as four lanes at 25Gbps. Using the same technology to address edge/access reaches beyond 10km is challenging. To minimize impairments due to fiber chromatic dispersion, these four wavelengths need to remain in the 1310nm range. Extending to further reaches in this wavelength range would require additional power budget to overcome optical fiber loss. For example, extending to a longer reach of 80km would not only require an additional 28dB* power budget compared to 10km, but also there would be additional loss from the effects of optical transmission impairments such as chromatic dispersion and polarization mode dispersion (PMD).

Unique requirements in the edge/access

In addition to the technological limitations of pluggable direct-detect solutions scaling to higher bandwidths and reaches, the landscape of the service provider edge/access network provides its own unique challenges. Different fiber types with a range of loss and dispersion characteristics have been deployed over the years in various segments of the network to optimize transmission for different generations of transmission technology. The range of fiber types include ITU-T G.652A/B/C/D, G.653, G.654, G.655, G.656, and G.657. Because a large capital investment is required to install fiber, it does not make sense to rip out the fiber whenever a new technology advancement is made. Rather, accommodations on the terminal equipment optical transceivers/transponders may be required to operate on legacy non-optimized fiber.

It is not unusual to have multiple bulkhead patch-panel fiberoptic connectors and splice points along a fiber route within the edge/access network, as shown in Figure 3. The cumulative effect of these is the accumulation of loss and back reflections (aggravated by unclean connectors), which can be detrimental to the optical transmission performance in a direct-detect link.

Direct-Detect and Coherent Comparison for 100Gbps Edge/Access

Direct Detection/Intensity modulation: Optical signal intensity is modulated. Receiver detects whether light is on or off.

- Non-Return to Zero (NRZ) intensity modulation and direct-detection: Signal intensity varied by modulating the laser output between either fully on or fully off. As a result, the transmitter only sends one bit per symbol. The challenge is that the optical modulation rate is limited, with impairments encountered in the fiber transmission becoming a limiting factor to achievable reach at these speeds. Four lasers and four detectors each operating at ~25Gbps are required for 100Gbps edge/access.

Coherent: Optical signal is modulated in both phase and amplitude. The number of bits per symbol using a single laser is increased, reducing the need for multiple laser sources. Optical signal can be modulated with two orthogonally polarized beams, known as dual-polarization (DP), further doubling the amount of data transmitted. Receiver recovers data from preserved phase and amplitude information. DP-QPSK provides robust 100Gbps transmission over edge/access fiber links. Most recent solutions are DP and hence the “DP” is typically dropped as it is implied. On the receiver end, amplitude and phase components are extracted from the received signal using an optical reference source (a.k.a, local oscillator) and to provide gain. This information is then processed to decode the original transmission data.

- Quadrature phase-shift keying (QPSK): Optical signal split, with one part phase shifted relative to the other, and amplitude held constant. Recombining them generates an optical signal that encodes two bits of data for every state change of the laser. DP-QPSK doubles the amount of data transmitted.

*Assuming 0.4 dB/km attenuation.

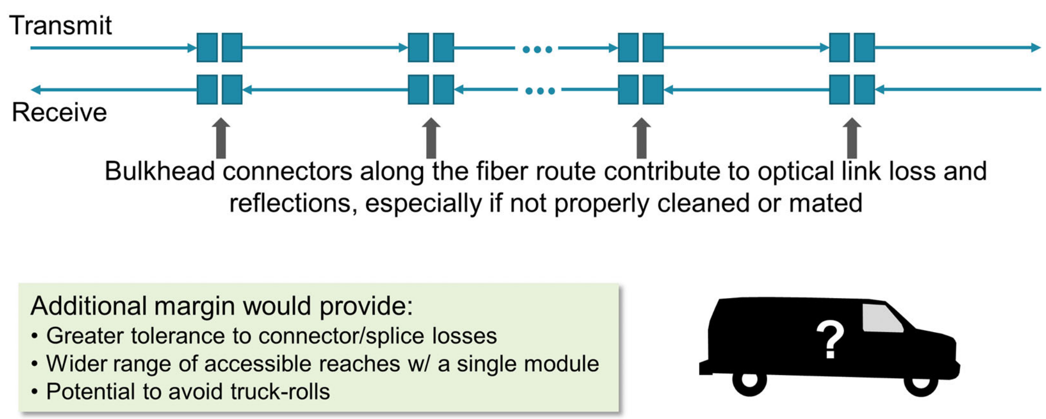


Figure 3. Additional margin in an access link would provide operational flexibility in deployments from increasing the number of addressable reaches to potentially avoiding the need for truck rolls to "shoot fiber" (OTDR measurements), especially for routes deemed marginal using direct-detect transmission.

To account for numerous potential impairments depending on the fiber-plant condition (fiber types, connector reflections and losses), truck rolls may be required to characterize each fiber route (chromatic dispersion, PMD, fiber loss, and reflections) before certifying a link as operational to ensure an optical link can be closed if there is uncertainty about link margin.

In addition to fiber types and connector/splice induced impairments, environmental conditions of the service provider edge/access network must also be considered. Edge/access equipment terminals may be located in uncontrolled outdoor cabinets requiring optical modules to endure temperature ranges beyond what is typically found in an indoor temperature-controlled environment. Managing the performance of a multiple-laser direct-detect solution to meet overall transmission requirements, including longer reach links, may make outdoor temperature resilience a challenge.

DWDM Access Aggregation Links

It is common for multiple dedicated P2P fiber links to aggregate to a network node (as shown in Figure 1), such as the service-provider edge or access aggregation site where traffic is combined into larger multi-transmission bandwidth pipes, transported via a DWDM link to the core of the network. These DWDM links can be either amplified or unamplified (Figure 4).

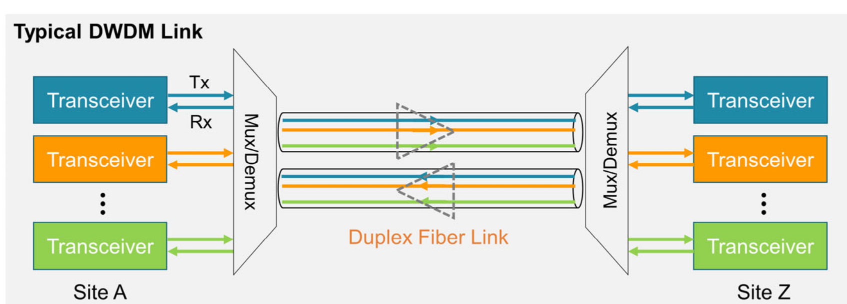


Figure 4. Typical DWDM link which may or may not be amplified.

These links are more complex than dedicated P2P fiber links since they require additional optical mux/demuxing components and may also include optical amplifiers for link extension without electrical regeneration along a fiber path.

Each individual DWDM wavelength experiences the similar impairments as in a single-wavelength dedicated P2P fiber link. With tunable laser capabilities, a common module can be used to cover multiple DWDM channels which lowers deployment and sparing costs.

Single-Fiber BiDi Links

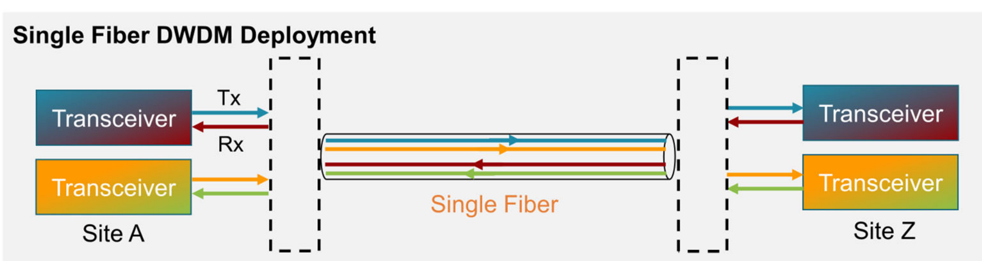
Gaining right-of-way access and digging up streets to install fiber optic cables are major hurdles in deploying service provider edge and access optical infrastructure to address the continuing growth in bandwidth demand. This predicament leads to constrained fiber situations in a variety of environments such as urban, suburban, rural, and metropolitan. Both previously discussed dedicated P2P and DWDM links in the service provider edge and access networks typically utilize single-mode *duplex* fiber in which data transmission from site A to Z travels on a fiber that is different from the data transmission traveling from site Z to A (Figures 2 and 4).

It is not unusual for a service provider to rely on a *single* strand of fiber optic cable in order to deliver services over this infrastructure, especially if the service provider is sharing a cable bundle or duct space with others. In these single-fiber routes, optical transmission is bi-directionally transmitted and received on the same fiber, as opposed to different fibers in a more typical duplex fiber route. A compounding challenge is how to perform upgrades over a single-fiber BiDi route from legacy bandwidth/distance-limited optical direct-detection technology, given the previously discussed fiber impairments which also affect a BiDi route.

Rather than digging up the streets, an alternative method to increasing bandwidth over service provider edge/access single-fiber routes is to upgrade the BiDi transmission technology used at the terminal equipment endpoints.

Figures 5a and 5b illustrate examples of BiDi deployments for single optical link and DWDM links. Figure 5a illustrates an example of a single-fiber path available in which the A-to-Z transmission and Z-to-A transmission travel bi-directionally along the same fiber route over different wavelengths. Figure 5b illustrates a similar A-to-Z scenario except that DWDM transmission is used.

(a)



(b)

Figure 5. Optical transmission in a service provider edge/access network over (a) a single fiber BiDi link and (b) a DWDM single fiber BiDi link—in both cases, the transmit wavelength is different from receive wavelength for each data transmission stream. The optical implementation to combine signals into a single fiber depends on the link requirements.

As Figures 5 illustrates, the optical transceiver modules used for single-fiber BiDi deployments must have the ability to transmit and receive on independent wavelengths, a capability dependent on the module design.

Coherent Technology Solves Service Provider Edge and Access Challenges

Optical coherent technology has come a long way since its early days when a full line-card of electronics and optics was required. Today, this technology can be housed in a small, compact pluggable module, made possible through advancements in silicon photonics, opto-electronic integration, and CMOS nodes with lower power consumption. These continued innovations have positioned coherent solutions to advance into applications with shorter reaches (Figure 6) such as service provider edge and access networks.

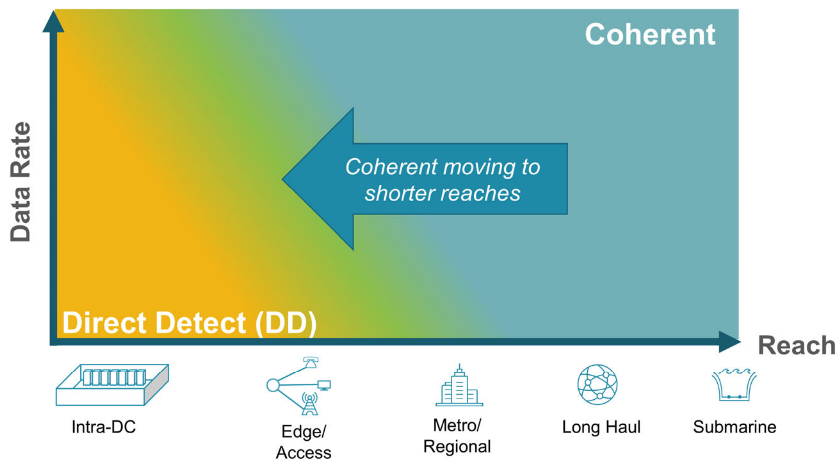


Figure 6. Coherent solutions are evolving towards shorter reaches.

Unlike bandwidth/distance limited direct-detect solutions for service provider edge and access links, coherent technology can easily bridge the gap to higher bandwidth and longer distances on any deployed fiber type. Coherent also provides an operationally simple solution, which played an important role in driving its adoption in longer-reach environments. Let's explore some of these advantages in more detail.

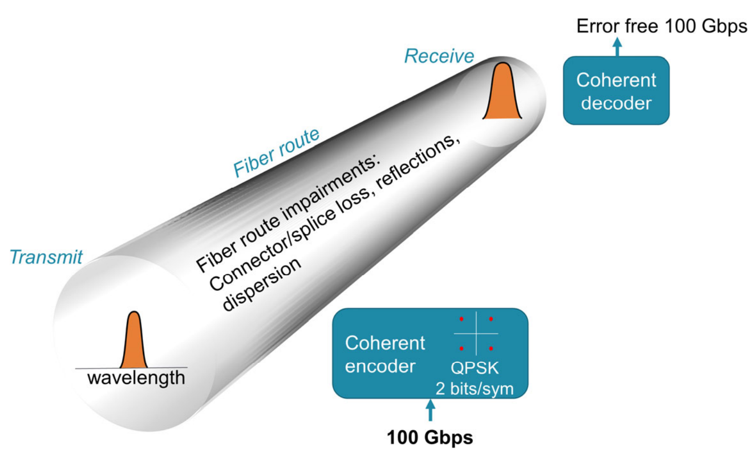


Figure 7. Error-free coherent transmission of 100Gbps QPSK modulation example, tolerant to multiple impairments (only one transmission direction shown).

Coherent transmission tolerant to various service provider edge/access route impairments

Coherent solutions have the ability to electronically overcome both chromatic and PMD transmission impairments, which allows the transmission to adapt over different edge/access fiber types and conditions in a plug-and-play fashion. It is also tolerant to the detrimental effects from loss and back reflections from multiple fiber connector/splice interfaces.

Unlike in intensity-modulated direct-detect transmission where reflections encountered over the fiber route can create noise in the transmission link, coherent modulation formats such as QPSK are inherently much more tolerant to optical reflections. Due to the single-laser coherent transmitter operating in the lowest loss 1550nm window in single mode fiber, and the coherent receiver having extremely high sensitivity due to its coherent detection technology, coherent pluggable modules have ample power budgets. This enables them to not only compensate for losses due to multiple fiber connectors/splices, but also address long transmission links.

Figure 8 illustrates how the effects of dispersion and losses along a fiber route result in a reach limitation for 100Gbps direct-detect solutions. In contrast, the coherent solution with its higher tolerance to impairments provides improved performance in the form of additional margin and longer reach capabilities.

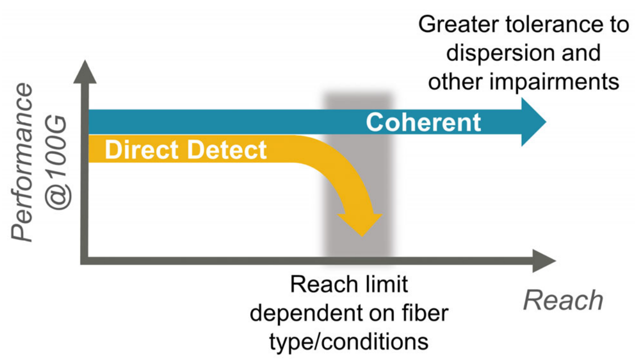


Figure 8. Direct-detect solutions hit a reach limit at a certain distance while the coherent solution will continue to operate beyond this reach limit.

Some of the other key benefits of coherent technology include the following:

Monitoring, Diagnostics and Troubleshooting. Built into pluggable coherent transceivers are monitoring and diagnostic capabilities to ensure robust data transmission. As previously stated, coherent 100Gbps solutions have a very wide receiver dynamic range compared to an equivalent direct-detect link, which enables a coherent link to accommodate optical loopback for troubleshooting. In comparison, some direct-detect solutions include internal optical amplification at the receiver to close longer links, resulting in direct optical loopback troubleshooting not being possible due to receiver overload.

Reliability. In the case of a dedicated P2P fiber link, a pluggable direct-detect 100Gbps solution relies on splitting the single-transmission traffic onto four transmitter lasers which may require operating at the higher end of their transmitter optical power range, especially for the longer reach links of an edge/access network. For these reaches, active optical amplification at the receiver end may also be required to close the link. Thus, a total of eight active elements must be taken into account when determining the reliability of these types of modules. In comparison, a pluggable coherent 100Gbps solution for duplex operation utilizes only one active optical element, the transmission laser, making it more reliable than the direct-detect solution. All of these benefits lead to operational simplicity and shorter provisioning times, which can result in operational savings in the service provider edge/access network.

Scaling to higher data rates

Pluggable coherent solutions enable higher data rates over the same, or greater, distances. Compared to today's access data rates, higher rate coherent options are already available in small form factor pluggable modules, providing a ready-made path to meeting the demands of service provider edge/access bandwidth growth. Coherent transmission solutions beyond 100Gbps are quite mature, and thus, there is no fundamental near-term impediment in coherent technology for scaling service provider edge and access to higher bandwidths.

Acacia's Solution

Acacia's service provider edge and access coherent pluggable solutions are designed for service provider edge and access applications, with a range of modules to address different network applications such as single-transmission P2P links, DWDM links, and single-fiber BiDi links. Acacia's 100Gbps coherent pluggable, offered in a quad small form-factor double density (QSFP-DD) that is widely used for client-optics solutions, are specifically designed for optimization in service provider edge and access applications with unamplified links including 80km reaches and beyond, as well as amplified or unamplified DWDM links. They were designed to provide network operators the ability to scale to higher data rates to meet growing bandwidth demands over some of the most challenging optical links, while also providing operational simplicity that may lead to overall network savings.

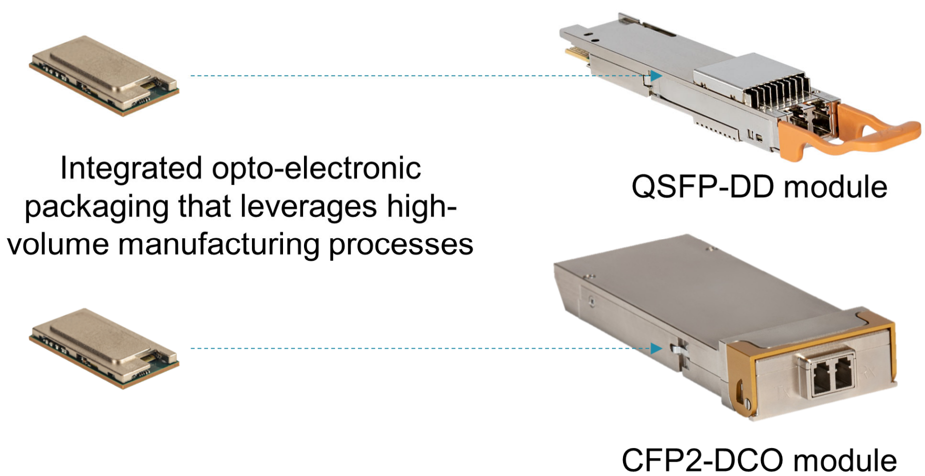


Figure 9. Integration in silicon enables a path to coherent transceivers for service provider edge/access in compact pluggable QSFP-DD and CFP2 modules.

Acacia's coherent BiDi CFP2 form-factor module delivers an operationally efficient and cost-effective way for network operators to increase capacity to 100Gbps and beyond over both single-fiber as well as diverse transmit/receive network architectures. For more details on how a coherent BiDi solution differs from a duplex fiber P2P or DWDM solution, see the *Design optimization for coherent BiDi* inset for a detailed explanation of how to enable this capability in a coherent transceiver.

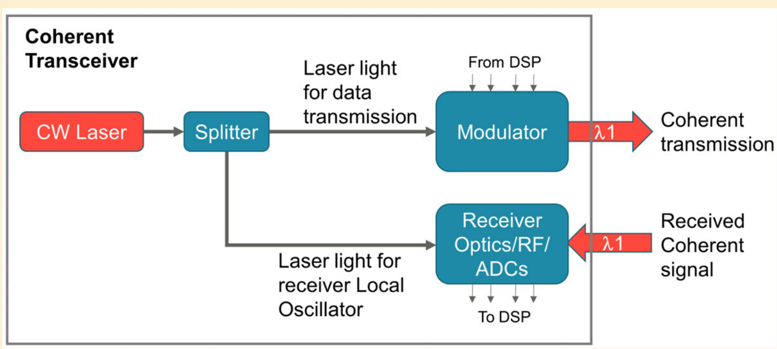
For single-fiber BiDi transmission, there are various implementation options to convert from a dual-port configuration to a single-port configuration such as passive optical mux/demuxes, splitter/combiners, or circulators, depending on the application and link requirements. The module supports both Ethernet and OTN standardized client protocols.

Acacia's 100Gbps P2P and DWDM QSFP-DD modules and coherent BiDi CFP2 module all feature Acacia's 3D Siliconization approach, which utilizes high-volume manufacturing processes and benefits from the maturity of Acacia's silicon photonics technology. Figure 10 illustrates how advances in optical/electrical component consolidation has resulted in size reductions of coherent modules. The use of silicon photonics to take discrete bulky optical components and integrate their functions into a CMOS-based silicon chip has been a key factor in module footprint reduction.

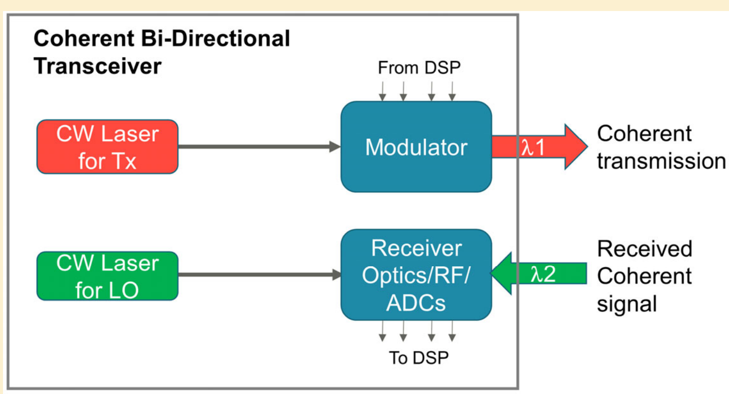
3D Siliconization follows the example of the electronics world and applies integration techniques such as 3D stacking to electronics and silicon photonic integrated circuit (PIC) co-packaging. This approach makes it possible to integrate crucial components into a compact package and reduce the number of electrical interconnects while preserving robust signal integrity. Integration involving silicon photonics follows progress already made in the semiconductor fabrication process suitable for volume production and high yields.

Design optimization for Coherent BiDi

A required element of any coherent optical transmission implementation is the local oscillator (LO), a stable continuous wave (CW) laser used as a clean reference source to optically mix with the received optical signal. It is typical for the transmitter and receiver wavelength in a coherent link to be the same, which allows for the sharing of the same CW laser source for transmission as well as the receiver LO.



However, for BiDi applications in which the transmit and received wavelengths are different, the LO should not be derived from the transmission laser. A separate second laser is required as the LO. Thus, a coherent BiDi module contains dual lasers, one used to transmit the data, while the other is used as the LO. This allows the transmit wavelength to be independent from the receive wavelength.



This coherent BiDi module is designed to support service provider edge and access optical network links with single-fiber routes, as illustrated in Figures 5. Wavelengths propagating in opposite directions have to be different in order to avoid in-band crosstalk due to back reflections. In addition, having the Tx laser and receiving module's LO laser be fully tunable enables the management of a single product code rather than managing an inventory of multiple fixed-wavelength pluggable module product codes, thus simplifying network deployment.

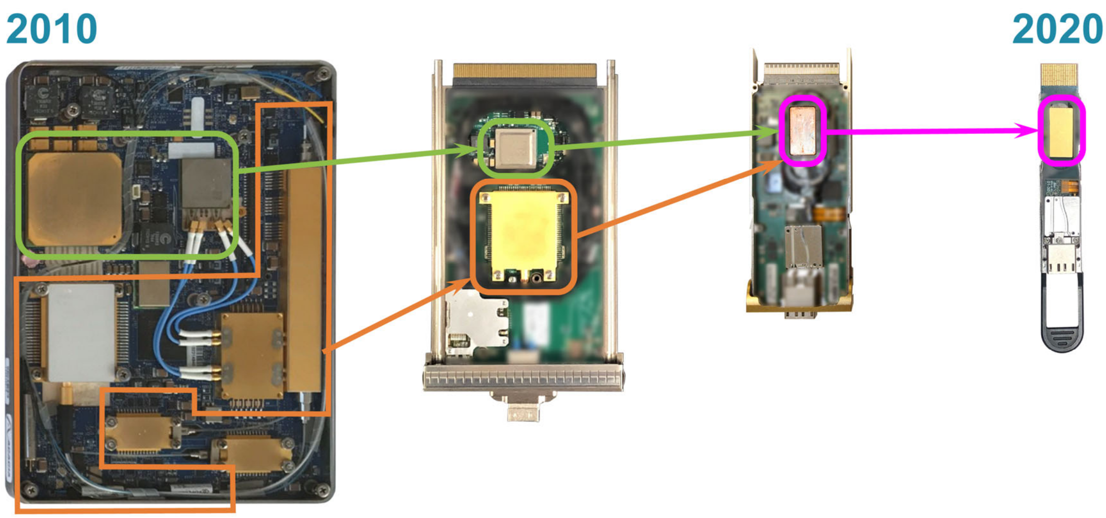


Figure 10. Evolution of coherent module size over time.

Conclusion

Applications such as 5G, gaming, telemedicine, autonomous vehicles, and cloud computing are driving increased network traffic at the edges of the network, which is placing enormous strain on traditional service provider edge and access networks. The amount of bandwidth required to deliver these new services and applications are expected to be higher than the legacy infrastructure can support based on traditional optical transmission technology. This is driving service providers to not only look for ways to deliver optical links at 100Gbps, which pose challenges to legacy direct-detect solutions, but also to ensure these new solutions can be supported over existing dedicated P2P fiber, DWDM, and BiDi infrastructure.

Based on recent advancements in silicon photonics, opto-electronic integration, and CMOS nodes with lower power consumption, coherent technology has emerged as an effective way of meeting this challenge. These advancements have enabled Acacia to develop and bring to market a full suite of edge and access coherent pluggable modules designed to address different network applications such as dedicated P2P fiber links, DWDM links, and single-fiber BiDi links. Leveraging these solutions can enable network operators to overcome the many challenges they face today when trying to scale to higher data rates in the future in a cost effective and operationally simplistic way.

References

[1] Cisco website: https://www.cisco.com/c/en/us/solutions/collateral/executive-perspectives/annual-internet-report/white-paper-c11-741490.html.

[2] CableLabs website: https://www.cablelabs.com/gigabit-internet-speeds.

About Acacia

Acacia's innovative silicon-based high-speed optical interconnect products accelerate network scalability through advancements in performance, capacity, and cost. Our silicon photonic PICs, DSP ASICs, and coherent modules inside a variety of network equipment products empower cloud and service providers to meet the fast-growing consumer demand for data.

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