Network Optimization in the 600G Era

Today's Coherent Capabilities Address Multiple Network Applications

Introduction

Bandwidth demand from consumer and enterprise applications continues to grow. Cloud-based applications, data center interconnections, streaming videos, as well as applications on the horizon such as 8k ultra-high-density video, 5G and Internet of Things (IoT) are contributors to bandwidth growth. Global IP traffic, per Cisco's Visual Networking Index[1] (VNI) indicates that by 2022 there is projected to be 28.5B networked devices and connections, as well as 82 percent of all IP traffic as video. The 2018 Global Interconnection Index[2] analysis by Equinix predicts private interconnection bandwidth between businesses is forecasted to exceed 8,200 Tbps by the year 2021. Clearly, transmission speeds should stay one step ahead to ensure there is sufficient capacity to meet the demand. Data rates of 100G per wavelength once confined to the long-haul core portions of the network are now extending towards the edges of the network. Today, 600G per wavelength speeds are becoming available for use in the core as well as for data center interconnect (DCI) traffic.

Maximizing return-on-investment (ROI) for a network infrastructure deployment involves ensuring the solution has the ability to optimize capacity and reach, as well as provide low cost-per-bit. Different portions of the network may have different optimization requirements (Figure 1). For example, an owned or leased optical interconnect linking two data centers may require the highest raw capacity achievable for low cost-per-bit between sites. For a multi-haul environment with disparate channel impairments within metro and/or long-haul links, filling up the available spectral channel with a flexible control mechanism to optimize fiber utilization may be required. For a long-haul or submarine link, achieving high capacity without sacrificing reach may be the main network requirement. Fortunately, the technology to achieve high performance network optimization is available today to meet these various application requirements in the same device.

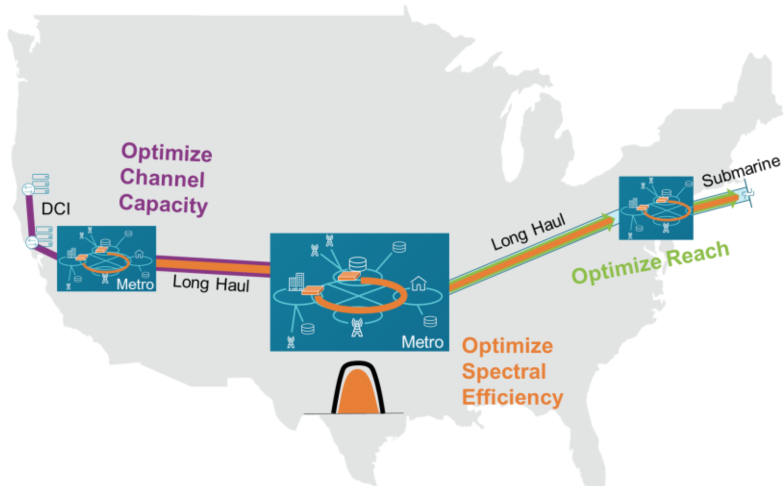

Figure 1. Achieving network optimization with 600G era coherent technology.

Planning a network to maximize capacity and reach requires a multi-faceted approach. Network operators are embracing coherent optical transmission for long-haul, metro, and DCI links due to various advantages. Coherent technology provides a means to overcome many of the degradation effects an optical signal encounters over a fiber optic link, as well as providing transmission speeds at 100 Gbps and beyond per wavelength.

Recent innovations in digital signal processing (DSP), optical, and mixed-signal component technologies have enabled the achievement of 600G-per-wavelength transmission speeds. High modulation orders (e.g., up to 64QAM) and high baud rates (e.g., up to ~70Gbaud) are now possible. In addition to this high speed achievement, these technologies also introduce advanced capabilities that allow the flexible fine-tuning of the optical transmission resulting in capacity optimization. Today's coherent technology enables common optical hardware to achieve the high-performance finesse of a long-distance link, the sheer raw capacity for shorter DCI/edge links, and everything in between. This is the reason why some refer to 600G era coherent technology as *multi*-haul technology since the same set of hardware can address long-haul, metro, and DCI/edge networks.

Figure 2. Acacia's AC1200 1.2T coherent module.

Acacia Communications recently introduced the AC1200 coherent module, powered by Acacia's Pico DSP, a low-power solution based on 16 nm CMOS technology incorporating algorithms and processing power to address a wide range of applications. The AC1200 also includes a silicon photonics integrated circuit (PIC), and high-speed RF electronics to achieve 1.2Tbps capacity by using two wavelengths operating at 600Gbps each. The AC1200, is a leading product in the 600G era offering key capabilities that feature high-performance and high-flexibility, with the goal of enabling network operators to improve efficiency and maximize capacity utilization while reducing network costs.

The AC1200 is rich with features that address multiple network applications including DCI/edge, metro, long-haul, and ultra-long-haul/submarine networks. Let's take a look at each type of network application and elaborate on how the AC1200 provides benefits for each of these applications.

Data Center Interconnects

Raw Capacity with Client Flexibility

In a DCI/edge network application, raw capacity at the highest achievable transmission speeds is a primary requirement for connecting data centers within the same campus or between sites across a metro region. The recent introduction of 600Gbps transmission per DWDM coherent wavelength, capitalizing on recent 64QAM technology advancements, is beneficial for DCI/edge links that require the highest channel capacity achievable at the lowest cost per bit. Integrating transceiver functions of more than one wavelength into the same device/module can improve cost-per-bit compared to a single-wavelength device/module.

The AC1200 uses a dual-core modem design to drive two tunable 600G C-band or L-band wavelengths from one DSP device for a total transmission capacity of 1.2Tb per module up to 64QAM. An interconnection fabric within the module enables flexible support to map client interface traffic onto these two line-side wavelengths. A dual-core modem plus interconnection fabric design is an efficient way to map 400GbE (Gigabit Ethernet) client traffic onto 600G wavelengths (i.e., 3x400GbE onto two 600G wavelengths). In data center environments where Ethernet is the predominant protocol, the AC1200 has the capability to not only support 3x400GbE client interfaces, but can also support 12x100GbE clients, as well as FlexE protocols.

In addition to short point-to-point links, more expansive data center networks may have metro and long-haul interconnects over private or leased connections. For these interconnects, the requirements for the optical transmission links resemble what you may find in a more traditional metro or long haul network with ring or mesh architectures traversing amplified links with reconfigurable optical add/drop multiplexers (ROADMs). Let's explore how these types of networks benefit from 600G era coherent optical technology.

Multi-Haul Networks

3D Shaping for Transmission Adaptability and Network Optimization

In comparison to DCI/edge links, metro and long-haul networks have a more diverse architecture with a range of fiber conditions and add/drop filters that may require the optical transmission to have multiple "knobs" to optimize capacity, reach, and spectral utilization. These multi-haul networks may require transmission flexibility to optimize multiple disparate links to achieve maximum capacity on a per-link and overall network basis. Multi-haul networks may benefit from shaping of the optical coherent transmission signal to optimize network performance. To provide the means to optimize the optical transmission, Acacia has introduced 3D Shaping technology, powered by the Pico DSP, which enables flexible fine-tuning of the line-side optical transmission allowing network operators to optimize capacity, reach, and spectral utilization. 3D shaping is a power-efficient technology solution that pushes optical transmission capacity closer to the Shannon limit, the theoretical maximum capacity that a communication channel can achieve, enabling the optical transmission to adapt to the line-system network.

Capacity Optimization with 3D Shaping

3D Shaping consists of three elements. The first element is the ability to shape the probability of the constellation points associated with the coherent transmission. A constellation diagram of the coherent transmission is a visual indicator of the efficiency and quality of the optical transmission. Each constellation point in the diagram represents a transmitted symbol. Previous generations of coherent DSPs transmitted each symbol with an equal probability, resulting in a uniform probability distribution of the constellation. Modifying the probability distribution of the constellation can increase the capacity of a channel.

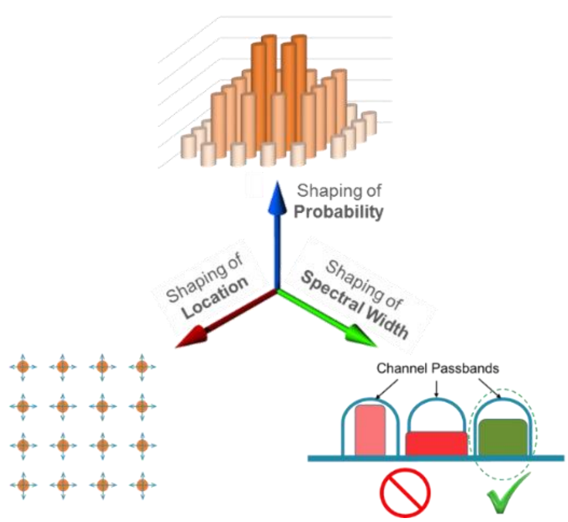

Figure 3. Three elements of AC1200 3D Shaping Feature.

The AC1200 shapes probability of the transmission constellation by using Acacia's patented Fractional QAM (F-QAM). F-QAM enables one to dial-in a more precise non-integer bit-per-symbol modulation-setting to improve capacity utilization on a channel. This technique that enables non-integer modulation orders—instead of being constrained to integer modulation, such as QPSK (2 bits-per-symbol), 8QAM (3 bits-per-symbol), and 16QAM (4 bits-per-symbol)—allows the link margin to be optimized with greater resolution than prior generation interconnect technology. Figure 4 illustrates how quantized integer modulation order settings may result in sub-optimal capacity utilization due to link margin gaps. F-QAM can be used to fill in capacity caps by “dialing in” a non-integer step modulation setting.

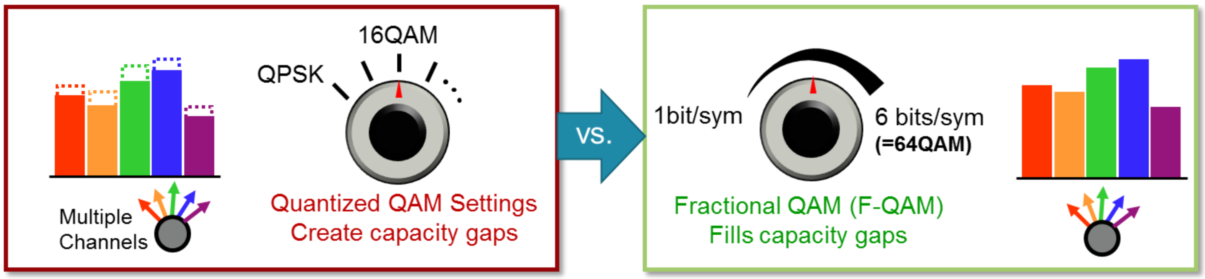

Figure 4. Example of capacity utilization improvement on each wavelength link using F-QAM.

Reach Optimization with 3D Shaping

The second element of 3D Shaping is the ability to shape the location (or position) of the constellation points, which optimizes transmission distance. Tolerance to noise can be represented by how the coherent transmission constellation diagram points are positioned next to each other. The closer the constellation points are to each other, the less tolerant the transmission is to noise. The farther apart the constellation points are to each other, the greater amount of tolerance the transmission has to noise. By shaping (or adjusting) the location of individual points within the constellation, the tolerance to noise can be optimized, which translates to a farther reach without costly regeneration.

Channel Spectral Optimization with 3D Shaping

The introduction of coherent transmission and flexible grid wavelength-selective-switch (WSS) technology into metro and long-haul networks enabled flexible wavelength routing using ROADMs and mixed spectral bandwidth DWDM transmission along the same link. Preserving transmission in the optical domain avoided the required CapEx investment into optical-electrical conversion for transport layer switching and routing. WSS technology enabled the line system network to adapt to the optical transmission with flexible grid channel spacing. The converse was limited in the sense that the optical transmission had limited flexibility, allowing only quantized levels of capacity and spectral usage as previously mentioned.

The third element of 3D Shaping, Adaptive Baud Rate, addresses these limitations by providing an improved level of flexibility with greater granularity compared to legacy fixed/quantized baud rate choices which can create spectral gaps in a channel. Using Adaptive Baud Rate, the AC1200 can adjust the width and shape of the transmission spectrum with flexible control of the baud rate over a wide range, enabling unused spectral gaps to be converted into usable bandwidth. This allows network operators to fully utilize the available channel capacity within a metro or long haul network, as well as provide the ability to reduce regeneration stages and increase network margin.

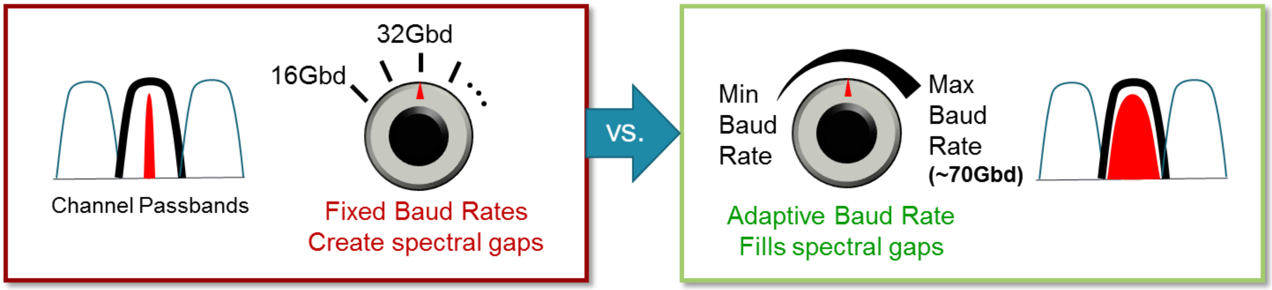

Figure 5. Adaptive Baud Rate enables the minimization of spectral gaps within a channel passband.

Using Adaptive Baud Rate, a network operator can adjust the transmission spectrum to better fit into the aggregate available passband of the channel by having the ability to continuously tune the baud rate, filling in any margin gaps (Figure 5).

This fine-tune Adaptive Baud Rate capability is very useful in a multi-haul network with multiple ROADM nodes as shown in Figure 6. As previously stated, channel passband widths can vary among links in the same network as well as between networks. Spectral margin gaps to account for worst-case cascaded passband conditions can result in stranded bandwidth. By using Adaptive Baud Rate, these margin gaps can be reduced to improve the spectral utilization of the channel.

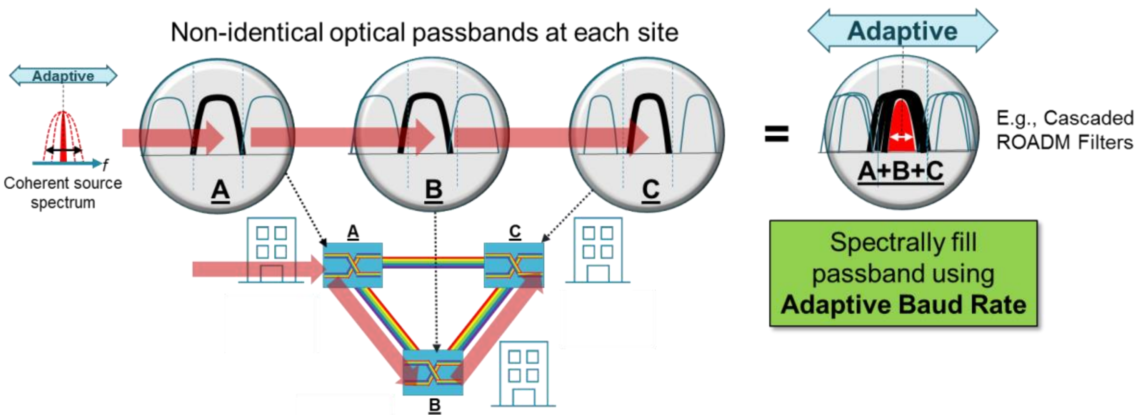

Figure 6. Adaptive Baud Rate implementation in a Multi-Haul network for spectral optimization.

With Adaptive Baud Rate, rather than adjusting the line system to match the optical transmission, the ability now exists for the optical transmission to more closely match the line system, giving rise to a new level of network utilization. Flexible grid channel spacing in a network can create bandwidth fragmentation as a result of spectral margin gaps across a network. Bandwidth fragmentation can be minimized using Adaptive Baud Rate, thus minimizing stranded bandwidth.

3D Shaping provides a flexible method to fine-tune line-side coherent modulation, enabling network operators to optimize their network’s capacity and reach. Using 3D Shaping to effectively mine for previously inaccessible capacity also enables network operators to lower cost-per-bit on a per link or aggregate network basis.

High-Capacity Long Haul and Ultra-Long Haul Links

Increasing capacity without sacrificing reach

3D Shaping is enabled by the Pico DSP inside the AC1200 module. Figure 7 shows a generalized AC1200 block diagram. In addition to 3D Shaping, the DSP engine includes other capabilities such as non-linear equalization and advanced Forward Error Correction (FEC). Beyond the DSP engine, there are elements (e.g., high-speed RF/mixed-signal) which contribute to high-baud rate performance. In this section we will discuss how high-baud-rate capabilities become important for optimizing capacity, especially for long and ultra-long haul/submarine links. For example, high-baud-rate capabilities enable a link to achieve high capacity without sacrificing reach by operating at a lower modulation order.

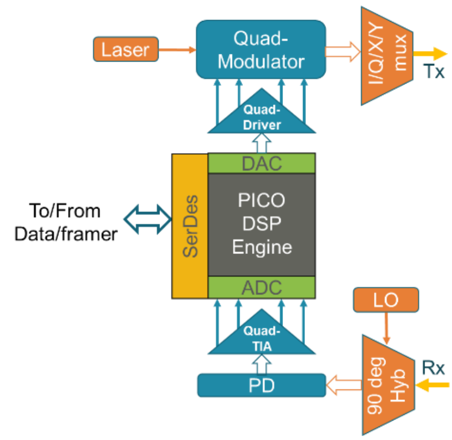

Figure 7. AC1200 simple block diagram. Shared local oscillator (LO) and Tx laser.

One school of thought is that to achieve higher capacity the modulation order should be increased (e.g. moving from 8QAM to 16QAM). While this is true, it comes at a price of decreased reach due to greater optical signal-to-noise ratio (OSNR) requirements of the higher order. A rule-of-thumb is that reach is reduced by at least a factor of two for every step increase in integer bit/symbol (e.g., going from 8QAM to 16QAM). A key to having the flexibility to optimize capacity versus reach is having the capability of operating at a high baud rate. High baud rate capabilities provide a knob that allows the transmission to operate at a lower modulation order, thus preserving reach, while increasing the channel capacity. Figure 8 illustrates an example of how the reach of a 400G link can be extended by moving to a higher baud rate without moving to a higher QAM modulation order.

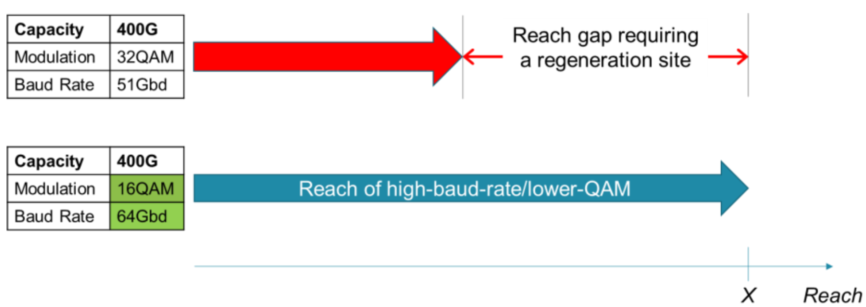

Figure 8. 400G example with different QAM/baud rate deployment options.

Suppose a network operator would like to increase the capacity of a link with distance of *X* to 400G. There are two potential options. Install a system that delivers a high QAM modulation order transmission, such as 32QAM. With this higher order modulation comes a reduced reach capability. An optical-to-electrical-to-optical regeneration site may be required to compensate for the reduced reach capability, resulting in incurred CapEx and OpEx expenditures. If the terminal equipment had higher baud rate capabilities, the reach can be maintained at distance *X* and still achieve 400G capacity by using 16QAM modulation and increasing the baud rate. This assumes that there is a sufficient spectral window to allow for the baud rate increase. Simply stated, the ability to modulate at these high baud rates brings flexibility of increasing capacity and reach.

The AC1200 coherent module achieves high baud rates of ~70Gbaud based on its design of advanced high-speed mixed-signal analog-to-digital converters (ADCs), digital-to-analog converters (DACs), and Acacia's high bandwidth silicon photonics. The combination of high-baud rate capabilities and the fine tuning of 3D Shaping means that a network operator can achieve a high-capacity long/ultra-long haul link with high spectral efficiency. This is especially important in a submarine network where multiple providers share the same fiber link, and are trying to optimize its capacity utilization of their assigned spectrum.

Reach Extension Based on Enhanced SD-FEC

FEC performance is one of the main elements in advancing the limits of reach and capacity. The introduction of soft-decision FEC (SD-FEC) compared to hard-decision FEC (HD-FEC) provided a significant improvement in net coding gain. While in the 600G era, further enhancements to SD-FEC algorithms have also brought about additional coding gain, resulting in improved performance and longer reaches for any baud and modulation format. The AC1200 features Enhanced Turbo Product Code SD-FEC with ultra-high net coding gain (NCG) to extend reach, while maintaining low power dissipation.

Performance Improvement Example

To illustrate the potential performance improvements of 3D Shaping, high-baud-rate technology, and advanced FEC, consider the transmission of 200Gbps across a coherent optical DWDM channel, based on 50GHz spacing, which includes ROADM nodes. Using Adaptive Baud Rate to increase the baud rate to fill the available spectrum, and by using F-QAM to operate at a lower order non-integer bit-per-symbol modulation, nearly 1.5dB improvement in performance can be achieved. High-resolution ADCs/DACs, high bandwidth silicon photonics, additional techniques to reduce implementation penalties, as well as nonlinear equalization, and FEC enhancements all can provide additional system margin improvement of the same order. The resulting system performance improvement potentially doubles the reach in comparison to previous generation coherent technology.

Flexible Client Support and Link Security

In the above DCI, metro, long haul, ultra-long haul network scenarios, there is a common requirement to support multiple client protocols and ensure link security. To support DCI links in which Ethernet is the prevalent protocol, the AC1200 client interface options include 100GbE, 400GbE, and FlexE. The AC1200 also supports OTU4 for network operators with an OTN transport network.

Link security has become an increasingly important requirement for network operators. Link security is achieved by providing encryption of the data traffic between sites. To augment Layer 2/3 encryption, the AC1200 offers Physical Layer 1 AES-256 wire-speed encryption for each optical channel link.

Intelligent Networking with Adaptive Transmission

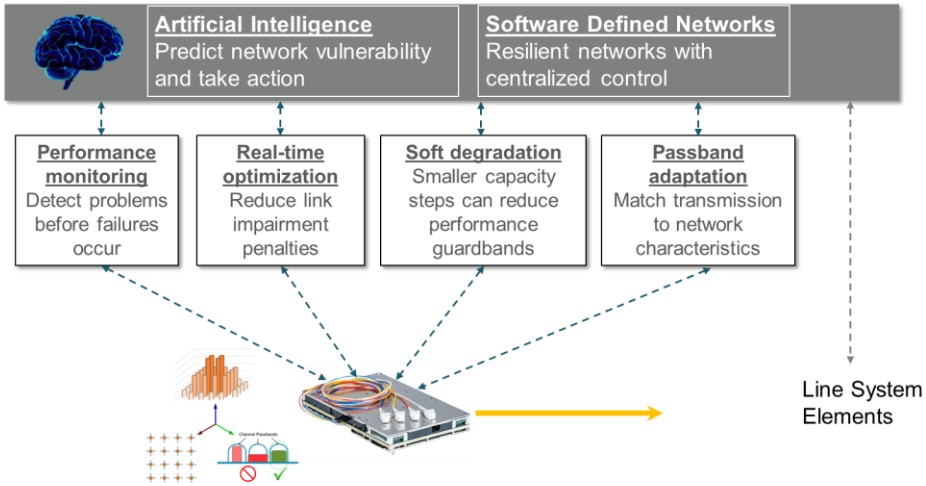

Figure 9. Acacia's coherent optics provide the flexibility to optimize networks for maximum capacity.

For network operators that are looking towards network intelligence for operational benefits, the challenge is whether the optical transmission technology has the capabilities beyond sheer capacity and performance to provide any benefits in an intelligent network. The AC1200 is well suited to be an integral element of an intelligent network. The intelligence of the AC1200 module enables operator ease-of-use by incorporating built-in optimization configurations to avoid manual adjustment of every knob. In conjunction with platform software, network equipment suppliers are empowered to develop configured optimization settings that may operationally benefit the network operator.

Having the capability of fine-tuning the coherent optical transmission characteristics is a good match for intelligent networks using some form of software-defined networking (SDN) and artificial intelligence (AI). With modules such as the AC1200 that provide performance monitoring of numerous advanced parameters, eventually, we may see a network that is able to adjust the optical transmission characteristics on-the-fly using AI to match or predict changing conditions of an open line system.

Conclusion

Table 1 summarizes the multiple network applications addressed by key features of the AC1200. Network operators require network flexibility and optimization to maximize ROI. Achieving capacity optimization and low cost-per-bit rely on advanced optical coherent technology to deliver high performance, high capacity, flexibility, in a compact, cost-effective, power-efficient solution. The AC1200 is a feature-rich coherent module that delivers these attributes, addressing multiple network applications.

<table>
<tr><th></th><th colspan="4">AC1200 Key Features</th></tr>
<tr><th>Application Requirement</th><th>DCI/Edge</th><th>Metro</th><th>Long Haul</th><th>Ultra Long Haul/ Submarine</th></tr>
<tr><td rowspan="2">Capacity Maximization/Optimization</td><td colspan="4">3D Shaping (Shaping of constellation—F-QAM)</td></tr>
<tr><td colspan="4">Dual-core DSP/dual wavelengths/64QAM</td></tr>
<tr><td rowspan="2">Reach Maximization/Optimization</td><td colspan="4">3D Shaping (Shaping of location)</td></tr>
<tr><td colspan="4">Enhanced SD-FEC</td></tr>
<tr><td>Channel Spectral Optimization</td><td colspan="4">3D Shaping
(Shaping of spectral width—Adaptive Baud Rate)</td></tr>
<tr><td>High Performance/High Baud Rate</td><td colspan="4">~70Gbaud transmission</td></tr>
<tr><td>Overcome Non-linear Impairments</td><td colspan="4">Non-linear equalization</td></tr>
<tr><td>Flexible Client Support</td><td colspan="4">100GbE, 400GbE, FlexE, OTU4</td></tr>
<tr><td>Encryption</td><td colspan="4">Layer-1 AES-256</td></tr>
</table>

Table 1. Multiple network applications addressed by key features of the AC1200.

References

[1] Cisco (November, 2018), "Cisco Visual Networking Index: Forecast and Trends, 2017-2022," Retrieved from: https://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/white-paper-c11-741490.pdf.

[2] Equinix (2018), "Global Interconnection Index: Measuring the Growth of the Global Digital Economy, Volume 2," Retrieved from: https://www.equinix.com/global-interconnection-index-gxi-report.

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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