Technical Considerations for Supporting Data Rates Beyond 100 Gb/s

Abstract

As traffic demands continue to grow, supporting data rates beyond 100 Gb/s will be required to increase optical channel capacity and support higher-rate client interfaces. Video, cloud, and data center interconnect applications are driving significant growth in both metro and long haul traffic. Internet and over-the-top (OTT) video is the biggest driver of bandwidth to consumers, while enterprise cloud applications, including Software as a Service (SaaS), Platform as a Service (PaaS), and Infrastructure as a Service (IaaS), are delivering a similar impact on enterprise bandwidth. Underlying both of these trends is the need to provide significant amounts of interconnects bandwidth between data centers housing cloud and video services. Advanced modulation formats that adapt to optimize spectral efficiency over a range of channel signal-to noise ratio conditions are required. Channels are constructed by varying parameters such as symbol rate, bits per symbol, number of polarizations, and number of optical and electrical subcarriers. Channel capacity can also be increased using advanced techniques such as optical time-division multiplexing, and fibers that support multiple cores and modes. Many channel designs can support higher data rates, but there are trade-offs between complexity, spectral efficiency, and optical reach.

Introduction

Driven by the escalating bandwidth requirements of Internet video, enterprise cloud, and data center interconnect, service providers worldwide have been migrating from 10G to 100G and beyond. The evolution of networks to support higher data rates is driven by market demand, standardization activities, and the availability of next generation optical transceiver technology. Standardizing a new data rate requires standards for optical transmission and framing, as well as the details of an optical transceiver implementation. It is also highly desirable to standardize a new client rate at the same time. For the 100 Gb/s data rate, for example, the IEEE defined the 100 GbE client interface, while the International Telecommunication Union — Telecommunication Sector (ITU-T) provided the optical transport unit 4 (OTU4) framing, and the Optical Internetworking Forum (OIF) standardized the polarization multiplexed quadrature phase shift keying (PM-QPSK) transceiver implementation. The transceiver implementations use coherent detection and digital signal processing which allows amplitude, phase, and polarization information to be exploited. The OIF developed implementation agreements for both the transmitter and receiver that define the functionality, interfaces, and mechanical requirements. This allows multiple sources for transceiver components, even though digital signal processor (DSP) design and algorithms are more commonly proprietary to each supplier's design.

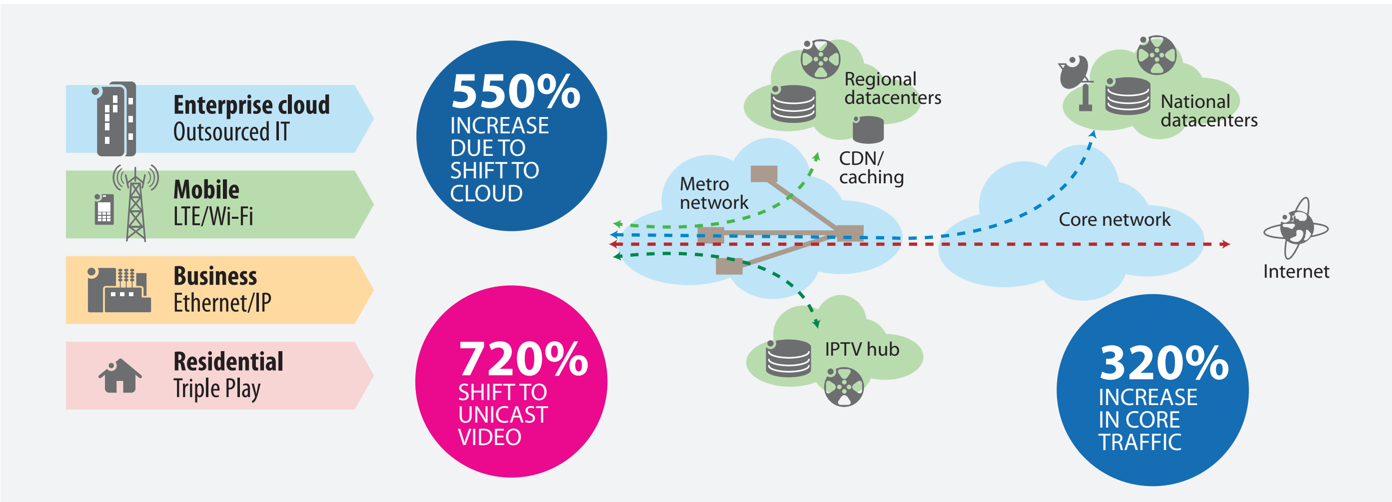

Figure 1: Various applications are helping to annual growth in Bandwidth demand

The above figure shows the evolution of optical and Ethernet standards. Optical transport and Ethernet client standards prior to 100 Gb/s were defined separately and did not always interwork well. For 100 Gb/s, the standardization activities proceeded in parallel leading to a cohesive set of standards that has accelerated introduction of the technology.

This paper focuses on technical considerations for optical transport with channel rates beyond 100 Gb/s.

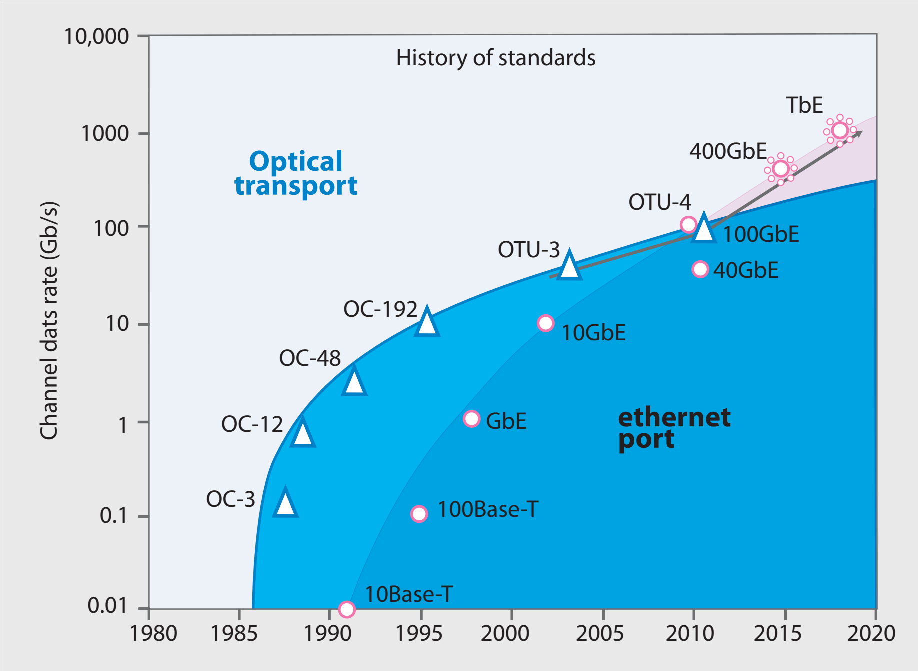

Figure 2: Data port speed and transport channel capacity evolution and predictions

The network considerations for rates beyond 100 Gb/s are discussed, and emerging technologies that will further improve network capacity and efficiency are covered.

Optical Technologies for supporting channel rates 100 Gb/s and Beyond

In a traditional optical transmission system, the optical spectrum is divided into a fixed number of channels that carry traffic using center frequencies and channel spacings as defined by the ITU-T G.694.1. There are many techniques to modulate a signal for transmission, but these techniques have become increasingly complex to support higher channel rates while maintaining or improving spectral efficiency. Traditionally, modulation of an optical signal was accomplished by turning the laser light on and off to represent 1 and 0. This modulation format, called on-off keying (OOK), is the predominant modulation format used for optical channel designs with data rates up to 10 Gb/s. Constellation charts that show symbol configurations in the complex plane for several modulation approaches are shown in Figure 3.

With the introduction of 100G, the industry shifted from very simple modulation techniques (OOK) that transported a single bit of data, to much more advanced phase modulation techniques (DP-QPSK) capable of encoding and sending multiple bits at once. Along with coherent receivers, these more advanced modulation techniques enable much higher data rates and improved compensation for optical impairments such as chromatic dispersion (CD), polarization mode dispersion (PMD), and optical loss. The trade-off with these advanced modulation techniques is they require higher Optical to Signal Noise Ratios (OSNR). OSNR translates directly into the optical distances that can be achieved prior to a regeneration node. In other words, the more sophisticated and powerful the modulation, the shorter the optical reach. This trade-off between modulation technique, channel size, and OSNR requirements are at the heart of current 400G research efforts.

Modulation Schemes for 100G and Beyond

Transmission of optical signals beyond 100 Gb/s by increase of spectral efficiency is currently of high interest at research. The major focus is on multi-level modulation format based on MQAM (quadrature-amplitude modulation) and coherent reception applied at single carrier as well as at multi-subcarrier modulations formats. The major target is to maximize their

Modulation format	OOK	OOK-VSB	DQPSK	RZ-DPSK-3ASK	PM-DQPSK	OP-FDM-RZ-DQPSK	PM-QPSK	PM-OFDM-QPSK
coh. / noncoh.	noncoh.	noncoh.	noncoh.	noncoh.	noncoh.	noncoh.	coh.	coh.
Bits/symbol	1	1	2	2.5	2x2	2x2	2x2	2x2x2
Symbol Rate (Gbd)	112	112	56	44	28	28	28	14
Constellation								x2
DWDM Grid (Ghz)	200	100	100	50	50	100	50	50
Spectral Efficiency (bit/s/Hz)	0.5	1	1	2	2	1	2	2

Figure 3: Main Features of 100G Modulation schemes

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spectral efficiency. With respect to potential future 400 Gb/s and 1 Tb/s options, the need of a flexible grid has been raised.

To achieve bitrates beyond 100 Gb/s on a single carrier higher level modulation schemes have to be applied. Recently QAM scheme together with polarization multiplexing is utilized to achieve a channel rate of 200 Gb/s with 16 QAM. In an M-QAM or 2m QAM signal, m bits are transmitted in a single time slot or symbol, where m is an integer value. Adding polarization multiplexing to make PM-2m-QAM format, 2 m bits are transmitted per symbol. A PM-M-QAM signals can be realized in principle by parallel arrangements of PM-QPSK modulators, where the modulators are driven with binary data signals, respectively. For example, two parallel PM-QPSK modulators are required to form a PM-16QAM modulator. A more compact and generic approach is based on the reuse of a PM-QPSK modulator, for the generation of all PM-M-QAM modulation formats, where the modulators are driven with electrical multilevel signals. Various constellations can be applied for PM-QAM modulation format, e.g. circular QAM symbol constellations or quadratic constellation with different sizes as depicted in Table.

years, the IEEE will define higher-rate Ethernet client interfaces that are likely to be 400GbE and/or 1 TbE. A 400GbE client could be mapped into a 400 Gb/s optical channel, but the actual data rate of the channel will be higher than 400 Gb/s since channel mapping overhead and forward error correction (FEC) must be included. The high-rate optical channel, however, can also be used to transport existing client data streams, such as 10 GbE, 40 GbE, and 100GbE. This multiplexing can be accomplished electronically by mapping the clients to containers that are then combined to form the channel. OTN switching and aggregation per the G.709 hierarchy is well suited to this task, but containers greater than 100Gb/s have not yet been standardized. It is also possible to map the clients directly to subcarriers.

Even though reconfigurable optical add/drop multiplexers **(ROADMs)** are an established technology for optical transport networks, introducing optical channels with rates higher than 100 Gb/s adds additional considerations due to the variable bandwidth requirements of these optical channels. The ROADM is divided into two sections: one for the express paths and the other to support channel add/drop. To support super-channels,

In the add/drop structure, channels originating or terminating at the node are switched from the network through the add/drop structure to the optical transceiver. Since each add/drop port can support one or more optical subcarriers, a super channel can use either a single port or span across several ports. To support super-channels with variable bandwidth a ROADM with a colorless, directionless, and contentionless (CDC) add/drop structure is preferred. A colorless and directionless add/drop structure allows any add/drop port to support a super-channel with configurable wavelength range that can then be switched to any degree of the ROADM. Adding the contentionless function simplifies operation since there are no restrictions on port assignments in the add/drop structure.

The optical subcarriers belonging to a super channel are required to travel on the same lightpath with the same endpoints. This allows the subcarriers to be spaced closely together since the typical WSS filter guard band required for single carriers that are individually be routed can be eliminated, thus enhancing spectral efficiency. Note that packing the optical subcarriers tightly to form a super-channel may

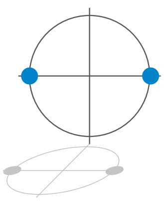
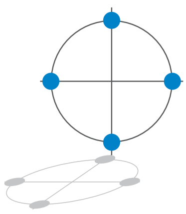
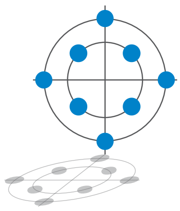
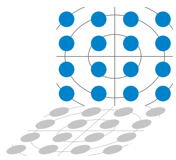
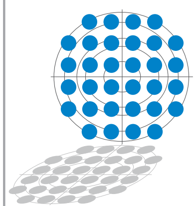
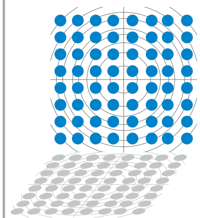
Modulation format	PM-BPSK	PM-QPSK	PM-8QAM	PM-16QAM	PM-32QAM	PM-64QAM
bits / Symbol	2x1	2x2	2x3	2x4	2x5	2x6
Constellation						
OSNR penalty (dB)	0	0	2	4	6	8.5

Figure 4: Comparison of modulation techniques for 100G and beyond

Networking Considerations for Supporting Channel Rates Beyond 100 Gb/s

One reason to develop optical channels with capacities beyond 100 Gb/s is to accommodate traffic flows from switches or routers. Over the next few

both the express path and the add/drop structure must support flexible bandwidth assignment. In the express path, channels from network directions that bypass the node are switched using a wavelength-selective switch (WSS) to the desired network direction.

not allow the center frequency of the subcarrier to be locked to the traditional ITU-T grid. In principle, the channel bandwidth should be selected to maximize spectral efficiency. However, in practice, there are restrictions such as the bandwidth granularity of the WSS, the frequency stability of the laser, the optical subcarrier spacing, and the WSS filter guard band requirements (determined by the worst case cascade of WSSs) that establish the actual bandwidth. At the receiver, coherent frequency selection can be used to minimize optical filtering requirements. We should note that the ITU has reached agreement on a center frequency granularity of 6.25 GHz and full slot widths as a multiple of 12.5 GHz. Furthermore, any combination of frequency slots is allowed as long as no two slots overlap. The frequency stability for both lasers and flexible grid WSS devices are within 1 GHz, but a channel with a 50 GHz minimum spacing that supports 25 GHz or 12.5 GHz bandwidth increments is practical today. In the near future a 37.5 GHz minimum bandwidth should be supportable, as WSSs with higher resolution become available. The ratio between carrier spacing and symbol rate can be varied to optimize spectral efficiency and channel reach requirements.

To improve fiber capacity, software configurable transceivers can optimize channel performance. The transmitter and receiver can select the channel modulation format to optimize the channel transmission rate and spectral efficiency. OSNR degradation is normally proportional to the transmission distance. Higher order modulation requires higher OSNR at the receiver to recover the signal, and is also more sensitive to nonlinear effects and crosstalk at ROADM locations. Therefore, in principle, longer transmission distances tend to use lower order modulation, while higher order modulation can be used for shorter transmission distances. The software configurable transceiver simplifies deployment by using the same hardware configuration to meet various reach and spectral efficiency requirements.

Emerging Technologies

New technologies are being developed to further improve the performance of high-rate optical channels. Digital signal processing with coherent detection has been used to compensate for linear impairments in fiber, such as chromatic dispersion and polarization mode dispersion, but signal processing can also be applied to improve nonlinear impairments. Fiber nonlinearity is a phenomenon that is dependent on local optical intensity and is therefore not easily compensated with traditional linear approaches.

To improve transmission performance for high-speed channels that use phase modulated signals, optical regeneration can be considered as an approach to replace power hungry and expensive optical-to-electrical-to-optical (OEO) regeneration. Practical all-optical regeneration has been a huge challenge; however, phase sensitive amplification (PSA) is a potential approach. Traditional optical amplifiers, such as Erbium doped fiber amplifiers (EDFAs), are phase insensitive. When a phase modulated signal enters the amplifier, both the in-phase component and the quadrature component will experience the same amount of amplification. In a phase sensitive amplifier, which is based on a parametric amplification process, the gain depends on the phase relationship between the signal and the pumps. The amplification can be tuned to favor signal phase rather than noise phase by adjusting the pumps. Therefore, a phase modulated signal can be regenerated by amplifying the signal and not the phase noise in a phase sensitive amplification process.

As channel rates have increased, optical component integration and power consumption have become significant concerns. Photonic integrated circuits (PICs) can provide improved optical component integration, reduced power consumption, and enhanced reliability, while reducing overall equipment cost. The current generation of equipment is primarily built using discrete optical components. The goal of a PIC is to integrate the functions provided by the individual components into a photonic circuit thus reducing the number of interconnections and power consumption. The challenge in implementing PIC technology, however, is that active and passive components are typically built using different materials. Silicon is the best material for passive waveguide related functions, such as couplers, splitters, and wavelength multiplexers, while III-V materials (e.g., gallium arsenide or indium phosphide) are best for active component related functions such as lasers, modulators, and receivers. The research and development for PIC technology has focused on the best approach to seamlessly integrate the passive and active functions into a single design.

Conclusion

Selecting the preferred set of channel parameters is a complex trade-off between symbol rate, spectral efficiency, optical reach, design complexity, and the availability of technology. Supporting bit rates beyond 100 Gb/s can be achieved by extending the technologies of today's PM-QPSK transceivers. Moving to higher symbol rates has traditionally been the approach to increase the bit rate, but limitations in electrical and optical components have made this increasingly difficult. Today's 100 Gb/s transceivers support symbol rates of 28–32 Gbaud, and the maximum symbol rate is only improving slowly. In the near term increasing the bits per symbol and/or using more optical carriers is the best approach to supporting rates beyond 100 Gb/s. More sophisticated transmitters that include digital signal processing and digital-to-analog converters will support higher order modulation and filtering of optical carriers to limit bandwidth.

The channel rate can be doubled by either implementing 16-QAM or using two optical subcarriers, but each approach has different trade-offs.

Moving to 16-QAM is more spectrally efficient and only requires a single transceiver, but there is a significant reach penalty. Creating a super channel with two optical carriers doubles the implementation cost and provides a smaller improvement in spectral efficiency, but with a minimal reduction in reach.

Over time, many additional techniques can be implemented to improve channel capacity, performance, and cost. Since these techniques are more speculative, their timeframes and benefits are still under review. Algorithms to compensate for nonlinear transmission impairments can be implemented using digital signal processing in the transceiver, although reducing the algorithm complexity to achieve a practical implementation is challenging. Photonic integrated circuits can be used to implement arrays of transmitters and receivers for super-channel applications and should significantly reduce size, power consumption, and cost. Optical regeneration can be implemented using a phase sensitive amplifier in place of traditional OEO regeneration, and fibers with multiple cores and modes can provide an alternative to using multiple fiber pairs.

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The necessary tools and techniques are available to implement rates beyond 100 Gb/s, and over time the implementations will be refined based on continued development of both current and more speculative approaches.