

## BEYOND 100G OPTICAL COMMUNICATIONS

# Technical Considerations for Supporting Data Rates Beyond 100 Gb/s

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## 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. Advanced modulation formats that adapt to optimize spectral efficiency over a range of channel signal-to-noise ratio conditions are required. Channels can be 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

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 [1]. 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 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. The IEEE has standardized the physical layer for 100GbE focusing on short reach parallel optics to reduce cost. As an example, the 100GBASE-LR4 standard uses four ~25 Gb/s wavelengths and supports a 10 km reach. The optical communications community has now started to search for the next milestone for client port speed, transport channel rate, and channel spectral efficiency. The speed of the next generation Ethernet physical layer is still being debated, with both 400 GbE and 1 TbE under consideration. If 400 GbE continues to use 25 Gb/s optics, 16 parallel lanes would be required. Higher rate parallel optics will need to be developed to efficiently support the next generation of Ethernet physical standards. In the short term, higher optical transport rates may be used without the need for a new client rate by utilizing multiple 100 GbE clients.

As new services, particularly video and cloud computing, demand huge bandwidths, overall network capacity and, in particular, capacity per fiber are increasingly important, especially in long-haul applications where fiber is at a premium. These services are supported by improvements in data processing and storage technologies that are scaling by an order of magnitude every four to six years, and it is expected that transport network requirements will need to scale similarly. Based on 100 Gb/s channels, currently deployed transmission systems provide fiber capacity between 6 and 10 Tb/s depending on fiber and line system limitations. Bandwidth demands are continuing to grow, and Fig. 2 shows two possible traffic models for a typical large central office in a national core network. Trend lines based on both conservative and aggressive growth show a possible range in traffic between 70 and 150 Tb/s by 2020. Today, this office has four fiber degrees, each capable of supporting 8–10 Tb/s, but this capacity is predicted to be exhausted in the 2015–2016 timeframe.

With currently estimated growth rates in the range of 40–60 percent a year [2, 3], traffic would increase by a factor of ~30 in 10 years based on a 40 percent growth rate and more than a factor of 100 with a 60 percent growth

rate. In the last decade commercial systems increased their line rate and system capacity by roughly a factor of 10; obtaining a similar improvement in this decade implies a line rate of 1 Tb/s and a system capacity of 100 Tb/s. Even if these challenging objectives are achieved, other breakthroughs such as spatial multiplexing in fibers will be required for system capacity to keep up with traffic growth.

The industry has converged on PM-QPSK as the preferred format for 100 Gb/s applications. When we consider channel rates beyond 100 Gb/s, several techniques are available to enhance channel performance. For example, the symbol rate can be increased, as shown in Fig. 3a. A higher symbol rate allows more symbols to be packed into the same time period, but this increases the required channel bandwidth and optical signal-to-noise ratio (OSNR) since the latter is proportional to the bit rate. Current 100 Gb/s implementations use a 28–32 Gbaud sym-

bol rate. The number of bits per symbol can also be increased. This allows the bit rate to be increased without increasing the symbol rate and the required channel bandwidth, thus increasing the spectral efficiency of the transport. The increase in constellation size also requires an increase in OSNR since the SNR per bit of the modulated signal increases. For example, Fig. 3b shows a four-point constellation, which represents two data bits per symbol and is used for QPSK modulation. Spectral efficiency can be doubled by using a square 16-point quadrature amplitude modulation (16-QAM) constellation where each symbol represents four data bits, requiring an increase in SNR per bit of 3.8 dB and an increase in the OSNR of 6.8 dB for the same baud rate (i.e., a doubling of the bit rate). A further doubling of spectral efficiency by using 256-QAM would require much larger additional increases of 8.8 and 11.8 dB, respectively. As the transmitter designs evolve, DSPs and digital-to-analog converters (DACs) are being added so that different constellations can easily be generated. Many optical carriers can be packed closely together to form a super-channel, as shown in Fig. 3c. The challenge for super-channel implementations is to tightly pack the optical subcarriers while minimizing the interactions between the carriers. With these techniques, capacity and spectral efficiency of a channel can be customized for the application. The ideal implementation would be a software-defined transceiver that would allow modulation parameters to be configured based on an application so that, for example, greater spectral efficiency could be achieved for a transmission link with better OSNR.

This article focuses on technical considerations for optical transport with channel rates beyond 100 Gb/s. Potential implementations for client interfaces beyond 100 GbE are not discussed. Advanced modulation formats that enhance spectral efficiency while maintaining low symbol rates are reviewed. 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 BEYOND 100 GB/S

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. Constella-

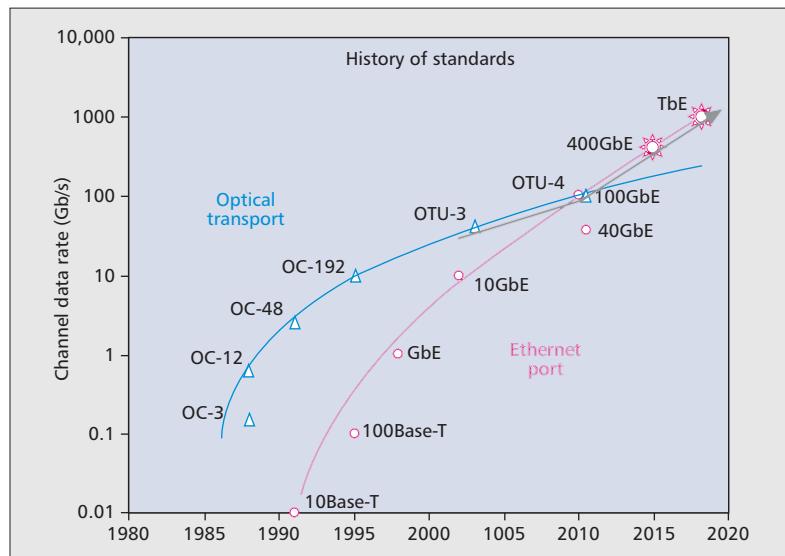


Figure 1. Data port speed and transport channel capacity evolution and predictions.

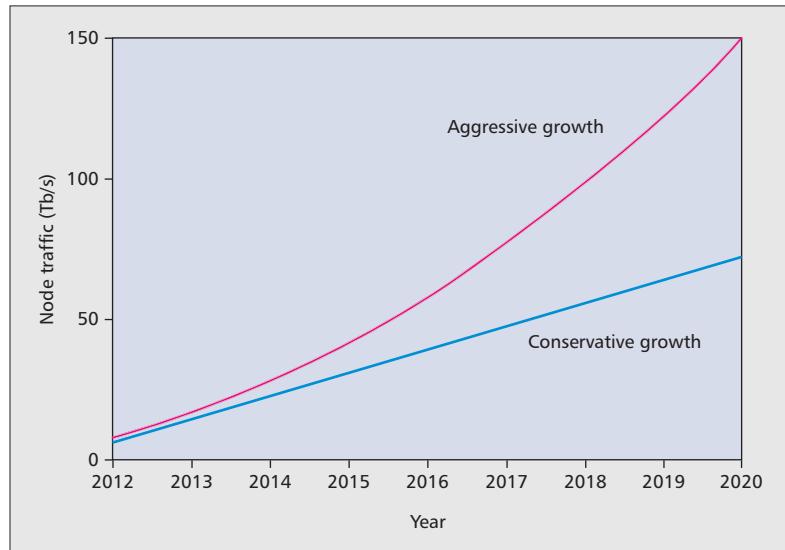


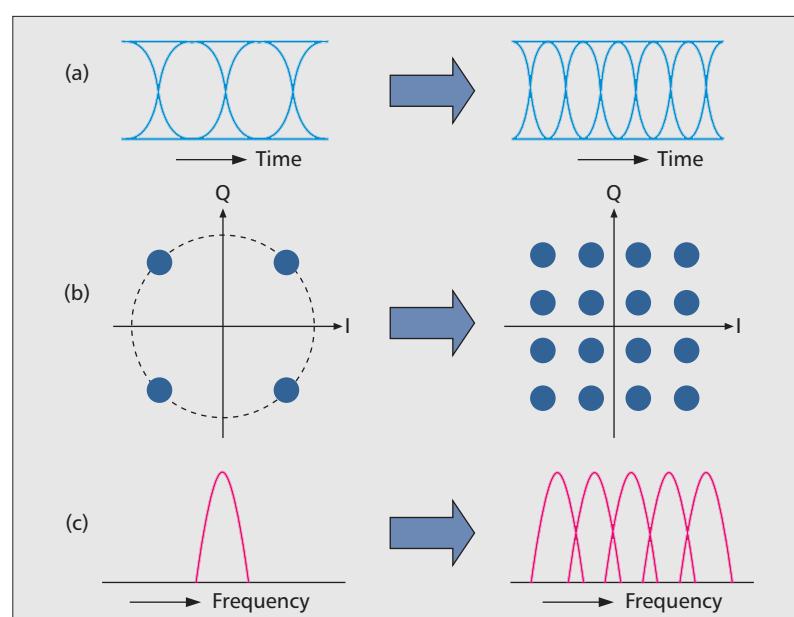
Figure 2. Traffic growth trends in a typical large office.

tion charts that show symbol configurations in the complex plane for several modulation approaches are shown in Fig. 4. The OOK format is shown in Fig. 4a. For OOK, the data rate and symbol rate (or baud rate) are the same since one optical symbol represents only one bit. For more complex modulation techniques, the symbol rate is not necessarily equal to the data rate since a symbol may represent multiple data bits. Historically, as traffic demands increased, the symbol rate was simply increased by modulating the laser faster. Eventually, the symbol rate is limited by the practical bandwidth (currently in the range of 30–40 GHz) of the modulator, but, more important, optical reach will be limited as the bit rate increases by the OSNR and nonlinear impairment of the transmission system. Transmission performance can be improved by using phase modulation techniques such as binary phase shift keying (BPSK), as shown in Fig. 4b. This technique will reduce the OSNR requirement, but not the channel bandwidth requirements. Increasing the number of bits per symbol can improve spectral efficiency and therefore has been used in wireless communication where bandwidth is at a premium. For example, as shown in Fig. 4c, a QPSK symbol represents two bits of information, since the symbol can take four different positions in the complex plane. For the same symbol rate, the bit rate could be doubled compared to QPSK by using a 16-QAM constellation where a symbol represents four bits, as shown in Fig. 4d. The square 16-QAM constellation shown is relatively easy to implement, provides excellent OSNR performance, and is often used; but other 16-ary constellations provide significantly more phase noise tolerance [4] and therefore might achieve longer transmission distances.

Polarization of light is another characteristic that can be used to increase the data rate. Initial optical channel designs used only one polarization, but the two orthogonal polarizations of a light beam can carry information independently. By using both polarizations, a channel's capacity can be doubled without increasing its symbol rate or required spectral bandwidth. Note that this doubles the required optical power. The process to combine two signal streams with orthogonal polarizations is called polarization multiplexing (PM), and the combined optical signal is said to have dual polarizations. The PM-QPSK 100 Gb/s implementation is generally suitable for long-haul applications with a reach of up to several thousand kilometers depending on the fiber and optical amplification characteristics. The approach uses 50 GHz channel spacing to provide a spectral efficiency of 2.0 b/s/Hz (100 Gb/s divided by 50 GHz).

## SUPER CHANNELS

To further increase channel rates beyond 100 Gb/s, the number of bits represented by each symbol and/or the symbol rate can be increased, but the introduction of additional parameters into the channel design is also beneficial. For example, more than one optical carrier can be used for a channel. A channel that uses more than one optical carrier is usually called a super-



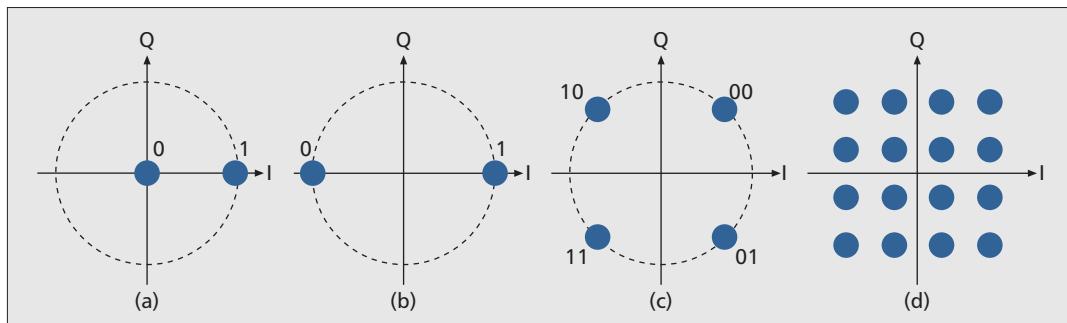
**Figure 3.** Exemplary techniques to construct a channel with a data rate beyond 100 Gb/s: a) increase symbol rate; b) increase bits per symbol; c) use more optical carriers.

channel [5]. All subcarriers in a super-channel are routed as a group, allowing the subcarriers to be spaced closer together than individual carriers that are routed separately.

Besides the symbol rate, the number of bits per symbol, the number of polarizations, and the number of optical carriers, several other parameters can be considered in channel designs. Using the concept of orthogonal frequency division multiplexing (OFDM), which was originally developed for multichannel data transmission [6, 7] and is widely used in wireless communication, coherent optical OFDM (CO-OFDM) has been introduced into optical channel design. Each CO-OFDM channel can be constructed with several optical subcarriers as long as the frequency spacing between any two subcarriers is a multiple of the symbol rate and the symbol transitions are temporally aligned. With this technique no attempt is being made to limit the bandwidth of each subcarrier and there is considerable spectral overlap as shown in Fig. 7b [8]. It is also possible to generate the orthogonal subcarriers in the electrical domain and use DAC and in-phase/quadrature (I/Q) modulators to generate the optical subcarrier [9]. Note that the bandwidth of the DAC and modulator determines the data rate of the optical subcarrier. For example, a 40 Gb/s CO-OFDM channel can be constructed with 50 electrical subcarriers, each of which is a 16-QAM signal with a symbol rate of 100 Mbaud. The carriers are then combined with a discrete Fourier transform to form a drive signal with about 5 GHz bandwidth. The combined signal is converted to analog using a DAC, and the resulting signal is used to drive a modulator. Polarization multiplexing is then applied to the modulated optical signal. The signal is normally coherently detected at the receiver.

Optical time-division multiplexing (OTDM) is one of the classical approaches used to increase

Using MCF and FMF provides the opportunity to increase the capacity for a strand of fiber by spatially multiplexing an optical channel over multiple propagation modes and/or multiple fiber cores. For example, an optical channel of 240 Gb/s has been constructed with six propagation modes supported by a three-core fiber.



**Figure 4.** Constellation charts for: a) OOK; b) BPSK; c), QPSK; d) 16-QAM.

the channel data rate. With OTDM, 100 Gb/s transmission and reception were realized in the 1990s, when electronic processing was not able to generate and detect 100 Gb/s signals directly. With the availability of high-speed electro-optical devices and digital signal processing chipsets, the applications of OTDM have been limited, although the technology is still under investigation. In a recent experiment, a 10.2 Tb/s channel was constructed using OTDM technology, in which a 10 Gb/s return-to-zero (RZ) signal with a 16-QAM modulation format was folded 128 times using TDM and then polarization multiplexed to form the 10.2 Tb/s channel [10].

Space-division multiplexing (SDM) is a new technology that uses multicore fiber (MCF) or few-mode fiber (FMF) to increase fiber capacity. Using MCF and FMF provides the opportunity to increase the overall capacity for a strand of fiber by spatially multiplexing an optical channel over multiple propagation modes and/or multiple fiber cores. For example, an optical channel of 240 Gb/s has been constructed with six propagation modes supported by a three-core fiber. Each mode carries a 20 Gbaud PM-QPSK optical signal, and the channel has traveled over 1200 km successfully [11]. Another experiment demonstrated transmission of a WDM signal, consisting of 10 128 Gb/s PDM QPSK signals, over each of the cores of a 7-core fiber over a 2688 km distance [12].

## TERABIT CHANNEL DESIGNS

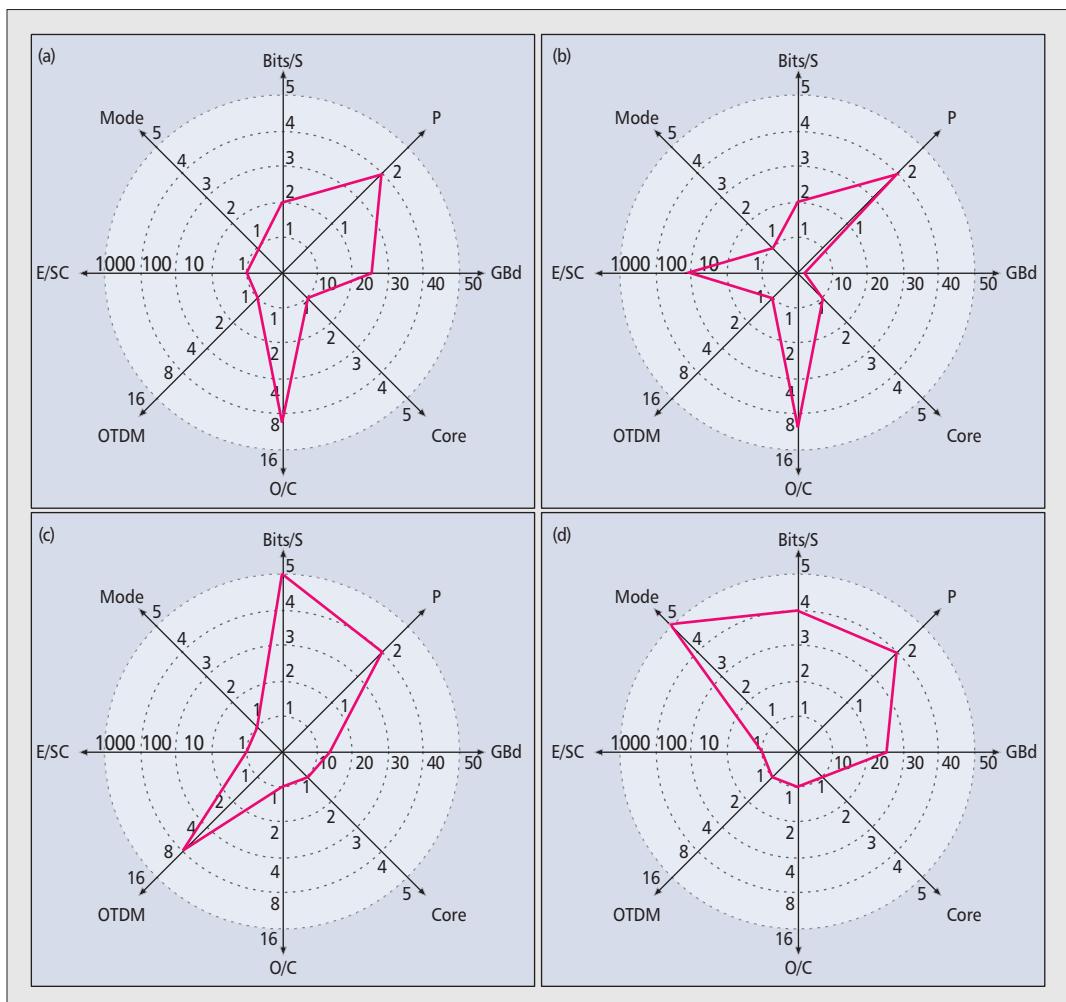
Figure 5 shows four hypothetical designs for 1 Tb/s channels, where the overhead is omitted for simplicity. Figure 5a shows a PM-QPSK super-channel that has a 25 Gbaud symbol rate and contains 10 optical carriers. Figure 5b shows a CO-OFDM super-channel that contains 10 optical subcarriers. Each optical carrier is constructed with 100 electrical QPSK subcarriers where each electrical subcarrier has a symbol rate of 250 Mbaud. Polarization multiplexing is also used for the optical carriers. Figure 5c shows an OTDM channel containing eight signal streams with the same wavelength that are optically multiplexed in time, where each stream uses a PM-32-QAM signal with a 12.5 Gbaud symbol rate. Figure 5d shows an SDM channel spread over five propagation modes where each mode carries a PM-16-QAM signal with a 25 Gbaud symbol rate.

The design evolution for a coherent transceiv-

er (transmitter/receiver) is shown in Fig. 6. The design evolves from a generic transceiver design with digital signal processing only in the receiver, to a design that includes digital signal processing in both the transmitter and receiver, and finally to a multiple-carrier design. The transmitter shown in Fig. 6a provides mapping and framing functionality, and then the precoded data is used to drive the modulators. The two independently modulated optical signals are then polarization multiplexed. In the receiver, a local oscillator is used to extract the amplitude and phase information for each polarization that is then sent via 90° hybrids to separate photo detectors. The received signals are then converted into digital and the DSP is used to recover the information in the data. Finally, the information is deframed and demapped before it is sent to the client. To enhance the transmitter design, a DSP and a DAC can be functionally included as shown in Fig. 6b. Replacing the fixed modulator structure with a DAC provides flexibility to implement many modulation schemes, including more complex approaches such as QAM. The signal processing can be used to filter the modulated signal to limit the bandwidth of the optical carrier so that the channel spacing can be reduced for super-channel applications. Figure 6c shows an arrangement of multiple single-carrier transceivers to implement a super-channel. Although this arrangement can be built from discrete transceivers, both optical and electrical integration will be required to reduce cost and complexity.

## BAND-LIMITING OPTICAL CARRIERS

A super-channel, by definition, contains multiple optical (sub)carriers, but different approaches can be used to form and arrange the carriers. Figure 7 shows the characteristics of a WDM super-channel, an all-optical OFDM super-channel, a Nyquist WDM super-channel, and an OFDM super-channel in the frequency domain. All of the super-channels are shown with four optical sub-carriers. A WDM super-channel is built using multiple single-carrier channels with minimal shaping of the optical spectrum, as shown in Fig. 7a. For example, a 400 Gb/s super-channel can be created by reducing the spectral gaps between four 100 Gb/s PM-QPSK channels. In this configuration the signal filtering is the result of inherent bandwidth limitations of the transmitter and some optical filtering to achieve



**Figure 5.** Several 1 Tb/s optical channel examples: a) PM-QPSK super-channel; b) PM-QPSK OFDM super-channel; c) PM-32QAM OTDM channel; d) PM-16QAM SDM channel.

the desired subcarrier spacing without too much crosstalk between the subcarriers. In current single-carrier systems such filtering is provided by the WSS. Unless specific filter shapes are used, the filtering may result in intersymbol interference (ISI) and an increase in the OSNR requirements [13]. Nyquist filtering results in a pulse shape (in the time domain) so that there is no ISI between successive pulses. The ideal Nyquist filter would have a rectangular spectrum with a bandwidth equal to the symbol rate. In the time domain this will result in a sync function whose amplitude decays slowly. Since successive symbols overlap in the time domain, imperfect sampling will result in significant ISI. A more practical filter has a raised cosine spectrum, which requires some additional bandwidth, usually expressed as a percentage of the symbol rate and referred to as the *roll-off factor*. For example, a filter with an often used roll-off factor of 0.1 would result in 10 percent more bandwidth. Note that a raised cosine filter with a roll-off factor of zero would result in the sync pulse. The pulse shape generated by a raised cosine filter with a roll-off factor greater than zero also decays much faster and is therefore less sensitive to sampling errors [14]. Figure 7c shows the spectrum of a Nyquist super-channel. Another

interesting option is to use a square root raised cosine filter at both the transmitter and receiver, which avoids ISI and optimizes SNR (for additive white Gaussian noise) since the receiver filter acts like a matched filter for the transmitted signal. A special case of the WDM super-channel is the all-optical OFDM channel in Fig. 7b, discussed earlier. Note that the ideal single-carrier OFDM spectrum has a sync-pulse-like shape that results in a square pulse in the time domain and therefore no ISI, while the orthogonal condition prevents crosstalk between subcarriers even with substantial spectral overlap. Figure 7d shows the spectrum of an OFDM super-channel that is very similar in shape to a Nyquist super-channel. The OFDM super-channel consists of multiple optical subcarriers, each of which is generated by a group of electrical subcarriers, which are orthogonal. Since each optical subcarrier is composed of many lower baud rate electrical carriers, there is little spectral overlap; therefore, interchannel interference (ICI) between the optical subcarriers when the orthogonality between the optical subcarriers is not maintained. The scheme, when combined with chromatic dispersion compensation in the receiver, has a number of advantages over conventional CO-OFDM that are discussed in [9].

Over the next few years, the IEEE will define higher rate Ethernet client interfaces that will likely be 400 GbE and/or 1 TbE. A 400 GbE 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 FEC must be included.

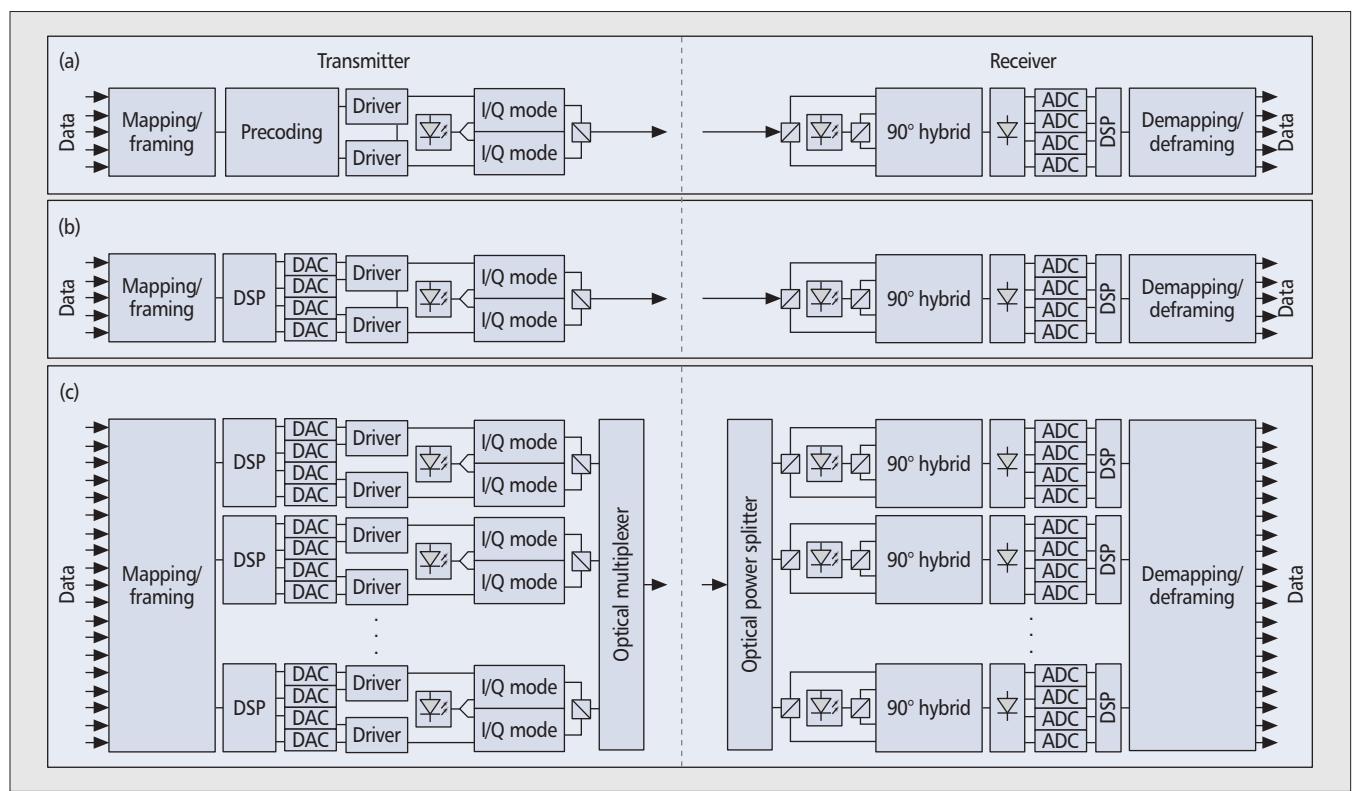


Figure 6. Evolution of coherent transceiver designs.

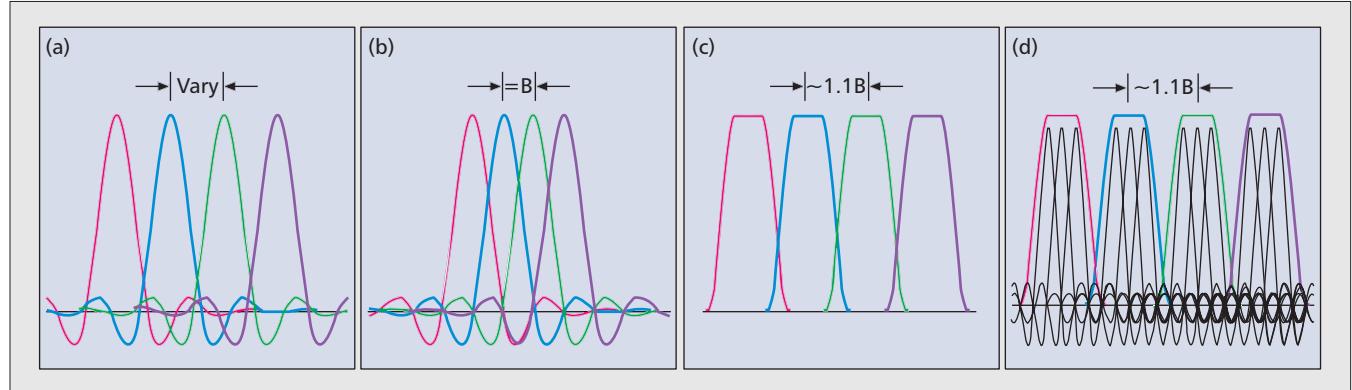


Figure 7. Spectral characteristics for: a) a WDM super-channel; b) an all-optical OFDM super-channel; c) a Nyquist WDM super-channel; d) an OFDM super-channel.

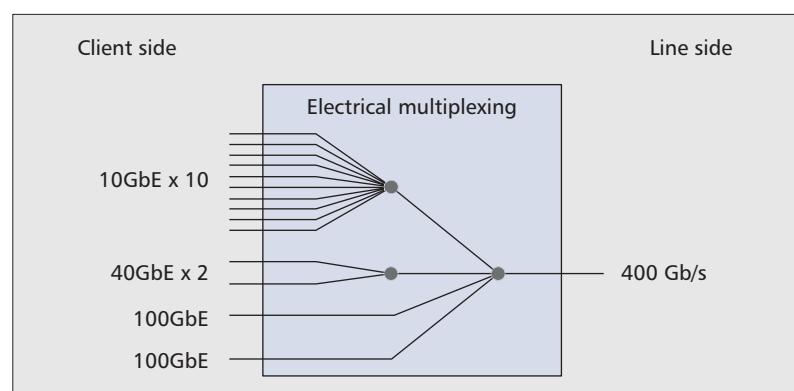
## NETWORKING CONSIDERATIONS FOR SUPPORTING CHANNEL RATES BEYOND 100 GB/S

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 years, the IEEE will define higher-rate Ethernet client interfaces that are likely to be 400 GbE and/or 1 TbE. A 400 GbE 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. Many

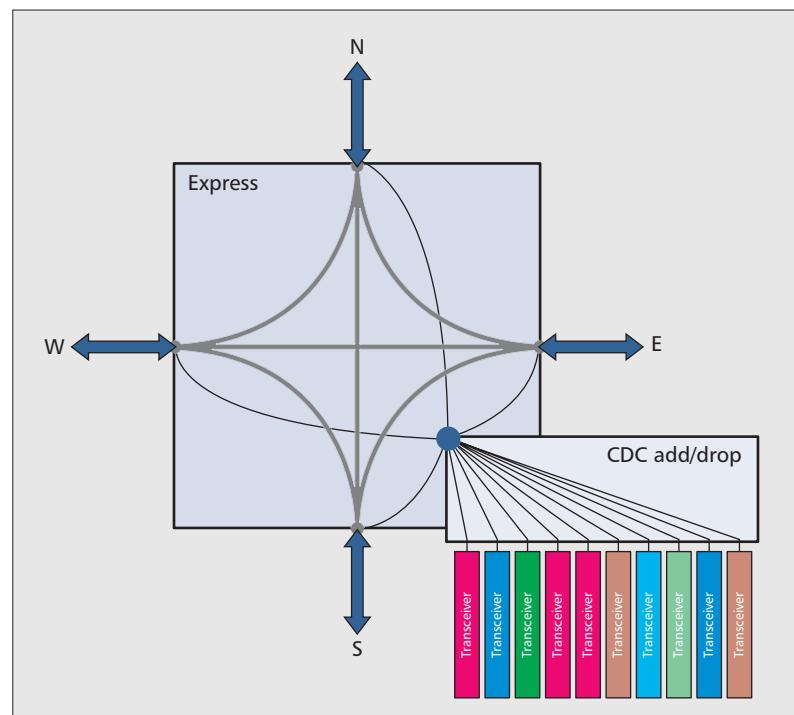
low-rate clients can be multiplexed to fill a 400 Gb/s or 1 Tb/s channel, as shown in Fig. 8. This multiplexing can be accomplished electronically by mapping the clients to containers that are then combined to form the channel. OTN switching and aggregation per the G.709 hierarchy is well suited to this task, but containers greater than 100 Gb/s have not yet been standardized. It is also possible to map the clients directly to subcarriers. For example, a 400 Gb/s super-channel that uses four 100 Gb/s PM-QPSK subcarriers could support direct mapping of a 100 GbE client to each subcarrier. Channel management can be simplified since for the same amount of client traffic, larger channel capacity results in fewer channels. Of course, the use of super-channels and the associated flexible grid spacing also require additional network management functions.

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 schematic shown in Fig. 9 is divided into two sections: one for the express paths and the other to support channel add/drop. To support super-channels, both the express path and the add/drop structure must support flexible bandwidth assignment. In the express path, channels from network directions (labeled as N, S, E, and W) that bypass the node are switched using a wavelength-selective switch (WSS) to the desired network direction. 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 [15]. 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 light-path 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 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 [16]. For Nyquist dense WDM (DWDM) implementations



**Figure 8.** Multiplexing low-speed clients to fill a 400 Gb/s super-channel.



**Figure 9.** Four-degree ROADM with CDC functionality [15].

with a roll-off factor of 0.1, a ratio of 1.1 is generally used, but the carrier spacing can be reduced for applications where additional crosstalk penalties can be tolerated [17]. For systems with coherent detection, the coherent receiver can be used to discriminate channels or subcarriers, but filtering between channels in the ROADM is performed using the WSS. Since the filtering in the current WSS is far from ideal (typically between 3rd and 5th order Gaussian) for 50 GHz channel spacing, only 25–35 GHz of bandwidth can be guaranteed for a worst case cascade of WSSs. For a carrier-spacing-to-symbol-rate ratio of 1:1, a super-channel with four PM-QPSK subcarriers, each with a 28 Gbaud symbol rate will require a bandwidth of 123.2 GHz. This can be supported with a 137.5 or 150 GHz channel spacing based on typical flexgrid WSS filter guard band requirements depending on the number of filtering nodes.

To improve fiber capacity, software configurable transceivers can optimize channel perfor-

mance. 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. For example, to support a transmission distance of 2,000 km, the channel may have to use PM-QPSK for each optical carrier. However, for a node that is only 500 km away, a channel may use the PM-16-QAM modulation format to double the spectral efficiency compared to the previous case, as shown in Fig.10. The software configurable transceiver simplifies deployment by using the same hardware configuration to meet various reach and spectral efficiency requirements.

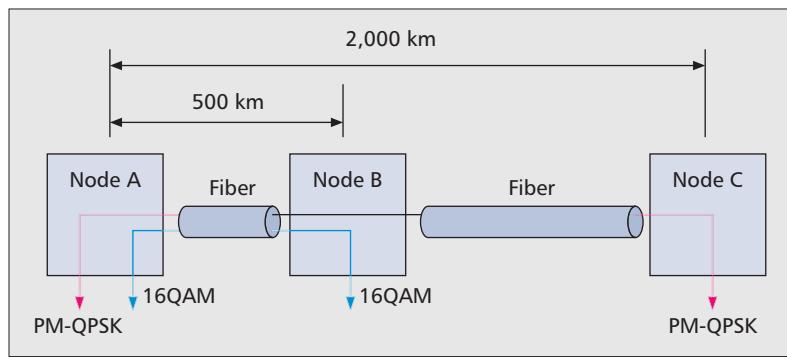
## EMERGING TECHNOLOGIES

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 ameliorate nonlinear impairments. For linear effects, DSP is now able to compensate for more than 50,000 ps/nm of chromatic dispersion and more than 100 ps of differential group delay (DGD). Fiber nonlinearity is a phenomenon that is dependent on local optical intensity and is therefore not easily compensated with traditional linear approaches.

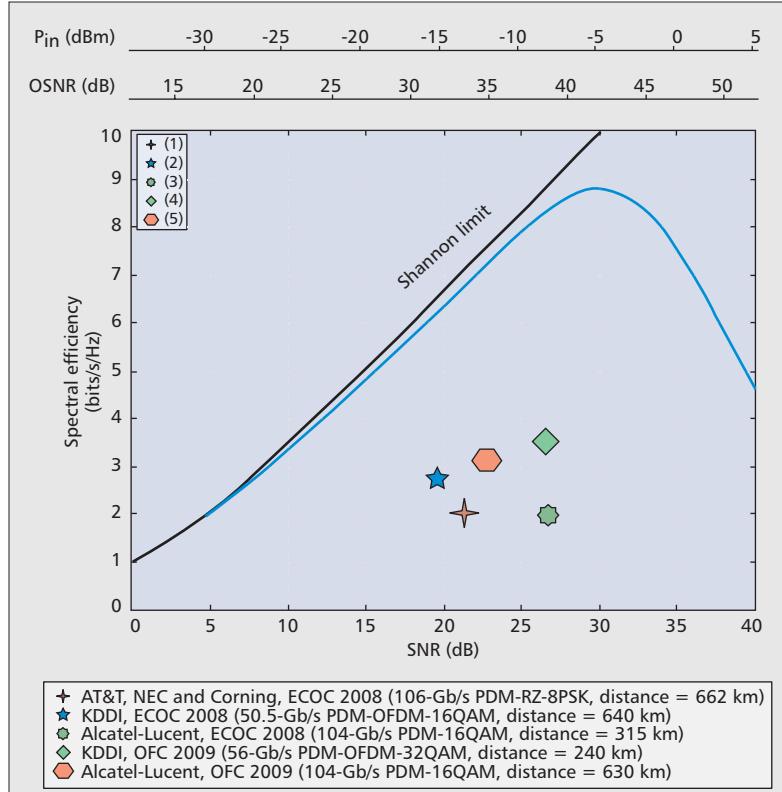
When linear fiber impairments are compensated, optical channel performance becomes limited by the OSNR and nonlinear effects. Figure 11 shows an example of the spectral efficiency vs. required OSNR [18]. The black line represents the spectral efficiency limit without considering fiber nonlinearity according to Shannon's information theory. The blue line is the result when fiber nonlinearities are considered. In recent years sophisticated nonlinear compensation schemes such as back-propagation have been introduced [19]. Note that even with nonlinear compensation, nonlinear effects eventually limit the spectral efficiency no matter how much the OSNR is improved.

Trellis coded modulation [20–23] is a technique that improves channel performance by combining and optimizing the coding and modulation steps that are traditionally separate. It is based on combining a binary convolutional code with an expanded signal constellation. The encoder can then select the appropriate subset in the constellation to maximize the distance between successive symbols. For example, the combination of 8-PSK modulation with a 2/3 convolutional code gives the same spectral efficiency as uncoded QPSK but with improved OSNR requirements. In optical communication the trellis code is usually used as an inner code and combined with an outer code. In this way, net coding gain (NCG), which is an indicator of the FEC performance, can be significantly improved without adding extra coding overhead [24].

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



**Figure 10.** Optimizing modulation format based on light path length.



**Figure 11.** Spectral efficiency vs. SNR. The capacity limit estimation curve is for 500 km of transmission; the upper axes apply only to the capacity estimation curve [18], reproduced with permission.

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. Recently using four-wave mixing in highly nonlinear fiber, phase signal regeneration has been demonstrated successfully [25]. Low-noise phase sensitive amplifiers have been demonstrated to operate with a noise figure of 1 dB and to achieve a 6 dB noise link improvement over EDFA [26, 27].

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. This integration has been accomplished by building both active and passive components using III-V materials or designing hybrid PICs where both material types are present.

## 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. Both Nyquist WDM filtering and orthogonal carriers created using OFDM can effectively minimize interference between carriers with little difference in spectral efficiency. Nyquist WDM super-channels are simpler and cheaper to implement and will be used initially, but if implementation complexities can be overcome, OFDM might have advantages, especially for larger numbers of subcarriers.

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. 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.

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.

## REFERENCES

- [1] E. Basch and T. Brown, "Introduction to Coherent Fiber-Optic Communication," Ch. 16, *Optical Fiber Transmission*, E. E. B. Basch, Ed., MacMillan, 1986.
- [2] Univ. of Minnesota, "Minnesota Internet Traffic Studies (MINTS)," <http://www.dtc.umn.edu/mints/home.php>.
- [3] B. Swanson and G. Gilder, "Estimating the Exaflood the Impact of Video and Rich Media on the Internet — A Zettabyte by 2015?," *Discovery Inst.*, Jan. 29, 2008.
- [4] T. Pfau, X. Liu, and S. Chandrasekhar, "Optimization of 16-ary Quadrature Amplitude Modulation Constellations for Phase Noise Impaired Channels," *ECOC '11 Tech. Dig.*, Tu.3.A.6.
- [5] R. Antosik, "Super-channel Architectures for In-service Capacity Expansion of CWDM/DWDM Systems," *ICTON '03*, We.C.8.
- [6] R. W. Chang, "Synthesis of Band-Limited Orthogonal Signals for Multichannel Data Transmission," *Bell Sys. Tech. J.*, vol. 45, 1966, pp. 1775–96.
- [7] S. B. Weinstein and P. M. Ebert, "Data Transmission by Frequency-Division Multiplexing," *IEEE Trans. Commun.*, COM-19, Oct. 1971, pp. 628–34.
- [8] T. J. Xia et al., "Field Experiment with Mixed Line-Rate Transmission (112-Gb/s, 450-Gb/s, and 1.15-Tb/s) over 3,560 km of Installed Fiber Using Filterless Coherent Receiver and EDFA Only," *OFC/NFOEC '11*, PDPA3.
- [9] X. Liu et al., "448-Gb/s Reduced\_Guard-Interval C-OFDM Transmission over 2000 km of Ultra-Large-Area Fiber and Five 80-GHz ROADMs," *IEEE/OSA J. Lightwave Tech.*, vol. 29, no. 4, Feb. 15, 2011, pp. 483–90.
- [10] T. Richter et al., "Single Wavelength Channel 10.2 Tb/s TDM-Data Capacity Using 16-QAM and Coherent Detection," *OFC/NFOEC '11*, PDPA9.
- [11] R. Ryf et al., "Coherent 1200-km 6 × 6 MIMO Mode-Multiplexed Transmission over 3-Core Microstructured Fiber," *ECOC '11*, Th.13.C.1.

- [12] S. Chandrasekhar et al., "WDM/SDM Transmission of 10 × 128-Gb/s PDM-QPSK over 2688-km 7-Core Fiber with A Per-Fiber Net aggregate Spectral-Efficiency Distance Product of 40,320 km.b/s/Hz," ECOC '11 Post-deadline Paper Th13.C4.
- [13] J. J. Jones, "Filter Distortion and Intersymbol Interference Effects on PSK Signals," *IEEE Trans. Commun.*, COM19, Apr. 1971, pp. 120–32.
- [14] J. G. Proakis, *Digital Communications*, 4th ed., McGraw-Hill, 2001.
- [15] S. Gringeri et al., "Flexible Architectures for Optical Transport Nodes and Networks," *IEEE Commun. Mag.*, vol. 48, no. 7, July 2010, p. 40.
- [16] T. Zami et al., "Higher Capacity with Smaller Global Energy Consumption in Core Optical Networks Due to Elastic Channel Spacing," *ECOC '10*, Mo.1.D.3.R-J.
- [17] G. Bosco et al., "Investigation on the Robustness of a Nyquist-WDM Terabit Superchannel on Transmitter and Receiver Non-Idealities," *ECOC '10*, paper Tu.3.A.4.
- [18] Essiambre et al., "Capacity Limits of Optical Fiber Networks," *IEEE/OSA J. Lightwave Tech.*, vol. 28, no. 4, Feb. 15, 2010, pp. 662–701.
- [19] X. Li et al., "Electronic Post-Compensation of WDM Transmission Impairments Using Coherent Detection and Digital Signal Processing," *Optics Express*, vol. 16, no. 2, 2008, p. 880.
- [20] G. Ungerboeck, "Channel Coding with Multilevel/Phase Signals," *IEEE Trans. Info. Theory*, vol. IT-28, no. 1, Jan. 1982, pp. 55–67.
- [21] S. Benedetto et al., "Trellis Coded Polarization Shift Keying Modulation for Digital Optical Communication," *IEEE Trans. Commun.*, vol. 43, no. 2–4, Feb./Mar./Apr. 1995, pp. 1591–1602.
- [22] R. H. Deng and D. J. Costello, "High Rate Concatenated Coding Systems Using Bandwidth Efficient Trellis Inner Codes," *IEEE Trans. Commun.*, vol. 37, no. 5, May 1989, pp. 420–27.
- [23] A. J. Viterbi et al., "A Pragmatic Approach to Trellis-Coded Modulation," *IEEE Commun. Mag.*, vol. 12, no. 7, July 1989, pp. 11–19.
- [24] M. Magarini et al., "Concatenated Coded Modulation for Optical Communications Systems," *PTL*, vol. 22, no. 16, 2010, p. 1244.
- [25] J. Kakande et al., "Phase Sensitive Amplifiers for Regeneration of Phase Encoded Optical Signal Formats," ICTON 2011, Tu.A1.6.
- [26] Z. Tong et al., "Towards Ultrasensitive Optical Links Enabled by Low-Noise Phase Sensitive Amplifiers," *Nature Photonics*, published online, 5 June 2011.
- [27] P. Andrekson, "Phase Sensitive Fiber Optic Parametric Amplifiers," *ECOC '11*.

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