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TUTORIAL PAPER

Changing phases of fiber optic communication

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Abstract Optical communication systems have evolved over the years from simple intensity modulation and direct detection systems to those involving modulation of amplitude, phase, polarization and transverse modal profile. This article provides a brief tutorial review of the different modulation schemes used in the state-of-the-art optical communication systems and the futuristic trends in this direction to improve the data rates and spectral efficiency. The additional challenges with the advanced modulation schemes are discussed and some experimental results related to the demonstration of high-speed communication with such advanced modulation schemes are presented.

Keywords Optical communication · Coherent communication · Laser phase noise · Optical frequency comb · Nyquist pulse shaping · Mode-division multiplexing · Orthogonal frequency-division multiplexing

Introduction

It is well reported that the first demonstration of "optical" communication system was carried out as early as 1880 by Alexander Graham Bell where he transmitted a wireless voice message over hundreds of meters with sunlight as the carrier of information [1]. The device used for this purpose was patented as photophone, which according to Bell's own admission was his greatest invention ever. Optical fibers were initially popular as light guides for illuminating body cavities by medical practitioners to help them in diagnosis – in fact the word "fiber optics" was first coined by Narinder Singh Kapany – an Indian-born American physicist who had used a bundle of fibers for better transmission of images [2]. Optical communication systems found a revival as late as 1960s with optical fiber as the channel and this was triggered by the invention of semiconductor laser sources operating in room temperature [3]. In 1966, Kao and Hockham predicted through theoretical and experimental studies that, a circular waveguide made with glassy material – comprising of a core and a cladding – provides much larger information carrying capacity than the then prevalent coaxial cables for radio systems, provided the attenuation in the optical waveguide is less than 20 dB/km [4]. The first major breakthrough in optical fiber communications happened in 1970 when Corning Glass Works successfully developed glass fibers with an attenuation of 20 dB/km [5]. A few years later, NTT-Japan developed single mode fibers with losses as low as 0.2 dB/km at 1.5 μm, which is close to the fundamental theoretical limit set by Rayleigh scattering for loss in bulk silica [6]. C-band (carrier wavelength: 1530–1550 nm) was soon identified as the low loss wavelength window for long distance communication, while short distance links continued to be operated with the 800 nm or 1310 nm wavelengths. Since then, the technologies used in optical communication – both in devices and in systems—have been continually and rapidly progressing.

A significant breakthrough was made when multiple carrier wavelengths were transported in the same optical fiber, with each wavelength modulated independently. The scheme is analogous to frequency-division multiplexing in wireless systems, and it came to be popularly known as

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wavelength-division multiplexing (WDM) in optical communication systems. Long-haul WDM links were enabled with the invention of erbium doped fiber amplifier (EDFA), which allows the compensation of loss experienced by an optically modulated signal, without converting to electrical signals. The key technology breakthrough with EDFA was that, it could optically amplify a band of wavelengths simultaneously. The range of wavelengths used in C-band (1530–1560 nm, about 8 THz of bandwidth) in fact corresponds to the range for which EDFA can be designed to provide uniform gain. There were at least three different groups (NTT, Fujitsu and AT&T Bell Labs), who reported the ability to operate at data rates of > 1 Terabits per second with WDM systems by 1996 [8, 9]. The details of evolution of lasers, fibers and receivers that enabled intensity modulation and direct detection schemes have been reviewed comprehensively in many classic textbooks on optical communication systems and review articles by stalwarts in this field [10–16].

What is the best achievable data rate?

The rapid increase in data rates and transmission over very large distances were made possible with advances in several active and passive optical components. Such an expeditious growth naturally leads to the following questions: (a) what is the largest data rate that can ever be transported through an optical fiber and (b) up to what lengths can these data rates be transported to? These fundamental limits are dictated by the very popular Shannon–Hartley theorem which states that the channel capacity (C) in bits/second (the maximum information rate that can be transported) through a linear additive white Gaussian channel is theoretically bounded by $B\log_2\left(1+\frac{S}{N}\right)$ where B represents the bandwidth of the channel, S and N represent the signal and noise powers respectively, so that S/N represents the signal to noise ratio (SNR) of the channel (in linear scale). Thus, the spectral efficiency of any given communication system—defined as the ratio of the data rate to the bandwidth -is bounded by the signal to noise ratio available at the receiver.

This limit on spectral efficiency is schematically represented in Fig. 1, which shows the best achievable spectral efficiency as a function of SNR. The shaded part in the figure is the region where error-free transmission is guaranteed by Shannon's theorem. Note that the ultimate capacity limit indicated as the bold line is achievable only with coding and error correction algorithms. As the length of the fiber link increases, the signal power degrades because of the attenuation in the fiber. Optical amplifiers introduced in the link compensate for this loss, but also add

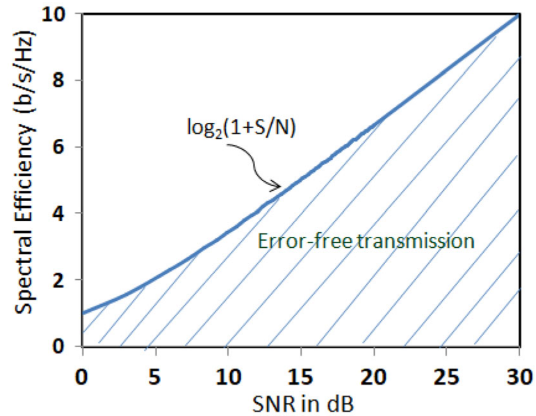


Fig. 1 Representation of capacity limits in communication with linear channel, calculated from the Shannon–Hartley theorem. The shaded region represents the achievable error-free transmission for the range of SNRs shown

noise in the process, thus degrading the SNR. Therefore, the longest distance that can be transported is decided by the available SNR *at that* distance. One may argue that the SNR at the transmitter may be increased indiscriminately by allowing larger power at the transmitter. However, this is not a viable solution since nonlinear effects in the optical fiber would distort the signal at higher power levels [12]. In case of optical fibers, it has been theoretically estimated that the capacity bound would in fact start *decreasing* with the increase in SNR beyond certain values of SNR, thus leading to nonlinear Shannon limit [17]. It is always desirable to operate the system in the linear regime so that the power levels are well below the nonlinear threshold levels.

The rest of this article provides a review of the significant technology changes in the last decade with the aim to increase spectral efficiency and some experimental results from our laboratory. In fact, it is curious to note that many of these techniques to improve spectral efficiency are adapted from corresponding advances in wireless systems in the recent times – several enabling technologies of which in its early days were demonstrated by Sir Jagadish Chandra Bose [18]. Section 2 discusses the details of the different multiplexing schemes used in modern optical communication systems. The challenges and impairments caused by the transmitter, receiver and the fiber and their impact on advanced modulation formats are discussed in Sect. 3. Section 4 describes the details of the experiments carried out in our laboratory that demonstrates data transmission of 100 Gbps and the technologies that are used to scale data rate beyond 100 Gbps.

Advanced modulation schemes for improved spectral efficiency

Optical modulation requires the modification of some property of the carrier electromagnetic wave in accordance with the modulating signal. In general, the electric field, $\overrightarrow{E}$ of the electromagnetic wave propagating through an optical fiber along the z direction can be written as

$$\vec{E}(x,y,z,t) = \hat{e}E_0A(x,y)e^{j(\omega t-\beta z+\emptyset)} \quad (1)$$

where $\hat{e}$ represents the direction of electric field vector (polarization), E_0 represents the strength of the field, $A(x,y)$ is the normalized transverse profile of the supported mode, ω represents the angular frequency of the carrier in radians/s (corresponding frequency of 193.4 THz for an optical wavelength of 1550 nm), β represents the propagation constant of the supported transverse mode in the fiber and $\emptyset$ represents the phase of the optical carrier. In the commonly deployed single mode fibers, the only supported transverse mode is the fundamental LP01 mode at the conventional communication wavelengths (1550 nm and 1310 nm). The corresponding form of $A(x,y)$ is approximately a Gaussian. In case of amplitude or intensity modulation, E_0 is changed according to the modulating signal.

All commercial optical communication systems transport digital data. The following was the method of modulation in all commercially deployed systems until very recently. Information to be transported is appropriately digitized and modulated on the optical carrier by simple ON–OFF keying, where E_0 (or the corresponding intensity) is made High or Low, based on whether the bit to be transported is a 1 (High) or a 0 (Low). Typically, a non-return-to-zero (NRZ) signaling scheme is deployed, where the signal is maintained to be in the respective state until the end of the bit duration. The typical NRZ signal operating at 10 Giga bits per second (Gbps) is shown in Fig. 2a; return-to-zero (RZ) signaling is also shown here for reference.

Figure 2b shows the baseband spectra corresponding to both these signals; where the x-axis represents the frequency offset from the carrier. The bandwidth occupied (measured between the two closest null points on either sides from the central peak) by the NRZ signal is evidently smaller compared to that of the RZ case and hence, NRZ signaling would result in higher spectral efficiencies. The commercial transponders working at 10 Gbps typically use a direct modulation lasers with NRZ modulation and a direct detection receiver with threshold detection.

It is also not uncommon in wireless technologies to use pulse shaping techniques where the waveforms in the time domain are modified so that the occupied spectrum is minimized. Once such pulse shaping technique is the raised-cosine (RC) pulse shaping and the corresponding time domain and spectral domain features are shown in Fig. 2. It is evident that the resulting spectrum is much more compact, but at the expense of digital processing in the time domain to achieve the desired pulse shape. Even though pulse shaping in optical communication systems is not commonly deployed yet in commercial links, it is being considered seriously for improving spectral efficiency. Receivers in all types of OOK systems use direct detection where the incoming intensity variations are converted to corresponding electric current variations and further to voltage variations using photodetectors and transimpedance amplifiers respectively. Thresholding operation is typically carried out to determine whether the received signal in each bit duration is a High or a Low.

Another technique popularly used in the wireless technology to increase spectral efficiency is to increase the number of bits represented in a given signaling duration. This is possible by encoding bits into symbols and thus allowing more bits to be transported per symbol duration. For instance, the bit sequences (00), (1,0), (11) and (10) are defined as unique symbols – say A, B, C and D, respectively, and these symbols are uniquely mapped to one of the parameters of the electromagnetic wave shown in Eq. (1) One may now think of transporting symbols, rather than individual bits. Rather than two unique levels, we need to represent one of the parameters of electromagnetic field as four unique levels. One simple way of accomplishing this is to use four levels of amplitude- or four possible values of E_0, instead of two in OOK. This leads to pulse-amplitude modulation with four levels (PAM4) modulation. Figure 3 shows some possible methods of implementation of multi-level modulations. Figure 3a shows the mapping from bits to symbols for PAM4 followed by the time domain waveforms corresponding to NRZ OOK and PAM4. Multi-level modulation can also be implemented by retaining constant amplitude and altering only the phase of the optical carrier in accordance with the symbol. This leads to quadrature phase-shift keying (QPSK), whose symbol mapping is shown in the table in Fig. 3b. The corresponding Argand diagram representation – also referred to as constellation map – is also shown in Fig. 3b. The methodology of mapping bits to symbols can be extended further to map more bits per symbol, leading to improved spectral efficiency. At the next higher level, four bits may be grouped to represent 16 unique symbols and these may be mapped to different amplitude and phase levels of the electromagnetic wave simultaneously, thus leading to 16 quadrature amplitude modulation (16QAM). The constellation for 16QAM is shown in Fig. 3c.

In such multi-level mapping schemes, the notion of bit duration is replaced with symbol duration. Since the

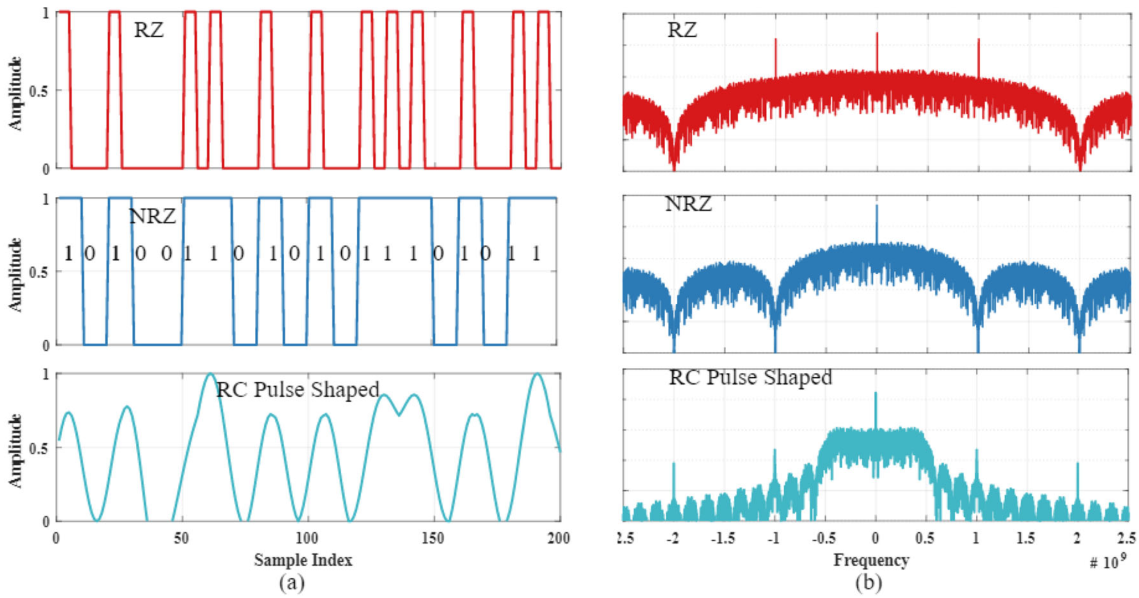


Fig. 2 RZ, NRZ and RC pulse-shaped signaling corresponding to 10 Gbps transmission (**a**) Time domain plots where the x-axis indicates sample index, ten samples represent one bit duration in this representation (**b**) corresponding spectra; y-axis represents power spectral density (PSD) in arbitrary units

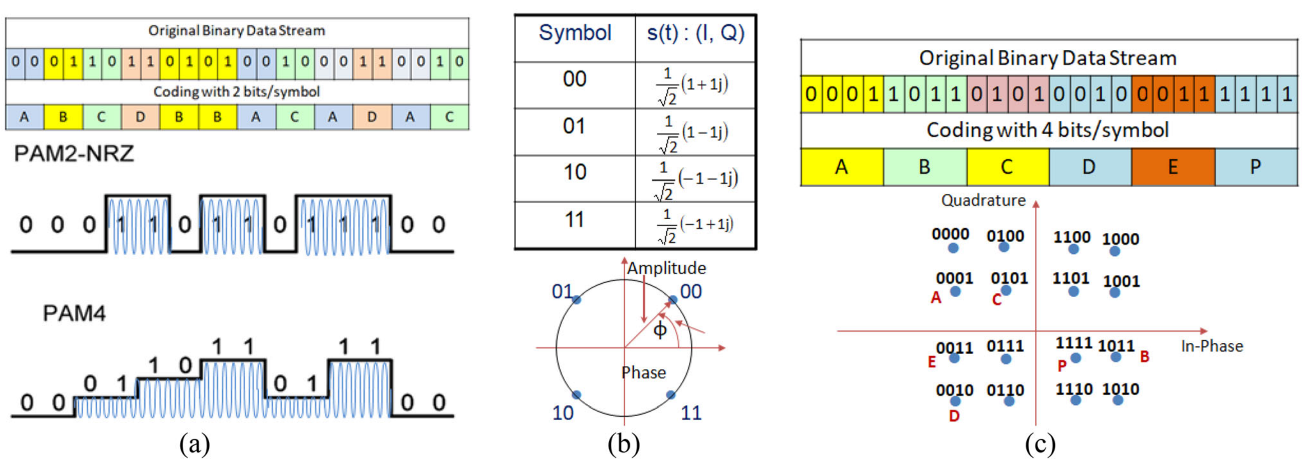


Fig. 3 **a** Bit to symbol mapping for PAM4 and QPSK modulation and the time domain representation for OOK/PAM2 and PAM4 modulation (**b**) symbol to phase mapping for QPSK modulation and the corresponding constellation diagram (**c**) bit to symbol mapping for 16QAM modulation and the corresponding constellation diagram

electronic signaling is carried out at the symbol rate, the location of the nulls in the occupied spectrum is not altered compared to OOK, but the bit rate is increased according to the number of bits mapped per symbol. This leads to improved spectral efficiency. For instance, for 10 Gbaud signaling, OOK, QPSK and 16QAM would result in bit rates of 10 Gbps, 20 Gbps and 40 Gbps respectively, with corresponding spectral efficiencies of 0.5 b/s/Hz, 1 b/s/Hz and 2 b/s/Hz.

In addition to modulation of amplitude and phase, one other parameter that is modulated is polarization, in order to increase the spectral efficiency. Given that any arbitrary polarization state can be resolved into two orthogonal components, each of these orthogonal components can be used for independent modulations. This leads to polarization multiplexing, which enables increase in the spectral efficiency by a factor of two. The current standard in long distance communication is 100 Gbps, which is enabled by QPSK modulation at 25 Gbaud symbol rate, aided with polarization multiplexing. Introduction of 100 Gbps standard marked the beginning of the era of coherent optical communication. Thus, advanced modulation formats entail modulation of amplitude, phase and polarization of the electromagnetic wave in order to improve the data rates in the available limited bandwidth of the system. However, implementation of such advanced modulation is associated with several challenges. These are discussed in detail in the following section.

Increased complexities with advanced modulation formats

The key impairments that affected traditional OOK systems at 10 Gbps data rates were primarily due to chromatic dispersion in the fiber and signal-to-noise ratio at the receiver. Lasers of linewidths of the order of several MHz were acceptable for OOK transmission. As discussed in the previous section, the state-of-the-art optical communication deploys high-spectral efficiency systems aided by phase and amplitude modulation along with polarization multiplexing. However, these systems are associated with increased complexity in demodulation, primarily due to the non-idealities in the transmitter, receiver and in the channel. We discuss these details in this section.

Impairments at the transmitter and receiver

Since data is modulated in-phase, there is a stringent requirement on the linewidth of the laser used. The term coherent in "coherent communication" is indicative of the fact that phase modulation is deployed, and this in turn which warrants highly coherent laser sources for transmission. Direct detection receivers are inadequate for coherent communication since they fail to detect phase. In a coherent receiver, the received signal is allowed to mix with a local oscillator – which is also another narrow-line laser. Ideally, the local oscillator should have the same operating wavelength as that of the transmitter laser so that there is no phase difference accumulated over time, because of the frequency difference between the laser sources. However, in practice, no two independent lasers will oscillate at identical frequencies, unless they are frequency-locked. Since the transmitter and receiver are at physically different locations, frequency locking is not a viable option. Hence, there is a finite difference (f_d) between the operating frequencies of the transmitter and the local oscillator, which also drifts with time. It is thus critical to choose narrow-line lasers where the timescales of the drift in the center frequencies are larger compared to the symbol duration (T_s). The frequency offset adds a phase to the received symbol, given by $\varphi_n = 2\pi f_d n T_s$, where φ_n is the phase added to the n^{th} symbol. Since n increases with time, phase added due to frequency offset has a cumulative effect. The expected QPSK constellation at an OSNR of 20 dB is shown in Fig. 4a and the distortion due to frequency offset of 1 GHz on a 25 Gbaud system is shown in Fig. 4b, where it is evident that the accumulated phase over multiple symbols makes the constellation points completely indistinguishable. This phase can be detrimental to optical communication system where the modulation format is dependent on the phase of the signal, and hence needs to be corrected through digital signal processing (DSP).

Ideally, in any communication system, the transmitting carrier and the local oscillator is assumed to generate monochromatic optical fields. For practical lasers, the phase of the optical carrier is not a constant, but is a slowly varying function of time, and hence is better represented as $\varnothing(t)$ in Eq. 1. The spectral width (also referred to as the linewidth) of the laser emission typically quantifies the phase noise. For a laser of linewidth Δf, the variance of the phase fluctuations (σ^2) within a symbol duration can be quantified as $\sigma^2 = 2\pi\Delta f T_s$. Thus, the phase error in low-symbol rate transmission is expected to be larger when compared to that of higher symbol rates. The distortion in QPSK constellation due to phase noise generated by a laser of linewidth 100 kHz on a 25 Gbaud system is shown in Fig. 4(c). It is seen that the constellation is significantly spread about the desired phase and this can prove to be very detrimental to the system performance. The tolerance to phase errors in case of higher order formats such as 16QAM is significantly lower due to its lower phase margin and hence constellation scaling is severely limited by the laser phase noise. These phase errors can be corrected to a certain extent through DSP at the receiver.

Impairments in the channel

Attenuation of signal when propagated through an optical fiber due to scattering losses, bending losses, splice losses and the intrinsic material absorption is one of the primary channel impairments. As discussed in Sect. 1, the advent of all-optical amplifiers such as EDFAs has alleviated this problem, thus the enabling operation of long-haul fiber links. EDFA is a phase-insensitive amplifier, thus allowing identical amplification of all input phase conditions. When operated in the linear regime, the gain experienced by different amplitude levels are the same and hence EDFA continues to be used for coherent communication systems. However, it should be noted that EDFA adds noise to the signal and typically the noise added in the In-phase and Quadrature components of the signal are identical.

Chromatic dispersion (CD) is the phenomenon in which the different spectral components of the pulse travel with different group velocities in the fiber. This results in a difference in the arrival times between the different spectral components of the pulses, thus leading to a pulse broadening in the time domain and a consequent intersymbol interference. The extent of broadening is decided

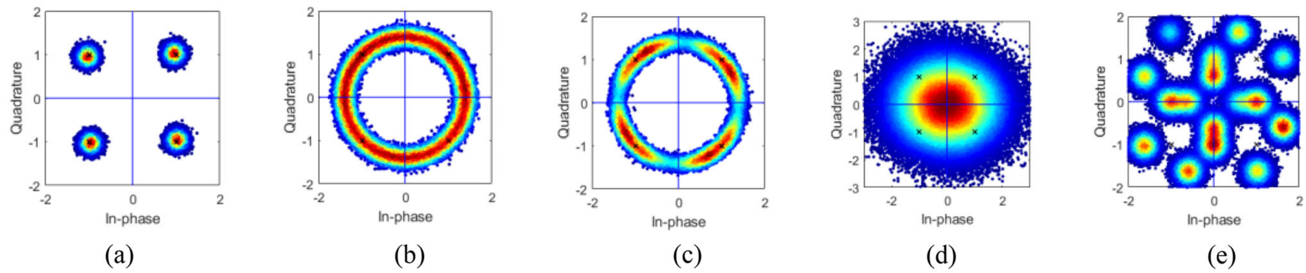


Fig. 4 Effect of different impairments in optical communication system on QPSK constellation (**a**) expected QPSK constellation. Distortions in constellation due to (**b**) frequency offset (**c**) phase noise (**d**) chromatic dispersion (**e**) polarization mode dispersion. Note that each of these impairments is assumed to be acting independently while generating these plots. In an actual system, all these impairments occur simultaneously

by the accumulated dispersion in the fiber and the symbol rate. The influence of chromatic dispersion introduced by one span of fiber link (80 km long) on the 25 Gbaud QPSK constellation is depicted in Fig. 4d. The spread in the time domain results in smearing of the constellation points as shown, warranting a correction – either in the optical or in the digital domain to enable data recovery.

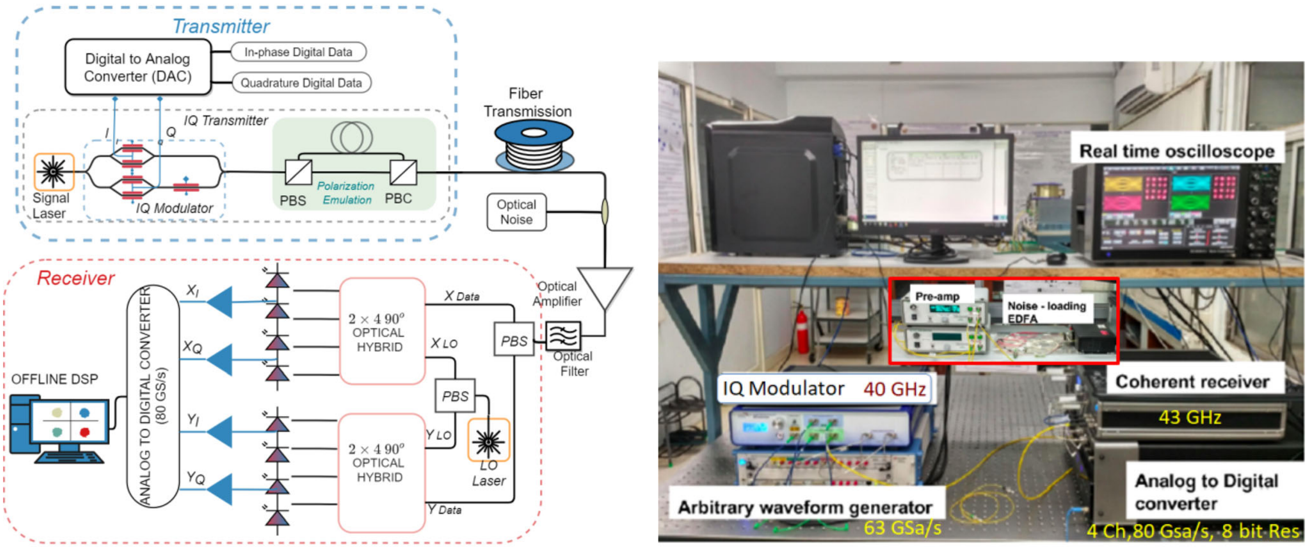
In a polarization multiplexed system, data modulated in two orthogonal polarizations are propagated through the fiber. Random deviations from perfect cylindrical symmetry along the length of the fiber leads to different effective refractive indices for the two orthogonal polarizations in the fiber—referred to as Principal States of Polarization (PSP). This leads to a differential group delay (DGD) between the two PSPs. In addition, due to the environmental fluctuations, there is a random rotation of the PSPs in a fiber leading to a statistically varying DGD between the two polarizations. The RMS time average of DGD is referred to as polarization mode dispersion (PMD). The cumulative influence of PMD and random polarization rotations of the PSPs introduced by an 80-km long fiber on one of the polarizations of 25 Gbaud QPSK constellation is shown in Fig. 4e. It is evident that the polarization mixing and polarization mode dispersion cause distortions in the constellation, which needs to be rectified to enable error-free demodulation. CD and PMD are the two major linear channel impairments that limit the performance of a high-speed optical fiber communication system. Traditionally, dispersion compensating fibers (DCF) were used to compensate for CD in the optical domain. However, DCFs introduce additional losses, therefore requiring additional optical amplifiers that would potentially increase the noise and the cost. The use of coherent optical receiver enables CD and PMD compensation in the electrical domain by using suitable DSP algorithms. A comprehensive account of the different DSP algorithms and the preferred sequence of operation are discussed in detail in [19, 20]. We now proceed to discuss the details of the experimental results involving such advanced modulation formats.

Experimental results of 100 Gbps transmission

Schematic of the coherent transmission test bed in our laboratory is shown in Fig. 5a. Light from a narrow-line laser (linewidth ~ 100 kHz) is allowed to pass through an IQ modulator that generates the desired constellation. The IQ modulator is driven by the digital-to-analog converters (DACs) in an arbitrary wave generator (64 GSa/s), that generates pseudorandom bit sequences in order to emulate the data to be transmitted. Polarization multiplexing is emulated by optically splitting the modulated signal, delaying one of the outputs of the splitter and combining with the other output using a polarization beam combiner (PBC). Polarization controllers (PC) are used at the input of the PBC in order to ensure that the input polarization states of the PBC are orthogonal.

Polarization multiplexed data are passed through the transmission fiber. The noise introduced by cascaded EDFAs in a long-haul link is emulated by injecting controlled optical noise into the data stream. The noise-loaded signal is now fed to the input of a heterodyne receiver- also referred to as a coherent receiver. The coherent receiver consists of a tunable local oscillator (LO) laser, the output of which is fed to a polarization beam splitter (PBS). The incoming signal is also projected onto two orthogonal polarization directions using a second PBS. The orthogonal polarization components of the incoming signal beats with the respective components of the LO in the 90-degree hybrid, followed by four balanced receivers. Consequently, the In-phase and Quadrature components in the orthogonal polarization directions are extracted at the output of the balanced receivers which are then fed to a four-channel analog-to-digital converter. The photograph of the laboratory setup is also shown in Fig. 5b.

The critical aspect of coherent communication system is the digital processing algorithms. As indicated in the previous section, several impairments are introduced at the transmitter, channel and in the receiver, and these acts simultaneously in the system. Since the physical



(a) (b)

Fig. 5 **a** Block diagram of experimental setup of coherent transmission test bed (**b**) photograph of the coherent communication test bed in IIT Madras

mechanism leading to each of these impairments are exactly known, appropriate digital signal processing algorithms that attempts to reverse or cancel these impairments in the electrical domain [19, 20] are devised. In a laboratory setting, the digitized outputs from the ADC are post-processed in a computer where all the digital signal processing algorithms are applied to demodulate and recover the transmitted signals. In a deployed system, these steps of digital signal processing are carried out in situ using application specific integrated processing chips.

Figure 6 captures the result from the experimental setup corresponding to 128 Gbps transmission. Different levels of noise are injected into the system and the corresponding spectra are shown in Fig. 6a. The sequence of application of different correction algorithms in the digital domain is optimized and the optimal sequence is shown in Fig. 6b. The flowchart also shows the corresponding constellations after application of each correction algorithm, and it is seen that the QPSK constellation is completely revived after application of all digital processing steps. The performance of the system is quantified in terms of the bit error rate (BER) which is essentially the ratio of number of error bits to that of the number of transmitted bits. BER is measured for different values of optical signal-to-noise ratios and the results are shown in Fig. 6a. The theoretically expected performance for 128 Gbps transmission is also shown in the same figure, with an acceptable difference which is primarily attributed to the bandwidth limitations of the ADC and the DAC.

Transmission at $\sim$ 128 Gbps described above with polarization multiplexed QPSK modulation has become the current operating standards in long-haul communication links. The demand for capacity is however increasing manifold due to the proliferation of internet, cloud-services and datacenter networks. Thus, it is imperative to discuss schemes that allow transmission beyond 100 Gbps.

Scaling beyond 100 Gbps

Super-channel transmission

Scaling the data rates to 400 Gbps and further to 1 Tbps and above requires an optimization of modulation formats, channel size and OSNR requirements. Retaining the baud rate at 25 Gbaud, a bit rate of 200 Gbps can be achieved with a progression from polarization multiplexed (PM) QPSK to PM16QAM. However, the increase in the number of phase levels in signaling results in a more stringent requirement on the OSNR for achieving the same bit error rates (BER) and hence is not practically feasible. Multiple sub-carrier channels—referred to as the *super-channels*—are envisaged for further scaling the data rates. Super-channels refer to the carrier frequencies that are generated from a single laser source such that they are frequency-locked; these carrier frequencies are synchronously modulated. The super-channels propagate and are detected as a single unit of traffic, unlike the WDM channels. The schematic of this implementation is shown in Fig. 7a. An optical frequency comb source is used to generate the carrier frequencies of the super-channel, filtered using a programmable optical filter (wave shaper). In our

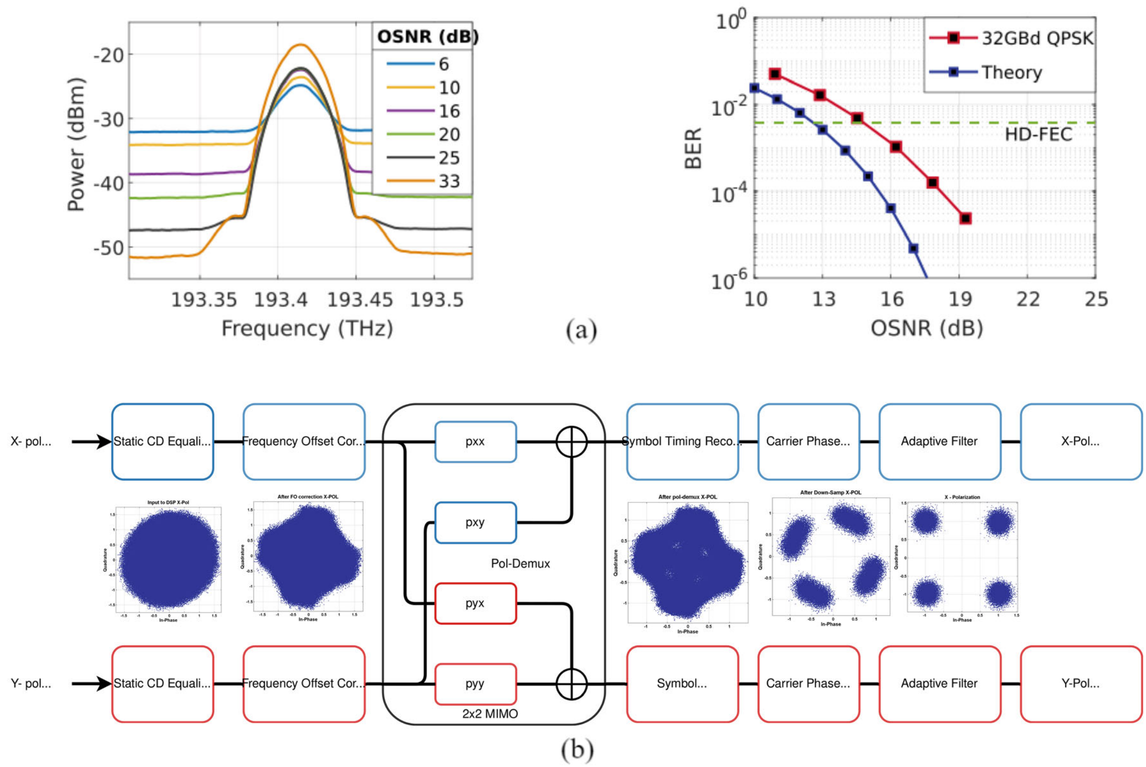


Fig. 6 **a** Optical spectrum of 32 Gbaud QPSK modulated data with polarization multiplexing for different optical signal-to-noise ratio (OSNR) conditions. The corresponding bit error rates evaluated after completing all the digital signal processing steps for different OSNR are also shown (**b**) flowchart depicting the sequence of digital signal processing algorithms and the corresponding constellations after the respective processing step

laboratory, a flexible optical frequency comb is generated by hard-driving an optical phase modulator with an RF signal. The optical spectrum of the comb indicating five equalized spectral lines with a spacing of 20 GHz is shown in Fig. 7b. Each of these lines could be independently modulated to realize high bit rate transmission. For proof-of-principle, we modulate the entire set of five comb lines with the same IQ modulator, which are in turn driven by RC pulse-shaped data in polarization multiplexed QPSK modulation at 20 Gbaud, resulting in 400 Gbps transmission with a spectral efficiency of 4 bits/seconds/Hz [21].

In a conventional single-carrier transmission, 100 GHz is occupied by two dense wavelength division multiplexed (DWDM) channels and the corresponding spectral efficiency for 25Gbaud PM QPSK transmission modulated on each of these WDM channels would be only 2 bits/seconds/Hz. The spectrum of the modulated data is also shown in Fig. 7b indicating that a total spectral width 100 GHz is completely occupied without any guard bands between the comb lines, enabled through pulse shaping. At the receiver, a tunable local oscillator is used in a heterodyne detector, where the LO is tuned to the channel of interested. The output of the balanced receiver is digitized using the ADC in a real-time oscilloscope. The data are post-processed using the DSP modules discussed earlier and the recovered constellations corresponding to each of the comb lines is shown in Fig. 7c, indicating error-free transmission. This technique can be extended for transmission rates of the order of Tbps, by increasing the number of super-channels.

Orthogonal frequency-division multiplexing

Another popular technique used in wireless communication systems to improve the spectral efficiency is orthogonal frequency-division multiplexing (OFDM). OFDM is a multi-carrier transmission technique where serial data are carried by several parallel and non-overlapping orthogonal sub-carriers, each operating at lower data rates. A notable advantage of this scheme is its ability to compensate for frequency distortions in the channel, along with the possibility of pre-compensating the distortions at the transmitter. Even though the concept of OFDM was first demonstrated as early as 1970s [22], it became popular with the introduction of Fast Fourier Transform (FFT) as an efficient way to generate orthogonal sub-carriers [23]. Excellent tutorial reviews on the fundamentals of optical OFDM can be found in [24, 25]. The basic principle of OFDM is to divide the high-speed serial data into number

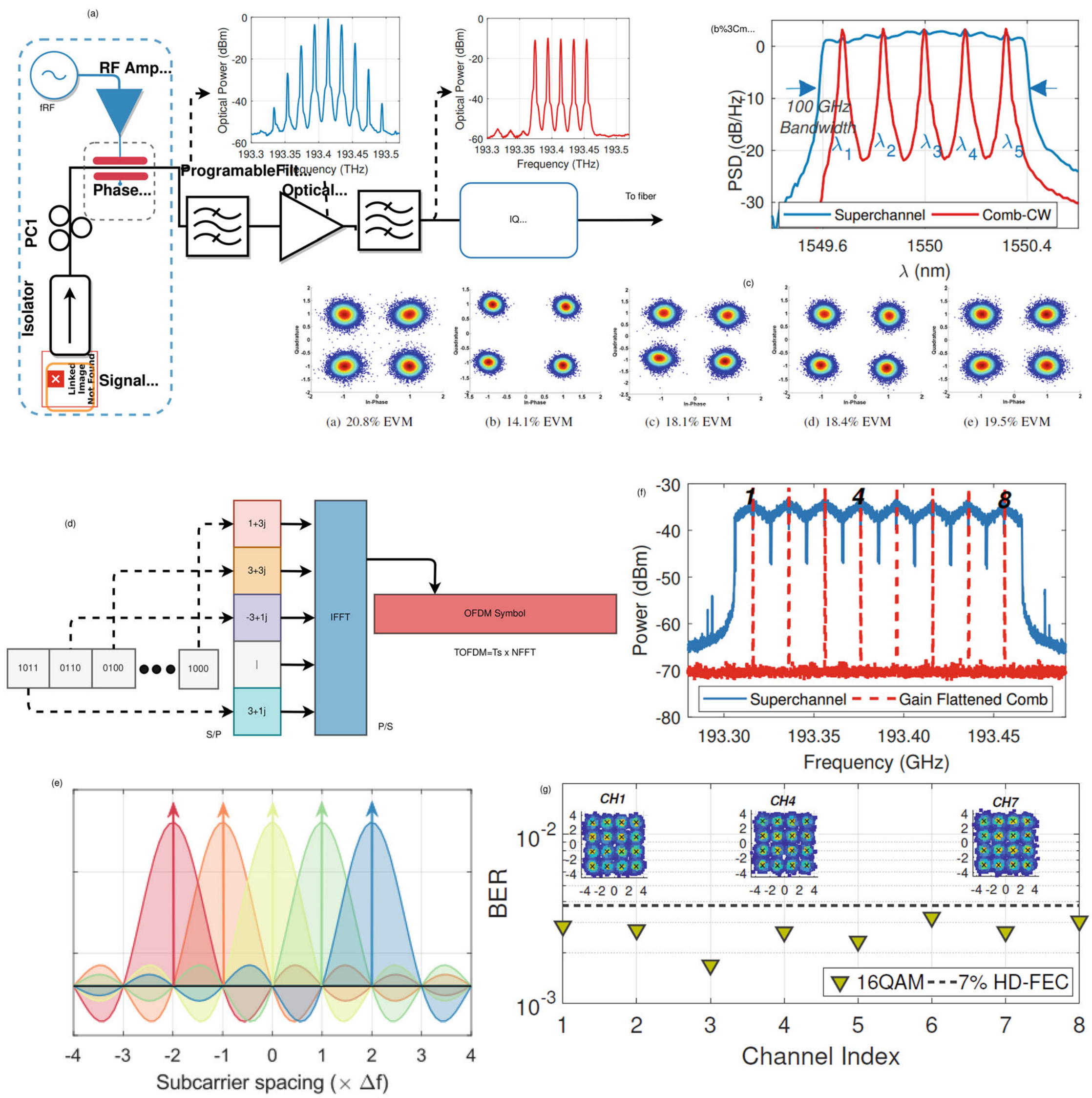


Fig. 7 **a** Schematic of experimental setup for phase-modulator-based comb generation and super-channel transmission (**b**) spectrum at the output of the equalized frequency comb (spacing 20 GHz)and that modulated with pulse-shaped data with a total transmission rate of 400 Gbps (**c**) constellation after applying all signal processing algorithms indicating error-free transmission of super-channel data at 400 Gbps (**d**) mapping of bits to symbols in sub-carriers through IFFT operation for OFDM (e) spectral representation of orthogonal sub-carriers in OFDM (**f**) spectrum at the output of modulated frequency comb with OFDM, 8 comb lines with comb spacing of 20 GHz, with total transmission rate of 608 Gbps (**g**) bit error rate performance of 608 Gbps transmission for each comb line. The eight comb super-channel experiment was carried out at Dublin City University as a part of collaborative program

of parallel data channels at lower speeds; modulate these on different frequencies so that the resultant symbol period is much longer compared to serial transmission in a single carrier, for the same total data rates. The schematic of OFDM generation is shown in Fig. 7d, where the bit to symbol mapping could be carried out either as QPSK or higher order QAM; the symbols are consequently loaded in orthogonal sub-carriers through the IFFT operation. Since the symbol period is longer compared to single-carrier systems, the effects due to intersymbol interference are reduced, thus equalization at the receiver is simpler. OFDM is different from conventional wavelength-division multiplexing (WDM) in optical systems in a way that OFDM sub-carriers are chosen such that the signals are orthogonal over one symbol period. The typical spectrum representing the sub-carriers in OFDM is shown in Fig. 7e. It is evident that the sub-carriers are seen to be overlapping but maintain orthogonality over symbol duration whereas in case of WDM, the frequencies are independently generated and hence are not orthogonal.

Figure 7f shows the output spectrum when such OFDM symbols are generated with 16QAM mapping and are modulated on eight different lines of the output of an optical frequency comb. The comb spacing is maintained at 20 GHz resulting in a total bit rate of 608 Gbps [26]. Digital signal processing algorithms are appropriately applied in order to recover the data from each comb line and the resulting bit error rate across the 8 lines are shown in Fig. 7g. The horizontal line indicates the limit of BER to be achieved so that error correction algorithms can further reduce the error rates. Another statistical method to quantify the quality of data is mutual information, which should ideally be 4 for 16QAM modulation. The results shown in Fig. 7g indicate mutual information close to 4 for all the channels. Thus, OFDM combined with the super-channels provide a pathway to demonstrate Terabit scale data rates.

In addition to making use of tailored electrical waveforms and optical spectra, there is another disruptive scheme that is proposed in the recent past that improves the channel capacity drastically. This involves modifying the channel itself slightly and the scheme is referred to as space-division multiplexing, discussed below.

Space-division multiplexing

Increase in data rates and spectral efficiencies by increasing the signaling rates and modulation formats are limited by the baud rates of the available electronics that drives the optical system and the processing capabilities of the chip that carries out the digital signal processing algorithms. A completely different way to improve the spectral efficiencies which has been recently explored s to use space as a degree of freedom for multiplexing independent streams of information. Instead of using a standard single core fiber supporting a single fundamental mode transmission, multiple spatial paths can be allowed in a single fiber by arranging multiple cores in specific geometries while maintaining the cladding dimension. These multi-core fibers need to be carefully designed to optimally control the crosstalk between the cores. Alternately, if the core diameter is slightly increased such that the fiber supports few higher order modes in addition to the fundamental Gaussian mode, data can be modulated on each of these modes and all modes can simultaneously be supported in the same fiber, thus increasing the spectral efficiency [27]. Such fibers are typically referred to as few mode fibers (FMFs) and are typically designed with a graded index core to minimize the intermodal dispersion. The components of a standard coherent communication system such as laser, modulator and coherent receiver support fundamental mode of operation. Hence, demonstration of any space-division multiplexing scheme (multi-core/ few mode) requires development of additional components such as fan-in and fan-out devices, space division multiplexed amplifiers and other switching and routing devices to be deployed in a practical network [27–32].

Figure 8a shows the schematic of a mode-division multiplexing system considering propagation of the fundamental and two higher order modes in a three-mode fiber supporting the fundamental LP01 mode and the next higher order LP11 mode with two-fold degeneracy (LP11a and LP11b).The spatial profiles of these modes are also shown in Fig. 8a. Note that, the three-mode fiber can also support two orthogonal polarizations in each of the modes, thus potentially increasing the spectral efficiency by a factor of 6. One approach to implement a fan-in and fan-out component in a mode-division multiplexed system is to use a pair of photonic lanterns (PLs) as mode (de)multiplexer at the input and output of the FMF. The input fibers of a photonic lantern are standard single mode fibers while the output is a few mode fiber. A mode selective lantern excites modes in the FMF based on the input port used for excitation while a non-mode selective lantern excites a linear combination of all the supported modes when excited at any input port. Propagation loss in the FMFs can be compensated with the use of few mode erbium-doped fiber amplifiers, which are also available commercially. In addition to the impairments discussed in Sect. 4, these systems would also pose additional distortions due to the mixing between the modes and the differential group delay between the modes. Even though the mathematical model of phenomena like intermodal mixing has been well studied and the differential group delay between the modes are accurately characterized, the randomness in the interplay of these physical processes makes it almost impossible for an all-optical compensation in communication system. Hence, multi-input multi-output (MIMO) algorithms are integrated with the standard DSP routines discussed earlier for successful signal recovery. Figure 8b shows the results of transmission through a few mode fiber, when the three modes are individually excited and for the case when all the three modes are simultaneously excited in the fiber. QPSK transmission in single polarization is used resulting in these experiments and an error-free transmission is observed when appropriate DSP routines are carried out at the receiver. These results prove the capability of data transmission through higher order modes. Mode-division multiplexing along with super-channel transmission coupled with the choice of optimal modulation format provides a pathway for several Tbps transmission in a single WDM channel.

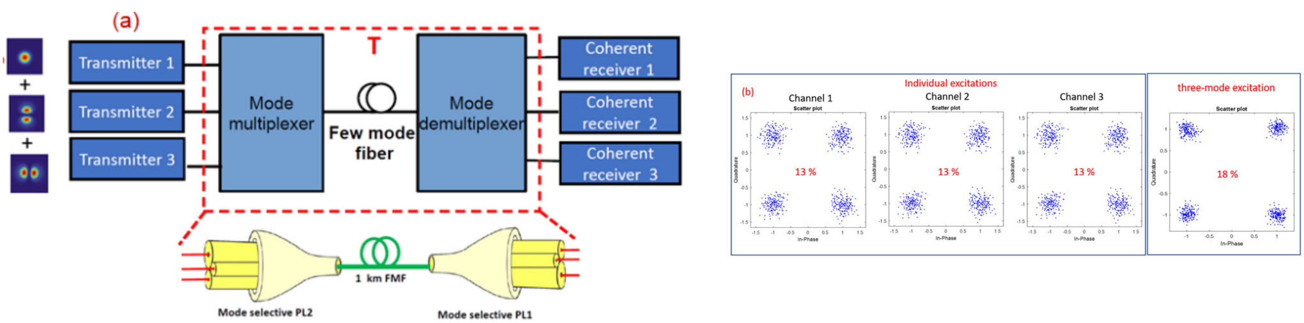


Fig. 8 **a** Schematic of a transmission test bed for mode-division multiplexing with few mode fibers (**b**) constellation observed at the output of the system when the three modes are excited independently and simultaneously, indicating error-free performance

Conclusions and outlook

The progress of optical communication over the last fifty years has been stupendous. The technological advances in this area are primarily driven by the demand for high data rates, trigged by the availability of high-speed wireless links. A key technological transformation in optical communication occurred in the recent times when the traditional On–Off keying was replaced by phase modulation. The era of coherent communication started with this change and digital signal processing has become an inevitable part of optical communication ever since. Higher order modulation along with polarization multiplexing has now evolved as the new standard in optical communication. The research community is still in the lookout for improved spectral efficiency systems with minimal signal processing so that the energy required to transport a bit is minimized.

Demand in capacities is now projected to be of the order of several exabits per second and this warrants the need of several translational technologies– both in the physical layer and in signal processing. In physical layer, there is ample scope for development of ultra-narrow line and stable lasers, flexible and compact optical frequency combs, efficient and stable multi-level modulators, commercially scalable few mode and multi-core fibers, few mode and multi-core fiber amplifiers, fan-in and fan-out devices for the few mode and multi-core fibers, and energy efficient coherent receivers. In addition, optically aided signal processing is a promising technology that is expected to optimize the digital signal processing with an overall goal of minimizing the energy required to transport each bit of information.

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