Advanced Modulation Formats for High-Capacity Optical Transport Networks

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Invited Paper

***Abstract*—Advanced optical modulation formats have become a key ingredient to the design of modern wavelength-division-multiplexed (WDM) optically routed networks. In this paper, we review the generation and detection of multigigabit/second intensity- and phase-modulated formats and highlight their resilience to key impairments found in optical networking, such as optical amplifier noise, chromatic dispersion, polarization-mode dispersion, WDM crosstalk, concatenated optical filtering, and fiber nonlinearity.**

***Index Terms*—Differential phase modulation, digital modulation, intensity modulation, optical communication, optical networks, wavelength-division multiplexing (WDM).**

I. INTRODUCTION

THE PAST few years have witnessed tremendous improvements in the areas of high-speed electronics and optical component technologies. Coupled with the desire to steadily lower the cost per end-to-end networked information bit in an environment of steadily increasing amounts of data traffic, these advances have led to two key paradigm shifts in the field of fiber-optic communications: 1) Modern optical communication systems no longer provide high-capacity point-to-point links only, but must now fulfill true optical networking functionalities enabled by mesh-capable reconfigurable optical add/drop multiplexers (ROADMs). 2) Progress in optical filtering technologies as well as in high-speed electronics and optoelectronics have made 40 Gb/s the data rate where the bandwidth of optical and electronic devices have met, which has enabled wavelength-division-multiplexed (WDM) optical networks at high spectral efficiencies. Such networks prove cost-effective by sharing optical components (such as optical fiber, optical amplifiers (OAs), or dispersion-compensating elements) among a multitude of WDM channels and by transporting information untouched on the physical layer for as long as possible. From an engineering perspective, the desire for high spectral efficiencies together with advances in high-speed electronics have led to an adaptation of well-known digital communication and signal processing techniques, such as advanced modulation, coding, and digital equalization.

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Today, research in digital optical communication techniques falls into two main areas, separated by the per-wavelength bit rates of interest.

1) At per-channel data rates of 10 Gb/s, *electronic signal processing* ranging from simple feedforward equalizers (FFE) and decision-feedback equalizers at the receiver (RX) all the way to maximum-likelihood sequence estimation (MLSE) is available today [1], [2]. Digital signal predistortion at the transmitter (TX) is starting to become possible [3], and coherent detection, allowing electronic signal processing to make use of the optical phase information, is experiencing renewed interest [4]. The main focus in this area is to increase the signal's robustness to fiber transmission impairments such as chromatic dispersion (CD) or polarization-mode dispersion (PMD).
2) At per-channel data rates of 40 Gb/s and above, the capabilities of electronic equalization are still limited to low-complexity electronic [5] or optical [6] FFE structures. In this area, *modulation formats* and *line coding* are at the center of interest and are used to mitigate linear and nonlinear impairments from fiber-optic transmission and to achieve high spectral efficiencies in optically routed network scenarios. In this context, multilevel modulation is also being studied, which opens the door to electronic preprocessing and postprocessing by using 10-Gbaud digital electronics hardware.

In this paper, we will be concerned about advanced optical modulation formats and line coding, making up the second of the above outlined areas of digital optical communications. Since this field has received considerable attention over the last few years, we want to point the reader to additional reviews on the topic [7]–[12]. A more extensive development of the material presented here is given in our companion paper [13].

This paper is organized as follows: Section II presents a classification of advanced optical modulation formats. Section III briefly discusses modulator technologies used to imprint data information onto a laser carrier. Section IV covers generation and detection strategies of various intensity modulation formats, and Section V deals with phase modulation. Finally, Section VI puts modulation formats in a systems context, describing fiber-optic propagation impairments and how they impact different modulation formats in high-capacity optically routed networks.

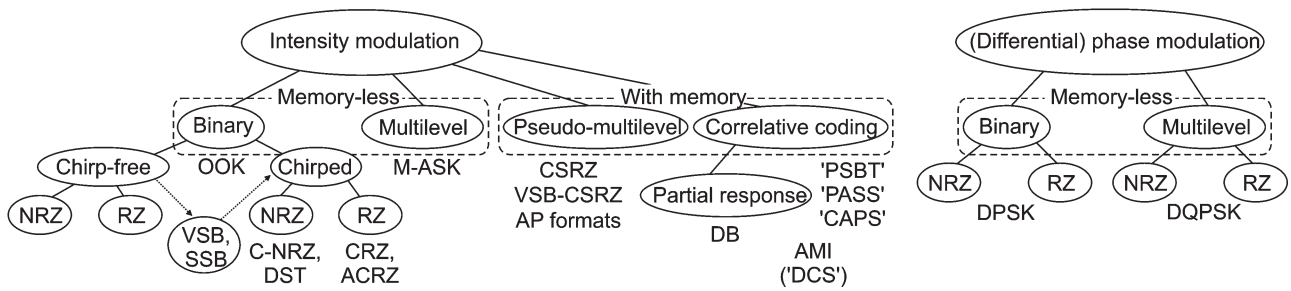

Fig. 1. Classification of the most important intensity and phase modulation formats discussed in optical communications today. (N)RZ: (non)return to zero; VSB: vestigial sideband; SSB: single sideband; OOK: on/off keying; C-NRZ: chirped NRZ; DST: dispersion-supported transmission; (A)CRZ: (alternate) chirped RZ; CSRZ: carrier-suppressed RZ; AP: alternate phase; DB: duobinary; PSBT: phase-shaped binary transmission; PASS: phased amplitude-shift signaling; CAPS: combined amplitude phase-shift coding; AMI: alternate-mark inversion; DCS: DB carrier suppressed; M-ASK: multilevel amplitude-shift keying; DPSK: differential phase-shift keying; DQPSK: differential quadrature phase-shift keying.

TABLE I
EXAMPLES FOR DIFFERENT SYMBOL ENCODINGS

Data sequence	0	0	1	0	1	1	1	0	0	1	0	1
Multilevel (DQPSK)	0		$+\frac{\pi}{2}$		π		$+\frac{\pi}{2}$		$-\frac{\pi}{2}$		$-\frac{\pi}{2}$	
Pseudo-multilevel (CSRZ)	0	0	+1	0	+1	−1	+1	0	0	−1	0	−1
Partial-response (DB)	0	0	+1	0	−1	−1	−1	0	0	−1	0	+1
Alternate-mark inv. (AMI)	0	0	+1	0	−1	+1	−1	0	0	+1	0	−1

II. Classification of Modulation Formats

A. Data Modulation Formats (DMFs)

In single-mode optical fibers, the optical field has three physical attributes that can be used to carry information: 1) intensity; 2) phase (including frequency); and 3) polarization. Depending on which of these is used for information transport, we distinguish between intensity, phase (or frequency), and polarization DMFs. Fig. 1 shows how the most important modulation formats discussed today fall into this classification. Note that this classification does not require a phase-modulated optical field to be constant envelope nor an intensity-modulated field to have constant phase. It is the physical quantity used to convey data information that drives the classification.

While intensity and phase DMFs have been widely used in high-speed optical communications, encoding information onto the polarization of light (polarization shift keying, Pol-SK) has received comparatively little attention [14]–[16]. This can primarily be attributed to the need for active polarization management at the RX, necessitated by random polarization changes in optical fiber [17], and the fact that Pol-SK does not offer a significant RX sensitivity improvement over intensity modulation [14], [15]. However, the polarization degree of freedom is used to improve the propagation properties of a format by pseudo-multilevel or correlative coding [18], [19], similar to an auxiliary optical phase modulation (see Section II-B). Furthermore, polarization is sometimes used in research experiments to increase spectral efficiency,[1] either by transmitting two different signals at the same wavelength but in two orthogonal polarizations (polarization multiplexing) or by transmitting adjacent WDM channels in alternating polarizations to reduce coherent WDM crosstalk or nonlinear interactions between the channels (polarization interleaving).

[1] The spectral efficiency (SE) [20] or information spectral density (ISD) [9] is defined as the ratio of net per-channel information data rate to the WDM channel spacing.

B. Symbol Alphabet Size

Using multilevel signaling, $\log_2(M)$ data bits are encoded on M symbols and are then transmitted at a reduced symbol rate of $R/\log_2(M)$, where R is the bit rate. In general, a symbol is assigned irrespective of the symbols sent before or after it (memoryless modulation [21]). Multilevel signaling offers the benefits of higher spectral efficiencies at the cost of a reduced tolerance to noise [21], [22]. Multilevel signaling allows single-channel data rates to exceed the limits of high-speed optoelectronics technology. Alternatively, multilevel signaling allows for lower symbol rates at a fixed data rate, which is beneficial in the presence of dispersive signal distortions, such as CD (Section VI-C) or PMD (Section VI-D), as well as for implementing digital electronic signal processing.

Multilevel intensity modulation [7], [23], multilevel phase modulation [24]–[26], as well as hybrid multilevel intensity/phase modulation [27], [28], have been discussed in the context of multigigabit/second transmission. Multilevel intensity modulation (i.e., multilevel amplitude-shift keying) has not proven beneficial for fiber-optic transport applications so far, mainly due to a substantial back-to-back RX sensitivity penalty compared to binary on/off keying (OOK) [7], [23]. One of the most promising multilevel optical modulation formats is differential quadrature phase-shift keying (DQPSK, Section V-B). An example for the mapping of a bit sequence into the 4-ary DQPSK symbol alphabet $\{0, +\pi/2, -\pi/2, \pi\}$ is given in Table I; a precoded data sequence, including Gray-coded symbol mapping [21], is assumed.

Within the class of modulation formats with more than two symbols, *correlative coding* and *pseudo-multilevel modulation* have received substantially more attention in optical communications than multilevel formats. For these two classes of formats, the symbol alphabet is enlarged not to increase the data rate or to reduce the symbol rate at a fixed data rate; rather, all symbols are transmitted at the bit rate, and the additional degrees of freedom gained by using an increased symbol alphabet

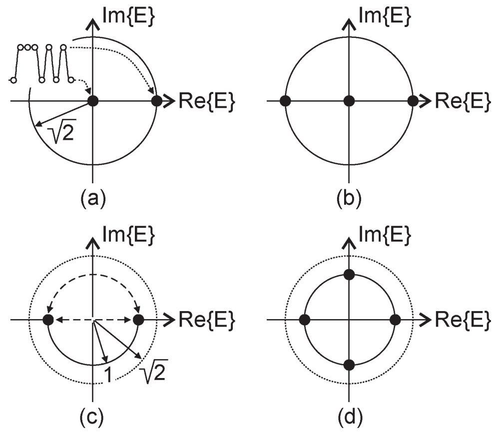

Fig. 2. Symbol diagrams capture the complex optical field values of data symbols used either for data transport or for improving specific format properties. All diagrams are shown on the same scale, normalized to unity average optical power. (a) OOK, chirped OOK. Dashed lines show examples for transitions between symbols for chirped formats. (b) CSRZ, DB, and AMI. (c) DPSK. Dashed double arrows represent different PM implementations (Section V-A). (d) DQPSK.

are exploited to shape the spectrum and to improve the tolerance of a format to specific propagation impairments by means of introducing *memory* into the modulation scheme, also referred to as *line coding* [21], [29]–[32]. If more than two symbols are used to represent a single bit, and if the assignment of redundant symbols to transmitted bits is data independent, we refer to pseudo-multilevel DMFs. If the assignment of symbols depends on the transmitted data information, we generally refer to correlative coding DMFs, where the most important subcategory is partial-response DMFs.

The most widespread (being the easiest to generate) pseudo-multilevel format is carrier-suppressed return to zero (CSRZ, Section IV-C), where the information is encoded on the intensity levels $\{0, 1\}$, but the phase is changed by π every bit, regardless of the data information, as visualized in Table I. The most important partial-response DMF is optical duobinary (DB, Section IV-D1). As for CSRZ, information is conveyed by the intensity levels $\{0, 1\}$, but π phase shifts occur only for 1-bits separated by an odd number of 0-bits. This correlation between auxiliary phase flips and information encoding is characteristic of partial-response formats. Note, however, that the phase information is generally not used for detection due to the phase-insensitive nature of direct-detection (square-law) RXs. More advanced line coding schemes (both pseudo-multilevel and correlative coding) are being designed to combat fiber nonlinearity, as discussed in Section VI-F.

Fig. 2 shows the four most important symbol diagrams encountered in optical communications, comprising almost all formats categorized in Fig. 1. As visualized in Fig. 2(a) for the case of OOK, a *symbol diagram* captures the intensity and phase levels of all digital data symbols (+1 and 0 in the case of OOK) and maps them into the complex optical field plane; idealized waveforms and optimum sampling instant are assumed. The symbol diagram in Fig. 2(b) represents CSRZ as well as DB and alternate-mark inversion (AMI). Fig. 2(c) and (d) represents differential phase-shift keying (DPSK) and DQPSK, respectively. The two phase modulation formats are shown for the same average optical power as the intensity modulation formats in Fig. 2(a) and (b).

While Fig. 2 only shows symbol diagrams in two dimensions (intensity and phase), multidimensional symbol constellations are possible by adding a polarization axis to the symbol diagram.

Note that DMFs with memory most beneficially use the symbol set $\{-1, 0, +1\}$ because optical RXs almost exclusively use square-law detection, i.e., they make use of the optical power $P = |E|^2$, the squared magnitude of the complex optical field E. As a consequence, a direct-detection RX is unable to distinguish between the two received symbols $E_{1,2} = \pm|E|$ since they both have the same optical power. Therefore, the ternary symbol set $\{+|E|, 0, -|E|\}$ is automatically mapped to the binary set $\{0, |E|^2\}$ at the RX.

C. *Pulsed Modulation RZ Versus NRZ*

If information is imprinted on the intensity, phase, or polarization of optical pulses, a DMF gets the qualifier *pulsed* or return to zero (*RZ*). In contrast, nonreturn to zero (NRZ) formats permit constant optical intensity over several consecutive bits. The benefits of RZ modulation will be discussed in detail in Section VI.

III. Modulator Technologies

As data rates in optical communication systems have traditionally been limited by the speed of available optoelectronic components, it is of utmost importance to always consider practical aspects of modulation and detection hardware when designing optical modulation formats. Finding the most cost-effective modulation technique for a particular system application involves aspects of modulation format and modulator technology. Three basic modulator technologies are widely in use today: directly modulated lasers, electroabsorption modulators, and Mach–Zehnder modulators (MZMs). Of these technologies,[2] MZMs are almost exclusively used for transport systems at 40 Gb/s and above, owing to their well-controllable modulation performance and the possibility of independently modulating intensity and phase of the optical field. Fig. 3 gives an overview of the different ways of utilizing the sinusoidal transmission characteristics of an MZM to generate a variety of important modulation formats, which will be discussed in detail in Sections IV and V.

IV. Intensity Modulation Formats

A. *NRZ-OOK*

The simplest to generate optical modulation format is NRZ-OOK, often just referred to as NRZ. When using an MZM to generate NRZ, the modulator is biased at 50% transmission (often referred to as the *quadrature point* and indicated by black circles in Fig. 3) and is driven from minimum to maximum transmission. Note that the nonlinear compression of the sinusoidal MZM transfer function at high and low transmissions

[2]For a detailed discussion of these modulators' properties in the context of digital communications, see [13], [33], and [34].

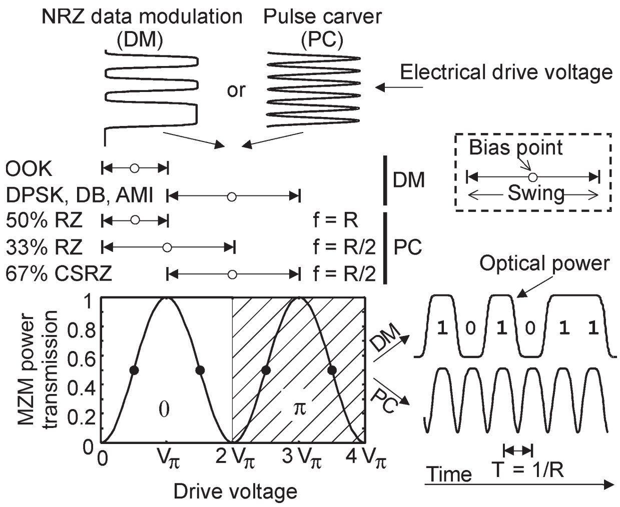

Fig. 3. Overview of different ways to drive an MZM, resulting in different optical modulation formats (DM: data modulation; PC: pulse carver; black circles: MZM quadrature points). See Sections IV and V for details.

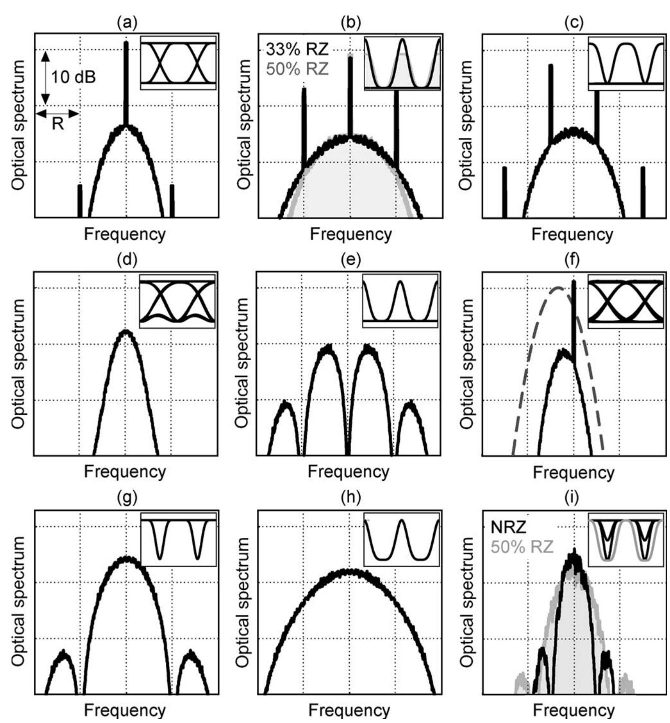

Fig. 4. Optical spectra and optical intensity eye diagrams of important modulation formats. (a) NRZ-OOK. (b) RZ-OOK. (c) 67% CSRZ-OOK. (d) DB. (e) 33% RZ-AMI. (f) VSB-NRZ-OOK. (g) NRZ-DPSK (MZM). (h) 33% RZ-DPSK (MZM). (i) DQPSK (MZM). See caption of Fig. 1 for an explanation of acronyms.

can suppress overshoots and ripple on the electrical NRZ drive signal upon conversion to optical power. Fig. 4(a) shows the optical spectrum and the optical intensity eye diagram of an idealized NRZ signal.

B. RZ-OOK

Return to zero TXs at 40 Gb/s and above typically employ a *pulse carver* in series with a data modulator to turn an optical NRZ format into its RZ equivalent. A pulse carver

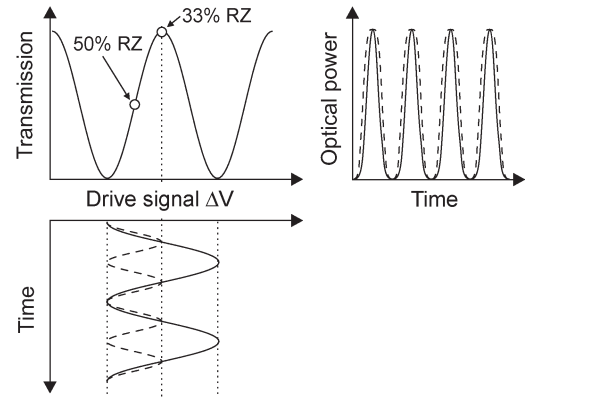

Fig. 5. Sinusoidally driven MZM as pulse carver for 33% duty cycle RZ (solid) and 50% duty cycle RZ (dashed). The MZM bias points are indicated by an open circle.

is conveniently implemented as a sinusoidally driven MZM since multigigahertz sinusoidal signals of appreciable drive amplitude are easily generated. One of the following three carving methods is usually employed:

1) sinusoidally driving an MZM at the data rate between minimum and maximum transmission results in optical pulses with a full-width at half-maximum of 50% of the bit duration (a duty cycle of 50%), as shown in Fig. 5 (dashed);
2) sinusoidally driving an MZM at half the data rate between its transmission minima produces a pulse whenever the drive voltage passes a transmission maximum, as visualized in Fig. 5 (solid). This way, duty cycles of 33% can be realized;
3) sinusoidally driving an MZM at half the data rate between its transmission maxima results in pulses with 67% duty cycle and with alternating phase. The resulting format is called CSRZ (Section IV-C).

Spectra and intensity eye diagrams of 50% duty cycle RZ (gray) and 33% duty cycle RZ (black) are shown in Fig. 4(b).

C. CSRZ

CSRZ [35], [36] is a pseudo-multilevel modulation format, characterized by reversing the sign of the optical field at each bit transition. In contrast to correlative coding formats, the sign reversals occur at every bit transition and are completely independent of the information-carrying part of the signal. CSRZ is most conveniently realized by sinusoidally driving an MZM pulse carver at half the data rate between its transmission maxima, as visualized in Fig. 6. Since the optical field transfer function (dashed) of the MZM changes its sign at the transmission minimum, phase inversions between adjacent bits are produced. Thus, on average, the optical field of half the 1-bits has positive sign, whereas the other half has negative sign, resulting in a zero-mean optical field envelope. As a consequence, the carrier at the optical center frequency vanishes, giving the format its name. Since the optical phase in a CSRZ signal is periodic at half the data rate, the CSRZ spectrum exhibits characteristic tones at $\pm R/2$.

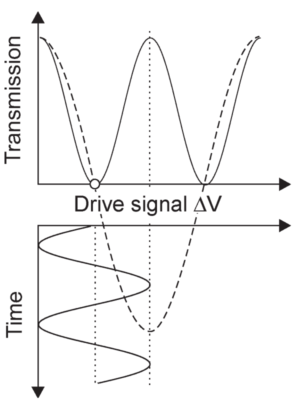

Fig. 6. Sinusoidally driven MZM as pulse carver for 67% duty cycle CSRZ. The solid and dashed transmission curves apply for the optical power and field, respectively. The MZM bias point is indicated by an open circle.

Spectrum and eye diagram of 67% duty cycle CSRZ are shown in Fig. 4(c). It is important to note that, due to its most widely used practical implementation with MZMs, the duty cycle of CSRZ signals usually differs from the one of standard RZ. Thus, care has to be taken when comparing the two formats since some performance differences result from the carrier-suppressed nature of CSRZ, whereas others simply arise from the different duty cycles.

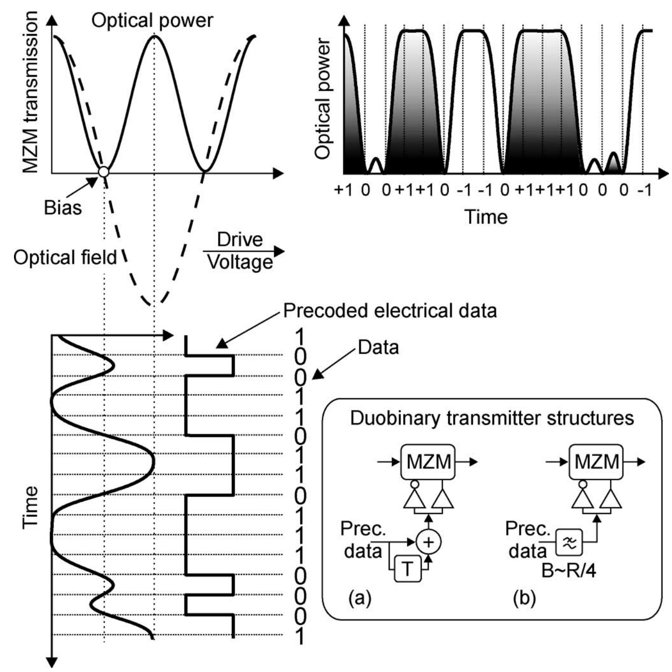

Fig. 7. DB signals are generated by driving an MZM around its transmission minimum using a three-level electrical drive signal, generated from the precoded data signal by either (a) delay-and-add circuit or (b) some other appropriate low-pass filter.

D. Correlative Coding and Partial-Response Formats

Optical DB and AMI belong to the general class of correlative coding formats, a subclass of which being referred to as partial-response signaling [21], [37], [38].

In contrast to CSRZ, correlative coding introduces a distinct correlation between the optical phase and the data information: In optical DB signaling, a phase change occurs whenever there is an odd number of `0`-bits between two successive `1`-bits, whereas for AMI, the phase changes for each `1`-bit (even for adjacent `1`-bits), independent of the number of `0`-bits in between. Table I visualizes these phase correlations.

1) DB [Phase-Shaped Binary Transmission (PSBT) and Phased Amplitude-Shift Signaling (PASS)]: The most prominent representative of partial-response formats is DB. In optical communications, DB modulation [39], [40] is also promoted under the names PSBT [31] and PASS [32]; although PSBT and PASS, like the combined amplitude phase-shift (CAPS) coding [29], are meant to comprise more general correlative coding rules between amplitude and phase, PSBT and PASS are mostly used as synonyms for DB.

The main benefit of DB signals is their higher tolerance to CD and narrow-band optical filtering compared to binary signaling formats, which can be understood both in the time domain [32], [41] and in the frequency domain [7], [42], [43].

As shown in the inset to Fig. 7, DB TXs use a differentially precoded version of the data signal [43] at the input; this precoded data stream exhibits a level change for every `0`-bit contained in the original data sequence and prevents error propagation after detection [38]. The precoded sequence is converted into a three-level electrical signal by means of severe electrical low-pass filtering. The low-pass filter can either be implemented digitally, as a delay-and-add filter [Fig. 7(a)], or as some other type of analog filter with suitable rolloff characteristics and a 3-dB bandwidth of about 25% of the bit rate [Fig. 7(b)]. Delay-and-add filters typically result in better back-to-back sensitivity, whereas carefully tailored low-pass characteristics better shape the sequence spectrum and yield higher tolerance to CD[3] [42] (cf. Section VI-A). The three-level electrical signal is then used to drive an MZM between its transmission maxima, as shown in Fig. 7. Alternatively, an MZM designed for one fourth of the desired data rate may be used to combine the functionality of low-pass filtering and modulation [44], [45], which has allowed MZM-based DB modulation up to 107 Gb/s [46].

Note that low-pass filtering can equivalently be performed in the optical domain: Passing a binary signal with levels $\{-1, +1\}$, also known as phase-shift keying (PSK, Section V-A), through a narrow-band optical bandpass filter produces optical DB [47] (cf. discussion in Fig. 9).

2) AMI [DB Carrier Suppressed (DCS)]: AMI, which is sometimes also classified as partial response due to the way it is generated [38], does not share the bandwidth limitation characteristic of other partial-response formats. In optics, AMI is typically implemented in RZ form (RZ-AMI). Like other RZ-OOK formats using auxiliary phase coding, the additional phase modulation of AMI can help to reduce the effects of some fiber nonlinearities (see Section VI-F). Optical spectrum and intensity eye diagram of 33% duty cycle RZ-AMI are shown in Fig. 4(e).

One possible AMI TX implementation is identical to the DB TX in Fig. 7(a), except that it uses an electrical

[3]Note that it is the entire spectral shape rather than just the 3-dB bandwidth that influences the robustness of a format to chromatic dispersion.

delay-and-subtract (high-pass) filter instead of the delay-and-add (low-pass) filter used for DB. To obtain RZ-AMI, the data modulator is then followed by an RZ pulse carver. Another TX structure [48]–[50] first generates binary (phase or intensity) modulation in NRZ form ($\{-1, +1\}$ or $\{0, +1\}$) and passes this signal through an optical delay-and-subtract filter, implemented by an optical delay interferometer (DI) with delay $\tau \leq T$, where T is the bit period. To act as a delay-and-subtract filter, the DI is set for destructive interference at its output in the presence of an unmodulated input signal. By varying τ, RZ-AMI signals with different duty cycles can be generated. Yet another possibility of generating RZ-AMI is readily understood by comparing the DB and AMI phase encodings in Table I: If a DB signal is passed through a CSRZ pulse carver, the bit-alternating phase reversals inherent to CSRZ convert DB into AMI (and vice versa). This fact has lead to the name DCS as a sometimes encountered synonym for AMI [49], [51].

In recent literature, the term "modified duobinary" has also been used to denote AMI. Note, however, that modified duobinary is not equivalent to AMI but represents a distinctly different modulation format. Modified duobinary is a partial-response format that is generated using a delay-and-subtract circuit with a 2-bit delay ($\tau = 2T$) [21], [38], [52].

E. Vestigial Sideband (VSB) and Single Sideband (SSB)

Apart from shaping (and compressing) the optical signal spectrum by means of (pseudo)multilevel signaling or correlative coding, it is possible for some modulation formats to additionally suppress half of their spectral content by appropriate optical filtering. Since the spectrum of real-valued baseband signals is symmetric around zero frequency, filtering out the redundant half of the spectrum (i.e., one of the two spectral sidebands) preserves the full information content. This is exploited in SSB signaling, where one sideband is completely suppressed, and in VSB signaling, where an optical filter with a gradual rolloff is offset from the optical carrier frequency to suppress major parts of one sideband, while at the same time performing some filter action on the other. A real-valued (chirp-free) double sideband signal is thus converted into a complex-valued (chirped) VSB or SSB format. As an important caveat, note that to be a successful candidate for VSB or SSB filtering in the presence of square-law detection, a real-valued modulation format has to maintain square-law detectability after conversion into VSB or SSB. While SSB filtering is hard to implement in practice due to difficulties in realizing the appropriate optical or electrical filter functions [7], [53], optical VSB has been successfully demonstrated on NRZ-OOK [9], [54], [55], RZ-OOK [56], and CSRZ-OOK [57], [58]. Fig. 4(f) shows the optical spectrum and intensity eye diagram of VSB-NRZ; the corresponding VSB filter shape is also shown (dashed).

In a WDM system, VSB filtering can either be done at the TX (i.e., before or in combination with multiplexing the WDM channels) [57], [58] or at the RX (i.e., after or in combination with demultiplexing) [9], [54], [55]. Filtering at the TX allows for ultimate spectral compression and highly spectrally efficient WDM transmission. The advantage from VSB when filtered at the RX comes from reduced WDM channel crosstalk for the desired sideband if unequal WDM channel spacings are employed [9], [54], [55].

V. Differential Phase Modulation Formats

To detect information carried by the optical field's phase by means of square-law detection, phase-to-intensity converting elements have to be inserted into the optical path prior to the photodiode. Due to the absence of an optical phase reference at such a (noncoherent) RX, the phase reference has to be provided by the signal itself: Each bit acts as a phase reference for another bit, which is at the heart of all DPSK formats [59].

A. Binary DPSK

DBPSK (or simply DPSK) encodes information on the binary phase change between adjacent bits: A 1-bit is encoded onto a π phase change, whereas a 0-bit is represented by the absence of a phase change. Like OOK, DPSK can be implemented in RZ and NRZ formats. The main advantage from using DPSK instead of OOK comes from a 3-dB RX sensitivity improvement [15], [60], which can be intuitively understood from Fig. 2(c), showing that the symbol spacing for DPSK is increased by $\sqrt{2}$ compared to OOK for fixed average optical power [59].

An optical DPSK TX differentially encodes the transmit data prior to modulation to avoid error propagation at the RX [38]. The precoded sequence then modulates the phase of the transmit laser between 0 and π. To perform optical phase modulation, one can either use a straight-line phase modulator (PM) or an MZM [61]. The difference between the two phase modulation schemes is indicated by the dashed double arrows in Fig. 2(c): A PM modulates the phase *along a circle* in the complex plane, leaving constant the intensity of the phase-modulated light. However, since the optical phase directly follows the electrical drive signal, the speed of phase transitions is limited by the combined bandwidth of driver amplifier and PM, and any overshoot or ringing in the drive waveform manifests itself in phase distortions. An MZM, which is symmetrically driven around zero transmission, modulates *along the real axis* through the origin of the complex optical field plane [cf. Fig. 2(c)], which always produces exact π phase jumps at the expense of residual optical intensity dips at the locations of phase transitions. Since exact phase modulation is more important for DPSK than a constant optical intensity, practical DPSK TXs are most conveniently implemented using an MZM as a PM [59]. Like for OOK, a pulse carver can be added in series with the data modulator to convert the NRZ-DPSK signal to RZ-DPSK.

Fig. 4(g) and (h) shows optical spectra and intensity eye diagrams for NRZ-DPSK and 33% duty cycle RZ-DPSK, respectively. Note the absence of a 0-bit rail in the eye diagrams, which is characteristic of phase-modulated formats. The intensity dips between two bits in the NRZ-DPSK eye represent the residual intensity modulation of the MZM caused by the finite NRZ drive signal bandwidth.

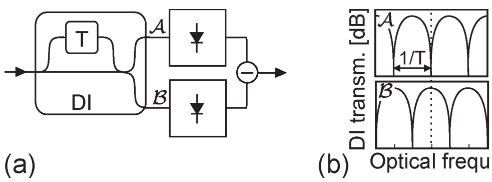

Fig. 8. (a) Balanced DPSK RX using an optical DI to convert phase modulation to intensity modulation. (b) Periodic DI power transmission characteristics for the destructive port ($\mathcal{A}$) and the constructive port ($\mathcal{B}$).

Since DPSK cannot directly be received using square-law detection, a DI is inserted in the optical path at the RX to convert the differential phase modulation into intensity modulation. As shown in Fig. 8(a), a DI splits the phase-modulated signal into two paths, which experience a delay difference equal to the bit duration T (25 ps at 40 Gb/s) to let two neighboring bits interfere at the DI output. At the DI output port $\mathcal{A}$ (the *destructive port*), the two optical fields interfere destructively whenever there is no phase change, and constructively whenever there is a phase change between subsequent bits, thus converting phase modulation into intensity modulation. Maintaining good interference is the most critical aspect in the design of DPSK RXs [59], [62]. Due to energy conservation within the DI, the second DI output port $\mathcal{B}$ (the *constructive port*) yields the logically inverted data pattern. In principle, one of the two DI output ports is sufficient to fully detect the DPSK signal (single-ended detection). However, the 3-dB sensitivity advantage of DPSK is *only* seen for balanced detection; as shown in Fig. 8(a), a balanced RX forms the difference of ports $\mathcal{A}$ and $\mathcal{B}$ to obtain the electrical decision variable. The reason for the superior performance of balanced detection compared to single-ended detection is the non-Gaussian statistics of square-law detected Gaussian noise, which is characteristic of beat-noise limited systems [59], [63], [64].

Note that the DI used for DPSK demodulation is functionally equivalent to the filters used to generate DB and AMI. Fig. 8(b) shows, on a logarithmic scale, the sinusoidal transmission characteristics of ports $\mathcal{A}$ and $\mathcal{B}$ of a DI as a function of frequency. The laser carrier frequency is indicated by a dotted line. The destructive DI output port $\mathcal{A}$ acts as a delay-and-subtract filter (high-pass characteristics to first order), whereas the constructive port $\mathcal{B}$ is a delay-and-add filter (low-pass characteristics to first order) [47]. Not surprisingly, the formats seen at ports $\mathcal{A}$ and $\mathcal{B}$ are AMI and DB, respectively. Fig. 9 summarizes the interesting relationship between the modulation formats discussed so far, all starting from the same binary transmit data stream. The apparent lack of symmetry in Fig. 9 (no arrow from NRZ to DB) is due to the fact that narrow-band optical filtering of NRZ-OOK results in an optical DB signal with three intensity levels [65], in analogy to the three-level electrical drive waveform shown in Fig. 7. Such a signal cannot take advantage of the square-law detecting property of photodiodes described at the end of Section II-B and requires special detection schemes [66], [67].

B. DQPSK

DQPSK is the only true multilevel modulation format (more than 1 bit per symbol) that has received appreciable attention in optical communications so far [24], [25], [68]–[71]. It transmits the four phase shifts $\{0, +\pi/2, -\pi/2, \pi\}$ at a symbol rate of half the aggregate bit rate (cf. Table I).

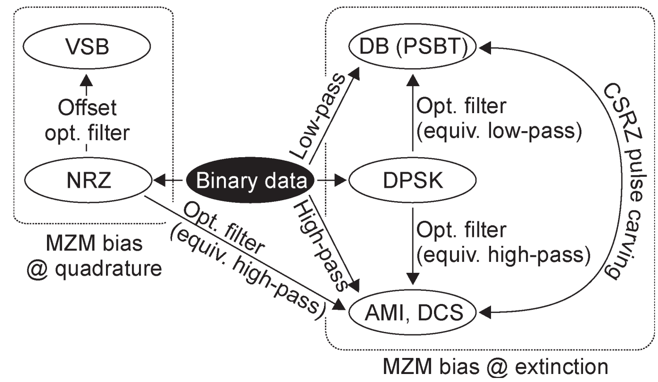

Fig. 9. Relationship between NRZ (including VSB-NRZ), DPSK, DB, and AMI. Arrows indicate how to transition from one format to another, starting from the same binary electrical data stream.

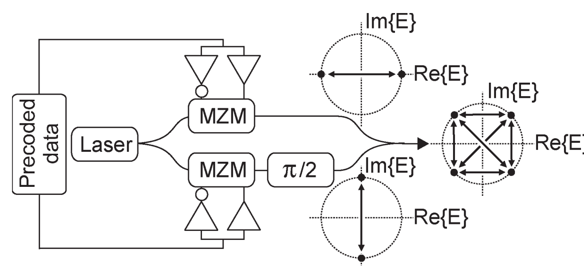

Fig. 10. Structure of a DQPSK TX. Two MZMs are used as PMs, and the two separately modulated fields are combined with a $\pi/2$ phase shift [24], [25].

As in the case of DPSK, a DQPSK TX is most conveniently implemented by two nested MZMs operated as PMs. Fig. 10 shows the corresponding TX setup [25], [72], consisting of a continuously operating laser source, a splitter to divide the light into two paths of equal intensity, two MZMs operated as PMs, an optical $\pi/2$ phase shifter in one of the paths, and a combiner to produce a single-output signal. The symbol constellations of the upper and lower paths as well as at the modulator output are also shown, together with the symbol transitions. Using this TX structure, one first takes advantage of the exact π phase shifts produced by MZMs, independent of drive signal overshoot and ringing. Second, this TX structure requires only binary electronic drive signals, which are much easier to generate at high speeds than multilevel drive waveforms. Optionally, a pulse carver can be added to the structure to produce RZ-DQPSK.

Optical spectrum and intensity eye diagra duty cycle RZ-DQPSK (gray) are shown in Fig. 4(i). Note that the *shape* of the DQPSK optical spectrum is identical to that of DPSK, but the DQPSK spectrum is compressed in frequency by a factor of 2 due to the halved symbol rate for transmission at fixed bit rate. The compressed spectrum is beneficial for achieving high spectral efficiencies in WDM systems [22], [24], [69] (Section VI-B), as well as for increased tolerance to CD [24], [73] (Section VI-C); the longer symbol duration compared to binary modulation formats makes DQPSK more robust to PMD (Section VI-D) [24], [73].

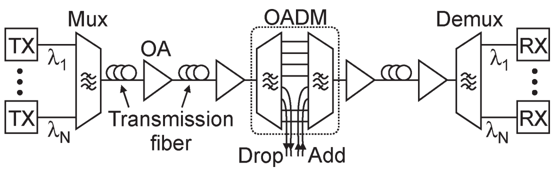

Fig. 11. Generic setup of a WDM optical line system, consisting of N TXs and RXs at wavelengths λ_i. Wavelength channels are combined and separated by WDM mux and demux. Each transmission span is followed by an OA. Intermediate wavelength routing is enabled by OADMs.

Like at the TX, one also strives to work with binary electrical signals at the DQPSK RX due to implementation benefits in high-speed electronics. At the RX, the DQPSK signal is thus first split into two equal parts, and two balanced RXs of the form depicted in Fig. 8(a), but with differently biased DIs, are used in parallel to simultaneously demodulate the two binary data streams contained in the DQPSK signal [24]. Note that the DI delay has to equal the symbol duration for DQPSK demodulation, which is twice the bit duration. Note that this RX structure has a six times lower tolerance to frequency drifts between transmit laser and DI compared to DPSK [74], [59]. For example, at 40 Gb/s and for a 1-dB penalty, DPSK tolerates ± 1.2 GHz of laser-to-DI frequency mismatch, whereas DQPSK only allows for ± 200 MHz. In general, feedback-controlled DI tuning within the RX is needed for both DPSK and DQPSK.

VI. Optical Networking With Advanced Modulation Formats

Advanced optical networks require densely packed WDM channels to propagate over long distances, including optical routing by means of optical add/drop multiplexers (OADMs), without optical-to-electrical-to-optical regeneration. The basic structure of such a WDM system is shown in Fig. 11. The optical signals generated by N TXs at wavelengths λ_i are multiplexed onto a single optical fiber using a WDM multiplexer (mux). Acting as an optical bandpass filter for each channel, a mux confines the spectral extent of a modulation format to avoid WDM crosstalk with neighboring channels (see Section VI-B). After propagating over a series of transmission fiber spans and periodically spaced OAs, the WDM channels are separated using a WDM demultiplexer (demux) and detected by per-channel RXs. The demux again acts as an optical bandpass filter for each channel to suppress both interference from neighboring WDM channels and OA noise. A possible OADM architecture, consisting of a demux followed by a mux, with intermediate access to the individual WDM channels, is also shown in Fig. 11.

In the remainder of this section, we address the question of how advanced optical modulation formats can help to combat impairments found in spectrally efficient optically routed WDM networks. In general, modulation formats simultaneously need to be resilient to OA noise, CD, PMD, fiber nonlinearity, and repeated optical filtering.

A. Loss, Amplification, and Noise

Single-mode optical fiber is an exceptionally transparent medium, with attenuation coefficients below 0.2 dB/km across a bandwidth of many terahertz. Nevertheless, after substantial propagation distances, as well as after passing through networking elements such as ROADMs, the signal power falls below the detectability threshold of optical RXs, which makes systems require optical amplification. OAs can either be designed as lumped elements (e.g., erbium-doped fiber amplifiers [75]), or amplification can be distributed by introducing gain along the transmission fiber (e.g., distributed Raman amplification [76]). From a digital communications point of view, the main impact of optical amplification is the generation of amplified spontaneous emission (ASE) [75], which by itself represents an optical source of Gaussian noise. Like the OA gain, the ASE spectrum is typically constant ("white") across the signal spectrum [75]. Note, however, that the statistical properties of ASE can be modified by nonlinear interactions during fiber propagation (cf. Section VI-E). If multiple OAs are concatenated to periodically compensate for fiber loss, ASE builds up in the system, captured by the optical signal-to-noise ratio (OSNR) [75]. The OSNR is typically defined as the average optical signal power divided by the ASE power, measured in both polarizations and in a (bit rate independent) 12.5-GHz optical reference bandwidth.

In converting the optical signal into an electrical signal $S(t)$, a square-law detecting optical RX lets the ASE field $N(t)$ beat against the optical signal field $E(t)$ to yield $S(t) \propto |E(t) + N(t)|^2 = |E(t)|^2 + |N(t)|^2 + 2\mathrm{Re}\{E(t)N^*(t)\}$. The first term on the right-hand side represents the desired electrical signal, whereas the second and third terms represent ASE–ASE beat noise and signal–ASE beat noise, respectively [75], [77]. Note that the signal–ASE beat noise term depends on the optical signal. This signal-dependent nature of detection noise is characteristic of optical communication systems. In well-designed fiber-optic RXs, the two beat noise terms dominate all other noise terms (e.g., thermal noise), and the RX is called beat-noise limited. The noise performance of a beat-noise limited RX is fully characterized by $\mathrm{OSNR}_{\mathrm{req}}$, which is the OSNR required for a specified target bit error ratio (BER) [78].

Table II gives an overview of some key characteristics of the optical modulation formats discussed in Sections IV and V. The second and third columns summarize TX and RX hardware complexities, respectively, in terms of the optoelectronic component requirements. The fourth column specifies $\mathrm{OSNR}_{\mathrm{req}}$ based on semianalytic BER simulations that properly take into account the non-Gaussian noise statistics of beat-noise limited detection through Karhunen–Loève series expansions (see [59, Appendix]). The assumed 42.7 Gb/s are representative of a 40-Gb/s per-channel bit rate, including a 7% overhead for forward error correction (FEC), as standardized for terrestrial fiber transmission systems [79]. Since enhanced FEC schemes for multigigabit/second optical communications are able to correct BER values of 10^{-3} to values below 10^{-16} [80], Table II is based on 10^{-3} as the target BER for stating $\mathrm{OSNR}_{\mathrm{req}}$. The TX implementations correspond to the ones underlying Fig. 4. All simulations assume an optical line system according to Fig. 11, with second-order super-Gaussian [81] mux and demux having 3-dB bandwidths of 85 GHz each; such filters are characteristic of a WDM system with a 100-GHz channel spacing standardized by the International Telecommunications

TABLE II
OVERVIEW OF MODULATION FORMATS AND SOME PERFORMANCE VALUES AT 42.7 Gb/s (REQUIRED OSNR AT BER $= 10^{-3}$)

Modulation format	TX complexity	RX complexity	$OSNR_{req}$ Back-to-back	$OSNR_{req}$ 10 OADMs (0.4 b/s/Hz)	$OSNR_{req}$ 5 OADMs (0.8 b/s/Hz)	CD [ps/nm] (2-dB pen.)	DGD [ps] (1-dB pen.)
NRZ-OOK	1 MZM	1 PD	15.9 dB	18.2 dB	n/a	54	8
50% RZ-OOK	1-2 MZMs	1 PD	14.4 dB	15.8 dB	n/a	48	10
67% CSRZ-OOK	2 MZMs	1 PD	14.9 dB	14.2 dB	n/a	42	11
DB	1 MZM	1 PD	16.6 dB	14.2 dB	18.4 dB	211 (152)	6
33%RZ-AMI	1-2 MZMs, 1 DI	1 PD	13.4 dB	14.8 dB	n/a	49	10
VSB-NRZ-OOK	1 MZM + 1 OF	1 PD	16.4 dB	15.6 dB	17.3 dB	63 (155)	6
VSB-CSRZ	2 MZMs + 1 OF	1 PD	14.8 dB	14.7 dB	16.7 dB	51 (154)	11
NRZ-DPSK	1 MZM	1 DI + 2 PDs	11.7 dB	12.1 dB	17.6 dB	74 (161)	10
50% RZ-DPSK	1-2 MZMs	1 DI + 2 PDs	11.1 dB	11.5 dB	17.0 dB	50 (161)	10
NRZ-DQPSK	2 nested MZMs	2 DIs + 4 PDs	13.2 dB	12.6 dB	12.9 dB	168 (176)	20
50% RZ-DQPSK	2 nested MZMs + 1 PC	2 DIs + 4 PDs	12.2 dB	12.0 dB	12.0 dB	161 (186)	21

PD: Photodiode; OF: Optical Filter; DI: Delay Interferometer; MZM: Mach–Zehnder Modulator; PC: Pulse Carver; CD: Chromatic Dispersion; DGD: Differential Group Delay; OADM: Optical Add/Drop Multiplexer.

Union (ITU) [82]. The RX electronics are assumed to have a fifth-order Bessel low-pass characteristics with 30-GHz bandwidth. Nonideal component characteristics (e.g., group delay ripple of filters and undesired frequency offsets of filters or DIs) are neglected.

While actually measured values for $OSNR_{req}$ may differ somewhat from the numbers given in Table II due to various optical and electronic hardware implementation aspects, some general facts are worth mentioning: First, RZ formats in general require 1–3 dB less OSNR for identical BER than their NRZ equivalents [83]. For beat-noise limited RXs, this is mostly due to the reduced impact of intersymbol interference (ISI) on RZ formats. RZ-AMI turns out to be particularly well performing among all OOK formats, which has also been proven experimentally [50].

The spectrally narrow DB format exhibits a back-to-back penalty of typically 1–2 dB compared to OOK formats. This penalty is generated by the V-shaped eye opening [cf. Fig. 4(d)], leading to poor 0-bit detection performance, as well as by the wider-than-optimum optical filtering assumed [84]. As such, the penalty depends on the choice of filters at TX and RX; for the numbers given in Table II, an 11-GHz fifth-order Bessel electrical low-pass filter was used to implement the DB TX. As discussed below, the penalty is reduced by tighter optical filtering (acting on the eye shape and on detection noise) or by residual CD (acting on the eye shape only).

Using DPSK instead of intensity modulation, OSNR requirements are significantly reduced. The gain of balanced-detection DPSK over OOK is generally independent of the target BER and typically amounts to around 3 dB (cf. RZ-OOK and RZ-DPSK in Table II). Depending on the modulation waveforms, extinction ratios, and optical as well as electrical filters, the gain of DPSK can also exceed 3 dB (cf. NRZ-OOK and NRZ-DPSK in Table II, where the 4.2-dB sensitivity difference is mainly due to an assumed 16-dB modulator extinction). The most sensitive of the modulation formats in Table II, which is practically suitable for multigigabit/second operation, is RZ-DPSK.

It is worth noting from Table II that DQPSK requires only 1–1.5 dB higher OSNR than DPSK at poor BER (e.g., 10^{-3}). At good BER (e.g., 10^{-12}), the OSNR gap between DPSK and DQPSK increases, and DQPSK approaches the performance of OOK [21]. Leaving aside TX/RX complexity aspects, the good OSNR performance at FEC error ratios makes DQPSK an attractive candidate for optically routed networks that require narrow optical signal spectra [69].

B. Filter Narrowing and WDM Crosstalk

One of the most striking differences among the modulation formats displayed in Fig. 4 is their different spectral extent. Not surprisingly, some formats are better suited than others when it comes to tight WDM channel packing, quantified by the SE [20] or ISD [9], which is defined as the ratio of net per-channel information data rate to the WDM channel spacing. Over the past few years, optical transport systems have been pushed to SEs of 0.8 bit/s/Hz [9], [68], [69], [85], [86] and, in some research experiments, even beyond, both without [71] and with the use of polarization multiplexing [87] or polarization interleaving [88]. Apart from important SE-dependent nonlinearity considerations (see Section VI-E), the two dominant impairments arising from dense WDM channel spacings in optically routed networks are coherent WDM crosstalk and filter narrowing.

Similar to signal–ASE beat noise, coherent WDM crosstalk between an optical signal field and the copolarized residual optical field of a neighboring WDM channel after WDM demultiplexing produces beat interference at square-law detection [89]. Careful mux and demux design has to ensure that WDM crosstalk is suppressed as much as possible, whereas signal distortions through overly narrow optical filtering are kept to a minimum [90].

Multiple OADMs in optically routed networks with high SE represent a "concatenation" of several mux–demux filters to the express channels, i.e., channels going through the OADM without being dropped (cf. Fig. 11); this concatenation narrows the overall optical filter bandwidth and distorts the signal.

The fifth and sixth columns in Table II give the required OSNR for the concatenation of ten OADMs in a system suitable for 0.4-bit/s/Hz SE (85-GHz bandwidth for mux and demux filters at the TX, RX, and within each OADM) and five OADMs for 0.8-bit/s/Hz SE (43-GHz bandwidth for mux and demux filters at the TX, RX, and within each OADM), respectively. It can be seen that some formats, most notably DB, exhibit an OSNR improvement when tightly filtered. This phenomenon arises both from ASE truncation and from beneficial waveform shaping through filtering [84], [91]. It can also be seen that supposedly narrow-band modulation formats (most notably NRZ-OOK) do not lend themselves well to concatenated filtering at high spectral efficiencies because of their high susceptibility to ISI and, hence, their low robustness to filter-induced signal distortions. Offsetting the laser frequency and properly shaping the mux filter to produce VSB enables 0.8 bit/s/Hz for both VSB-NRZ and VSB-CSRZ. (In Table II, both VSB mux and laser frequency offset were numerically optimized for five OADMs in a system suitable for 0.8-bit/s/Hz SE.)

Note that the simulation results shown in Table II represent the effect of filter concatenation only, as they were carried out for a single WDM channel. Strictly speaking, the values therefore apply to a WDM system using polarization interleaving. Depending on the modulation format, coherent WDM crosstalk can lead to further penalties, especially at 0.8-bit/s/Hz SE; properly capturing coherent WDM crosstalk in numerical simulations for various modulation formats is still a topic of active research [90]. However, it has been shown experimentally that RZ-DQPSK [69] and VSB-CSRZ [58] show no penalty in a 0.8-bit/s/Hz SE WDM networking environment.

Another aspect of filter narrowing is closely related to nonlinear fiber propagation: Since OADMs can be spaced by several hundred kilometers in optically routed networks, a modulation format suitable for high-SE networks has to simultaneously lend itself to multiple passes through OADMs and to nonlinear fiber propagation over appreciable distances. The impact of joint impairments incurred in this scenario has been experimentally studied for 40-Gb/s systems with 0.4- and 0.8-bit/s/Hz SE using a variety of modulation formats [8], [85], [86], [92], [93]. In these studies, DB, VSB-CSRZ, and RZ-DQPSK are identified as the best suited formats for optically routed networks at 0.8-bit/s/Hz SE.

C. CD

As discussed in standard textbooks on fiber optics [81], CD produces a spread in the propagation speed for different spectral components contained in a modulated optical signal, which in the time domain results in signal distortions and typically in pulse broadening. The resulting ISI degrades the signal quality; for OOK, it corrupts the peak amplitude of the `1`-bits and raises the amplitude within the `0`-bits through optical interference of neighboring `1`-bits. Due to the symmetric transfer function of CD, optical signal fields whose spectral phase is symmetric (or antisymmetric) around zero frequency experience the exact same amount of distortion for equal *positive* and *negative* values of dispersion. This applies in particular to real-valued unchirped modulation formats. In contrast, chirped formats are distorted differently for positive and negative dispersions.

The sevenths column in Table II quantifies the accumulated CD (in picoseconds per nanometer) that yields a 2-dB penalty in $\mathrm{OSNR}_{\mathrm{req}}$ at 42.7 Gb/s, assuming no OADMs and mux/demux bandwidths of 85 GHz. Most modulation formats exhibit dispersion tolerances on the order of 50 ps/nm, the exception being some spectrally narrow[3] formats, which in general yield significantly better dispersion tolerance [7], [23]. This is reflected by the high values for DB and DQPSK. Note that CD tolerance values, like back-to-back OSNR requirements, can depend, to an appreciable extent, on the waveforms and filters used in the system. Where applicable, the numbers in brackets in the seventh column of Table II refer to the dispersion tolerance in a system with five OADMs at 0.8-bit/s/Hz SE (cf. Section VI-B). Since filter narrowing curtails the signal spectrum, an increase in dispersion tolerance is typically observed. Only DB, tailored for high dispersion tolerance in the absence of severe optical filtering, sees a reduction in dispersion tolerance (albeit an improvement in sensitivity) when tightly filtered. This discussion shows that the performance of a modulation format to various impairments cannot be taken in isolation but has to be evaluated in the context of the system it is operating in. Another important example is the format-dependent shrinkage of dispersion tolerance in the presence of fiber nonlinearity, which, for example, is more pronounced for DB than for NRZ-OOK [94]. Furthermore, we want to point out that advanced digital signal processing can significantly increase the dispersion tolerance, which has been demonstrated widely at 10 Gb/s [1].

Note that the CD values given in Table II apply for 42.7 Gb/s and scale quadratically with bit rate: A fourfold increase in bit rate is accompanied by a 16-fold reduction in dispersion tolerance.

D. PMD

Because of its circular symmetry, the transverse propagation mode of single-mode fiber exists in two degenerate polarization modes, which have identical propagation properties in ideal optical fibers. In reality, however, minute waveguide asymmetries, either due to manufacturing imperfections or to mechanical stress imposed on the fiber, let the two polarization modes become slightly nondegenerate. The resulting two polarization eigenstates are called principal states of polarization (PSP), exhibiting different group velocities and giving rise to a differential group delay (DGD). The DGD manifests itself in dispersive pulse broadening: After square-law detection, the electrical signal is given by the sum of the signal powers in both (x and y) polarizations, $S(t) = |E_x(t)|^2 + |E_y(t - \mathrm{DGD})|^2$. This phenomenon is called PMD [95]. If the DGD is constant over wavelength, we refer to first-order PMD, which dominates higher orders for many applications.

The eighth column in Table II quantifies the tolerance of different modulation formats to first-order PMD. It shows the (instantaneous) DGD (in picoseconds) that leads to a 1-dB OSNR penalty. For most modulation formats, a 1-dB penalty occurs at a DGD between 30% and 40% of the symbol duration, with RZ formats being in general more resilient to PMD than NRZ formats [95]. Note that the resilience to PMD, in addition, depends to an appreciable extent on the waveforms and filters [96], as well as on other residual distortions. For example, the tolerable amount of DGD for DB is almost doubled (1-dB penalty at 11-ps DGD) when operated at 211-ps/nm residual CD [97]. A similar effect is seen for VSB-NRZ when passing through five OADMs at 0.8-bit/s/Hz SE (1-dB penalty at 10-ps DGD). Note that the tolerance to first-order PMD scales linearly with symbol duration. Therefore, DQPSK has about twice the PMD tolerance of binary modulation formats at the same bit rate.

The main problem with PMD in optical fiber systems is its stochastic nature, letting PSPs and instantaneous DGD vary on timescales between milliseconds (acoustic vibrations) and months (temperature variations of buried fiber) [98]. The rare occurrence of exceedingly high DGD values prohibits worst-case system design; instead, systems are allocated some margin (e.g., 1 dB), and the rare occurrence of DGDs exceeding the margin results in system outage [95].

E. Fiber Kerr Nonlinearity

Due to the high confinement of light within the core of a single-mode fiber, very high optical intensities can be reached inside the fiber. Such high intensities induce changes in the fiber's refractive index (Kerr nonlinearity). Kerr nonlinearity induces signal distortions over long propagation distances [81]. Several distinct regimes of transmission exist in systems incorporating dispersion compensation. All these regimes are geared toward minimizing the impact of fiber nonlinearities. Associated with each regime are a few dominant types of fiber nonlinearities. The dominant nonlinearities in a system often determine the suitability of advanced modulation formats to improve nonlinear transmission.

1) Nonlinear Transmission Regimes: At per-channel data rates of 10 Gb/s and above, three regimes of transmission over optical fibers are prominent: dispersion-managed solitons; quasi-linear transmission; and pseudo-linear transmission.

If fiber dispersion is periodic across the transmission path, with a sufficiently low path-averaged value (preferably anomalous dispersion, i.e., positive dispersion parameter D [81]), pulses with a periodic evolution exist for which fiber nonlinearity and dispersion are on average compensated.[4] Such pulses are called dispersion-compensated solitons or dispersion-managed solitons [99]. Dispersion-managed solitons are the solitons that best fit fiber-optic communication systems using dispersion compensation and have been used in many system experiments [100]–[103] at 10 Gb/s, where the required moderate balance between dispersion and nonlinearity occurs.

One alternative to dispersion-managed solitons at 10 Gb/s is the chirped RZ (CRZ) regime [104], [105], which can also be considered part of the quasi-linear regime. Here, an analog periodic phase modulation is imprinted on the RZ-OOK signal, with a phase modulation index tailored to the length of the transmission line. This decreases the solitonic effect in the line, generally resulting in similar or slightly better performance than dispersion-managed soliton systems [105].

Another regime of transmission, referred to as *pseudo-linear transmission* [106]–[108], allows efficient nonlinear transmission for high-speed signals ($\gtrsim$ 10 Gb/s). In this regime, the signal waveform evolves very rapidly along the fiber length, which averages out the nonlinearities between bits from the same channel as well as the nonlinearities between different channels. Very short pulses (symbol durations of 20 ps and less) are required to enter this regime. Signals at per-channel bit rates as high as 320 Gb/s have been transmitted in this regime [109].

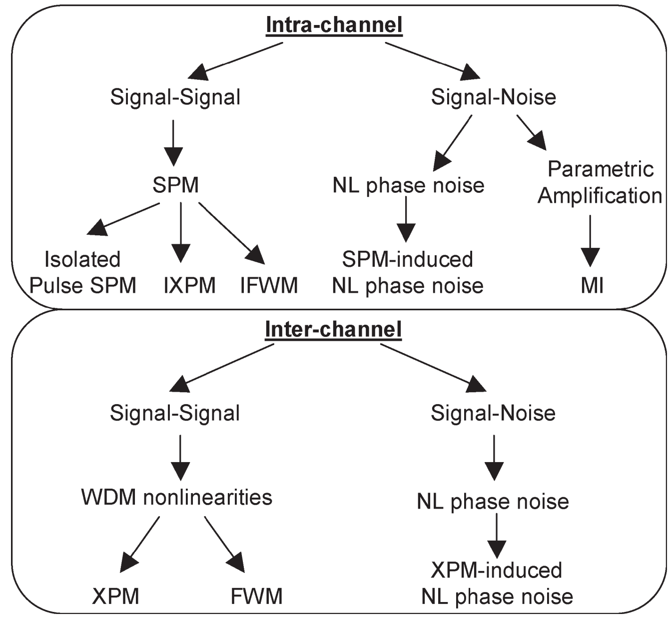

Fig. 12. Classification of nonlinearities in optical fibers. Intra-channel and inter-channel stand for nonlinearities occurring within or between WDM channels, respectively. SPM: self-phase modulation; (I)XPM: (intra-channel) cross-phase modulation; (I)FWM: (intra-channel) four-wave mixing; MI: modulation instability; NL: nonlinear.

2) Types of Nonlinear Distortions: Fig. 12 presents a summary of the various nonlinear interactions. Fiber nonlinearities occurring between pulses of the same WDM channel or between a single WDM channel and ASE are referred to as *intra-channel* nonlinearities. When the nonlinearities require the presence of two or more WDM channels, we use the expression *inter-channel* nonlinearities. The importance of each class of nonlinearities depends significantly on the per-channel bit rate. As a rule of thumb, inter-channel effects affect WDM systems most strongly at per-channel bit rates of 10 Gb/s and below (i.e., dispersion-managed solitons and quasi-linear regime), whereas intra-channel nonlinearities affect systems most strongly at bit rates above 10 Gb/s (i.e., pseudo-linear transmission). The impact of fiber nonlinearity also depends on the local fiber dispersion: In general, lower dispersion fibers have stronger inter-channel effects than fibers with high local dispersion.

Nonlinear interactions between signal and noise depend significantly on the noise level and become stronger if the OSNR is poor during propagation, which has become a common situation for systems using FEC.

The impact of fiber nonlinearity on various modulation formats depends strongly on the physical characteristics of the underlying optical network. Fig. 13 presents the results of an extensive numerical study, showing the dominant nonlinearity for a given spectral efficiency and fiber dispersion for OOK modulation with various RZ duty cycles. The transmission distance is 2000 km, and nonlinear interactions between signal and noise are neglected. For a given spectral efficiency (upper x-axis), the figure gives the optimum per-channel bit rate (lower

[4] This is in contrast to the exact balance of dispersive effects and nonlinear effects required for fundamental solitons.

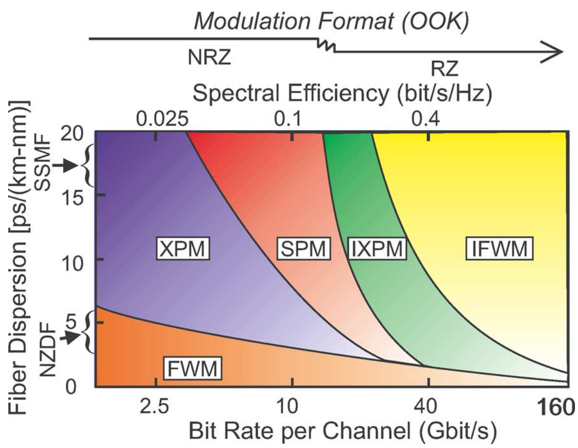

Fig. 13. Significance of inter-channel and intra-channel nonlinear impairments in WDM systems of different per-channel bit rates. For high-speed TDM systems exceeding 10 Gb/s per channel, the dominant nonlinear interactions are intra-channel nonlinearities. SSMF: standard single-mode fiber; NZDF: non-zero dispersion fiber. (Color version available online at http://ieeexplore.ieee.org.)

x-axis) that allows for maximum energy per bit transported at a fixed penalty due to nonlinearities; this results in the best BER. The figure then shows the most important nonlinearity that limits transmission for various local fiber dispersion values (vertical axis). The broken arrow at the top of Fig. 13 shows that the optimum modulation format in terms of nonlinear transmission changes from NRZ to RZ (50% and 33% duty cycles) at around 10 Gb/s per channel.

3) Signal–Signal Interactions: Both inter-channel and intra-channel nonlinearities can be broken down into more elementary interactions, as displayed in Fig. 12. This can be performed by decomposing an aggregate of WDM channels into the sum of individually interacting WDM channels (for inter-channel nonlinearities) or a single WDM channel into the sum of individually interacting bits (for intra-channel nonlinearities). Decomposition into individual channels results in the phenomena of cross-phase modulation (XPM) and four-wave mixing (FWM) occurring between WDM channels. Decomposition of a channel into individual pulses leads to the phenomena of intra-channel XPM (IXPM) and intra-channel FWM (IFWM). The nonlinear interaction of a channel or a pulse with itself is referred to as self-phase modulation (SPM). Whether SPM relates to an entire channel or an isolated pulse depends on the context.

Intra-channel nonlinearities are particularly important to advanced optical modulation formats at high per-channel bit rates. Numerous detailed analyses reveal how these nonlinearities impact transmission [108], [110]–[112]. Fig. 14 shows the effects of IXPM and IFWM, respectively, as experienced by a 40-Gb/s RZ-OOK signal after nonlinear propagation. In the case of dominating IXPM (upper graph), timing jitter is present after transmission. In a system limited by IFWM (lower graph), shadow pulses (ghost pulses) [106], [107] are created in originally empty time slots. Amplitude jitter is also present, and both effects impair transmission for systems limited by IFWM [108]. IFWM is particularly affected by auxiliary phase coding (pseudo-multilevel or correlative coding) used by advanced modulation formats [113].

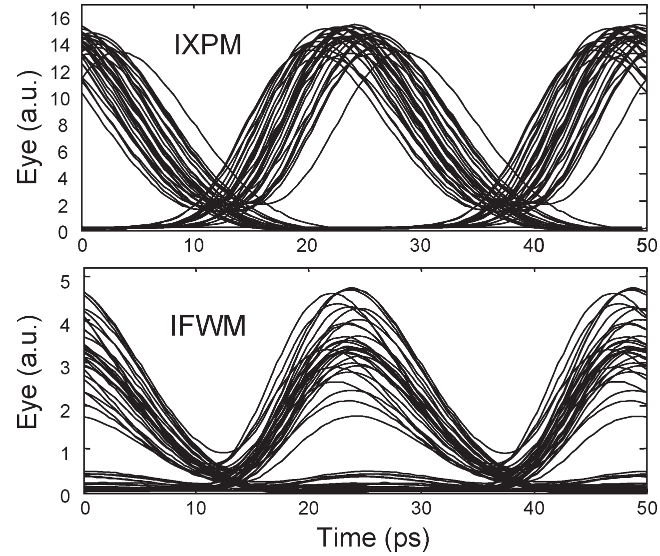

Fig. 14. Effect of IXPM and IFWM on a 40-Gb/s RZ-OOK signal. One can easily see on the upper graph the timing jitter for a system limited by IXPM, whereas amplitude jitter and shadow (ghost) pulses can be observed in the eye diagram for the lower graph for a system limited by IFWM.

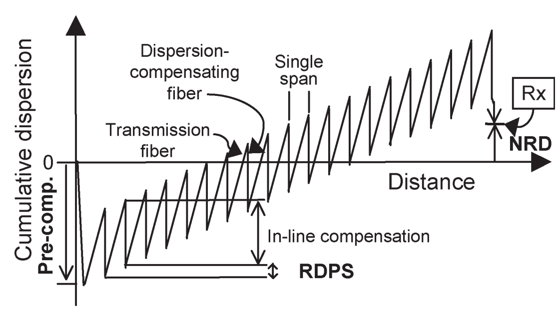

Fig. 15. Example of a dispersion map showing the cumulative dispersion as a function of distance.

4) Dispersion Mapping: One of the most powerful and most widely used techniques to reduce the impact of fiber nonlinearity is the use of dispersion mapping, referring to the precise placement of dispersion-compensating fiber in optical networks [108], [114], [115]. Fig. 15 shows an example of a dispersion map. This type of dispersion map, having the same residual dispersion for every span, is referred to as a singly periodic dispersion map. Such a map represents an idealization of real terrestrial systems, which show variations of dispersion due to geographic boundary conditions. Only three parameters are necessary to define a singly periodic dispersion map: 1) dispersion precompensation; 2) residual dispersion per span (RDPS); and 3) net residual dispersion (NRD). The optimization of these three parameters for a given fiber type, bit rate, channel spacing, and modulation format allows for maximum signal launch power and thus largest delivered OSNR at the RX and best BER [116] while keeping low nonlinearity-induced signal distortions.

An example of the way dispersion maps are analyzed is given in Fig. 16. The transmission performance is represented by contours of isopenalties for NRZ-OOK [Fig. 16(a)] and 20% duty cycle RZ-OOK [Fig. 16(b)]. Transmission is for a single channel at 12 dBm per channel over eight spans of 80 km. The

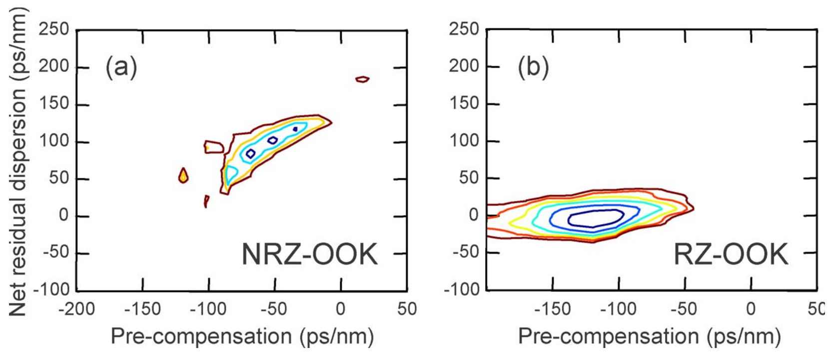

Fig. 16. Example of a robustness analysis for a singly periodic dispersion map and NRZ-OOK (left) and 20% duty cycle RZ-OOK (right) at 40 Gb/s. The outermost contour of each "island" represents 5-dB penalties decreasing by 1 dB going inward. Notice the differences in the optimum dispersion values of NRD and precompensation between the two formats. (Color version available online at http://ieeexplore.ieee.org.)

fiber dispersion is $4\ \mathrm{ps/(km \cdot nm)}$ and an RDPS of 16 ps/nm. The fiber effective area is 55 $\mu\mathrm{m}^2$. Such contour plots allow to find optimally robust dispersion map parameters. Additional contour plots for different values of RDPS are necessary to establish the robustness of a singly periodic dispersion map to variations of RDPS. Note that the optimum dispersion map and robustness of a map may depend on the modulation format as is the case for the two formats in Fig. 16.

5) Signal–Noise Interactions: In addition to the signal–signal interactions described in the previous section, the signal can also interact with optical noise through fiber nonlinearities. The dominant optical source of noise in a transmission line is typically the ASE generated by inline optical amplification.

The dominant form of nonlinear signal–noise interactions manifests itself in noise-induced nonlinear distortions of specific signal characteristics (e.g., amplitude, timing, phase, or frequency [117]). Upon nonlinear propagation, the temporal pulse profile can be well preserved, but fluctuations in other pulse characteristics due to nonlinear interactions can largely exceed the fluctuations induced by the simple accumulation of noise in the absence of fiber nonlinearities. An example of signal–noise nonlinear interaction that is particularly relevant to advanced phase modulation formats is nonlinear phase noise, which is sometimes referred to as the Gordon–Mollenauer effect [118]. This effect can be explained as follows: Noise that happens to add constructively to some bits in a pulse train results in an increase in amplitude for these bits, whereas noise that adds destructively to some other bits results in reduced pulse amplitudes. These noise-induced random differences in pulse amplitudes among different bits affect SPM-induced phase rotations. Random amplitude differences are therefore translated into random phase differences by fiber nonlinearity. This bit-to-bit randomization of the optical phase is particularly harmful to modulation formats that use phase coding to transmit data, such as DPSK [119], [120] and DQPSK. Fig. 17 shows the effect of nonlinear phase noise on a 50% duty cycle RZ-DPSK signal at 42.7 Gb/s using a balanced RX [121]. In these Monte Carlo-based simulations, the noise field is added to the signal field at different locations along the transmission line. The signal distortion is measured by the required OSNR necessary to obtain a BER of 10^{-3}. The lower curve (circles) applies to a hypothetical system

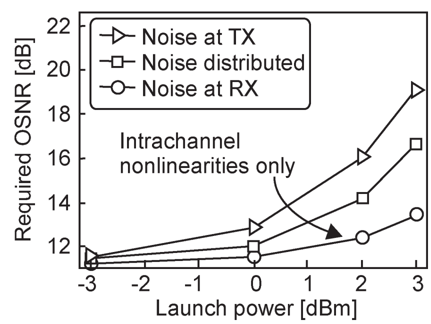

Fig. 17. Effect of nonlinear phase noise on the required OSNR for single-channel transmission of a 42.7-Gb/s 50% RZ-DPSK signal. Fiber parameters are 32 spans of 80 km, $D = 4.5\ \mathrm{ps/(km \cdot nm)}$, $S = 0.045\ \mathrm{ps/(nm^2 \cdot km)}$, $\alpha = 0.2$ dB/km, $n_2 = 2.5 \times 10^{-20}\ \mathrm{m^2/W}$, and $A_{\mathrm{eff}} = 52.86\ \mu\mathrm{m}^2$. The dispersion map is a SPDM with precompensation $= -250$ ps/nm, RDPS $=$ 20 ps/nm, and NRD $=$ 20 ps/nm.

where noise is only added at the RX. Thus, only deterministic (intra-channel) signal–signal nonlinearities are present but no nonlinear phase noise. When, again hypothetically, all the noise is added at the TX and copropagates with the signal over the entire transmission line, the RX needs a higher OSNR to maintain BER $= 10^{-3}$ due to nonlinear phase noise (triangles). A realistic system, where noise is added at every OA along the transmission path (32 OAs in this case), is represented by squares in Fig. 17.

In addition to SPM, XPM can also mediate nonlinear phase noise [122]. The amplitude variations created by noise on channels can be transferred as phase distortions onto other channels through XPM. This phenomenon can become an important limitation for tight channel spacings ($\sim$50 GHz and below) at low bit rates ($\lesssim$ 10 Gb/s) [122].

F. Nonlinearities and Modulation Formats

Although a detailed understanding of the limitations from fiber nonlinearities for advanced modulation formats is still an active research topic, some numerical and experimental investigations suggest the types of nonlinear effects that are typically limiting transmission: Intensity-modulated formats are limited by the nonlinear effects shown in Fig. 13. For phase-modulated formats, at 2.5 and 10 Gb/s, the main limitations on nonlinear transmission generally come from nonlinear phase noise. At 40 Gb/s and above, intra-channel nonlinearities dominate, although nonlinear phase noise can become a limitation at low OSNR (see Fig. 17). Since fiber nonlinearity depends on a multitude of system parameters, the comparison of modulation formats with respect to their resilience to fiber nonlinearity often greatly depends on the system design and operating conditions. As a result, one should be careful to specify the characteristics of the system considered when quoting the impact of nonlinearities on an advanced modulation format.

The remainder of this section focuses mostly on per-channel data rates of 40 Gb/s since this is where advanced modulation formats start to become most beneficial. Additional comparisons of various advanced modulation formats for nonlinear transmission can be found in [123]–[125].

One of the first advanced modulation formats that was discussed in the context of optically amplified transmission systems was DB. At 10 Gb/s, the primary goal for using DB is to increase dispersion tolerance, whereas at 40 Gb/s, DB is mainly attractive for high spectral efficiency WDM systems. Despite its early implementation [39], [40], only a limited number of long-distance DB transmission demonstrations have been performed [125]–[129]. At 40 Gb/s, the resistance of DB to nonlinear transmission (with near-optimum dispersion mapping) does not differ substantially from similar duty cycle OOK [125], [130].

Early studies of the effect of fiber nonlinearity on advanced modulation formats at per-channel data rates of 40 Gb/s used CSRZ [35], [131]. High powers over short reach showed that CSRZ is capable of suppressing IFWM due to the alternating phases from bit to bit [36], [132]. CSRZ was later used for longer reach experiments [133], and high spectral efficiencies of 0.8 bit/s/Hz using strong optical filtering at the TX were achieved [134].

As mentioned in Section IV-E, narrow optical filtering can be applied at the TX or at the RX to generate VSB formats [9], [18], [135], [136]. Experimental demonstrations [9], [56] suggest that, in the pseudo-linear transmission regime, nonlinear transmission of VSB formats does not significantly differ from the transmission of the same signal without VSB filtering (double-sided formats).

Since IFWM depends on the relative phase between pulses [108], a variety of ways to encode an auxiliary optical phase modulation on the signal can be developed to suppress the specific effects of IFWM [30], [137]–[143]. In a particularly interesting study [139], Randel *et al.* showed that an optimum choice of relative phases between adjacent pulses to suppress IFWM in a set of four consecutive bits can be either $\{0, \pi/2, 0, \pi/2\}$ or $\{0, 0, \pi, \pi\}$. The mechanism for the reduction of IFWM using these coding schemes is by destructive interference of IFWM effects [139], [144]. These auxiliary phase encoding leads to modulation schemes with memory, either using pseudo-multilevel modulation or correlative coding (cf. Fig. 1).

Phase modulation (DPSK and DQPSK) has received considerable attention in recent years, mainly due to improved RX sensitivity relative to OOK when balanced detection is employed (cf. Table II). The nonlinear transmission of phase modulation formats is affected mainly by nonlinear phase noise [119], [122] (at 10 Gb/s) and by IFWM (at 40 Gb/s and higher). Because phase modulation is affected by nonlinear phase noise, transmission penalties are determined not only by the signal evolution but also by the level of copropagating noise, which should always be quoted in this context (cf. Fig. 17).

Propagation of 40-Gb/s DPSK over the most common fiber types [non-zero dispersion fiber (NZDF) and standard single-mode fiber (SSMF)] indicates that DPSK has a similar resistance to fiber nonlinearity as CSRZ when operated at an OSNR at the RX that yields a BER of around 10^{-3}, which is suitable for FEC decoding. Although DPSK and CSRZ may have similar resistance to fiber nonlinearity, the improved RX sensitivity of DPSK generally results in better BER for DPSK relative to CSRZ, resulting in better system performance.

Many flavors of DPSK exist, including various RZ duty cycles ranging typically from 33% (RZ-DPSK) to 100% (NRZ-DPSK). In pseudo-linear transmission, formats with lower duty cycles are generally more resistant to intra-channel nonlinearities for OOK formats [108]. However, for DSPK, the differences in nonlinear transmission between similar ranges of duty cycles are rather small [145], [146].

Promising transmission results of DQPSK have also been reported [68], [69], [147]. A comparison of some aspects of transmission performance of DQPSK relative to other modulation formats can be found in [148] and [149].

Finally, future optically routed networks will incorporate OADMs and the simultaneous resistance to the effects of optical filtering from OADMs on the one hand, and fiber nonlinearity on the other hand is required. A study [92] of long-haul propagation of different binary formats at 42.7 Gb/s in a transmission line that incorporate OADMs shows that nonlinear transmission can be strongly altered after tight optical filtering. Such findings emphasize how severely the nonlinearity performance of advanced modulation formats depends on the particular network specifications.

VII. Conclusion

High per-fiber capacities at an attractive cost per transported information bit are enabled by spectrally efficient WDM transport on flexible optically routed networks. Advanced modulation formats play an important role in the design of such networks. We discussed the generation and detection of the most important optical modulation formats for multigigabit/second per-channel data rates, where limits of available RF technology place important restrictions on the implementation of transponders. We compared intensity and phase modulation formats with respect to their back-to-back RX performance and discussed the robustness of modulation formats to signal distortions induced by CD, PMD, narrowband optical filtering, and fiber Kerr nonlinearity.

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