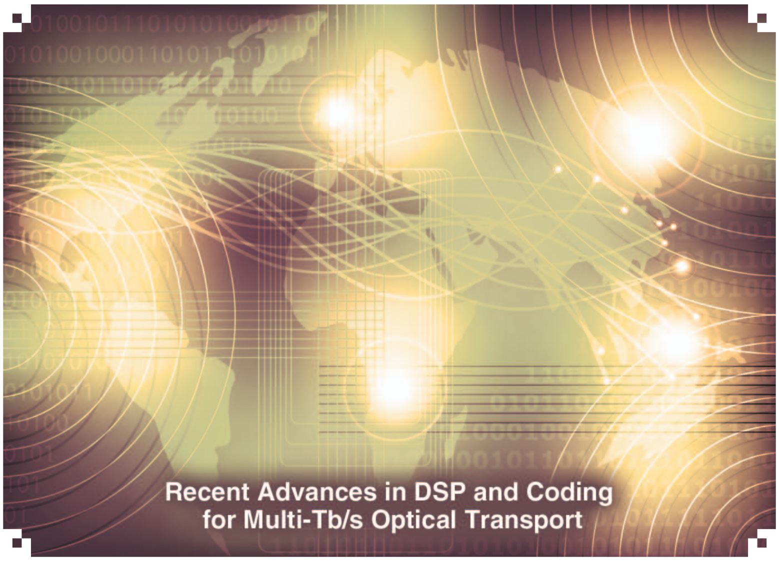
Liang B. Du, Danish Rafique, Antonio Napoli, Bernhard Spinnler, Andrew D. Ellis, Maxim Kuschnerov, and Arthur J. Lowery

Digital Fiber Nonlinearity Compensation

Toward 1-Tb/s transport



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The world is connected by a core network of long-haul optical communication systems that link countries and continents, enabling long-distance phone calls, data-center communications, and the Internet. The demands on information rates have been constantly driven up by applications such as online gaming, high-definition video, and cloud computing. All over the world, end-user connection speeds are being increased by replacing conventional digital subscriber line (DSL) and asymmetric DSL (ADSL) with fiber to the home. Clearly, the capacity of the core network must also increase proportionally.

In the 1980s and 1990s, speeds in the core network were pushed forward by technologies such as external modulation and the erbium doped fiber amplifier (EDFA), which supported wavelength division multiplexing (WDM)—transmission of information using different colors. In the last decade, commercial systems have adopted coherent optical receivers and digital signal processing (DSP) to transmit 100 Gb/s per wavelength on over 80 wavelengths, enabling transmission capacity of ≥ 8 Tb/s per fiber. However, even with this impressive technological development, such system capacities will soon be insufficient to meet the demands of consumers.

The data rate in an optical transmission system is currently limited by amplified spontaneous emission (ASE), which determines the minimum power launched into each fiber span, and the interplay between chromatic dispersion (CD) and Kerr fiber nonlinearity, which limits the maximum launch power [1]. To increase the data rate of current-generation coherent systems, fiber nonlinearity compensation is required to enable higher launch powers, thereby providing enough optical signal-to-noise ratio (OSNR) to support larger constellation sizes [2]. Although

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fiber nonlinearity and CD are both deterministic effects, their interplay along the length of the fiber is difficult to undo with optical components or DSP.

In this article, we describe the nonlinear fiber channel and its impact on optical communication systems. We then introduce two promising fiber nonlinearity compensation techniques: inverse fiber models [2]–[6] and pilot-aided phase compensation [7], [8], which may be useful in transmission systems operating at 400 Gb/s, 1 Tb/s, and beyond. We review the fundamental limitations of each method and illustrate their effectiveness, both for single-carrier and multicarrier systems. Finally, the practicality of various approaches is compared, in terms of the hardware requirements for digital nonlinear compensation.

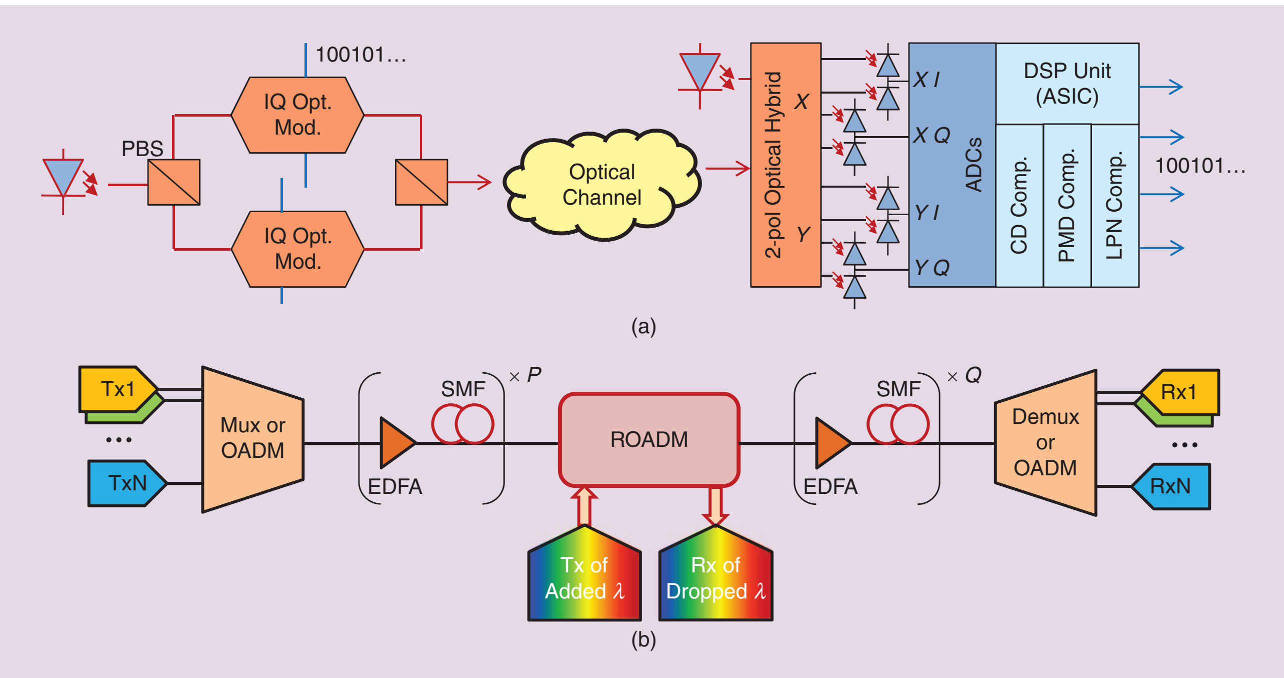
IN THIS ARTICLE, WE DESCRIBE THE NONLINEAR FIBER CHANNEL AND ITS IMPACT ON OPTICAL COMMUNICATION SYSTEMS.

REVIEW OF OPTICAL COMMUNICATIONS

BRIEF HISTORY

Optical fibers were first proposed by Nobel Laureate Kao as a suitable medium for transmitting growing telecommunications traffic at the time. He argued that the low loss and the large transmission bandwidth made them ideal for long-distance point-to-point communications. Systems using single-mode fibers (SMFs) became prominent in the 1980s, offering increased bandwidth and repeater spacing compared with copper lines. These systems operated at tens to hundreds of megabits per second. Technological breakthroughs enabled 960 Gb/s in a single fiber by 1999. These breakthroughs included dispersion engineered fibers to overcome pulse spreading from CD, wavelength selective multiplexers to combine multiple wavelengths in a single fiber (commonly referred as WDM), EDFAs to amplify multiple wavelengths, and external modulators to enable symbol rates of >10 Gbaud. Binary information was coded on the intensity of the light and detected with photodiodes, which produce an electrical current proportional to the intensity. These systems were referred to as *nonreturn-to-zero (NRZ)* or *intensity-modulated direct-detection systems.*

In 2005, Nortel (now Ciena) developed a 10 Gb/s NRZ system that used DSP to compensate for the CD in over 1,000 km of standard-SMF (S-SMF) by pre-compensating for CD at the transmitter. The high computational power required was provided by parallelization and application-specific integrated circuits (ASICs). Soon after, they introduced 40 Gb/s coherent optical quadrature-phase-shift keying (CO-QPSK) transmission [9]. This system used a coherent optical receiver that linearly mapped the optical field to the electrical field, enabling detection of phase modulation. Additionally, the receivers were polarization diverse, which allowed the two independently modulated polarizations of light to be detected. Signals were generated using integrated I-Q optical modulators with polarization beam splitters (PBSs)—a technique known as polarization multiplexing (POLMUX). Using only 10 Gbaud, 40 Gb/s was achieved. DSP was a key enabler of this technology as it compensated for CD, polarization mode dispersion (PMD), and laser phase noise (LPN), as illustrated in Figure 1(a). This technological breakthrough was followed by



[FIG1] (a) The coherent optical transmitter and receiver for current generation 40 Gb/s and 100 Gb/s systems. (b) The conceptual optical link with a single ROADM.

the introduction of 100 Gb/s CO-QPSK systems, which were commercialized a few years after the initial introduction of the first coherent 40 Gb/s chip set. CD compensation using DSP is commonly referred to as electronic dispersion compensation (EDC), contrasting it to in-line optical CD compensation.

OPTICAL LINKS

Figure 1(b) illustrates a typical optical transmission system. At each node, reconfigurable optical add-drop multiplexers (ROADMs) add and drop wavelength channels. The gain bandwidth of EDFAs is between 1,530 to 1,565 nm (191.56 THz to 195.95 THz) and is known as the C-band, which can support ~100 channels uniformly spaced at 50 GHz. Often, as a rule of thumb, the amplifier spacing is assumed to be ~70–80 km (~50 miles). However, in reality, amplifiers are placed wherever it is most convenient from cost and network architecture viewpoints.

IN ADDITION TO LINEAR IMPAIRMENTS, OPTICAL FIBERS ARE ALSO INHERENTLY NONLINEAR.

SMF only allows one mode to propagate, which prevents multipath interference; this mode supports two orthogonal polarizations. Typically SMF has 0.2–0.3 dB/km loss. The loss of each fiber span is compensated with an EDFA; this generates noise in the form of ASE, which is typically modeled as additive white Gaussian noise (AWGN) to the optical field. ASE is proportional to an amplifier's gain, so sufficiently high powers (around 1 mW) are launched into each span to provide enough OSNR at the end of the link.

Most terrestrial links are $<$1,500 km (a few are $>$2,500 km) and are often in mesh networks where neighboring wavelength channels may change at ROADMs. Submarine links can be up to 9,000-km long, have regularly spaced amplifiers, and typically have no in-line ROADMs.

LINEAR FIBER IMPAIRMENTS

SMF is not a perfect transmission medium: it induces different distortions than those common in copper or wireless systems. The greatest source of pulse spreading is caused by CD [3], which causes different spectral components of a signal to propagate at different velocities, giving a quadratic phase response [6]

$$\theta(\omega) = \frac{\beta_2}{2} L \cdot (\Delta\omega)^2, \tag{1}$$

where $\theta(\omega)$ is the phase at a given angular frequency, L is the length of the fiber, β_2 is the group velocity dispersion parameter, and $\Delta\omega$ is the difference in angular frequency from the center frequency of the channel.

Prior to DSP, CD was typically mitigated using dispersion compensating fiber (DCF)—fiber engineered to provide a dispersion opposing the CD of the transmission fiber. The loss of DCF often requires additional amplifiers. The locations of the DCF were determined by optimizing the performance of WDM systems; such communication networks are usually referred to as *dispersion managed* (*DM*) systems. Optical systems may also use dispersion engineered fibers for transmission, like dispersion shifted fibers (DSFs) (CD of ~0 ps/nm/km) or nonzero DSF (NZ-DSF) (CD of ~4 ps/nm/km). Compared with the most commonly deployed fiber—S-SMF (CD of ~17 ps/nm/km)—these lower dispersion fibers allow longer links without DCFs. However, the distortion due to fiber nonlinearity in WDM systems is reduced by the presence of CD because of the phase-array effect [6], [10]. Therefore, current systems are moving toward non-DM (NDM) S-SMF links and EDC for optimal performance.

SMF can support a pair of orthogonal polarizations, so two independent signals can be transmitted along a single SMF. Imperfections in the fiber manufacturing process cause light in the two principle polarizations to travel at slightly different speeds; this is called PMD. The pulse spreading caused by PMD is referred to as *differential group delay* (*DGD*). Scattering in the fiber randomly changes the signal's state of polarization (SOP) along the fiber on a millisecond timescale, thus a signal on any initial SOP travels through a random combination of fast and slow paths to reach its destination. The random scattering of SOP along the fiber causes the mean DGD of links to be proportional to the square root of the length. Current-generation fiber links have DGDs typically $<$24 ps. This is considerably less than their accumulated CD, which can be in the order of nanoseconds.

FIBER NONLINEARITY

In addition to linear impairments, optical fibers are also inherently nonlinear. This nonlinearity is caused by the optical fiber's refractive index being slightly dependent on the optical power propagating within the fiber, called the Kerr effect. Therefore, the signal imposes an instantaneous phase retardation proportional to the instantaneous signal power given by [6]:

$$\phi_X(t) = \gamma L_{\text{eff}} \left[|E_X(t)|^2 + \frac{2}{3} |E_Y(t)|^2 \right], \tag{2a}$$

$$\phi_Y(t) = \gamma L_{\text{eff}} \left[|E_Y(t)|^2 + \frac{2}{3} |E_X(t)|^2 \right], \tag{2b}$$

where $\phi_X(t)$ and $\phi_Y(t)$ are the instantaneous phase shifts of the signal in the X and Y polarizations respectively, $E_X(t)$ and $E_Y(t)$ are the field of the optical signal in two orthogonal SOPs normalized to the square root of the optical power, γ is the nonlinearity parameter, and L_{eff} is the effective length [6], which is given by

$$L_{\text{eff}} = \frac{1 - \exp(-\alpha L)}{\alpha}, \tag{3}$$

where α is the attenuation coefficient in nepers/m.

The combined effects of CD, PMD, attenuation, and fiber nonlinearity can be described by [11]

$$\frac{\partial E_X(z,t)}{\partial z} = \left(-\frac{j}{2}\beta_2\frac{\partial^2}{\partial t^2} - \frac{\alpha}{2} + j\gamma\left[|E_X|^2 + \frac{2}{3}|E_Y|^2\right]\right)E_X(z,t), \tag{4a}$$

$$\frac{\partial E_Y(z,t)}{\partial z} = \left(-\frac{j}{2}\beta_2\frac{\partial^2}{\partial t^2} - \frac{\alpha}{2} + j\gamma\left[|E_Y|^2 + \frac{2}{3}|E_X|^2\right]\right)E_Y(z,t). \tag{4b}$$

The first term on the right describes the effects of CD, the second the loss of power, and the final the nonlinear phase shifts. This is commonly known as the nonlinear Schrödinger equation (NLSE).

To use these equations for nonlinearity compensation, the SOP must be accurately tracked along the link. This is almost impossible. However, the SOP tends to scatter over a very short distance, which allows the powers in the two polarizations to be averaged. This is described by the Manakov equations [11]:

$$\frac{\partial E_{X,Y}(z,t)}{\partial z} = \left(-\frac{j}{2}\beta_2\frac{\partial^2}{\partial t^2} - \frac{\alpha}{2} + j\gamma\frac{8}{9}[|E_Y|^2 + |E_X|^2]\right) \times E_{X,Y}(z,t). \tag{5}$$

There are currently no closed-form solutions to the NLSE. However, numerical simulations can be used to optimize optical systems. Most commercial software, such as VPItransmissionMaker, use the split-step Fourier method (SSFM) to model the nonlinear fiber. Each step contains a linear and a nonlinear section [6], [12]. A large number of short steps are required to obtain accurate simulation results. This is a very computationally intensive process and real-time simulations at Gb/s rates are well beyond the computational power available today.

DSP OF CURRENT-GENERATION COHERENT SYSTEMS

The important functional blocks of current-generation 100 Gb/s coherent systems are shown in Figure 1(a). To maximize the spectral efficiency, these systems use both orthogonal polarizations in the fiber, and signal on both the in-phase (I) and quadrature (Q) dimensions. After accounting for the overheads due to framers and forward error correction (FEC), the required gross bit rate is around 112 Gb/s. Since these systems employ four independent dimensions, a symbol rate of 28 Gbaud is used. Typically, these systems operate on a 50-GHz WDM grid, achieving the spectral efficiency of ~2.2 bits/s/Hz and occupy around 60% of the spectrum.

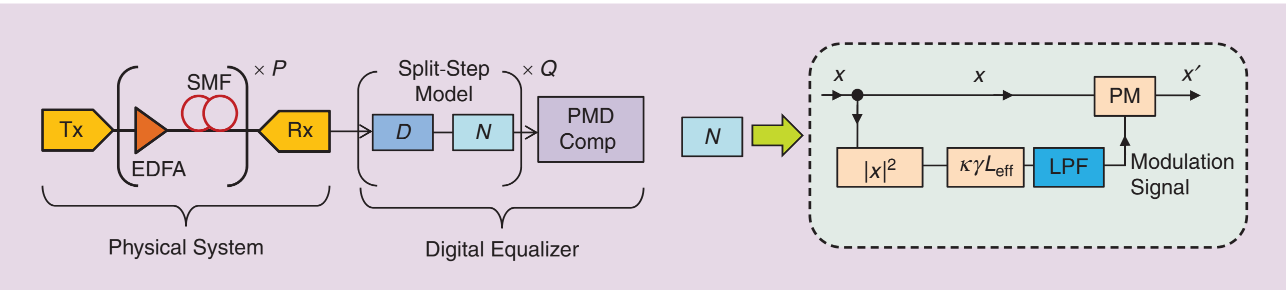
At the receiver, DSP is used to compensate for the impairments of the physical channel. The bulk of the CD in an NDM link is compensated by a frequency-domain equalizer, while the residual CD and PMD are equalized by using a 2×2 multiple-input, multiple-output (MIMO) butterfly structure, realized by means of a finite impulse response (FIR) filter. This can be realized either by blind- or training-based methods. Laser phase noise is then digitally tracked and compensated to obtain the transmitted constellations. To reduce the computational complexity of the equalizer, fibers are assumed to be linear (i.e., nonlinear mitigation is not present). The maximum reach of these systems is limited by the ASE generated within the EDFA stages and the interplay between CD and fiber nonlinearity [10], [13].

INVERSE MODEL NONLINEARITY COMPENSATION

NONLINEAR DIGITAL BACKWARD PROPAGATION

The NLSE governs the propagation of signals in optical fiber [see (4)]. If the polarities of loss, dispersion, PMD, and nonlinearity parameters are reversed, the same equation can be used to model a fictitious fiber with exactly opposite characteristics compared to the real fiber used for transmission. The distortions produced by the fictitious fiber will cancel the ones of the real fiber [14]. Although such a fiber does not exist, this concept paved the way for digital backward propagation (DBP), which digitally solves the reversed NLSE.

DBP was first proposed in 2005. A digital inverse link model was placed before the transmitter to launch a predistorted signal into the physical transmission link [15]. The predistortion is removed by the physical link so the received signal is almost perfect. Since the SOP along the link is almost impossible to track, the Manakov equations, shown in (5), were used. In 2008, an inverse nonlinear model was used after a coherent receiver [3]–[5], similar to that shown in Figure 2. The addition of the low-pass filter (LPF) was later proposed as explained in the section "Filtered DBP." The nonlinear sections are memoryless, and are therefore computationally trivial. However, they separate the linear sections, which are FIR filters. Because the linear sections are typically implemented in the frequency domain using fast Fourier transforms, a linear step representing a "long" section of fiber requires only slightly more computational effort than a "short" section. Therefore, the number of



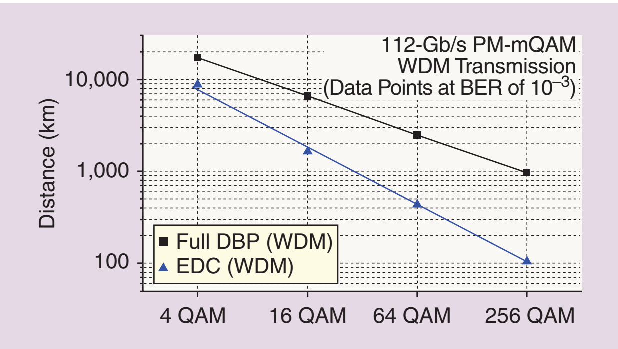
[FIG2] An optical system with DBP: dispersion section (*D*), nonlinear section (*N*), number of amplified spans in the link (*P*), number of steps used in DBP (*Q*), scaling factor to be optimized κ, and phase modulator (PM).

steps determines the total computational effort (discussed in the section "Complexity of Nonlinearity Compensation"). Most proof-of-concept demonstrations of fiber nonlinearity compensation have used offline signal processing; therefore, the processing time per bit was not an issue.

AN INTERESTING TRADEOFF BETWEEN PERFORMANCE AND COMPLEXITY MAY BE DERIVED BY ONLY DIGITALLY BACK-PROPAGATING LIMITED WDM BANDWIDTH.

The upper bound in the performance enhancement of DBP was investigated by compensating for intrachannel and interchannel nonlinear fiber impairments in systems using different modulation formats [2]. In this work, numerous short steps were used. Although this is impractical in a real system because of the excessive computational power required, it established the fundamental limits of DBP. A nine-channel WDM system was considered. The power and modulation format was the same for all channels. The bit rate for each channel was fixed to 112 Gb/s; the baud rate was changed accordingly and the baud rate to channel spacing ratio was fixed to 0.56. Figure 3 shows full-band DBP significantly increases the reach for all the modulation formats tested. For QPSK, the reach is improved by a factor of three. This benefit becomes even greater for higher-order modulation formats. Counterintuitively, full-band DBP does not support unlimited transmission distances because intermixing of the ASE and signal eventually limit the performance [16]. Since the ASE component is random, nonlinear products originating from ASE cannot be compensated, even with the most detailed model.

Even though full-band DBP gives significant advantages, the computational cost is greatly increased because the maximum step size is inversely related to the total bandwidth of the WDM signal. Additionally, full-band DBP will only work for point-to-point links and places additional requirements on the receiver architecture [11], as explained in the section "Nonlinearity Compensation in 1-Tb/s Systems." Single-channel DBP (SC-DBP) has been more widely researched because it is typically considered to be more realistic in the near- to mid-term. Since a single-wavelength signal is back-propagated, SC-DBP only compensates for intrachannel nonlinearity, e.g., self-phase modulation (SPM). However, an interesting tradeoff between performance and complexity may be derived by only back-propagating limited WDM bandwidth, such as DBP of an entire superchannel (further discussed in the section "Digital Nonlinearity Compensation in Next-Generation Systems"), rather than full-band DBP.



[FIG3] **The maximum transmission distance at optimal power achieving a BER of 10^{-3} for a WDM system.**

INTENSITY-DRIVEN PHASE MODULATION

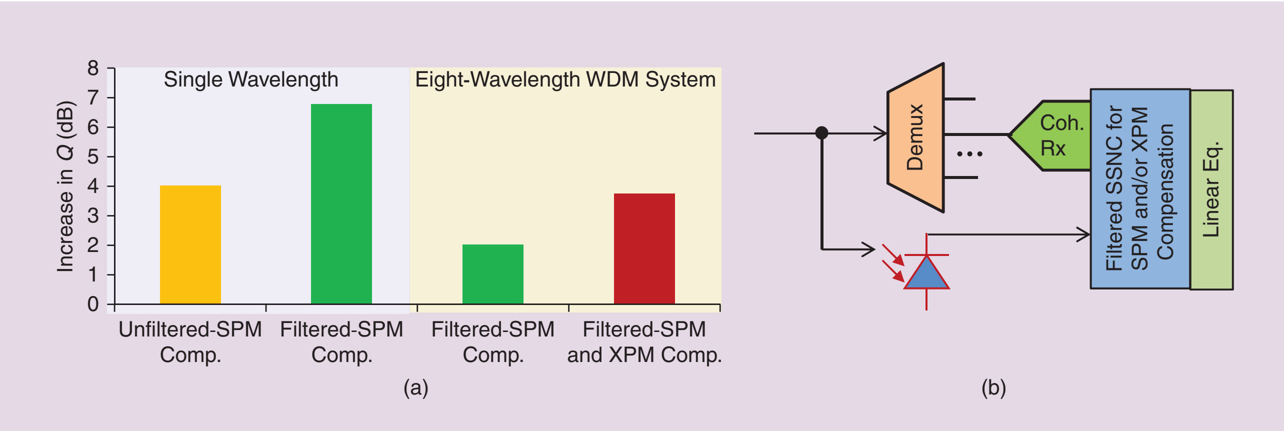
If CD is ignored, then only a single nonlinear step is required to fully mitigate deterministic nonlinear fiber impairments, thereby making it computationally trivial. In 2002, Xu and Liu successfully compensated for SPM in a DM link by phase modulating a differential PSK signal by its own intensity [17]. This system would perfectly compensate dispersionless nonlinear fiber. In 2007, digital implementations were proposed for coherent optical systems [18]. Neglecting CD means only the memoryless nonlinear section is required, which significantly simplifies the hardware complexity. Single-step nonlinearity compensation (SSNC) will still work in dispersive links if the CD in the link is sufficiently low, such as NZ-DSF links and DM S-SMF links [19], [20]. In these low-dispersion links, the phase shifts induced by CD causes the four-wave mixing (FWM) efficiency to be lower for larger frequency separations [10], [19]; the nonlinear phase shifts produced by high-frequency intensity fluctuations are therefore weaker than those produced by low-frequency intensity fluctuations. Inserting an LPF in the nonlinear section, as shown in Figure 2, was shown to improve SSNC [19]. Figure 4(a) shows the increase in signal quality, Q [18], at nonlinearity-limited powers from unfiltered- and filtered-SSNC for 100 Gb/s coherent optical orthogonal frequency division multiplexing (CO-OFDM) in a typical DM link.

Figure 4(a) shows that in a WDM system, the benefit from SPM compensation alone is greatly reduced because XPM is the dominant source of nonlinear distortion. XPM can be compensated using filtered SSNC by detecting the low-frequency intensity fluctuations of a band of WDM channels using a photodiode before the demultiplexer, as shown by Figure 4(b). The photodiode output can then be scaled and digitally filtered for optimal XPM compensation [20].

FOLDED DBP

Another possible DSP technique is folded DBP [21], where the symmetry of DM systems is exploited to greatly reduce the number of DBP steps without compromising performance. In a fully dispersion-compensated link (zero residual CD after each span), the solution collapses to SSNC. In typical DM links with some residual CD, two or three steps may still be sufficient.

Figure 5(a) shows numerical simulation results of folded DBP for a 10×224-Gb/s 16-QAM system with an eight-span DM S-SMF link [22] on a standard International Telecommunication Union (ITU) grid of 50 GHz. The case labeled with folded DBP uses only three nonlinear sections separated by two dispersive sections; DBP-8s use one DBP step per each S-SMF



[FIG4] (a) The nonlinear threshold increase for 100-Gb/s CO-OFDM in a DM S-SMF link; (b) the SSNC for SPM and XPM compensation.

span; DBP-15s use a DBP step for each S-SMF and DCF span. The performance of folded DBP is clearly comparable to DBP-8s and DBP-15s. Different spans can be merged because a small amount of residual CD is beneficial for the approximation carried out by DBP, similar to that in the Wiener-Hammerstein model [23]. Figure 5(a) shows there is no penalty due to this coarse approximation and the computational cost is reduced by a factor of five.

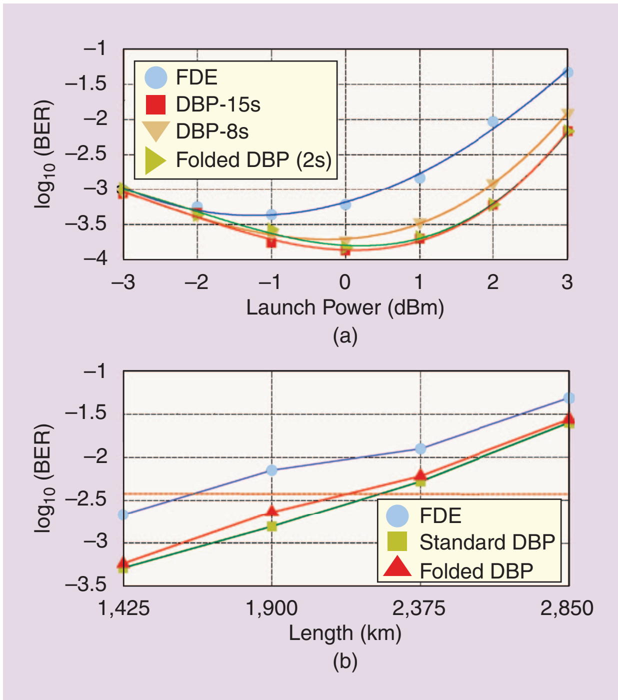
Similar experimental results for WDM transmission are displayed in Figure 5(b) on the setup described in [24], where 10×111 Gb/s POLMUX-RZ-DQPSK signals were propagated by employing standard ITU grid with 50-GHz channel spacing. Folded DBP has similar performance to DBP with one step per span and increases the reach by about 500 km, assuming a hard FEC limit of 3.8×10^{-3}, represented by the dashed orange line.

FILTERED DBP

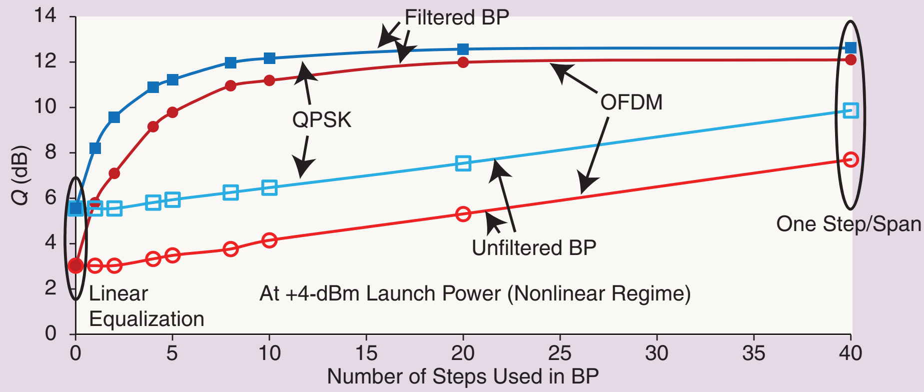
As with single-step methods, the effect of CD can partially be accounted for by suppressing the high-frequency intensity fluctuations with an LPF [6]. In the time domain, this can be understood as taking into account the effect of nonlinear phase shift on a particular symbol, arising from multiple symbols interfering (via dispersion) with that particular symbol. Such an effect can be modeled in DBP by taking a weighted average of the intensity waveform, which is simply an FIR filter [25]. This is commonly referred to as filtered or correlated DBP and enables compensation of multiple physical spans with each DBP step. This approach has been shown to be effective in both single- and multicarrier systems, as shown in Figure 6. For both CO-OFDM and CO-QPSK, four-step filtered DBP provides a similar improvement to 40-step unfiltered DBP for a 40-span NDM link. Therefore, filtered DBP reduces the step-size requirements by a factor of ten, for a similar improvement in performance.

NL COMPENSATION USING PHASE ESTIMATION

Pilot-tone-aided phase noise compensation was first proposed to compensate for intrasymbol laser phase noise in CO-OFDM systems [26]. This was then extended to compensate for fiber nonlinearity [7]. In this method, an unmodulated pilot tone is transmitted; this tone can be in the center of the information band, as shown in Figure 7 [8], or toward one side [27]. At the receiver, this tone is filtered out from the signal and used to capture the phase noise experienced by the signal. This method compensated for all forms of phase noise; laser phase noise is treated identically to fiber nonlinearity. There are two limitations: 1) there must be no signal on either side of the pilot tone to allow the pilot tone to be separated from the signal by filtering and 2) only phase distortions within the bandwidth of the filter can be compensated.



[FIG5] (a) Simulation results for a 10×224-Gb/s POLMUX 16-QAM over a 8×80-km DM link. (b) Experimental results for a 10×111 Gb/s POLMUX-RZ-DQPSK system at 0-dBm launch power into each span [24].



[FIG6] The Q-factor of a 4-QAM 40 × 80-km NDM link with filtered and unfiltered DBP [6].

The ASE close to the pilot tone will also be passed by the filter; this noise will be multiplied with the signal and cause distortions. In the ASE limited regime, the resulting SNR after pilot-based nonlinearity compensation (PB-NLC) is determined by both the SNR of the signal and of the pilot. Therefore, the amount of power allocated to the pilot should be optimized to maximize the SNR after compensation. The optimum power and the attainable SNR are also affected by the bandwidth of the LPF; a wider bandwidth will increase the amount of noise in the filtered pilot. The optimal bandwidth is around ~500 MHz and 15% of total power in a DM link [28]. This will be even lower for an NDM link, due to the phase array effect [4], [19]. PB-NLC is therefore only suitable for the compensation of narrow-bandwidth phase noise. Because SPM effects are typically wider band, PB-NLC is enhanced if SPM is first compensated using the inverse model technique [8].

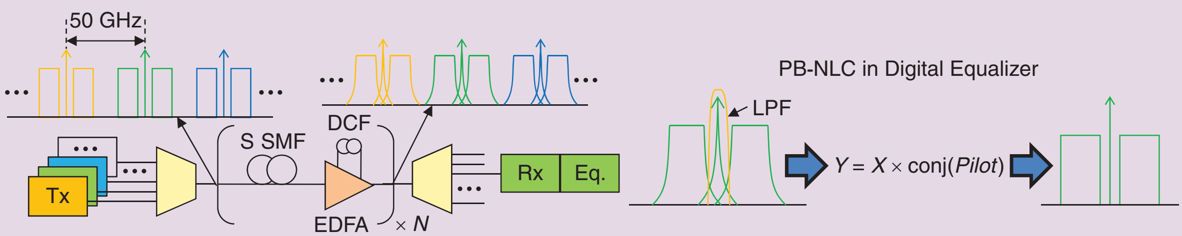
Figure 8 shows the benefit from PB-NLC and DBP [27] for an NDM link. The optimum power of the pilot was 20 dB below the signal with an optimized frequency gap of 24 GHz. The optimal filter bandwidth to extract information from the pilot was ~100 MHz. PB-NLC alone extended reach for both systems slightly; the benefit is enhanced if used after DBP. The broadband phase noise generated by SPM was compensated using DBP. The "cleaned" pilot gives a better estimation of narrowband phase noise generated by laser phase noise and XPM.

In general, all phase compensation methods work for all sources of phase noise, such as from fiber nonlinearity or the laser. Therefore, XPM can also be compensated using blind phase estimation techniques. However, the properties of the phase noises are different; phase noise generated from XPM is mostly between 10–100 MHz. Therefore, the parameters will most likely need to be adjusted to compensate for XPM effectively.

DIGITAL NONLINEARITY COMPENSATION IN NEXT-GENERATION SYSTEMS

FUTURE 1-Tb/s SYSTEMS

Future 1-Tb/s systems will be required to not only increase the capacity of the core optical network but also be more cost and energy efficient per bit. Transmitting more bits per symbol will increase the capacity utilizing similar hardware architecture, thereby lowering the cost per bit. Therefore, gross bits per symbol are likely to increase from four, in POLMUX CO-QPSK systems, to eight or more. However, reach is inversely proportional to the bits per symbol so this cannot be exploited indefinitely [1], [2]. Therefore, a 1-Tb/s signal will occupy around 130–180 GHz of optical bandwidth. This is certainly beyond the bandwidth of a single transmitter and coherent receiver so the signal will comprise multiple lower-rate channels. To maximize the spectral efficiency of the 1-Tb/s superchannel, the subchannels are likely to be squeezed together. Tighter channels will increase interchannel



[FIG7] An optical system with PB-NLC.

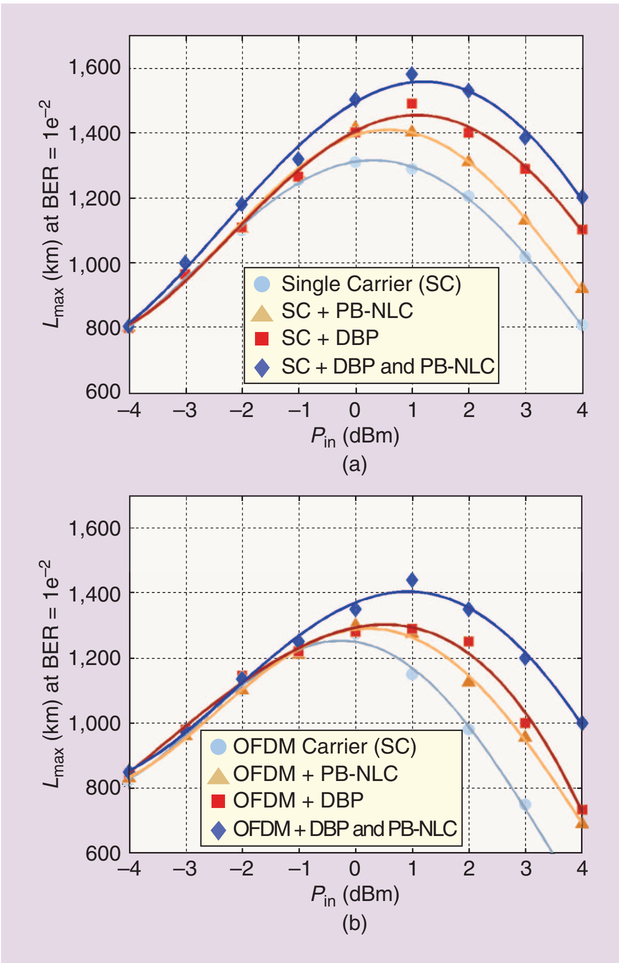
nonlinear distortions, which will also decrease the reach of the system. Therefore, improvements in the link and DSP, such as digital nonlinearity compensation, will be required to achieve a similar reach to current 100 Gb/s systems [2]. However, digital nonlinearity compensation is typically considered to be a complex approach, even at current commercial bit rates (100 Gb/s). Therefore, before discussing the application of nonlinearity mitigation in Tb/s, it is important to establish the required computational requirements for various digital nonlinearity mitigation techniques to give us a better understanding of what is possible.

A KEY CHALLENGE IN REALIZING NONLINEAR COMPENSATORS IS THE CHIP COMPLEXITY—THE NUMBER OF GATES REQUIRED TO IMPLEMENT A GIVEN ALGORITHM.

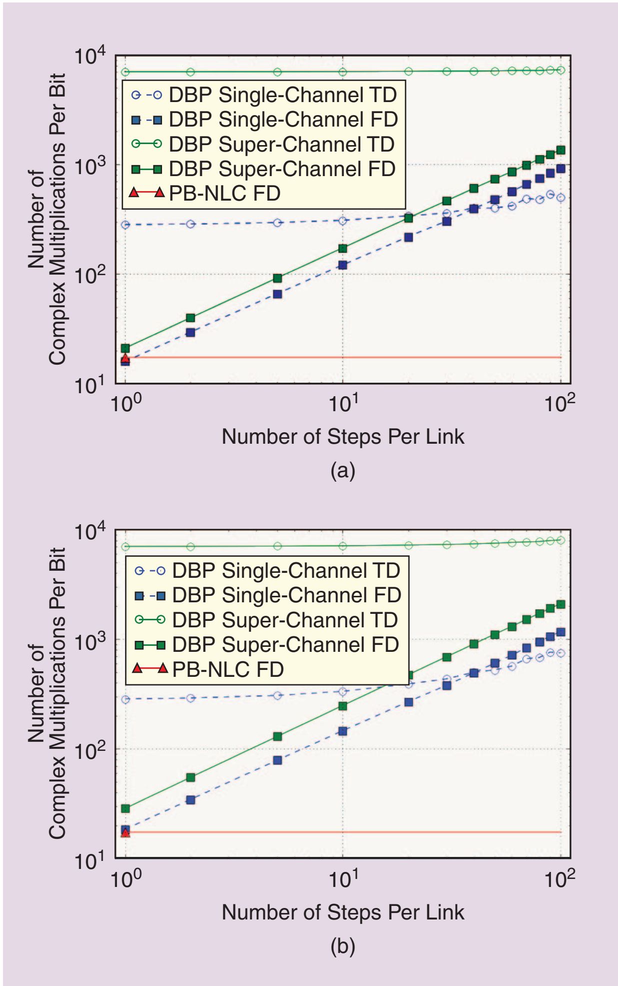
COMPLEXITY OF NONLINEARITY COMPENSATION

Advances in DSP usually mean more complex algorithms and higher computational cost. Hence, a key challenge in realizing nonlinear compensators is the chip complexity—the number of gates required to implement a given algorithm. As an example, we consider a 1-Tb/s superchannel with a 4% Ethernet overhead and 15% FEC overhead, giving a total bit rate of 1.204 Tb/s. This is split evenly between five subchannels, each modulated with DP-16-QAM at 30.1 Gbaud. A root-raised-cosine pulse shape with roll-off 0.2 was used to confine each subchannel to 36.1 GHz, making the superchannel 186.86 GHz. We assume a 10 × 80 km NDM link, using EDFA amplification and S-SMF.

Figure 9 shows the number of complex multiplications per transmitted bit for conventional single-channel DBP, superchannel DBP, and pilot-based nonlinearity compensation. The details on the number of multiplies needed are presented in [29]. For DBP, the linear operator is assumed to be implemented either in the time domain as an FIR filter or in the frequency domain using the overlap-save technique and FFT/IFFTs. Results for one step per link can be interpreted as the complexity of a conventional EDC. For PB-NLC, we assume that the pilot is filtered by a fifth-order Gaussian filter



[FIG8] The maximum reach distance versus launch power for 9 WDM 16-QAM at 224 Gb/s over an NDM link for (a) single carrier and (b) CO-OFDM [27]. The maximum distance was calculated by assuming a soft-decision FEC with a threshold of 1.0×10^{-2}.



[FIG9] The computational cost for PB-NLC and DBP for a given number of steps per link: (a) the conventional unfiltered DBP and (b) filtered digital DBP.

with a bandwidth of 100 MHz, which is implemented in the frequency domain.

Figure 9(a) shows the complexity of conventional unfiltered DBP (see the section "Nonlinear Digital Backward Propagation"). The complexity of the time-domain implementation is essentially independent of the number of steps used for DBP. This is because the length of the impulse response, N_{taps}, required in each section is inversely proportional to the number of steps and therefore the complexity for all steps together is constant. The small increase for high number of steps is caused by quantization effects, since the length of the filter is rounded up to integer values. As mentioned in the section "Nonlinear Digital Backward Propagation," the nonlinear sections are computationally trivial. In contrast, the complexity of the frequency-domain implementation is roughly proportional to the number of DBP steps and is much more efficient than the time-domain implementation for a small number of steps. The break-even between time-domain and frequency-domain solution is somewhere around 40 steps per link for single-channel DBP and far beyond 100 for superchannel DBP.

The complexity of PB-NLC is dominated by the filtering operation and therefore requires a similar number of multiplies to DBP with only one step per link. Since PB-NLC is independent of the number of DBP steps, the total complexity of combined DBP and PB-NLC can be determined by linearly adding the constant PB-NLC complexity on top of the DBP complexity for any number of steps.

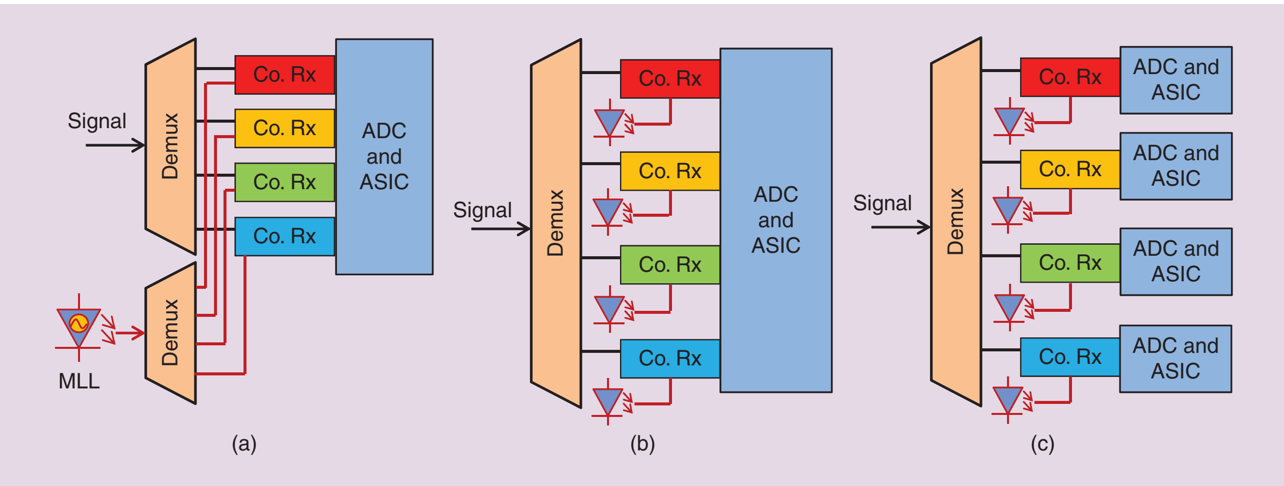
Figure 9(b) shows the complexity of filtered DBP, where we assumed an additional real-valued FIR filter with ten and 30 taps for each DBP step for single-channel and superchannel DBP, respectively. For convenience, the complexity of PB-NLC is shown in this plot as well. The impact of additional filtering has only a very small impact for a small number of steps and becomes more noticeable as the number of steps increases. However, compared to the overall complexity, the additional increase due to filtering is still moderate.

FOR HIGHER-ORDER CONSTELLATIONS, PB-NLC'S JOINT ABILITY TO COMPENSATE FOR LASER PHASE NOISE ALSO BECOMES MORE VALUABLE BECAUSE BLIND CARRIER PHASE RECOVERY IS MORE DIFFICULT.

NONLINEARITY COMPENSATION IN 1-Tb/s SYSTEMS

Even though the complexity of DBP seems excessive from today's perspective, the very fast development in DSP technology means that nonlinear compensation techniques, such as DBP, are likely to be a part of future commercial chip-integrated transponders. The novel system architecture of 1-Tb/s systems will produce new challenges for effective nonlinearity compensation. It has been observed that single-channel DBP reduces in effectiveness if the channel spacing is reduced [30]. This is because interchannel effects, such as XPM, will be stronger. Therefore, the benefit from subchannel DBP will be small in 1-Tb/s systems.

One way of overcoming XPM between the subchannels is to use DBP in the whole superchannel. This would require the optical local oscillators of the multiple receivers be phase locked to reproduce the received superchannel [11], as shown in Figure 10(a). Figure 9 shows superchannel DBP is only slightly higher in complexity than single-channel DBP if implemented in the frequency domain, which is optimum if <40 steps are used. However, the wider signal bandwidth of the superchannel will also mean that shorter steps will be required; multiple steps per span are likely to be required [21]. Filtered DBP may be useful in superchannel DBP to reduce the number of steps. Additionally, superchannel DBP must be performed on a single ASIC. This will pose new challenges for the ASIC design because of the required number of gates on a single chip.



[FIG10] Superchannel receiver architectures for a four subchannel system: (a) with a joint ASIC and phase-locked LOs for superchannel DBP, (b) with a joint ASIC and unlocked LOs for coupled-field DBP, and (c) with independent ASICs and coherent receivers for single-channel DBP. *Mode-locked laser* is represented by the acronym MLL.

Alternatively, the XPM of neighboring subchannels can be compensated using coupled-field DBP [11]. Coupled-field DBP does not require the local oscillators to be phase locked because a separate SSFM is used for each subchannel. However, a large amount of information transfer is required between the DBP hardware of the subchannels. This likely means that the DSP still must be contained in a single ASIC, as shown in Figure 10(b). This method does not compensate for FWM between the subchannels so will have inferior performance compared to superchannel DBP. The lower bandwidth signals will mean fewer steps are required.

Another possibility is to use the PB-NLC to compensate for the XPM between the subcarriers. The additional complexity of PB-NLC is similar to EDC of today's systems, as shown in Figure 9, making it relatively light in complexity. This method will allow individual ASICs to be used for each subchannel and phase-independent local oscillators to be used, as shown in Figure 10(c). This makes implementation of both the optics and the DSP easier. For higher-order constellations, PB-NLC's joint ability to compensate for laser phase noise also becomes more valuable because blind carrier phase recovery is more difficult. PB-NLC removes the possibility of cycle slips and therefore eliminates the need to use differential encoding. This partially offsets the loss in sensitivity. Despite the benefits, PB-NLC is an approximate method and will not deliver the performance of full superchannel DBP. We conjecture that this method will be always used together with others, such as subchannel DBP, since it is ineffective in compensating for SPM.

CONCLUSIONS

In this article, we have reviewed current commercial optical communication systems and discussed promising nonlinearity compensation methods that may help enabling Tb/s transmission over longer distances. The inverse fiber model, often known as DBP, is capable of doubling the data rate. However, the computational power required by DBP of a full WDM band might be prohibitive. We presented the recent advances to reduce the computational effort needed without compromising performance. Another promising method of nonlinearity compensation is to use pilot tones as probes to detect the nonlinear phase distortions experienced by the signal, thereby compensating interchannel effects. Such methods work well in conjunction with DBP. Finally, we provided an outlook for the application of fiber nonlinearity compensation techniques in 1-Tb/s transmission systems, and analyzed the computational effort of various digital nonlinearity mitigation methods, both for conventional single-channel and multichannel nonlinearity compensation.

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AUTHORS

Liang B. Du (liangbydu@gmail.com) received his bachelor of engineering (honors) and commerce degree in 2008 and received his Ph.D. degree in 2012 from Monash University, Australia. His Ph.D. project was on fiber nonlinearity compensation for optical communication systems. He was awarded the Corning Outstanding Student Paper Award at the 2011 Optical Fiber Communication Conference (OFC) and the Best Student Paper Award in transmission systems at the 2012 Optoelectronics and Communications Conference. Since 2012, he has been a research fellow in the Department of Electrical and Computer Systems Engineering at Monash University. His research interests include optical OFDM, equalization techniques for coherent optical systems, and optical nonlinearity compensation techniques.

Danish Rafique (danish.rafique@coriant.com) holds B.Sc. (2007, Foundation for Advancement of Science and Technology–National University, Pakistan), M.Sc. (2009, KTH, Sweden), and Ph.D. (2012, Tyndall National Institute, University College Cork, Ireland) degrees, all in electrical engineering. During his Ph.D. studies, he published more than 34 articles and was a semifinalist in the OFC Best Student Paper Competition (in 2011 and 2012). Currently, he is pursuing a career with R&D Labs of Coriant GmbH, Germany, where he is working on next-generation transponder solutions involving flex-grid networks. His research interests include nonlinear effects in fiber, DSP, and flex-grid optical networks. He is a reviewer for *IEEE Photonics Technology Letters, IEEE Journal of Lightwave Technology*, and Optical Society of America's *Optics Express*.

Antonio Napoli (antonio.napoli@coriant.com) received the master's and Ph.D. degrees in electronics engineering from Politecnico di Torino in 2002 and 2006, respectively. He was a visiting student at the Technische Universität Wien (2001), and a visiting researcher at Universitat Politècnica de Catalunya in Barcelona (2004) and at University College London, United Kingdom (2005). In 2006, he joined Siemens COM, where he worked on EDFA transient suppression and DSP for long-haul optical networks. In 2007, he joined Nokia Siemens Networks, where he worked on optical transmission up to 400 Gb/s. He has been with Coriant since 2013, where is leading a work-package on data plane within the EU FP-7 IDEALIST project. He regularly supervises students and teaches at several universities. His interests are focused on DSP and advanced modulation formats for long-haul systems. He is author or coauthor of more than 60 papers and six patents.

Bernhard Spinnler (bernhard.spinnler@coriant.com) received the Dipl.-Ing. degree in communications engineering and the Dr.-Ing. degree from the University of Erlangen-Nürnberg, Germany, in 1994 and 1997, respectively. Since 1997, he has worked on low-complexity modem design of wireless radio relay systems at Siemens AG, Information and Communication Networks. In

2002, he joined the optical networks group of Siemens Corporate Technology, which later became Nokia Siemens Networks. He has been with Coriant since 2013, where he is working on robust and tolerant design of optical communications systems. His interests focus on advanced modulation and equalization for single and multicarrier systems.

Andrew D. Ellis (andrew.ellis@aston.ac.uk) received the B.Sc. degree in physics with a minor in mathematics from the University of Sussex, Brighton, United Kingdom, in 1987. He received the Ph.D. degree in electronic and electrical engineering from The University of Aston in Birmingham, United Kingdom, in 1997 for his study on all optical networking beyond 10 Gb/s. He previously worked for British Telecom Research Laboratories, Corning Research Centre, and Tyndall National Institute in Cork, Ireland, where he was also a member of the Department of Physics, University College Cork. He is currently a professor of optical communications at Aston University, an adjunct professor of electronic engineering at Dublin City University, and a founder of the Dublin-based start-up Pilot Photonics. He research interests include all optical OFDM and optical and electrical signal processing.

Maxim Kuschnerov (maxim.kuschnerov@coriant.com) graduated from the Technical University of Munich in 2006 and received his Ph.D. degree in electrical engineering from the University of the Federal Armed Forces, Munich, Germany, in 2011. His Ph.D. research was conducted in collaboration with Nokia Siemens Networks (NSN) in Munich focusing on the development of digital signal processing algorithms for optical coherent systems. In 2010, he joined NSN full time, focusing on the development of 100-Gb/s transponders and beyond. He has authored and coauthored more than 100 peer-reviewed papers and conference contributions. In 2009, he received the NSN Quality Award for Innovation. Currently, he leads the system trial work package of the Modegap project, focusing on space division multiplexing over multimode fibers.

Arthur J. Lowery (arthur.lowery@monash.edu) is an ARC Laureate Fellow and professor at Monash University, Australia, and leads Monash Vision Group's development of a bionic eye based on a cortical implant. He is also the science leader of the Tbit/s project of ARC CUDOS. His Laureate Fellowship is in developing novel combinations of electronics and photonics for optical networks. In 1996, he cofounded VPIsystems (now VPIphotonics) and led the development of VPItransmissionMaker and VPIcomponentMaker simulation tools. He is a Fellow of the IEEE and of the Australian Academy of Technological Sciences and Engineering.

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