Channelized Chromatic Dispersion Compensation for XPM Suppression and Simplified Digital SPM Compensation

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Abstract: Channelize dispersion compensation strongly suppresses inter-channel nonlinearities. We show that it also supports folded digital backpropagation, which can compensate for the intra-channel nonlinearity at a computational cost of only 1.8-times that of CD compensation alone.

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Introduction

Coherent optical systems support compensation of linear optical impairments using digital signal procession (DSP) [1]. Therefore, the reach of such systems is limited by amplified spontaneous emission (ASE) and fiber nonlinearity [2]. Most investigations have suggested that optimum nonlinear performance is achieved by using non-dispersion managed (NDM) links and electronic dispersion compensation (EDC) to take advantage of the phased-array effect to minimize cross-phase modulation (XPM) [3-5]. However, Xie showed dispersion managed (DM) links using channelized dispersion compensation can have similar performance to NDM links [6].

In this paper, we use numerical simulations to investigate the benefits of using inline channelized chromatic dispersion (CD) compensation in combination with digital backpropagation for nonlinearity mitigation [2]. We simulated a typical 28-Gbaud (112 Gbit/s) dual-polarization (DP) quadrature phase shift keying (QPSK) system over 10×80 km of standard single-mode fiber (S-SMF) using erbium doped fiber amplifiers (EDFA). A NDM link was compared with a DM link using channelized CD compensators using, say, fiber Bragg gratings [7]. As observed in [6], the two links had a similar performance if nonlinearity compensation was not used. Advantageously, channelized DM link enables *folded* backpropagation (BP) for self-phase modulation (SPM) compensation [8]; near optimal SPM compensation can be achieved with an 8-step folded-BP. The 800-km DM link with folded-BP performs more than 5 dB better in the nonlinearity-limited region than the 800-km NDM link with EDC; folded-BP for the DM link only requires 1.8-times more multiplies than just implementing dispersion compensation digitally (EDC) for the NDM link, so is computationally tractable.

Channelized CD compensation

In the past, links for 10-G legacy systems used carefully engineered dispersion maps to minimize the effects of fiber nonlinearity, such as by partially compensating the CD after each span. This in-line dispersion compensation keeps the peak-to-average power ratio (PAPR) low, thereby reducing nonlinear phase modulation. However, a small amount of uncompensated (residual) dispersion per span is beneficial for suppressing inter-channel effects, such as XPM and four-wave mixing (FWM), via the phased-array effect [9]. Unfortunately, the high spectral occupancy in 50-GHz-spaced 100-Gb/s DP-QPSK systems makes it impossible to simultaneously keep PAPR low and allow enough residual dispersion per span to suppress XPM and FWM. Thus NDM links (without inline dispersion compensation) out-perform DM links [10] because the large walk-off between the neighboring wavelength division multiplexed (WDM) channels allows the phase-array effect to suppress XPM [3, 4].

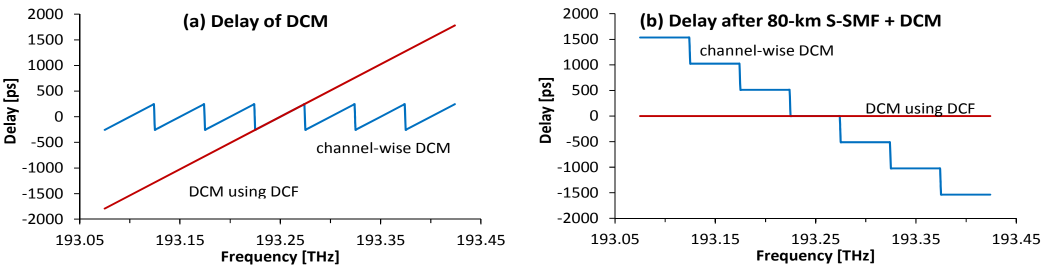

Fig. 1. Relative delays: (a) of 80-km DCM only; (b) of 80-km of S-SMF and 80-km DCM.

Channelized CD compensators, such as those using FBGs [7], compensate for the CD within the bandwidth of each WDM channel. However, the walk-off between neighboring WDM channels is not compensated. Therefore, channelized CD compensators are capable of keeping the PAPR of each channel low while supporting walk-off between WDM channels to take advantage of the phase-array effect for XPM suppression. A suitable delay versus frequency plot of an ideal channelized CD compensator is shown in Fig. 1(a), and the delay after a fiber span shown in Fig. 1(b). In reality, the bandwidth of each WDM channel will be limited, and the edges of the band may have phase ripple [11]. However, these linear impairments can be easily compensated using DSP [12].

The CD within each WDM channel is compensated after every span; thus, the SPM products generated in each span will be in phase with those from other spans, and hence will add coherently. Thus, SPM dominates signal degradation; therefore SPM compensation is essential. SPM can be completely compensated using DBP [2, 13]. Fortunately, as each span produces the same SPM with this dispersion map, the DBP for one span can be used to compensate all spans simultaneously, by 'folding' [8], greatly reducing the computational effort required.

Numerical Simulations

Fig. 2 shows the simulation setup. Each transmitter generates a 30-Gbaud DP-QPSK signal, typical of 100-Gb/s systems. Seven wavelength channels are multiplexed together on a 50-GHz grid. The WDM signal is then transmitted through one of two 10×80-km links: a NDM reference link; or a DM test link using channelized CD compensation. These compensators are assumed to be lossless; in reality, their loss can be compensated increasing the amplifier output power up since they are a linear device [12], unlike dispersion compensation fiber. The transmission fiber had an attenuation of 0.2 dB/km, CD of 16 ps/nm/km, nonlinear coefficient, γ, of 1.3 /W/km, and polarization mode dispersion (PMD) of 0.1 ps/$\sqrt{}$km, typical values for S-SMF. The loss of each 80-km span was compensated by an erbium doped fiber amplifier (EDFA) with a noise figure of 6 dB. After the 800-km link, the WDM signal is optically demultiplexed and the central channel is received using a typical coherent receiver.

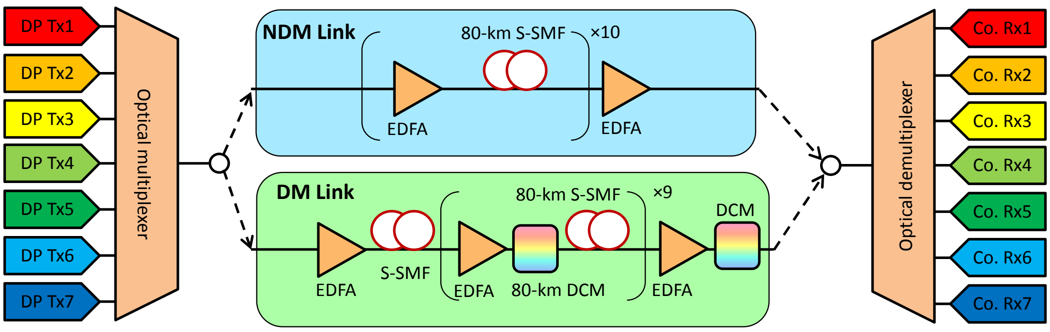

Fig. 2. Simulation setup showing the test and reference links: Co. – coherent.

The DSP operated at two-times oversampling in all cases. Different types of static equalizers for compensating the bulk of the CD and/or fiber nonlinearity were considered for both systems. PMD was then compensated using a butterfly-structured 11-tap time-domain equalizer (TDE) optimized using the constant modulus algorithm [1]. Laser phase noise is ignored in the simulations to focus on the phase noise from fiber nonlinearity.

In Fig. 3, the lines show the Q calculated from the constellation spread. 32268 constellation points were simulated. Fig. 3(a) shows the performance of the two links. Without nonlinearity compensation, the two links have similar performance, as observed in [6]. In a DM link, self-phase modulation (SPM) can be effectively compensated using only a single-step, which is computationally trivial [5]. This improves the nonlinearity-limited performance by 2.6 dB. However, single-step nonlinearity compensation is ineffective for NDM links; for a similar performance improvement, 10-step filtered-BP [14] is required.

The performance of the channelized NDM link can be further improved by using folded-BP [15]; 8-step folded-BP further improves the nonlinearity-limited performance by 2.1 dB. Compared with 100-step BP (which is computationally intractable, practically), folded-BP had a penalty of 0.2 dB for the DM link, and filtered-BP had a penalty of 0.4 dB for the NDM link. This shows that channelized CD compensation suppresses XPM, by keeping the PAPR low after each amplifier. The reduced XPM allows a greater benefit from SPM compensation to be realized.

Fig. 3(b) plots the approximate number of multiplications required for the two links with the different static equalizers for EDC or BP for using similar assumptions to [15]. The Q at the optimum launch power is also shown. For EDC of a NDM link, ~127 multiplies are required. The residual CD in the DM link can be compensated using the adaptive TDE so a linear static EDC is not required. For folded-BP, the final optical DCM is removed and the

CD of a single span is compensated using 8-step BP with logarithmic steps [13]. Compared to EDC for the NDM link, folded-BP requires less than two-times the number of multiplies and improves performance by over 5 dB at high powers and 2 dB at the optimum launch power. The short linear steps of folded-BP allow a TDE to be used for each linear section, which makes it significantly simpler than the filtered-BP of NDM links.

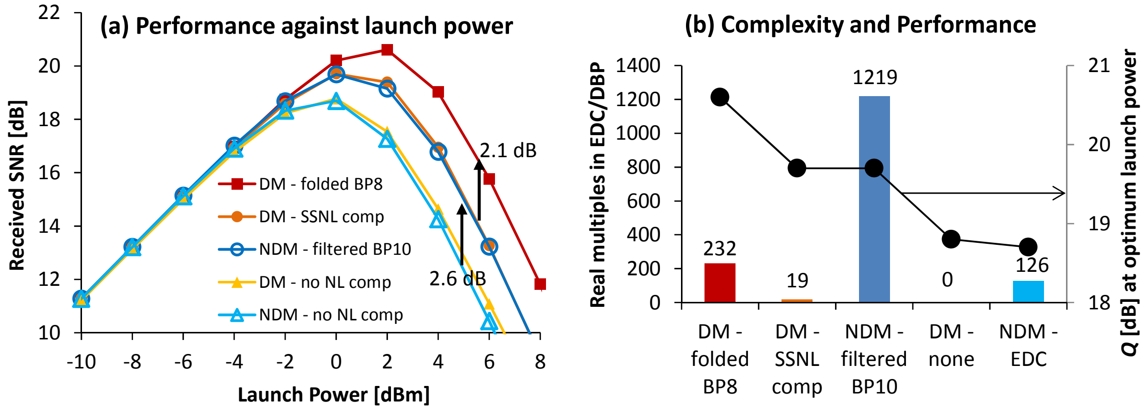

Fig. 3. (a) Received Q vs. launch power; (b) Real multiplies per symbol for different static equalizers and Q at optimum power.

Conclusion

In this paper, we propose the use of channelize optical CD compensation to: (*i*) simplify SPM compensation by using inline dispersion compensation in each channel to allow folded-BP; and (*ii*) suppress XPM by reducing the PAPR each WDM channel along the transmission link while simultaneously allowing neighboring WDM channels to 'walk-off' from each other to prevent the XPM products from being coherent. Numerical simulations show a 2-dB improvement in transmission performance is provided by using channelized CD compensation with 8-step folded-BP. The number of multiplies for 8-step folded-BP is only 1.8-times more than just EDC for a NDM link.

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