Journal of information and communication convergence engineering
http://jicce.org

J. Inf. Commun. Converg. Eng. 16(2): 67-71, Jun. 2018 Regular paper

Dispersion-Managed Links Formed of SMFs and DCFs with Irregular Dispersion Coefficients and Span Lengths

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Abstract

The various techniques to compensate for the signal distortion due to the group velocity dispersion (GVD) and nonlinear Kerr effects of optical fibers in the optical links have been proposed in the literature. We propose a flexible dispersion-managed link configuration consisted of single-mode and dispersion-compensating fibers with irregular dispersion coefficients over all fiber spans, and an optical phase conjugator added midway along the optical links. By distributing the lengths of the single mode fibers, we achieve a flexible optical link. The simultaneous ascending and descending distribution of the single-mode fiber lengths before and after the optical phase conjugator, respectively, best compensates the distorted wavelength division multiplexed signals in the optical link with non-fixed coefficients. Our result is consistent with those of our previous work on fixed coefficients. Therefore, to improve the compensation at any magnitude of dispersion coefficient, we must artificially distribute the lengths of the single-mode fibers into a dispersion-managed link.

Index Terms: Dispersion coefficient, Dispersion-managed link, Net residual dispersion, Residual dispersion per span

I. INTRODUCTION

In conventional fiber-optic systems, group velocity dispersion (GVD) of standard single-mode fibers (SMFs) causes severe temporal distortion of wavelength division-multiplexed (WDM) pulses [1]. Also, the nonlinear impairments deteriorate as they pass through the cascaded erbium-doped fiber amplifier (EDFA) of the system, because the fiber nonlinearities depend on the signal intensity amplified by the EDFA [2, 3]. The optical signal distortions induced by GVD and the nonlinear effects can be mitigated by combined dispersion management (DM) and optical phase conjugation [4-6]. Dispersion-managed optical link dramatically reduce the path-averaged GVD by adding dispersion compensating fibers (DCFs) with anomalous GVD to SMFs with normal GVD for every fiber spans consisting of optical link [7]. Besides, in mid-span spectral inversion, the phase-conjugated waves are generated at an optical phase conjugator (OPC) placed around the midway of the overall link by using the distorted waves suffered through the first half of the link (before OPC) [8]. Afterward, by propagating the phase-conjugated wave into the second half of the link the optical waves received at the end of the link are mostly similar to the original waves.

In our previous work, we showed that DM combined with midway insertion of OPC into optical links improves the receiving performance of transmitted 40 Gbps × 24 channels WDM signals [9-11]. For a flexible optical link configuration, we freely specified the lengths of the SMFs and residual dispersions per span (RDPSs), but fixed the dispersion coefficients of the SMFs and DCFs to 17 ps/nm/km and -100 ps/nm/km, respectively.

However, to achieve a truly flexible optical link configuration, we must unfix the dispersion coefficients of the two

Received 03 March 2018, **Revised** 29 May 2018, **Accepted** 29 May 2018
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Open Access https://doi.org/10.6109/jicce.2018.16.2.67 print ISSN: 2234-8255 online ISSN: 2234-8883

fibers. Therefore, we now propose a new flexible optical link configuration with irregular dispersion coefficients, which depend on the lengths of the SMFs and DCFs in the 960-Gbps WDM transmission system.

II. MODELLING OF DISPERSION-MANAGED OPTICAL LINK AND WDM SYSTEM

Fig. 1 shows a 960-Gbps WDM transmitters (Tx), receivers (Rx), and dispersion-managed link with the midway OPC, which consists of 20 fiber spans. The lengths of SMF (l_{SMF}) in the first half (spans 1 to 10) and second half (spans 11 to 20) are artificially ordered as ascending-ascending (AA; i.e., ascending distribution in both fibers before and after OPC), ascending-descending (AD), descending-ascending (DA), or descending-descending (DD), as the number of fiber spans increases. Moreover, the dispersion coefficients of the SMFs (D_{SMF}), the lengths of the DCFs (l_{DCF}), and the dispersion coefficients of the DCFs (D_{DCF}) are decided such that in each artificial distribution, the RDPS of each fiber span is 0 ps/nm. The link parameters of these artificial distributions are summarized in Table 1.

The attenuation coefficient (α_{SMF}) and the nonlinear coefficient (γ_{SMF}) of the SMF per fiber span is assumed to 0.2 dB/km and 1.35 $W^{-1}km^{-1}$ (at 1,550 nm), respectively. On the other hand, the attenuation coefficient (α_{DCF}) and the nonlinear coefficient (γ_{DCF}) of the DCF per fiber span is assumed to be 0.6 dB/km and 5.06 $W^{-1}km^{-1}$ (at 1,550 nm), respectively.

Because the RDPS in each span is set to 0 ps/nm, we need to control the net residual dispersion (NRD) of each half link for achieving the best compensation of the distorted WDM signals. The NRDs of the first and second halves of the link are, respectively, determined from the DCF lengths of the first and last fiber spans (l_{pre} and l_{post}, respectively). However, to simplify the numerical simulation procedures, we fix l_{post} to ensure 0 ps/nm for the NRD of the second half of the link, and vary l_{pre} alone to determine the NRD of the whole link. Namely, the pre-dispersion calibrator (hereafter "pre-DC") in Fig. 1 controls the entire NRD under the condition of fixed l_{post} (zero NRD of the second half of the link).

Modeling of the Tx is based on the distributed feedback laser diodes (DFB-LD). The center wavelengths of each DFB-LD range from 1,550 nm to 1,568.4 nm, and wavelength space between each channel is assumed to be 100 GHz (0.8 nm), based on recommendation G.694.1 from the ITU-T [12]. An independent 40 Gbit/s 127(= 2^7 – 1) pseudo random bit sequence (PRBS) externally modulate the DFB-LDs, and consequently 127 return-to-zero (RZ) signals per a channel are generated through the external optical modulator. RZ pulses are assumed to be a chirp-free second-order super-Gaussian pulse with a 10 dB extinction ratio (ER), and a 50 % duty cycle.

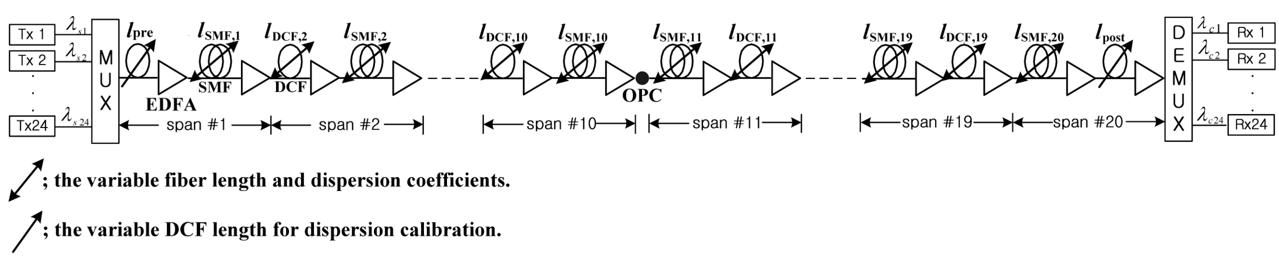


Fig. 1. The proposed 960-Gbps WDM system and dispersion-managed link with the midway OPC. From Chung and Lee, *Proceedings of AWICE*, pp. 72-75, 2016 [11]. EDFA: erbium-doped fiber amplifier, SMF: single-mode fiber, DCF: dispersion compensating fiber, OPC: optical phase conjugator.

Table 1. Link parameters in the artificial distribution of SMF lengths

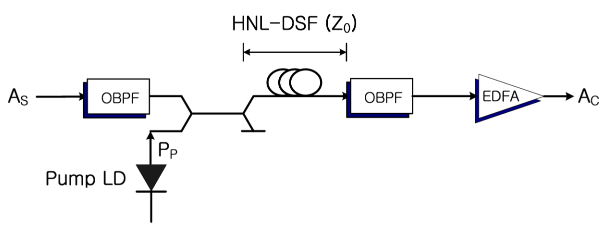
Distribution	Symbol	Fiber span number									
		1, 11	2, 12	3, 13	4, 14	5, 15	6, 16	7, 17	8, 18	9, 19	10,20
Ascending	l_{SMF} (km)	56	61	67	70	75	80	85	90	94	100
	D_{SMF} (ps/nm/km)	16.95	16.87	17.01	17.00	17.07	17.00	17.00	16.89	17.01	17.10
	l_{DCF} (km)	13.0	10.5	12.0	17.0	16.0	13.6	17.0	20.0	20.5	19.0
	D_{DCF} (ps/nm/km)	-73	-98	-95	-70	-80	-100	-85	-76	-78	-90
Descending	l_{SMF} (km)	100	94	90	85	80	75	70	67	61	56
	D_{SMF} (ps/nm/km)	17.10	17.01	16.89	17.00	17.00	17.07	17.00	17.01	16.87	16.95
	l_{DCF} (km)	19.0	20.5	20.0	17.0	13.6	16.0	17.0	12.0	10.5	13.0
	D_{DCF}(ps/nm/km)	-90	-78	-76	-85	-100	-80	-70	-95	-98	-73

From Chung and Lee, *Proceedings of AWICE*, pp. 72-75, 2016 [11].

Each channel is multiplexed in the arrayed waveguide grating multiplexer (AWG MUX), and then transmitted to dispersion-managed link. We use a highly nonlinear dispersion-shifted fiber (HNL-DSF) OPC. The configuration of OPC and the parameters of the HNL-DSF are plotted and summarized in Fig. 2. Because the wavelength of the pump light is assumed to be 1,549.75 nm, the conjugated wavelengths of 24 channels waves range from 1,549.5 nm to 1,528.5 nm for 1,550–1,568.4 nm of the signal at the mid-way OPC.

The conversion efficiency η of OPC is defined as a ratio of the four-wave mixing (FWM) product power to the input probe (signal) power [13]. The 3-dB bandwidth of η is obtained to 48 nm (1,526–1,574 nm) as shown in Fig. 3. The conjugated wavelengths as well as the signal wavelengths are included in the 3-dB bandwidth.

The 24 conjugated multiplexed channels are propagated through the second half of link, demultiplexed, and sent into each Rx, for direct detection. Each Rx in Fig. 1 consists of EDFA as a pre-amplification stage, an optical filter, a photodetector, a pulse shaping Butterworth filter, and a decision circuit. The noise figure of EDFA is 5 dB, and bandwidth of optical filter is 1 nm in this study. Modeling of the photodetector is based on the PIN diode. The receiver bandwidth is assumed to be 0.65 × 40 Gbps [14].



HNL−DSF loss : $\alpha_0 = 0.61 dB/km$

HNL−DSF nonlinear coefficient : $\gamma_0 = 20.4 W^{-1} km^{-1}$

HNL−DSF zero dispersion wavelength : $\lambda_0 = 1550.0 nm$

HNL−DSF length : $z_0 = 0.75 km$

HNL−DSF dispersion slope : $dD_0 / d\lambda = 0.032 ps/nm^2/km$

Pump light power : $P_p = 18.5 dBm$

Pump light wavelength : $\lambda_p = 1549.75 nm$

Fig. 2. The configuration and parameters of HNL-DSF optical phase conjugator.

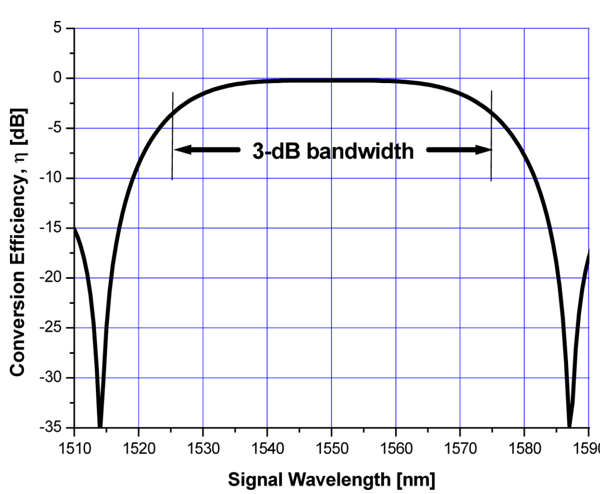


Fig. 3. The conversion efficiency obtained in this research.

To assess the system performance of the receiving WDM channels, we use an eye opening penalty (EOP). The EOP is defined as the following:

$$EOP\,[\text{dB}] = 10\log_{10}\frac{EO_{rec}}{EO_{btb}}, \tag{1}$$

where EO is the eye opening of optical pulse, which is calculated by the following equation:

$$EO = \frac{2P_{\text{av}}}{P_{\text{mark,min}} - P_{\text{space,max}}} \tag{2}$$

where P_{av} is the mean value of the total power of the overall signals, $P_{\text{mark,min}}$ and $P_{\text{space,max}}$ are the lowest power of the mark pulse and the highest power of the space pulse, respectively. In (1), EO_{rec} and EO_{btb} are the eye openings of the receiving optical pulse and the input optical pulse, respectively.

The behavior of optical signal propagated through the optical fiber is well explained by the nonlinear Schrödinger equation (NLSE). The split-step Fourier (SSF) method is employed as a numerical approach for solving the NLSE. In this research, the SSF method is implemented in MATLAB.

III. SIMULATION RESULTS AND DISCUSSIONS

Fig. 4 shows the EOPs of the worst channel versus the NRD for finding the optimal NRD in the case of Pi = 5 dBm, where Pi is the launch power of WDM channel. Here, the worst channel is defined as the channel resulting the maximum EOP. Clearly, the EOPs depend on NRD and SMF length distribution. The NRDs are optimized at 10–15 ps/nm in the "AA" distribution, 5–8 ps/nm in the "AD" distribution, and 5–10 ps/nm in the "DA" and "DD" distributions.

Fig. 5 shows the relation of the launch power and the worst channel's EOP. Here, the NRD is optimized for each artificial distribution, where the optima are derived from Fig. 4. For analyzing the EOP characteristics of each artificial distribution, Fig. 5 also plots the EOP of the uniform distribution with l_{SMF} = 78 km, D_{SMF} = 17 ps/nm/km, l_{DCF} = 15.6 km, and D_{DCF} = -85 ps/nm/km in all fiber spans. These length values are their respective means calculated across all artificial distributions.

In case of assessing system performance by the EOP, the criterion of EOP generally is 1 dB, equivalent to bit error rate (BER) of 10^{-12} and a pulse broadening of 1.25 [15]. Here, pulse broadening is defined as the ratio of the received pulse root mean square (RMS) width to the initial pulse RMS width. By the criterion of 1 dB EOP, the maximum launch power in the “AD” configuration is almost 1 dB higher than in the uniform distribution.

Fig. 6 presents eye diagrams of the worst channels with 9 dBm launched into the optical links configured in the uniform distribution and two artificial distributions (“AD” and “DA”). Although the eye openings of the received WDM signals slightly differ among the distributions, the WDM signals are excellently compensated by the proposed dispersion-managed optical links configured in the “AD” and “DA” distributions with the midway OPC, even at the high transmission power of 9 dBm.

Analyzing the results of Fig. 4, we confirm that many NRD values including the optimal NRD that reduces the EOP to <1 dB are in each optical link, regardless of the launch power. The NRDs that reduce the EOP to <1 dB constitute the effective NRD contour. Fig. 7 illustrates the effective NRD contours of the conventional configuration (i.e., the uniform distribution) and the four artificial distributions for the worst channel. Even at relatively high launch power, the NRD control margin in the optical link is wider in the “AD” distribution than in the uniform and the other artificial distributions.

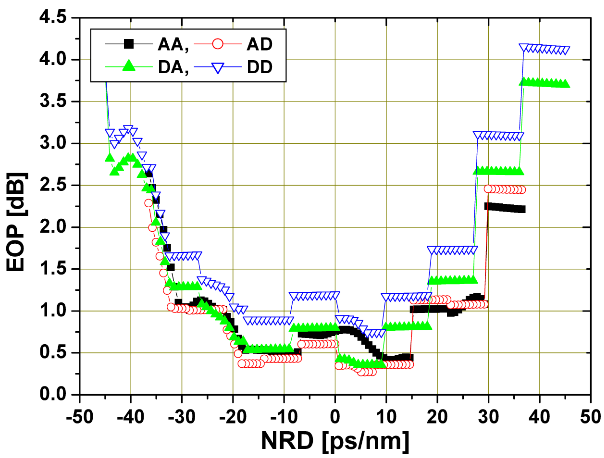


Fig. 4. Inducing of the optimal NRD for the artificial distributions. From Chung and Lee, *Proceedings of AWICE*, pp. 72-75, 2016 [11].

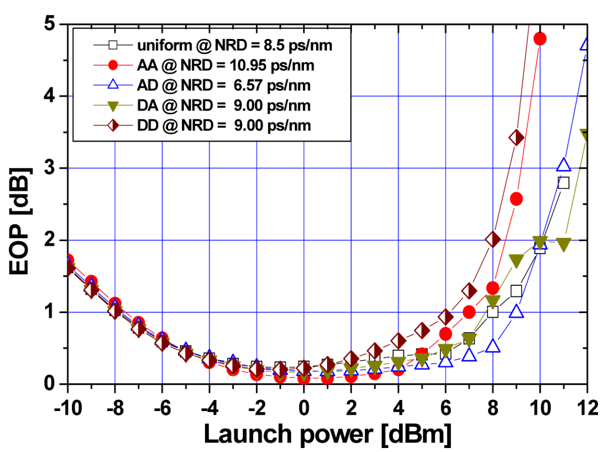


Fig. 5. The EOPs of the worst channel versus the launch power.

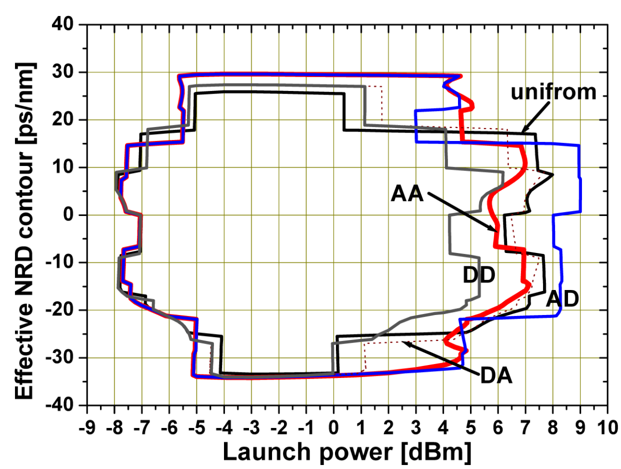


Fig. 7. Effective NRD contours of the link configurations.

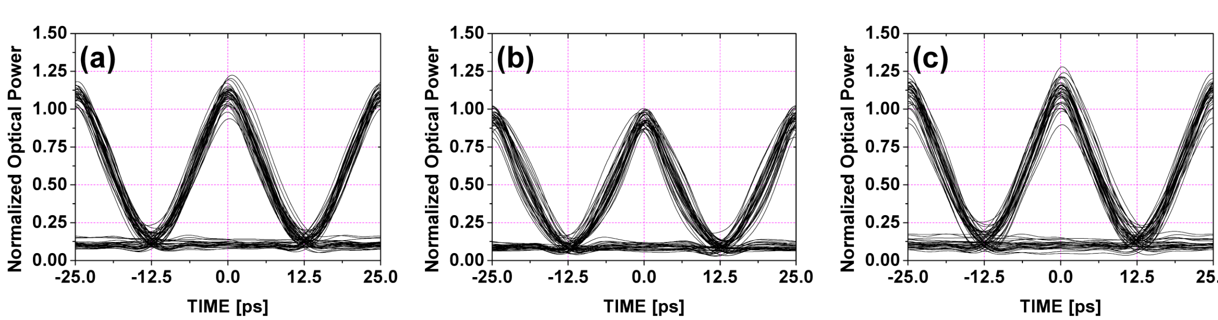


Fig. 6. Eye diagrams: uniform with NRD = 8.5 ps/nm (a), AD distribution with NRD = 6.57 ps/nm (b), and DA distribution with NRD = 9.0 ps/nm (c).

IV. CONCLUSION

This study discussed various artificial distributions of SMFs and DCFs with irregular dispersion coefficients that depend on span lengths. The four artificial distributions were applied to dispersion-managed optical links with midway OPC, which transmitted the WDM signals of 40 Gbps × 24 channels, and their effects on the system performance were evaluated. The "AD" distribution, in which the SMF lengths are gradually ascended and descended before and after the OPC, respectively, best compensated the distorted WDM signals in the optical link with irregular coefficients. This result is remarkably consistent with those of our previous work, in which the dispersion coefficients of SMFs and DCFs were fixed at 17 ps/nm/km and -100 ps/nm/km, respectively. Therefore, we confirmed that artificially distributing the SMFs and/or RDPSs into a DM link can improve the compensation effect, regardless of the magnitude of the dispersion coefficient.

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