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Dispersion-Managed Links for WDM Transmission Arranged by Linearly or Nonlinearly Incremented Residual Dispersion per Span

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Abstract

Combining dispersion-managed optical links with midway optical phase conjugation (OPC) is a possible method of compensating for optical signal distortion due to group velocity dispersion and nonlinear Kerr effects. Although an improvement in the performance of these optical links has been reported, the fixed residual dispersion per span (RDPS) that is typically used restricts the flexibility of link configurations. Thus, in this paper, a flexible dispersion-managed link configuration, comprising artificial distributions of linearly/nonlinearly incremented RDPS, is proposed. Simulations show that a descending distribution of RDPS before the midway OPC, and an ascending distribution of RDPS after the midway OPC, gives the best artificial distribution pattern as the number of fiber spans is increased, regardless of the RDPS incrementation method.

Index Terms: Dispersion management, Linear/nonlinear increment, Net residual dispersion, Optical phase conjugation, Residual dispersion per span

I. INTRODUCTION

Fiber dispersion and nonlinearities such as self-phase modulation (SPM), cross-phase modulation (XPM), and four-wave mixing (FWM), which depend on the signal power [1], degrade propagating pulse signals, causing communication errors. In long-haul communication systems, dispersion compensation is used to minimize pulse broadening. Mid-span spectral inversion (MSSI) using midway optical phase conjugators (OPC), is a technique for mitigating the occurrence of impaired wavelength division multiplexed (WDM) signals due to SPM and group velocity dispersion (GVD) [2–4]. The advantages of MSSI are its effectiveness for multiple channel transmission, its operational independence with respect to modulation format [4], and its availability for use in coherent optical transmission schemes, such as coherent optical orthogonal frequency division multiplexing (CO-OFDM) [5].

Despite these advantages, SPM compensation using OPC is limited by the asymmetry of strength of the nonlinearity along the fiber, with respect to the position of the OPC. This asymmetry in strength is caused by the asymmetric change in light intensity along the fiber, due to fiber loss and amplifier gain. This drawback can be overcome by combining MSSI with optical link dispersion management (DM) [6–8]. The improved performance of a 960 Gbit/s WDM transmission system (40 Gbit/s × 24 channels), implemented with optical link DM and a midway OPC, has

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been demonstrated [9–11].

In conventional DM systems, the normal nonzero GVD of standard single-mode fibers (SMFs) is periodically adjusted using dispersion-compensating fibers (DCFs) of appropriate length, placed at the start or end of a compensation interval [12]. The average dispersion of each fiber span is selected to make the path average dispersion (PAD) close to zero [13]. A significant advantage of DM is the ability to compensate the dispersion and the dispersion slope of the transmission fiber simultaneously [14].

As perfect dispersion compensation can only be achieved for a single channel in WDM systems with DM links and the DM link with a combined OPC, other wavelength channels encounter different magnitudes of cumulative dispersion, which are proportional to their wavelength separations from the zero average-dispersion wavelength channel [12]. In such systems, because of the nonlinear nature of propagation, the performance depends on the power at the input of the different fibers [15] and on the power of each wavelength channel after passing through the OPC. In WDM systems, waveform distortion induced by the nonlinear interaction between SPM and the cumulative residual GVD cannot be compensated using a conventional dispersion map, which typically consists of uniform residual dispersions per span (RDPSs), in whole fiber spans. A possible solution to this problem is to use an artificially configured dispersion map, which brings net residual dispersion (NRD) at the end of a link close to zero. One way to minimize the NRD is to increment the RDPS of each fiber span linearly or nonlinearly, as the number of fiber spans is increased. To the best of the author’s knowledge, artificially configuring DM links by linearly or nonlinearly incrementing RDPSs has not been proposed. Furthermore, the effect of compensation on WDM signals, in this link configuration, is yet to be reported.

In this research, we have investigated the effect of artificial distributions of linearly and nonlinearly incremented RDPSs, in which the average RDPS over the whole link is set to zero, on the compensation of distorted signals from a 24-channel 40-Gbit/s WDM system. The rest of the paper is organized as follows. In Section II, a model, and specifications for the proposed optical transmission links and the 960-Gbit/s WDM system, is presented. In Section III, we present the results of simulations and corresponding analysis. Finally, a conclusion is addressed in Section IV.

II. SYSTEM CONFIGURATIONS

A. Optical Links

Fig. 1 shows the configuration of the DM optical link with the midway OPC, for 960 Gbit/s (24 channel × 40 Gbit/s) WDM transmission. The complete transmission link consists of *n* fiber spans, where *n* is twice the number of fiber spans in each half transmission section (*m*), and is assumed to be 64 for the linear increment, and 52 for the nonlinear increment. As the performance of the optical system depends on the position of the DCF [16] and the amount of residual dispersion [15, 17], we classify the dispersion compensation scheme as precompensation and postcompensation, where the DCF is located before and after the SMF in every fiber span in the former half transmission section (FHTS), i.e., before the midway OPC, and in the latter half transmission section (LHTS), i.e., after the midway OPC, respectively, in case of pre/post-dispersion calibration (Fig. 1(a)). This configuration is reversed in the case of front/rear-mid-dispersion calibration (Fig. 1(b)).

To assess the effect of artificial residual dispersion distributions on performance, we varied the RDPSs from the second span to the (*n*-1)-th span using linear (or nonlinear) increments in pre/post-dispersion calibration, plotted in Fig. 1(a). In front/rear-mid-dispersion calibration, plotted in Fig. 1(b), the RDPSs of all fiber spans, except the *m*-th span and (*m*+1)-th span, were varied using linear (or nonlinear) increments. The artificial distributions detailed above, were deployed in all the dispersion calibration schemes considered. The rest of the fiber parameters were fixed as follows: the length of the SMF, l_{SMF} = 80 km, the attenuation coefficient of the SMF, α_{SMF} = 0.2 dB/km, the dispersion coefficient of the SMF, D_{SMF} = 17 ps/nm/km, the nonlinear coefficient of the SMF, γ_{SMF} = 1.35 W^{-1} km^{-1} at 1550 nm, attenuation coefficient of the DCF, α_{DCF} = 0.6 dB/km, the dispersion coefficient of the DCF, D_{DCF} = -100 ps/nm/km, and the nonlinear coefficient of the DCF, γ_{DCF} = 5.06 W^{-1} km^{-1} at 1550 nm.

For linear incrementation, the RDPS increment between adjacent fiber spans is assumed to be ±10 ps/nm, from 0 ps/nm to ±1200 ps/nm. The average RDPS over the whole link is set to be close to zero, i.e. the values of the RDPSs considered were 0, ±10, ±30, ±60, ±100, ±150, ±210, ±280, ±360, ±450, ±550, ±660, ±780, ±910, ±1050, and ±1200 ps/nm, in each half transmission section. In contrast, for nonlinear incrementation, the RDPS increment between adjacent fiber spans is assumed to be ±10 × (1.5^m) ps/nm, from 0 ps/nm to ±1290 ps/nm, i.e., the values of the RDPSs considered were 0, ±10, ±20, ±30, ±50, ±70, ±110, ±170, ±250, ±380, ±570, ±860, and ±1290 ps/nm.

We assume that the average RDPS over *m*-1 fiber spans is equal to 0 ps/nm in each half section. The individual RDPSs in both half sections are arranged in ascending or descending order of the values mentioned above, as the fiber span increases. There are two combinations of artificial distribution patterns for both half sections, for each

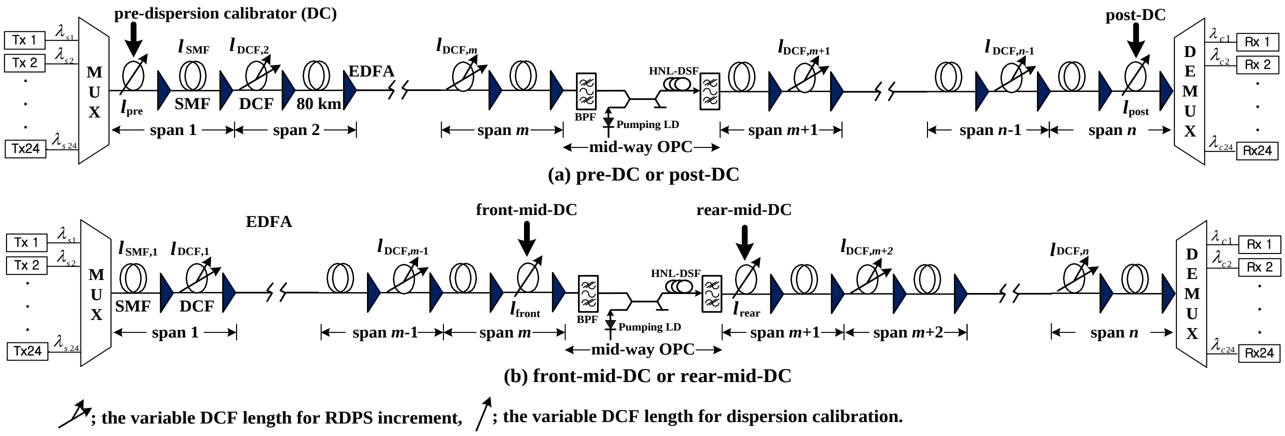

Fig. 1. Configuration of an optical link for transmitting 24-channel wavelength-division multiplexing (WDM) signals. EDFA: erbium-doped fiber amplifier, SMF: single-mode fiber, DCF: dispersion compensating fiber, OPC: optical phase conjugator, DC: dispersion calibrator.

Table 1. Residual dispersions per span (RDPSs) determined by linear and nonlinear increments

Linear increment																		
AD	Ascending	FHTS	#2	#3	#4	#5	#6	......	#15	#16	#17	#18	#19	......	#28	#29	#30	#31	#32
		RDPS	-1200	-1050	-910	-780	-660	......	-30	-10	0	10	30	......	660	780	910	1050	1200
	Descending	LHTS	#33	#34	#35	#36	#37	......	#46	#47	#48	#49	#50	......	#59	#60	#61	#62	#63
		RDPS	1200	1050	910	780	660	......	30	10	0	-10	-30	......	-660	-780	-910	-1050	-1200
DA	Descending	FHTS	#2	#3	#4	#5	#6	......	#15	#16	#17	#18	#19	......	#28	#29	#30	#31	#32
		RDPS	1200	1050	910	780	660	......	30	10	0	-10	-30	......	-660	-780	-910	-1050	-1200
	Ascending	LHTS	#33	#34	#35	#36	#37	......	#46	#47	#48	#49	#50	......	#59	#60	#61	#62	#63
		RDPS	-1200	-1050	-910	-780	-660	......	-30	-10	0	10	30	......	660	780	910	1050	1200
Nonlinear increment																		
AD	Ascending	FHTS	#2	#3	#4	#5	#6	......	#11	#12	#13	#14	#15	......	#21	#22	#23	#24	#25
		RDPS	-1290	-860	-570	-380	-250	......	-20	-10	0	10	20	......	250	380	570	860	1290
	Descending	LHTS	#26	#27	#28	#29	#30	......	#35	#36	#37	#38	#39	......	#47	#48	#49	#50	#51
		RDPS	1290	860	570	380	250	......	20	10	0	-10	-20	......	-250	-380	-570	-860	-1290
DA	Descending	FHTS	#2	#3	#4	#5	#6	......	#11	#12	#13	#14	#15	......	#21	#22	#23	#24	#25
		RDPS	1290	860	570	380	250	......	20	10	0	-10	-20	......	-250	-380	-570	-860	-1290
	Ascending	LHTS	#26	#27	#28	#29	#30	......	#35	#36	#37	#38	#39	......	#47	#48	#49	#50	#51
		RDPS	-1290	-860	-570	-380	-250	......	-20	-10	0	10	20	......	250	380	570	860	1290

incrementation method: ascending-descending (AD), i.e., an ascending distribution in the FHTS, and a descending distribution in the LHTS, and descending-ascending (DA), which are summarized in Table 1. The exact RDPS of each fiber span is then identified by determining the DCF length, l_{DCF}, according to the equation, $(l_{SMF} \cdot D_{SMF} - \text{RDPS}) / |D_{DCF}|$.

Although the average RDPS in each half transmission section is set to be 0 ps/nm, control of the NRD in each half section is required, to yield the best compensation condition. In Fig. 1(a), NRDs of the former and latter halves of the transmission section are determined using the lengths of the DCFs of the first and last fiber spans (l_{pre} and l_{post}), respectively. We considered two methods for NRD control for this dispersion compensation configuration. The first method is detailed as follows: the NRD of the entire transmission link is determined by the NRD of the FHTS alone, through control of l_{pre}. At the same time, the NRD of the LHTS is set to zero (i.e., complete dispersion compensation is present in the LHTS). This control method is called the pre-dispersion calibrator (pre-DC) method. The other method, called post-DC, proceeds as follows: the NRD of the entire transmission link is determined through control of l_{post}, while complete dispersion compensation is fulfilled in the FHTS, simultaneously.

In Fig. 1(b), the lengths of the DCFs for the *m*-th and (*m*+1)-th fiber spans, i.e., l_{front} and l_{rear}, act as NRD controllers for the FHTS and the LHTS, respectively. We again considered two methods for NRD control. The first method, front-mid-DC, proceeds as follows: the NRD of the entire transmission link is determined by controlling l_{front}, while complete dispersion compensation is fulfilled in the LHTS. The second method, rear-mid-DC, proceeds as follows: the NRD of the entire transmission link is determined by l_{rear}, while complete dispersion compensation is fulfilled in the FHTS.

B. Modeling the WDM Transmitter, Receiver and Midway OPC

The transmitters (Tx) plotted in Fig. 1 were modelled as distributed feedback laser diodes (DFB-LD). The center wavelength of the DFB-LD is assumed to be between 1550 nm and 1568.4 nm, with a 100 GHz (0.8 nm) spacing between each channel, based on Recommendation G.694.1 from the ITU-T. Thus, if each wavelength is allocated for one WDM channel, the total wavelength considered corresponds to 24-channel WDM transmission. The DFB-LD was externally modulated using an independent 40 Gbit/s 127 (=2^7-1) pseudo random bit sequence (PRBS). A return-to-zero (RZ) format was assumed for the external optical modulator. The output of the external optical modulator was assumed to be a chirp-free second-order super-Gaussian pulse with a 10 dB extinction ratio (ER), and a 50% duty cycle.

Each channel is multiplexed in the arrayed waveguide grating multiplexer (AWG MUX), and then transmitted to the FHTS. The nonlinear medium of the midway OPC was assumed to be a highly nonlinear dispersion-shifted fiber (HNL-DSF). The parameters of the OPC were as follows: the loss coefficient of the HNL-DSF, α_0 = 0.61 dB/km, the nonlinear coefficient of the HNL-DSF, γ_0 = 20.4 W^{-1} km^{-1}, the length of the HNL-DSF, z_0 = 0.75 km, the zero-dispersion wavelength of the HNL-DSF, λ_0 = 1,550 nm, the dispersion slope, $dD_0/d\lambda$ = 0.032 ps/nm^2/km, the pump light power, P_p = 18.5 dBm, and the pump light wavelength, λ_p = 1549.75 nm. The optical signals propagating through the FHTS were converted to conjugated signals with wavelengths between 1549.5 nm and 1528.5 nm, by the midway OPC. From the previously mentioned OPC parameters, the 3-dB conversion efficiency bandwidth [18] was calculated to be approximately 48 nm (1526–1574 nm). Thus, all of the signal wavelengths and the conjugated wavelengths were within this bandwidth.

The 24 conjugated multiplexed channels were propagated through the LHTS, demultiplexed, and sent into each receiver (Rx), for direct detection. Each Rx in Fig. 1 consists of an erbium-doped fiber amplifier (EDFA) with a noise figure of 5 dB, as a preamplification stage, an optical filter with a 1 nm bandwidth, a PIN diode, a pulse shaping Butterworth filter, and a decision circuit. The receiver bandwidth was assumed to be 0.65 times the bit-rate [19].

In this work, an eye opening penalty (EOP) was used to assess the performance of the system in receiving WDM signals, as detailed in the following equation:

$$EOP\ [dB] = 10\ log_{10}\frac{EO_{rec}}{EO_{btb}}, \quad (1)$$

where EO_{rec} and EO_{btb} are the eye openings (EO) of the receiving optical pulse and the input optical pulse, respectively. EO is defined as $2P_{av}/(P_{1,min} - P_{0,max})$, where P_{av} is the average power of the optical signals, $P_{1,min}$ is the minimum power of the “1” optical pulse, and $P_{0,max}$ is the maximum power of the “0” optical pulse.

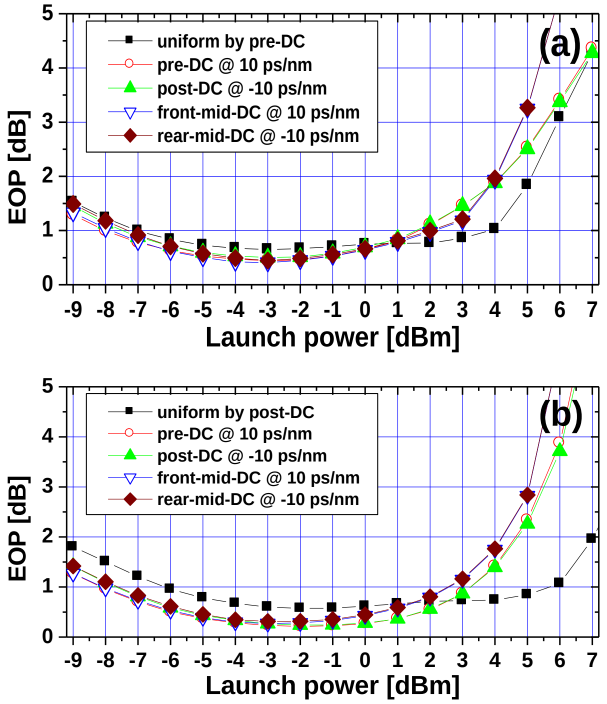

Fig. 2. Eye opening penalties (EOPs) of the worst channel as a function of the launch power (a) for linearly incremented dispersion compensation arranged in ascending-descending (AD) order, and (b) nonlinearly incremented dispersion compensation arranged in descending-ascending (DA) order.

The split-step Fourier (SSF) method was employed as a numerical approach for solving the nonlinear Schrödinger equation, which can express the propagation of a signal in a lossy dispersive nonlinear medium. In this research, the SSF method was implemented in MATLAB.

III. SIMULATION AND DISCUSSIONS

It has previously been reported that the optimal NRD is -10 ps/nm or 10 ps/nm, depending on the position of NRD control, i.e., the method of dispersion calibration [9–11]. This result is consistent with the result detailed in [20], where a “pseudolinear” system was discussed. The optimal NRD of the optical links proposed in this paper were obtained as follows: 10 ps/nm for the pre-DC and front-mid-DC conditions, and -10 ps/nm for the post-DC and rear-mid-DC conditions. Thus, assessment and analysis of the performances of the optical systems will be carried out at these values for each dispersion calibration configuration.

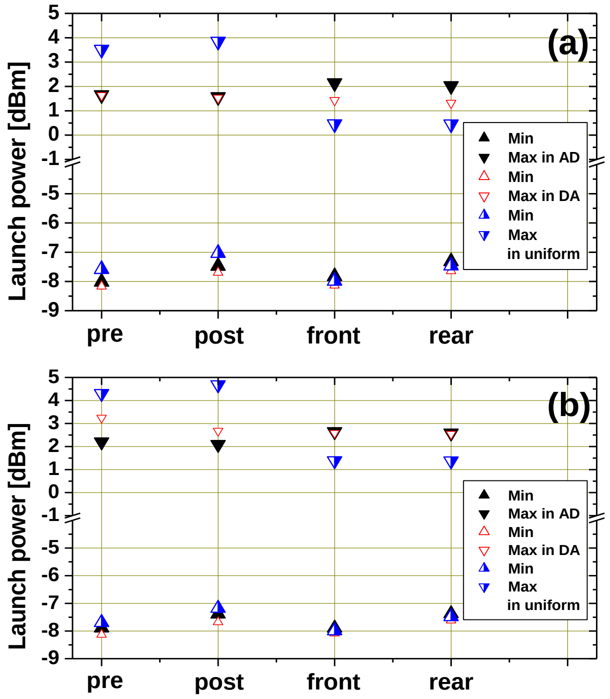

Fig. 3. Effective launch power of the worst channel for (a) linear increment cases, and (b) nonlinear increment cases.

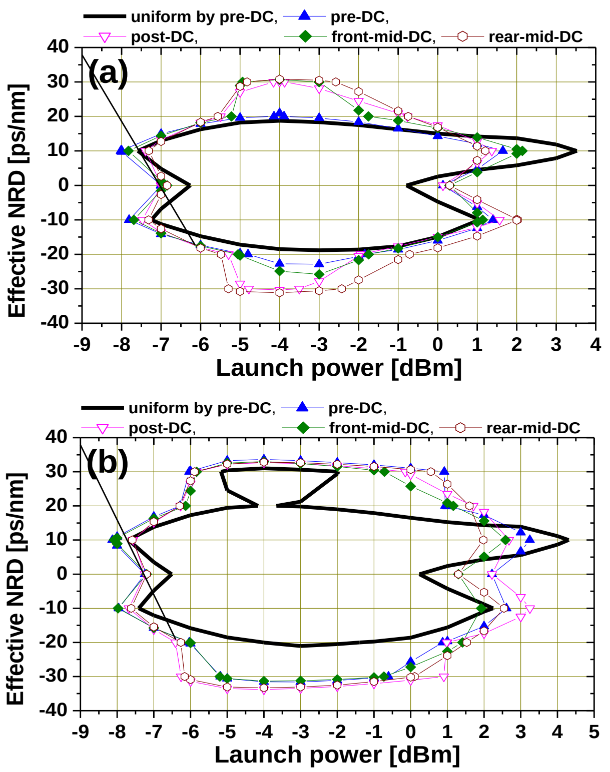

Fig. 4. Effective net residual dispersion (NRD) ranges as a function of launch power for (a) linearly incremented dispersion compensation arranged in ascending-descending (AD) order, and (b) nonlinearly incremented dispersion compensation arranged in descending-ascending (DA) order.

Fig. 2(a) and (b) show the EOPs of the worst channel as a function of the launch power in the dispersion-managed optical links, arranged in AD order for linearly incremented RDPSs, and in DA order for nonlinearly incremented RDPSs. The NRD of all dispersion-managed optical links was set to the optimal value of 10 ps/nm or -10 ps/nm, depending on the method of dispersion calibration. The “uniform” legend entry in Fig. 2 refers to the situation when the RDPS of each fiber span in the DM link was 0 ps/nm. In fiber communication systems, an EOP of 1 dB is typically used as the performance criterion, which is equivalent to a pulse broadening ratio (the ratio of the root mean square [RMS] width of the received pulse to the RMS width of the initial pulse) of 1.25, and corresponds to a bit error rate (BER) of 10^{-12} [21]. All the maximum launch powers obtained in the proposed link configurations were lower than those obtained in the uniform distribution, as assessed by a 1 dB EOP.

Fig. 3(a) and (b) illustrate the effective launch power ranges, i.e., the range of the minimum launch power to the maximum launch power, which results in an EOP below 1 dB, from the linearly incremented RDPSs and the nonlinearly incremented RDPSs, respectively. Although the maximum launch powers obtained with the proposed link configurations were lower than those obtained with the uniform distribution, the effective launch power ranges depended on a combination of the type of RDPS increment, the artificial pattern of the RDPSs, and the NRD control position. We thus confirmed that for linearly incremented RDPSs, the maximum launch power of front-mid-DC configured optical links with AD distribution showed the best improvement, in comparison to other artificial distributions considered. For nonlinearly incremented RDPSs, the maximum launch power of pre-DC configured optical links with DA distribution showed the best improvement, in comparison to other artificial distributions considered.

The range of the maximum to the minimum NRD resulting in an EOP below 1 dB is defined as the effective NRD range. Fig. 4(a) and (b) show the effective NRD ranges (i.e., the effective NRD contour) of the worst channel as a function of the launch power of the dispersion-managed optical links, arranged in AD order for linearly incremented RDPSs, and in DA order for nonlinearly incremented RDPSs, respectively. We confirmed that in transmitting with a high launch power (greater than 2 or 3 dBm), effective NRD contours were only present with the uniform distributions. However, the effective NRD contours observed with the proposed optical link configurations were wider than with the uniform distributions, when transmitting with a launch power of less than 2 or 3 dBm. Therefore, if the launch power of the WDM channels is somewhat limited, dispersion-managed optical links can be implemented with

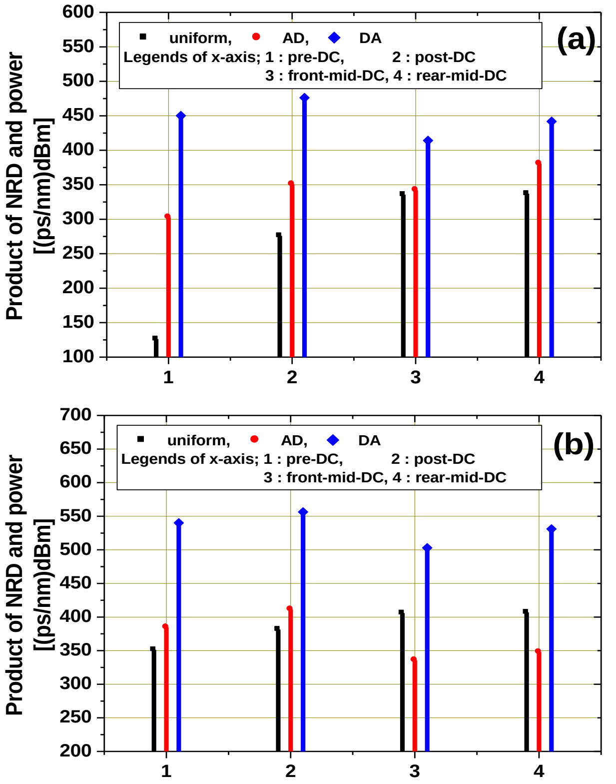

Fig. 5. Product of net residual dispersion (NRD) and launch power (a) for linearly incremented dispersion compensation, and (b) nonlinearly incremented dispersion compensation.

greater flexibility using the proposed configurations, because of the increased NRD margin.

The results in Fig. 5 are a different representation of the results in Fig. 4, for easier quantitative analysis. The "product of NRD and (launch) power" in Fig. 5, is defined as the area of the contour, for the corresponding result in Fig. 4. The flexibility expands as the product of NRD and launch power increases. Thus, we confirmed that DA distribution is superior to other RDPS distribution methods, and in optical links configured with this distribution, post-DC performed better than pre-DC, in terms of NRD control.

IV. CONCLUSIONS

The simulations described in this paper were performed to investigate the possibility of implementing a flexible dispersion-managed link configuration consisting of artificial distributions of linearly/nonlinearly incremented RDPS. We confirmed that the maximum launch power in the proposed links depends on the NRD control position, as well as the artificial distribution pattern. We also confirmed that, as the number of fiber spans increase, a gradually descending RDPS distribution before the midway OPC, and a gradually ascending RDPS distribution after the midway OPC, is the best distribution pattern, with respect to flexibility, regardless of the type of RDPS incrementation.

Consequently, with this research, we confirmed that an artificial distribution of linearly or nonlinearly incremented RDPSs dependent on span length, total transmission length, signal launch power, and number of WDM channels is able to realize flexible optical link implementation.

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