International Journal of Multimedia and Ubiquitous Engineering
Vol.11, No.11 (2016), pp.145-154
http://dx.doi.org/10.14257/ijmue.2016.11.11.12

The Compensation for Distorted WDM Signals in the Optical Long-Haul Transmission Link with the Artificially Distributed Lengths of Single Mode Fiber and Residual Dispersion Per Span

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Abstract

The possibility of the flexible configuration of dispersion-managed optical links combined with optical phase conjugation by adopting an artificial distribution of the lengths of single mode fiber (SMF) and residual dispersion per span (RDPS) of the fiber spans has been numerically investigated. We confirmed that 'DA-DA' pattern – i.e., the lengths of SMF and RDPS around the front and the rear of OPC are smaller, but the lengths of SMF and RDPS closer to the transmitter and the receiver are larger – is the best artificial pattern among the considered 16 artificial distribution patterns. Furthermore, the system performance in the optical link configured with this pattern is more improved than with the conventional uniform distribution of the SMF lengths and RDPS.

***Keywords**: Dispersion-Managed Optical Links, Optical Phase Conjugator, Artificial Distributions, Residual Dispersion per Span, Single Mode Fiber Length*

1. Introduction

Dispersion-management (DM) and optical phase conjugation can be adopted for constructing long-haul wavelength division multiplexing (WDM) transmission systems for mitigating the signal distortion due to the group velocity dispersion (GVD) and nonlinear Kerr effects [1-3]. The DM transmission link is built as a periodic chain of the spans, each including fiber segments with normal and anomalous GVD, whose lengths are selected so as to make the path average dispersion (PAD) close to zero [4]. Generally, this is accomplished by inserting the dispersion compensating fiber (DCF) with anomalous GVD into the single mode fiber (SMF) with normal GVD. In optical phase conjugation, an optical phase conjugator (OPC), which is usually placed midway along the entire transmission link, converts the optical signal waves propagating in the former half section (before OPC) into the phase-conjugated waves. The received signal wave is compensated for by propagating the phase-conjugated waves through the latter half section (after OPC).

However, each technique has certain limitations, such as less compensation for the optical signal distortion due to nonlinear Kerr effects in only DM, and the practical difficulty of the symmetry of the dispersion distribution and the strength of the optical power distribution along the fiber with respect to the position of the OPC [5]. Fortunately, a combination of DM and OPC has been recently proposed for overcoming these problems [6-8].

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ISSN: 1975-0080 IJMUE

Optical system performance depends on the position of the DCF [9], and on the amount of residual dispersion [10-12]. From the viewpoint of DCF's position, the dispersion compensation scheme is specified into the pre- and post-compensation where the DCF is located before or after the SMF in every fiber spans, respectively. However, some researchers have called these schemes as in-line compensation, and defined pre- or post-compensation as the compensated dispersion using DCF after the transmitter or before the receiver in whole transmission line, respectively [13]. In the case of DM applied to every fiber span, residual dispersion per span (RDPS) is defined as the dispersion accumulated in each fiber span, while the net residual dispersion (NRD) is defined as the total dispersion accumulated at the end of the transmission link.

Authors have confirmed through the previous studies that the DCF's position with respect to the SMF in the fiber spans before OPC and after OPC should be opposite to each other for the symmetric distribution of the local dispersion in the optical links with DM and optical phase conjugation [14-15]. That is, if the compensation scheme is pre-compensation before OPC, then post-compensation will be applied into the fiber spans after OPC for effective compensation, especially the distorted WDM signals.

In the techniques mentioned above, the SMF length and RDPS of every fiber span are assumed to be uniform for simplicity of optical link configuration. However, the SMF length and RDPS need to be unlimited for flexible implementation of optical network topology. By randomly distributing the SMF lengths and RDPSs, the flexible link configuration can be implemented. However, this method can result in a complex link configuration, and it is difficult to obtain an optimal random pattern. An alternative way would be to set up a flexible link configuration by artificially distributing the SMF length and RDPS, such as ascending and/or descending distribution of each of them as the fiber spans increase. This distribution method is more advantageous for obtaining an optimal distribution pattern, since the number of cases to be investigated is fewer than the random distributions.

Therefore, this work numerically investigates the possibility of the flexible configuration of the optical links with OPC and DM by adopting an artificial distribution of the SMF length and RDPS. The artificial distribution patterns considered in this paper are generated by combinations of ascending distributions and/or descending distributions of each SMF length and RDPS, as the propagation distance is more increased. The dispersion-managed link in this research consists of pre-compensation in the former half section and post-compensation in the latter half section to raise the effective symmetry of the dispersion distribution and the optical power distribution with respect to OPC.

2. Modeling of Optical Link with Artificial Distributions

The optical transmission link shown in Figure 1 consists of n fiber spans, which include SMF and DCF. The number of fiber spans (*i.e.*, n) considered in this research are 30, 50, 70 and 90. The number of each half transmission section is denoted by m (*i.e.*, $n/2$). The SMF lengths of all of the spans and the DCF lengths from the second span to the (n-1)-th span are varied for artificial distributions. The rest of the fiber parameters are fixed as follows: the attenuation coefficient of SMF α_{SMF} = 0.2 dB/km, dispersion coefficient of SMF D_{SMF} = 17 ps/nm/km, nonlinear coefficient of SMF γ_{SMF} = 1.35 $W^{-1}km^{-1}$ at 1550 nm, attenuation coefficient of DCF α_{DCF} = 0.6 dB/km, dispersion coefficient of DCF D_{DCF} = -100 ps/nm/km, and nonlinear coefficient of DCF γ_{DCF} = 5.06 $W^{-1}km^{-1}$ at 1550 nm.

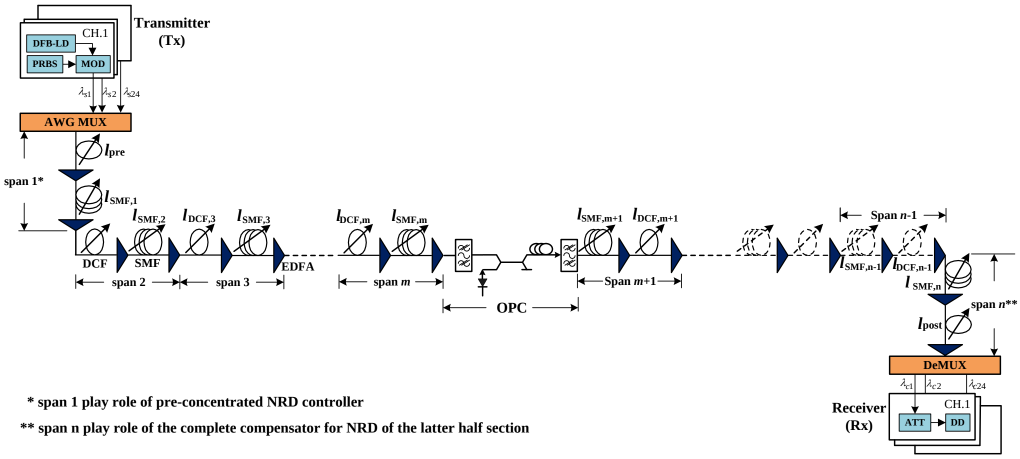


Figure 1. Configuration of WDM Transmission System and Optical Link with the Artificially Distributed SMF Lengths and RDPS

The SMF length distributions in both half sections are ascending from 50 to 110 km, or descending from 110 to 50 km (60/*m* km interval) for the artificial distribution as the fiber span increases. There are 4 combinations of artificial distribution patterns of both half sections: ascending distribution in the earlier half section + ascending distribution in the latter half section (labeled "AA"), descending + descending (labeled "DD"), ascending + descending (labeled "AD"), and descending + ascending (labeled "DA").

The average RDPS is assumed to be equal to the value of 200 ps/nm for both half sections. However, the exact RDPS distributions in both half sections are ascending from 0 ps/nm to 400 ps/nm or descending from 400 ps/nm to 0 ps/nm (400/(*m*-1) ps/nm interval). There are also 4 combinations of artificial distribution patterns of the two half sections: AA, DD, AD and DA. The exact RDPS of each fiber span is then identified by determining the DCF length l_{DCF}, according to $(l_{SMF} \cdot D_{SMF} - \text{RDPS}) / |D_{DCF}|$.

Thus, there are 16 combinations of artificial distribution patterns of the SMF length and exact RDPS. We notate these combinations as the artificial distribution pattern label of SMF length – the artificial distribution pattern label of RDPS, such as AA-AA, AA-DD, and DD-DD, *etc*. For example, AD-DA means the optical link with ascending distribution of the SMF lengths in the former half section, descending distribution of SMF lengths in the latter half section, descending distribution of the exact RDPSs in the former half section, and ascending distribution of the exact RDPSs in latter half section.

Because we assume the averaged RDPS to be 200 ps/nm, the NRDs of each half section are not zero, but rather very large. Thus, controlling the NRD of each half section by using the arbitrary span is needed to obtain the optimal value for the good compensation. The DCF length of the first fiber span and the last fiber span, *i.e*., l_{pre} and l_{post}, are used to determine the NRD of the former and latter half transmission section, respectively. We design the optical link configuration based on the concept as following: 1) pre-compensation (*i.e*., DCF+SMF) in the former half section and post-compensation (*i.e*., SMF+DCF) in the latter half section for the effective symmetric distribution of local dispersion with respect to OPC, 2) the NRD of the entire transmission link is determined by the NRD of the former half section, and 3) the NRD of the latter half section is zero (that is, the complete dispersion compensation is presented in the latter half section). The complete compensation of the latter half section is accomplished by setting up the fixed DCF length of the last span, which depends on *m* and the artificially distributed RDPSs for the various *n*. And then, the specific NRD of the entire link is only determined by selecting the DCF length of the first span depending on *m* and the artificially distributed RDPSs in the former half section. We call this NRD control scheme as pre-concentrated compensation. That is, our optical transmission link configuration consists of the pre-concentrated compensation and the complete compensation with respect to OPC at the midway of the total transmission line.

The configuration of the OPC is illustrated in the middle of the optical links shown in Figure 1. The nonlinear medium of the OPC is assumed to be the highly nonlinear dispersion-shifted fiber (HNL-DSF). The parameters of the OPC are as follows: loss of HNL-DSF α_0 = 0.61 dB/km, nonlinear coefficient of HNL-DSF γ_0 = 20.4 $W^{-1}km^{-1}$, the length of HNL-DSF z_0 = 0.75 km, zero dispersion wavelength of HNL-DSF λ_0 = 1,550 nm, dispersion slope $dD_0/d\lambda$ = 0.032 ps/nm^2/km, pump light power P_p = 18.5 dBm, and pump light wavelength λ_p = 1,549.75 nm.

3. Modeling of WDM Transmission System and Numerical Assessment

The transmitter (Tx) for the 24-channel WDM shown in Figure 1 is assumed to be a distributed feedback laser diode (DFB-LD). The center wavelength of the DFB-LD is assumed to be 1,550-1,568.4 nm by spacing of 100 GHz (0.8 nm) based on ITU-T recommendation G.694.1. The DFB-LD is externally modulated by an independent 40 Gbps 127 (=2^7-1) pseudo-random bit sequence (PRBS). The modulation format from the external optical modulator is assumed to be RZ. Also, the RZ format is assumed to be a second-order super-Gaussian pulse with a 10-dB extinction ratio (ER), duty cycle of 0.5, and chirp-free.

The optical signals propagating through the former half section are converted to the conjugated signals with wavelengths of 1549.5-1528.5 nm by the midway OPC. The 3-dB bandwidth of conversion efficiency [14] is calculated to almost 48 nm (1526-1574 nm) from the previously mentioned OPC parameters. Thus, all of the signal wavelengths and these conjugated wavelengths belong within the 3-dB bandwidth of the conversion efficiency.

We assume that the receiver (Rx) consists of the pre-amplifier of the EDFA with a 5-dB noise figure, the optical filter of 1-nm bandwidth, PIN diode, pulse shaping filter (Butterworth filter) and the decision circuit. The receiver bandwidth is assumed to be a 0.65×bit-rate [16].

The propagation of the signal in a lossy, dispersive, and nonlinear medium can be expressed by the nonlinear Schrödinger equation (NLSE), assuming a slowly varying envelope approximation [17]:

$$\frac{\partial A_j}{\partial z} = -\frac{\alpha}{2}A_j - \frac{i}{2}\beta_{2j}\frac{\partial^2 A_j}{\partial T^2} + \frac{1}{6}\beta_{3j}\frac{\partial^3 A_j}{\partial T^3} + i\gamma_j|A_j|^2 A_j + 2i\gamma_j|A_k|^2 A_j, \quad (1)$$

where j,k = 1,2,…,24 ($j \neq k$), A_j represents the complex amplitude of the signal of the j-th channel, z is the propagation distance, β_{2j} is the GVD, β_{3j} is third-order dispersion, γ_j is the nonlinear coefficient, and $T = t - z/v_j$ is the time measured in a retarded frame. The last two terms of (1) induce SPM and cross-phase modulation (XPM), respectively. The effects of XPM on WDM signals decrease as the fiber dispersion increases [18]. Thus, XPM's effect on SMF links is generally neglected in the analysis of NLSE. The numerical approach of (1) is completed by using the split-step Fourier method [17].

Eye opening penalty (EOP) is used to assess the system performance of the receiving WDM signals in this work, as shown in the following equation:

$$EOP\ [dB] = 10\ log_{10}\frac{EO_{rec}}{EO_{btb}}, \quad (2)$$

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

In the proposed artificial distribution, the differences of the lengths of SMF and RDPSs between the fiber span are more decreased, as m is more increased. That is, it is required to restrict m, because the artificial distribution of SMF lengths and RDPSs is more approximate to the uniform distribution, as the more number of the fiber spans. In our simulation, first we assess the system performances in the case of m = 25 (*i.e.*, n = 50), and then the assessments of the system performances in other m are based on the results of 50 fiber spans.

It had been confirmed that the optimal NRD controlled by pre-concentrated compensation was resulted to 10 ps/nm, regardless of the SMF length, RDPS, launch power, dispersion coefficient [14, 15]. This result is remarkably consistent with the result of Reference [13] by Xiao's research dealing with "pseudolinear" system. It is confirmed that the optimal NRD of the optical links proposed in this paper is also obtained to be the above mentioned value. Thus, the assessment and the analysis of system performances will be carried out, under the conditions of NRD = 10 ps/nm by pre-concentrated compensation.

4. Simulation Results and Discussion

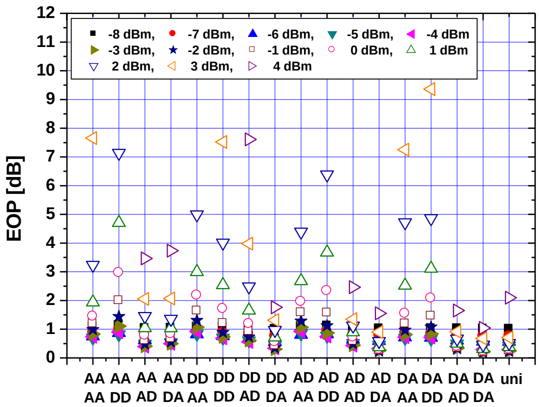
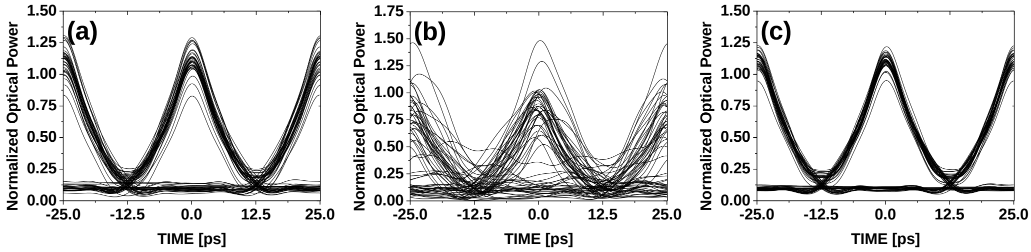


Figure 2. The EOP of the Worst Channel for the Various Launch Power as a Function of 16 Artificial Distributions and the Uniform Distribution

Figure 2 shows the EOPs of the worst channel among 24 WDM channels depending on launch power as a function of 16 combinations of artificial distribution patterns in the optical links consisting of 50 fiber spans with the optimal NRD of 10 ps/nm. Figure 2 simultaneously shows the EOPs of the worst channel in the optical links with the uniform distribution (marked by 'uni' in x-axis) for the performance comparison. It is confirmed that the EOPs depend on the launch power and distribution pattern of SMF lengths and RDPSs, however, the EOP characteristics of particular artificial distribution patterns are superior to the uniform distribution of SMF length and RDPS. In case of Figure 2, all EOPs for the considered launch power, *i.e.*, from -8 dBm to 4 dBm, in the optical link configurations arranged by 'DD-DA' 'AD-DA' 'DA-AD' and 'DA-DA' combinations are lower than that of 'uni'. Moreover, it is confirmed that 'DA-DA' pattern among these combinations is the best artificial distribution pattern.

DA-DA pattern means the lengths of SMF and RDPS around the front and the rear of OPC are smaller, but the lengths of SMF and RDPS closer to Tx and Rx are larger. That is, it is required to temporally broaden the optical pulse widths of WDM channels in the beginning of transmission, and then to further compress the optical pulse widths as the transmission distance is increased up to OPC. Also, the temporally compressed and spectrally inverted optical pulses after OPC are more inversely broadened as the transmission distance is closer to Rx for the best compensating of the distortions.



(a) (b) (c)

Figure 3. The Eye Diagrams of the Several Worst Channels with the Launch Power of 4 Dbm in the Optical Links of the Uniform Distribution (a), of the 'AA-AA' Distribution (b), and of the 'DA-DA' Distribution (c), Respectively

Figure 3 (a), (b) and (c) show the eye diagrams of the worst channels with the launch power of 4 dBm in the optical links with the uniform distribution, 'AA-AA' and 'DA-DA' of the artificial distribution, respectively. It is confirmed that, although the overall bits transmitted through the uniform distribution and 'DA-DA' distribution are detected as error-free, the eye openings of the received bits through the optical link configuration of 'DA-DA' distribution are more expanded than the received bits in the uniform distribution. On the other hand, many bits are not sufficiently compensated for by DM and OPC in the optical link configuration deployed by 'AA-AA' distribution. That is, the results of Figure 3 show that the system performance in DM link with the midway OPC is intensely affected by the artificial distribution pattern of the SMF lengths and RDPSs.

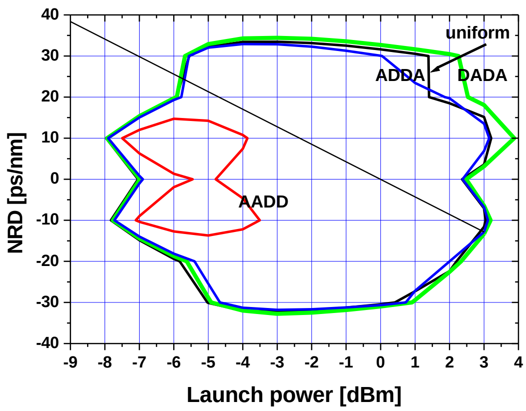
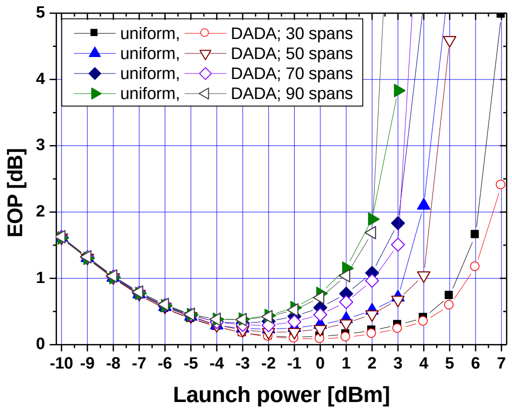
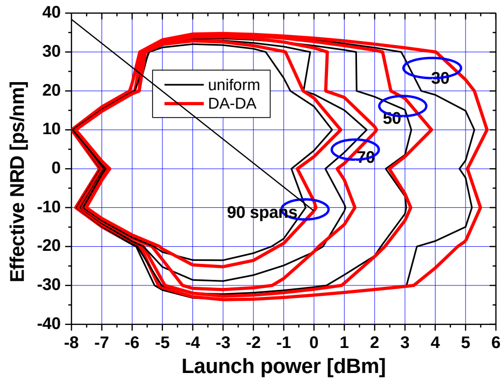


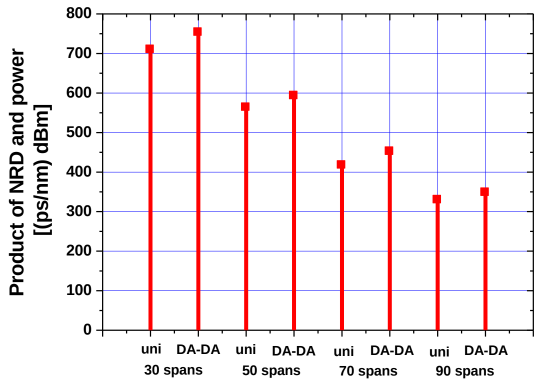
Figure 4. The Effective NRD Ranges of the Worst Channel Transmitted in 50 Fiber Spans as a Function of the Launch Power

In fiber communication systems, 1 dB EOP is used for the system performance criterion, which is equivalent to the pulse broadening (the ratio of the received pulse RMS width to the initial pulse RMS width) of 1.25 and corresponds to 10^{-12} bit error rate (BER) [17]. Through the analysis of previous studies, it is confirmed that the EOPs below 1 dB at arbitrary launch power are obtained in the various NRD values besides 10 ps/nm. These NRD values result in the EOP below 1 dB are defined as the effective NRD range. Figure 4 illustrates the effective NRD ranges of the worst channel transmitted in 50 fiber spans as a function of the launch power in the optical links of the uniform distribution and several artificial distributions. It is shown that the wider NRD margin than 60 ps/nm (*i.e.*, ±30 ps/nm) is obtained both in the optical link with the uniform distribution and the optical link with 'DA-DA' pattern for the launch power of -5~1 dBm. However, in the higher launch power upper than 1 dBm, the NRD margin in 'DA-DA' pattern is slightly expanded than that in the uniform distribution.



(a)





(b) (c)

Figure 5. The Simulation Results in 30, 50, 70 and 90 Fiber Spans with Uniform Distribution or 'DA-DA' Distribution; the Eops versus the Launch Power (a), the Effective NRD Ranges as a Function of the Launch Power (b), and Production of NRD and Power (c), Respectively

Figure 5 (a) shows the EOPs of the worst channel in the uniform distribution and the artificial distribution by 'DA-DA' pattern as a function of the launch power in order to compare the compensation characterized by *m*. It is first confirmed that the performance in 'DA-DA' pattern is slightly improved than the uniform distribution, irrelevant of *m*. From the viewpoint of 1 dB EOP criterion, the EOP improvements in 'DA-DA' pattern over the uniform are more decreased as *m* is more increased. We think this result in the relative long haul is attributed to that the magnitudes of SMF length and RDPS between the fiber spans by the artificial distribution are so small that the compensation effect from 'DA-DA' pattern is more decreased, as the more number of the fiber spans .

Figure 5 (b) illustrates the effective NRD ranges of the uniform distribution and of 'DA-DA' pattern for *m* = 30, 70 and 90 as a function of the launch power. As the previous results of Figure 5 (a), the effective NRD ranges in 'DA-DA' pattern is slightly improved than the uniform distribution, irrelevant of *m*. It should be required to quantitatively analyze the factor for the easy comparison of the effective NRD ranges affected by *m* and link configurations. Thus, we use the area of contour from the results of Figure 4 and Figure 5 (b) as a quantitative factor. We define the area of contour as 'product of NRD and (launch) power', and this is plotted in Figure 5 (c) as a function of *m* and link configurations. It is confirmed that the improvements of product of NRD and power in 'DA-DA' pattern over the uniform are more decreased as *m* is more increased, like the previous results.

5. Conclusion

The simulations described in this paper were aimed at investigating the implementation possibility of the flexible optical links configuration using the artificial distribution of the SMF lengths and RDPS in dispersion-managed optical links with the midway OPC. We first confirmed that several artificially distributed patterns, such as 'DD-DA' 'AD-DA' 'DA-AD' and 'DA-DA', can further improve system performance than the uniform distribution. The 'DA-DA' is the best artificial pattern for compensating for the distorted WDM channels. It is also confirmed that the compensation effect by 'DA-DA' pattern is more increased when the number of fiber spans are fewer, because the differences of the length of SMF and RDPS between adjacent fiber spans are more increased.

It would be misleading to restrict 'DA-DA' pattern to the relative short-haul optical transmission link for improving the system performance. However, this judgement is based on the idea that the maximum deviations in SMF length and RDPS are same, regardless of number of fiber spans. This simultaneously means that the improved compensation effect by 'DA-DA' can be obtained by increasing the deviations in SMF length and RDPS as much as number of fiber spans increase. Unfortunately, the simulations related with the performance assessments in the long-haul optical links (m > 90) with the wide deviations in SMF length and RDPS are not included in this research. Through future study, we intend to evaluate and analyze the effects of the above-mentioned DM schemes on the compensation for the distorted WDM channels in the long-haul optical links.

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