Compensation Characteristics of the Distorted WDM Signals Depending on the Variation Degree of RDPS Random Variables in the Optical Links with Dispersion Management and Optical Phase Conjugation

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Abstract

The effects of the variation degree of residual dispersion per span (RDPS) random variables on the compensation characteristics of the distorted signals in optical links with the dispersion management (DM) and the mid-way optical phase conjugator (OPC) are investigated in this paper. In order to obtain this goal, the effective launch power range and the effective net residual dispersion (NRD) range are induced as a function of the variation degree of RDPS random variables. We confirm that it is needed to select the RDPS random variables of the narrow deviation in each fiber spans for implementing the flexible optical links transmitting the relative higher launch power. Also, we confirmed that it is more advantageous to use postcompensation rather than precompensation for expanding the effective NRD range.

Keywords: *Random distribution of Residual Dispersion per Span, Variation Degree of RDPS random Variable, Optical Phase Conjugator, Dispersion-Managed Optical Links, Net Residual Dispersion, Pre(post)compensation*

1. Introduction

Most of standard single mode fibers (SMF) have high-chromatic dispersion in the wavelength window around 1,550 nm. For this reason, 40 Gbps transmission would be limited to few kilometers if compensating techniques of the group velocity dispersion (GVD) were not used [1-3]. Dispersion management (DM) is one of the most effective techniques to transmit high capacity on already installed standard SMF links both in the return-to-zero (RZ) [4] and nonreturn-to-zero (NRZ) signal formats [5, 6]. DM is through the insertion of a dispersion compensating fiber (DCF) into SMF for eliminating or mitigating the impact of distortion due to GVD. Precompensation, postcompensation, residual dispersion per span (RDPS) and net residual dispersion (NRD) are the major parameters for improving the system performances in the dispersion-managed optical links. Pre- and postcompensation are defined as dispersion

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compensation using the DCF after the transmitter and before the receiver, respectively. In the case of the DCF applied to every fiber span, RDPS is defined as the dispersion accumulated in each fiber span. And, the NRD is defined as the total dispersion accumulated at the end of the transmission link [7]. Generally, the NRD is decided by controlling pre- or postcompensation and RDPS.

In the absence of Kerr nonlinearity, by adopting the DM method in principle, any bit rate could be transmitted for any distance if the input power is sufficient to overcome amplified spontaneous emission (ASE) noise impairment [2, 3]. Unfortunately the presence of the Kerr effect induces a distortion that accumulates along the link and it is more evident for high bit rates, where higher powers are required to ensure a good optical signal-to-noise ratio (OSNR).

The use of optical phase conjugator (OPC) in the mid-way of total transmission length is another effective technique to reduce Kerr nonlinear impairment as well as the GVD impairment. However, the effective suppression of nonlinear impairment is not obtained in the optical transmission systems using only OPC, because nonlinearity cancellation by OPC requires a perfectly symmetrical distribution of power and local dispersion with respect to OPC position [8]. Due to the presence of fiber attenuation, this condition cannot be satisfied in real links. Fortunately, the available techniques for overcoming this drawback, such as optimizing OPC position [9, 10] or combining appropriate dispersion mapping [9, 11, 12] have been proposed recently.

The most works relating with the only DM techniques and with the combined DM and OPC techniques had been focused on the uniformly distributed RDPS. This scheme means that the lengths of SMF and DCF have to be fixed, hence the uniformly distributed RDPS makes the optical link configurations simple, but the implementation of reconfigurable optical link is very difficult. The authors have shown the possibility of implementing the flexible optical links for wavelength division multiplexing (WDM) transmission by applying the randomly distributed RDPS into combined DM and OPC links [13]. In previous research, the random distribution of RDPS were made by selecting the random variables of DCF length for each fiber spans with the fixed SMF length. However, only one case of the variation degree of RDPS random variables was considered in previous work. It is predicted that the variation degree of RDPS random variables affect system performance, even though the averaged RDPS is same [14].

Therefore, in this paper, we investigate the effects of the variation degree of RDPS random variables on the compensation characteristics of the distorted signals in 960 Gbps WDM transmission systems. We consider 3 cases of the variation degree, such as gentle, moderate, and extreme variation of RDPS for each fiber spans. The random distribution RDPS is determined by only DCF lengths but not SMF lengths, as like as the previous work.

The rest of the paper is organized as follows. In Section 2, the modeling and specifications of the proposed optical transmission links and WDM systems for 960 Gbps are presented. Numerical assessment method and the system performance are also described in Section 2. In Section 3, the simulation results and our analysis are presented. And, the conclusion is addressed in Section 4.

2. Modeling of Optical Links and 960 Gbps WDM Transmission Systems

2.1. Modeling of optical links

Figure 1 shows the optical transmission link configuration and WDM transmission system investigated in this research. The total transmission link consists of 14 fiber spans, which include the SMF and the DCF for DM. We consider 3 cases of the randomly distributed RDPS according to the variation degree, in the optical link with the fixed SMF length of 80 km in all fiber spans. In other words, 3 cases are classified as "gentle", "moderate" and "extreme" by the maximum deviation in RDPS of each fiber spans, shown in Table 1. The maximum deviation in RDPS of "gentle", "moderate" and "extreme" are 60 ps/nm, 400 ps/nm, and 2,300 ps/nm, respectively.

In 3 cases, the averaged RDPSs are assumed to be equal value of 150 ps/nm in both half transmission sections from transmitter(Tx) to the OPC and from the OPC to receiver(Rx), except the first and the last fiber span for pre- and postcompensation, respectively. The DCF length of all of the spans are designed to be fixed 12.1 km for the uniform distribution of RDPS = 150 ps/nm. However, in the randomly distributed RDPS optical link, RDPS of each half transmission section is assumed to be randomly selected to be one of six values summarized in Table 1.

All of the SMFs are characterized by the attenuation coefficient α_{SMF} = 0.2 dB/km, dispersion coefficient D_{SMF} = 17 ps/nm/km, and nonlinear coefficient γ_{SMF} = 1.35 W^{-1}km^{-1} at 1,550 nm. Also, all of the DCFs are characterized by dispersion coefficient D_{DCF} = -100 ps/nm/km, attenuation coefficient α_{DCF} = 0.6 dB/km, and nonlinear coefficient γ_{DCF} = 5.06 W^{-1}km^{-1} at 1,550 nm.

The NRD is controlled by precompensation or postcompensation as plotted in Figure 1. In case of determining the NRD by only precompensation, the NRD depends on the variable length of the first DCF, *i.e.*, l_{pre}, the accumulated dispersion in the first SMF, and the total RDPS in the former half section, when the total accumulated dispersion in the latter half section has been fixed to be 0 ps/nm. On the other hand, when the NRD is determined by only postcompensation, it depends on the variable length of the last DCF, *i.e.*, l_{post}, the accumulated dispersion in the last SMF, and the total RDPS in the latter half section when the total accumulated dispersion in the former half section has been fixed to be 0 ps/nm.
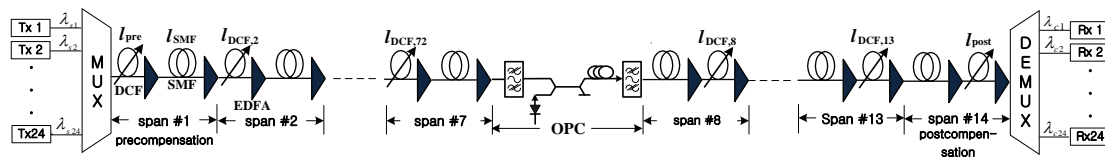

Figure 1. Configurations of WDM transmission system and the optical link [14]

Table 1. RDPS and l_{DCF} for the random distribution

Degree of variation		Random variables					
Gentle	RDPS [ps/nm]	120	130	140	160	170	180
	l_{DCF} [km]	12.4	12.3	12.2	12.0	11.9	11.8
Moderate	RDPS [ps/nm]	0	50	100	150	200	400
	l_{DCF} [km]	13.6	13.1	12.6	12.1	11.6	9.6
Extreme	RDPS [ps/nm]	-1000	-600	-300	600	900	1300
	l_{DCF} [km]	23.6	19.6	16.6	7.6	4.6	0.6

2.2. Modeling of WDM transmission system and Numerical Assessment

The WDM system consists of a Tx, Rx, dispersion managed optical links, and the OPC nearby the mid-way of total transmission length. The Tx plotted 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. Thus, if each wavelength is allocated for one WDM channel, the total wavelength considered corresponds to 24-channel WDM transmission. 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 return-to-zero(RZ), and the output electric field of 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 nonlinear medium of the OPC is assumed to be highly nonlinear dispersion-shifted fiber (HNL-DSF). The parameters of the OPC using HNL-DSF are summarized in Table 2. The 3-dB bandwidth of conversion efficiency η of the OPC is set at 48 nm (1526–1574 nm). The signal wavelengths are converted to 1,549.5–1,528.5 nm (these are called the conjugated wavelength) through the OPC. Thus, the 24 signal wavelengths and these conjugated wavelengths belong within the 3-dB bandwidth of η.

Table 2. The parameters of OPC

Parameters	Values
Loss of HNL-DSF	0.61 dB/km
Nonlinear coefficient of HNL-DSF	20.4 $W^{-1}km^{-1}$
Length of HNL-DSF	0.75 km
Zero dispersion wavelength of HNL-DSF	1,550 nm
Dispersion slope of HnL-DSF	0.032 $ps/nm^2/km$
Pump light power	18.5 dBm
Pump light wavelength	1549.75 nm

The conjugated wavelengths are sent into the Rx of direct detection. The Rx of Figure 1 consists of the pre-amplifier of erbium-doped fiber amplifier (EDFA) with 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 at 0.65×bit-rate [15].

The 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:

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

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 $2\ P_{av}/(P_{1,min} - P_{0,max})$, 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.

3. Simulation Results and Discussion

There are many random distribution patterns of RDPS. It is difficult to assess the system performance of the overall patterns because it is a time consuming process. Therefore, in this work, 50 patterns of random distribution are considered for an accurate and simple assessment. Figure 2 illustrates the EOPs of the worst channel among the 24 WDM channels with the launch power of -5 dBm and 0 dBm as a function of the NRD controlled by pre- and postcompensation, respectively, in the optical transmission links with the randomly distributed RDPS depending on the variation degree. In x-coordinate of each figures, the first, the second and the third plot correspond to "gentle", "moderate" and "extreme", respectively.

(a) -5 dBm; precompensation

(b) -5 dBm; postcompensation

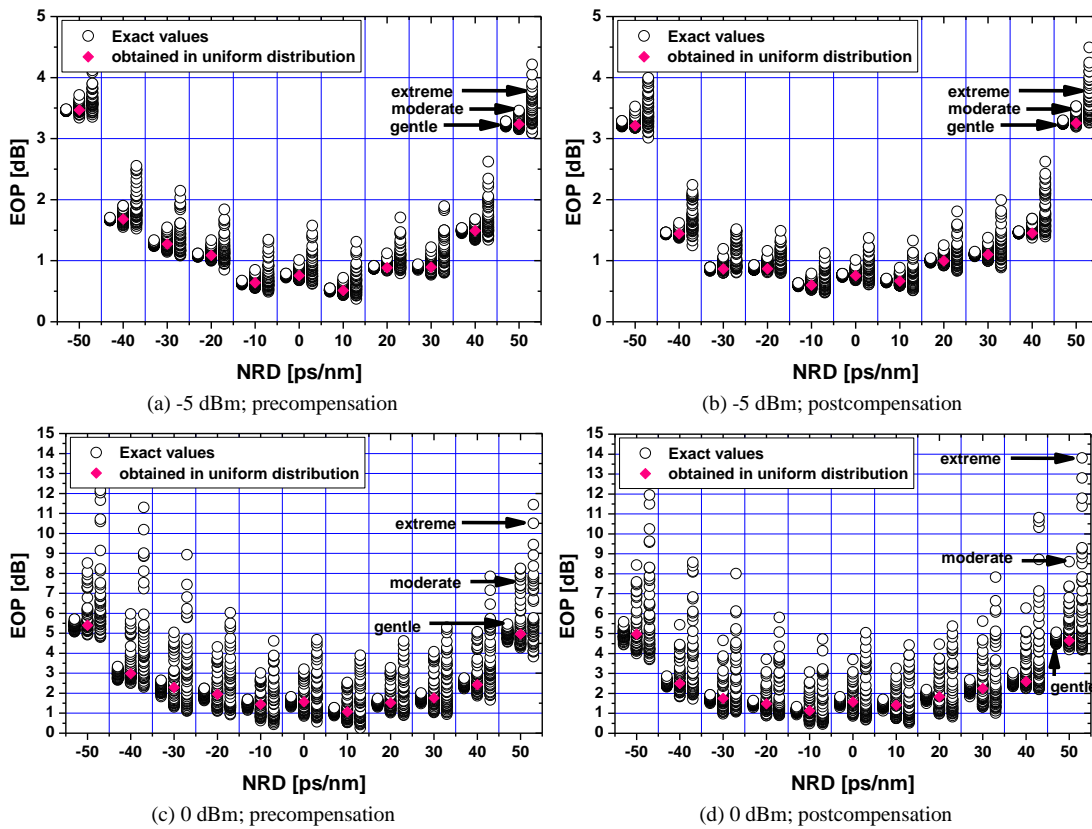(c) 0 dBm; precompensation

(d) 0 dBm; postcompensation

Figure 2. The EOPs as a function of the NRD controlled by precompensation and postcompensation in the optical links with the random distribution of RDPS

It is confirmed that the optimal NRDs are found to be 10 ps/nm or -10 ps/nm in the optical link controlled by precompensation and postcompensation, respectively, because the worst EOPs of 50 random patterns at these NRDs are smaller and the deviation of

EOPs are narrow than other NRDs. These optimal NRDs are consistent in the results of our previous research of [13]. We also confirm that the optimal NRDs of the considered other launch power (-9∼3 dBm) are obtained to be the same values, i.e., 10 ps/nm or -10 ps/nm. The results of Figure 2 also show the variation of system performance is more increased as the variation degree of RDPS random variable is more increased and the NRD is more increased.

Figure 3(a) and (b) illustrate the worst EOPs of the worst channel as a function of the launch power in the optical links with the optimal NRD of 10 ps/nm and -10 ps/nm by precompensation and postcompensation, respectively. 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) [16]. Therefore, we define the launch power results in the EOP below 1 dB as the effective launch power. It is confirm that the range of the effective launch power strongly depends on the variation degree of the random variable of RDPS. The results of Figure 3 shows that the difference in the effective launch power between "gentle" distribution and the uniform distribution is less than 0.6 dB. However, the effective launch power in "extreme" distribution cannot be obtained from the criterion of 1 dB EOP. Therefore, it is also confirmed that it is needed to use the RDPS random variables of the narrow deviation in each fiber spans for implementing the flexible optical links transmitting the relative higher launch power.
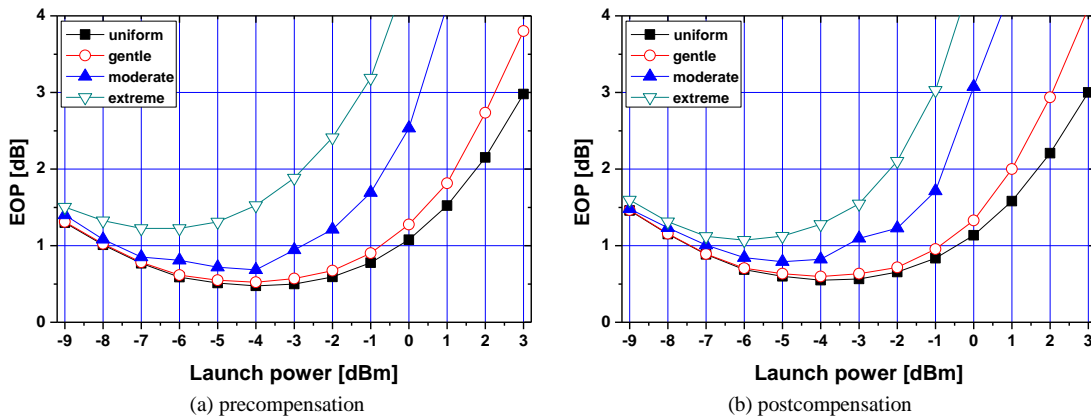

(a) precompensation
(b) postcompensation

Figure 3. The EOPs as a function of the launch power in the optical links with the optimal NRD

From the results of Figure 2, in other NRDs as well as the optimal NRDs range, the worst EOPs of the worst channels result in below 1 dB depending on the launch power, except for "extreme" distribution. Therefore, we define the NRD values result the EOP below 1.5 dB but 1.0 dB as the effective NRD range in this research. Figure 4 shows the effective NRD ranges for the uniformly distributed RDPS and the randomly distributed RDPS depending on the variation degree, as a function of the launch power.

It is shown that the effective NRD ranges are largely dependent on the RDPS distribution and RDPS random variables. However, it is confirmed that there are little differences of the effective NRD ranges between the "gentle" distribution of RDPS random variables and the uniform RDPS distribution. We also confirmed that it is more advantageous to use postcompensation for controlling the NRD rather than precompensation, because the

wider effective NRD can be obtained in the same condition. Therefore, the flexible implementation of the optical links with the randomly distributed RDPS is possible through the use of postcompensation, and the limitation of -8~-6 dBm launch power and -20~10 ps/nm NRD, even though the maximum deviation of RDPS random variables in each fiber spans is wide.
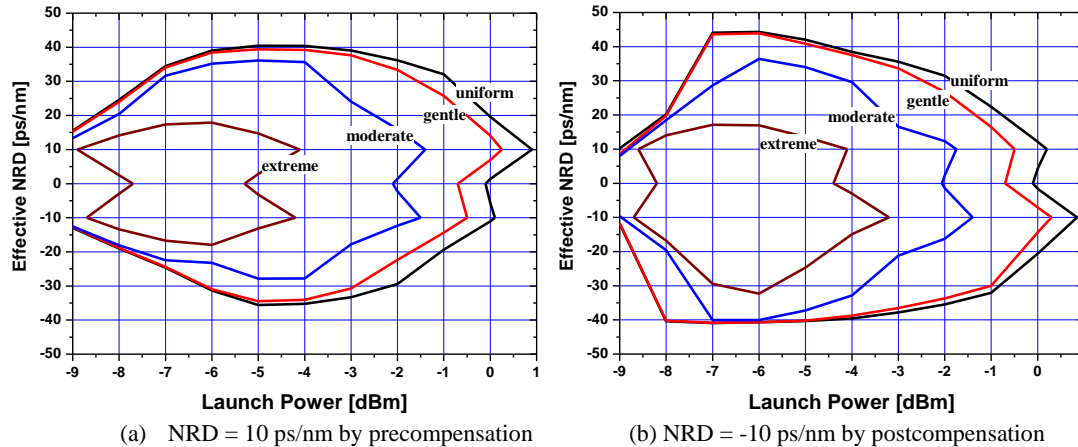

(a)   NRD = 10 ps/nm by precompensation   (b) NRD = -10 ps/nm by postcompensation

Figure 4. The effective NRDs as a function of the launch power

4. Conclusions

This paper discussed the effects of the variation degree of RDPS random variables on the compensation characteristics of the distorted signals in the dispersion-managed optical links with the mid-way OPC for 960 Gbps WDM transmission. It was confirmed that the optimal NRDs were 10 ps/nm or -10 ps/nm controlled by precompensation and postcompensation, respectively. We assessed the system performance affected by the variation degree of RDPS random variables by using the effective launch power in the obtained optimal NRD and the effective NRD range for the launch power. Through the assessment of two performance, it was confirmed that it is needed to use the RDPS random variables of the narrow deviation in each fiber spans for implementing the flexible optical links transmitting the relative higher launch power. Also, we confirmed that it is more advantageous to use postcompensation for controlling the NRD rather than precompensation for expanding the effective NRD range. Consequently, the simulation results show that the more the variation degree of RDPS random variables increase, the more the system performance is deteriorated.

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