International Journal of Multimedia and Ubiquitous Engineering
Vol.11, No.7 (2016), pp.243-252
http://dx.doi.org/10.14257/ijmue.2016.11.7.24

The Effects of the Number of Fiber Spans and Residual Dispersion per Span on the System Performance in Dispersion-Managed Optical Links Combined with Optical Phase Conjugation

Hwang-Bin Yim and Seong-Real Lee (Corresponding Author)

Department of Information & Communication Engineering, Gangwon Provincial College,270 Yeonju-ro, Jumunjin-eup, Gangneung-shi, Gangwon-do, 210-804, Korea
hbinyim@gw.ac.kr
Department of Marine Information & Communication Engineering, Mokpo National Maritime University, Haeyangdaehang-ro 91, Mokpo-si, Jeollanam-do, 58628, Korea
reallee@mmu.ac.kr

Abstract

The compensation effects of number of fiber spans and the residual dispersion per span (RDPS) in the combining of dispersion management (DM) and the midway optical phase conjugation on the optical transmission link consisted of the long fiber spans with 94 km of SMF length and -160 ps/nm/km of the dispersion-compensating fiber's dispersion coefficient for 24 channels x *40 Gbps wavelength division multiplexed (WDM) signals. We confirm that the combining technique of DM and the midway optical phase conjugation is still effective to compensate for the distorted WDM signals through the optical link consisted of the long fiber spans. It is also confirmed that the compensation effect on the distorted WDM channels is more increased as the portion of the concentrated compensation is more increased than the portion of in-line compensation.*

Keywords*: Optical Phase Conjugator, Dispersion-Managed Optical Links, Residual Dispersion per Span, Net Residual Dispersion, Pre(post)-concentrated compensation*

1. Introduction

An optical wavelength-division multiplexed (WDM) system is currently very much preferred because of its high bit rate capability and of the successful implementation of optical amplifiers such as an erbium-doped fiber amplifier (EDFA) [1]. Dispersion compensation technique is essential in WDM systems, because group-velocity dispersion (GVD) of standard single-mode fibers (SMFs) intensely induces the temporal distortion of WDM pulses. In the conventional dispersion-managed (DM) optical links, the nonzero anomalous GVD of the SMFs is periodically compensated by the proper length of dispersion-compensating fibers (DCFs) placed at the input or output end of the compensation interval [2].

Apart from fiber GVD, fiber nonlinear effects, such as self-phase modulation (SPM), four-wave mixing (FWM), cross-phase modulation (XPM), stimulated Raman scattering, and stimulated Brillouin scattering, cause performance degradation of long-haul WDM system, because the nonlinearities depend upon the pulse intensity, and the intensity of WDM pulses is more increased by the cascaded EDFA [3]. Especially, the interaction of SPM among these nonlinearities and GVD dominantly affects the WDM signal of the return-to-zero (RZ) format. Thus, the technique suppressing or mitigating the WDM signal distortion due to the interaction of GVD and SPM is necessary. Optical phase conjugation is one of the candidate techniques for mitigating such limitation. The key

ISSN: 1975-0080 IJMUE

subsystem of this technique is an optical phase conjugator (OPC) in the midway along the entire transmission link. The use of OPC for compensation was proposed by Yariv *et al.* [4] in 1979. The OPC converts the optical signal waves propagating in the former half section (before OPC) into the phase-conjugated waves. In systems using the midway OPC, the distortion generated in the former half section can be compensated for by propagating the phase-conjugated waves through the latter half section (after OPC).

However, DM and optical phase conjugation have 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].

In the optical link with combining of DM and optical phase conjugation, the compensation for the signal distortions depends upon the fiber spans' parameters, such as the SMF's length, the DCF's length, the dispersion coefficient of DCF and residual dispersion per span (RDPS) [1]. Especially, for a wavelength-division multiplexed (WDM) system, it is difficult to find out the best link condition determined by the above-mentioned parameters. Because, if perfect dispersion compensation is accomplished for a particular channel of the WDM system, other wavelength channels may encounter different amounts of cumulative dispersion proportional to their wavelength separations from the zero-average-dispersion wavelength channel [9].

Because of the reasons above-mentioned, the current researches have been studied for a single-channel system with complete compensation [10] and for a WDM system with residual dispersion [11]. Also, the considerations of these researches are confined within the relative short length of fiber span, the relative small number of fiber span, and the restricted RDPSs. To the best of the authors' knowledge, the effects of number of fiber spans and the RDPSs on the system performance in the ultra-long WDM links consisted of the relative long SMF lengths and the large dispersion coefficient of DCF are yet to be reported.

Therefore, in this work, we assess and analyze the compensation effects of number of fiber spans and the RDPSs in the combining of DM and the midway optical phase conjugation on the transmission of 24 channels x 40 Gbps WDM signals. The considered optical link for WDM consists of the cascaded fiber spans with 94 km of the SMF length and -160 ps/nm/km of DCF's dispersion coefficient. The RDPSs for analyzing the system performance are assumed to be 0 ps/nm to 1,600 ps/nm (160 ps/nm interval). The 0 ps/nm of RDPS and 1,600 ps/nm of RDPS mean the complete compensation and no-compensation of the dispersion accumulated in one fiber span, respectively.

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 for the WDM of 24 channels x 40 Gbps. The total transmission link consists of *n* fiber spans. Number of the former half transmission section (before OPC) and the latter half transmission section (after OPC) are *n*/2. In this work, we consider 10 to 600 as *n*, spacing 2 apart. In Figure 1, the arranged order of fibers in one span of the former half section is the DCF, then the SMF, and vice versa in the latter half section. We expect the symmetric distribution of the local dispersion with respect to the midway OPC will be somewhat fulfilled by these configurations.

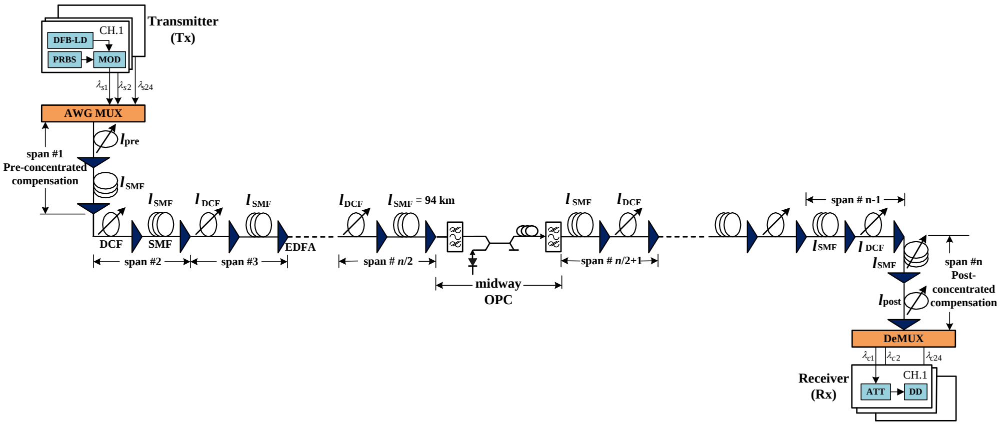

Figure 1. Configuration of the Optical Link for WDM Transmission

The length of the SMF in every fiber span, l_{SMF}, is assumed to be 94 km. Furthermore, the SMF is characterized by attenuation coefficient α_{SMF} = 0.2 dB/km, dispersion coefficient D_{SMF} = 17.0213 ps/nm/km, and nonlinear coefficient γ_{SMF} = 1.35$W^{-1}km^{-1}$ at 1,550 nm. On the other hand, the DCF of every fiber span is characterized by dispersion coefficient D_{DCF} = –160 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.

One goal of this research is assessing the effect of the fiber span's RDPS on the system performance. Thus, the RDPS is assumed to be 0 - 1,600 ps/nm, spacing 160 ps/nm apart. The RDPS of 0 ps/nm means the complete dispersion compensation for every fiber spans, meanwhile the RDPS of 1,600 means without dispersion compensation for every fiber spans. Each RDPS can be selected by controlling the lengths of DCF in the fiber spans, *i.e.*, l_{DCF} represented in Figure 1.

Except the RDPS of 0 ps/nm, the net residual dispersion (NRD) of each half section is not zero, rather very large as *n* is more increased. Thus, it is needed to control the NRD of each half section by using the arbitrary span 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. The dispersion compensation scheme of our research is called to the bi-end concentrated dispersion compensation, because which play a role of controlling the accumulated dispersion at every fiber spans due to the RDPSs. In this research, we assumed that l_{post} is fixed for setting the NRD of the latter half section to be zero ps/nm, depending on the selected RDPS, meanwhile only l_{pre} is varied for determining the NRD of the entire link, for the simplicity of the numerical simulation procedures. That is, the pre-concentrated compensation (this is called 'pre-CC') represented in Figure 1 only play a role of controlling the entire NRD under the condition of the zero NRD of latter half section by the fixed l_{post}.

2.2. 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 wavelengths of the DFB-LD are allocated 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 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 WDM 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 nonlinear medium of the midway OPC is assumed to be the highly nonlinear dispersion-shifted fibre (HNL-DSF). The parameters of the OPC are as follows: loss of HNL-DSF $\alpha_0 = 0.61$ dB/km, nonlinear coefficient of HNL-DSF $\gamma_0 = 20.4$ $\mathrm{W}^{-1}\mathrm{km}^{-1}$, the length of HNL-DSF $z_0 = 0.75$ km, zero dispersion wavelength of HNL-DSF $\lambda_0 = 1{,}550$ nm, dispersion slope $dD_0/d\lambda = 0.032$ $\mathrm{ps/nm^2/km}$, pump light power $P_\mathrm{p} = 18.5$ dBm, and pump light wavelength $\lambda_\mathrm{p} = 1{,}549.75$ nm. The 3-dB bandwidth of conversion efficiency [8] is calculated to almost 48 nm (1526-1574 nm) from the above-mentioned OPC parameters. Thus, all of the signal wavelengths and these conjugated wavelengths belong within the 3-dB bandwidth of the conversion efficiency.

We adopt the direct detection (DD) in 24 receivers (Rx) for the WDM signals. The 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 [12].

The propagation of the signal in a lossy, dispersive, and nonlinear medium can be expressed by the nonlinear Schrődinger equation (NLSE), assuming a slowly varying envelope approximation [13]:

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

where $j,k = 1,2,\ldots,24$ ($j \neq k$), 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 [14]. 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 [13].

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 [13]:

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

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

Figure 2 shows the eye opening penalties (EOPs) of the worst channel among 24 WDM channels, which are propagated through the optical link consisted of 30, 70 or 250 fiber spans, respectively, as a function of the RDPSs. The launch power of each channels are assumed to be -5 dBm or 3 dBm. It is generally expected that the system performance is more deteriorated as the launch power is more increased and the number of fiber spans is more increased. By comparison of the results for 3 dBm channels propagated through 70 fiber spans and for -5 dBm channels propagated through 250 fiber spans, it cannot be so easily concluded that the increases of the launch power and number of fiber spans cause the deterioration of performance. It is also shown that the launch power and number of fiber spans less affect to the degradation of EOP in the optical links without dispersion compensation (*i.e.*, RDPS = 1,600 ps/nm). Therefore, it must be recognized that the compensation for the distorted WDM signals depend upon the complicated relation of the launch power, RDPS and transmission length.

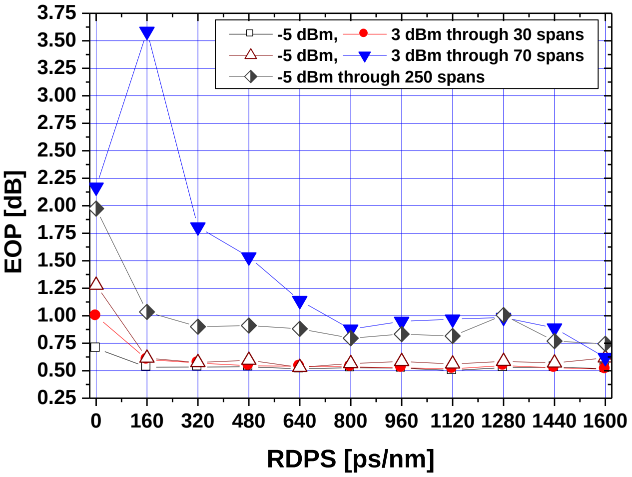

Figure 2. The Eye Opening Penalty (EOP) Versus the RDPS at Several Number of Fiber Spans

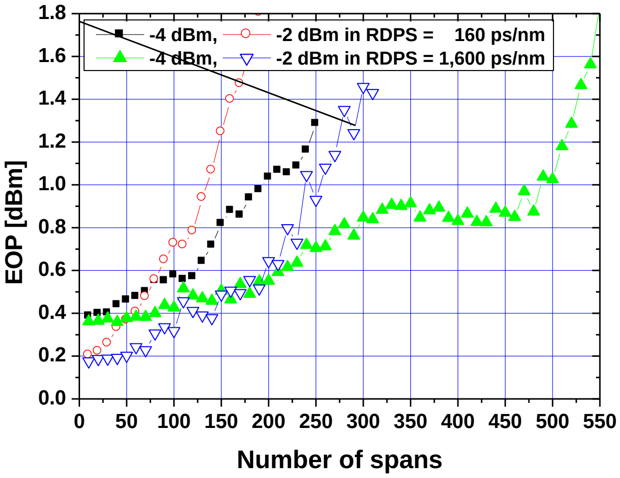

Figure 3. The Eops as a Function of Number of Fiber Spans in the Optical Links with RDPS = 160 Ps/Nm Or 1,600 Ps/Nm

Figure 3 shows the EOPs of the worst channel with -4 dBm or -2 dBm launch power as a function of number of fiber spans, in which the RDPS is set to be 160 ps/nm or 1,600 ps/nm. The performance dependency on the launch power and the RDPS can be confirmed from the results of Figure 3 as following. First, in the same launch power transmission, the total transmission length can be more increased in the optical link without dispersion compensation (*i.e.*, RDPS = 1,600 ps/nm) than RDPS = 160 ps/nm. Second, however, from the view point of 1 dB EOP criterion, the difference of number of fiber spans resulting in 1 dB EOP is bigger in the optical link with 1,600 ps/nm of the RDPS than 160 ps/nm, for the launch power difference of 2 dBm. That is, the system performance is more sensitive to the launch power in the optical link without dispersion compensation.

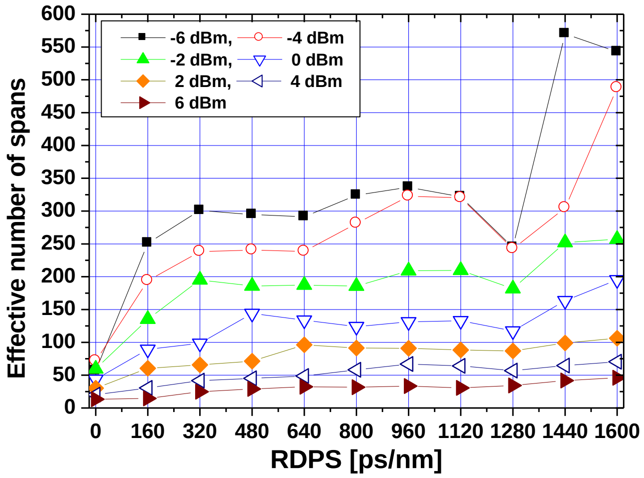

Figure 4. The Effective Number of Fiber Spans Depends Upon the RDPS and the Launch Power

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) [15]. Figure 4 shows the effective number of fiber spans, in which the EOP below 1 dB can be obtained, as a function of the RDPS for the several launch power. Only case of transmitting the WDM channels with high launch power (*i.e.*, 6 dBm in Figure 4), the increase of the effective number of fiber spans is proportion to the RDPS. However, this characteristic is not valid for transmitting the WDM channels with other launch powers. That is, the effective number of fiber spans depends upon the complex relation of the launch power and the RDPS. However, as with the previous results, the maximum effective number of fiber spans is obtained in the optical link without dispersion compensation (*i.e.*, RDPS = 1,600 ps/nm), irrelevant with the launch powers.

In this study, no (*i.e.*, without) dispersion compensation means the dispersion compensation by the DCF is not applying into each fiber spans, instead, the dispersion accumulated in each half transmission section is compensated for by pre-CC and post-CC using the first DCF and the last DCF, respectively. Therefore, 1,600 ps/nm of RDPS, which results in the maximum effective number of fiber spans, means the dispersion compensation scheme through pre(or post)-CC is superior to the in-line compensation (*i.e.*, the low RDPSs). Most notable, though, the result in the case of RDPS = 1,280 ps/nm. The dispersion compensation is fulfilled by 20% of the in-line compensation and 80% of pre(post)-CC in this RDPS. That is, although the rates of the concentrated compensation are higher than the rate of the in-line compensation, the effective number of fiber spans is more decreased than RDPS = 1,120 ps/nm for the most launch power.

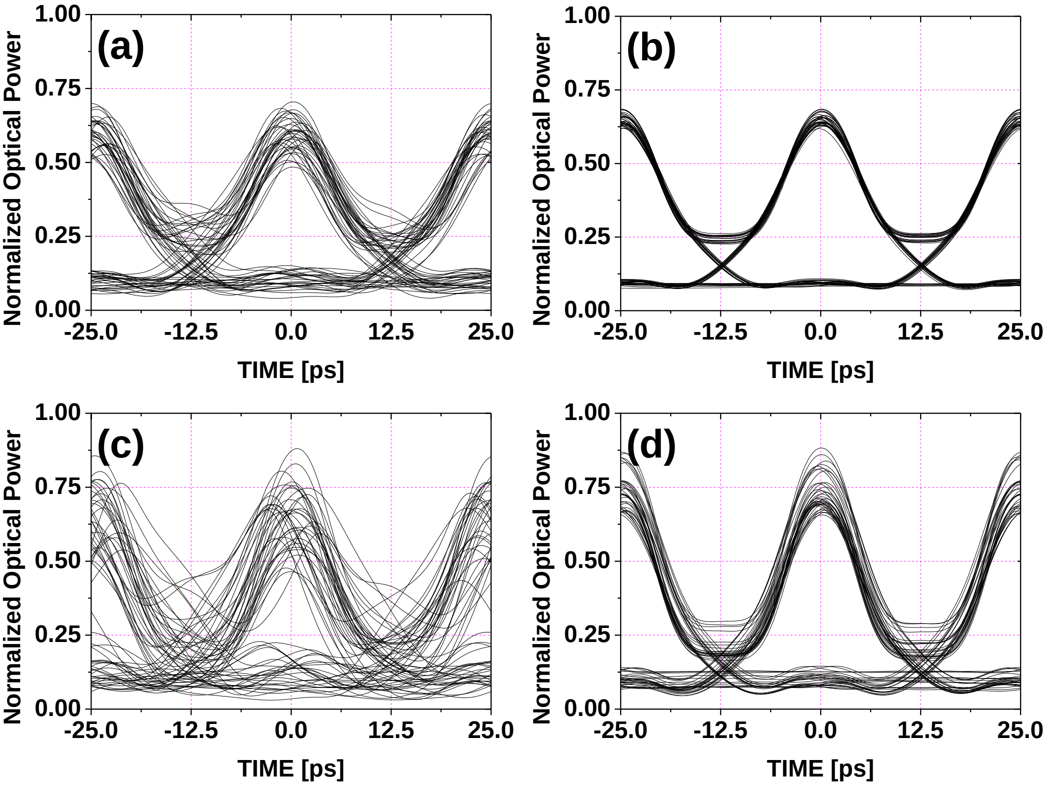

Figure 5. The Eye Diagrams of the Worst Channel Received through 500 Fiber Spans; in Case of RDPS = 0 ps/nm and Launch Power of -6 dBm (a), in Case of RDPS = 1,600 ps/nm and Launch Power of -6 dBm (b), in Case of RDPS = 0 ps/nm and Launch Power of -3 dBm (c), and in Case of RDPS = 1,600 ps/nm and Launch Power of -3 dBm (d), Respectively

Figure 5 shows the eye diagrams of the worst channels launched with -6 dBm or -3 dBm into the optical links consisted of 500 fiber spans and with RDPS of 0 ps/nm or 1,600 ps/nm. It is shown that the signal compensations through DM link with RDPS of 1,600 ps/nm are greatly better than DM link with RDPS of 0 ps/nm, excluding the effect of launch power on the compensation, because the signal compensation is inversely proportional to the launch power of WDM channel. The results shown in Figure 5 correspond to the results obtained from Figure 4. The noticeable result from Figure 5 is that intrachannel nonlinear effects, such as intrachannel four-wave mixing (IFWM) and intrachannel cross-phase modulation (IXPM), are not sufficiently compensated by DM and midway OPC, even in the optical link with RDPS of 1,600 ps/nm.

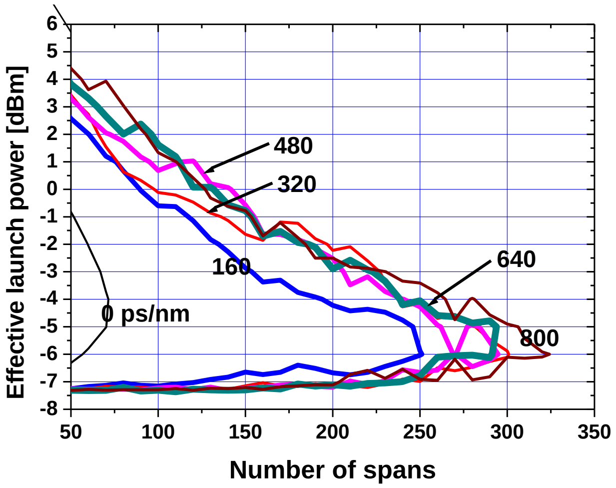

Figure 6. The Effective Launch Power as a Function of Number of Fiber Spans for the Rdpss Lower than 800 Ps/Nm

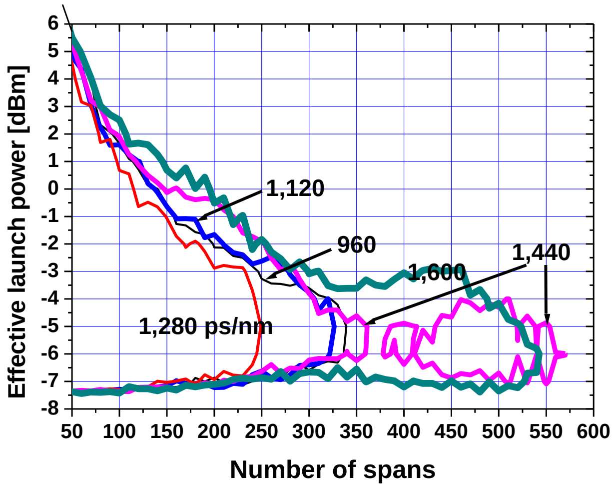

Figure 7. The Effective Launch Power as a Function of Number of Fiber Spans for the Rdpss Upper than 960 Ps/Nm

Figure 6 and Figure 7 show the effective launch power as a function of number of fiber spans for the RDPSs lower than 800 ps/nm and upper than 960 ps/nm, respectively. As with the previous results, the effective launch power in the optical links with RDPS = 1,280 ps/nm ranges over the relative fewer number of fiber spans than other RDPSs. For example, in the case of transmitting the WDM channels with -5 dBm launch power, the effective number of fiber spans in the optical link with RDPS = 1,280 ps/nm is reduced by as much as 80 spans than RDPS = 1,120 ps/nm. The long haul transmission is of advantage to the optical link with RDPS = 1,440 ps/nm rather than 1,600 ps/nm for the relative low launch power from -7 dBm to -5 dBm. However, for the optical links consisted of number of fiber spans from 300 to 500, the ranges of the effective launch power in RDPS = 1,600 ps/nm are broader than 1,440 ps/nm.

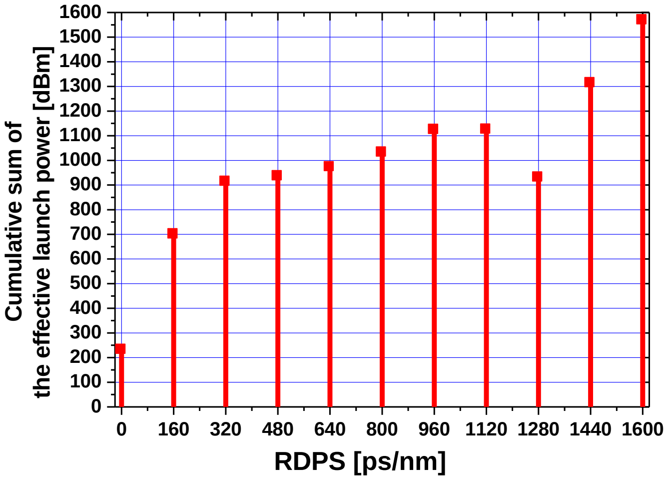

Figure 8. The Cumulated Sum of the Effective Launch Power in each RDPS

Thus, it should be required to quantitatively analyzing factor for the easily comparison of DM condition related with the launch power, number of fiber spans and the RDPS. In order to quantitatively analyze, we calculate the area of contour for the RDPSs in the results of Figure 6 and 7. The area of contour corresponds to the cumulative sum of the effective launch power obtained at each number of fiber spans, thus we define the area of contour as 'sum of the effective launch power', and this is plotted in Figure 8 as a function of the RDPSs. The large cumulated sum of the effective launch power can be obtained through the large launch power ranged over the bigger fiber spans. Generally, the cumulated sum of the effective launch power is proportion to the RDPSs, except for RDPS = 1,280 ps/nm. That is, the mean of the result of Figure 6 is that the distorted WDM signals due to the accumulated dispersion and the fiber nonlinearities is more effective compensated for, as the portion of the concentrated compensation is more increased than the portion of in-line compensation.

4. Conclusions

This paper discussed the compensation effects of number of fiber spans and the RDPSs in the combining of DM and the midway optical phase conjugation on the optical transmission link consisted of the long fiber spans with 94 km of SMF length and -160 ps/nm/km of the DCF's dispersion coefficient for 24 channels x 40 Gbps WDM signals. We confirm that the combining technique of DM and the midway optical phase conjugation is still effective to compensate for the distorted WDM signals through the optical link consisted of the long fiber spans, therefore, this compensation technique is advantageous for implementing the ultra-long haul transmission link for WDM. It is also confirmed that the compensation effect on the distorted WDM channels is more increased as the RDPS is more larger, that is, as the portion of the concentrated compensation is more increased than the portion of in-line compensation. The induced results mean that the proposed bi-end dispersion compensation scheme plays a huge role in the performance improvement than the conventional in-line compensation scheme.

References

[1] M. A. Talukder and M. N. Islam, "Performance of bi-end compensation in a wavelength-division multiplexed system considering the effect of self-phase modulation", Opt. Eng., vol. 44, **(2005)**, pp. 115005-1~115055-6.

[2] C. C. Chang and A. M. Weiner, "Fiber transmission for sub-500-fs pulses using a dispersion-compensating fiber", IEEE J. Quantum Electron., vol. 33, **(1997)**, pp. 1455–1464.

[3] M. F. Uddin, A. B. M. N. Doulah, A. B. M. I. Hossain, M. Z. Alam and M. N. Islam, "Reduction of four-wave mixing effect in an optical wavelength-division multiplexed system by utilizing different channel spacing and chromatic dispersion schemes," Opt. Eng., vol. 42, **(2003)**, pp. 2761–2767.

[4] A. Yariv, D. Feketa and D. M. pepper, "Compensation for channel dispersion by nonlinear optical phase conjugation", Opt. Lett., vol. 4, **(1979)**, pp. 52-54.

[5] S. Watanabe and M. Shirasaki, "Exact compensation for both chromatic dispersion and Kerr effect in a transmission fiber using optical phase conjugation", J. Lightwave Technol., vol. 14, **(1996)**, pp. 243-248.

[6] A. Chowdhury and R.-J. Essiambre, "Optical phase conjugation and pseudolinear transmission", Opt. Lett., vol. 29, **(2004)**, pp. 1105-1107.

[7] P. Minzioni and A. Schiffini, "Unifying theory of compensation techniques for intrachannel nonlinear effects", Opt. Exp., vol. 13, **(2005)**, pp. 8460–8468.

[8] S. R. Lee, "Dispersion management and optical phase conjugation in optical transmission links with a randomly distributed single-mode fiber length", Journal of Inform. & Comm. Converg. Eng., vol. 11, **(2013)**, pp.1-6.

[9] A. H. Gnauck, J. M. Wiesenfeld, L. D. Garrett, M. Eiselt, F. Forghieri, L. Arcangeli, B. Agogliata, V. Gusmeroli and D. Scarano, "16x20 Gb/s, 400 km WDM transmission over NZDSF using a slope compensating fiber-grating module", IEEE Photon. Technol. Lett., vol. 12, **(2000)**, pp. 437-439.

[10] D. M. Rothnie and J. E. Midwinter, "Improving standard fiber performance by positioning the dispersion compensating fiber", Electron. Lett., vol. 32, **(1996)**, pp. 1907-1908.

[11] G. Bellotti, A. Bertaina and S. Bigo, "Dependence of self-phase modulation impairments on residual dispersion in 10-Gb/s-based terrestrial transmissions using standard fiber", IEEE Photon. Technol. Lett., vol. 11, **(1999)**, pp. 824-826.

[12] G. P. Agrawal, "Fiber Optic Communication Systems 3rd ed.", John Wiley & Sons, New York, **(2002)**.

[13] G. P. Agrawal, "Nonlinear Fiber Optics 3rd ed.", Academic Press, San Francisco, **(2001)**.

[14] P. Minzioni, F. Alberti, and A. Schiffini, "Optimized link design for nonlinearity cancellation by optical phase conjugation", IEEE Photon. Technol. Lett., vol. 16, **(2004)**, pp. 813-815.

[15] N. Kikuchi and S. Sasaki, "Analytical evaluation technique of self-phase modulation effect on the performance of cascaded optical amplifier systems", Journal Lightwave Technol., vol. 13, **(1995)**, pp. 868-878.

Authors

Hwang-Bin Yim, He received Ph.D. degrees from Soonchunhyang University, Seoul, Korea, in Information Communication Engineering in 2003. He has been working as a Professor in Gangwon Provincial College from March 2003. His research interests include Communication Application System, Optical Communication, Electronic circuit design and so on.

Seong-Real Lee, He received the B.S., M.S. and Ph. D. from Korea Aerospace University, Korea in 1990, 1992, and 2002, respectively. He is currently an associate professor of the Department of Marine Information and Communication Engineering at Mokpo National Maritime University. His research interests include optical WDM systems, optical soliton systems, and optical nonlinear effects.