3rd International Conference on Electrical & Computer Engineering
ICECE 2004, 28-30 December 2004, Dhaka, Bangladesh

EFFECT OF SELF-PHASE MODULATION ON OPTICAL COMMUNICATION SYSTEM IN PRESENCE OF DISPERSION COMPENSATION

Muhammad Anisuzzaman Talukder and Mohammed Nazrul Islam

Department of Electrical and Electronic Engineering, Bangladesh University of Engineering and Technology, Dhaka, Bangladesh
E-mail: anistal@eee.buet.ac.bd, nazrul@eee.buet.ac.bd

ABSTRACT

The effect of self-phase modulation (SPM) on 10 Gb/s pulse transmission over dispersion compensated fiber link using standard single-mode fiber is investigated. Degradation of eye opening at the output of the transmission fiber due to SPM and dispersion interplay is studied for different compensation configurations, namely, post-, pre- and bi-end compensation. It is found that at high powers the SPM effect degrades the pulse recompression process and hence limits the upper bound of the transmitted pulse power. The power margins set by the SPM effect are estimated through computer simulation for different compensation configurations.

1. INTRODUCTION

With the advent of erbium-doped fiber amplifier (EDFA), fiber loss at 1.55 μm wavelength can be compensated efficiently [1]. Optical communication system also suffers from another limiting factor, group velocity dispersion (GVD) in fiber, which distorts the signal waveshape. By employing periodic dispersion compensation using dispersion compensating fibers (DCF) along with standard single mode fiber (SMF), one can achieve high-speed and long-haul transmission system [2]. In a DCF compensating system, the bandwidth-distance product of the transmission link is no longer limited by the GVD rather by higher order dispersion and nonlinear effects. The dominant nonlinear effect in an SMF is the self-phase modulation (SPM), which is caused by the nonlinear dependence of the refractive index on the pulse intensity [3]. Because of large power requirement by high-speed data transmission systems for error-free detection, their performances are eventually limited by the interaction of the SPM effect and the fiber dispersion, which depends on the position of the DCF in the transmission link [4]. However, to the best of our knowledge there has been no investigation in detail on the effect of SPM on the performance limitations for different compensating schemes.

The objective of this paper is to study the impact of the SPM effect on the performance of an optical communication system. Three different dispersion compensating schemes are considered, namely, post-compensation configuration (POCC), pre-compensation configuration (PRCC) and bi-end compensation configuration (BECC). The power penalty suffered by the system due to SPM for these schemes is estimated with a view to obtain the most effective compensating scheme for practical applications.

2. THEORETICAL ANALYSIS

At modest input power level, the single-mode fiber behaves as a dispersive and linear medium, where the transmitted spectrum does not change during propagation. Only the pulse gets weaker due to attenuation and broadened in the time domain by the second and third-order dispersion. In a dispersion compensated link consisting of a standard SMF and a DCF, the input pulses first broaden due to SMF and then subsequently recompress to their original shape due to DCF, which has the opposite dispersion coefficient to that of SMF. As the input power is increased, the fiber nonlinear effects, especially SPM, affect significantly the pulse dynamics in the transmission link. The nonlinear Schrodinger equation (NLSE) is modified to include higher-order dispersion, which is successful in accurately modeling pulse propagation in SMF for many diverse applications [5-6]. The modified NLSE incorporating the effects of fiber loss, SPM and GVD is given by

$$i\frac{\partial A}{\partial z} = -\frac{i}{2}\alpha A + \frac{1}{2}\beta_2\frac{\partial^2 A}{\partial T^2} + \frac{i}{6}\beta_3\frac{\partial^3 A}{\partial T^3} - \gamma|A|^2 A \tag{1}$$

ISBN 984-32-1804-4

where A is the slowly varying amplitude of the pulse envelope, z is the longitudinal coordinate and T is measured in a frame of reference moving with the pulse at the group velocity v_g ($T=t-z/v_g$). β_2 and β_3 are the dispersion and the dispersion slope parameters of the fiber, respectively, α is the loss coefficient and γ is the nonlinear coefficient.

A normalized super-Gaussian pulse shape is used as the input for the numerical analysis as given by

$$U(0,T) = \exp\left[-\frac{1}{2}\left(\frac{T}{T_0}\right)^{2m}\right] \tag{2}$$

$$T_b = 2[2\ln 2]^{\frac{1}{2m}} T_0 \tag{3}$$

where T_0 is the half-width at $1/e$-intensity point, T_b is the bit period and m represents the degree of the super-Gaussian pulse. In this simulation, m is assumed to have a value of 1.5. So the pulse envelope amplitude $A(z,T)$ in equation (1) is given by

$$A(z,T) = \sqrt{P_0}\exp(-\alpha z/2)U(z,T) \tag{4}$$

where P_0 is the peak power.

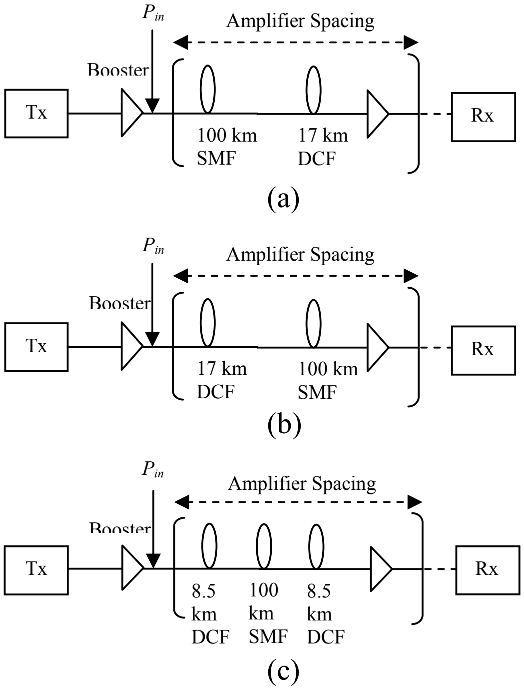

Fig. 1: Schematic diagram of (a) post-, (b) pre-, and (c) bi-end compensation configuration.

3. RESULTS

Computer simulations are performed for the pulse propagation through a dispersion compensated transmission link using the split-step Fourier transform method [3]. A single information channel, modulated with a 10 Gb/s nonreturn-to-zero (NRZ) bit sequence, is generated through a chirp free transmitter and is launched into the fiber link composed of spans of 100 km of SMF and 17 km of DCF connected in either pre- (PRCC), post- (POCC) or bi-end compensation configuration (BECC) as shown in Fig. 1. Fiber lengths are so chosen to completely compensate the dispersion.

Fiber dispersion, dispersion slope, attenuation, nonlinear coefficient and effective area are taken to be 17 ps/km-nm, 0.07 ps/nm^2-km, 0.2 dB/km, 1.36 W^{-1}km^{-1} and 80 μm^2, respectively, for SMF; and –100 ps/km-nm, 0.09 ps/nm^2-km, 0.6 dB/km, 5.4 W^{-1}km^{-1} and 20 μm^2, respectively, for DCF. The in-line amplifiers, EDFAs, are assumed to be flat and noiseless, with gain equal to the span loss. The accumulated amplified spontaneous emission (ASE) noise of the in-line amplifiers has been neglected in this simulation, because due to high fiber dispersion the effect of nonlinear propagation on the ASE spectrum (i.e., modulation instability) is insignificant [7]. Thus the impact of the accumulated ASE noise is simply to add an extra penalty, which decreases with the increase of input power, and which can be easily calculated as in a linear link [1].

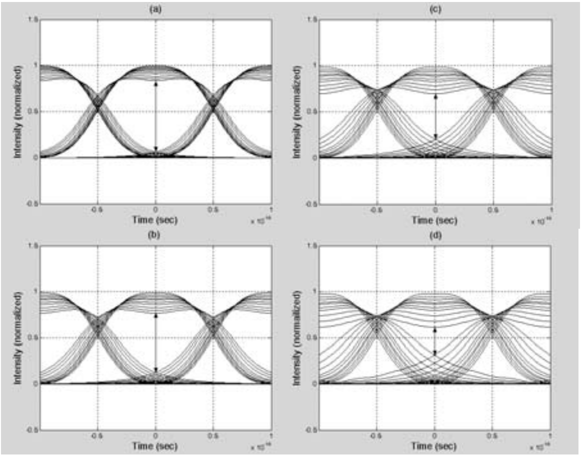

Fig. 2: Eye diagrams for a post-compensated transmission link at (a) 1000 km, (b) 2000 km, (c) 3000 km and (d) 4000 km. Peak input power varied from –10 dBm to 7 dBm.

Eye diagrams for a post-compensated fiber link are simulated with peak input varied from –10 dBm to 7 dBm as shown in Fig. 2. It can be observed that the eye opening decreases with the increase of input power for a given fiber length because of the SPM effect. The maximum eye opening is found for –10 dBm power and the minimum eye opening is found for 7 dBm power. Again the eye opening at a fixed input power decreases with the fiber length due to the accumulation of SPM and dispersion effects as can be observed by comparing Fig.s 2(a) through 2(d). The impact of GVD and SPM is different in a pre- and a bi-end compensation configuration. In PRCC and BECC, positive chirping of DCF and that of SPM support one another. When such a pulse enters the SMF, it is compressed. So the eye opening increases with the increase of peak input power for a given fiber length, and also increases with the fiber length for a given input power as illustrated in Fig.s 3 and 4. However, the pulse compression reaches its maximum value at a certain input power or a certain fiber length. Beyond this input threshold power, the pulse shape gets distorted and oscillating. In a PRCC this compression becomes too much that the increase of input peak power distorts the output pulse at a very lower value as shown in Fig. 3. At a peak input power of 4.77 dBm, the output pulse of a 2000 km pre-compensated fiber link gets oscillating and distorted such that further increase of input power or fiber length will greatly deteriorate the eye diagram.

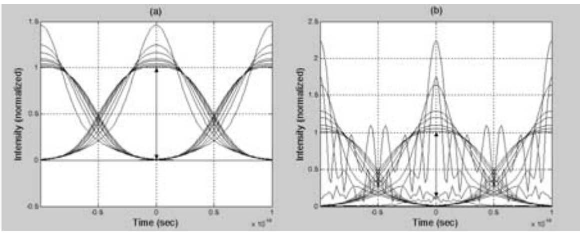

Fig. 3: Eye diagrams for a pre-compensated transmission link at (a) 1000 km and (b) 2000 km. Peak input power varied from –10 dBm to 4.77 dBm.

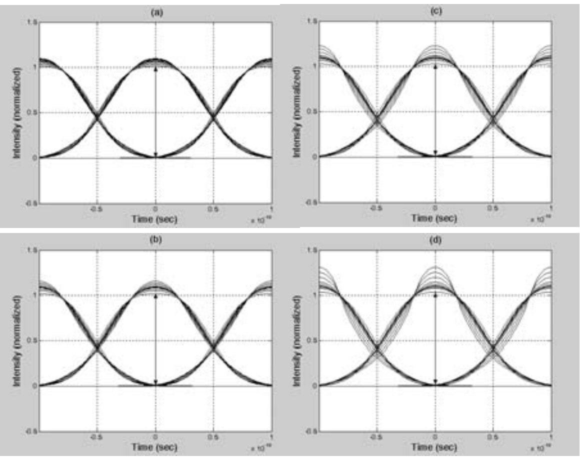

Fig. 4: Eye diagrams for a bi-end compensated transmission link at (a) 1000 km, (b) 2000 km, (c) 3000 km and (d) 4000 km. Peak input power varied from –10 dBm to 7 dBm.

Figure 4 shows the eye diagrams for BECC scheme. The minimum eye opening is found for −10 dBm power and the maximum eye opening is found for 7 dBm power. The output pulse compresses with the increase of input power due to compression effect of SPM in anomalous dispersive medium of SMF. But if the power is increased beyond a limit, the pulse compression reaches the maximum and, as a result, it gets distorted and the eye opening decreases. Since up to 7 dBm input power level the pulses do not broaden rather compress, the inter-symbol interference from neighbouring pulses decreases, which causes a decrease in the eye opening penalty.

From the eye opening, the eye penalty can be calculated using the relation given by

$$\text{Penalty} = 20\log_{10}\left(\frac{a}{b}\right) \tag{5}$$

where a and b are the eye openings at the input and output of the transmission fiber, respectively, at the bit center. Then the threshold input power is estimated below which the eye opening penalty is less than 3 dB. As shown in Fig. 5, the threshold input power decreases with the increase of fiber length for all the configurations due to SPM accumulation. But the threshold power in POCC and PRCC schemes decreases greatly as compared to that in BECC scheme. At 1000 km, the threshold power is higher in PRCC than in POCC. This justifies the findings in Ref. 4, which dealt with a 500 km terrestrial transmission link using SMF. For PRCC, though the threshold power is much higher at 1000 km transmission fiber, it decreases rapidly. It is mainly because of the fact that the pulse compression becomes too much due to the SPM effect accumulation such that the pulse gets distorted and oscillating within the bit slot. In case of BECC, the pulse compresses but the compression is controlled. The maximum threshold power level decreases with the increase of fiber length. Since no dispersion accumulation occurs with the length of the fiber, this decrease of threshold power is due to the SPM effects accumulation. It is shown that the maximum threshold peak input power is 20.3 dBm at 1000 km transmission fiber for BECC. This value is greater than that of both PRCC and POCC. It is also found that even at 5000 km 9.4 dBm peak input power can be applied to a BECC fiber link, whereas this threshold peak input power becomes as low as 2.3 dBm and 0.5 dBm for POCC and PRCC fiber links, respectively.

4. CONCLUSION

A detailed investigation is carried out to evaluate the performance of the DCF compensating technique in presence of the SPM effect at 10 Gb/s bit rate using standard SMF. The three compensating techniques, POCC, PRCC and BECC, perform differently under the influence of SPM. BECC is observed to be the best suitable dispersion compensating technique. Therefore, in case of strong nonlinear transmission or long-haul transmission, DCF should be placed at both ends of SMF. The interaction between the fiber dispersion and the SPM effect is found to be a major factor that limits the amount of energy allowed to be launched into the transmission link. This power limit eventually imposes an upper bound on the length of the transmission link due to the increasing loss for the longer link.

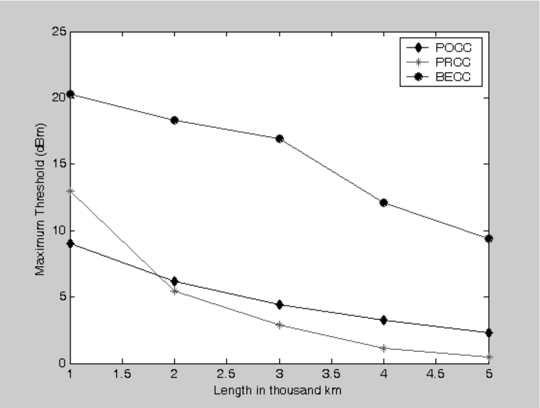

Fig. 5: Maximum threshold input peak power at 3 dB eye opening penalty with fiber length for POCC, PRCC and BECC schemes.

REFERENCES

[1] N. A. Olsson, "Lightwave systems with optical amplifiers," *J. Lightwave Technol.*, vol. 7, pp. 1071-1082, 1989.

[2] R. J. Nuyts, Y. K. Park and P. Gallion, "Dispersion equalization of a 10-Gb/s repeatered transmission system using dispersion compensating fibers," *J. Lightwave Technol.*, vol. 15, pp. 31-42, 1997.

[3] G. P. Agrawal, *Nonlinear Fiber Optics*, 3rd ed., Academic Press, San Diego, CA, 2001.

[4] 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, pp. 824-826, 1999.

[5] W. J. Tomlinson, R. H. Stolen, and C. V. Shank, "Compression of optical pulses chirped by self-phase modulation in fibers," *J. Opt. Soc. Amer. B*, vol. 1, pp. 139-149, 1984.

[6] J. P. Gordon, "Dispersive perturbations of solitons of the nonlinear Schrodinger equation," *J. Opt. Soc. Amer. B*, vol. 9, pp. 91-97, 1992.

[7] S. Bigo, D. Penninckx and M. W. Chbat, "Investigation of self-phase modulation limitation on 10-Gb/s transmission over different types of fiber," *Proc. OFC*, Feb. 1998.