SRS and XPM in 32 Channel Multiamplified WDM Optical Systems with DS Fibers at 10 Gb/s

Shirley P. Neves, Renato T.R. de Almeida, Marcio Freitas, Luiz C. Calmon

***Abstract* ¾ This paper numerically analyzes the effects of Stimulated Raman Scattering (SRS) and Cross Phase Modulation (XPM) on 8, 16 and 32 Wavelength Division Multiplexed (WDM) Optical Systems, with channels allocated in the band of frequencies recommended by the International Telecommunications Union (ITU). Propagation is done along a Dispersion Shifted (DS) Fiber in 10 Gb/s. Analysis is conducted for different power levels along 10x100 km links, under total linear Dispersion Compensation scheme.**

***Index Terms* ¾ Stimulated Raman Scattering, Cross Phase Modulation, Nonlinear effects in optical fibers, Wavelength Division Multiplexing**

1. INTRODUCTION

Erbium Doped Fiber Amplifiers (EDFA's) and compensation dispersion mechanisms [1] permitted the possibility of high bit rates in long distance optical fiber communication systems without electronic regeneration. It has been shown [2] that fiber nonlinearities as Self Phase Modulation (SPM), Cross Phase Modulation (XPM), Four Wave Mixing (FWM), Stimulated Raman Scattering (SRS) and Stimulated Brillouin Scattering (SBS), can cause severe degradations in these systems. Fortunately clever designs may substantially reduce the impact of many of these effects , and ultimately the system performance is expected to be limited by stimulated Raman Scattering [3]. This paper investigates SRS and XPM effects on the performance of 8, 16, 32 WDM channels spaced of 100 GHz and placed in the middle of ITU's frequency grid recommendation G.692 [6]. Propagation is done along a DS fiber at a bit rate of 10Gb/s, with dispersion compensation implemented.

2. SYSTEM MODELING

Analysis is conducted in a IM-DD system depicted in Fig. 1, with 32xWDM channels placed from 194.7 THz (1540.8 nm) to 191.6 THz (1565.8 nm), 16xWDM channels placed from 193.9 THz (1547.2 nm) to 192.4 THz (1559.3 nm) and 8xWDM channels placed from 193.5 THz (1550.4 nm) to 192.8 THz (1556 nm), respectively. Fiber parameters are shown on table 1.

Loss (dB/km)	0.2
A_{eff} (μm)^2	50
Zero Dispersion (nm)	1550
Slope (ps/nm^{2}km)	0.075
Dispersion 1540.8 nm (ps/km.nm) in Higher freq. channel (32 channels)	-0.69
Dispersion 1547.2 nm (ps/km.nm) in Higher freq. channel (16 channels)	-0.21
Dispersion 1550.4 nm (ps/km.nm) in Higher freq. channel (8 channels)	0.03

TABLE 1 - DS FIBER PARAMETERS

Each wavelength transmits a 64 pseudo-random bit sequence in a NRZ format. Pulse temporal shape is super-gaussian of degree 2 . Signals are multiplexed into the fiber and transmitted along distances of 1000 Km, with optical amplifiers (EDFA's) placed at 100 Km intervals just to compensate the loss suffered at each interval. At the receiver, after demultiplexing, each channel is detected and electrically filtered by a low pass Gaussian filter with a bandwidth in Hertz equal to 1.75 of the bit rate . Eye opening penalty was evaluated in relation to a back to back situation, for the shorter wavelength channel, because this is the one, which suffers the greatest SRS depletion. Total Linear Dispersion Compensation is implemented as depicted in Fig. 1 alternating fibers DS$^+$ and DS$^-$ at each section between amplifiers, where DS$^-$ corresponds to a fiber with the same

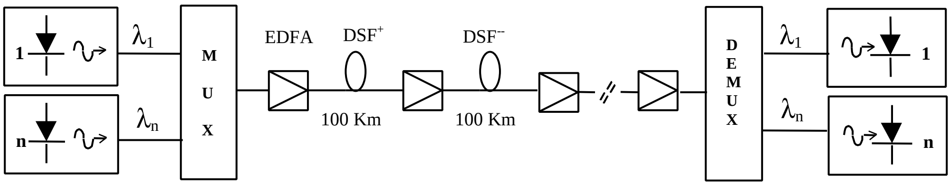

Fig. 1 System Configuration

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dispersion parameters as the DS^+ fiber but, with opposite sign at the various frequency channels.

Pulse propagation is described in this case by n-channel coupled nonlinear Schrodinger equations (1). Dispersion and nonlinear effects such as SPM, XPM, and SRS were included on the modeling. Four-wave mixing was not included since our purpose in this work is to evaluate separately only the effects of SPM, XPM and SRS.

$$\frac{\partial A_1}{\partial z} + \frac{j}{2}\beta_{2_1}\frac{\partial^2 A_1}{\partial T^2} + \frac{\alpha_1}{2}A_1 = j\gamma_1\left(|A_1|^2 + \left(\sum_{n=1}^{NC} 2|A_n|^2\right) - 2|A_1|^2\right)A_1 - \sum_{n=2}^{Nc}\frac{g_{p_n}}{2}|A_n|^2 A_1 \tag{1}$$

$$\frac{\partial A_N}{\partial z} - d_{1,N}\frac{\partial A_N}{\partial T} + \frac{j}{2}\beta_{2_N}\frac{\partial^2 A_N}{\partial T^2} + \frac{\alpha_N}{2}A_N = j\gamma_N\left(|A_N|^2 + \left(\sum_{n=1}^{Nc} 2|A_n|^2\right) - 2|A_N|^2\right)A_N + \sum_{n=1}^{N-1}\frac{g_{s_n}}{2}|A_n|^2 A_N - \sum_{n=N+1}^{Nc}\frac{g_{p_n}}{2}|A_n|^2 A_N$$

$$\frac{\partial A_{Nc}}{\partial z} - d_{1,Nc}\frac{\partial A_{Nc}}{\partial T} + \frac{j}{2}\beta_{2_{Nc}}\frac{\partial^2 A_{Nc}}{\partial T^2} + \frac{\alpha_{Nc}}{2}A_{Nc} = j\gamma_{Nc}\left(|A_{Nc}|^2 + \left(\sum_{n=1}^{Nc} 2|A_n|^2\right) - 2|A_{Nc}|^2\right)A_{Nc} + \sum_{n=1}^{Nc-1}\frac{g_{s_n}}{2}|A_n|^2 A_{Nc}$$

$$T = t - z/v_{g_1}, \qquad d_{1,n} = v_{g_1}^{-1} - v_{g_n}^{-1}$$

$$g_{s_n} = g_{R_n} / A_{eff} \qquad g_{p_n} = (\omega_n/\omega_{n+1})\, g_{s_{n+1}}$$

In these equations A(z,T) are the complex amplitudes of the pulses, z is the longitudinal coordinate, T is the time measured in a coordinate system which moves with the group velocity of the shorter wavelength channel (Channel 1). The equation with amplitudes with index 1 refers to the highest frequency channel, or pump channel. The equation with index N refers to intermediate frequency channels. The lowest frequency channel is shown for amplitudes with the index N_c , where N_c denotes the number of channel propagated in the fiber. Group velocity dispersion (GVD) parameter is β_{2j} with j= 1,2 ...N_c . Nonlinearity parameter is $\gamma_j = 2\pi N_2/\lambda_j A_{eff}$, with $N_2 = 2.45 \times 10^{-20}$ m^2 /W, α_j is the fiber attenuation coefficient, supposed the same for the various wavelengths. Raman gain coefficients are $g_{S,p(i,j)}$. Walk-off parameter between channels 1 and N is $d_{1,N}$. The system of coupled equations (1) was solved by the split-step Fourier method [4], with the step size controlled for a maximum phase deviation of 2.5 mrad at each step.

Simulation was done considering:

(a) Links 1000 Km, with amplifiers placed at every 100 Km.
(b) Number of WDM channels being 8, 16 and 32, and separated of 100 GHz.
(c) Total dispersion compensation scheme for the channels analyzed, alternating fibers DS^+ and DS^- at each section between amplifiers, where DS^- corresponds to a fiber with the same dispersion parameters as the DS^+ fiber but with opposite sign at the channel frequencies .
(d) All nonlinear effects included, compared to a situation where only SRS was suppressed, to evaluate the influence of this effect separately.
(e) All nonlinear effects included, compared to a situation where only XPM was suppressed, to evaluate the influence of this effect separately.

3. RESULTS AND DISCUSSION

A . 8 Channels

Figs. 2 shows eye-opening penalties for channel 1 due to SRS, XPM, and SPM in various combined situations, for 8 channels WDM system. This figure shows that XPM effect is dominant over others, and that peak power levels must be maintained bellow 10 mW per channel, to keep eye penalties under 2 dB .

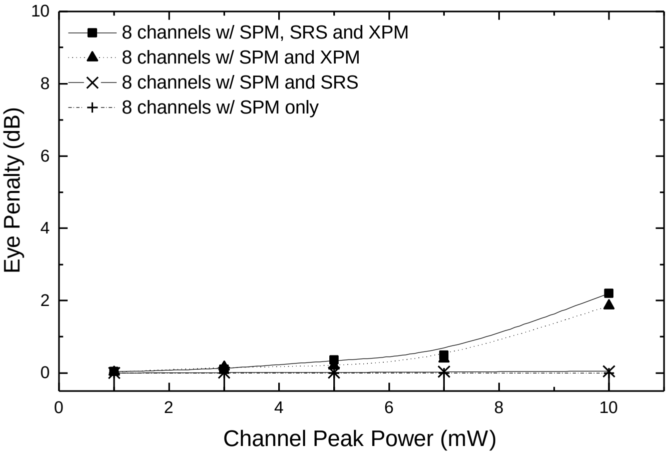

Fig. 2. Eye Opening Penalty for Channel 1 in a multiamplified 10x100 km DS fiber system due to the combination of various nonlinear effects, in a 8 channel ITU -WDM system, and total linear dispersion compensation.

In this figure it can be seen that the Raman effect contributes to a negligible fraction of penalty, being restricted to the higher power levels. Also it is shown that the SPM effect does not cause any significant penalty at any power levels.

B. 16 Channels

Fig. 3 shows the case for 16 channels WDM system. The system is now more sensible to power levels, but again shows predominance of the XPM effect. The Raman effect is a little more significant here, contributing with a maximum 0.5 dB penalty at high power levels. Now, it is seen that the power levels must be maintained bellow 4 mW per channel to ensure eye penalty bellow 2 dB. SPM effect is also of little concern here.

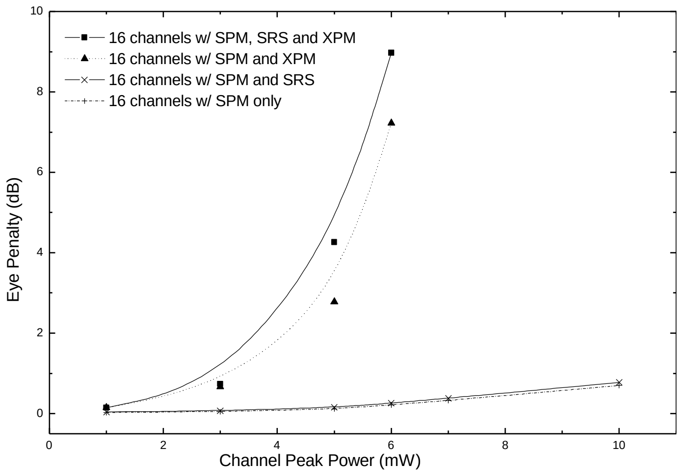

Fig. 3. Eye Opening Penalty for Channel 1 in a multiamplified 10x100 km DS fiber system due to the combination of various nonlinear effects in a 16 channel ITU -WDM system, and total linear dispersion compensation.

C . 32 Channels

Fig. 4 shows the case for 32 channels WDM system.

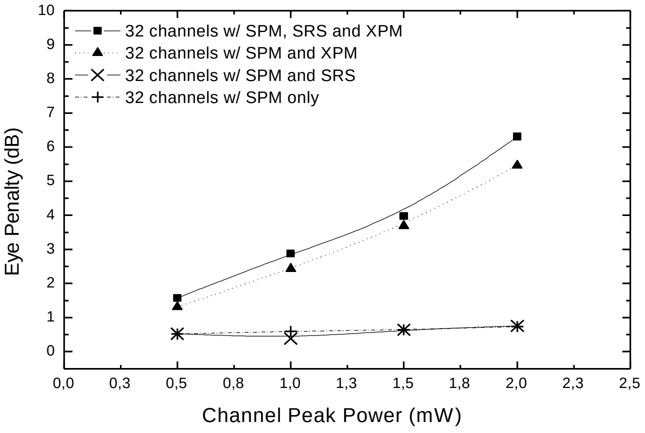

Fig. 4. Eye Opening Penalty for Channel 1 in a multiamplified 10x100 km DS fiber system due to the combination of various nonlinear effects in a 32channel ITU -WDM system, and total dispersion compensation.

The system now appears much more sensible to channel power levels, but again shows predominance of the XPM effect. Now the Raman effect appears a little bit more, approximating 1 dB penalty contribution for power levels around 2 mW, compared to 5 dB penalty by XPM at the same power level. It can be seen that the power levels must be maintained under 0.5 mW per channel to maintain eye penalty bellow 2 dB, which clearly indicates that as we increase the number of channels we must design a better dispersion compensation scheme in order to reduce the XPM effect. SPM effect is also of little concern in this system.

4. CONCLUSIONS

From our analysis with 8, 16 and 32 WDM channels in DS fibers at 10 Gb/s under ITU G.692 Recommendation, and propagation along 1000km with total dispersion compensation at each 100km, we conclude that the main responsible for bit degradation is the XPM effect. It is observed that power levels must be decreased as the number of channels is increased to avoid high penalties. Therefore, in order not to have problems with attenuation margin limits per 100 km due to low power levels, better dispersion compensation schemes must be implemented in WDM systems over 32 channels. It can be suggested either under-compensation or over-compensation schemes [7].

In the present analysis SRS effect was always inferior to XPM, although it was conjectured early on this paper that SRS could present a ultimate limit for dense WDM systems given that this effect increases with the number of channels, and from SMF standard fiber analysis [5] it was expected that XPM would not increase with this number. Unfortunately the XPM effect in DS fiber systems also increases in proportion to the number of channels, and did not attained a stabilized level after the inclusion of 4 or 5 channels as occurred with standard single mode fiber system [5]. This non-stabilizing effect in DS fibers can be attributed to the small walkoff, which occurs between channels near the zero dispersion wavelength. As a result we can not expect that the SRS effect will ever be able to surpass the XPM effect in DS fiber systems. So far, to mitigate the XPM effect more effectively in this case, optimum dispersion compensation schemes must be found in the vein investigated by [7] .

REFERENCES

[1] A.H.Gnauck and R.M.Jopson, “Dispersion Compensation for Optical Fiber Systems, Chapter 7 of *Optical Fiber Telecommunications IIIA*, San Diego, CA, Academic Press, pp. 162-195, 1997.

[2] A.R.Chraplyvy, “Limitations on lightwave communications imposed by optical-fiber nonlinearities”, *IEEE J. Lightwave Technol.*, vol. 8, pp.1548-1557, 1990

[3] A.R.Chraplyvy and R.W.Tkach, “What is the actual capacity of single mode fiber in amplified ligthwave systems?”, *IEEE Photon. Technol. Lett.*, vol. 5, No. 6, pp.1548-1557, 1993

[4] G. P. Agrawal, *Nonlinear Fiber Optics*. 2nd Ed., San Diego, CA, Academic Press, 1995.

[5] M. Freitas, L.C.Calmon and R.T.R.Almeida, “Análise da Interferência entre Canais causada pelo efeito de Modulação Cruzada de Fase em Sistemas WDM”, Simpós. Brasileiro de Telecom. , pp. 639-642, 1999.

[6] ITU Recommendation G. 692, Geneve, Oct. 98.

[7] R. T. R. de Almeida, M. Freitas, and L. C. Calmon, “Limites de Aplicação de Fibras Compensadoras de Dispersão em Sistemas Ópticos NRZ de Longo Alcance em 10 Gb/s”, *SBT2000*, this issue, Sept. 2000