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Analytical Modeling of Stimulated Raman Scattering in WDM Systems with Dispersion Compensated Links

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Summary

The probability density function of Stimulated Raman Scattering (SRS) crosstalk for WDM systems with dispersion compensated links is studied and the parameters, mean power depletion and crosstalk variance, are derived. Contrary to the present papers, where these parameters are determined for the most affected channel, the expressions derived here are applicable for any channel. In addition, the presented analysis is more realistic in the sense that the SRS generated by the DCF is taken into account. The derived expressions facilitate in studying the effects of the modulation format (NRZ versus RZ) on the strength of SRS. The procedure of calculating the power penalty due to SRS and the optimum threshold are also presented.

1 Introduction

Optical networks are entering the multi-Terabit transmission capacity regime and most major telecommunications vendors have announced such systems. As Wavelength-Division-Multiplexed (WDM) systems operating within the gain spectrum of the erbium-doped-fiber-amplifier (EDFA) window are turning into their maturity phase, the only way of gratifying the capacity demand is to exploit systems employing both the C and L bands as well as the S band. The total optical bandwidth, thus, could span anything between 80 nm and 200 nm of optical spectrum. It is exactly this broad spectrum that renders the effect of Stimulated Raman Scattering (SRS) as a major limit to the maximum transmission distance that can be attained. Although the deterministic part could be controlled by means of properly designed equalisation filters, the statistical variations of SRS remain a limiting factor. A simple but still exact analytical model is required to describe this process.

The limitations due to SRS have been considered in a number of papers [1–6]. Unfortunately, in [1–3, 5, 6] only the deterministic part of the SRS was taken into account. Also, in these studies the SRS of the most affected channel only due to a single span was considered. The analysis presented in [4] is the most comprehensive so far with respect to both deterministic part and SRS crosstalk. Nevertheless, the analysis in [4] takes, again, into account the effect of SRS only on the most affected channel. An additional restriction in [4] is that when WDM system with dispersion compensated links are considered, it is assumed that the dispersion compensated fiber (DCF) does not induce SRS. The question of finding an analytical model of SRS valid for any channel and in the case when DCF induces SRS is still open.

In this paper the parameters, mean power depletion and crosstalk variance, of the probability density function of stimulated Raman crosstalk for WDM systems with dispersion compensated links are derived. Contrary to the present papers, where these parameters are determined for the most affected channel [1–8], the expressions derived here are applicable for any channel. At the same time our model is more realistic since it is valid even in the case where the DCF induces SRS. It is pointed out the analysis presented here allows the most precise comparison to date with respect to the effect of the modulation format (NRZ versus RZ) on SRS. The power penalty due to SRS and the optimum threshold are also determined.

2 Model description

In dispersion compensated (DC) links a DCF segment is inserted after each SMF fiber segment followed by an optical amplifier (EDFA) that restores the optical power, as shown in Fig. 1. The dispersion accumulated along a SMF segment of length L_1 is compensated by that of a DCF segment of length L_2 with an opposite sign of second order dispersion. Typical characteristics of conventional SMF and DCF fibers are given in Table 1. WDM systems with N channels of wavelengths $\lambda_i = \lambda_1 + (i-1)\Delta\lambda$, $(i = 1, 2, \ldots, N)$, with λ_i being the wavelength of i[th] channel and $\Delta\lambda$ being the channel separation, are considered. The total bandwidth is $(N-1)\Delta\lambda$. The wavelength $\lambda = 1545$ nm is taken to be the middle one, so that the wavelength of the fist channel can be determined by $\lambda_1 = \lambda - (N-1)\Delta\lambda/2$. The assumptions

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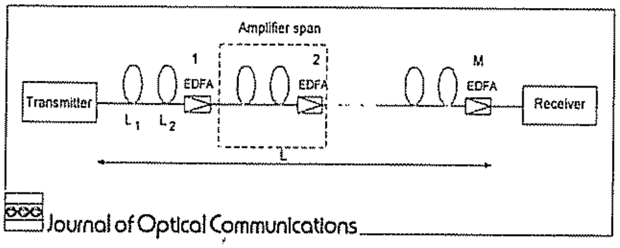

Fig 1: Block diagram of a WDM transmission system with dispersion compensated links

Tab. 1: Typical fiber characteristics

	Fiber attenuation coefficient (dB/km)	Effective cross-sectional area (μm^2)	Dispersion ($ps\ nm^{-1}\ km^{-1}$)	Dispersion slope ($ps\ nm^{-2}\ km^{-1}$)	Raman gain slope ($10^{-17}\ m\ W^{-1}\ Hz^{-1}$)
SMF	0.23	65	17	0.085	4.9
DCF	0.5	22	-85	-0.3	9.5

made here are that the amplifier gain is constant for the bandwidth of interest and that the amplifier gain completely compensates the total SMF + DCF losses as well as the node input-output coupling losses. The amplifier spacing is assumed to be constant.

2.1 Derivation of the probability density function

Following the similar procedure and the same assumptions as in paper [4], the normalized power on n^{th} channel after the M^{th} dispersion compensated link when ONE is transmitted can be written as

$$P_n\big(M(L_1+L_2),t\big)=e^{-x_n(M(L_1+L_2),t)}, \tag{1}$$

where

$$x_n\big(M(L_1+L_2),t\big)=$$

$$=\sum_{k=1,k\neq n}^{N}\left[\sum_{i=-\infty}^{\infty} b_i^{(k)} q_M^{(k)}\left(t-M\left(\frac{L_1}{v_{g1}^{(k)}}+\frac{L_2}{v_{g2}^{(k)}}\right)\right)-iT\right] \tag{2}$$

$$q_{n,M}^{(k)}=\sum_{m=1}^{M} q_n^{(k)}\left[t-(m-1)\left(d_{k,n}^{(1)}L_1+d_{k,n}^{(2)}L_2\right)\right] \tag{2a}$$

$$q_n^{(k)}(t)=K_1(k,n)\int_0^{L_1} p\left(t-d_{k,n}^{(1)}z'\right)e^{-\alpha_1 z'}dz'+e^{-\alpha_1 L_1}K_2(k,n)$$

$$\int_{L_1}^{L_1+L_2} p\left(t-d_{k,n}^{(1)}L_1-d_{k,n}^{(2)}(z-L_1)\right)e^{-\alpha_2(z-L_1)}dz \tag{2b}$$

with $b_i^{(k)}\in\{0,1\}$ being the binary digit transmitted on i^{th} bit of the k^{th} channel,

$$K_l(k,n)=g_l'(k-n)\Delta f/(2A_{el}),\ (l=1,2);$$

$$d_{k,n}^{(l)}=1/v_{gk}^{(l)}-1/v_{gn}^{(l)}=\int_{\lambda_n}^{\lambda_k} D_l(\lambda)d\lambda$$

is the walkoff parameter (D_l, $l = 1, 2$ is the second order dispersion of the corresponding fiber segment) between n^{th} and k^{th} channel. With $v_{gj}^{(l)}$ is denoted the group velocity of the jth channel ($j = k, n$) on l^{th} fiber segment. In the above expressions g'_l, A_{el} and α_l ($l = 1, 2$) are the Raman gain slope, the effective cross-sectional area and the fiber attenuation coefficient of corresponding fiber segments, respectively. With Δf is denoted the channel separation in frequency domain, while p(t) is the initial pulse shape. (N is the number of channels, M – the number of DC links, T – the bit duration).

It is known that the result of the summation of many independent random variables, through the central limit theorem [10], follows a Gaussian distribution. Therefore, the distribution for x_n is Gaussian and using the transformation $y = e^{-x}$ the probability density function (PDF) of P_n, as derived through (1), has a lognormal distribution

$$w_n(y)=\frac{1}{y\sigma_x(n)\sqrt{2\pi}}\exp\left[-\frac{(\log y+\mu_x(n))^2}{2\sigma_x^2(n)}\right],\ y\geq 0. \tag{3}$$

(With log(·) is denoted the logarithm to the base e). The mean value μ_y and the standard deviation σ_y of P_n are

$$\mu_y(n)=\exp\left[-\mu_x(n)+\sigma_x^2(n)/2\right]\ \text{and}$$

$$\sigma_y(n)=\mu_y(n)\sqrt{\exp[\sigma_x^2(n)]-1}. \tag{4}$$

Note that the only difference from the expressions for PDF presented in [4] is in sign of μ_x in eq. (3)–(4). Although this difference may seem to be not so important, the expressions derived in [4] changes the nature of SRS process. Namely, the worst affected channel, according to expressions (A2) and (A3) of [4], is amplified through SRS (the fact that for the worst affected channel $\mu_x>0$ and $\sigma_x^2>0$ implies $\mu_y>1$, what is impossible). Contrary, according to eq. (4), as expected, the worst affected channel is depleted through SRS process ($\mu_y<1$).

The mean power depletion and the SRS crosstalk standard deviation for WDM systems with dispersion compensated links are determined in the subsequent two subsections.

2.2 Calculation of the mean power depletion

The mean power depletion is studied in [9]. There it was found that the power depleted due to SRS as measured on the n^{th} channel after propagation through M SMF (of length L_1) – DCF (of length L_2) spans is

$$\mu_D(n)=\frac{P_0e^{-(\alpha_1L_1+\alpha_2L_2)}-P_n(L_1+L_2)}{P_0e^{-(\alpha_1L_1+\alpha_2L_2)}}\frac{L}{L_1+L_2}, \tag{5}$$

with the implicit assumption that the launched power is equal for all channels, i. e. $P_n(0) = P_0$ ($n = 1, 2, \ldots, N$) and that with α_1 and α_2 are denoted the attenuation coefficients of the SMF and DCF, respectively. If with $P_n(L_1 + L_2)$ is denoted the power of n^{th} channel after the end of the DCF section, then

$$P_n(L_1+L_2)=\frac{P_n(L_1)J_0e^{-\alpha_2L_2}\exp\left[\frac{g_2'\Delta fJ_0(n-1)L_{e2}}{2A_{e2}}\right]}{\sum\limits_{m=1}^{N}P_m(L_1)\exp\left[\frac{g_2'\Delta fJ_0(m-1)L_{e2}}{2A_{e2}}\right]} \quad (6)$$

where $J_0 = \sum\limits_{m=1}^{N} P_m(L_1)$, while g'_2 and $L_{e2} = (1 - e^{-\alpha_2 L_2})/\alpha_2$ are the Raman gain slope and the effective length of dispersion compensating fiber segment, respectively and Δf is the channel spacing frequency. Finally $P_n(L_1)$ is the power of the n^{th} channel at the end of SMF and it is

$$P_n(L_1)=NP_0e^{-\alpha_1L_1}\exp\left[\frac{g_1'\Delta fNP_0L_{e1}}{4A_{e1}}(2n-N-1)\right]\frac{\sinh\left(\frac{g_1'\Delta fNP_0L_{e1}}{4A_{e1}}\right)}{\sinh\left(\frac{g_1'\Delta fN^2P_0L_{e1}}{4A_{e1}}\right)} \quad (7)$$

where $g'_1 = dg_1/df$ and $L_{e1} = (1 - e^{-\alpha_1 L_1})/\alpha_1$ represents the Raman gain slope and the effective length of the SMF fiber segment, respectively.

To simplify the analysis of SRS, the effective Raman gain slope-length/cross-sectional area $(g'L/2A)_{eff}$ of a fiber link section, composed of two segments with lengths L_1 and L_2, can be defined starting from [9] as

$$P_0\left(\frac{gL}{2A}\right)_{eff}=\frac{g_1'P_0}{2A_{e1}}\int\limits_0^{L_1}e^{-\alpha_1z}dz+\frac{g_2'P_0e^{-\alpha_1L_1}}{2A_{e2}}\int\limits_{L_1}^{L_1+L_2}e^{-\alpha_2(z-L_1)}dz,$$

and

$$\left(\frac{g'L}{2A}\right)_{eff}=\frac{g_1'}{2A_{e1}}\frac{1-e^{-\alpha_1L_1}}{\alpha_1}+e^{-\alpha_1L_1}\frac{g_2'}{2A_{e2}}\frac{1-e^{-\alpha_2L_2}}{\alpha_2}. \quad (8)$$

Therefore the mean power depletion of the n^{th} channel at the end of the DCF fiber section is

$$\mu_D(n)=\left\{1-N\exp\left[-\frac{\Delta fNP_0}{2}\left(\frac{g'L}{2A}\right)_{eff}(N+1-2n)\right]\frac{\sinh\left(\frac{\Delta fNP_0}{2}\left(\frac{g'L}{2A}\right)_{eff}\right)}{\sinh\left(\frac{\Delta fN^2P_0}{2}\left(\frac{g'L}{2A}\right)_{eff}\right)}\right\}\frac{L}{L_1+L_2} \quad (9)$$

In the case of the reasonable channel crosstalk, that is when $P_0\Delta f(g'L/2A)_{eff} \ll 1$, the previous expression is simplified to

$$\mu_D(n)\cong\frac{1}{2}N(N+1-2n)P_0\Delta f\left(\frac{g'L}{2A}\right)_{eff}\frac{L}{L_1+L_2}. \quad (9b)$$

To take into account the statistics of the transmitted symbols, the previous two expressions are to be multiplied with the probability of transmitting a bit on mark-state, which usually is ½; that is

$$\mu_D(n)\cong\frac{1}{4}N(N+1-2n)P_0\Delta f\left(\frac{g'L}{2A}\right)_{eff}\frac{L}{L_1+L_2}. \quad (10)$$

Notice, that for $n = 1$ (the worst case scenario i. e. the worst affected channel), single span and only one fiber segment (10) is reduced to

$$\mu_D(n)\cong\frac{1}{4}N(N-1)P_0\Delta f\frac{g'L_e}{2A_e}, \quad (10b)$$

which is the expression given in [6].

The validity of the aforementioned analysis related to the mean power depletion of the channel under study can be confirmed using a statistical approach. Namely, the power that flow due to SRS from n^{th} to m^{th} channel after the first SMF-DCF span, using the triangle approximation [6], follows

$$\left(\frac{g'L}{2A}\right)_{eff}P_0\cdot(m-n)\Delta f$$

The mean power depletion of the observed channel can be found by averaging the previous expression assuming that the probability of transmitting the mark state is ½

$$\mu_D(n)=\sum_{m=1,m\neq n}^{N}\left(\frac{g'L}{2A}\right)_{eff}P_0(m-n)\Delta f\cdot\frac{1}{2}=\frac{1}{4}N(N+1-2n)P_0\Delta f\left(\frac{g'L}{2A}\right)_{eff},$$

which is in fact is the same expression as (10) for a single span. For $n > \lfloor N + 1/2 \rfloor$, with $\lfloor\,\rfloor$ being the integer part, $\mu_D < 0$ which means that those channels are amplified through the SRS process.

2.3. Derivation of the SRS crosstalk variance

Starting from [4] and taking into account the fact that process described by (2) is cyclostationary, the Raman crosstalk variance after the first SMF-DCF span as calculated on the n^{th} channel, follows

$$\sigma_D^2(n)=\sum_{k=1,k\neq n}^{N}\sigma_k^2(n), \quad (11)$$

with $\sigma_k^2(n)$ being the SRS crosstalk variance of the n^{th} channel due to the k^{th} channel, that is

$$\sigma_k^2(n)=\frac{1}{8\pi T}\int_{-\infty}^{\infty}\left|Q_k^{(n)}(\Omega)\right|^2 d\Omega, \tag{12}$$

where

$$\left|Q_k^{(n)}(\Omega)\right|^2=\left|P(j\Omega)\right|^2 \cdot \left| K_1(k,n)\frac{1-\exp\left[-\left(\alpha_1-jd_{k,n}^{(1)}\Omega\right)L_1\right]}{\alpha_1-jd_{k,n}^{(2)}\Omega}+ +\exp\left[-\left(\alpha_1-jd_{k,n}^{(1)}\Omega\right)L_1\right] K_2(k,n)\frac{1-\exp\left[-\left(\alpha_2-jd_{k,n}^{(2)}\Omega\right)L_2\right]}{\alpha_2-jd_{k,n}^{(2)}\Omega}\right|^2 \tag{13}$$

$Q_k^{(n)}(\Omega)$ is in fact the Fourier Transform (FT) of the expression (2b). $P(j\Omega)$ is the Fourier transform of NRZ rectangular pulse

$$P(j\Omega)=P_0 T\frac{\sin(\Omega T/2)}{\Omega T/2}e^{-j\Omega T/2} \tag{14}$$

In the following the expression of the dispersion coefficient as a function of wavelength for the SMF is used

$$D^{(1)}(\lambda)=\frac{S_0}{4}\lambda\left(1-\frac{\lambda_0^4}{\lambda^4}\right), \tag{15}$$

with λ_0 and S_0 being the zero-dispersion wavelength and the dispersion slope at λ_0, respectively. The corresponding approximation for DCF follows

$$D^{(2)}(\lambda)=S_c(\lambda-\lambda_c)+D_c, \tag{16}$$

with S_c and D_c being the dispersion slope and the dispersion at the wavelength $\lambda_c = 1550$ nm.

Using (15), (16) the walkoff parameter between two wavelengths λ_k, λ_n due to their propagation in the SMF is

$$d_{k,n}^{(1)}=\frac{S_0}{8}\left(\lambda_k^2-\lambda_n^2\right)\left(1-\frac{\lambda_0^4}{\lambda_k^2\lambda_n^2}\right), \tag{17}$$

whereas the corresponding expression for DCF fiber segment follows

$$d_{k,n}^{(2)}=(\lambda_k-\lambda_n)\left[D_c+\frac{S_c}{2}(\lambda_k+\lambda_n-2\lambda_c)\right] \tag{18}$$

In the case of RZ pulses, using the results given in Appendix B of paper [4], the corresponding expression for SRS crosstalk variance of the n^{th} channel due to the k^{th} channel can be written as

$$\sigma_k^2(n)=\frac{1}{8\pi T}\int_{-\infty}^{\infty}\left|Q_k^{(n)}(\Omega)\right|^2 d\Omega+\frac{1}{2T^2}\sum_{k=1}^{\infty}\left|Q_k^{(n)}\left(\frac{2k\pi}{T}\right)\right|^2 \tag{19}$$

with $|Q_k^{(n)}(\Omega)|^2$ defined by (13), wherein the RZ pulse FT follows

$$P(j\Omega)=P_0\tau\frac{\sin(\Omega\tau/2)}{\Omega\tau/2}\exp[-j\Omega\tau/2],\ \tau<T; \tag{20}$$

with τ being the RZ pulse duration.

To determine the amount of Raman crosstalk variance on the observed channel after M sections of SMF-DCF, the factor $Q_k^{(n)}(\Omega)$ should be multiplied by factor

$$\sum_{m=1}^{M}\exp\left[-j(m-1)\left(d_{k,n}^{(1)}L_1+d_{k,n}^{(2)}L_2\right)\Omega\right] =\exp\left[-j(M-1)\left(d_{k,n}^{(1)}L_1+d_{k,n}^{(2)}L_2\right)\Omega/2\right]\cdot \frac{\sin\left[M\left(d_{k,n}^{(1)}L_1+d_{k,n}^{(2)}L_2\right)\Omega/2\right]}{\sin\left[\left(d_{k,n}^{(1)}L_1+d_{k,n}^{(2)}L_2\right)\Omega/2\right]}, \tag{21}$$

which in fact is the Fourier Transform of (2a).

2.4. Calculation of the Bit-Error-Rate (BER) and the power penalty

The bit-error rate (BER) can be calculated using the following expression

$$P_e=\frac{1}{4}\mathrm{erfc}\left(\frac{d}{\sigma_0\sqrt{2}}\right)+\frac{1}{4}\int_0^{+\infty}\mathrm{erfc}\left(\frac{y-d}{\sigma_0\sqrt{2}}\right)w(y)dy, \tag{22}$$

where d is the normalized decision level, σ_0 is the standard deviation of receiver Gaussian noise, and w(y) is defined by (3). The erfc(x) function is defined by

$$\mathrm{erfc}(x)=\frac{2}{\sqrt{\pi}}\int_x^{+\infty}\exp\left(-u^2\right)du.$$

In the absence of SRS crosstalk, the decision threshold is placed in the middle (d = 1/2) and the required Q-factor, in order to achieve BER of 10^{-9}, is $Q_0=\mu_y/(2\sigma_0)=6$. In the presence of SRS crosstalk a greater value of the Q factor is needed to achieve the same BER, so that the power penalty (PP) can be defined as Q/6. In the previous definition of the PP it is implicit that after each DC link an equalising filter is used to compensate both the nonuniform gain of EDFA and the deterministic part of SRS, which is the common practice in the long-haul communications.

Making use of the Gaussian approximation of the PDF given by (3) the power penalty follows

$$PP[dB]=-10\log_{10}(Q/6) =-10\log_{10}\left(\frac{2}{1+\sqrt{1+4\cdot 36\ \sigma_D^2}}\right) \tag{23}$$

Note that this expression is quite different form (23) of paper [4]. When the crosstalk is no so great

($\sigma_D^2 \ll 1/(4 \cdot 36)$) the previous expression is approximated by

$$PP[\mathrm{dB}] \approx 10\log_{10}\left(1+36\sigma_D^2\right), \tag{24}$$

which is consistent with the expression (8.45) of [6].

3 Numerical results

In Figure 2a, the probability density function versus SRS crosstalk for different walk-off lengths (L_w), is illustrated. In Figure 2b, 2c the power penalty due to the SRS crosstalk standard deviation and the optimum threshold for NRZ pulses, respectively, are shown. The

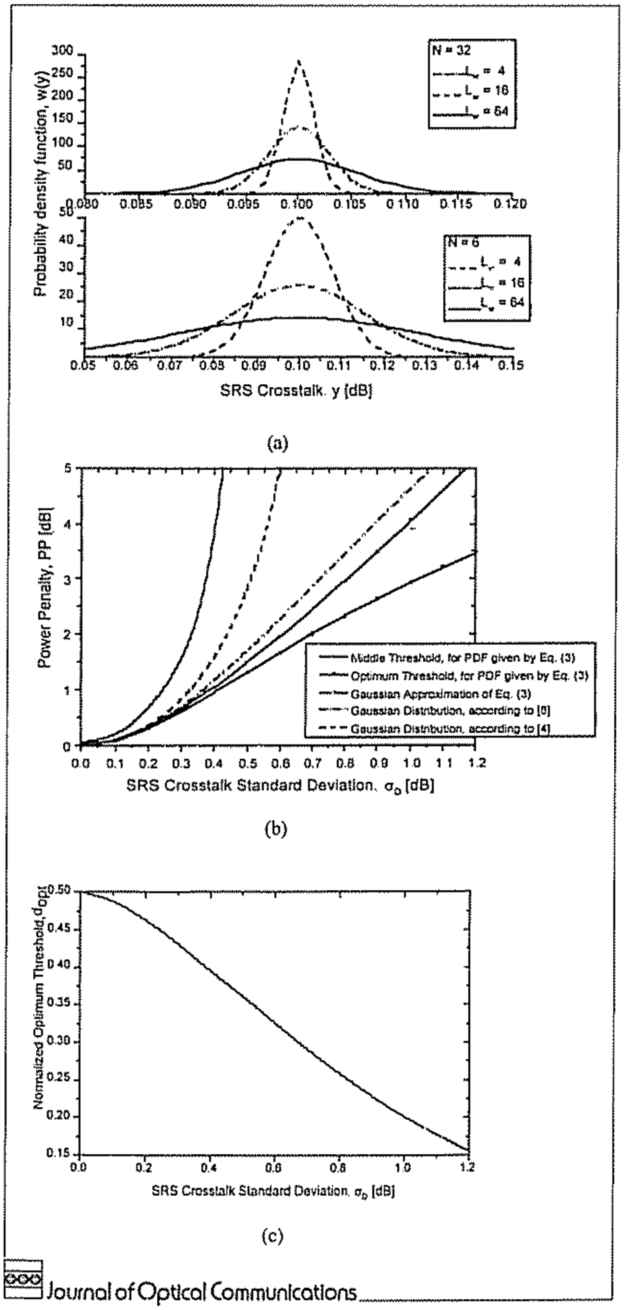

Fig. 2: (a) Probability density function (for a mean power depletion of 0.1 dB), (b) power penalty due to SRS crosstalk and (c) optimum threshold

walk-off length is defined as $L_w = \rho T/|D\Delta\lambda|$, with $\rho = \tau/T$ ($0 < \rho < 1$) being the duty cycle, T – the bit duration, D – dispersion, and $\Delta\lambda$ being the channel spacing.

As expected the greater the walk-off length, the wider the PDF curve is, and the system is more susceptible to SRS crosstalk. When the threshold is set to its optimum value the system is much more immune to the SRS crosstalk. It can be also observed that for a PP of less than 1 dB, the Gaussian approximation of (3) is in a good agreement with the results obtained from the exact model and can be used instead. When the level of SRS crosstalk that can be tolerated is known, the threshold giving the best immunity to SRS can be derived from Fig. 2(c).

In Figure 3, the crosstalk standard deviation-to-mean power depletion ratio vs. the number of channels assuming RZ pulses is shown. It should be pointed out that the walk-off lengths and the average power for both NRZ and RZ pulses were set at the same levels. The relation between the peak P and the average P_{av} power is $P = P_{av}/\rho$ ($0 < \rho < 1$). The power per channel P_0 used in (5) and (9) was the peak power.

From Figure 3, it can also be deduced that for the same average power and walk-off length, the RZ systems are more sensitive to SRS crosstalk than NRZ. Also since

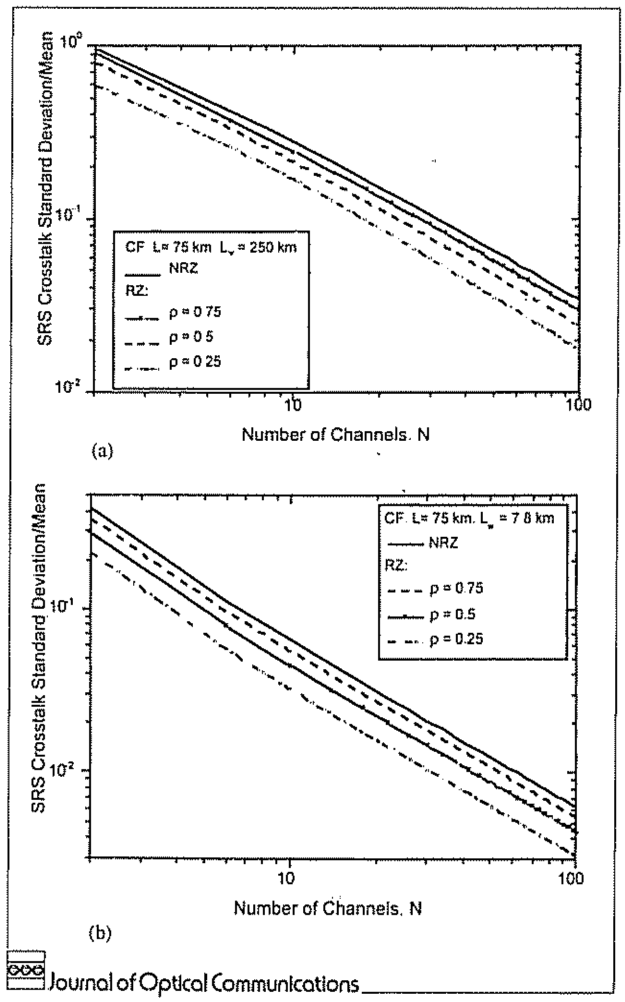

Fig 3: The standard deviation-to-mean power depletion ratio due to SRS crosstalk vs. the number of channels for two different walk-off lengths for SMF of 75 km in length

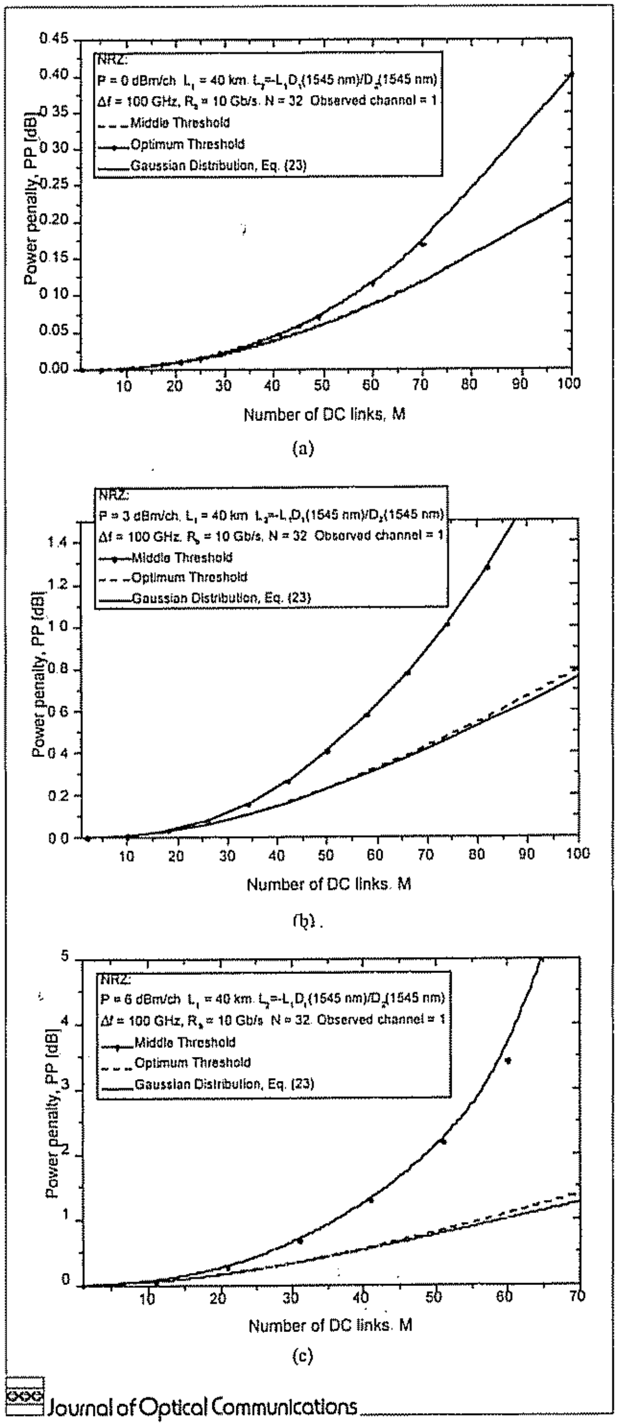

Fig. 4: SRS Power penalty vs number of DC links for different peak powers per channel: (a) 0 dBm/ch, (b) 3 dBm/ch and (c) 6 dBm/ch ; the observed channel is the first (n = 1)

the lunched power in (5) and (9) is in fact the peak power, for the same average power the RZ systems experiencing greater performance degradation than the NRZ systems. The smaller the pulse duration is, the greater performance degradation due to SRS is observed and, hence, the ratio σ_D/μ_D is always greater in NRZ systems.

To illustrate the proposed method, the power penalty is calculated as a function of the total number of DC spans (M) for different peak powers per channel (0 dBm, +3 dBm, +6 dBm) and two different channel indexes: the first (Fig. 4) and the sixteenth (Fig. 5). A 32 channel

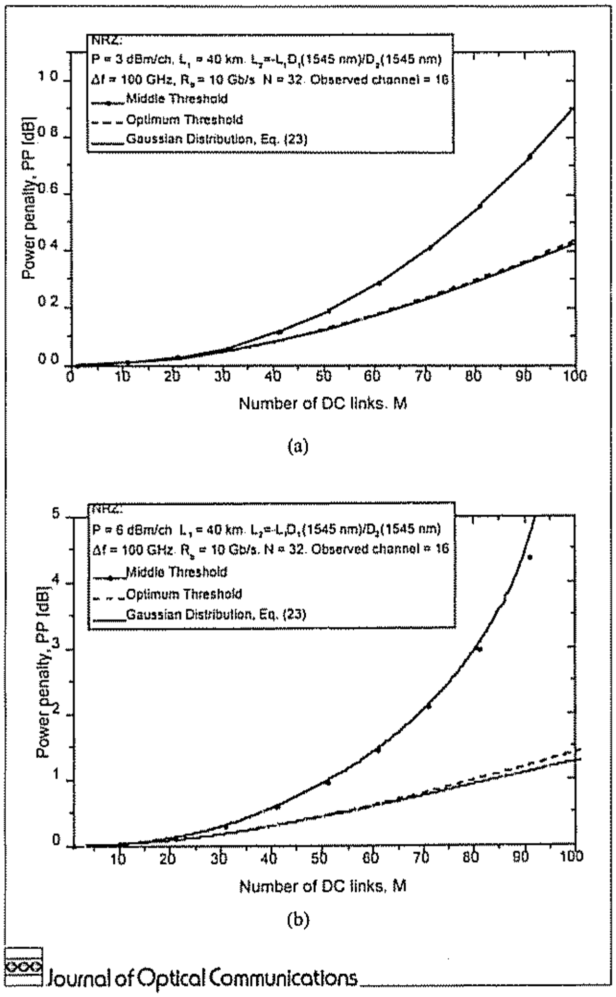

Fig. 5: SRS Power penalty vs number of DC links for different peak powers per channel: (a) 3 dBm/ch, (b) 6 dBm/ch ; the observed channel is the sixteenth (n = 16)

NRZ WDM system of SMF + DCF links (with SMF length of 40 km), 10 Gbit/s bit rate and a channel spacing of 100 GHz, was considered.

As expected, the first channel is more affected by SRS than the sixteenth channel. Again, the worst performance degradation occurs for the systems with the largest peak power. Equally well, given a power penalty one making use of Figs. 4–5 can find out the maximum transmission distance. It should be pointed out that when the threshold is set to its optimum value a very accurate approximation of the distribution given by (3) is the Gaussian distribution.

4 Conclusion

The probability density function of SRS crosstalk is well approximated by lognormal distribution. The parameters of this distribution like the mean power depletion and the crosstalk variance for WDM systems for dispersion compensated links, are derived. Contrary to the present papers, where these parameters are determined for the most affected channel, the expressions derived here are applicable for any channel. In addition, the presented analysis is more realistic in the sense that the SRS generated by the DCF is taken into account. The derived expressions facilitate in studying the effects of the modulation format (NRZ versus RZ) on the strength of SRS. The RZ modulation format was found more susceptible to SRS.

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