# Stabilization of "Bit-Rate ×Repeater Spacing" Product in High-Speed Nonlinear Optical Communication Networks


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**ABSTRACT**

Stabilization of the product "bit-rate × repeater spacing" of high-speed performance nonlinear optical communication networks is deeply investigated where ultra-wide wavelength division multiplexing (UWWDM) and space division multiplexing (SDM) techniques are employed.
The stabilization of the product is processed for four different transmission techniques as well as two amplification methods. In order to obtain good high speed stable performance of nonlinear optical networks, three affecting parameters are tailored, namely the Raman pumping power, the input signal power, and the fiber link characteristics (radius; germania percentage, x%, in silica fiber; and relative refractive index difference Δn). The tailoring parameters sustain the repeater spacing and the transmitted bit rate at constant value, and consequently constant product of the bit-rate-repeater spacing. In the UWWDM, 2400 channels are processed into groups of 4, 6, .. to 24 links in SDM. The physical parameters of fibers and the employed amplifier are thermal-dependent as well as spectral-dependent parameters.


## 1. INTRODUCTION

Thermal environmental conditions affect severely the stability and the good high-speed performance of nonlinear optical networks. Variations of temperature lead to:

a) amplifier gain variations [1,2],
b) variations of the spectral losses [3-9], and
c) variations of the chromatic dispersion coefficient 10,11]

The integration of these effects yields the following:

a) variations of the processed bit-rate, and
b) variations of the repeater spacing,

and consequently variations of the product "bit-rate× repeater spacing" and signal-to-noise ratio.

Raman amplifier gain possesses spectral gain as well as thermal variations. Based on the measurements and the theoretical predictions of Refs. [1,2], El-Halafawy et. al.[3] modeled the thermal gain variations as well as the spectral variations under the form:

$$g = g_o + g_m \cos\left(\frac{T-80}{120}\right)\cos 2\pi\left(\frac{\lambda - 1530}{80}\right) \quad (1)$$

where $g_o$ is the static flat gain at 20 °C, $g_m$ is the maximum gain variations (5 dB), T is the temperature in °C ($-40 \le T \le 80$), and λ is the optical wavelength, ($1530 \le \lambda, \mu m \le 1610$).

Walker [4], Nakashima et al[5], and based on the work of Knox [6], El-Khamry [7] had derived a polynomial feature for the spectral losses respectively under the forms:

$$\sigma_w = A\lambda^{-4} + Be^{C/\lambda} + De^{-E/\lambda} + F \quad (2)$$

$$\sigma_N = \sum_i a_i \lambda^i + 7\Delta n \quad (3)$$

$$\sigma_E = E_o + E_1(\lambda - \lambda_m) + E_2(\lambda - \lambda_m)^2 + E_3(\lambda - \lambda_m)^3 + E_4(\lambda - \lambda_m)^4 + E_5(\lambda - \lambda_m)^5 \quad (4)$$

where W stands for Walker, N for Nakashima, and E for El-Khamry. These expressions possess a minimum values at λ = $\lambda_m$ = 1.55 μm in the range 0.19 → 0.2 dB/km. All the coefficients in these equations are thermal-dependent parameters [8,9]. The chromatic dispersion is a strong thermal-dependent function as the refractive index, and its derivative depend on the optical wavelength, the fiber chemical structure, and the ambient temperature [12,13].

The advanced transmission techniques applied in this study are:

i) soliton propagation,
ii) nonlinear chirped propagation,
iii) maximum time division multiplexing (MTDM) propagation, and
iv) "Shannon" propagation.

In the present paper, we investigate the stability of the product where 2400 channels are multiplexed in SDM where the links are 4, 6, .. or 24 links. The organization of the present paper is as follows. Section I above is a general introduction, Section II presents the basic model and analysis of the tailoring technique, Section III presents the obtained results and a discussion, and finally Section IV summarizes and concludes.

## 2. BASIC MODEL AND ANALYSIS

The soliton bit rate, $B_{ri}$ is a distance-free quantity [14] as:

$$\frac{P_{slo}}{B_{rsi}^2} = 59.7\left(\frac{\lambda_{si}}{1.54}\right)^3\left(\frac{A_e}{20}\right)\left(\frac{3.2x10^{-20}}{n_2}\right)|D_t|x10^6 \quad (5)$$

where $A_e$: is the effective cross section, μm²

$n_2$: is the nonlinear refractive index coefficient [15,16], where $n_2$ for pure silica is given by $n_2 = 3.2x10^{-19}$ m²/W, while for germania doped silica $n_2$ is given by:

$$n_2 = 3.2x10^{-19}(1.0 + 2.81294x - 16.6123x^2 + 45.9808x^3) \quad (6)$$

with x the percentage of germania in the germania-doped silica fiber.

$|D_t|$ :is the total dispersion coefficient, ps/(km.nm)

The MTDM bit rate of the i$^{th}$ channel is $B_{mi}$ where [17]:

$$B_{mi} = \frac{1}{4\tau_{mi}(\lambda_{si}, z_{iR}, \tau_{io}, N_o)} \quad (7)$$

where:

$\tau_{mi}$: is the pulse width at distance $z_{iR}/N_o$ of the i$^{th}$ channel
$N_o$: is the number of successive sections of alternative dispersion,
$\tau_{io}$: is the initial pulse width

The pulse width in the nonlinear chirping is reduced due to the initial chirp [18,19] and is given by:

$$\tau_{cri}/\tau_{cio} = \sqrt{1 + 0.543\mu((z_{iR} + z_o)/N_o)^2} \quad (8)$$

or exactly:

$$\tau_{cri}/\tau_{cio} = \sqrt{1+0.543\mu((z_{iR}+z_a)/N_a)^2} - a_o \quad (9)$$

where $\tau_{cri}$ and $\tau_{cio}$ are respectively the chirped pulse width and the initial pulse width of the $i^{th}$ channel. In this technique the initial chirp reduced the total dispersion coefficient and consequently reduces $\sigma_o$ and gives the chirped bit rate of the $i^{th}$ channel $B_{ci}$ as:

$$B_{ci} = \frac{1}{4\tau_{cri}} \quad (10)$$

Tang [20,21] presented a ceiling value of "Shannon" capacity of multi-channels, and multi spans dispersion-free nonlinear optical fiber taking into account the effects of multi span, "Kerr" nonlinearity and amplifier noises where "Shannon" capacity is cast as ShC, where:

$$ShC = BW\ Log_2\left[1+\left(\frac{C}{N_s^2 N_c k_{ci}(P_W BW_i)}\right)^{2/3}\right] \quad (11)$$

and consequently the "Shannon" product in Tbit.km/s is:

$$SHP = \sum_{i=1}^{N_c} BW_i L_s \text{ Log}_2\left[1+\left(\frac{C}{N_s^2 N_c k_{ci}(P_W BW_i)}\right)^{2/3}\right] \quad (12)$$

where:

- $BW_i$ : is the channel bandwidth, THz
- $i$ : indicates that the computation is at $\lambda_{si}$
- $L_s$ : is the span length, km
- $N_c$ : is the number of channel, = 2400
- $N_{cL}$ : is the number of channels / link = $N_c/N_L$
- $N_L$ : is the number of links (4,6,8,10…24)
- $C$ : is a constant (dimensionless), = 1.9746
- $k_{ci}$ : is a constant related to the "Kerr" nonlinear coefficient, $W^{-1}$
- $P_W$ : is the noise power density, W/THz

where:

$$10^{-5} \le P_W,\ W/THz \le 10^{-3}$$

$$k_{ci} = k_{oi}\left[1-e^{-\sigma_s(\lambda_{si})L_s}\right]/\sigma_s(\lambda_s) \quad (13)$$

with:

$k_o = 1.22km^{-1}W^{-1}$ : is "Kerr" nonlinear coefficient

$\sigma_s(\lambda_s)$ : is a spectral loss in $\text{km}^{-1}$

The constant C in Eqn.(12) is given by:

$$C = \left[2\left(\frac{2\pi}{9}\right)^{2/3}\right]^{3/2} = \frac{2\pi}{9}.2^{3/2} = 1.9746$$

The optimal operating power $P_{max,i}$ in W is given by [22,23]:

$$P_{max,i} = \left[\frac{C_p P_W BW_i}{N_s(N_c k_{ci})^2}\right]^{1/3} \quad (14)$$

where: $C_p = \dfrac{4\pi^2}{3} = 13.1595$ (Dimensionless)

SHP is considered as the ceiling value in present analysis.

These transmission techniques yield transmitted bit rates $B_S$, $B_C$, $B_M$, and $B_{SH}$ (soliton, chirped, MATM, and Shanon, respectively) and repeater spacing, $R_s$ which depend strongly on the dispersion characteristics, spectral losses, and amplifier gain, thus depend consequently on the ambient temperature.

In the present study, we have $N_c$ as the total UWWDM channels, $N_s$ as the numbers of links in SDM where $N_c$ = 2400 channels and $N_s$ = 4, 6,.. or 24 links. These groups of links transmit $2400/N_s$, i.e 600, 400, … or 100 channels/link, $N_{cL}$, in UWWDM.

The fiber radius, $R_f$ is tailored under the form:

$$R_f = R_1\left(1+\alpha\left(\frac{N_L-1}{N_s}\right)\right) \quad (15)$$

where $R_1$ is the radius of the first link, $N_L$ is the order of the link (1,2,3,………, ($N_s - 1$)) and α is a constant tailoring parameter.

The input "Raman power," $P_R$ in the link is tailored in such a manner to compensate the spectral loss as:

$$P_R = P_{Ro}\exp\left(\frac{(\sigma_a - \alpha_T\sigma_m - 7\Delta n - S_i)}{(\sigma_m\alpha_T + 7\Delta n + Si)}\right) \quad (16)$$

where $P_{Ro}$ is the minimum pumping, = 1 W or 2 W, $\sigma_a$ is the average spectral loss of the transmitted channels in the link, $\sigma_m$ is the minimum spectral loss, = 0.19 dB/km, and $\alpha_T$ accounts for the thermal variations. In Eq. (4), $\sigma_a$ is cast based on the works of [4-7] under the form:

$$\sigma_z = \left\{E_o + E_1(\lambda_a - \lambda_m) + E_2(\lambda_a - \lambda_m)^2 + E_3(\lambda_a - \lambda_m)^3\right\}\alpha_T$$
$$+\left\{E_4(\lambda_a - \lambda_m)^4 + E_5(\lambda_a - \lambda_m)^5\right\}\alpha_T + 7\Delta n + S_i \quad (17)$$

where $\lambda_a$ is the average wavelength over a link, and $S_i$ is the intrinsic loss, = 0.03 dB/km [10].

The input signals power, $P_s$ of the channels in each link is given by:

$$P_s = P_{so}\exp\left(\frac{(\sigma_a - \sigma_m\alpha_T - 7\Delta n - S_i)}{(\sigma_m + 7\Delta n + S)}\right)$$

where $P_{so}$ is signal power which satisfies the limitation [13] as:

$$P_{so} = 500/(N_{cL}(N_{cL}-1)\Delta f)\ \text{W} \quad (18)$$

where Δf is the channel spacing in GHz, and is given by:

$$\Delta f = \left(\Delta\lambda_s c/J_c.\lambda_a^2\right) = 3x10^5\left(\Delta\lambda_s/J_c.\lambda_a^2\right)\ \text{GHz} \quad (19)$$

The processing of the total channels is in the range $1.45 \le \lambda_s\ \mu m \le 1.65$, thus $\Delta\lambda_s$ = 0.2 μm.

The repeater spacing $R_s$ is the solution of:

$$P_s(z) = P_{so}(1+\alpha_p)\left[1+\alpha_p\exp(-\alpha_R f(z))\right]e^{-\sigma_a z}$$
$$= 10^{-3}\,ASE \quad (20)$$

where $f(z) = 1-\exp(-\sigma_R z)$, and $\alpha_p$ and $\alpha_R$ are coefficients related to "Raman gain" and the number of channels, $\sigma_R$ is the spectral loss at Raman pumping wavelength, and ASE is the amplified spontaneous emission. The factor $10^{-3}$ in the R.H.S of Eq. (20) is due to Erbium doped fiber amplifier (EDFA).

## 3. RESULTS AND DISCUSSION

The stabilization of the processed problem in this investigation is carried out using a special designed software over ambient temperature range, $280 \le T,^o k \le 295$ for 2400 channels UWWDM and SDM where the channels are divided into subgroups of multifibers 4, 6, …24 links where each fiber in each subgroup carries channels 600, 400,…100, respectively. The obtained results are displayed in Figs.1-4, where the standard deviation are also calculated. The average values of the five quantities under investigation namely $R_s$, SHP, SLP, MXP, NLP are displayed against the variations of the multifibers in the SDM technique.

These results clarify that the stabilization can be achieved where the standard deviations of the processed quantities are very small if compared to the average values. In the process of computation, special software is done to yield total dispersion coefficient $D_t \cong -0.1$ ps/(km.nm). The model would be processed for other values of $D_t$ [22].

Samples of variations of the five processed quantities are displayed for link No.1 in subgroups of 6 links and 8 links against the variations of the ambient temperature, T, K in Figs. 5-8. These figures assure the thermal stabilization process b.

## 4. CONCLUSION

The tailoring of the different causes (Raman pumping power, signal power, fiber characteristics (x, Δn, R), stabilizes the performance product: bit-rate × repeater spacing of high-speed nonlinear optical communication networks employing the techniques of UWWDM and SDM with two amplification. The obtained standard deviations assure the stabilization phenomena. Both the average values and its standard deviations increase with the increase of the number of channels. Thus less number of links yields greater stability. The impact of the tailoring techniques to achieve the stabilization of the processed quantities is assured.


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| $1.45 < \lambda_s$, μm < 1.65 | 280 < T, °K <294 | $P_{Ro}$=1.0 W | R=2 μm | $\lambda_R$=1.45 μm |
|---|---|---|---|---|
| RS : repeater spacing, km | | PSH/ch : Shannon product, Tbit.km/sec | | |
| SDRS : stand. dev. of repeater spacing, km | | SDSH/ch :stand. dev. of Shannon product, Tbit.km/sec | | |
| PSL/ch : soliton product, Tbit.km/sec | | PML/ch : max. time product, Tbit.km/sec | | |
| SDSL/ch : stand. dev. of soliton product, Tbit.km/sec | | SDMT/ch : stand. dev. of max. time product, Tbit.km/sec | | |
| PNL/ch : nonlinear product, Tbit.km/sec | | SDNL/ch : stand. dev. of nonlinear product, Tbit.km/sec | | |

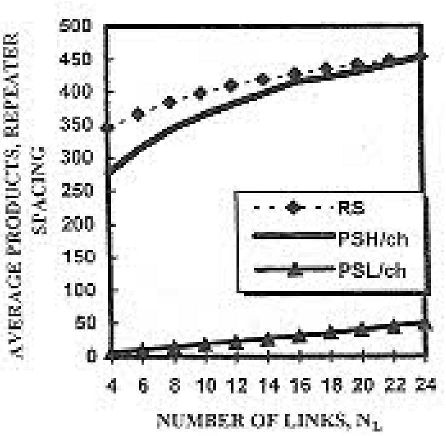


Fig. 1. Variations of averages ($P_{SH}$/ch $P_{SL}$/ch, $R_s$) against variations of $N_L$ at the assumed set of parameters.

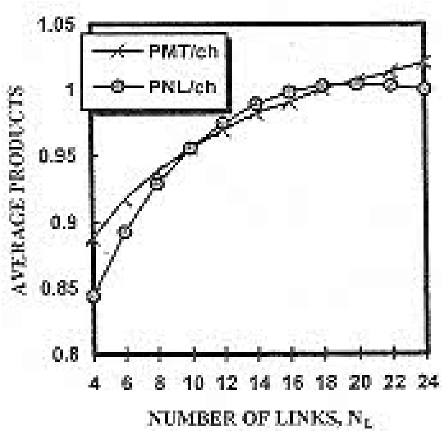


Fig. 2. Variations of averages ($P_{MT}$/ch $P_{NL}$/ch) against variations of $N_L$ at the assumed set of parameters

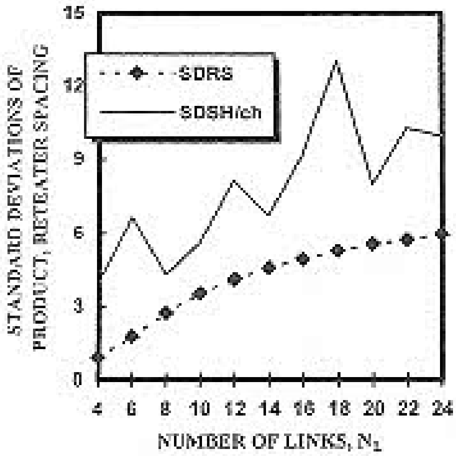


Fig. 3. Variations of standard deviations of ($P_{sh}$/ch, $R_s$) against variations of $N_L$ at the assumed set of parameters.

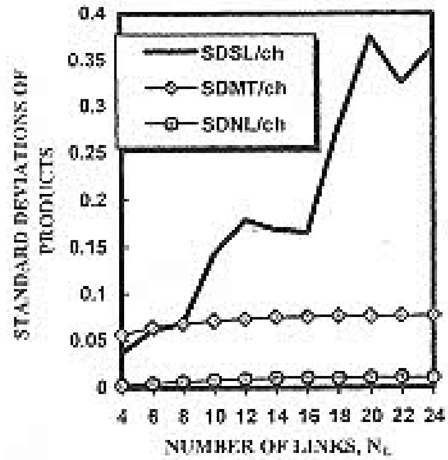


Fig.4. Variations of standard deviations of ($P_{SL}$/ch $P_{MT}$/ch $P_{NL}$/ch) against variations of $N_L$ at the assumed set of parameters

| | | | | |
|---|---|---|---|---|
| $1.45 < \lambda_S$, μm < 1.65 | 280 < T, °K <294 | $P_{So}$=1.0 W | R=2 μm | $\lambda_g$=1.45 μm |
| RS : repeater spacing, km | | PSH/ch : Shannon product, Tbit.km/sec | | |
| SDRS : stand. dev. of repeater spacing, km | | SDSH/ch :stand. dev. of Shannon product, Tbit.km/sec | | |
| PSL/ch : soliton product, Tbit.km/sec | | PML/ch : max. time product, Tbit.km/sec | | |
| SDSL/ch : stand. dev. of soliton product, Tbit.km/sec | | SDMT/ch : stand. dev. of max. time product, Tbit.km/sec | | |
| PNL/ch : nonlinear product, Tbit.km/sec | | SDNL/ch : stand. dev. of nonlinear product, Tbit.km/sec | | |

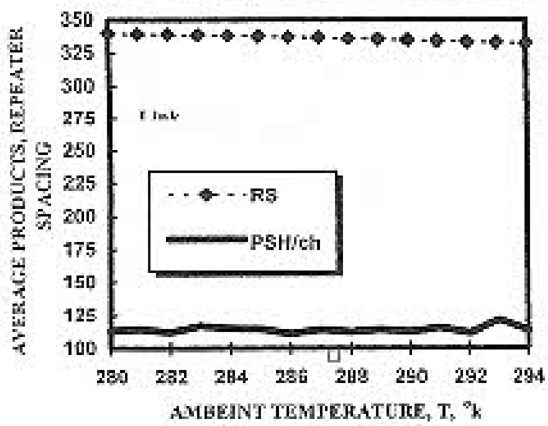


Fig. 5. Variations of averages ($P_{sh}$/ch, $R_s$) against variations of T at the assumed set of parameters.

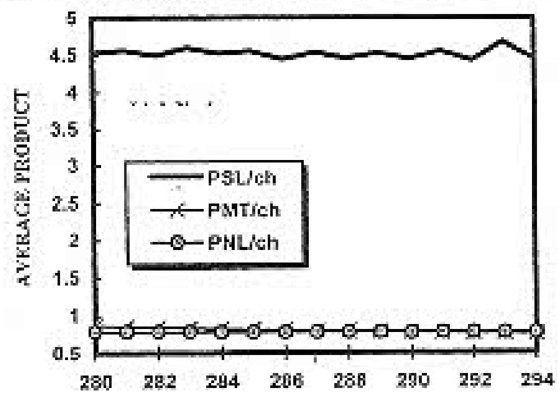


Fig. 6. Variations of averages ($P_{SL}$/ch, $P_{MT}$/ch $P_{NL}$/ch) against variations of T at the assumed set of parameters

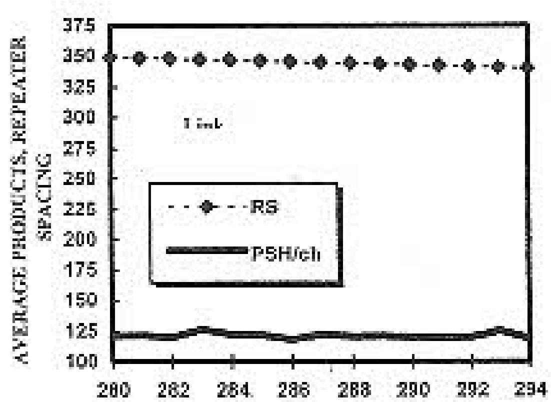


Fig. 7. Variations of standard deviations of ($P_{sh}$/ch, $R_s$) against variations of T at the assumed set of parameters.

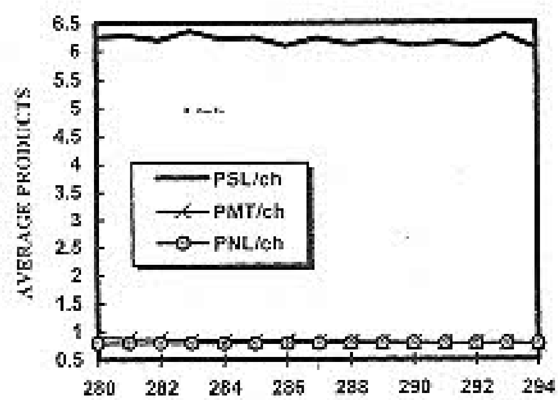


Fig.8. Variations of standard deviations of ($P_{SL}$/ch $P_{MT}$/ch $P_{NL}$/ch) against variations of T at the assumed set of parameters