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Full Length Research Paper

Comparison performance evolution of different transmission techniques with bi-directional distributed Raman gain amplification technique in high capacity optical networks

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In the present paper, we have been modeled parametrically the comparison performance evolution of different transmission techniques such as maximum time division multiplexing (MTDM) technique and Soliton technique with bi-directional Raman Amplification technique in high capacity optical communication networks over wide range of the controlling parameters. Moreover, we have analyzed and investigated the soliton and MTDM techniques to be processed to handle both bit rate and product either per link or per channel for cables of multi-links (4 - 24 links/core). Two multiplexing techniques are applied, dense wavelength division multiplexing (DWDM) and space division multiplexing (SDM), where maximum number of transmitted channels in the range of 200 - 600 channels are processed to handle the product of bit rate either per channel or per link for cables of multi-links. The soliton and MTDM transmission bit rates and products either per link or per channel are also treated over wide range of the affecting parameters.

Key words: Pumping direction, soliton technique, MTDM technique, high capacity optical networks.

INTRODUCTION

Optical amplifiers are key elements of any fiber-optic communication system. Even though modern optical fibers have losses below 0.2 dB/km (Ahmad et al., 2009), a repeated amplification of the transmitted signal to its original strength becomes necessary at long enough distances. One solution for signal regeneration is the conversion of the optical signal into the electrical domain and subsequent re-conversion into a fresh optical signal. However, purely optical amplifiers are usually preferred (Chen et al., 2006). They simply amplify the electromagnetic field of the signal via stimulated emission or stimulated-scattering processes in a certain optical frequency range. The amplification process is essentially independent of the details of the spectral channel layout, modulation format or data rate of the transmission span, thus permitting the system operator to later re-configure these parameters without having to upgrade the amplifiers (Kakkar and Thyagarajan, 2005). For a distributed Raman fiber amplifier (RFA), power is provided by optical pumping of the transmission fiber; the pump wavelength is shorter than the wavelength to be amplified by an amount that corresponds to an optical frequency difference of about 13.2 THz. The signal then experiences gain due to Stimulated Raman Scattering (SRS), a nonlinear optical process in which a pump photon is absorbed and immediately reemitted in the form of a phonon and a signal photon, thus amplifying the signal (Liu and Li, 2004). Multi-wavelength pumped Raman amplifiers (RAs) have attracted more and more attention in recent years. In this type of amplification a widely used concept, for high capacity long distance wavelength division multiplexing (WDM) transmission systems was used. They have been already used in many ultra long-haul dense WDM (DWDM) transmission systems (Emami and Jafari, 2009). It supports high bit

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rate data transmission over long fiber spans, due to its benefits such as proper gain and optical signal–to-noise ratio (OSNR). In addition, it can be used for increasing the bandwidth of Erbium-doped fiber amplifiers (EDFAs) in hybrid systems. Another important feature of RAs is its gain bandwidth, which is determined by pump wavelength. Multi-wavelength pumping scheme is usually used to increase the gain flattening and bandwidth for high capacity WDM transmission systems. In backward-pumped fiber Raman amplifiers (Jahromi and Emami, 2009), other noise sources, such as the relative-intensity noise transfer are minimized, because this scheme can suppress the related signal power fluctuation. Reported results in the literatures show the OSNR of this excitation is tilted, and channels with longer wavelength have longer OSNR respect to the shorter wavelength channels. These amplifiers also have the unique characteristic of being tunable at any wavelength, simply by changing the pump frequency, since gain depends only on the signal-pump frequency shift. The saturation power of fiber Raman amplifiers is by far larger than that of the equivalent EDFAs, thus, limit the effects of cross-gain modulation in reconfigurable DWDM systems (Emami and Jafari, 2009).

In the present work, we have presented the different transmission techniques such as soliton and MTDM with distributed bi-directional Raman amplification technique to handle the bit rates and products either per link or per channel to improve the high capacity optical communication networks over wide range of the affecting and controlling parameters. Also, two multiplexing techniques are taken in to account such as DWDM, and SDM in order to increase total number of transmitted channels and then to increase number of subscribers or users in high capacity and long distance transmission optical communication networks.

SYSTEM MODEL AND EQUATIONS ANALYSIS

Bi-directional raman amplification

It is assumed that the power of the first pump source is S P_P and the second source pump is (1-S) P_P respectively, where P_P is the pump power and S is a coefficient showing the power that is being pumped in the signal direction. The evolution of the signal power (P_s) and the power of the pump source propagating along single mode optical fiber can be described by different equations called propagation equations and Figure 1 shows different pumping direction configurations such as forward, backward and therefore bi-directional pumping direction configurations. The signal and pump power equations can be expressed as follows (Jordanova and Topchiev, 2008):

$$\pm\frac{dP_P}{dz}=-\frac{\nu_P}{\nu_S}g_R P_P P_S-\alpha_P P_P \quad , \tag{1}$$

$$\frac{dP_S}{dz}=g_R\, P_P P_S-\alpha_S P_S \quad , \tag{2}$$

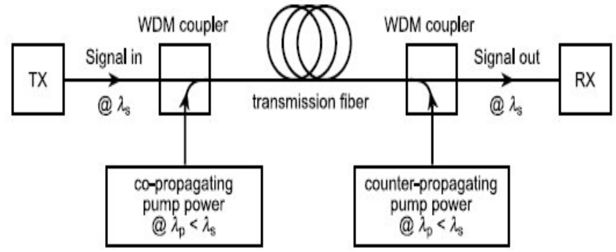

Figure 1. Schematic of a distributed Raman fiber amplifier. The pump power at wavelength λ_p, often provided by Raman fiber lasers, may be co- or counter-propagating (or both) with the signal to be amplified at λ_s.

Where g_R in $W^{-1}m^{-1}$is the Raman gain coefficient of the fiber cable length, α_S and α_P are the attenuation of the signal and pump power in silica-doped fiber, ν_S and ν_P are the optical signal and pump frequencies. The signs of "+" or "-" are corresponding to forward and backward pumping. In the general case, when a bi-directional pumping (Raghuawansh, 2006) is used (S = 0 - 1) the laser source work at the same wavelength at different pump power. Therefore to calculate the pump power at point z it can be used:

$$P_P(z)=SP_P(0)\exp(-\alpha_P\, L)+(1-S).\\ P_P(0)\exp[-\alpha_P\,(L-z)], \tag{3}$$

If the values of P_P are substituted in differential Equation (2), and it is integrated from 0 to L for the signal power in the forward and the backward pumping can be written as:

$$P_S(L)=P_S(0)\exp\left[g_R\; S\; P_0\;\frac{1-\exp(-\alpha_P z)}{\alpha_P}-\alpha_S z\right]\\ =G_F P_S(0), \tag{4}$$

$$P_S(L)=P_S(0)\exp\left[\begin{array}{l} g_R(1-S)P_0\; x\dfrac{\exp(-\alpha_P L)(\exp(\alpha_P z)-1)}{\alpha_P}-\\ \alpha_S z\end{array}\right]\\ =G_B P_S(0), \tag{5}$$

Where G_F, G_B are the net gain in the forward and backward pumping respectively. With P_0 being the pump power at the input end. The signal intensity at output of amplifier, fiber cable length L is determined by the following expression (Raghuawansh et al., 2006):

$$P_S(L)=P_S(0)\exp\left(\frac{g_R\; P_0\; L_{eff}}{A_{eff}}-\alpha_S\; L\right) \quad , \tag{6}$$

The maximum allowed transmit power per channel, as a function of fiber cable length can be expressed as (Jalali, 2006):

$$P_{Ts/c}\,\langle\,\frac{4\times10^4}{N_{ch}(N_{ch}-1)\Delta\lambda_S\; L} \quad , \tag{7}$$

Where N_{ch} be the number of channels, $\Delta\lambda_S$ be the channel spacing in nm, and L is to be the length of the fiber cable link in km.

Soliton transmission technique

The term soliton has recently been coined to describe a pulse-like non-linear wave having unchanged shape and speed. In an ideal lossless medium, the soliton would have also the same amplitude during propagation. The balance between the non-linearity effects from one side and the dispersion effects from the other side creates a solitary wave. The dispersion of a medium (in the absence of non-linearity) makes the various frequency components propagate at different velocities; while the non-linearity (in the absence of dispersion) causes the pulse energy to be continually injected, via harmonic generation, into higher frequency modes. We can assume that the standard single mode optical fiber cable is made of the silica material which the investigation of the spectral variations of the waveguide refractive-index (n) require Sellemeier equation under the form (Fleming, 1985):

$$n^2 = 1+\frac{A_1\lambda^2}{\lambda^2 - A_2^2}+\frac{A_3\lambda^2}{\lambda^2 - A_4^2}+\frac{A_5\lambda^2}{\lambda^2 - A_6^2} \qquad (8)$$

The parameters of Sellmeier equation coefficients for pure silica material, as a function of ambient temperature as the following expression: $A_1 = 10.668422193$, $A_2 = 0.0301516485 * (T/T_0)^2$, $A_3 = 3.043474218 \times 10^{-3}$, $A_4 = 1.1347511235 * (T/T_0)^2$, $A_5 = 1.54133408$, $A_6 = 1.104 \times 10^3$. Where T is the temperature of the material, °C, and T_0 is the reference temperature and is considered as 27°C. Then the second differentiation of Equation (15) w. r. t λ yields:

$$\frac{d^2n}{d\lambda^2} = \frac{1}{n}\left[\frac{A_1\left(\lambda^2 - A_2^2\right)-4\lambda^2}{\left(\lambda^2 - A_2^2\right)^3}+\frac{A_3\left(\lambda^2 - A_4^2\right)-4\lambda^2}{\left(\lambda^2 - A_4^2\right)^3}+\frac{A_5\left(\lambda^2 - A_6^2\right)-4\lambda^2}{\left(\lambda^2 - A_6^2\right)^3}\right], \qquad (9)$$

The total bandwidth is based on the total chromatic dispersion coefficient D_t where:

$$D_t = D_m + D_w \qquad (10)$$

Both D_m, and D_w are given by (for the fundamental mode):

$$D_m = -\frac{\lambda}{c}\left(\frac{d^2n}{d\lambda^2}\right), \quad n\sec/nm.km \qquad (11)$$

$$D_w = -\left(\frac{n_{cladding}}{c\,n}\right)\left(\frac{\Delta n}{\lambda}\right)Y \ , \quad n\sec/nm.km \qquad (12)$$

Where c is the velocity of the light, 3×10^8 m/sec, n is the refractive-index of the fiber cable core, Y is a function of wavelength, the relative refractive-index difference Δn is given by the following expression:

$$\Delta n = \frac{n - n_{cladding}}{n} \quad , \qquad (13)$$

In any infinitesimal segment of fiber, dispersion on one hand and non linearity of the refractive-index on the other hand produce infinitesimal modulation angles which exactly compensate reciprocally. In the sense that their sum is an irrelevant constant phase shift. Under such conditions the pulse shape is the same everywhere. All this provided that a soliton waveform be used with a peak power (Yabre, 2000):

$$P_1 = \frac{\Delta\lambda^3 D_t A_{eff}}{4\pi^2 c\, n_2\, t_0^2} \ , \qquad (14)$$

Where n_2 is the nonlinear Kerr coefficient, 2.6×10^{-20} m^2/Watt, Δλ is the spectral line width of the optical source in nm, P_1 is the peak power in watt, A_{eff} is the effective area of the cable core fiber in μm^2, D_t is the total chromatic dispersion coefficient in nsec/nm.km. Then the pulse intensity width in nsec is given by:

$$t_0 = \sqrt{\frac{\Delta\lambda^3 D_t\ A_{eff}}{4\pi^2\ P_1\, n_2\, c}} \ , \quad n\sec \qquad (15)$$

Then the Soliton transmission bit rate per optical network channel or unit is given as follows (Abd El-Naser et al., 2009):

$$B_{rsc} = \frac{1}{10t_0} = \frac{0.1}{t_0}, \ Gbit/\sec/channel \qquad (16)$$

Then the Soliton transmission bit rate per link is given as follows:

$$B_{rsl} = \frac{0.1 * N_{link}}{t_0}, \quad Gbit/\sec/link \qquad (17)$$

Also in the system model analysis, the transmitted channels per link is given by the following expression:

$$\Delta N_{ch} = \frac{N_{ch}}{N_L} \quad , \qquad (18)$$

Where N_{Link} is the total number of links in the fiber cable core, and N_{ch} is the total number of channels. The available soliton transmitted bit rate B_{rs} is compared as the fiber cable length, L, and consequently the soliton product P_{rsc} per channel is computed as the following expression:

$$P_{rsc} = B_{rsc} * L, \ Tbit.km/\sec \qquad (19)$$

Also, in the same way, the soliton product P_{rsl} per link is computed as the following expression:

$$P_{rsl} = B_{rsl}\ *\ L, \ Tbit.km/\sec \qquad (20)$$

The soliton product either per channel or per link can be expressed in another form as follows:

$$P_{rsc} = 1000 * B_{rsc} * L, \ Gbit.km/\sec \qquad (21)$$

$$P_{rsl} = 1000 * B_{rsl}\ *\ L, \ Gbit.km/\sec \qquad (22)$$

Where B_{rsc} is the soliton transmission bit rate per channel in Gbit/sec, B_{rsl} is the soliton transmission bit rate per link in Gbit/sec, and L is the fiber cable length in km.

MTDM transmission technique

To achieve a high data transmission bit rate in the telecommunication field is the goal of DWDM technology. The maximum bit rates are determined by numerous factors, including the signal modulation rate, the transmission bandwidth through the transmission media, and the response time of the optoelectronic devices. In a communications network, the DWDM system is simply one part of the transmission regime. The pulse broadening of grating-based DWDM imposes inherent limitations on the data transmission bit rates. According to our assumption that the standard single mode optical fiber cable is made of the pure silica material which the investigation of the spectral variations of the waveguide refractive-index (n) is shown in Equation (8), Then the first and third differentiation of Equation (8) w. r. t λ yields:

$$\frac{dn}{d\lambda} = -\frac{1}{n}\left[\frac{A_1\,\lambda^2}{\left(\lambda^2 - A_2^2\right)^2} + \frac{A_3\,\lambda^2}{\left(\lambda^2 - A_4^2\right)^2} + \frac{A_5\,\lambda^2}{\left(\lambda^2 - A_6^2\right)^2}\right], \tag{23}$$

$$\frac{d^3 n}{d\lambda^3} = -\frac{1}{n}\left[\begin{array}{l}\frac{12\,A_1\,\lambda^2\left(\lambda^3 + A_1^2\,\lambda\right)}{\left(\lambda^2 - A_2^2\right)^4} + \frac{12\,A_3\,\lambda^2\left(\lambda^3 + A_3^2\,\lambda\right)}{\left(\lambda^2 - A_4^2\right)^4} \\ + \frac{12\,A_5\,\lambda^2\left(\lambda^3 + A_5^2\,\lambda\right)}{\left(\lambda^2 - A_6^2\right)^4}\end{array}\right], \tag{24}$$

Where the second differentiation of waveguide refractive index (n) w. r. t λ is shown in Equation (9). Therefore, the total chromatic dispersion in standard single mode fiber (SSMF) that limits the transmission bit rates in system based DWDM communication can be calculated as follows (Yeung et al., 1979):

$$D_t = \frac{\Delta\tau}{\Delta\lambda.\,L} = -\left(M_{md} + M_{wd}\right),\ n\sec/nm.km \tag{25}$$

Where M_{md} is the material dispersion coefficient in nsec/nm.km, M_{wd} is the waveguide dispersion coefficient in nsec/nm.km, Δτ is the total pulse broadening due to the effect of total chromatic dispersion, Δλ is the spectral linewidth of the used optical source in nm, and L is the fiber cable length in km. The material dispersion coefficient is given as follows:

$$M_{md} = -\frac{\lambda_s}{c}\frac{d^2 n}{d\lambda^2} - \frac{\Delta\lambda}{2c}\left(\lambda\frac{d^3 n}{d\lambda^3} + \frac{d^2 n}{d\lambda^2}\right), \tag{26}$$

The waveguide dispersion coefficient is given by the following expression:

$$M_{wd} = -n_2\left(\frac{\Delta n}{c\,\lambda_s}\right)F(V), \tag{27}$$

Where n_2 is the refractive-index of the cladding material, Δn is the relative refractive-index difference, λ_s is the optical signal wavelength, F (V) is a function of V number or normalized frequency. Based on the work (Bates and Jackson, 1995), they designed the function F (V) is a function of V as follows:

$$F(V) = 1.38V - 6.98V^2 + 13.45V^3 - 4.84V^4 - 1.48V^5 \tag{28}$$

When they are employing V-number in the range of ($0 \le V \le 1.15$) yields the above expression. In our simulation model design, we are taking into account V-number as unity to emphasis single mode operation. Equation (25) can be written in another expression as follows (Koike et al., 1995; Bates and Jackson, 1995):

$$\Delta\tau = D_t\,.\Delta\lambda\,.L\,,\quad n\sec \tag{29}$$

Then the MTDM transmission bit rate per optical network channel or unit is given by:

$$B_{rmc} = \frac{1}{4\,\Delta\tau} = \frac{0.25}{\Delta\tau},\ Gbit/\sec/\,channel \tag{30}$$

Then the MTDM transmission bit rate per link is given as:

$$B_{rml} = \frac{0.25 * N_{link}}{\Delta\tau},\quad Gbit/\sec/\,link \tag{31}$$

The available MTDM transmitted bit rate Brm is compared as the fiber cable length, L, and consequently the MTDM product Prmc per channel is computed as follows:

$$P_{rmc} = B_{rmc} * L,\ Tbit.km/\sec \tag{32}$$

Also, in the same way, the MTDM product Prml per link is computed as the following expression:

$$P_{rml} = B_{rml} * L,\ Tbit.km/\sec \tag{33}$$

The MTDM product either per channel or per link can be expressed in another form as follows:

$$P_{rmc} = 1000 * B_{rmc} * L,\ Gbit.km/\sec \tag{34}$$

$$P_{rml} = 1000 * B_{rml} * L,\ Gbit.km/\sec \tag{35}$$

Where Brmc is the MTDM transmission bit rate per channel in Gbit/sec, Brml is the MTDM transmission bit rate per link in Gbit/sec, and L is the fiber cable length in km.

RESULTS AND DISCUSSION

In the analysis of our results, we have investigated parametrically and numerically the different transmission techniques with distributed bi-directional Raman amplification for allowing high capacity and long distance transmission optical networks in the interval of 1.45 to 1.65 μm under the set of affecting and controlling parameters of temperature ranges varied from (25 - 45°C). The following set of the numerical data of our simulation system model design are employed to obtain the high capacity and long distance transmission for optical communication networks within different transmission and propagation techniques with distributed bi-directional Raman amplification technique as follows:

$1.5 \le \lambda_{si}$, optical signal wavelength, $\mu m \le 1.65$, $1.4 \le \lambda_p$, pumping wavelength, $\mu m \le 1.55$, α_{si} = 0.2 dB/km, α_P = 0.35 dB/km, Pumping power: P_P = 0.25 Watt/pump, $2 \le P_{si}$, optical signal power, mwatt ≤ 20, $A_{eff} = 85\ \mu m^2$, N_L:

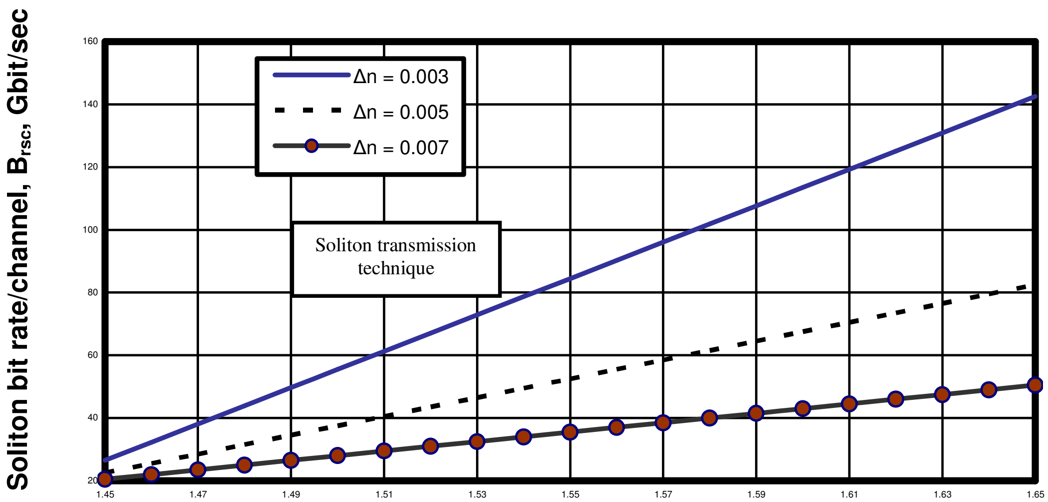

Figure 2. Variations of the soliton bit rate/channel with optical signal wavelength at the assumed set of parameters. Optical signal wavelength, λ, μm

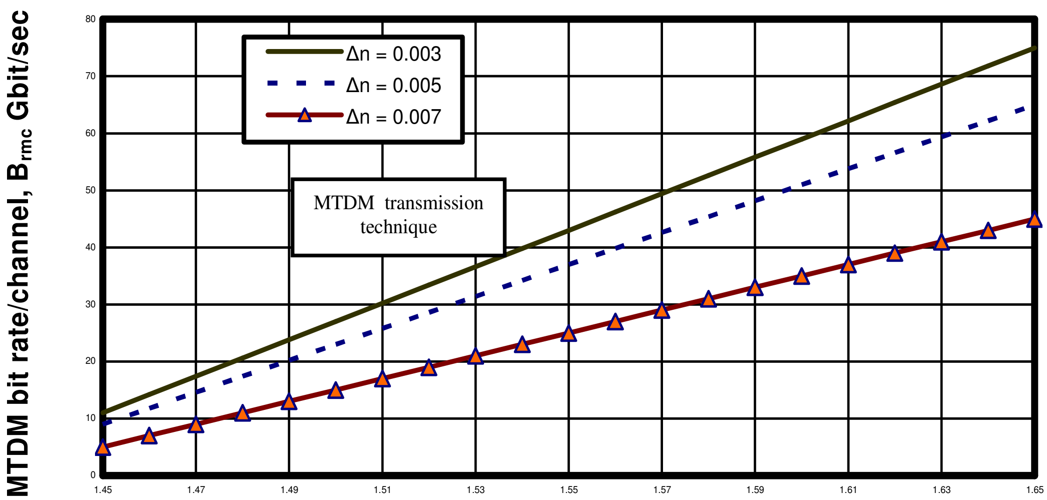

Figure 3. Variations of the MTDM bit rate/channel with optical signal wavelength at the assumed set of parameters. Optical signal wavelength, λ, μm.

total number of links up to 24 links, $\Delta\lambda_s$ = 0.2 nm, 0.001 ≤ Δn, relative refractive-index difference ≤ 0.009, N_t: total number of channels up to 600 channels, n_2 = 1.445, Raman gain coefficient: g_R= 0.7 W^{-1}. km^{-1}.

Based on the set of Figures 2 - 19, the following facts and obtained features are assured to present the high capacity and long haul transmission optical communication networks within transmission, propagation, multiplexing and amplification techniques as the following:

1) As shown in Figures 2 and 3, both soliton and MTDM bit rates per channel increase as the optical signal wavelength increases at the same relative refractive-index difference (Δn). But as Δn increases, both soliton and MTDM bit rates per channel decrease at the same optical signal wavelength. While we can find that soliton transmission technique yields higher bit rate/channel than MTDM transmission technique at the same relative refractive-index difference, Δn.

2) Figures 4 and 5 have indicated that as the number of links in the fiber cable core increases, both soliton and MTDM bit rates per link increase at the same number of transmitted channels. But as number of transmitted channels increases, both soliton and MTDM bit rates/link decrease at the same number of links in the fiber cable core. Moreover, we can conclude that soliton transmission technique yields higher bit rate/link than MTDM transmission technique at the same number of transmitted channels.

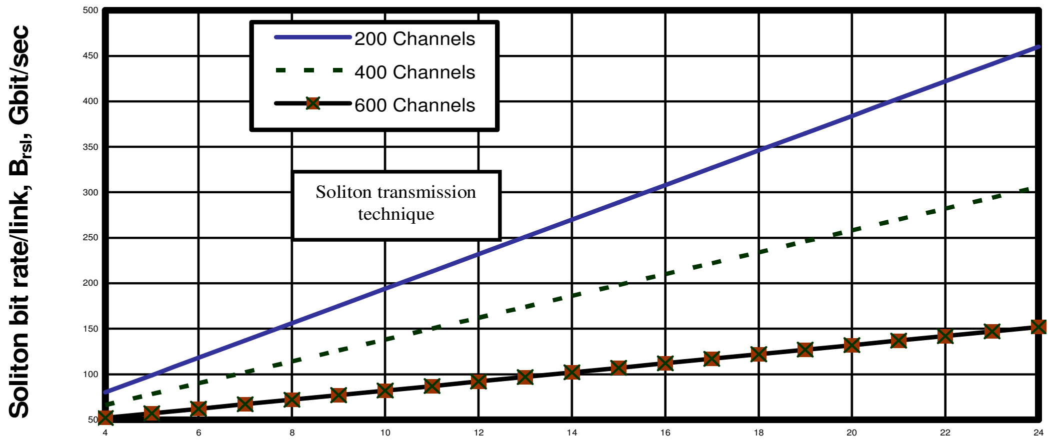

Figure 4. Variations of the soliton bit rate/link with number of links in fiber cable at assumed set of parameters. Number of links in the fiber cable core, N_L.

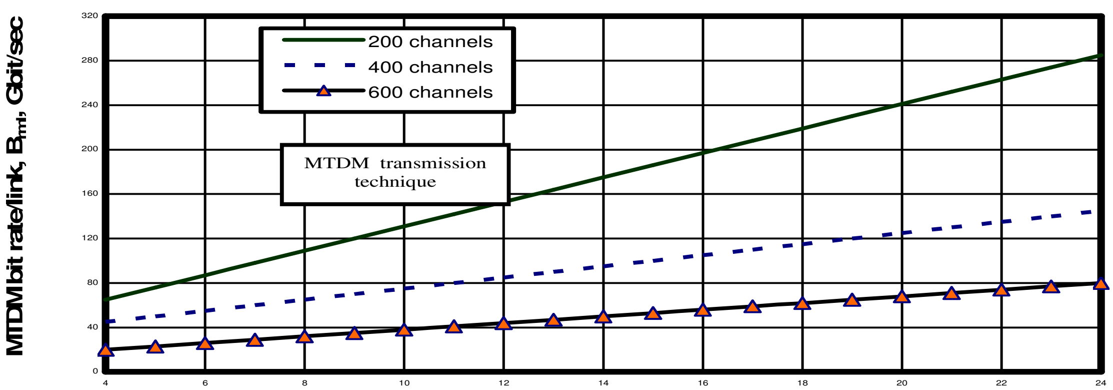

Figure 5. Variations of the MTDM bit rate/link with number of links in fiber cable core at the assumed set of parameters. Number of links in the fiber cable core, N_L.

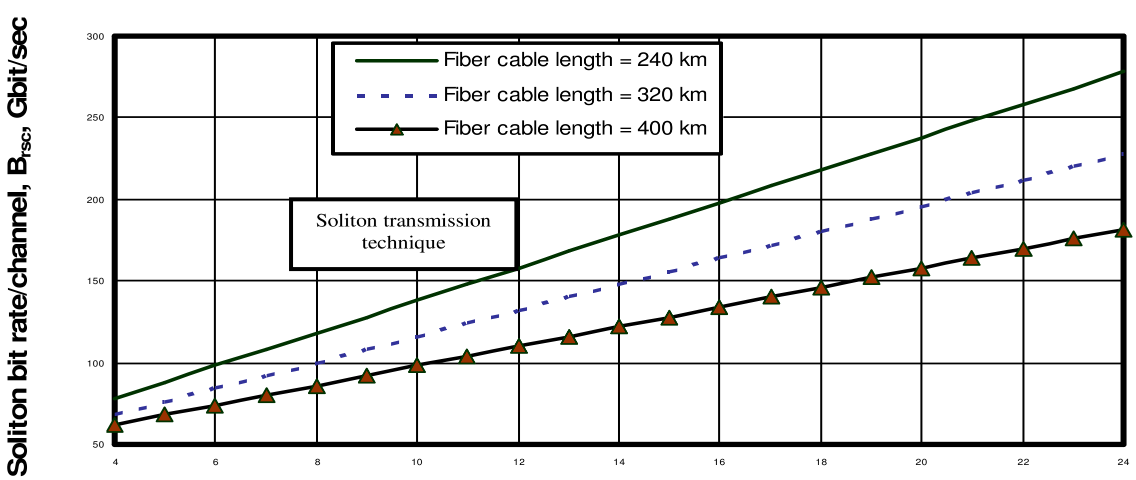

Figure 6. Variations of the soliton bit rate/channel with number of links in fiber cable at assumed set of parameters. Number of links in the fiber cable core, N_L.

3) Figures 6 and 7 have assured that as the number of links in the fiber cable core increases, both soliton and MTDM bit rates per channel increase at the same fiber cable length. But as the fiber cable length increases, both

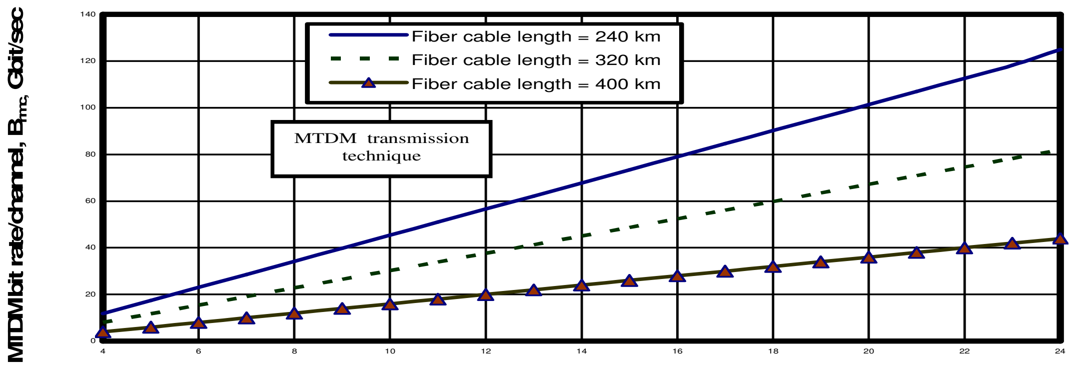

Figure 7. Variations of the MTDM bit rate/channel with number of links in fiber cable at assumed set of parameters. Number of links in the fiber cable core, N_L.

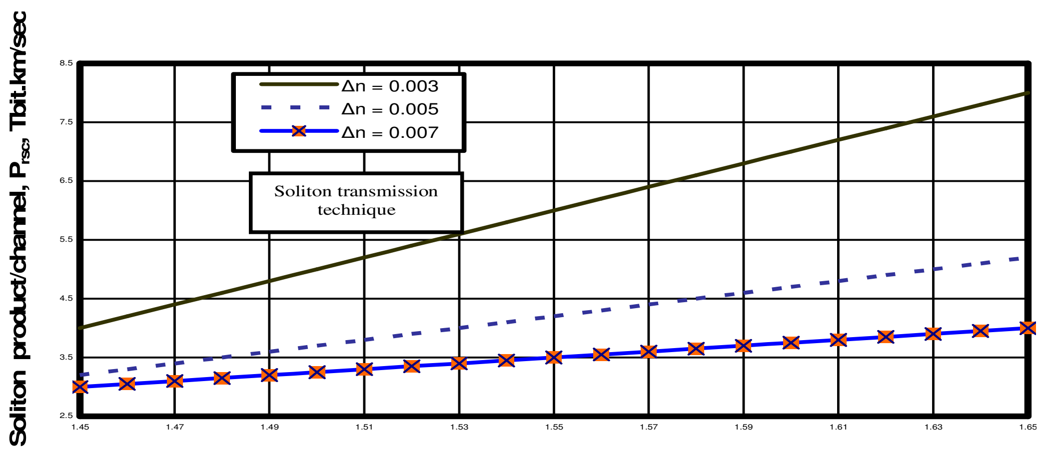

Figure 8. Variations of the soliton product/channel with optical signal wavelength at assumed set of parameters. Optical signal wavelength, λ, μm.

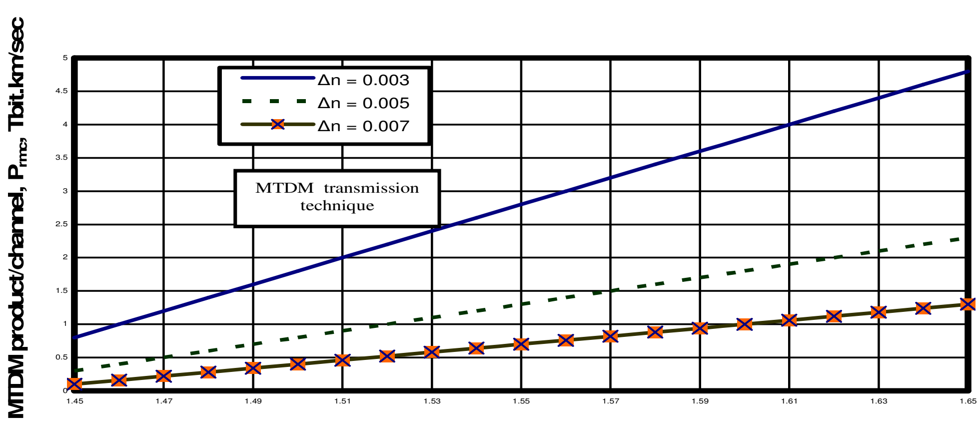

Figure 9. Variations of the MTDM product/channel with optical signal wavelength at the assumed set of parameters. Optical signal wavelength, λ, μm.

soliton and MTDM bit rates/channel decrease at the same number of links in the fiber cable core. Moreover, we can find that soliton transmission technique yields higher bit rate/channel than MTDM transmission technique at the same fiber cable length.

4) As shown in Figures 8 and 9, both soliton and MTDM

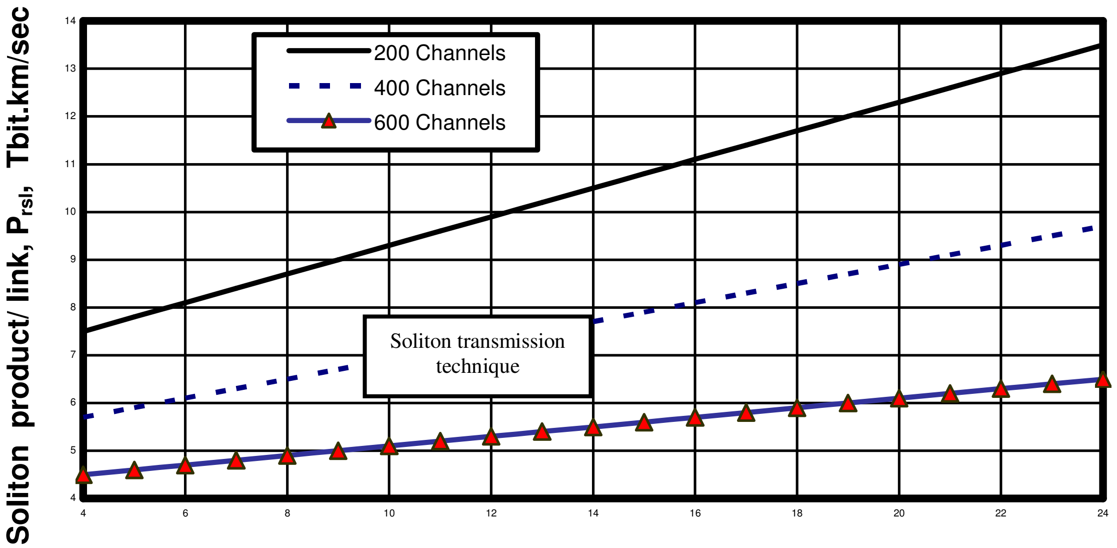

Figure 10. Variations of the soliton product/link with number of links in fiber cable at assumed set of parameters. Number of links in the fiber cable core, N_L.

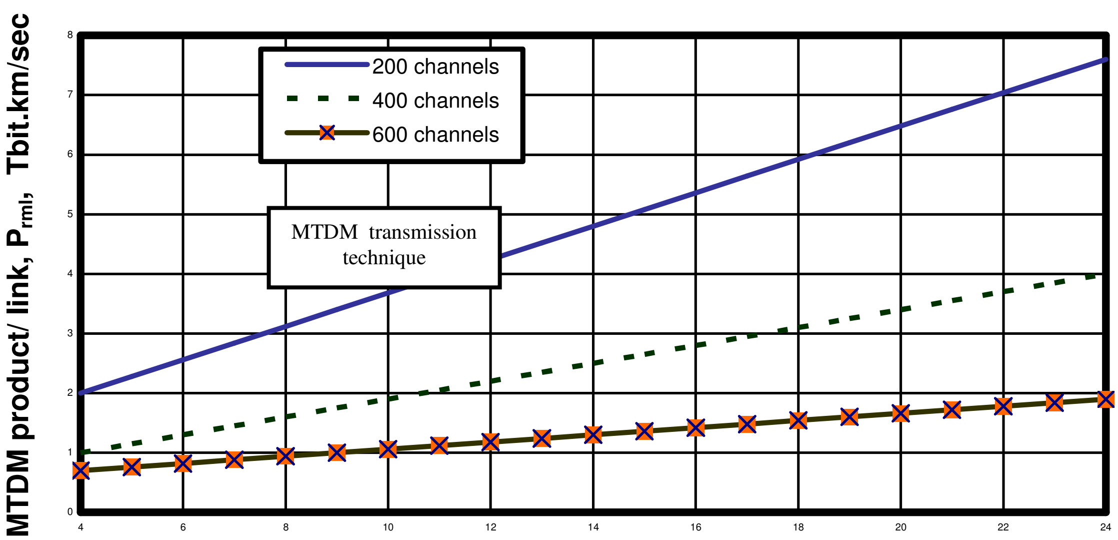

Figure 11. Variations of the MTDM product/link with number of links in fiber cable at assumed set of parameters. Number of links in the fiber cable core, N_L.

products per channel increase as the optical signal wavelength increases at the same relative refractive-index difference (Δn). But as Δn increases, both soliton and MTDM products per channel decrease at the same optical signal wavelength. While we can find that soliton transmission technique yields higher product/channel than MTDM transmission technique at the same relative refractive-index difference, Δn.

5) Figures 10 and 11 have indicated that as the number of links in the fiber cable core increases, both soliton and MTDM products per link increase at the same number of transmitted channels. But as number of transmitted channels increases, both soliton and MTDM products/link decrease at the same number of links in the fiber cable core. Moreover, we can conclude that soliton transmission technique yields higher product/link than MTDM transmission technique at the same number of transmitted channels.

6) In the series of Figures 12 and 13 has demonstrated that both soliton and MTDM products per channel increase as the fiber cable length increases at the same relative refractive-index difference (Δn). But as Δn increases, both soliton and MTDM products per channel decrease at the same fiber cable length. While we can

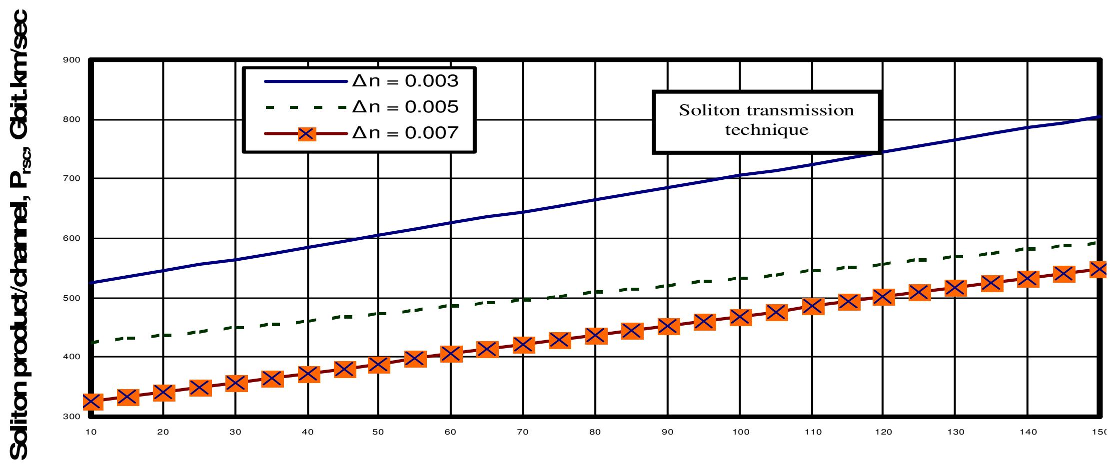

Figure 12. Variations of the soliton product/channel with fiber cable length at the assumed set of parameters. Fiber cable length, L, km.

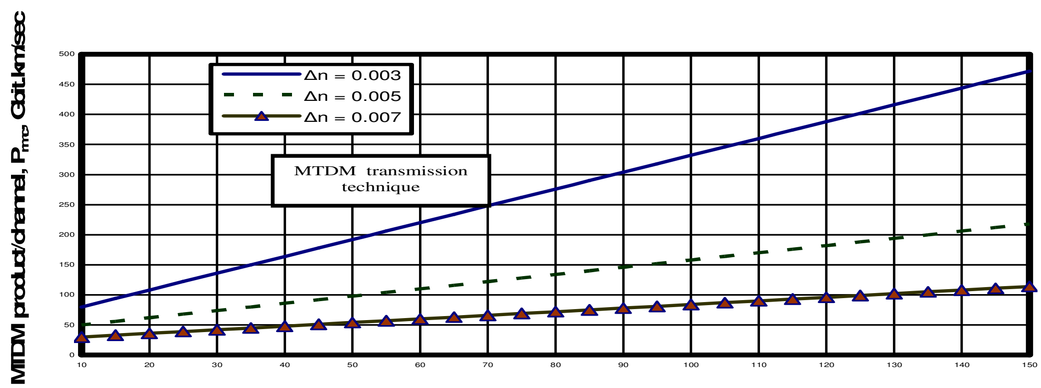

Figure 13. Variations of the MTDM product/channel with fiber cable length at the assumed set of parameters. Fiber cable length, L, km.

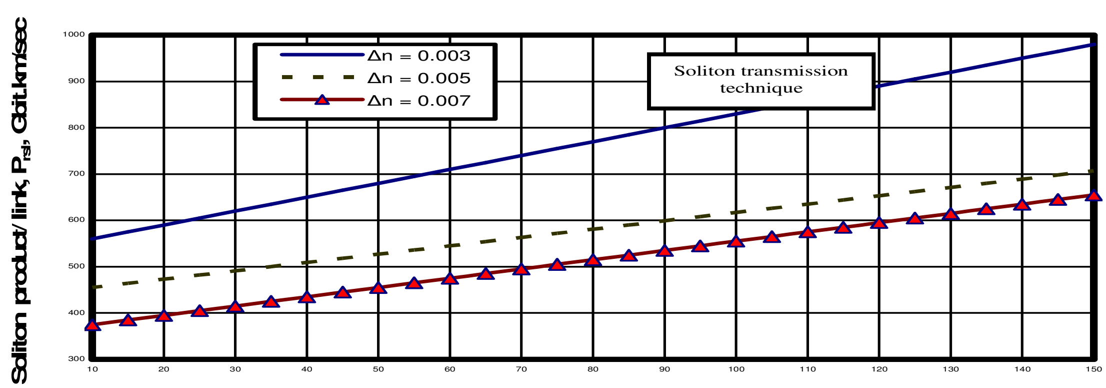

Figure 14. Variations of the soliton product/link with fiber cable length at the assumed set of parameters. Fiber cable length, L, km.

find that soliton transmission technique yields higher product/channel than MTDM transmission technique at the same relative refractive-index difference, Δn.

7) In the series of Figures 14 and 15 has indicated that both soliton and MTDM products per link increase as the fiber cable length increases at the same relative

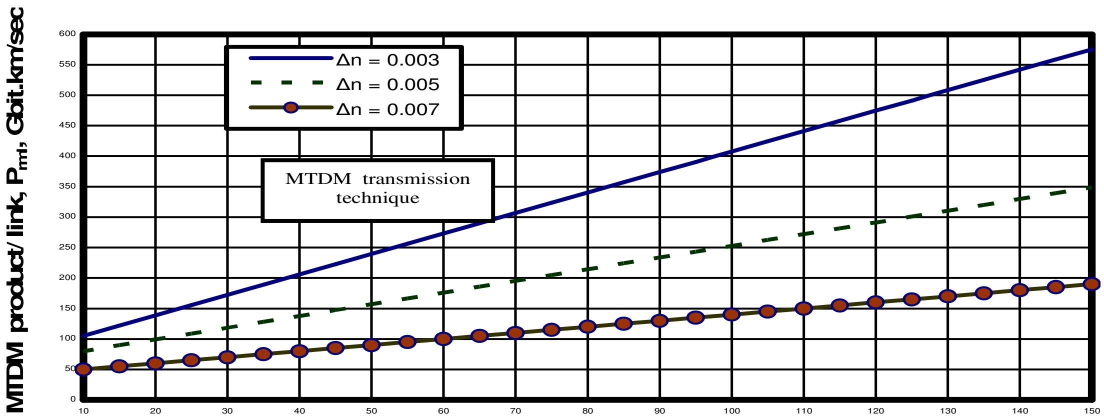

Figure 15. Variations of the MTDM product/link with fiber cable length at the assumed set of parameters. Fiber cable length, L, km.

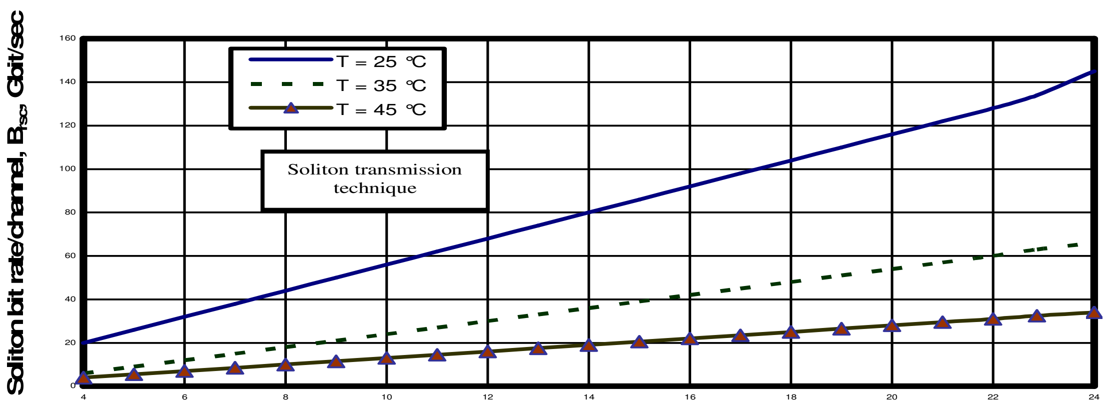

Figure 16. Variations of the soliton bit rate/channel with number of links in fiber cable at assumed set of parameters. Number of links in the fiber cable core, $N_{L..}$

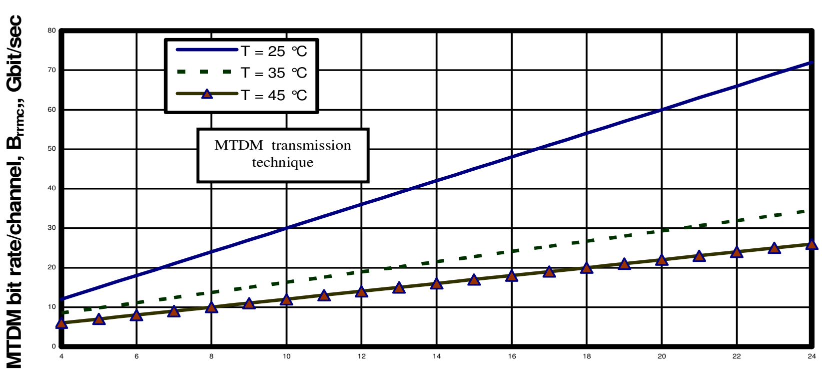

Figure 17. Variations of the MTDM bit rate/channel with number of links in fiber cable at assumed set of parameters. Number of links in the fiber cable core, $N_{L.}$

refractive-index difference (Δn). But as Δn increases, both soliton and MTDM products per link decrease at the same fiber cable length. Moreover, we can conclude that soliton transmission technique yields higher product/link than MTDM transmission technique at the same relative refractive-index difference, Δn.

8) As shown in Figures 16 and 17, both soliton and MTDM bit rates per channel increase as the number of

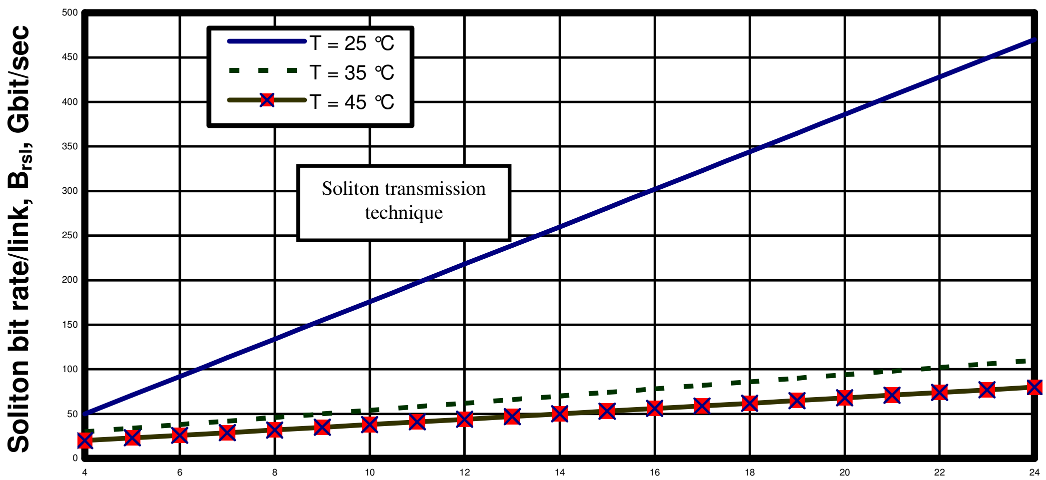

Figure 18. Variations of the soliton bit rate/link with number of links in fiber cable at assumed set of parameters. Number of links in the fiber cable core, N_L.

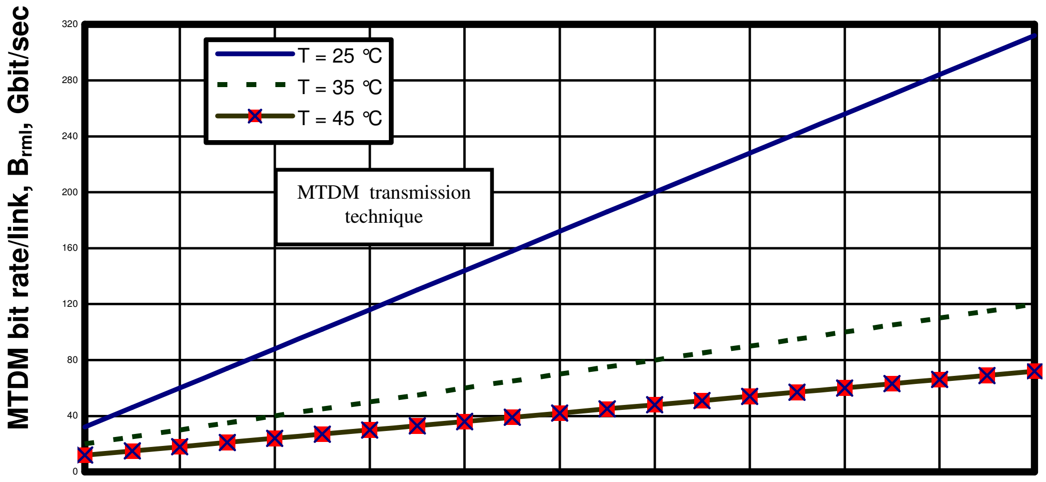

Figure 19. Variations of the MTDM bit rate/link with number of links in fiber cable at assumed set of parameters. Number of links in the fiber cable core, N_L.

links in the fiber cable core increases at the same ambient temperature (T). But as ambient temperature (T) increases, both soliton and MTDM bit rates per channel decrease at the same fiber cable length. While we can find that soliton transmission technique yields higher bit rate/channel than MTDM transmission technique at the same ambient temperature.

9) Figures 18 and 19 have assured that both soliton and MTDM bit rates per link increase as the number of links in the fiber cable core increases at the same ambient temperature (T). But as ambient temperature (T) increases, both soliton and MTDM bit rates per link decrease at the same fiber cable length. Moreover, we can conclude that soliton transmission technique yields higher bit rate/link than MTDM transmission technique at the same ambient temperature.

CONCLUSIONS

In a summary, we have presented analytically and parametrically the different transmission techniques with distributed bi-directional Raman amplification for allowing high capacity and long haul transmission optical networks. We have demonstrated that the lower number of transmitted channels, ambient temperature and relative refractive-index difference (Δn), the higher soliton and MTDM bit rates and products either per link or per channel at the same optical signal wavelength, and number of links in the fiber cable core. Moreover, we have assured that the increased fiber cable length, the higher soliton and MTDM product either per link or per channel at the same relative refractive-index difference (Δn). It is evident from our simulation results that the soliton transmission technique has presented higher bit rates and products either per link or per channel than MTDM transmission technique at the assumed set of controlling and affecting parameters.

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