EFFECTIVE DESIGN FOR DWDM LONG-HAUL SYSTEM

H. A. M. Harb[a]

Faculty of computing and information, Al-Baha University, Saudi Arabia

ABSTRACT:

In this work the upper bound of the spectral efficiency (i.e. the channel capacity) of the DWDM long haul transmission system (100×10Gb/s) is estimated, considering the presence of fiber nonlinear effects with different modulation/detection regimes, considering the collision induced timing jitter of the soliton based DWDM system with amplification and filtering, also the BER is calculated for each channel.

Keywords

DWDM, Spectral efficiency, Amplified spontaneous emission, Dispersion compensating fiber.

1. INTRODUCTION

The past decade saw an explosive growth in the data capacity offered by optical fiber communication systems and especially in DWDM systems which have rapidly moved from the status of exotic laboratory experiments to almost ubiquitous acceptance and applications [1].

The classical theory for channel capacity developed by Shannon[2] for the communication systems based on the electromagnetic propagation through air, which is in fact linear channel with additive noise, however in optical fiber communications the propagation in linear regime requires low DWDM channel power, which is impractical because of fiber attenuation, and when the power exceeds certain threshold, the fiber nonlinear effects limit the performance of the system and the Shannon results are no longer valid. Although there is a mathematical difficulty in evaluating the information capacity, a very good approximation of the information capacity is presented for optical fiber channel by considering the non linear effects [1], [3]. The overall capacity of DWDM transmission system is governed by the available bandwidth and the achievable spectral efficiency. The spectral efficiency limit depends on choice of modulation and detection techniques[4,5].

Although DWDM offers the potential for a large increase in the total capacity, the use of DWDM raises a number of issues of theoretical and practical importance. Timing displacement due to collisions of pulses which induce permanent frequency and velocity shifts of the pulses is one of these issues [6]. And for along time, there is no analytical expression known for the collision induced timing jitter for more than two channels. But recently, a statistical analysis was developed for the root mean square timing jitter [7].

Therefore, in the next section, the topic of information capacity for DWDM systems discussed compared with the conventional Shannon formula, considering different modulation/detection techniques. In section 3, the collision induced timing jitter discussed, beginning from the fundamental equations then computing the timing shift resulting from a single collision between two wavelengths, which allows to compute the root mean square timing jitter of multi-channel systems. And these formulae were used to analyze the bit error rate of the system, and estimate the maximum number of error free channels.

2-INFORMATION CAPACITY AND SPECTRAL EFFICIENCY.

2-1 OPTICAL FIBER CHANNEL:

Before proceeding with the analysis of the fiber channel, a couple of definitions should be made clear. The fiber channel is defined as the medium in which light propagates. DWDM channel capacity is defined as the capacity of single DWDM channel and the information capacity is defined as the capacity when all DWDM channels are considered together.

Figure (1) shows the model of an optical fiber channel and its basic components. The optical fiber channel is composed of a glass fiber with low attenuation (0.2-0.5dB/km) and the optical amplifier which compensates the loss due to the signal propagation in the fiber. The basic structure of the optical channel is called span, whose elements are the fiber and the optical amplifier. The hole spectrum can be divided into several DWDM channels at different wavelengths, which are modulated by using independent electrical bit streams. If we assume that, the optical channel is linear with additive white Gaussian noise (AWGN), the DWDM channel capacity is given by the famous Shannon formula [2].

$$C = W\log_2(1+\frac{P_0}{P_N}) = W\log_2(1+SNR) \qquad (1)$$

where C is the capacity, W is the bandwidth, P_o is the signal power, P_N is the noise power and SNR is the signal to noise ratio. Therefore, the performance of the communication system is basically limited by the SNR of the received signal and the spectral bandwidth. For example, if the *SNR* of the DWDM is set to 1000=30dB and considering the optical bandwidth of the fiber approximately 15 THz, the capacity is 150Tbit/s[8]. However, the fiber channel is not linear and in order to evaluate its information capacity, the nonlinear effects in the fiber should be well understood.

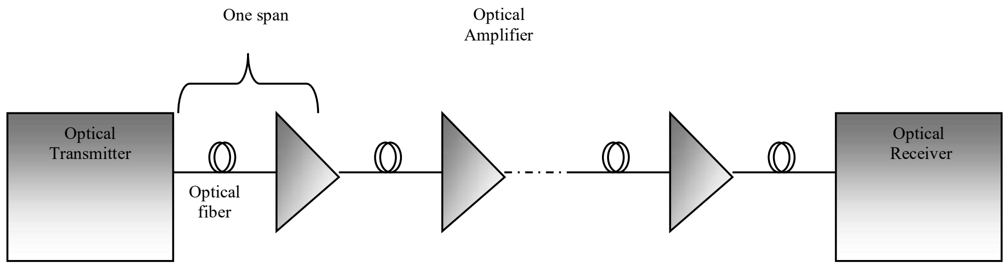


Figure (1) Representation of the optical fiber channel

2-2 NONLINEAR EFFECTS IN THE FIBER:

In an optical fiber different frequency components interact to generate new frequency components. This phenomenon is known as Four Wave Mixing (FWM). Also, due to the dependence of the refractive index of the fiber on the power of propagating signals, different channels interact. The interaction of a channel with itself is known as Self Phase Modulation (SPM) and the interaction of different channels with each other is known as Cross Phase Modulation (XPM) [8]. The propagation of the pulses inside the optical fiber is primarily influenced by the power dependent refractive index. This effect is the main source of fiber nonlinearity and is called in physics theoptical Kerr effect. The equation below shows the power dependence of the refractive index [8].

$$n' = n + n_2\left(\frac{P}{A_{eff}}\right) \qquad (2)$$

where n is the power independent refractive index, n_2 is the nonlinear index coefficient, P is the instantaneous power and A_{eff} is the effective area of the fiber.

2-3 CACULATION OF THE INFORMATION CAPACITY :

The capacity of a communication channel is the maximal rate at which information may be transferred through the channel without error. The capacity can be written as a product of two conceptually distinct quantities, the spectral bandwidth W and the maximal spectral efficiency which we will denote $C_{bit/s/Hz}$

According to Mitra and Stark [3], the upper bound of the DWDM channel spectral efficiency is given by:

$$C_{bit/s/Hz} = \log_2\left(1 + \frac{P_s e^{-(P_s/P_{so})^2}}{P_N + Ps(1 - e^{-(P_s/P_{so})^2})}\right) \qquad (3)$$

where P_s is the total DWDM channel power and P_{so} is a non linear threshold defined by:

$$P_{so} = 10^{1.5}\sqrt{\frac{B \cdot D \cdot \Delta\lambda}{2 \cdot \gamma \cdot L_{eff} \cdot \ln(m/2)}} \qquad (4)$$

where D is the fiber dispersion, $\Delta\lambda$ is the channel spacing, γ is the Kerr index coefficient, B is the bandwidth, L_{eff} is the nonlinear effective length and m is the number of DWDM channels. We note that if $P_{so} \to \infty$, the results converges to the famous Shannon formula for capacity (equation (1)). P_N is the noise power and is given by:

$$P_N = 2kn_{sp}h\nu BG \qquad (5)$$

where k is the number of spans, n_{sp} is the spontaneous emission factor, h is Plank's constant, v is the central frequency, B is the channel bandwidth, G is the Gain of the amplifier. Now we will consider DWDM system with 100 channels *(m=100), B=10Gb/s,* $\Delta\lambda$*=0.63nm, D=1 ps/nm/Km,* L_{eff}*=100 Km, k=5, G=100,* $\gamma=1W^{-1}.Km^{-1}$, $\lambda=1.55\mu m$, $n_{sp}=1$.

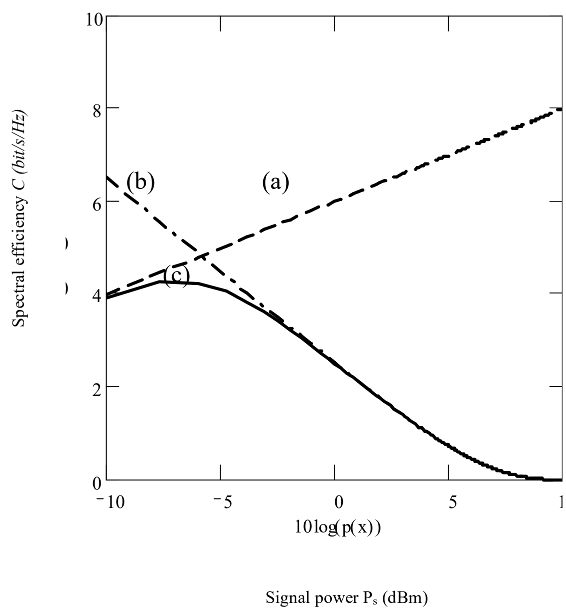


Figure (2) Spectral efficiency versus signal power (a) represents the linear case when nonlinearities are not present. (b) Represents the nonlinear case when the noise power is zero. (c) Represents the case when both nonlinearities and noise power are considered

Figure (2) plots the spectral efficiency of the DWDM system described above (a) represents the linear case when nonlinearities are not present. (b) Represents the nonlinear case when the noise power is zero. (c) Represents the case when both nonlinearities and noise power are considered. And the following figures show the relation of DWDM spectral efficiency with various parameters of the system (i.e. Dispersion, channel spacing and channel bandwidth).

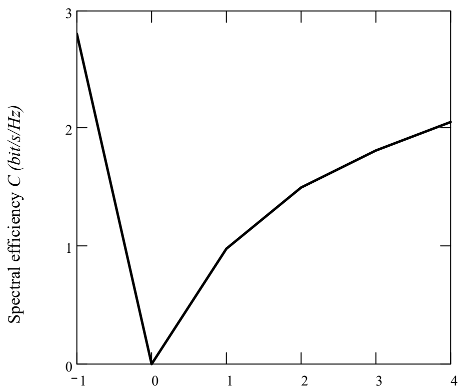


Figure (3-a) Spectral efficiency versus dispersion in ps/nm/km.

Figure (3). The DWDM spectral efficiency with various system parameters. (a) Spectral efficiency versus dispersion in ps/nm/km. (b) Spectral efficiency versus channel spacing in nm. (c) Spectral efficiency versus channel bandwidth in Gb/s. (d) Spectral efficiency versus signal power with different modulation / detection techniques. (I. coherent detection. II. Constant intensity modulation coherent detection. III. Direct detection.)

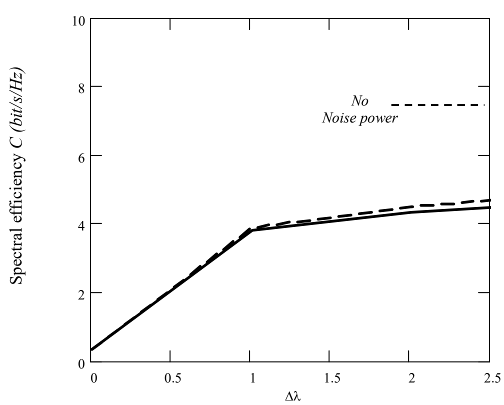


Figure (3-b) Spectral efficiency versus channel spacing in nm.

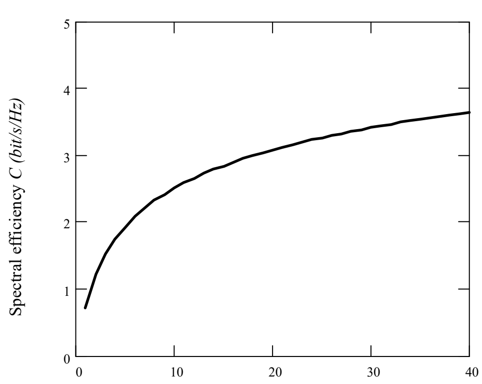


Figure (3-c) Spectral efficiency versus channel bandwidth in Gb/s

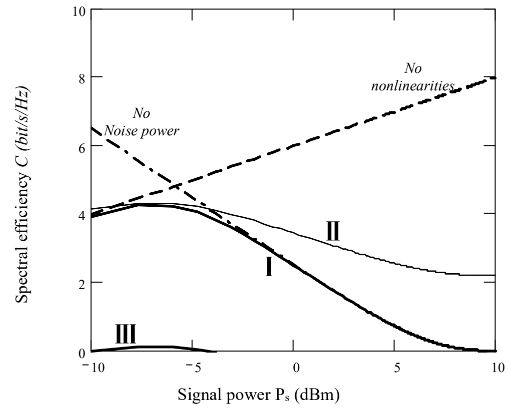


Figure (3-d) Spectral efficiency versus signal power with different modulation / detection techniques. (I. coherent detection. II. Constant intensity modulation coherent detection. III. Direct detection).

As shown from figure (3-d) that the spectral efficiency depends on the choice of modulation techniques (e.g. unconstrained, constant intensity), detection technique (coherent or direct). The curve (I) represents the case of unconstrained modulation with coherent detection, in this case the optical signal is modeled as a complex-valued electric field. Noise arising from optical amplifier and the local oscillator can be modeled as additive, signal independent complex circular Gaussian noise. The curve (II) represents the case of constant intensity modulation with coherent detection (differential phase shift keying (DPSK), and continuous phase frequency shift keying (CPFSK) having nominally constant intensity)[9],[12], as shown, it is superior to the case of unconstrained modulation for the same system parameters. Finally, the curve (III) represents the case of direct detection, where the optical signal is modeled as a non negative, real electric field magnitude. Typically, the dominant noise is signal spontaneous beat noise, which is additive and signal dependant [12].

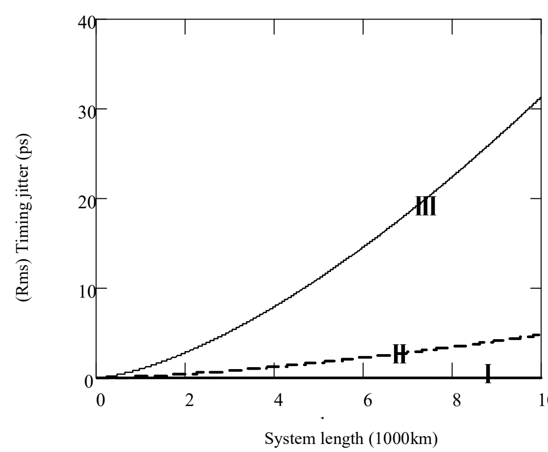


Figure (4-a) Root mean square (rms) timing jitter versus the total length of fiber (without filter) with different values of z_c/z_a (I. z_c/z_a =2, II. z_c/z_a =1.4, III. z_c/z_a =0.7).

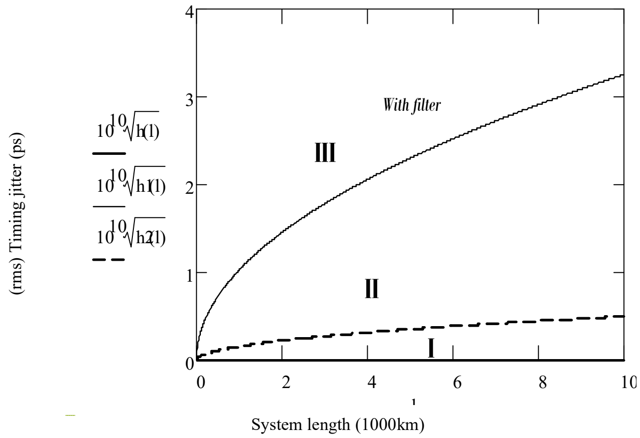


Figure (4-b) Root mean square (rms) timing jitter versus the total length of fiber (with filter) with different values of z_c/z_a (I. z_c/z_a =2, II. z_c/z_a =1.4, III. z_c/z_a =0.7).

3-TIMING JITTER IN DWDM TRANSMISSION SYSTEMS:

Now we are going to study the collision induced timing jitter in 100 channels soliton DWDM systems. The calculation of the root mean square timing jitter done by M. Ablowitz *et. al* [7] will help us to calculate the BER of each DWDM channel. And to better evaluate the system performance, we will begin with the fundamental propagating equation, Nonlinear Schrödinger equation (NLS) with amplification, and filtering terms[7],[6], [21]:

$$iu_z + \frac{1}{2}D(z)u_{tt} + |u|^2 u = iP[z] + iF[t]u \quad (6)$$

where the operator $P[z]$ describes the periodic amplification and $F[t]$ represents the filter action, averaged over an amplification period. The function $D(z)$ describes the particular choice of dispersion. In this study we consider the case of constant dispersion, i.e. we set $D(z)$ =1. Expanding the filter response in Taylor series up to third order $F[z]$ can be written as [7]:

$$F[t] = \eta_0 - \eta_2 (i\partial_t - \omega_f)^2 - i\eta_3 (i\partial_t - \omega_f)^3 \quad (7)$$

where ω_f is the filter peak frequency, η_2, η_3 are the distributed filter parameters and η_0 is the additional gain required to overcome the energy loss of the pulses due to the presence of filters. The variables z and t are the usual dimensionless space and retarded time, normalized to the dispersion length z_* and the characteristic time $t_* : z_* = 2\pi c t_*^2/(\lambda^2 \overline{D})$, $t_* = \tau/1.763$ respectively, where λ= 1.55 µm is the central wavelength, $\overline{D}$ is the average dispersion parameter, τ is the full width at half maximum of the pulse intensity and c is the speed of light in vacuum. If filtering is accomplished by Fabry-Perot e´talons, the corresponding dimensionless parameters are

$$\eta_2 = [2R/(1-R)^2](d^2/c^2 t_*^2 z_a) \quad (8)$$

$$\eta_3 = [(1+R)/(1-R](2d/3ct_*)\eta_2 \quad (9)$$

where d is the mirror spacing, R is the mirror reflectivity, $z_a = l_a / z_*$ is the amplifier spacing in dimensionless units, l_a is the amplifier spacing. The value of d determines the frequency separation between adjacent maxima of the filter function, and is chosen so that this separation coincides with the frequency/ wavelength separation between channels, $d = \pi c/\Delta\omega = \lambda^2/(2\Delta\lambda)$. In turn the frequency separation usually depends on the pulse width τ in the time domain. For $\Delta\lambda$=0.63 nm the corresponding value of d is d=1.90 mm. The quantity R is essentially a free parameter which determines the amount of filtering applied to the pulses. For τ=20 ps and amplifier spacing l_a=25 km, choosing R=0.045 and d=1.90 mm yields η_2=0.25 and η_3=0.41. If R= 0.083 is used, the corresponding values are η_2=0.50 and η_3=0.44. (Note that D=1 ps/nm/km. And z_*= 201.94 km is used throughout this work). The effects of amplification are described by taking P[z] to be[6]:

$$P[z] = -\Gamma + (e^{\Gamma za} - 1)\sum_{n=-\infty}^{\infty} \delta(z - nz_a) \quad (10)$$

where $\Gamma = \gamma z_*$ *is* the dimensionless amplification coefficient and $z_a = l_a / z_*$ *is* the dimensionless amplifier spacing, while $\delta(z)$ is Dirac delta function. Typical experimental values for γ and l_a are 2γ=0.20 dB/km = 0.046 km and l_a =25 km. For τ=20 ps. These values yield Γ=4.62 and z_a =0.12. We rescale the field amplitude as $u(z,t) = [g(z)^{1/2} u'(z,t)]$, where the function $g(z)$ denotes the periodic energy gain cycle and varies on the length scale of the amplifier distance ,which is small compared to the dispersion distance, since z_a <1. That is, $g(z)$ is the periodic function[5].

$$g(z) = a_0^2 \exp[-2\Gamma(z - nz_a)] \quad (11)$$

$$nz_a \le z \prec (n+1)z_a$$

The quantity a_0^2 which represents the ratio between the pulse power after an amplifier and the average power is chosen so that the average of g(z). is unity over an amplification cycle; i.e.

$$a_0^2 = 2\Gamma z_a / [1 - \exp(-2\Gamma z_a)] \quad (12)$$

With the substitution $u(z,t) = [g(z)^{1/2} u'(z,t)]$ equation becomes

$$iu'_z + (1/2)D(z)u'_{tt} + g(z)|u'|^2 u' = iF[t]u' \quad (13)$$

And for a system with two channels we put

$$u'(z,t) = u'_1(z,t) + u'_2(z,t) \quad (14)$$

After a long mathematical analysis, the variance of the total timing shift in the presence of filters of the 2 channels system is given by the equation according to [12].

$$\left\langle (\Delta t^2) \right\rangle_f = \sum_{n=1}^{N} \frac{\left\langle \delta t(z_n)^2 \right\rangle_f}{2} = (\frac{3}{8\eta_2})^2 \|a\|^2 \left(\frac{L}{z_s}\right) \quad (15)$$

where,

$$\left\langle \delta t(z_n)^2 \right\rangle_f = \left(\frac{3}{4\eta_2}\right)^2 \|a\|^2 / 2 \quad (16)$$

$$\|a\|^2 = \sum_{m=1}^{\infty} a_m^2 \tag{17}$$

$$a_m = c_m \left| g_m \right| \tag{18}$$

$$c_m = (\pi^5 / \Omega^4 z_a{}^3) m^3 \operatorname{csc} h^2 (m\pi^2 / 2\Omega z_a) \tag{19}$$

$$\left| g_m \right| = \frac{\Gamma z_a}{\sqrt{(\Gamma z_a)^2 + (m\pi)^2}} \tag{20}$$

and the variance when no filters are present is given by[12]:

$$\left\langle (\Delta t)^2_{nf} \right\rangle = \left(\frac{1}{12} \right) \|a\|^2 L^3 / z_s \tag{21}$$

In figure (4-a) and (4-b) we plot the root mean square (rms) timing jitter in a two channel system with and without filters versus the total length of fiber with different values of z_c/z_a (I. z_c/z_a =2, II. z_c/z_a =1.4, III. z_c/z_a =0.7). We can convert the dimensionless quantities in to physical units by multiplying them with appropriate scale factors. t_*=11.34ps, z_*=201.4 km. It is evident from figure (4-a) and (4-b) that there is an order of magnitude decrease in the collision induced timing jitter when filters are induced. The value of the rms timing jitter in ps at 10000 km as a function of z_c/z_a is displayed in figure (5) for a no filter system. It shows when the collision is distributed over many amplifiers that for large values of z_c/z_a the contribution of the amplifiers begin to cancel each other. Conversely, for very small values of z_c/z_a the collision is too rapid in order for the amplifiers to have a significant effect.

3-1 TIMING JITTER FOR MULTI-CHANNEL SYSTEM:

The total variance in the relative arrival times in jth channel is simply the sum of the variances resulting from the interactions with the other J-1 channels, where J is the total number of channels. The total mean square timing jitter in each channel j is[6],[14]:

$$\left\langle (\Delta t)^2 \right\rangle_j = \sum_{\substack{k=1 \\ k \neq j}}^{J} \left\langle (\Delta t)^2 \right\rangle_{jk} \tag{22}$$

where $\left\langle (\Delta t)^2 \right\rangle_{jk}$ is given by equation (15), $z_c^{jk} = \tau / (\Omega_{jk} t_*)$

$\Omega_{jk} = (\pi c t_* / \lambda^2) \Delta\lambda_{jk}$, and

$\Delta\lambda_{jk} = (j-k)\Delta\lambda_{\min} = (j-k)(1.575\lambda^2 / c\tau)$.

Since the values of Δt follow a Gaussian distribution, the expected bit error rates (BER) of a DWDM system is given by [6], [7], [14]:

$$BER = erfc\left[\frac{rT}{\sqrt{2\left\langle (\Delta t)^2 \right\rangle}} \right] \tag{23}$$

where $erfc(x)$ is the complimentary error function and r is a parameter which measures the sensitivity of the receiver, which is defined by assuming that the maximum time displacement tolerated by the receiver is rT. Typical values of r are 0.2 or 0.4.

Depending on equations (22) and (23) we report the total timing jitter experienced as a result of collisions between pulses in a 100 channels soliton DWDM transmission system and we calculate the BER of each channel. Figures (6-a) and (6-b) show each channel, and the corresponding timing jitter and the BER. As the number of channels increases, the bit error rate of the system grows not only because of the increased number of collisions, but also because the outermost channels undergo rapid collisions.

Figure (7) shows the relation between the BER and the timing jitter. Also here we can estimate the maximum distance of error free transmission attainable with any number of channels, or the maximum number of channels compatible with a desired system length. The dimensionless maximum length is given by [7]:

$$L_{\max}^{f} \leq \frac{65.2\eta_2^2 r^2}{\max\limits_{j=1,\ldots,J} C_j} \tag{24}$$

where, $C_j = \sum_{k=1;k\neq j}^{J} \Omega_{jk} \|a\|_{jk}^2$ the corresponding limit in dimensional units is obtained by multiplying with z_*. The maximum length is limited by the channel with the largest overall timing jitter. By increasing the number of channels the corresponding C_j increase both because the sum k is taken over a larger number of channels and because the channels added are the outermost ones in the frequency domain, and interact more strongly with all the others

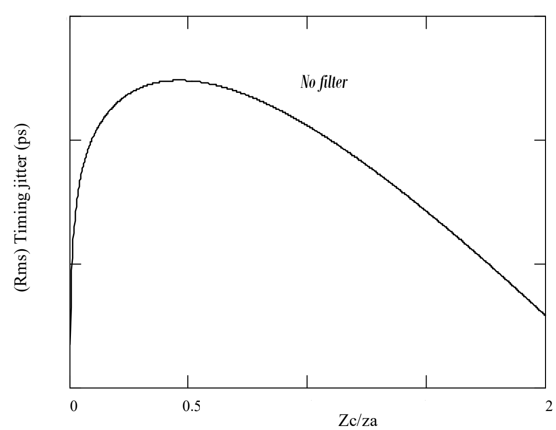
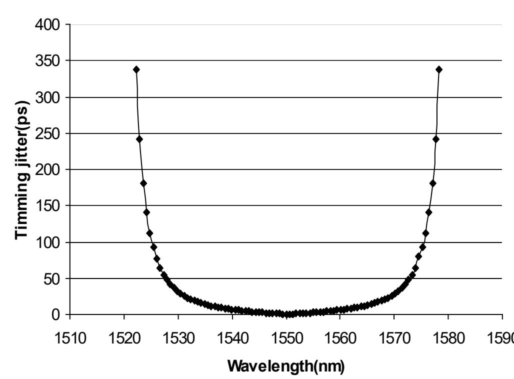
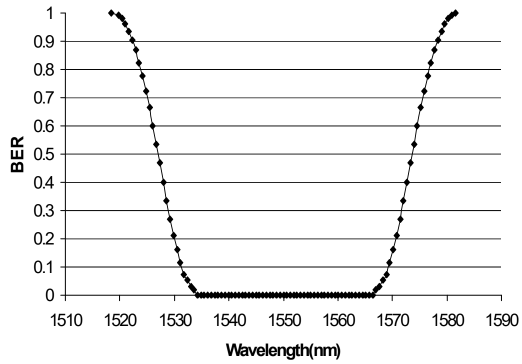


Figure (5) Rms timing jitter in ps at 10000 km versus z_c/z_a is for a no filter system.





The system length in physical units is plotted in figure (8) versus the total number of channels.

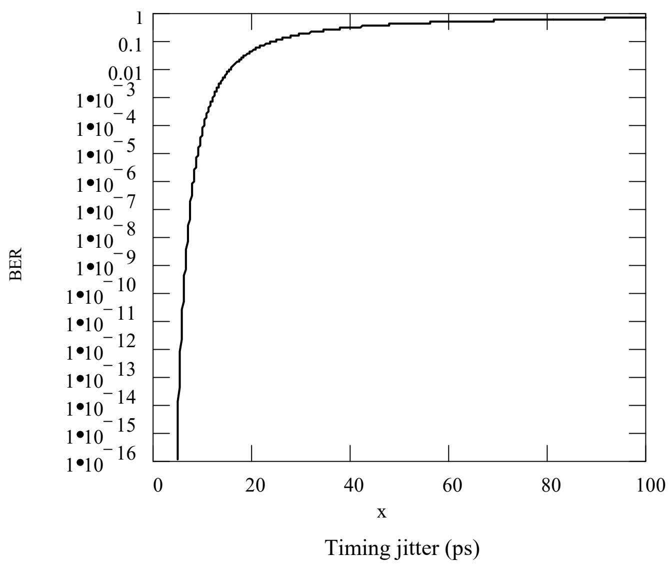


Figure (7) Relation between the BER and the timing jitter.

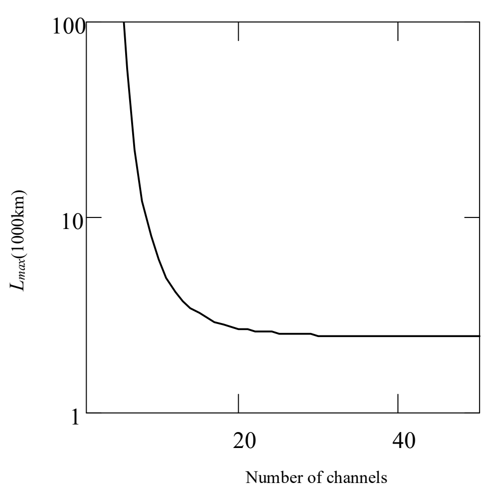


Figure (8) System length in physical units (1000km) versus the total number of channels

4- DISCUSSION

Spectral efficiency of the DWDM transmission system (100×10Gbps) is studied in section 2.3 considering typical system parameters (*B=10Gb/s, Δλ=0.63nm, D=1 ps/nm/Km,* L_{eff}*=100 Km, k=5, G=100, γ=1W*$^{-1}$*.Km*$^{-1}$*, λ=1.55μm,*n_{sp}*=1.*) for 100 channel system, fig(3-a) shows the spectral efficiency versus dispersion in (ps/nm/km), which indicate that small amount of dispersion is required, so with DWDM system we can't use zero dispersion fiber. Fig(3-d) shows the spectral efficiency with different modulation /detection techniques. We can conclude that constant intensity modulation coherent detection is the effective technique with DWDM system.

In section 3 the timing jitter in DWDM transmission system is calculated. fig.(4) shows the r.m.s timing jitter in a two channel system with and without filters, there is an order of magnitude decrease in the collision timing jitter when filters induced.

Fig.(6) shows the timing jitter and the corresponding BER for each channel of the DWDM system, the BER of the system grows as the number of the channels increases.

5- CONCLUSION

In this paper a study of DWDM system is introduced. First, the concept of information capacity and the spectral efficiency of 100 channel DWDM transmission system is investigated, considering different parameters of the system and its effect on the spectral efficiency, because the most economical mean to increase the DWDM system capacity is increasing the spectral efficiency [3]. Choosing the appropriate modulation/detection technique may increase the spectral efficiency with the same system parameter [13]. Also, the timing jitter resulting from the collisions between different pluses in soliton DWDM system is calculated, assuming the cross phase modulation is the main source of nonlinearity. The BER of each channel is calculated, and finally the maximum system length is studied.

This study may further extended by studying the effect of dispersion compensation on improving the BER and the maximum system length, also considering other important and complex effects such as four wave mixing [16], [17-20].

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