Bit Rate and Losses Limitations in Single Mode Fiber

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Abstract

In a WDM system a laser with only one line in its spectrum is needed, so the linewidth of laser must be specified. The required linewidth will depend on the number of channels and bit rate in the proposed system. In general the narrower the linewidth the better but this will usually be a cost/benefit tradeoff. In this paper the limitations of bit rate and losses in single mode fiber are studied, and propose the perfect limitation that is used in the optical design.

All simulation was implemented using programs written in MALTAB 7.

Keywords: WDM, DWDM, TDM, OLA, XPM, SPM, FWM.

الخلاصة:

في التقسيم المضاعف للطول الموجي نحتاج ليزر يمتلك طيف ذو خط واحد ،لذا عرض المجرى لليزر يجب ان يحدد. عرض المجرى الضروري يعتمد على عدد القنوات ومعدل النقل في النظام المقترح . بصورة عامة ضيق عرض المجرى هو افضل لكن هذا عادة يكون مكلف. في هذا البحث سوف ندرس التحديدات في معدل النقل والخسائر في انظمة التقسيم المضاعف للطول الموجي وسوف نقترح التحديد الامثل المستخدم في التصميم الضوئي. كل المحاكاة قد نفذت بأستخدام برامج كتبت بأستعمال (MALTAB 7).

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2- Control of Dispersion in Single-Mode Fiber Links

Dispersion broadens a pulse by an amount unrelated to the length of the pulse. Dispersion becomes a problem for a receiver when it exceeds about 20% of the pulse length. Thus, if a pulse at 200 Mbps is dispersed on a given link by 15% then the system will work. If the data rate is doubled to 400 Mbps the dispersion will be 30% and the system will probably not work. Hence the higher the data rate, the more important the control of dispersion becomes [1].

3- Control of Spectral Width

Perhaps the most obvious thing we can do about dispersion is to control the spectral width of the signal

(Chromatic dispersion is a linear function of spectral width). If the spectral width is doubled the dispersion will doubled.

An important factor is that modulation adds to the bandwidth of the signal (Indeed modulation broadens the signal by twice the highest frequency present in the modulating signal). Modulation with a square wave implies the presence of significant harmonics up to 5 times the fundamental frequency of the square wave (Indeed a perfect square wave theoretically contains infinite of frequency components).

For example, if we want to modulate at 1 Gbps then the fundamental frequency is 500 MHz. A significant harmonic at 2.5 GHz will be present and therefore the broadening of the signal will be 5 GHz or about 0.04 nm. If we want to modulate at 10 GHz then signal broadening will be perhaps 0.4 nm.

It is easily seen that these amounts are not significant if the laser spectral width is 5 nm but critically significant if the spectral width is 0.01 nm. This can be controlled by filtering the square wave modulating signal to remove higher frequency harmonics. But this filtering reduces the quality of the signal at the receiver.

In practical systems we don't worry about the 5th harmonic and usually can be content with the 3rd. So if we filter a 1 Gbps signal at about 1.5 GHz (at the transmitter) then we can usually build a receiver to suit.

WDM can also help here because (almost by definition) a 2.5 Gbps signal has a quarter of the problem with dispersion as a 10 Gbps signal. (Albeit on a given link both will have the same amount of dispersion.) So if you send 4×2.5 Gbps streams instead of 1×10 Gbps stream you can go 4 times as far (on a given link) before dispersion becomes a problem [1] [2] [3].

4- Limitations on the Bit Rate

The limitation imposed on the bit rate by fiber dispersion can be quite different depending on the source spectral width. It is instructive to consider the following two cases separately.

4-1 Optical Sources with a Large Spectral Width

This case corresponds to $V_w >> 1$ in broadening factor equation [4]:

$$\frac{\sigma^2}{\sigma_0^2} = \left(1+\frac{C\beta_2 L}{2\sigma_0^2}\right)^2 + (1+V_w^2)\left(\frac{\beta_2 L}{2\sigma_0^2}\right)^2 + (1+C^2+V_w^2)^2\left(\frac{\beta_3 L}{4\sqrt{2}\sigma_0^3}\right)^2 \quad (1)$$

Where V_w is defined as $V_w = 2\sigma_w\sigma_0$, σ_w is the RMS spectral width, σ_0 is the RMS width of the input pulse, C is the parameter governs the frequency chirp imposed on the pulse, L is the fiber length, β_2 & β_3 is the second and third order dispersion parameter.

This equation provides an expression for dispersion-induced broadening of Gaussian input pulses under quite general Conditions.

Consider first the case of a light wave system operating away from the zero-dispersion wavelength (1550 nm) so that the β_3 term can be neglected. The effects of frequency chirp are negligible for sources with a large spectral width. By setting C=0 in Eq. (1), we obtain:

$$\frac{\sigma^2}{\sigma_0^2} = 1 + V_w^2\left(\frac{\beta_2 L}{2\sigma_0^2}\right)^2$$

$$\sigma^2 = \sigma_0^2 + (\beta_2 L\sigma_w)^2 \equiv \sigma_0^2 + (DL\sigma_\lambda)^2 \quad (2)$$

Where σ_λ is the RMS ;source spectral width in wavelength units, D is the dispersion parameter and $\sigma_w \equiv \frac{D}{\beta_2}\sigma_\lambda$. The output pulse width is thus given by:

$$\sigma = (\sigma_0^2 + \sigma_D^2)^{0.5} \quad (3)$$

Where $\sigma_D \equiv |D|L\sigma_\lambda$ provides a measure of dispersion-induced broadening.

We can relate σ to the bit rate by using the criterion that the broadened pulse should remain inside the allocated bit slot, $T_B = 1/B$, where B is the bit rate. A commonly used criterion is $\sigma \le T_B/4$; for Gaussian pulses at least 95% of the pulse energy then remains within the bit slot. The limiting bit rate is given by $4B\sigma \le 1$. (4) In the limit $\sigma_D >> \sigma_0$, $\sigma \approx \sigma_D = |D|L\sigma_\lambda$, and the condition becomes [5]:

$$BL|D|\sigma_\lambda \le \frac{1}{4} \quad (4)$$

For zero dispersion wavelength, $\beta_2 = 0$ in equation (1).

By setting C =0 as before and assuming $V_w >> 1$, equation (1) can be approximated by:

$$\frac{\sigma^2}{\sigma_0^2} = 1 + (1 + V_w^2)^2 \left(\frac{\beta_3 L}{4\sqrt{2}\sigma_0^3} \right)^2$$

$$= 1 + V_w^4 (\frac{\beta_3 L}{4\sqrt{2}\sigma_0^2})$$

$$\sigma^2 = \sigma_0^2 + \frac{1}{2}(\beta_3 L \sigma_w^2)^2 \equiv \sigma_0^2 + \frac{1}{2}(SL\sigma_\lambda^2) \quad (5)$$

Where S is the dispersion slope that is equal to $S = (2\pi c / \lambda^2)^2 \beta_3$. The output pulse width is thus given by equation (3) but now $\sigma_D \equiv |S| L \sigma_\lambda^2 / \sqrt{2}$.

As before, we can relate σ to the limiting bit rate by the condition $4B\sigma \le 1$. When $\sigma_D >> \sigma_0$, the limitation on the bit rate is governed by:

$$BL|S|\sigma_\lambda^2 \le 1/\sqrt{8} \quad (6)$$

4-2 Optical Sources with a Small Spectral *Width*

This case corresponds to $V_w << 1$ in equation (1). As before, if we neglect the β_3 term and set C=0, equation (1) can be approximated by:

$$\sigma^2 = \sigma_0^2 + (\beta_2 L / 2\sigma_0)^2 \equiv \sigma_0^2 + \sigma_D^2 \quad (7)$$

A comparison with equation (3) reveals a major difference between the two cases. In the case of a narrow source spectrum, dispersion-induced broadening depends on the initial width σ_0, whereas it is independent of σ_0 when the spectral width of the optical source dominates. In fact, σ can be minimized by choosing an optimum value of σ_0. The minimum value of σ is found to occur for $\sigma_0 = \sigma_D = (|\beta_2| L/2)^{1/2}$ [1] and is given by $\sigma = (|\beta_2| L)^{1/2}$. The limiting bit rate is obtained *by* using $4B\sigma \le 1$ and leads to the condition:

$$B\sqrt{|\beta_2 L|} \le \frac{1}{4} \quad (8)$$

For zero dispersion wavelength, $\beta_2 \approx 0$ in equation (1)

Using $V_w << 1$ and C=0 the pulse width is then given by: (9)

$$\sigma^2 = \sigma_0^2 + (\beta_3 L / 4\sigma_0^2)^2 / 2 \equiv \sigma_0^2 + \sigma_D^2$$

Similar to the case of equation (7), σ can be minimized by optimizing the input pulse width σ_0. The minimum value of σ occurs for $\sigma_0 = (|\beta_3| L/4)^{1/3}$ and is given by [4]:

$$\sigma = (\frac{3}{2})^{1/2} (|\beta_3| L/4)^{1/3} \quad (10)$$

σ_0. The minimum value of σ occurs for $\sigma_0 = (|\beta_3| L/4)^{1/3}$ and is given by [4]:

$$\sigma = (\frac{3}{2})^{1/2} (|\beta_3| L/4)^{1/3} \tag{10}$$

The limiting bit rate is obtained by using the condition $4B\sigma \leq 1$, or

$$B(|\beta_3| L)^{1/3} \leq 0.324 \tag{11}$$

The figure (1) compares the decrease in the bit rate with increasing σ_λ = 0, 1, and 5 nm using D = 16 ps/(km-nm). Equation (8) was used in the case $\sigma_\lambda = 0$. When β_3 = 0.1 ps^3/km, the bit rate can be as large as 150 Gb/s for L=100 km. It decreases to only about 70 Gb/s even when L increases by a factor of 10 because of the $L^{-1/3}$ dependence of the bit rate on the fiber length.

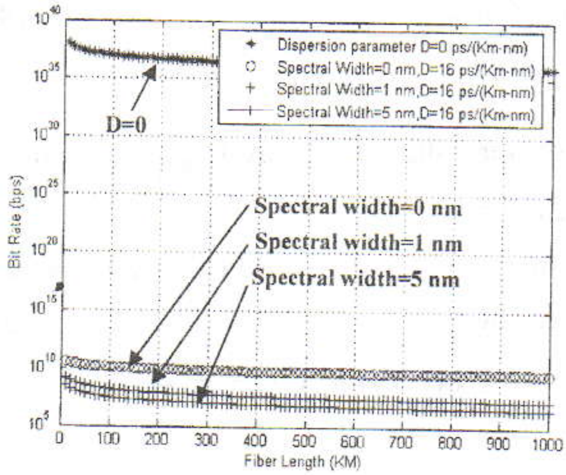

Figure (1): Limiting bit rate of single-mode fibers as a function of the fiber length for σ_λ = 0, 1 and 5 nm. The case σ_λ = 0 corresponds to the case of an optical source whose spectral width is much smaller than the bit rate.

The performance of a light wave system can be improved considerably by operating it near the zero-dispersion wavelength of the fiber and using optical sources with a relatively narrow spectral width [4].

5- Sensitivity Optical Receiver

This component simulates an optical receiver, including the photo detector. By "sensitivity" it is meant the value of the average optical signal power at receiver input needed to achieve a certain BER (Bit Error Rate) performance. This component simulates an optical receiver by supplying a sensitivity value and the test conditions under which such sensitivity is measured. The test conditions assume direct detection in the absence of optical Amplified Stimulated Emission (ASE) noise. A typical system set-up for such measurement would be a back-to-back transmission test with no fiber and just an optical attenuator inserted between transmitter and receiver, as shown in figure (2).

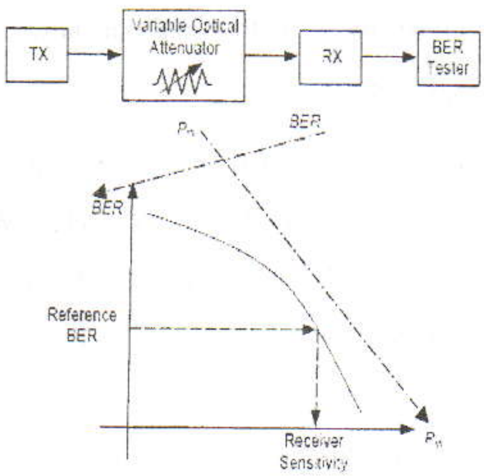

Figure (2) Test conditions

The Q-factor at the output of an optical receiver, in the presence of electrical receiver noise and photo detection shot noise (possibly enhanced by avalanche gain in an APD) [6] [7], satisfies the following expression:

$$\overline{P}_R = \frac{Q^2}{2\eta} h\nu G^x \frac{w_0}{r_0^2} + \frac{Q}{G\eta} h\nu \frac{\sigma_{th}}{q r_0} \qquad (12)$$

Where:

1- r_0 is derived from $r(t)$, sampled at the time-instant t_0 that maximizes it: $r_0 = r(t_0) = \max_t\{r(t)\}$. In turn, $r(t) = p(t)*h_L(t)$, where $h_L(t)$ is the electrical impulse response of the receiver that is output to the photodiode, and p(t) is the normalized optical power pulse shape. The '*' means "convolution". By definition: $p(t) = P(t)/(2\overline{P}_R)$, where $P(t)$ is the un normalized pulse shape in [W] and $\overline{P}_R$ is the average optical power at the receiver input in [W].

2- w_0 is derived from $w(t)$, sampled at the time-instant t_0 that maximizes $r(t)$. By definition: $w(t) = p(t) * h_L^2(t)$

3- η is the photodiode quantum efficiency (without avalanche gain).

4- G is the photodiode avalanche gain.

5- x is photodiode excess noise factor. Note that an equivalent notation is also in widespread use: $G^x = F$ where F is the avalanche photo detector noise figure.

6- σth is the standard deviation of the receiver noise (photo detection shot noise and avalanche excess noise are not included) due to the electronics, at the receiver output. It is very common to characterize the receiver noise by means of an equivalent current noise source added to the detector photocurrent. If such source has a bilateral Power Spectral Density (PSD) $G_{th}(f)$, then

$$\sigma_{th} = \int_{-\infty}^{\infty} G_{th}(f) \left| H_L(f) \right|^2 df \qquad (13)$$

Where $H_L(f)$ is the Fourier Transform of $h_L(t)$.

The above expression for the Q-factor is exact, takes into account the contribution of shot noise and avalanche excess noise [3].

Receiver sensibility is measured with respect to a particular BER (say 10^{-9}) which is achieved by reduced (attenuated) received power at the input of the receiver, BER of 2 x 10^{-6} corresponds to on average 2 errors per million bits. A commonly used criterion for digital optical receivers requires the BER be below $1*10^{-9}$. So the receiver sensitivity is then defined as the minimum average received power $\overline{P}_{rec}$ required by the receiver to operate at a BER of 10^{-9}.

The receiver sensitivity is given by:

$$\overline{P}_{rec} = N_P h\nu B/2 = \overline{N}_p h\nu B \qquad (14)$$

The quantity $\overline{N}_p$ is the average number of photons/bit required by receiver, $h\nu$ is the photon energy =0.8ev and B is the bit rate [4].

The Bit Error rate is equal to:

$$\text{BER} = \exp(\overline{N}_P) \qquad (15)$$

Figure (3) shows the receiver sensitivity for different average number of photon that is obtained from equation (14).

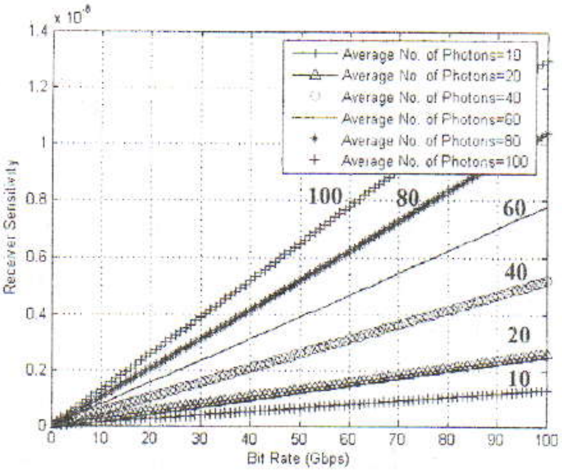

Figure (3) the receiver sensitivity for different number of $\overline{N}_p$

6- Loss-Limited Light wave Systems

Fiber losses play an important role in the system design. Consider an optical transmitter that is capable of launching an average power $\overline{P}_{tr}$. If the signal is detected by a receiver that requires a minimum average power $\overline{P}_{rec}$ at the bit rate B, the maximum transmission distance is limited by [5]:

$$L = \frac{10}{\alpha_f}\log_{10}\left(\frac{\overline{P}_{tr}}{\overline{P}_{rec}}\right) \qquad (16)$$

Where α_f is the net loss (in dB/km) of the fiber cable, including splice and connector losses. The bit-rate dependence of L arises from the linear dependence of $\overline{P}_{rec}$ on the bit rate B. Noting that the distance L decreases logarithmically as B increases at a given operating wavelength [4].

Figure (4) shows the dependence of L on B for three common operating wavelengths of 0.85, 1.3, and 1.55 μm by using α_f = 2.5, 0.4, and 0.25 dB/km, respectively. The transmitted power is taken to be $\overline{P}_{tr}$ = 1 mW at the three wavelengths, whereas $\overline{N}_P$ = 300 at λ = 0.85 μm and $\overline{N}_P$ = 500 at 1.3 and 1.55 μm.

The smallest value of L occurs for first-generation systems operating at 0.85 μm because of relatively large fiber losses near that wavelength. The repeater spacing of such systems is limited to 10-25 km, depending on the bit rate and the exact value of the loss parameter. In contrast, a repeater spacing of more than 100 km is possible for light wave systems operating near 1.55 μm.

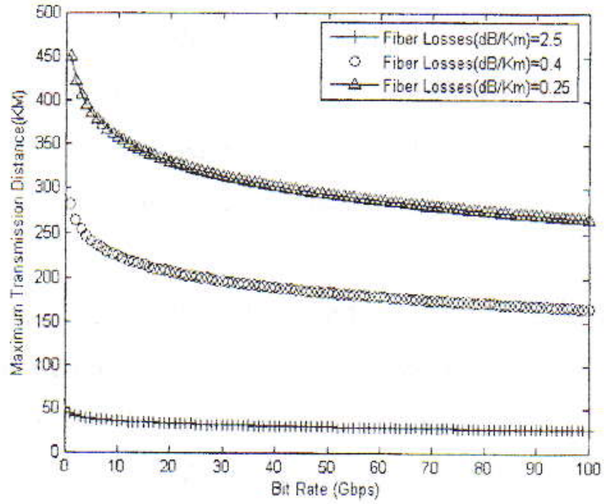

Figure (4) the maximum transmission distance vs bit rate for different value of fiber losses

7- Discussion

In this paper Bit Rate vs Fiber Length are plotted for different number of spectral width and dispersion parameter (figure 1), from this figure we can get that in order to design a system with large bit rate we must use narrow spectral width and small value of dispersion parameter (D=0 ps/(Km-nm)). In addition, we plot Receiver Sensitivity vs Bit Rate for different number of photons, so from equation (15) we can get that for BER<10^{-9}, $\overline{N}_p$ must exceed 20 (figure 3), that mean each 1 bit must contain at least 20 photons to be detected with a BER<10^{-9}.

Here, we must ensure that the transmit power is high enough so that it can maintain signal power > R (The minimum power requirement of the receiver) at the receiver end, despite the attenuation along the transmission line. That does not mean that if we increase the transmit power to a high level, we can send bits across great distances. High input power also is a breeding ground for impairments (nonlinearities such as cross-phase modulation [XPM], self-phase modulation [SPM], four-wave mixing [FWM] and so on). In addition, an upper limit exists for every receiver (APD type or PIN type) for receiving optical power. The dynamic range of the receiver gives this, and it sets the maximum and minimum power range for the receiver to function. For example, –7 dBm to –28 dBm is a typical dynamic range of a receiver. Therefore, the maximum input power that we can launch into the fiber is limited. This also limits the maximum transmission distance as shown in figure (4), so from this figure we can see that the distance L decrease logarithmically as B increases at a given operating wavelength. The smallest value of L occurs for first generation systems operating at 0.85 μm (α_f=2.5 dB/Km) because of relatively large fiber losses near that wavelength. The repeater spacing of such systems is limited to 10-25 Km, depending on the bit rate and the exact value of the loss parameter. In contrast, a repeater spacing of more than 100 Km is possible for ligthwave systems operating near 1.55 μm (α_f=0.25 dB/Km).

Note that the optical power at the receiver end has tσ be within the dynamic range of the receiver; otherwise, it damages the receiver (if it exceeds the maximum value) or the receiver cannot differentiate between 1s and 0s if the power level is less than the minimum value.

8- Conclusions

This paper demonstrated the performance of a light wave system (Bit Rate and Losses Limitations), that can be improved considerably by operating it near the zero-dispersion wavelength of the fiber (1550 nm) and using optical sources with a relatively narrow spectral width. In addition, in practical receivers, the average number of photon must exceed 20 in order to get BER < 10^{-9} (figures 2 & 3). Another issue that we conclude it is, in order to get maximum distance and with fewer losses and with repeater spacing more than 100 Km the system must operate in 1.55 μm, and in order to get this large distance we must work with bit rate smaller than 10 Gbps for example, by using 2.5 Gbps the maximum transmission distance is 425 Km for fiber losses 0.25 dB/Km (figure 4). In addition, we must ensure that the transmit power is high enough so that it can maintain signal power larger than the minimum power requirement of the receiver at the receiver end.

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