FIBER OPTICS

Prof. R.K. Shevgaonkar

Department of Electrical Engineering

Indian Institute of Technology, Bombay

Lecture: 24

Optical Receivers-

Receiver Sensitivity Degradation

The analysis of an optical receiver performance and noise characteristics carried out, so far, has been indeed based on several idealistic pre-assumptions that testify the optical receiver under discussion to be more of an ideal nature. Some of the assumptions were:

1) Absolute absence of incident optical power onto the photo-detector material during logic '0' transmission.
2) Constant incident optical intensity level onto the photo-detector material during logic '1' transmission
3) Perfectly stable clock and so on.

However in case of practical receivers, such conditions rarely occur and most often we witness deviations from the above conditions. So, the main aim of the present discussion is to investigate the necessary steps and measures that need to be adopted, so that, even under practical conditions, the receiver performance remains almost the same i.e. the same BER.

RECEIVER SENSITIVITY DEGRADATION

Due to the deviations from the ideal conditions mentioned above, a practical optical receiver always shows a reduction in the sensitivity of the receiver and this phenomenon is known as the receiver sensitivity degradation. In order to restore sufficient satisfactory sensitivity in the optical receiver i.e. the same BER, more power has to be supplied to the optical system than that with an idealistic receiver. This extra power required to be supplied to the receiver is known as the power penalty of the optical system. Power penalty in an optical system may be accounted to various factors such as the finite extinction ratio, the relative intensity noise (RIN) and the timing jitters. These factors shall be investigated in detail in the subsequent sections. However, while investigating power penalty due to one factor, the contribution of the other factors may be assumed to be negligible and the total power penalty would then be a sum total of the power penalties (in dB) due to all the factors.

POWER PENALTY DUE TO EXTINCTION RATIO

In a practical optical system, the optical intensity incident onto the optical receiver during the transmission of logic '0' level is, however, not zero and there is always some residual optical flux that is incident onto the optical receiver. This residual optical flux may be assumed to be composed of two types of optical fluxes:

1) The ambient light incident onto the photo-detector during the logic '0' transmission which constitutes the dark current of the optical receiver.
2) A residual optical output from the optical source (LASER) due to the finite bias voltage at which it is biased to increase speed of operation. This output optical flux from the optical source travels through the optical fiber and thus, even during the logic '0' transmission, the optical intensity onto the photo-detector is non-zero.

The extinction ratio (r_{ex}) of an optical system is defined as the ratio of the optical power received during logic '0' transmission (P_0) to the optical power received during logic '1' transmission (P_1). That is,

$$\mathbf{r_{ex} = \frac{P_0}{P_1}} \tag{24.1}$$

In ideal cases, P_0=0 and so, the extinction ratio is zero. The average received optical power ($\bar{\mathbf{P}}_{\mathbf{rec}}$) may be calculated as the arithmetic mean of the two optical powers, as shown below:

$$\mathbf{\bar{P}_{rec} = \frac{P_0+P_1}{2}} \tag{24.2}$$

The photo-currents corresponding to the two optical power levels above are given as:

$$\mathbf{Photocurrent\ during\ logic'0'}\boldsymbol{level}\mathbf{,\ I_0 = RP_0} \tag{24.3}$$

$$\mathbf{Photocurrent\ during\ logic'1'}\boldsymbol{level}\mathbf{,\ I_1 = RP_1} \tag{24.4}$$

In the above equations, 'R' is the responsivity of the optical receiver. The 'Q' parameter of the data transmission may also be calculated as:

$$\begin{aligned}\mathbf{Q} &= \mathbf{\frac{I_1-I_0}{\sigma_1+\sigma_0}}\\ &= \mathbf{\frac{RP_1(1-r_{ex})}{\sigma_1+\sigma_0}}\\ &= \mathbf{\frac{(1-r_{ex})}{(1+r_{ex})}\cdot\frac{2\bar{P}_{rec}R}{\sigma_1+\sigma_0}}\end{aligned} \tag{24.5}$$

If the noise in the receiver is only thermal noise i.e. the receiver operation is only thermal noise dominated, the variances in the two levels may be assumed to the almost equal and is given by the variance of thermal noise as:

$$\mathbf{\sigma_1 \approx \sigma_0 = \sigma_T(thermal\ noise\ variance)} \tag{24.6}$$

Using this assumption in equation 24.5 to obtain the expression for average received power, we get:

$$\mathbf{\bar{P}_{rec} = \frac{(1+r_{ex})}{(1-r_{ex})}\cdot\frac{\sigma_T Q}{R}} \tag{24.7}$$

For an ideal receiver, r_{ex}=0 and therefore:

$$\mathbf{\bar{P}_{rec} = \frac{\sigma_T Q}{R}} \tag{24.8}$$

However, due to a finite (non-zero) value of 'r_{ex}', the average power received must be higher than that for an ideal receiver. This extra power requirement may then be termed as the power penalty in the system owing to the extinction ratio or more appropriately 'finite extinction ratio'. That is,

$$\mathbf{Power\ Penalty}, \boldsymbol{\partial}_{\mathbf{ex}} = \mathbf{10\log}\left\{\frac{\overline{\mathbf{P}}_{\mathbf{rec}}(\mathbf{r}_{\mathbf{ex}}\neq \mathbf{0})}{\overline{\mathbf{P}}_{\mathbf{rec}}(\mathbf{r}_{\mathbf{ex}}=\mathbf{0})}\right\} \qquad (24.9)$$

Substituting the values of the terms in the R.H.S. from the equations 24.7 and 24.8, we have the expression for the power penalty as:

$$\boldsymbol{\partial}_{\mathbf{ex}} = \mathbf{10\log}\left\{\frac{\mathbf{1+r}_{\mathbf{ex}}}{\mathbf{1-r}_{\mathbf{ex}}}\right\} \qquad (24.10)$$

If the power penalty (dB) is plotted with respect to varying extinction ratio, the resultant curve would look like the one shown below:

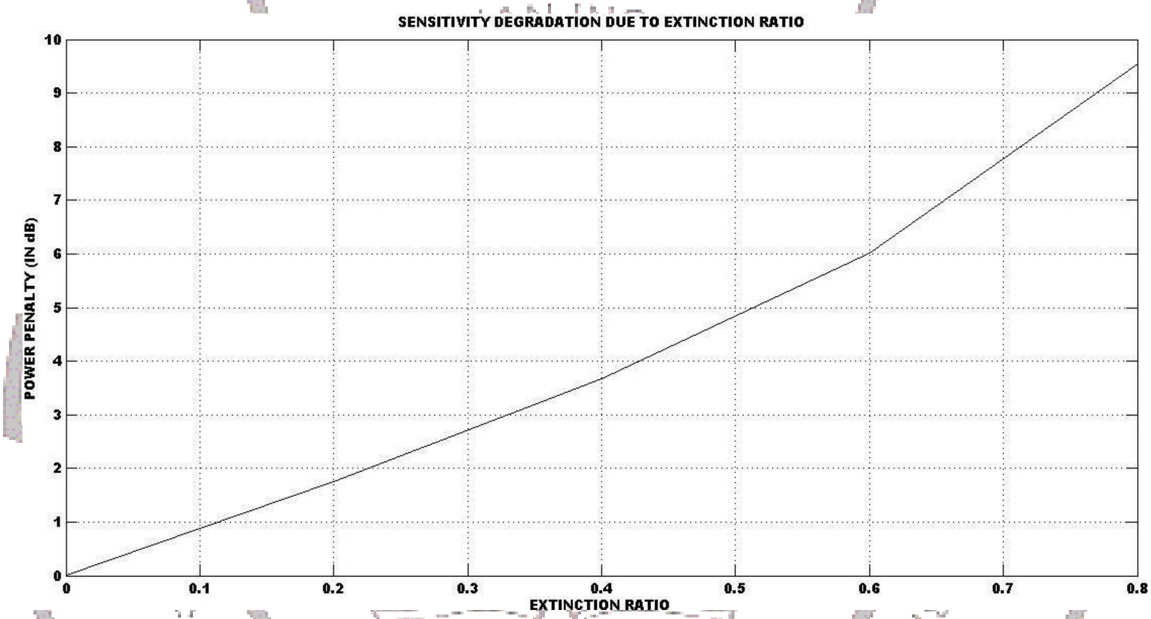

Figure 24.1: Plot of Power Penalty versus Extinction ratio.

From the above plot, the power penalty corresponding to any arbitrary value of extinction ratio may be graphically calculated. For an extinction ratio of about 0.12, the power penalty corresponds to 1dB and that for an extinction ratio of about 0.5, the power penalty corresponds to about 4.8dB. In typical situations the power penalty of the optical system due to extinction ratio ranges between the above values.

POWER PENALTY DUE TO **RIN**

Whenever there is a transition in the data signal from a logic '0' to logic '1' or vice versa, there are some oscillations observed in the output of the LASER diode before the optical output stabilizes to the optical intensity level corresponding to the data bit. These oscillations are known as relaxation oscillations (already discussed in transcript 18) and the amplitude of these oscillations is found to be proportional to the amplitude of the optical pulse itself. The noise introduced into the optical system due to the relaxation oscillations is termed as the relative intensity noise (RIN). The total noise variance (σ^2 in the received output signal may therefore be assumed to be sum of the variances due to thermal noise ($\sigma_T{}^2$), the shot noise ($\sigma_s{}^2$) and the relative intensity noise ($\sigma_I{}^2$). That is:

$$\boldsymbol{\sigma^2 = \sigma_T{}^2 + \sigma_s{}^2 + \sigma_I{}^2} \qquad (24.11)$$

Here,

$$\boldsymbol{\sigma_I = R\langle \Delta P_{in}{}^2\rangle^{1/2}} \qquad (24.12)$$

The term 'R' in the above expression is the responsivity of the optical receiver. The above expression 24.12 may also be written as:

$$\boldsymbol{\sigma_I = RP_{in}r_I} \qquad (24.13)$$

Where, $\mathbf{r_I} = \langle \Delta \mathbf{P_{in}}^2\rangle^{1/2} / \mathbf{P_{in}}$.

Since the discussion deals with power penalty due to RIN, the power penalty due to the finite extinction ratio and the timing jitter may be considered negligible. In fact, the extinction ratio may be assumed to be zero which signifies that there is no light onto the photo detector during logic '0' level. Hence, the photo-current generated during logic '1' level may then be calculated as:

$$\boldsymbol{I_1 = 2R\bar{P}_{rec}} \qquad (24.14)$$

The Q factor in this situation would be:

$$\boldsymbol{Q = \frac{I_1 - I_0}{\sigma_1 + \sigma_0}}$$

In the present case, during logic '1' transmission, all noises namely shot-noise, thermal noise and RIN are present. However, the extinction ratio being 0, only thermal noise exists during logic '0' transmission. Therefore,

$$\boldsymbol{\sigma_1 = (\sigma_T{}^2 + \sigma_s{}^2 + \sigma_I{}^2)^{\frac{1}{2}}}$$

$$\boldsymbol{\sigma_0 = \sigma_T}$$

$$\boldsymbol{I_0 = 0}$$

The expression for the Q factor, hence, modifies to:

$$\boldsymbol{Q = \frac{2R\bar{P}_{rec}}{(\sigma_T{}^2 + \sigma_s{}^2 + \sigma_I{}^2)^{\frac{1}{2}} + \sigma_T}} \qquad (24.15)$$

The expressions for the variances of the shot noise and the RIN may be written as:

$$\boldsymbol{\sigma_s = 2\{qR\bar{P}_{rec}B\}^{\frac{1}{2}}} \qquad (24.16)$$

$$\boldsymbol{\sigma_I = 2r_I\bar{P}_{rec}R} \qquad (24.17)$$

If we now concentrate on equations 24.15, 24.16 and 24.17, we find that all the three equations are dependent on the value of the average optical received power. Solving these three equations, the expression for the average received power may be obtained as:

$$\bar{\mathbf{P}}_{\mathbf{rec}}(\mathbf{r_I}) = \frac{\mathbf{Q}\boldsymbol{\sigma}_{\mathbf{T}}+\mathbf{qBQ^2}}{\mathbf{R}(\mathbf{1}-\mathbf{r_I}^2\mathbf{Q}^2)} \qquad (24.18)$$

The above equation clearly shows that, due to a non-zero value of $\mathrm{r_I}$, the average optical power required to be received is more than that when $\mathrm{r_I} = 0$. Therefore in this case the power penalty '∂_I' (in dB) may be defined to be equal to the ratio of the average received power from equation 24.18 to the average received power with $\mathrm{r_I} = 0$. That is:

$$\boldsymbol{\partial_I} = \mathbf{10\log}\left\{\frac{\bar{\mathbf{P}}_{\mathbf{rec}}(\mathbf{r_I}\neq\mathbf{0})}{\bar{\mathbf{P}}_{\mathbf{rec}}(\mathbf{r_I}=\mathbf{0})}\right\}$$

$$= \mathbf{10\log}\,(\mathbf{1}-\mathbf{r_I}^2\mathbf{Q}^2) \qquad (24.19)$$

From our earlier discussions, we know that for an acceptable BER of about 10^{-9}, the value of the Q factor is approximately equal to 6. Therefore, the expression for the power penalty may be written as:

$$\boldsymbol{\partial}_\mathbf{I} = \mathbf{10\log}(\mathbf{1}-\mathbf{36r_I}^2) \qquad (24.20)$$

The plot of the above equation looks like the one in the following figure 24.2:

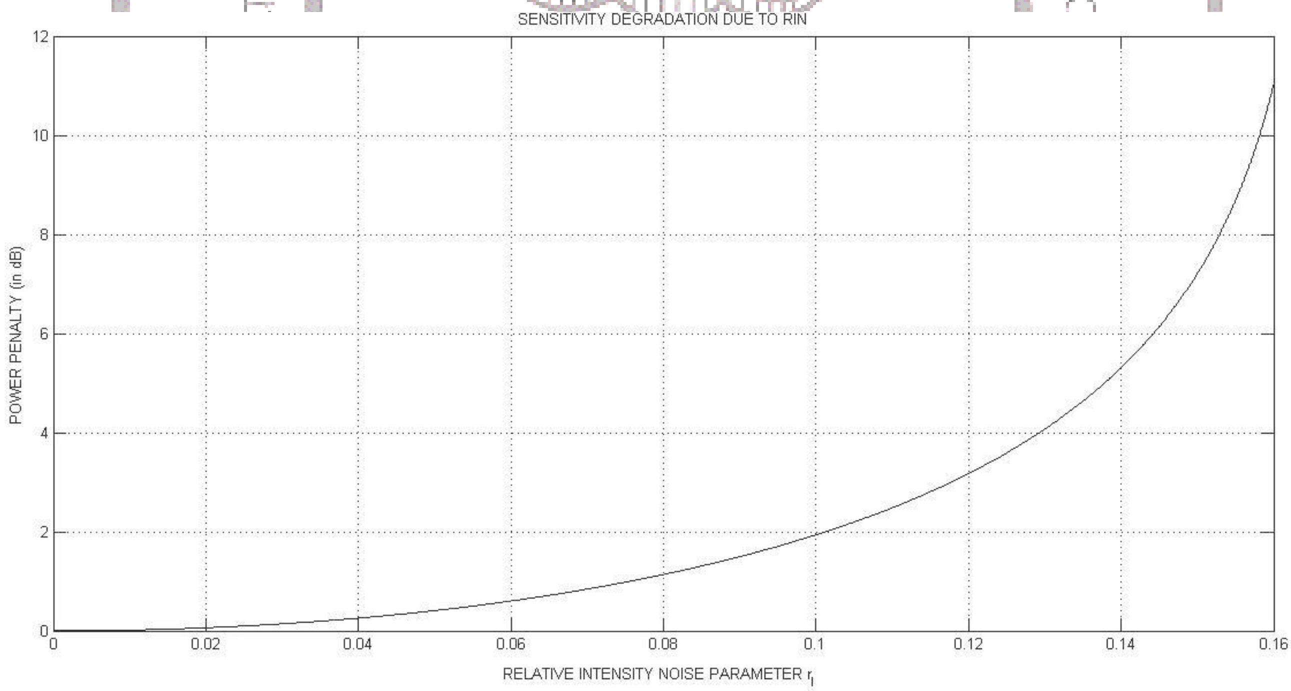

Figure 24.2: Sensitivity Degradation due to RIN

The plot clearly shows that the system degradation increases very rapidly with increasing RIN parameter value. One should note that the values along the x-axis are, in fact, indicating the value of the variance due to the RIN. The peak-to-peak value of the variations is approximately equal to 5 or 6 times of the variance value. That is, on one side the peak value is about 2.5 to 3 times the variance value. So if the amplitude of the pulse decreases, the increasing value of 'σ' of the RIN variations cause a major part of the intensity to fall below the threshold level. This leads to an increase in the probability of bit errors and the system, thus, degrades very rapidly as shown in the above plot. It is interesting to note that for $r_I = Q^{-1}$, the power penalty is infinity which means that infinite amount of power has to be added to the optical system to restore satisfactory BER performance. In other words, the desired system BER performance becomes unachievable.

POWER PENALTY DUE TO **TIMING JITTER**

In digital detection schemes, the received pulse is sampled at particularly clocked timing intervals. The value of the sample is then compared with a pre-set threshold level and based on the decision making mechanism, the bit is assigned to be either '0' or '1'.

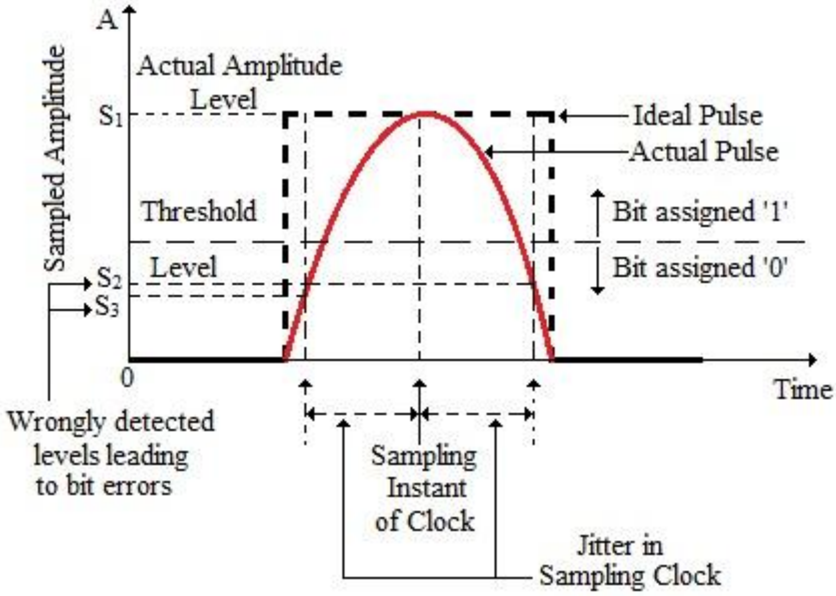

Figure 24.3: Bit errors due to timing jittter

In such ideal situations, mild timing jitters in the clock intervals do not cause any significant difference in the BER performance because the signal level in the ideal pulse remains constant during the entire bit period. Any sample during this bit period would, hence, be accurately detected without any error. However, in practical cases, due to the finite bandwidth of the system or the need for the prevention of inter-symbol-interference, the shape of the received pulse may not be perfectly rectangular and so, with a jitter in the clock, probability of bit-errors increase thereby degrading the system BER performance. This may be clearer from the figure 24.3.

From the above figure it may be observed that, the statistical jitters in the clock instants indirectly get converted to some form of relative intensity errors or equivalent RIN leading to bit errors and degradation of system performance. In a similar manner to the derivation of the power penalty due to RIN, we assume here that the power penalty due to the remaining factors to be negligible and that the photo-current during the logic '0' level is zero. Under these assumptions, the Q factor of the system may be written as:

$$\mathbf{Q} = \frac{\mathbf{I_1} - \langle \Delta \mathbf{I_j} \rangle}{(\boldsymbol{\sigma_T}^2 + \boldsymbol{\sigma_j}^2)^{\frac{1}{2}} + \boldsymbol{\sigma_T}} \qquad (24.21)$$

In the above expression, ΔI_j is the current generated due to the timing jitter in the system and σ_j is the R.M.S. value of the variance of the noise introduced into the system due to the timing jitter. The amount of jitter-noise introduced into the system depends on the shape of the pulse.

Let us now assume that the actual pulse in the figure 24.3 be represented by the function h(t) where the time 't' is measured from the correct (ideal) sampling instant such that t=0 signifies that instant. Also, let us assume 'Δt' be the jitter that occurred in the sampling instant and the consequent difference in the photo-current is ΔI_j. Then this difference in the photo-current produced may be expressed as:

$$\Delta \mathbf{I_j} = \mathbf{I_1}\{\mathbf{h}(\mathbf{t}=\mathbf{0}) - \mathbf{h}(\Delta \mathbf{t})\} \qquad (24.22)$$

For preventing inter-symbol interference (ISI), we generally choose the shape of the pulse to be represented by the square of a cosine function. Hence,

$$\mathbf{h}(\mathbf{t}) = \mathbf{cos}^2\left(\frac{\boldsymbol{\pi}\mathbf{Bt}}{\mathbf{2}}\right) \qquad (24.23)$$

In the above equation, 'B' signifies the bit-rate of data transmission. The transfer function of the raised cosine filter (for minimum ISI) which is generally used in the above type of systems may be written as:

$$\boldsymbol{H}(\boldsymbol{f}) = \begin{cases} \frac{1+\cos(\frac{\pi f}{B})}{2} & f < B \\ 0 & f \geq B \end{cases} \qquad (24.24)$$

The impulse response of the above filter may be written as:

$$\mathbf{h}(\mathbf{t}) = \frac{\sin(2\pi Bt)}{2\pi Bt} \cdot \frac{1}{1-(2Bt)^2} \qquad (24.25)$$

When the timing jitter is very small in comparison to the bit duration, i.e. when $B\Delta t \ll 1$, the jitter produced in the photo-current (ΔI_j) can be expressed as:

$$\Delta \mathbf{I_j} = \frac{2}{3}(\boldsymbol{\pi}^2 - 6)(\mathbf{B}\Delta \mathbf{t})^2 \mathbf{I_1} \qquad (24.26)$$

If we now assume the timing jitter in the photo-current has a Gaussian distribution, the probability density function of the timing jitter may be written as:

$$\mathbf{P}(\Delta \mathbf{t}) = \frac{1}{\sqrt{2\pi}\tau_j} \mathbf{e}^{-(\Delta t)^2/2\tau_j^2} \qquad (24.27)$$

In the above expression 'τ_j' is the standard deviation of the clock jitter. The probability density function for the jitter in the photo-current can be expressed as:

$$\mathbf{P(\Delta I_j) = (\pi b \Delta I_j I_1)^{\frac{-1}{2}} e^{\frac{-\Delta I_j}{b I_1}}} \quad (24.28)$$

Here, $\mathbf{b = \frac{4}{3}(\pi^2 - 6)(B\tau_j)^2}$

The value of the parameter depends on the value of 'τ_j'. If we now substitute the above into the expression for the equivalent RIN produced due to the timing jitter, we can then obtain the average optical received power as a function of the parameter 'b' for a given value of the Q factor as:

$$\mathbf{\bar{P}_{rec}(b) = \frac{\sigma_T Q}{R}\left\{\frac{1-\frac{b}{2}}{\left(1-\frac{b}{2}\right)^2 - \frac{b^2Q^2}{2}}\right\}} \quad (24.29)$$

The power penalty '∂_j' in the system due to timing jitter may now be expressed as follows:

$$\boldsymbol{\partial_j} = \mathbf{10\log\left\{\frac{\bar{P}_{rec}(b\neq 0)}{\bar{P}_{rec}(b=0)}\right\}} \quad (24.30)$$

If the power penalty is plotted as function of the quantity ($B\tau_j$), we obtain the following curve:

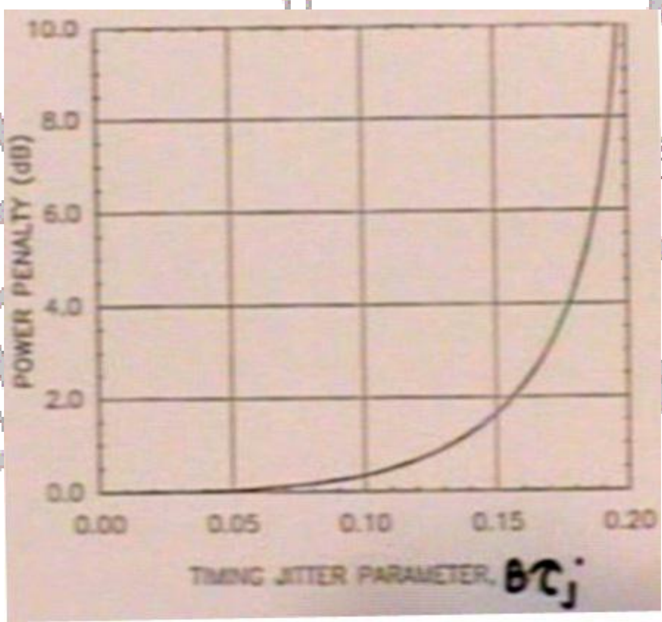

Figure 24.4: Plot of power penalty due to timing jitter

The above figure shows that for a value of about 0.2 of the timing jitter parameter, the power penalty becomes infinity which may also be seen from the EYE diagram of the receiver. For an acceptable system, the jitter in the timing must be kept as low as possible.