

# Module 12 : System Degradation and Power Penalty

## Lecture : System Degradation and Power Penalty

### Objectives

In this lecture you will learn the following

- Degradation during Propagation
- Modal Noise
- Dispersion
- System Degradation due to Imperfect Components
- Extinction Ratio
- Relative Intensity Noise(RIN)
- Timing Jitter
- The SNR calculation and or the BER calculation assumes that the optical signal consists of ideal bit streams. That is, it assumes that the bit-1 consists of optical pulse of constant energy, and there is no energy in bit-0.
- In practice however, the bits are distorted due to various reasons and the optical signal is degraded in addition to the system noise.
- To compensate for the system degradation, the signal power has to be increased to achieve the same SNR or BER performance as that of an ideal system. This increase in power is called the **Power Penalty**.

- There are two types of signal degradation which can contribute to the power penalty.

1) Degradation during propagation in the optical fiber

2) Degradation due to peripheral electronic and optic components in the system like the lasers, photo-detectors, couplers etc.

### Degradation during Propagation

#### Modal Noise

- The modal noise is associated with the multimode fiber. Various propagating modes inside a multimode fiber interfere to produce a speckle pattern on the photo detector.
- Since the speckle is a spatial redistribution of the energy, and the photo-detector detects the total energy falling on the detector, as such the modal noise degrades the system performance.
- However, in practice, the photo-detector does not have a uniform response over its surface. Also the speckle pattern varies as a function of time due to temperature and pressure variations giving a fluctuating photo current. This is the modal noise.
- The formation of speckle due to coherent interference of the various modes. Now, since various modes travel with different speeds, the coherent addition of different modes is possible only if the differential delay between different modes is much smaller compared to the coherence time.

The coherence time of light is of the order of  $1/\Delta f$ , where  $\Delta f$  is the bandwidth of the

- source. The speckles would vanish if the modal delay is much larger than coherence time reducing the modal noise.
- For a source like LED, the spectral width is about 30-50 nm, giving spectral width of 3-5 THz. The coherence time of LED would be 0.2-0.3 psec.
- Since the typical inter-modal dispersion inside a multimode fiber is few nsec/Km, even for small networks, where usually the multi-mode fiber is used, the modal noise is very small.

- Modal noise becomes a problem when laser diodes are used as optical sources.

## Dispersion

- As seen earlier, the optical pulse broadens due to dispersion. On a single mode optical fiber, the pulse broadening is due to chromatic dispersion.
- The pulse broadening affects the system performance in two ways:
  - 1) Part of the bit energy spreads in the neighboring bits causing inter-symbol-interference (ISI).
  - 2) The reduction in the pulse energy because there is energy spread due to dispersion.
- Due to reduction in the pulse energy inside a bit, causes reduction in SNR and consequently reduction in BER. To get the same BER back, the signal power has to be increased, giving dispersion induced power penalty.
- The dispersion induced power penalty depends upon many factors like, the pulse shape, spectral profile of laser, fiber dispersion etc. The analysis however, generally carried out assuming that the pulse broadening is Gaussian.
- The dispersion induced power penalty then is related to the reduction in the peak of the Gaussian due to dispersion.
- Let a Gaussian pulse of width  $\sigma_i$  be launched inside a fiber. The pulse is given as

$$p(t) = A \exp(-t^2 / 2\sigma_i^2) / \sigma_i \sqrt{2\pi}$$

- Due to dispersion the pulse will broaden to have a width of

$$\sigma_o = \sqrt{\sigma_i^2 + (DL\sigma_\lambda)^2}$$

where D is the dispersion of the fiber, and  $\sigma_\lambda$  is the spectral width of the source. L is the

$$\sigma_\lambda$$

length of the fiber.

- The output pulse is

$$p(t) = A \exp(-t^2 / 2\sigma_o^2) / \sigma_o \sqrt{2\pi}$$

- The reduction in the peak amplitude of the pulse is

$$R = \sigma_i / \sigma_o = \frac{1}{\sqrt{1 + (DL\sigma_\lambda / \sigma_i)^2}}$$

- Now the ISI is minimized if  $4B\sigma_o \leq 1$ , where B is the bit rate. Even for the equality sign we get,

$$\sigma_i = R\sigma_o = R/4B$$

- Substituting in above equation we get

$$R = \frac{1}{\sqrt{1 + (4BDL\sigma_\lambda / R)^2}}$$

$$\Rightarrow R = \sqrt{1 - (4BDL\sigma_\lambda)^2}$$

- The power penalty due to dispersion is

$$\delta_D = 5 \log \{1 - (4BDL\sigma_\lambda)^2\}$$

### Dispersion Power Penalty

$BLD\sigma_\lambda$	$\sigma_D$ (dB)
0	0
0.05	0.088
0.10	0.378
0.15	0.97
0.20	2.22

0.25

 $\infty$ 

- The system sensitivity degrades rapidly with the dispersion.

## System Degradation due to Imperfect Components

### Extinction Ratio

- A typical transmitter does not have zero photo-current during bit-0. This happens due to two reasons.
  - 1) A small optical energy is transmitted during bit-0. This is due to the fact that the laser is not biased at the zero current but is rather biased at the threshold current to increase the switching speed of the laser. For bit-0 then, a small incoherent light is emitted by the laser.
  - 2) There is dark current in a photo-diode.
- If  $I_0$  and  $I_1$  are the photo-currents for the 0 and 1 bit respectively corresponding to optical powers  $P_0$  and  $P_1$ , the extinction ratio for the data is defined as

$$r_{ex} = I_0 / I_1$$

- The parameter Q (defined earlier) can be written as

$$Q = \frac{1 - r_{ex}}{1 + r_{ex}} \frac{2 \Re P_{av}}{\sigma_0 + \sigma_1}$$

where the average received power is  $P_{av} = \frac{P_1 + P_2}{2}$  and  $\Re$  is the responsivity of the receiver.

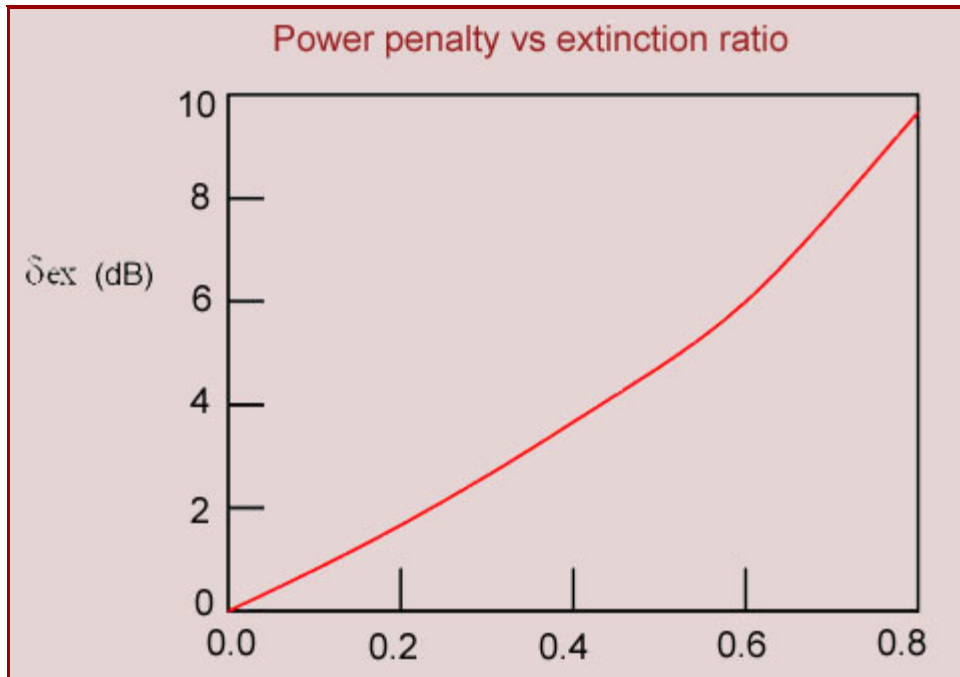
- Inverting the relation we get

$$P_{av}(r_{ex}) = \frac{1 + r_{ex}}{1 - r_{ex}} \frac{\sigma_T Q}{\Re}$$

- We can note that for a given Q, the average power requirement increases with the extinction ratio. We can then define the power penalty as

$$\sigma_{ex} = 10 \log \left( \frac{P_{av}(r_{ex})}{P_{av}(0)} \right) = 10 \log \left( \frac{1+r_{ex}}{1-r_{ex}} \right)$$

- Following Fig. shows the power penalty as a function of the extinction ratio.

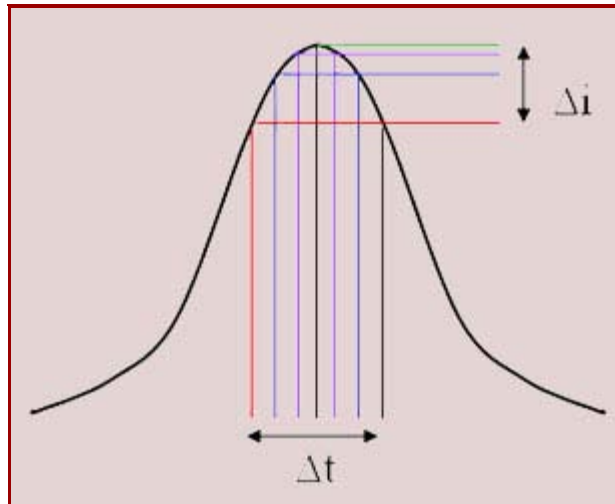


- The power penalty may become significant if the semiconductor laser is biased above the threshold. For lasers biased below threshold, the extinction ratio is typically 0.05 and the power penalty is less than 0.4 dB.

### Timing Jitter

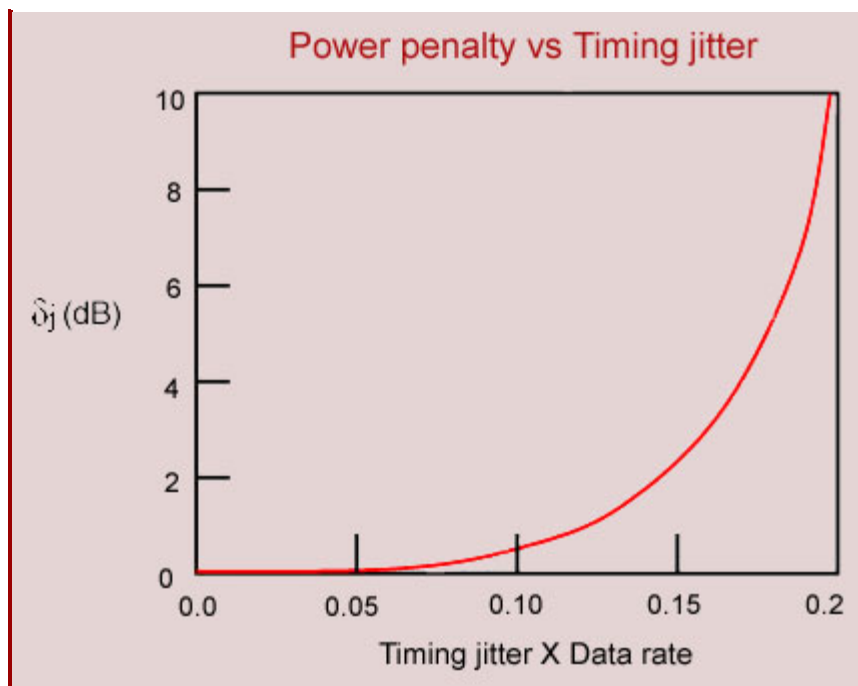
- In a digital system the signal is generally sampled at the center of the pulse.
- Due to inaccuracy of the clock recovery at the receiver, the sampling of the pulse is not precisely at the center of the pulse but is little shifted in time.
- The sampling instant jitters around the mean with some variance.
- As such if the pulse has constant amplitude, the timing jitter does not affect the sampler output. However, due to dispersion and due to reshaping, the pulses are rectangular. The sampling jitter then gets converted to the amplitude fluctuation which appears as the noise

on the output as shown in Fig.



- The sampling jitter  $\Delta t$  is a random variable and hence the fluctuation in current is also a random variable.
- Due to the fluctuations the mean of the peak current is reduced, decreasing the SNR.
- The SNR can be restored by increasing the pulse amplitude. Hence there is a power penalty for timing jitter.
- For raised cosine pulse shaping, this can be analytically calculated.
- A plot of power penalty due to timing jitter is shown in the Fig.





- The timing jitter penalty obviously depends upon the fractional timing error in comparison to the bit duration. The plot therefore gives the power penalty as function of product of the rms value of the timing jitter and the data rate (inverse of bit duration).
- It can be noted that the power penalty very rapidly increases with the timing jitter. When the rms value of the timing jitter is about 0.15, the power penalty becomes infinite. For a Gaussian variable, the peak to peak deviation is about 6 times the standard deviation. A 0.15 fractional jitter means peak to peak variation in sampling time equal to the bit duration. In this case then, the bits can not be sampled properly, and hence the power penalty is infinite, meaning irrespective of the power, the system will never be able to get the data correctly.

## Recap

In this lecture you have learnt the following

- Degradation during Propagation
- Modal Noise
- Dispersion
- System Degradation due to Imperfect Components
- Extinction Ratio



- Relative Intensity Noise(RIN)
- Timing Jitter

Congratulations, you have finished Module 12. To view the next lecture select it from the left hand side menu of the page