

# *COMS3100/7100*

## *Introduction to Communications*

### ***Lecture 24/25: Communications Link Design***

This lecture:

- Transmission loss, gain and decibels
- Optical Link Design
  - Link Power Budget
  - Rise-Time Budget
  - Line Coding

*Ref: Carlson*, Chapter 3.3; *J. C. Palais*, “Fiber optic communications” Prentice Hall, 1998; *G. Keiser*, “Optical Communications essentials” McGraw Hill 2003

## *Transmission Loss and Decibels*

- Transmission system introduces loss of signal strength as well as the distortion of the signal.
- Signal strength reduction is expressed in terms of transmission power loss
- Loss of power can be compensated by amplification, but this increases the noise
- Power loss or gain is frequently expressed using logarithmic units - *decibels*

## Power Gain

- The system's **power gain** is defined as

$$g \hat{=} \frac{P_{out}}{P_{in}}$$

- It is convenient to express power gain in **decibels** (dB) defined as

$$g_{dB} \hat{=} 10 \log \frac{P_{out}}{P_{in}} = 10 \log(g)$$

- N.B: 0 dB is **unity gain**; Given a gain value in dB the ratio value is

$$g = 10^{(g_{dB}/10)}$$

- Frequently the **signal power** may be expressed in dB units as a power relative to 1mW

$$P_{dBm} \hat{=} 10 \log \frac{P_{out}}{1mW}$$



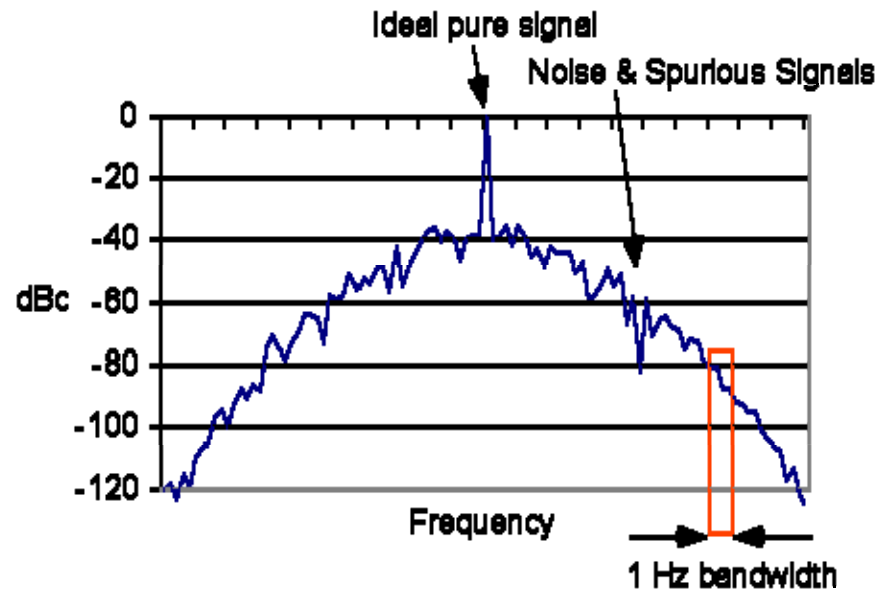
## Power Gain (cont)

- Frequently the **signal power** may be expressed in dB units as a power relative to 1mW

$$P_{\text{dBm}} \cong 10 \log \frac{P_{\text{out}}}{1\text{mW}}$$

- Another unit frequently found in communications literature is **power referenced to the carrier** – dBc. Similarly, dBc/Hz is decibels relative to the carrier per Hertz. These units are used to describe in decibels how far down signals and noise are relative to a known signal.

$$P_{\text{dBc}} \cong 10 \log \frac{P_{\text{sig}}}{P_{\text{carr}}}$$





## Transmission Loss and Repeaters (amplifiers)

- Any passive transmission medium has power loss rather than gain since  $P_{out} < P_{in}$ . In such cases we prefer to work with **power loss** or **attenuation**

$$L \hat{=} \frac{1}{g} = \frac{P_{in}}{P_{out}}$$

- Loss in **decibels** is given by

$$L_{dB} = -g_{dB} = 10 \log \frac{P_{in}}{P_{out}}$$

- In fibres, waveguides and cables power decreases exponentially with the distance.

$$P_{out} = 10^{-(\alpha \ell / 10)} P_{in}$$

- Where  $\alpha$  is the attenuation coefficient and  $\ell$  is the length of the cable.

$$L = 10^{(\alpha \ell / 10)} \quad L_{dB} = \alpha \ell$$

## *Optical Link Design – System Considerations*

- Interrelated performance parameters of individual components
- Link design is usually done in several iterations and as a combination of the “back-of-the-envelope” calculation shown here and the use of the sophisticated CAD tools.
- ***System requirements*** needed in analysing a fibre-optic link
  - The transmission distance
  - The data rate or channel bandwidth
  - The bit-error-rate (BER)
  - The number of WDM channels
  - The link margin
  - Acceptable power penalties

# Optical Link Design – Components used

- Types and characteristics of typical components used for optical link design

Component	Type	Characteristics
Optical fibers	Single-mode or multimode	Attenuation, dispersion, CWDM or DWDM use
Light source	LED, DFB laser, VCSEL, or other	Modulation rate, output power, wavelength, spectral width, cost
Photodetector	<i>pin</i> or APD	Sensitivity, responsivity
Connectors	Single- or multiple-channel	Loss, size, mounting type
Wavelength multiplexers	AWG, TFF, grating-based	Cost, channel width
Optical amplifiers	EDFA, Raman, SOA	Complex long-haul, lower-cost metro, gain, wavelength range
Passive components	Optical filters, OADM, dispersion compensators, optical isolators, couplers	Peak wavelength, spectral range, loss, size, cost, reliability
Active components	VOA, dynamic gain equalizers, tunable optical filters, optical add/drop multiplexers	Tuning speed, peak wavelength, spectral range, loss, size, cost, reliability
Monitoring devices	BER tester, spectrum analyzer, power meter	Optical power, wavelength, OSNR

## *Optical Link Design – Link margin*

- ***Link margin***: (or loss margin or a ***system margin***) is an optical safety factor for link design.
- Involves adding extra Db to the power requirements to compensate for possible unforeseen link degradation factors.
- Degradation could arise from loss of laser power over time, aging of the link components, bad splices or connectors etc.
- ITU-T Recommendation is to have a ***link margin between 3.0 and 4.8 dB***
- Typically more than that is used! (3 to 10 dB)

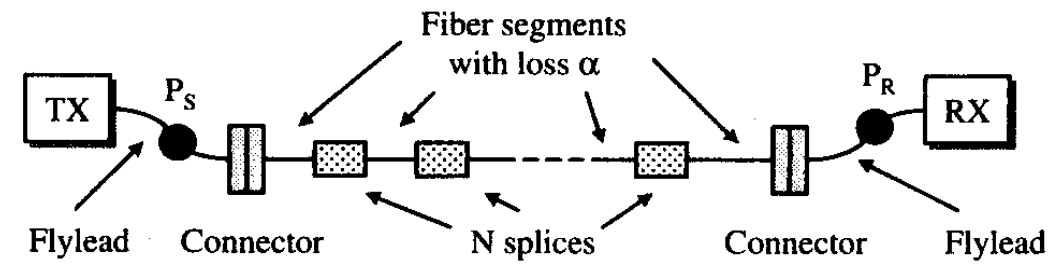
## *Optical Link Design – Power Penalties*

- Certain operational factors in a link usually contribute to signal degradation. Among these are
  - Modal noise (power fluctuation due to inter-mode coupling in the fibre)
  - Chromatic dispersion (CD) in the fibre (different wavelengths propagating at different speed– causes pulse spreading and inter-symbol interference)
  - Polarisation mode dispersion (PMD) is caused by different speed of propagation of two orthogonally polarised waves in the fibre
  - Reflection noise in the link (
  - Low extinction ration in the laser transmitter (ratio of “on” and “off” laser power)
  - Frequency chirping (dynamic spectral broadening of the laser signal –FM)
- These factors reduce the signal-to-noise ratio (SNR) in the link in comparison to the ideal link. This reduction in SNR is known as the *power penalty*

## *Optical Link Design – Link Power Budget*

- First need to determine the **power margin** between the optical transmitter output and the minimum receiver sensitivity needed to establish a required Bit-Error-Ratio BER (for digital systems) or signal-to-noise ratio SNR (for analogue systems).
- This margin can be allocated to fibre, splice, connector losses, plus additional margins required for other components
- **Link Power Budget**
  1. Designer needs to determine the carrier wavelength (frequency) to be used and select the components based on that.
  2. Interrelate the link performance to main components Tx, Rx and the fibre. Choose the two components and specify the third to satisfy the link requirement

# Optical Link Design –Power budgeting process



A hypothetical point-to-point link that contains  $N$  periodic splices along the cable and has connectors on each end.

- Consider total optical power loss  $P_T$  that is allowed between the TX (light source) and the RX (photodetector) and allocate loss to factors such as cable attenuation, connector and splice losses, losses in other link components, and system margin

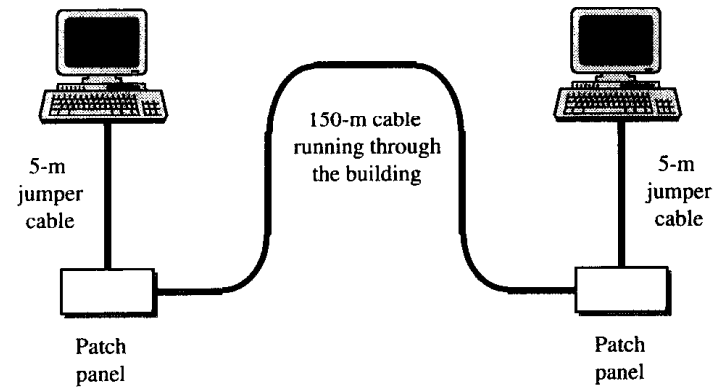
$$\begin{aligned}
 P_T &= P_S - P_R \\
 &= 2 \times \text{connector loss} + \alpha L + N \times \text{splice loss} \\
 &\quad + \text{other losses} + \text{system margin}
 \end{aligned}$$

All powers and losses in dB or dBm

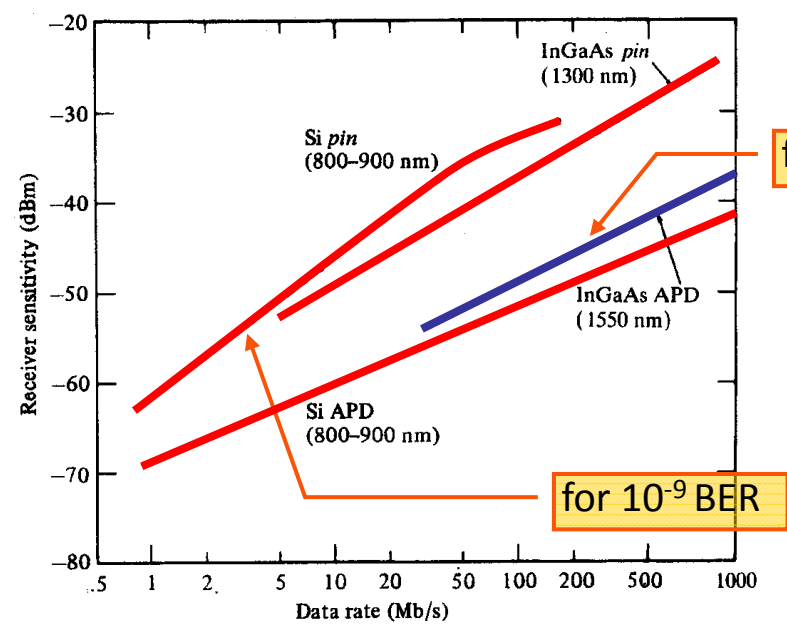
# Optical Link Design – Fast Ethernet LAN example

## Example of a 100BASE-T link

- **Wavelength** used – 850 nm
- **Fibre** loss 2.5 dB/km
- Four **connectors**, no splices
- Assume **BER** is  $10^{-9}$  (one error for every  $10^9$  bits sent)
- Silicon pin **detector** requires at 100 MB/s at least -32dBm (or 630 nW) input optical power for  $BER = 10^{-9}$
- **Transmitter** (LED) couples -20 dBm ( $10 \mu\text{W}$ ) of optical power into the fibre
- **Connector** loss – max 0.7 dB per connector



Two computers connected by a 150-m fiber link plus two jumper cables within a building.



## Optical Link Design – Fast Ethernet LAN example

- Example of a 100BASE-T link

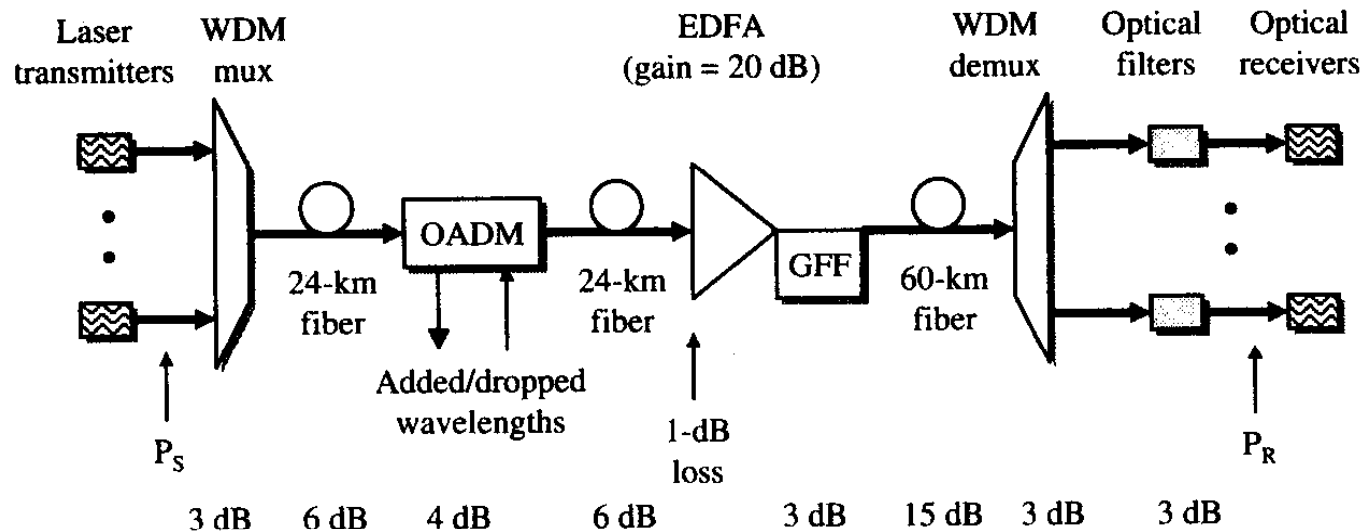
$$P_T = P_S - P_R = -20 \text{ dBm} - (-32 \text{ dBm}) = 12 \text{ dB}$$

Component/loss parameter	Output/sensitivity/loss	Power margin, dB
Coupled LED output	-20 dBm	
<i>pin</i> sensitivity at 100 Mbps	-32 dBm	
Allowed loss [-20 - (-32)]		12
Source connector loss	-0.7 dB	11.3
2 × Jumper connector loss	-1.4 dB	9.9
Cable attenuation (160 m)	-0.4 dB	9.5
Receiver connector loss	-0.7 dB	8.8 (final margin)

The final power margin is 8.8 dB, which is a sufficient margin for this link.

## Optical Link Design – DWDM link example

- Four channel link, each channel running at 10 Gbps
- System has to operate in the C-band and contains two optical add-drop multiplexers (**OADM**), **EDFA** with 20dB gain, gain flattening filter (**GFF**) and optical filters at the receiver end.
- **Fibre** attenuation 0.25 dB/km
- **Laser** power coupled into fibre  $P_S = 2$  dBm; InGaAs **APD** needs a power level of at least  $P_R = -24$  dBm to maintain a **required  $10^{-11}$  BER**



- Optical power losses of various components in WDM link are indicated

## Optical Link Design – DWDM link example

- Spreadsheet for calculating the WDM link power budget

Component/loss parameter	Output/sensitivity/loss	Power margin, dB
Coupled laser diode output	+2 dBm	
APD sensitivity at 10 Gbps	-24 dBm	
Allowed loss [+2 - (-24)]		26.0
WDM mux loss	-3 dB	23.0
Cable attenuation (24 km)	-6 dB	17.0
OADM loss	-4 dB	13.0
Cable attenuation (24 km)	-6 dB	7.0
EDFA coupling loss	-1 dB	6.0
EDFA gain	+20 dB	26.0
GFF loss	-3 dB	23.0
Cable attenuation (60 km)	-15 dB	8.0
WDM demux loss	-3 dB	5.0
Optical filter loss	-3 dB	2.0 (final margin)

- 2 dB margin **not enough** – no power penalties included, *needs additional amplifier*



## Rise-Time budget

- A convenient method for determining the dispersion limitation of an optical link, in particular digital link
- System rise time is the root-sum-square of the rise times from each contributor

$$t_{sys} = \sqrt{\left( \sum_{i=1}^N t_i^2 \right)}$$

- Main contributors are the
  - Laser rise-time  $t_{TX}$
  - Modal dispersion rise time  $t_{mod}$  of a multimode fibre
  - Chromatic dispersion (CD) rise time  $t_{CD}$  of the fibre
  - Polarisation mode dispersion (PMD) rise time  $t_{PMD}$  of the fibre
  - Receiver rise-time  $t_{RX}$

$$t_{sys} = \sqrt{t_{TX}^2 + t_{mod}^2 + t_{CD}^2 + t_{PMD}^2 + t_{RX}^2}$$

- For single mode fibre modal dispersion rise time  $t_{mod} = 0$



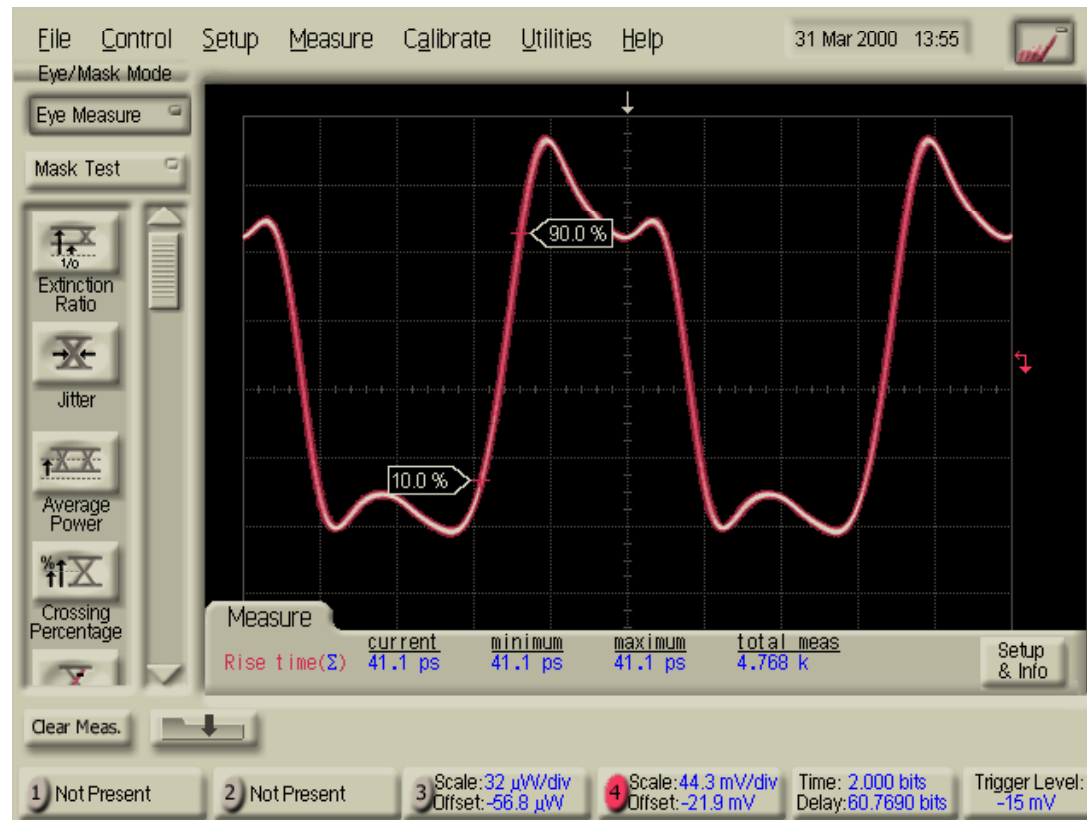
## Rise time and the Receiver bandwidth $B$

- **Rise Time:** time it takes the RX output to increase from the 10% to the 90% point of the waveform
- Should not exceed 70% of NRZ (non-return to zero) bit period or 35% for the RZ (return to zero) data.
- 1-bit period is  $T_B = 1/(\text{bitrate})$

$$\begin{aligned} t_{rise} &= 2.2RC \\ &= 2.2 \left( \frac{1}{\omega_c} \right) \\ &= \frac{0.35}{f_c} \end{aligned}$$

$$t_{rise} = \frac{0.35}{B}$$

$$t_{rise} [\text{ns}] = \frac{350}{B[\text{MHz}]}$$



## Other Basic Rise-Times

- Chromatic dispersion (CD) rise time  $t_{CD}$  of the fibre

$$t_{CD} \approx |D_{CD}|L\Delta\lambda$$

- $\Delta\lambda$  is the spectral linewidth of the source
- $L$  is the length of the link
- $D_{CD}$  is the fibre chromatic dispersion coefficient

- Polarisation mode dispersion (PMD) rise time  $t_{PMD}$  of the fibre

$$t_{PMD} \approx |D_{PMD}|\sqrt{\text{fibre length}}$$

Where  $D_{PMD}$  is the polarisation dispersion measured in unites of ps/km<sup>1/2</sup>

- Modal dispersion rise time  $t_{mod}$  of a multimode fibre

$$t_{mod} = \frac{440L}{B_{mod}}$$

Where  $B_{mod}$  is the modal dispersion bandwidth (in MHz·km) determining the information carrying capacity of the multimode fibre



## Example of maximum length of Gigabit Ethernet Links

Now suppose the LAN consists of Gigabit Ethernet links that use VCSEL sources and 62.5- $\mu\text{m}$  fibers. Also assume that now the link length is 220 m. In this case we have the following conditions:

- A VCSEL with a 0.1-ns rise time and a 1-nm spectral width
- A *pin* photodiode receiver with a front-end bandwidth  $B_{\text{RX}} = 1000 \text{ MHz}$
- A multimode fiber with  $D_{\text{CD}} = -20 \text{ ps}/(\text{nm}\cdot\text{km})$  and  $B_{\text{mod}} = 160 \text{ MHz}\cdot\text{km}$  at 850 nm

Then  $t_{\text{mod}} = 0.60 \text{ ns}$ ,  $t_{\text{CD}} = 0.01 \text{ ns}$ , and  $t_{\text{RX}} = 0.35 \text{ ns}$ , so that (again leaving out the negligible PMD effects) the total rise time is

$$\begin{aligned} t_{\text{sys}} &= (t_{\text{TX}}^2 + t_{\text{mod}}^2 + t_{\text{CD}}^2 + t_{\text{RX}}^2)^{1/2} \\ &= [(0.10)^2 + (0.60)^2 + (0.01)^2 + (0.35)^2]^{1/2} = 0.70 \text{ ns} \end{aligned}$$

Since the Gigabit Ethernet signal uses an NRZ format, the rise time needs to be less than  $0.7/(1000 \text{ Mbps}) = 0.70 \text{ ns}$ . Here the rise-time criterion is just satisfied, so that the maximum link length is 220 m for Gigabit Ethernet operating at 850 nm on 62.5- $\mu\text{m}$  fibers. The maximum length for Gigabit Ethernet running on 50- $\mu\text{m}$  fibers is 550 m due to the higher bandwidth of these fibers.

## Example of a SONET Link rise time

The following components are used in the 2.5-Gbps SONET link in Sec. 16.2.3:

- A laser transmitter with a 0.1-ns rise time and a 1.0-nm spectral width
- An APD receiver with a front-end bandwidth  $B_{RX} = 2500$  MHz
- A G.655 single-mode fiber with  $D_{CD} = 4$  ps/(nm·km) and  $D_{PMD} = 0.1$  ps/ $\sqrt{\text{km}}$  at 1310 nm

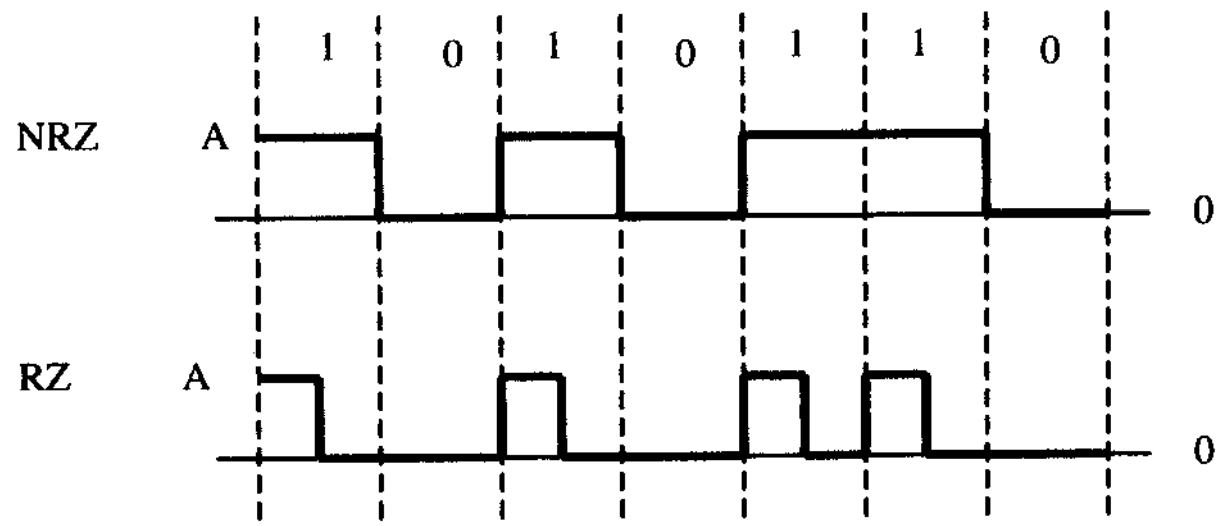
Then  $t_{CD} = 0.12$  ns,  $t_{PMD} = 0.001$  ns, and  $t_{RX} = 0.14$  ns, so that the total rise time is

$$\begin{aligned} t_{\text{sys}} &= (t_{\text{TX}}^2 + t_{\text{CD}}^2 + t_{\text{PMD}}^2 + t_{\text{RX}}^2)^{1/2} \\ &= [(0.10)^2 + (0.12)^2 + (0.001)^2 + (0.14)^2]^{1/2} = 0.21 \text{ ns} \end{aligned}$$

Since the SONET signal uses an NRZ format, the rise time needs to be less than  $0.7/(2500 \text{ Mbps}) = 0.28$  ns, so there is enough rise-time margin in this case.

# Coding

- RZ and NRZ formats

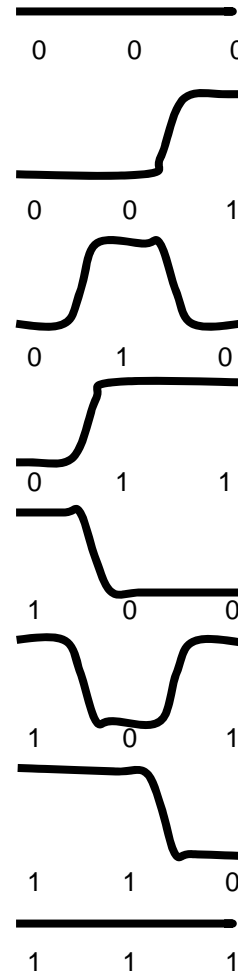


- NRZ format – lack of timing capabilities can lead to misinterpretation of the bit stream at the receiver



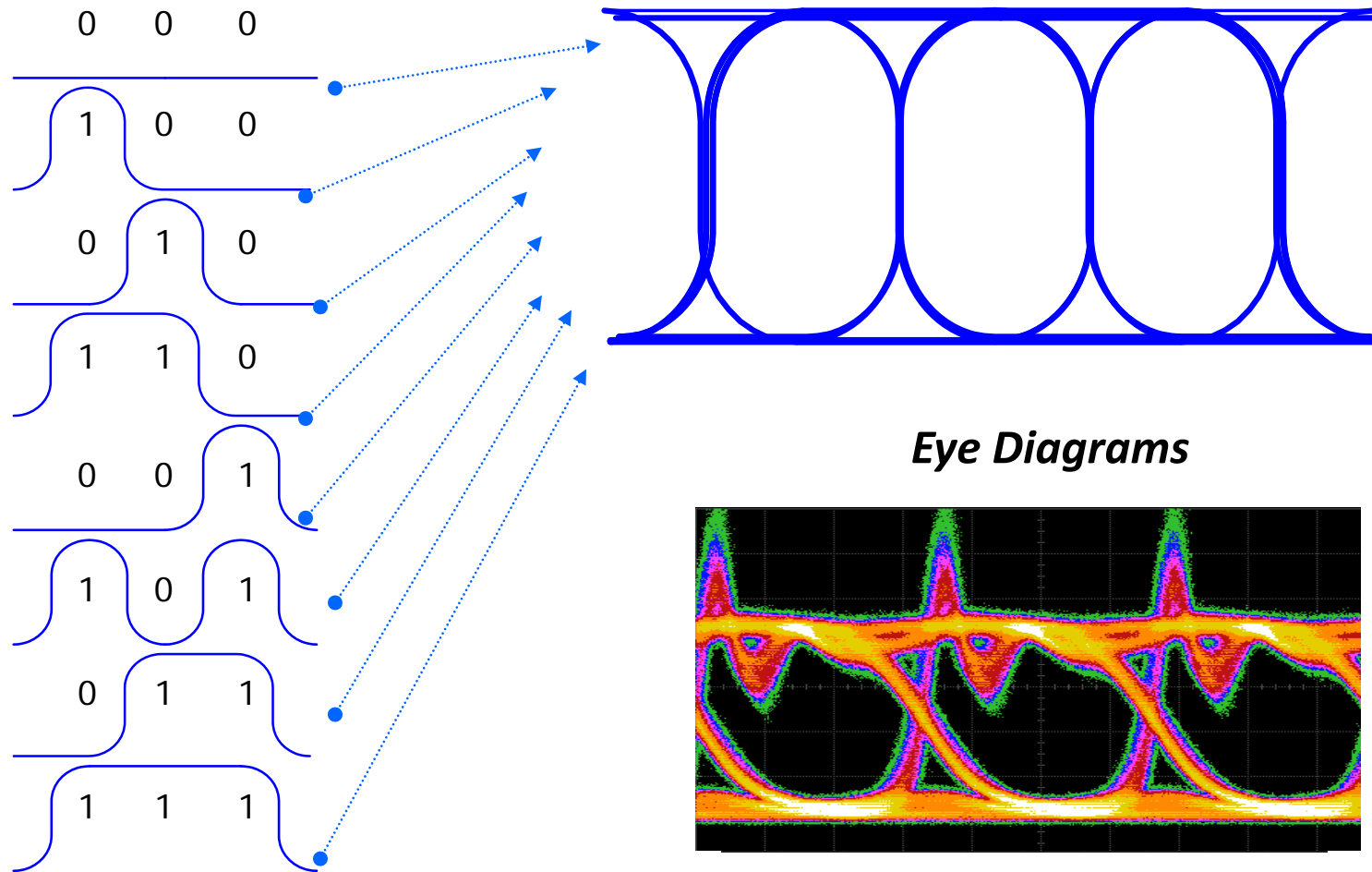
## What is the Eye Diagram?

- The eye diagram is a composite view of a very long data stream.
- It allows you to see all data patterns and combinations in a single display.
- It is achieved by using a clock signal to trigger the oscilloscope.





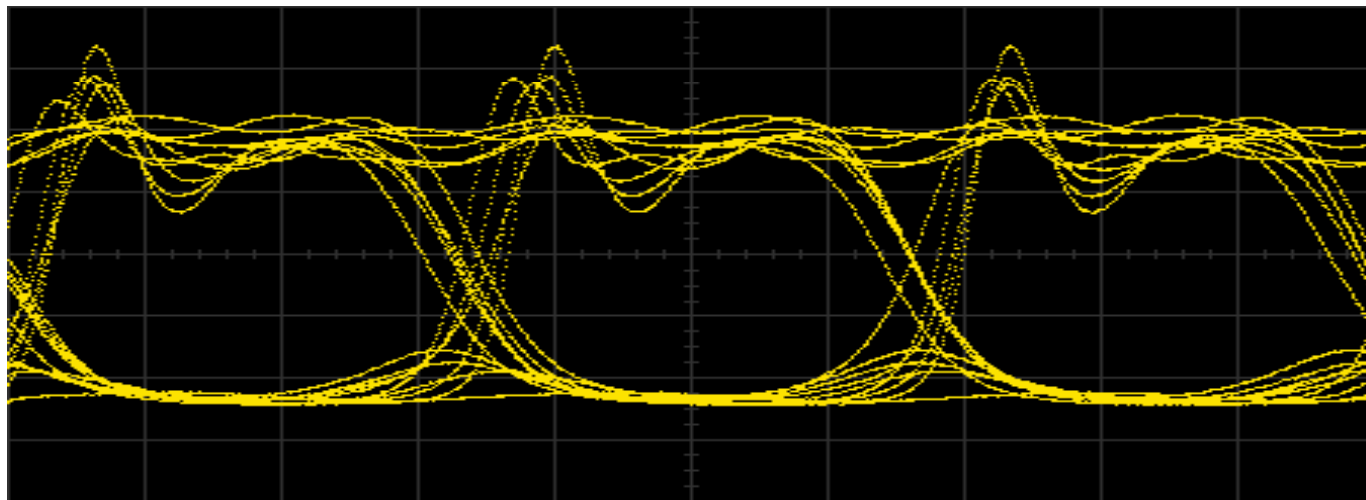
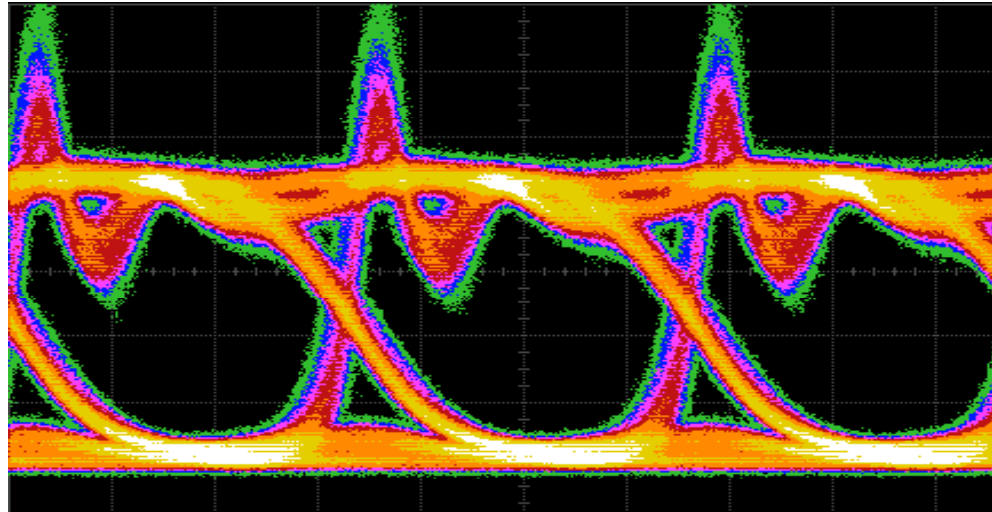
# The Eye Diagram is a Statistical Representation



An eye diagram is a statistical representation of a bit stream, based on the contribution of randomly selected bits

# The Unfiltered Eye

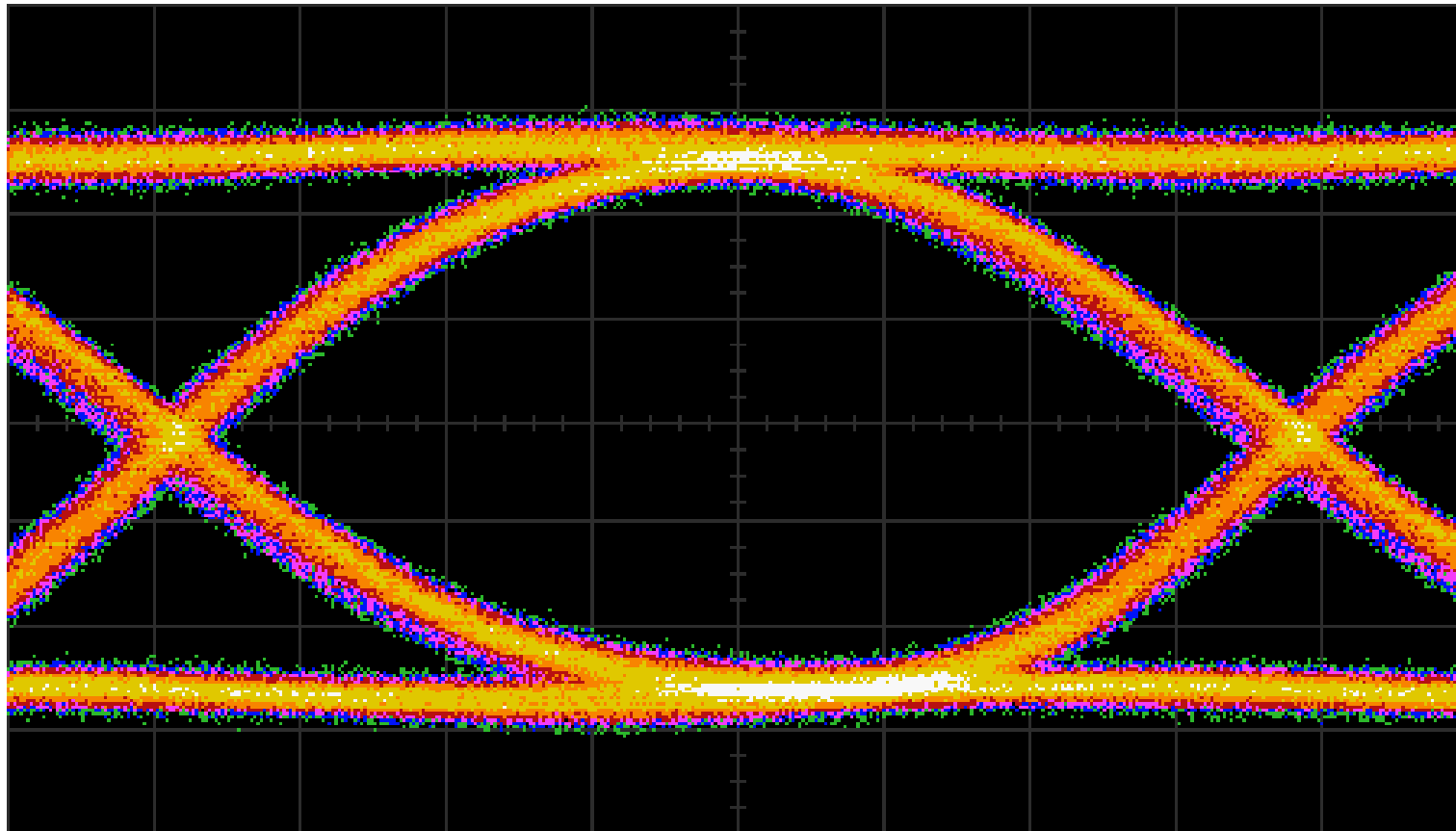
Higher Order Effects –  
The bandwidth of the  
oscilloscope captures  
fast transients and  
harmonics





## *The Filtered Eye*

The filter limits higher order effects for compliance measurements.



4<sup>th</sup>-order Bessel Thompson low-pass filter bandwidth =  $0.75 * \text{bit rate}$



## Radio Link

- We will look at the power loss in a *line-of-sight* RF link

$$P_{CD} = -5 \log[1 - (4BLD\Delta\lambda)^2]$$

$$P_{ER} = -10 \log \frac{r_e - 1}{r_e + 1}$$