Light Wave Systems

Overview

- In this section we cover point-to-point digital transmission link design issues (Ch8):
  - Link power budget calculations
  - Link rise time calculations

A link should satisfy both these budgets

- The basic system design verification can be done through:

1- Power budget: The Ratio of P_T/P_R expressed in dB is the amount of acceptable loss that can be incurred.
2- Rise time budget: A rise-time budget analysis is a convenient method to determine the dispersion limitation of an optical link.

- The power budget involves the power level calculations from the transmitter to the receiver.

1. Attenuation
2. Coupled power
3. Other losses
4. Equalization penalty (D_L)
5. SNR requirements
6. Minimum power at detector
7. BER
8. Safety margin (M_a)

Photonic Digital Link Analysis & Design

- Point-to-Point Link Requirement:

 - Data Rate

 - BER

 - Distance

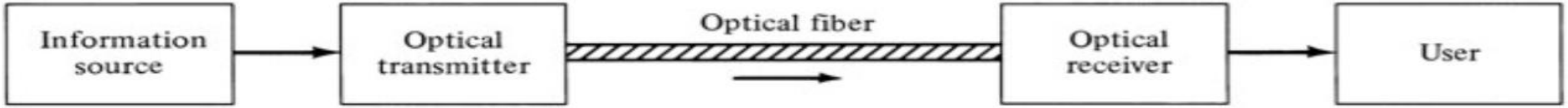
 - Cost & Complexity

- Analysis Methods:

 - Link loss & S/N analysis (link power budget analysis and loss allocation) for a prescribed BER

 - Dispersion (rise-time) analysis (rise-time budget allocation)

Fig. 8-1: Simple point-to-point link



This p-p link forms the basis for examining more complex systems

System Requirements

1. Transmission Distance
2. Data Rate for a given BER
3. Cost

Selecting the Fiber

Bit rate and distance are the major factors

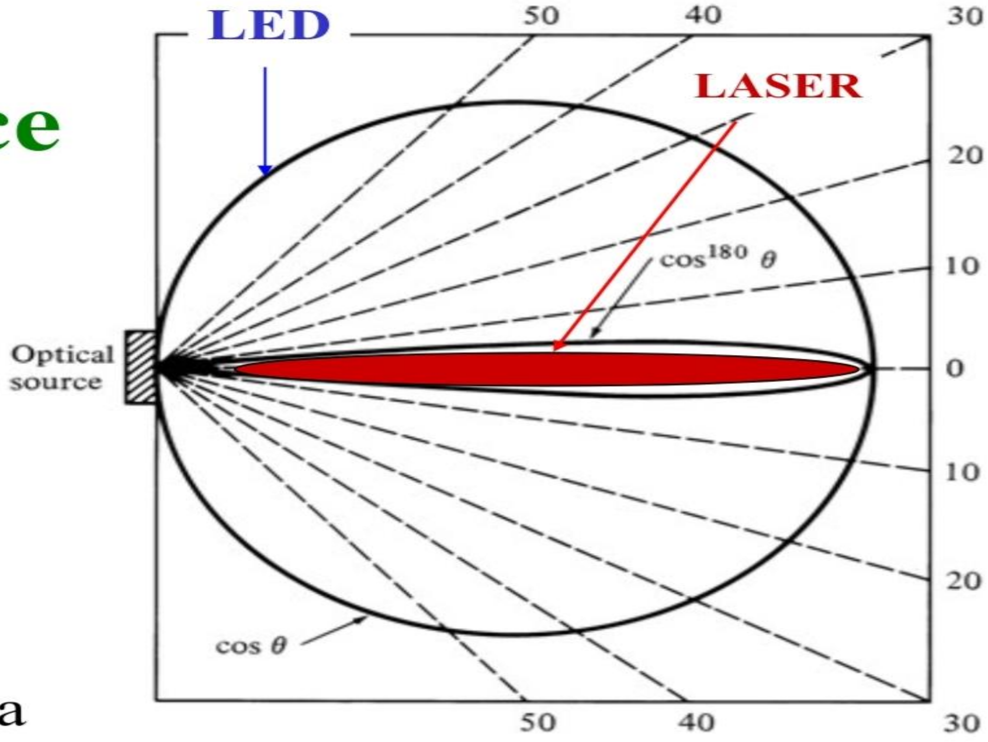
Other factors to consider: attenuation (depends on?) and distance-bandwidth product (depends on?) cost of the connectors, splicing etc.

Then decide

- Multimode or single mode
- Step or graded index fiber

Selecting the Optical Source

- Emission wavelength
- Spectral line width (FWHM) and number of modes
- Output power
- Stability
- Emission pattern
- Effective radiating area



Selecting the detector

- Type of detector
  - **APD**: High sensitivity but complex, high bias voltage (40V or more) and expensive
  - **PIN:** Simpler, thermally stable, low bias voltage (5V or less) and less expensive
- Responsivity (that depends on the avalanche gain & quantum efficiency)
- Operating wavelength and spectral selectivity
- Speed (capacitance) and photosensitive area
- Sensitivity (depends on noise and gain)

Typical bit rates at different wavelengths

Wavelength	**LED** Systems	**LASER** Systems.
800-900 nm (Typically Multimode Fiber)	150 Mb/s.km	2500 Mb/s.km
1300 nm (Lowest dispersion)	1500 Mb/s.km	25 Gb/s.km (InGaAsP Laser)
1550 nm (Lowest Attenuation)	1200 Mb/s.km	Up to 500 Gb/s.km (Best demo)

System Design Choices: Photodetector, Optical Source, Fiber

- Photodetectors: Compared to APD, PINs are less expensive and more stablewith temperature. However PINs have lower sensitivity.
- Optical Sources:

1- LEDs: 150 (Mb/s).km @ 800-900 nm and larger than 1.5 (Gb/s).km @ 1330 nm

2- InGaAsP lasers: 25 (Gb/s).km @ 1330 nm and ideally around 500 (Gb/s).km @ 1550 nm. 10-15 dB more power. However more costly and more complex circuitry.

- Fiber:

1- Single-mode fibers are often used with lasers or edge-emitting LEDs.

2- Multi-mode fibers are normally used with LEDs. NA and Δ should be optimized for any particular application.

Design Considerations

- Link Power Budget
  - There is enough power margin in the system to meet the given BER
- Rise Time Budget
  - Each element of the link is fast enough to meet the given bit rate

These two budgets give necessary conditions for satisfactory operation

Design Components

1. Multimode or single-mode optical fiber
   (*a*) Core size
   (*b*) Core refractive-index profile
   (*c*) Bandwidth or dispersion
   (*d*) Attenuation
   (*e*) Numerical aperture or mode-field diameter
2. LED or laser diode optical source
   (*a*) Emission wavelength
   (*b*) Spectral line width
   (*c*) Output power
   (*d*) Effective radiating area
   (*e*) Emission pattern
   (*f*) Number of emitting modes
3. *pin* or avalanche photodiode
   (*a*) Responsivity
   (*b*) Operating wavelength
   (*c*) Speed
   (*d*) Sensitivity

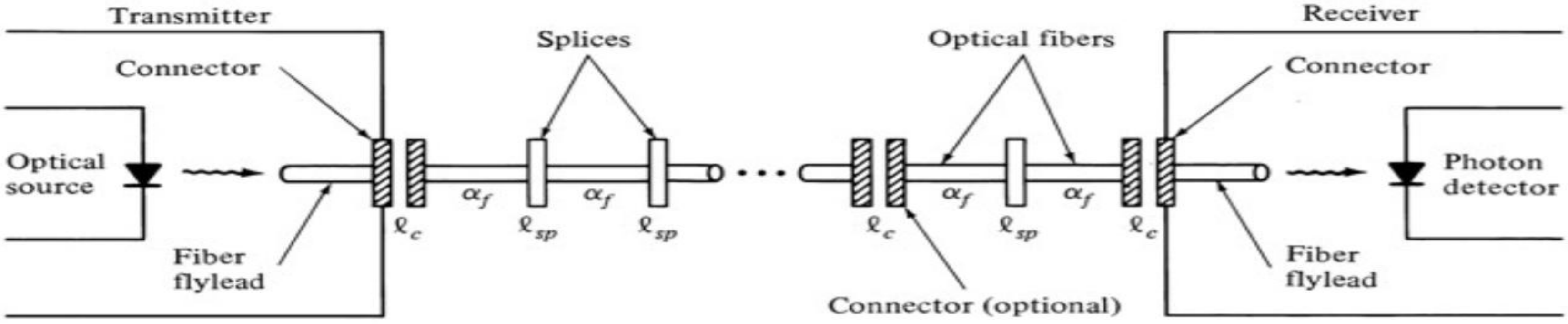
System factors for designing from scratch: Design Verification

Factor	*Available choices*
Type of fiber	Single mode, multimode, plastic
Dispersion	Repeaters, compensation
Fiber nonlinearities	Fiber characteristics, wavelengths used, transmitter power
Operating wavelength (band)	780, 850, 1310, 1550, 1625 nm typical
Transmitter power	~0.1 to 20 mw typical; usually expressed in dBm
Light source	LED, laser
Receiver characteristics	Sensitivity, overload
Multiplexing scheme	None, CWDM, DWDM

System factors (continued)

Factor	*Available choices*
Detector type	PIN diode, APD, IDP
Modulation scheme	OOK, multilevel, coherent
End-end bit error rate	$<10^{-9}$ typical; may be much lower
Signal-to-noise ratio	Specified in dB for major stages
Max number of connectors	Loss increases with number of connectors
Max number of splices	Loss increases with number of splices
Environmental	Humidity, temperature, sunlight exposure
Mechanical	Flammability, strength, indoor/outdoor/submarine

Fig. 8-2: Optical power-loss model



$$P_T = P_s - P_R = ml_c + nl_{sp} + \alpha_f L + System\ \mathrm{Margin}$$

P_T: Total loss; P_s : Source power; P_R: Rx sensitivity

m connectors; n splices

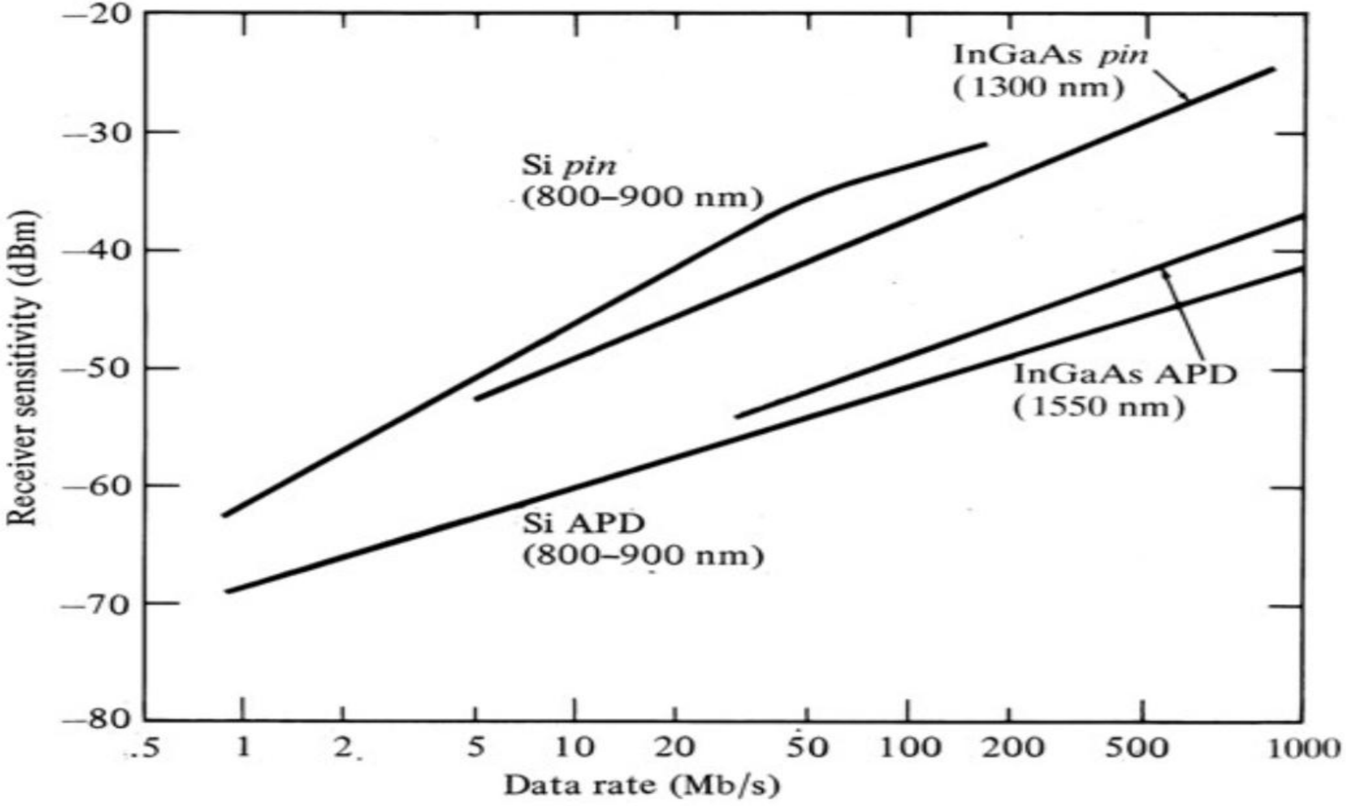
Try Ex: 8.1

Example 8-1. To illustrate how a link loss budget is set up, let us carry out a specific design example. We shall begin by specifying a data rate of 20 Mb/s and a bit-error rate of 10^{-9} (i.e., at most one error can occur for every 10^9 bits sent). For the receiver, we shall choose a silicon *pin* photodiode operating at 850 nm. Figure 8-3 shows that the required receiver input signal is −42 dBm (42 dB below 1 mW). We next select a GaAlAs LED that can couple a 50-μW (−13-dBm) average optical power level into a fiber flylead with a 50-μm core diameter. We thus have a 29-dB allowable power loss. Assume further that a 1-dB loss occurs when the fiber flylead is connected to the cable and another 1-dB connector loss occurs at the cable–photodetector interface. Including a 6-dB system margin, the possible transmission distance for a cable with an attenuation of α_f dB/km can be found from Eq. (8-2):

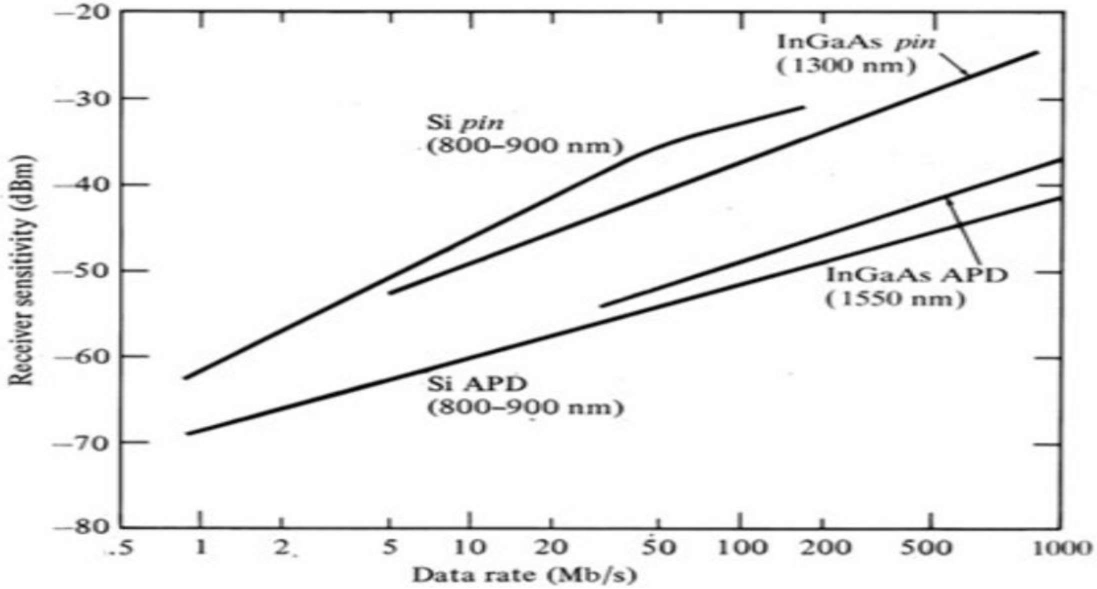
$$
\begin{aligned}
P_T &= P_S - P_R = 29\,\text{dB} \\
&= 2(1\ \text{dB}) + \alpha_f L + 6\,\text{dB}
\end{aligned}
$$

If $\alpha_f = 3.5$ dB/km, then a 6.0-km transmission path is possible.

Fig. 8-3: Receiver sensitivities Vs bit rate



Receiver Sensitivities vs. Bit Rate



The Si PIN & APD and InGaAsP PIN plots for BER= 10^-9 .
The InGaAs APD plot is for BER=10^-11 .

The link power budget can be represented graphically as is shown in Fig. 8-4. The vertical axis represents the optical power loss allowed between the transmitter and the receiver. The horizontal axis give the transmission distance. Here, we show a silicon *pin* receiver with a sensitivity of −42 dBm (at 20 Mb/s) and an LED with an output power of −13 dBm coupled into a fiber flylead. We subtract a 1-dB connector loss at each end, which leaves a total margin of 27 dB. Subtracting a 6-dB system safety margin leaves us with a tolerable loss of 21 dB that can be allocated to cable and splice loss. The slope of the line shown in Fig. 8-4 is the 3.5-dB/km cable (and splice, in this case) loss. This line starts at the −14-dBm point (which is the optical power coupled into the cabled fiber) and ends at the −35-dBm level (the receiver sensitivity minus a 1-dB connector loss and a 6-dB system margin). The intersection point *D* then defines the maximum possible transmission path length.

A convenient procedure for calculating the power budget is to use a tabular or spreadsheet form. We will illustrate this by way of an example for a SONET OC-48 (2.5 Gb/s) link.

Example 8.4

An optical link was designed to transmit data at a rate of 20 Mbps using RZ coding. The length of the link is 7 km and uses an LED at 0.85μm. The channel used is a GRIN fiber with 50μm core and attenuation of 2.6dB/km.

The cable requires splicing every kilometer with a loss of 0.5dB per splice. The connector used at the receiver has a loss of 1.5dB. The power launched into the fiber is 100μW. The minimum power required at the receiver is –41dBm to give a BER of 10^{-10}. It is also predicted that a safety margin of 6dB will be required.

Show by suitable method that the choice of components is suitable for the link.

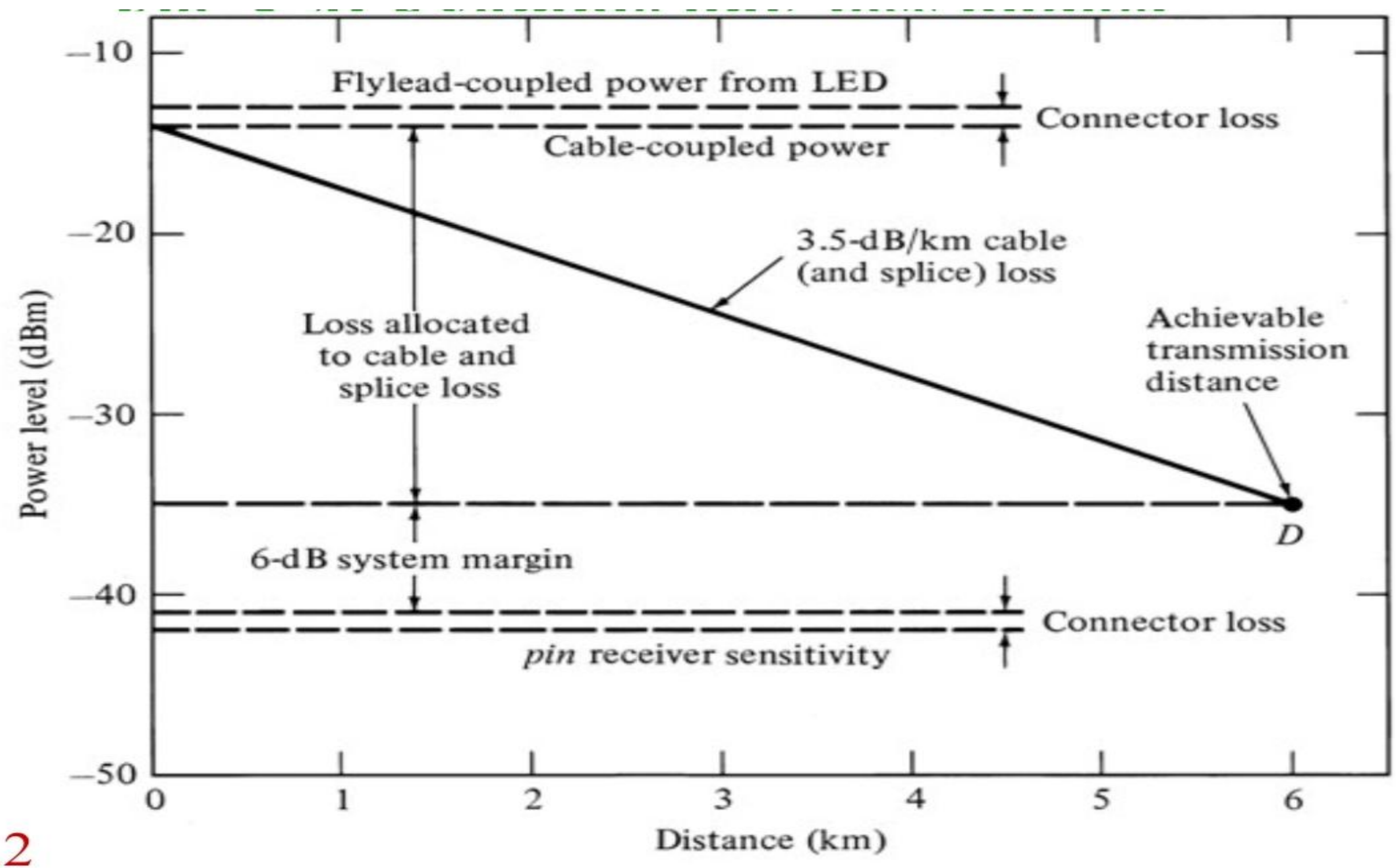
Solution

The power launched into the fiber		$100\mu W$ = -10 dBm
Minimum power required at the receiver		- 41dBm
Total system margin		- 31 dBm

Fiber loss	7 x 2.6	18.2dB
Splice loss	6 x 0.5	3.0 dB
Connector loss		6.0 dB
Safety margin		28.7dB

Excess power margin = -31 dBm - 28.7 dB = 2.3 dBm

Based on the figure given, the system is stable and provides an excess of 2.3 dB power margin. The system is suitable for the link and has safety margin to support future splices if needed..



Try Ex. 8.2

FIGURE 8-4
Graphical representation of a link-loss budget for an 800-nm LED/*pin* system operating at 20 Mb/s.

Example 8-2. Consider a 1550-nm laser diode that launched a +3-dBm (2-mW) optical power level into a fiber flylead, an InGaAs APD with a −32-dBm sensitivity at 2.5 Gb/s, and a 60-km long optical cable with a 0.3-dB/km attenuation. Assume that here, because of the way the equipment is arranged, a short optical jumper cable is needed at each end between the end of the transmission cable and the SONET equipment rack. Assume that each jumper cable introduces a loss of 3 dB. In addition, assume a 1-dB connector loss occurs at each fiber joint (two at each end because of the jumper cables).

Table 8-1 lists the components in column 1 and the associated optical output, sensitivity, or loss in column 2. Column 3 gives the power margin available after subtracting the component loss from the total optical power loss that is allowed between the light source and the photodetector, which, in this case, is 35 dB. Adding all the losses results in a final power margin of 7 dB.

TABLE 8-1
Example of a spreadsheet for calculating an optical-link power budget

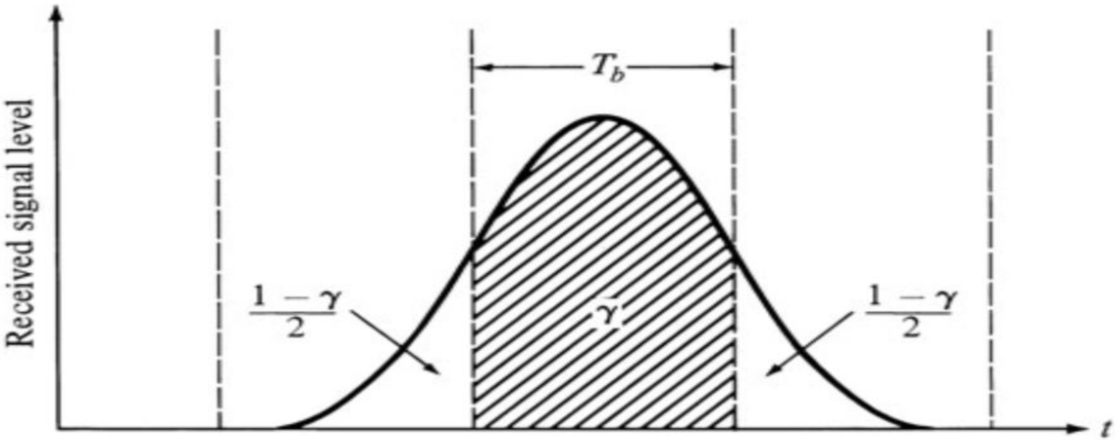
Component/loss parameter	Output/sensitivity/loss	Power margin (dB)
Laser output	3 dBm	
APD sensitivity at 2.5 Gb/s	−32 dBm	
Allowed loss [3 − (−32)]		35
Source connector loss	1 dB	34
Jumper + connector loss	3 + 1 dB	30
Cable attenuation (60 km)	18 dB	12
Jumper + connector loss	3 + 1 dB	8
Receiver connector loss	1 dB	7 (final margin)

Rise Time Budget

- Total rise time depends on:
  - Transmitter rise time (t_{tx})
  - Group Velocity Dispersion (t_{GVD})
  - Modal dispersion rise time (t_{mod})
  - Receiver rise time (t_{rx})

Total rise time of a digital link should not exceed 70% for a NRZ bit period, and 35% of a RZ bit period

InterSymbol Interference (ISI)



Pulse spreading in an optical signal, after traversing along opt
leads to ISI. Some fraction of energy remaining in appropriate
is designated by γ, so the rest is the fraction of energy that h
Into adjacent time slots.

The risetime budget is assembled as:

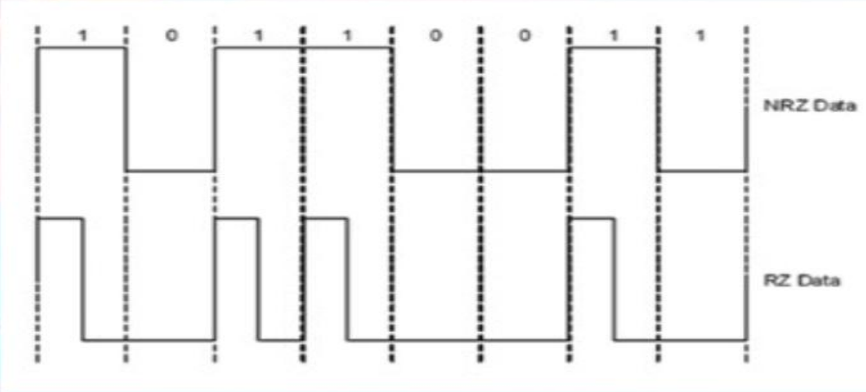
$$T_{syst} = 1.1(T_S^2 + T_F^2 + T_D^2 + T_A^2)^{1/2}$$

For non-return-to-zero (NRZ) data

$$T_{syst} = \frac{0.7}{B_T}$$

For return-to zero (RZ) data

$$T_{syst} = \frac{0.35}{B_T}$$



- Risetime budget includes the following:

1. Risetime of the source, T_S
2. Risetime of the fiber (dispersion), T_F
3. Risetime of the amplifier, T_A
4. Risetime of the detector, T_D

Example 8.1

We need to design a digital link to connect two points 10-km apart. The bit rate needed is 30Mb/s with BER = 10^{-12}.
Determine whether the components listed are suitable for the link.

Source: LED 820nm GaAsAl; couples 12μW into 50μm fiber; risetime 11ns

Fiber: Step Index fiber; 50μm core; NA = 0.24; 5.0 dB/km loss; dispersion 1ns/km; 4 connectors with 1.0dB loss per connector

Detector: PIN photodiode; R = 0.38A/W; C_j = 1.5pF, I_d = 10pA; risetime = 3.5ns; minimum mean optical power = - 86dBm

Calculate also the SNR of the link if R_L given is 5.3kΩ

Solution :

For this example, 3 factors need to be considered:

a) Bandwidth
b) Power levels
c) Error rate (SNR)

<u>Risetime Budget</u>

We start with the risetime budget. Assume using NRZ coding, the system risetime is given by:

$$T_{syst} = \frac{0.7}{B_T} = \frac{0.7}{30x10^6} = 23.3ns$$

Also:

$$\mathbf{T_{syst} = 1.1(T_S^2 + T_F^2 + T_D^2)^{1/2}}$$

Now we can assemble the total system risetime:

Total system risetime = 23.3 ns
Risetime of the source, T_S = 11.0ns
Risetime of the fiber (dispersion), T_F 10 x 1.0ns = 10.0ns

Allowance for the detector risetime, T_D

$$T_D = \sqrt{\left(\frac{Tsys}{1.1}\right)^2 - T_F^{\,2} - T_S^{\,2}} = 15.09ns$$

Power Budget

Total power launched into fiber = -19dBm

Losses: Fiber attenuation 5dB/km x 10 = 50dB

4 connectors 1dB x 4 = 4dB

Power available at detector =[(-19dBm – 50dB- 4dB)] = -73 dBm

Since power available at the detector is –73 dBm, the sensitivity of the detector must be less than this.

The safety margin, M_a= -73-(-86) dB

= 13dB

The choice of components are suitable because;

a) T_D calculated is greater than T_D given

b) Total power available at the detector is greater than the minimum power required by the detector i.e M_a is positive.

Example 8.2

An optical link is to be designed to operate over an 8-km length without repeater. The risetime of the chosen components are:

Source:		8 ns
Fiber:	**Intermodal**	5 ns/km
	Intramodal	1 ns/km
Detector		6ns

From the system risetime considerations estimate the maximum bit rate that may be achieved on the link using NRZ code.

Solution:

$T_{syst} = 1.1(T_S^2 + T_F^2 + T_D^2)$

$= 1.1\ [8^2 + (8 \text{ x } 5)^2 + (8 \text{ x } 1)^2 + 6^2)^{1/2}]$

$= 46.2$ ns

Max bit rate = $B_{T(\max)} = \dfrac{0.7}{T_{syst}} = 15.2 Mbps$

Maximum bit rate = 15.2Mbps

Or 3 dB optical BW = 7.6MHz

Example 8.5

An optical communication system is given with the following specifications:

Laser: $\lambda = 1.55\mu m$, power = 5dBm, $t_r = 1.0ns$
Detector: $t_D = 0.5ns$, sensitivity = -40dBm
Pre-amp: $t_A = 1.3ns$
Fiber: total dispersion = 0.0025 ns /km, length = 100km, α = 0.25dB/km
Source coupling loss = 3dB
Connector (2) loss = 2dB
Splice (50) loss = 5dB
System: 400 Mbps, NRZ, 100km

Solution

For risetime budget

system budget, $T_{syst} = \frac{0.7}{B_T} = \frac{0.7}{400 \times 10^6} = 1.75\text{ns}$

source	t_s	$= 1.0\text{ns}$	...(1)
fiber	t_F	$= 0.0025ns \times 100$	
		$= 0.25\text{ns}$	...(2)
detector	t_D	$= 0.5\text{ns}$	
pre-amp	t_A	$= 1.3\text{ns}$	

for receiver,

total $= \sqrt{t_D^2 + t_A^2}$

$= 1.39\text{ns}$ ...(3)

$\therefore$ System risetime from (1),(2) and (3)

$= \sqrt{1.0 + 0.25^2 + 1.39^2} = 1.73\text{ns}$

Since the calculated T_{syst} is less than the available T_{syst} the components is suitable to support the 400 Mbps signal.

For the power budget:

Laser power output	5 dBm
Source coupling loss	3 dB
Connector loss	2 dB
Splice loss	5 dB
Attenuation in the fiber	25 dB
Total loss	35 dB

Power available at the receiver = (5 dBm -35 dB) = -30 dBm

The detector's sensitivity is -40 dBm which is 10 dB less. Therefore the chosen components will allow sufficient power to arrive at the detector. Safety margin is +10 dB,

Dispersion Analysis (Rise-Time Budget)

$$t_{sys} = [t_{tx}{}^2 + t_{\mathrm{mod}}{}^2 + t_{GVD}{}^2 + t_{rx}{}^2]^{1/2}$$

$$= \left[t_{tx}{}^2 + \left(\frac{440L^q}{B_0} \right)^2 + D^2 \sigma_\lambda{}^2 L^2 + \left(\frac{350}{B_{rx}} \right)^2 \right]^{1/2}$$

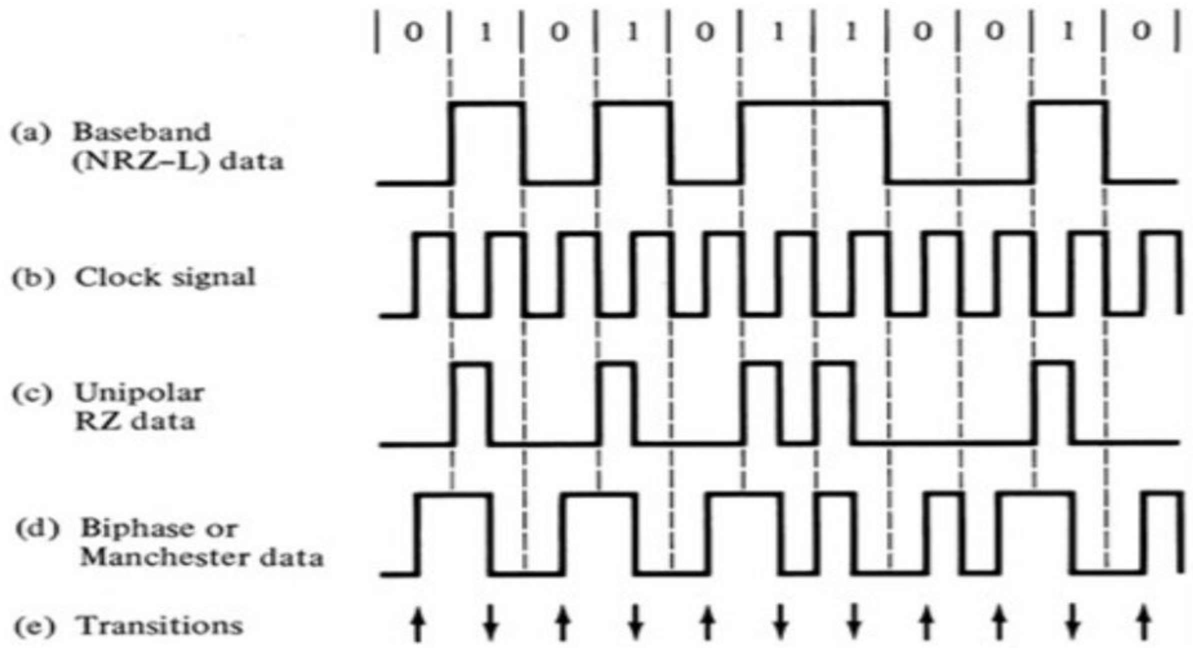
$t_{tx}[ns]$: transmitter rise time $t_{rx}[ns]$: receiver rise time $t_{\mathrm{mod}}[n]$: modal dispersion

$B_{rx}[MHz]$:3dB Electrical BW $L[km]$:Length of the fiber $B_0[MHz]$:BW of the 1 km of the fiber;

$q \approx 0.7$ t_{GVD}[ns]: rise-time due to group velocity dispersion

$D[ns/(km.nm)]$:Dispersion σ_λ[nm]: Spectral width of the source

Two-level Binary Channel Codes



System rise-Time & Information Rate

- In digital transmission system, the system rise-time limits the bit rate of the system according to the following criteria:

$$t_{sys} < 70\% \text{ of NRZ bit period}$$

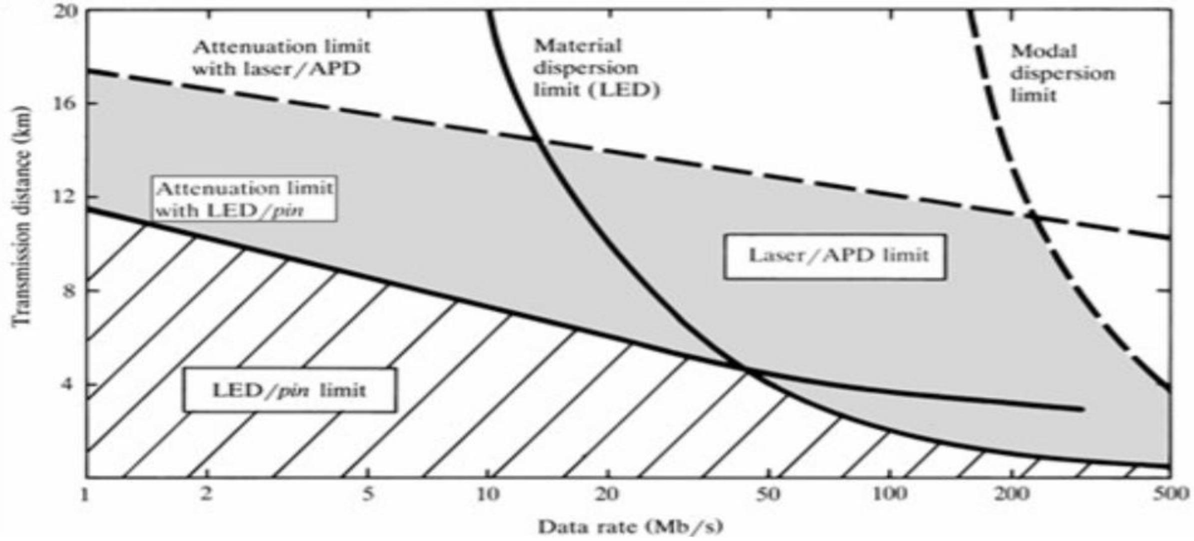
$$t_{sys} < 35\% \text{ of RZ bit period}$$

Example

- Laser Tx has a rise-time of 25 ps at 1550 nm and spectral width of 0.1 nm. Length of fiber is 60 km with dispersion 2 ps/(nm.km). The InGaAs APD has a 2.5 GHz BW. The rise-time budget (required) of the system for NRZ signaling is 0.28 ns whereas the total rise-time due to components is 0.14 ns. (The system is designed for 20 Mb/s).

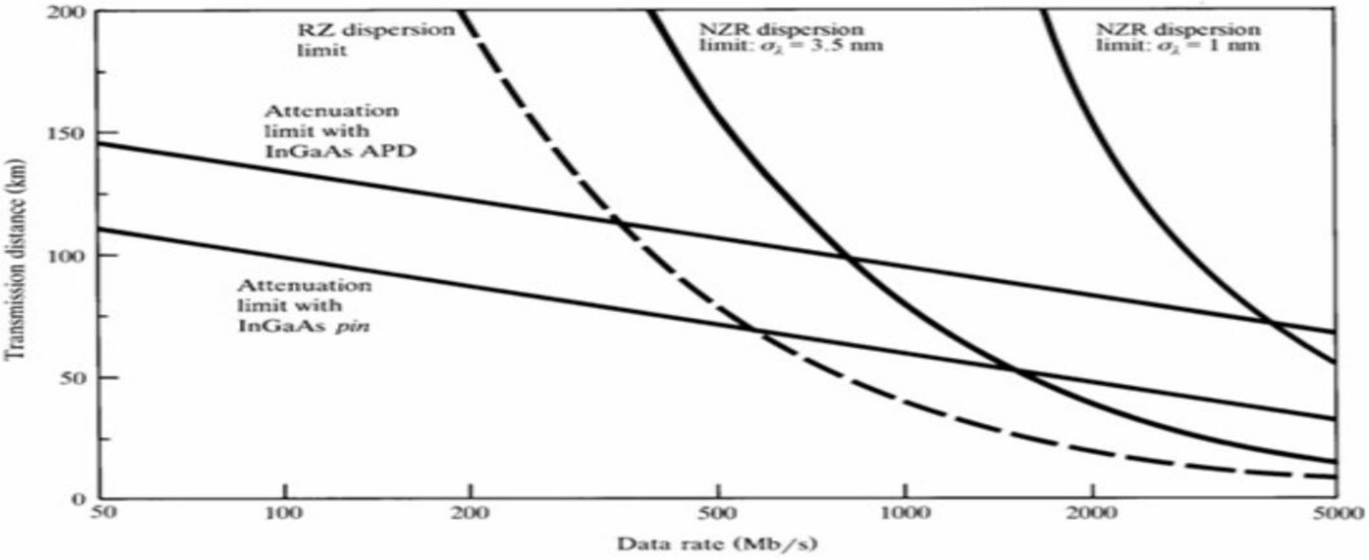
Example: Transmission Distance for MM-Fiber

- NRZ signaling, source/detector: 800-900 nm LED/pin or AlGaAs laser/APD combinations. $BER = 10^{-9}$; LED output=-13 dBm;fiber loss=3.5 dB/km;fiber bandwidth 800 MHz.km; q=0.7; 1-dB connector/coupling loss at each end; 6 dB system margin, material dispersion ins 0.07 ns/(km.nm); spectral width for LED=50 nm. Laser ar 850 nm spectral width=1 nm; laser ouput=0 dBm, Laser system margin=8 dB;



Example:Transmission Distance for a SM Fiber

- Communication at 1550 nm, no modal dispersion, Source:Laser; Receiver:InGaAs-APD (11.5 log B -71.0 dBm) and PIN (11.5log B-60.5 dBm); Fiber loss =0.3 dB/km; D=2.5 ps/(km.nm): laser spectral width 1 and 3.5 nm; laser output 0 dBm,laser system margin=8 dB;



Rise Time...

Similarly

$$t_{tx} = 350 / B_{tx} \quad \text{ns}$$

Assuming both transmitter and receiver as first order low pass filters

Modal Dispersion Rise Time

Bandwidth $B_M(L)$ due to modal dispersion of a link length L is empirically given by,

$$B_M(L) = B_o / L^q$$

B_0 is the BW per km (MHz-km product) and q ~0.5-1 is the modal equilibrium factor

$$t_{\text{mod}} = 0.44 / B_M = 440 L^q / B_0 \text{ (ns)}$$

Group Velocity Dispersion

Where,

D is the dispersion parameter (ns/km/nm) given by eq. (3.57)

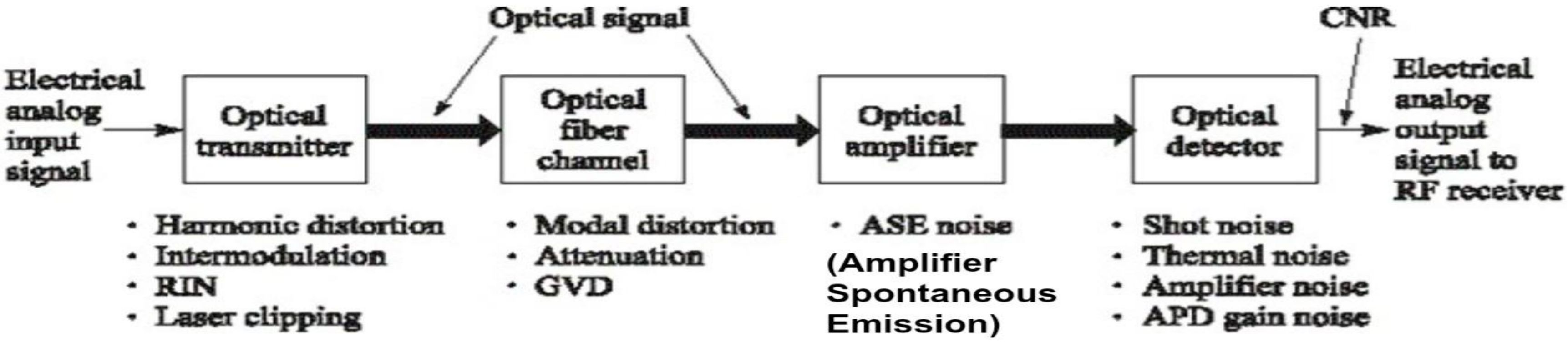
σ_λ is the half power spectral width of the source (nm)

L is the distance in km

$$t_{sys} = \left[t_{tx}^2 + t_{rx}^2 + D^2 \sigma_\lambda^2 L^2 + 440^2 L^{2q} \Big/ B_0^2 \right]^{1/2}$$

Try examples 8.3 and 8.4

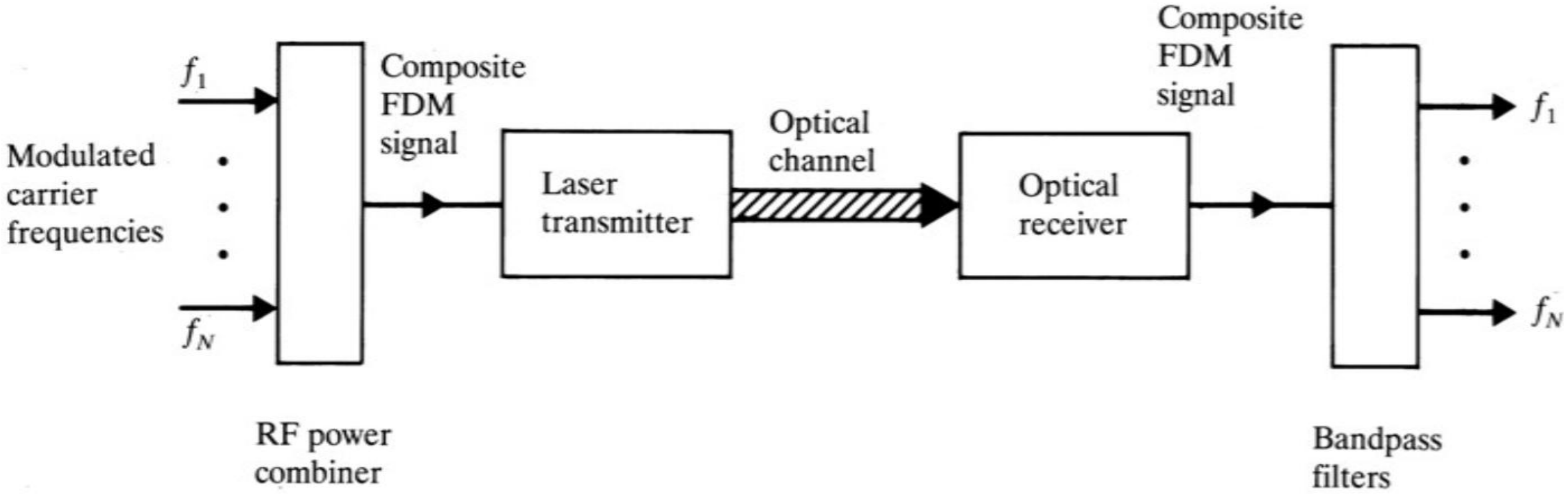
Analog Communication Links



Analog (RF) links are used in

- Analog TV and audio services (Legacy)
- Cable modem services
- Satellite base stations

Multi Channel Systems



Number of RF carriers can be summed and directly modulate the laser

Multi Channel Systems

- These have the capability to multiplex several RF channels
- Each RF channel is independent, it may carry different type of data (analog video, digital video, digital audio etc.)
- The data could be modulated onto the RF carrier using different techniques (AM, FM, QAM etc.)
- Nonlinearity is the major concern

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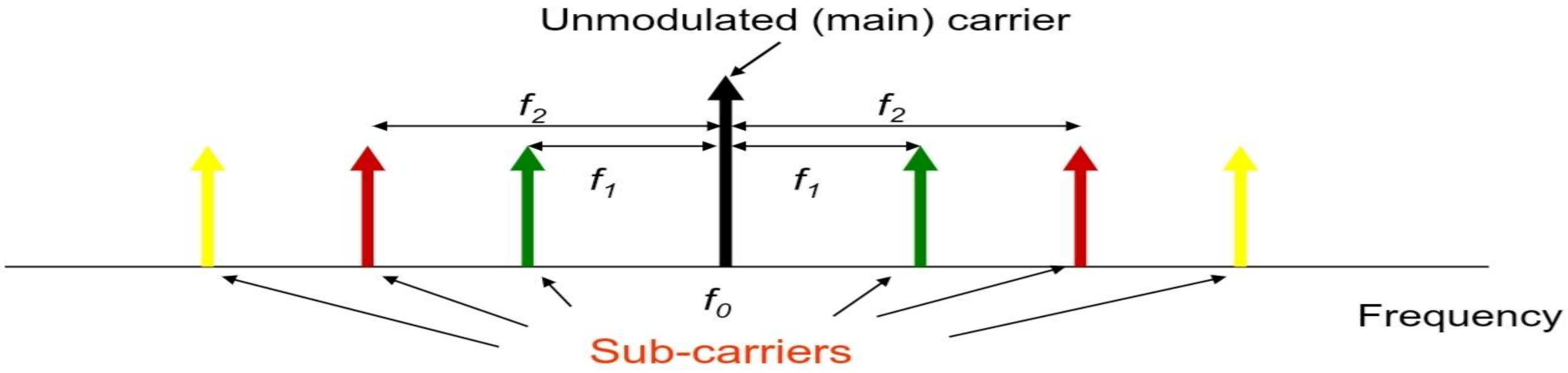
Sub Carrier Multiplexing



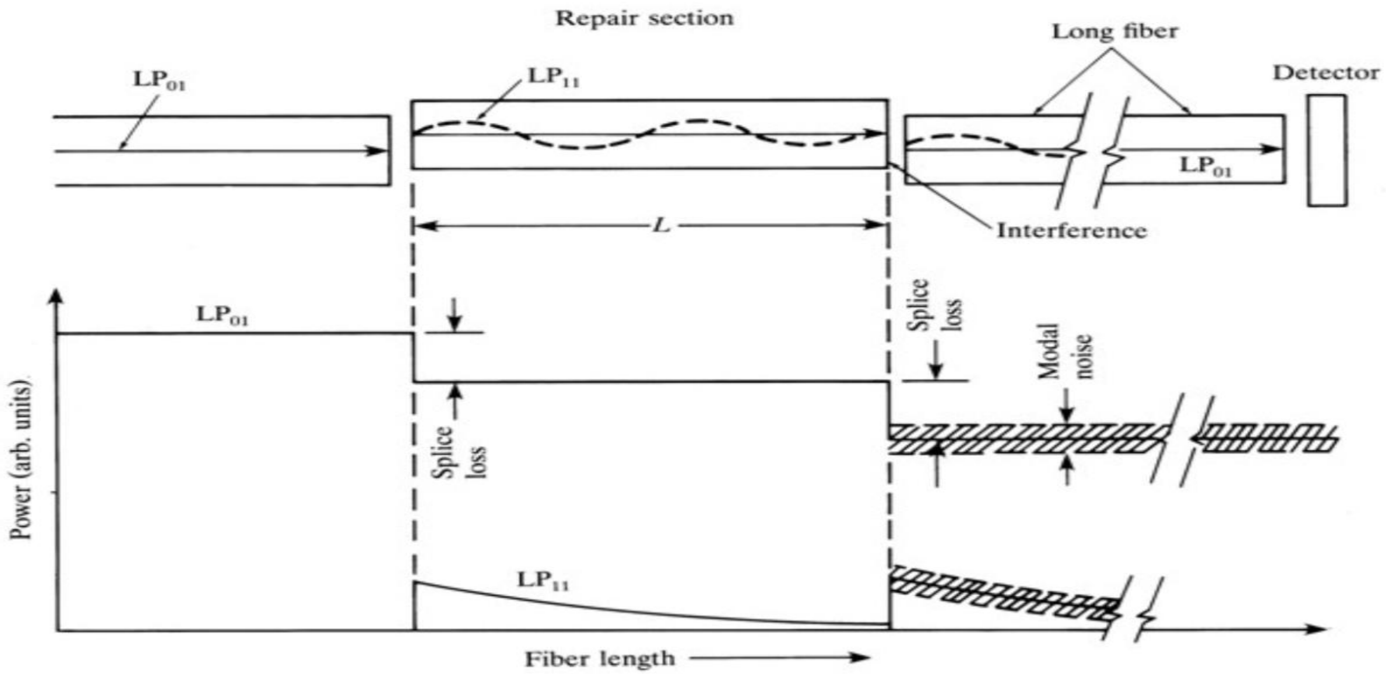
- Each modulating RF carrier will look like a sub-carrier
- Unmodulated optical signal is the main carrier
- Frequency division multiplexed (FDM) multi channel systems also called as SCM

Link Noise

Modal Noise: When a laser is coupled to a multi mode fiber (MMF) modal noise exists. To avoid this,

- Use LED with MMF
- Use a laser with large number of modes
- Use a MMF with large NA
- Use single mode fiber with laser

Modal noise at a connection of a SMF



Mode Partition Noise

- This is the dominant noise in single mode fiber coupled with multimode laser
- Mode partition noise is associated with intensity fluctuations in the longitudinal modes of a laser diode
- Each longitudinal mode has different λ
- The SNR due to MPN can not be improved by increasing the signal power