Carrier – to – Noise Ratio (CNR)

- Carrier – to – Noise Ratio (CNR) is defined as the ratio of r.m.s. carrier power to r.m.s. noise power at the receiver.
- CNR requirement can be relaxed by changing the modulation format from AM to FM.
- The BW of FM carrier is considerably larger (30 MHz in place of 4 MHz).
- The required CNR for FM receiver is much lower (16 dB compared to 50 dB in AM) because of FM advantage.
- As a result, the optical power needed at the receiver can be small as 10 µW.
- But the receiver noise of FM system is generally dominated by the thermal noise.

- The important signal impairments includes –
  - Laser intensity noise fluctuations.
  - Laser clipping noise.
  - Photodectercotr noise.
  - Optical Amplifier Noise (ASE noise).
  - Harmonic noise.
  - Intermodulaiton noise.
  - Shot noise.

Carrier Power

- To calculate carrier power signal generated by optical source is considered.
- The optical source is a square law device and current flowing through optical source is sum of fixed bias current and a time varying current (analog signal).
- If the time-varying analog drive signal is s(t), then the instantaneous optical output power is given by,

$$P(t) = P_t[1 + m\, s(t)] \qquad \dots (4.1.1)$$

where

P_t is optical output power at bias level,

m is modulation index $= \left(\frac{P_{peak}}{P_t}\right)$

You

- The received carrier power C is given by,

$$C = \frac{1}{2}(m\,\Re_0\,MP)^2 \qquad \dots (4.1.2)$$

where,

$\Re_0$ is responsivity of photodetector.

M is gain of photodetector.

P is average received optical power.

Photodetector and Preamplifier Noises

- Photodetector noise is given by,

$$\langle i_N^2 \rangle = 2q\,(I_p + I_D)\,M^2\,F(M)B \quad \ldots (4.1.3)$$

where,

I_p is primary photocurrent

I_D is detector dark current.

M is gain of photodetector.

F(M) is noise figure.

B is bandwidth.

- Preamplifier noise is given by,

where,
$$\langle i_N^2 \rangle = \frac{4k_B T}{R_{eq}} . B F_t \qquad \dots (4.1.4)$$

R_{eq} is equivalent resistance.

F_t is noise factor of preamplifier.

Relative Intensity Noise (RIN)

- The output of a semiconductor laser exhibits fluctuations in its intensity, phase and frequency even when the laser is biased at a constant current with negligible current fluctuations.
- The two fundamental noise mechanisms are
  i. Spontaneous emission and
  ii. Electron-hole recombination (shot noise).
- Noise in semiconductor lasers is dominated by spontaneous emission.
- Each spontaneously emitted photon adds to the coherent field a small field component whose phase is random, and thus deviate both amplitude and phase in random manner, is called **Relative Intensity Noise (RIN)**.
- The resulting mean-square noise current is given by,

$$\langle i_R^2 \rangle = RIN\ (\Re_0 P)B$$

- RIN is measured in dB/Hz. Its typical value DFB Lasers is ranging from -152 to -158 dB/Hz.

Reflection Effects on RIN

- The optical reflections generated within the systems are to be minimized. The reflected signals increases the RIN by 10 – 20 dB. Fig. below shows the effect on RIN due to change in feedback power ratio.

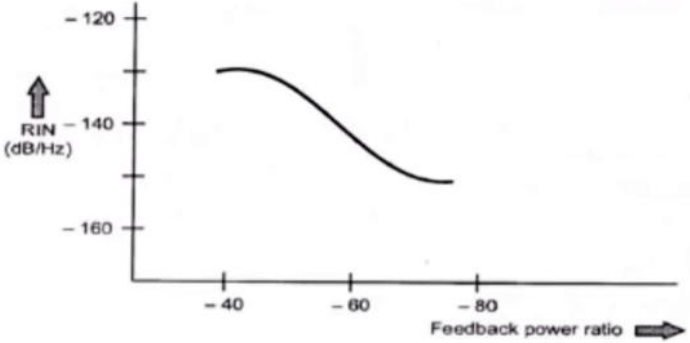

Fig. 6.1.2 Feedback power ratio (dB)

- The feedback power ratio is the amount of optical power reflected back to the light output from source.

- The feedback power ratio must be less than -60 dB to maintain RIN value less than -140 dB/Hz.

Limiting Conditions

- When optical power level at receiver is low, the preamplifier noise dominates the system noise.
- The quantum noise of photodetector also dominates the system noise.
- The reflection noise also dominates the system noise.
- The carrier-to-noise ratio for all three limiting conditions are shown in table.
- Fig. shows carriers-to-noise ratio as a function of optical power level at the receiver with limiting factors.
- For low light levels, thermal noise is limiting factor causes 2 dB roll of in C/N for each 1 dB drop in received power.
- At intermediate levels, quantum noise is limiting, factor causing 1 dB drop in C/N for every 1 dB decrease in received optical power.
- At high received power source noise is dominator factor gives a constant C/N.

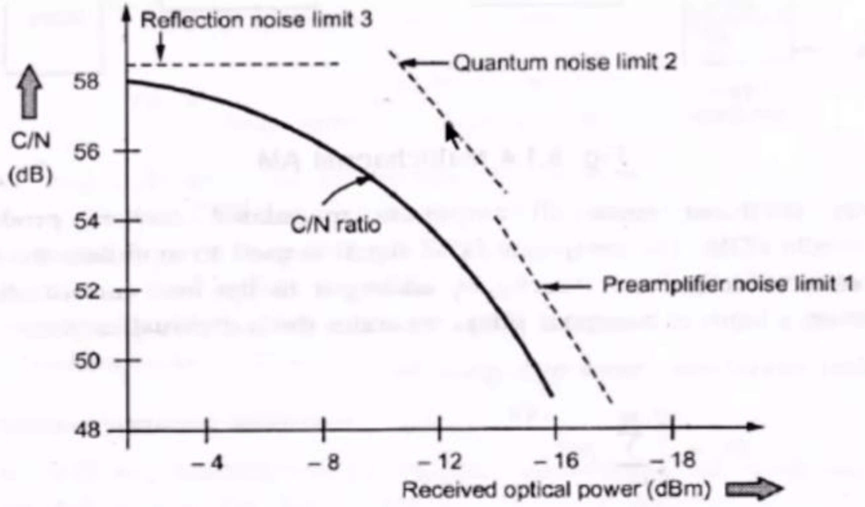

Fig. 6.1.3 C/N ratio as a function of received optical power

Multichannel Transmission Techniques

- Multiplexing technique is used to transmit multiple analog signals over the same higher capacity fiber cable.
- Number of baseband signals are superimposed on a set of N sub-carrier of frequencies f_1, f_2, f_3 …fN.
- Channel or signal multiplexing can be done in the time or frequency domain through Time-Division Multiplexing (TDM) and Frequency Division Multiplexing (FDM).
- The methods of multiplexing includes Vestigial Sideband Amplitude Modulation (VSB-AM), frequency Modulation (FM) and Sub-Carrier Multiplexing (SCM).
- All the schemes have different advantages and disadvantages.

Multichannel Amplitude Modulation

- In some applications the bit rate of each channel is relatively low but the number of channels are quite large.
- Typical example of such application is cable television (CATV).
- Fig. below shows the technique for combining N independent channels.
- Different channel information are amplitude modulated on different carrier frequencies.

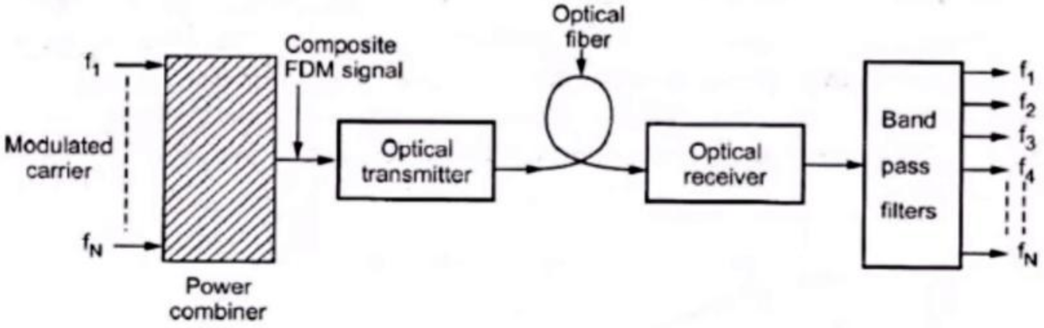

Fig. 6.1.4 Multichannel AM

- Power combiner sums all amplitude modulated carriers producing a composite FDM.
- The composite FDM signal is used to modulate the intensity of semiconductor laser directly by adding it to the bias current.
- At optical receiver, a bank of bandpass filters separates the individual carriers.
- Optical modulation index m is given by

$$m = \left(\sum_{i=1}^{N} m_i^2\right)^{1/2}$$

where, N is no. of channels

m_i is per channel modulation index

- Since the laser diode is a non-linear device and when multiple carrier frequencies pass through such device, the analog signal is distorted during its transmission, the distortion is referred to as intermodulation distortion (IMD).
- The IMD causes undersirable signals to produce called intermodulation product (IMP).
- The new frequencies (IMPs) are further classified as
  i. Two-tone IMPs and
  ii. Triple-beat IMPs.
- The classification is depending on whether two frequencies coincide or all three frequencies are distinct.
- The triple-bear IMPs tend to be a major source of distortion because of their large number.
- An N-channel system generates N (N – 1) (N – 2)/2 triple-beat terms compared with N (N – 1) two-tone terms.

- Depending on channel carrier spacing some of Imps fall within the bandwidth of a specific channel and affect the signal recovery. This is called as beat-stacking.
- The beat stacking result in two types of distortions, which adds power for all IMPs that fall within the passband of a specific channel, these distortions are:

   i) Composite Second Order (CSO) and
   ii) Composite Triple Bear (CTB)

$$\text{CSO} = \frac{\text{Peal carrier power}}{\text{Peack power in composite } 2^{\text{nd}} \text{order IM tone}}$$

$$\text{CTB} = \frac{\text{Peal carrier power}}{\text{Peack power in composite } 3^{\text{rd}} \text{order IM tone}}$$

- CSO and CTB are used to describe the performance of multichannel An links.
- CSO and CTD are expressed in dBc units, where 'c' in dB_c denotes normalization with respect to the carrier power.
- Typically, CSO and CTB distortion values should be below – 60 dB_c for negligible impact on the system performance.
- Both CSO and CTB increases rapidly with increase in modulation index.

Multichannel Frequency Modulation

- The CNR requirement can be relaxed by changing the modulation format from AM to FM.
- The BW of FM carrier is considerably larger (30 MHz in place of 4 MHz). This results in S/N ratio improvement over C/N ratio.
- S/N ratio at the output of FM detector is :

$$\left(\frac{S}{N}\right)_{out} = \left(\frac{C}{N}\right)_{in} + 10\log\left[\frac{3B}{2f_v}\left(\frac{\Delta f_{pp}}{f_v}\right)^2\right] + w \ldots.$$

where,

B is required bandwidth.

Δf_{pp} is peak to peak frequency deviation of modulator.

f_v is highest video frequency.

W is weighing factor for white noise.

- The total S/N improvement is ranging between 36-44 dB.

Sub-Carrier Multiplexing (SCM)

- Sub-Carrier Multiplexing (SCM) is employed in microwave engineering in which multiple microwave carriers for transmission of multiple channels are used.
- If the microwave signal is transmitted optically by using optical fibers, the signal bandwidth can be exceeded up to 10 GHz for a single optical carrier.
- Such a scheme is referred to as SCM.
- Since multiplexing is done by using microwave sub-carrier rather than the optical carrier.
- The input can be analog or digital baseband signal.
- The input signals are modulated sub- carriers are then combined to give FDM signal.
- The FDM signals are then combined in microwave combiner.
- The combine signal is then modulates the intensity of semiconductor laser by adding it to bias current. Fig. 6.1.5 shows this arrangement.

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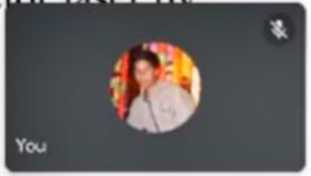


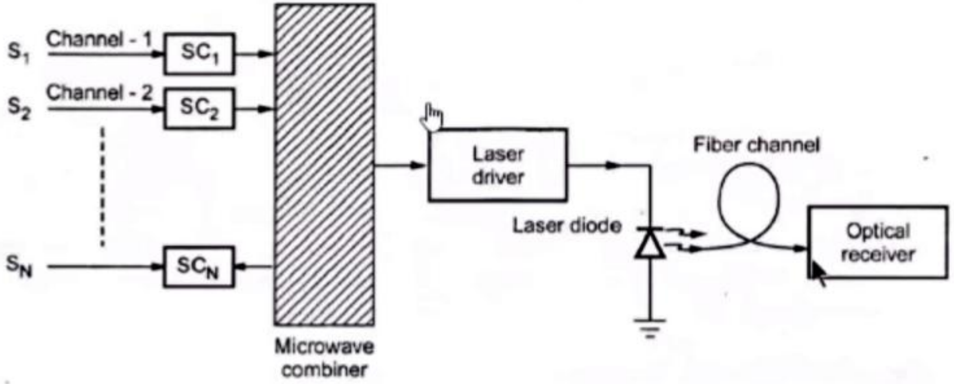
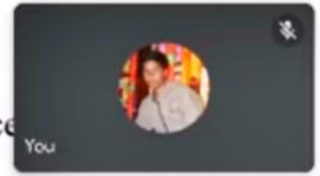


Fig. 6.1.5 Sub-carrier multiplexing

- The received optical signal is then passed through low noise pin photodetector to convert it to original signal.

Advantages of SCM

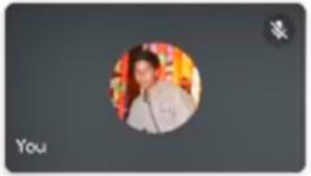
1. Wide bandwidth.
2. Flexibility and upgradability in design of broadband networks.
3. Analog or digital modulation or combination of two for transmitting multiple voice, data and video signals to large number of users.
4. Both AM and FM techniques can be used for SCM.
5. A combination of SCM and WDM can realize DW upto 1 MHz.
6. SCM technique is also being explored for network management and performanc



RF over FIBER

Microwave photonics

- High frequency low loss
- High slope efficiencies
- Respond to signal freq
- Same task as RF filters



2. Digital Links

System Design Considerations

- In optical system design major consideration involves
  - Transmission characteristics of fiber (attenuation & dispersion).
  - Information transfer capability of fiber.
  - Terminal equipment & technology.
  - Distance of transmission.
- In long-haul communication applications repeaters are inserted at regular intervals as shown in Fig. below

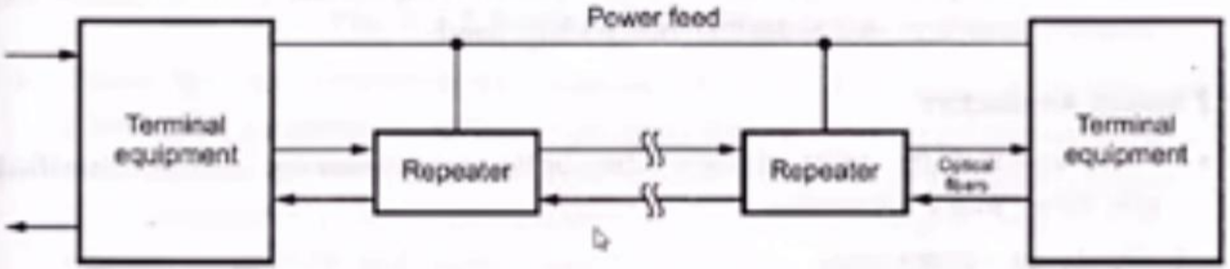


Fig. 6.2.1 Repeaters in long-haul communication system

- Repeater regenerates the original data before it is retransmitted as a digital optical signal.
- The cost of system and complexity increases because of installation of repeaters.
- An optical communication system should have following basic required specifications –

  a) Transmission type (Analog / digital).

  b) System fidelity (SNR / BER)

  c) Required transmission bandwidth

  d) Acceptable repeater spacing

  e) Cost of system

  f) Reliability

  g) Cost of maintenance.

Multiplexing

- Multiplexing of several signals on a single fiber increases information transfer rate of communication link.
- In Time Division Multiplexing (TDM) pulses from multiple channels are interleaved and transmitted sequentially, it enhance the bandwidth utilization of a single fiber link.
- In Frequency Division Multiplexing (FDM) the optical channel bandwidth is divided inot various nonoverlapping frequency bands and each signal is assigned one of these bands of frequencies.
- By suitable filtering the combined FDM signal can be retrieved.
- When number of optical sources operating at different wavelengths are to be sent on single fiber link Wavelength Division Multiplexing (WDM) is used.
- At receiver end, the separation or extraction of optical signal is performed by optical filters (interference filters, differaction filters prism filters).
- Another technique called Space Division Multiplexing (SDM) used separate fiber within fiber bundle for each signal channel.
- SDM provides better optical isolation which eliminates cross-coupling between channels.
- But this technique requires huge number of optical components (fiber, connector, sources, detectors etc) therefore not widely used.

System Architecture

- From architecture point of view fiber optic communication can be classified into three major categories.
  1. Point – to – point links
  2. Distributed networks
  3. Local area networks.

Point-to-Point Links

- A point-to-point link comprises of one transmitter and a receiver system.
- The simplest form of optical communication link and it sets the basis for examining complex optical communication links.
- For analyzing the performance of any link following important aspects are to be considered.

  Distance of transmission , Channel data rate and Bit-error rate
- All above parameters of transmission link are associated with the characteristics of various devices employed in the link.
- Important components and their characteristics are listed below.

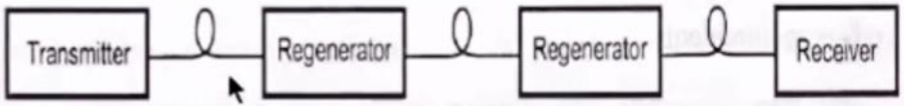


Fig. 6.2.2 Point-to-point fiber links

- When the link length extends between 20 to 100 km, losses associated with fiber cable increases.
- In order to compensate the losses optical amplifier and regenerators are used over the span of fiber cable.
- A regenerator is a receiver and transmitter pair which detects incoming optical signal, recovers the bit stream electrically and again convert back into optical from by modulating an optical source.
- An optical amplifier amplify the optical bit stream without converting it into electrical form.
- The spacing between two repeater or optical amplifier is called as repeater spacing (L).
- The repeater spacing L depends on bit rate B. The bit rate-distance product (BL) is a measure of system performance for point-to-point links.
- Two important analysis for deciding performance of any fiber link are –

i) Link power budget / Power budget

ii) Rise time budget / Bandwidth budget

- The Link power budget analysis is used to determine whether the receiver has sufficient power to achieve the desired signal quality.
- The power at receiver is the transmitted power minus link losses.
- The components in the link must be switched fast enough and the fiber dispersion must be low enough to meet the bandwidth requirements of the application.
- Adequate bandwidth for a system can be assured by developing a rise time budget.

System Consideration

- Before selecting suitable components, the operating wavelength for the system is decided.
- The operating wavelength selection depends on the distance and attenuation.
- For shorter distance, the 800-900 nm region is preferred but for longer distance 100 or 1550 nm region is preferred due to lower attenuations and dispersion.
- The next step is selection of photodetector.

- While selecting a photodetector following factors are considered –
  i) Minimum optical power that must fall on photodetector to satisfy BER at specified data rate.
  ii) Complexity of circuit.
  iii) Cost of design.
  iv) Bias requirements.
- Next step in system consideration is choosing a proper optical source, important factors to consider are –
  i) Signal dispersion.
  ii) Data rate.
  iii) Transmission distance.
  iv) Cost.
  v) Optical power coupling.
  vi) Circuit complexity.
- The last factor in system consideration is to selection of optical fiber between single mode and multimode fiber with step or graded index fiber.

- Fiber selection depends on type of optical source and tolerable dispersion.
- Some important factors for selection of fiber are :
  i) Numerical Aperture (NA), as NA increases, the fiber coupled power increases also the dispersion.
  ii) Attenuation characteristics.
  iii) Environmental induced losses e.g. due to temperature variation, moisture and dust etc.

Link Power Budget

- For optiming link power budget an optical power loss model is to be studied as shown in Fig. 6.2.3.
- Let l_c denotes the losses occur at connector.
  L_{sp} denotes the losses occur at splices.
  α_f denotes the losses occur in fiber.

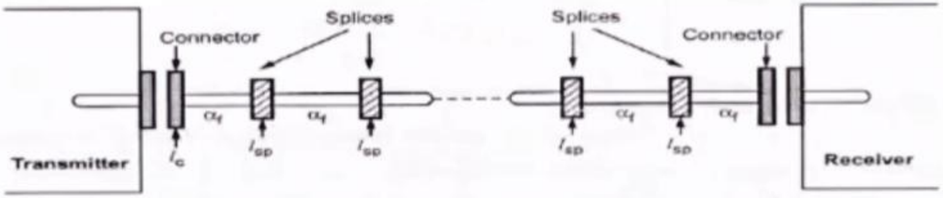


Fig. 6.2.3 Optical power loss model

- All the losses from source to detector comprises the total loss (P_T) in the system.
- Link power margin considers the losses due to component aging and temperature fluctuations.
- Usually a link margin of 6-8 dB is considered while estimating link power budget.
- Total optical loss = Connector loss + (Splicing loss + Fiber attenuation) + System margin (P_m)

$$P_T = 2l_c + \alpha_f L + \text{System margin } (P_m)$$

where, L is transmission distance.

Rise Time Budget

- Rise time gives important information for initial system design.
- Rise-time budget analysis determines the dispersion limitation of an optical fiber link.
- Total rise time of a fiber link is the root-sum-square of rise time of each contributor to the pulse rise time degradation.

$$t_{sys} = \sqrt{t_{r1}^2 + t_{r2}^2 + t_{r3}^2 + \cdots}$$

$$\boxed{t_{sys} = \left(\sum_{i=1}^{N} t_{ri}^2\right)^{1/2}}$$

- The link components must be switched fast enough and the fiber dispersion must be low enough to meet the bandwidth requirements of the application adequate bandwidth for a system can be assured by developing a rise time budget.
- As the light sources and detectors has a finite response time to inputs.
- The device does not turn-on or turn-off instantaneously.
- Rise time and fall time determines the overall response time and hence the resulting bandwidth.
- Connectors, couplers and splices do not affect system speed, they need not be accounted in rise time budget but they appear in the link power budget.
- Four basic elements that contributes to the rise-time are,

  Transmitter rise-time (ttx)

  Group Velocity Dispersion (GVD) rise time (tGVD)

  Modal dispersion rise time of fiber (tmod)

  Receiver rise time (trx)

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

- Rise time due to modal dispersion is given as

$$t_{mod} = \frac{440}{B_M} = \frac{440\ Lq}{B_0}$$

where,

BM is bandwidth (MHz)

L is length of fiber (km)

q is a parameter ranging between 0.5 and 1.

B0 is bandwidth of 1 km length fiber,

- Rise time due to group velocity dispersion I

$$t_{GVD} = D^2 \sigma_\lambda^2 L^2$$

where,

D is dispersion

Σ_λ is half-power spectral width of source L is length of fiber

L is length of fiber

- Receiver front end rise-time in nanoseconds is

$$\boxed{t_{rx} = \frac{350}{B_{rx}}} \quad \text{.... (4.2.4)}$$

where,

B_{rx} is 3 dB – bW of receiver (MHz).

- Equation (4.2.1) can be written as

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

$$\boxed{t_{sys} = \left[t_{tx}^2 + \left(\frac{440\ Lq}{B_0}\right)^2 + D^2\sigma_\lambda^2 L^2 + \left(\frac{350}{B_{rx}}\right)^2\right]^{1/2}} \quad \text{... (4.2.5)}$$

All times are in na…noseconds.

- The system bandwidth is given by

$$BW = \frac{0.35}{t_{sys}} \quad \text{... (4.2.6)}$$

Line coding in optical lilnks

- Line coding or channel coding is a process of arranging the signal symbols in a specific pattern.
- Line coding introduces redundancy into the data stream for minimizing errors.
- In optical fiber communication, three types of line codes ar eused.

  Non-return-to-zero (NRZ)

  Return-to-zero (RZ)

  Phase-encoded (PE)

Desirable Properties of Line Codes

- The line code should contain timing information.
- The line code must be immune to channel noise and interference.
- The line code should allow error detection and correction.

NRZ Codes

- Different types of NRZ codes are introduced to suit the variety of transmission requirements.
- The simplest form of NRZ code is NRZ-level.
- It is a unpolar code i.e. the waveform is simple on-off type.
- When symbol '1' is to be transmitted, the signal occupies high level for full bit period.
- When a symbol '0' is to be transmitted, the signal has zero volts for full bit period.

  Fig.6.2.4 shows example of NRZ-L data pattern.

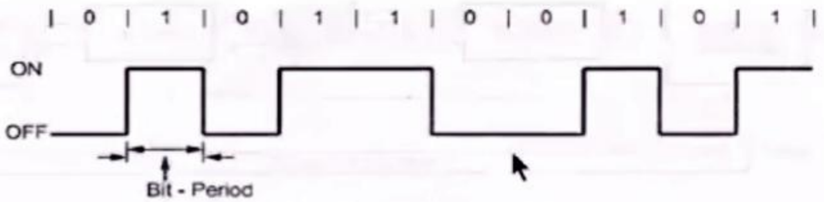


Fig. 6.2.4 NRZ-level data pattern

Features of NRZ codes

Simple to generate and decode.
No timing (self-clocking) information.
No error monitoring or correcting capabilities. NRZ coding needs minimum BW.

RZ Codes

In unipolar RZ data pattern a 1-bit is represented by a half-period in either first or second half of the bit-period. A 0 bit is represented by zero volts during the bit period. Fig. 6.2.5 shows RZ data pattern.

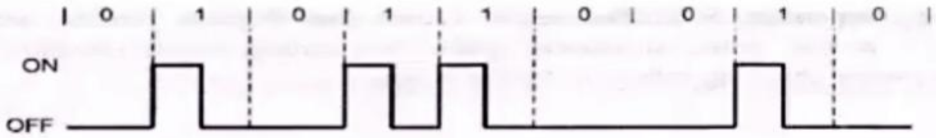


Fig. 6.2.5 RZ unipolar codes

Features of RZ codes

The signal transition during high-bit period provides the timing information.

Long strings of 0 bits can cause loss of timing synchronization.

Error Correction

- The data transmission reliability of a communication system can be improved by incorporating any of the two schemes Automatic Repeat Request (ARQ) and Forward Error Correction (FEC).
- In ARQ scheme, the information word is coded with adequate redundant bits so as to enable detection of errors at the receiving end.
- It an error is detected, the receiver asks the sender to retransmit the particular information word.
- Each retransmission adds one round trip time of latency.
- Therefore ARQ techniques are not used where low latency is desirable. Fig. 6.2.6 shows the scheme of ARQ error correction scheme.

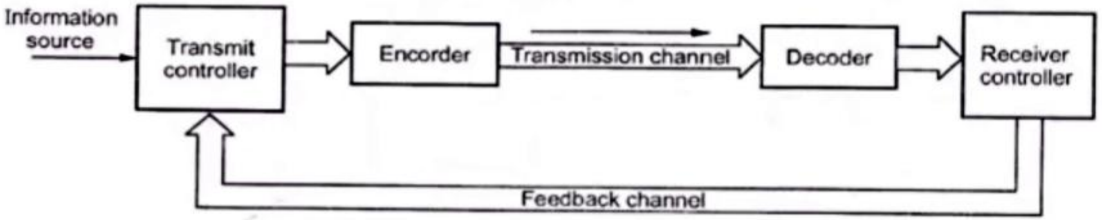


Fig. 6.2.6 ARQ scheme

- Forward Error Correction (FEC) system adds redundant information with the original information to be transmitted.
- The error or lost data is used reconstructed by using redundant bit.
- Since the redundant bits to be added are small hence much additional BW is not required.
- Most common error correcting codes are cyclic codes.
- Whenever highest level of data integrity and confidentiality is needed FEC is considered.

Sources of Power Penalty

- Optical receiver sensitivity is affected due to several factors combinely e.g. fiber dispersion, SNR.
- Few major causes that degrade receiver sensitivity are – modal noise, dispersive pulse broadening, mode partition noise, frequency chirping, reflection feedback noise.

Modal Noise

- In multimode fibers, there is interference among various propagating modes which results in fluctuation in received power.
- These fluctuations are called modal noise.
- Modal noise is more serious with semiconductor lasers.

Fig. 6.2.7 shows power penalty at

BER = 10^{-12}

$\lambda = 1.3\ \mu m$

B = 140 mb/sec.

Fiber : GRIN (50 μm)

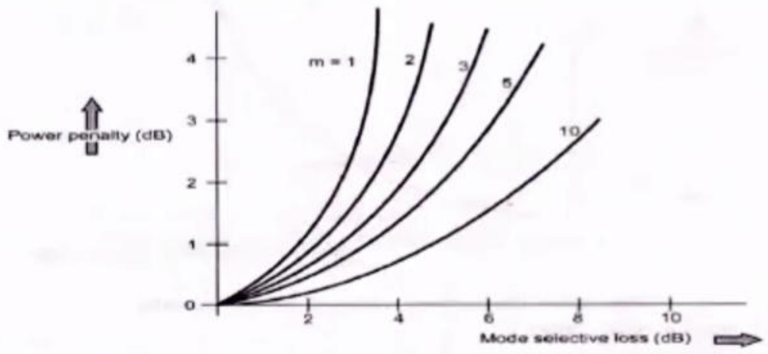


Fig. 6.2.7

Dispersive Pulse Broadening

- Receiver sensitivity is degraded by Group Velocity Dispersion (GVD).
- It limits the bit- rate distance product (BL) by broadening optical pulse.
- Inter symbol interference exists due to spreading of pulse energy.
- Also, decrease in pulse energy reduces SNR at detector circuit.

Fig. 6.2.8 shows dispersion-induced power penalty of Gaussian pulse of width σ_λ.

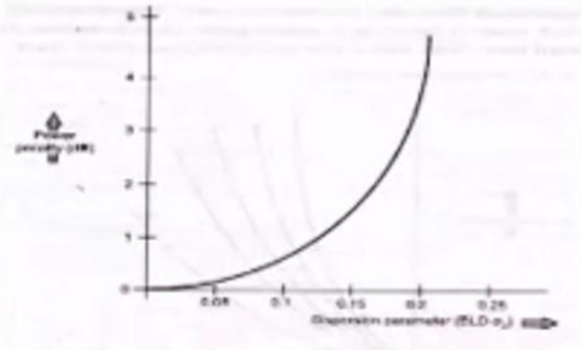


Fig. 6.2.8 Dispersion-induced power penalty

Mode Partition Noise (MPN)

- In multimode fiber various longitudinal modes fluctuate eventhough intensity remains constant.
- This creates Mode Partition Noise (MPN).
- As a result all modes are unsynchronized and creates additional fluctuations and reduces SNR at detector circuit.
- A power penalty is paid to improve SNR for achieving desired BER. Fig. 6.2.9 shows power penalty at BER of 10^{-9} as a function of normalized dispersion parameter (BLD σ_λ) for different values of mode partition coefficient (K). (See Fig. 6.2.9)

Frequency Chirping

- The change in carrier frequency due to change in refractive index is called frequency chirping.
- Because of frequency chirp the spectrum of optical pulse gets broaden and degrades system performance.

Fig. 6.2.10 shows power penalty as a function of dispersion parameter BLD σ_λ for several values of bit period (Btc).

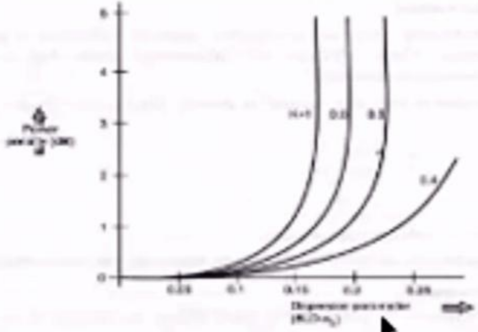


Fig. 6.2.9 MPN induced power penalty

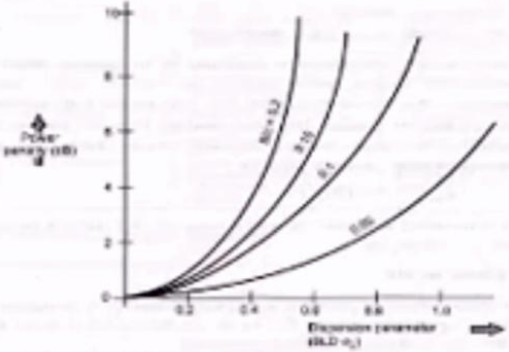


Fig. 6.2.10 Chirp induced power penalty

Reflection Feedback

- The light may reflect due to refractive index discontinuities at splices and connectors. These reflections are unintentional which degrades receiver performance considerably.
- Reflections in fiber link originate at glass-air interface, its reflectivity is given by

$$R_f = \frac{(n_f - 1)^2}{(n_f + 1)^2}$$

Where,

n_f is refractive index of fiber material.

- The reflections can be reduced by using index-matching get at interfaces.

Relative Intensity

- The output of a semiconductor laser exhibits fluctuations in its intensity, phase and frequency even when the laser is biased at a constant current with negligible current fluctuations.
- The two fundamental nose mechanisms are
  i. Spontaneous emission and
  ii. Electron-hole recombination (shot noise)
- Noise in semiconductor lasers is dominated by spontaneous emission.
- Each spontaneously emitted photon adds to the coherent field a small field component whose phase is random, and thus deviate both amplitude and phase is random manner.
- The noise resulting from the random intensity fluctuations is called **Relative Intensity Noise (RIN).**
- The resulting mean-square noise current is given by :

$$\langle i_R^2 \rangle = RIN\ (\Re_0 P)B \qquad \ldots (4.2.7)$$

RIN is measured in dB/Hz. Its typical value for DFB lasers is ranging from -152 to -158 dB/Hz.

Reflection Effects on RIN

- The optical reflection generated within the systems are to be minimized.
- The reflected signals increases the RIN by 10 – 20 dB. Fig. 6.2.11 shows the effect on RIN due to change in feedback power ratio.
- The feedback power ratio is the amount of optical power reflected back to the light output from source.
- The feedback power ratio must be less than – 60 dB to maintain RIN value less than -140 dB/Hz.

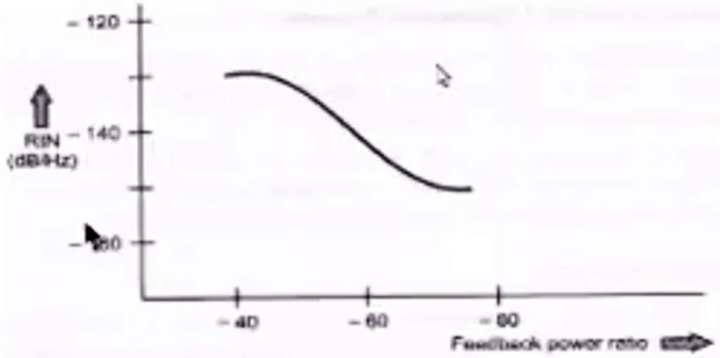


Fig. 6.2.11 Feedback power ratio (dB)

6.3 Loss Limited Lightwave Systems

Maximum transmission distance is given by –

$$L = \frac{10}{\alpha_f} \log_{10}\left(\frac{P_{transmitted}}{P_{received}}\right)$$

Where,

α_f is net fiber loss.

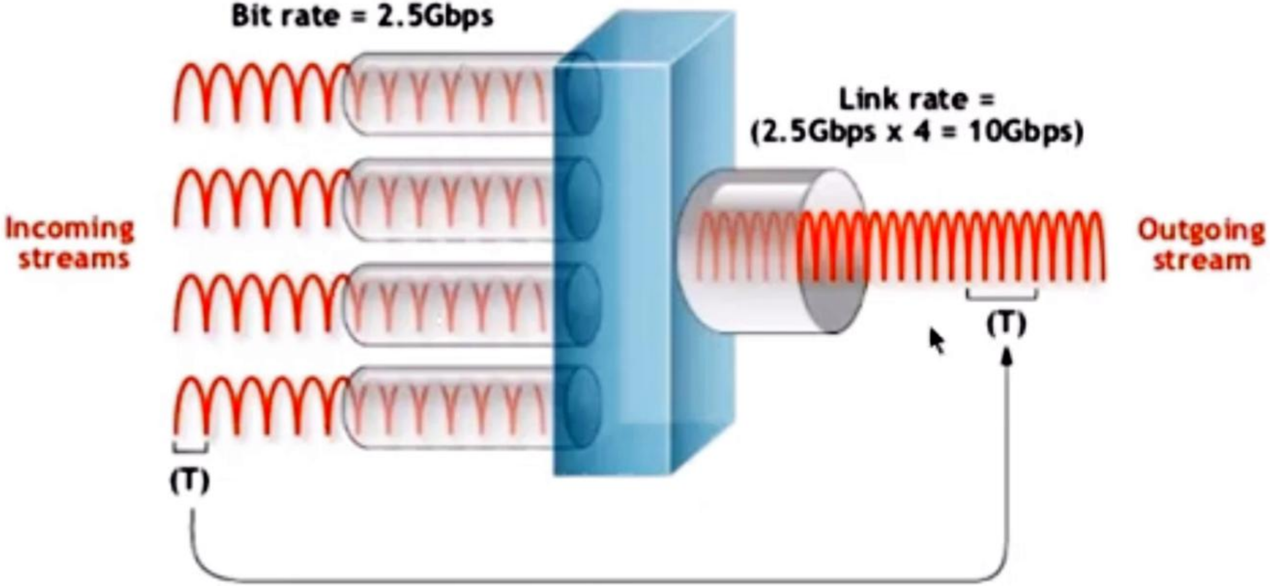
- Maximum transmission distance L determines the repeater spacing.
- It ranges from 10 km to 100 km.
- Typical value of bit error rate (BER) < 10^{-9}.

WDM CONCEPTS AND COMPONENTS

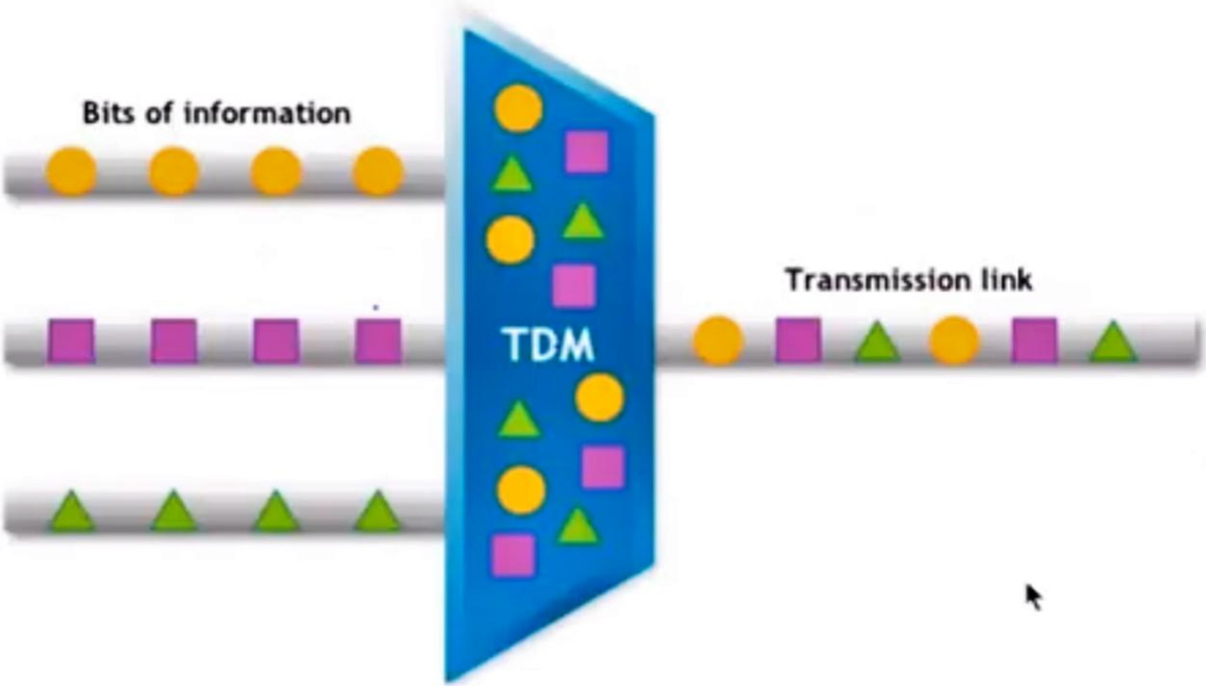
WDM concepts

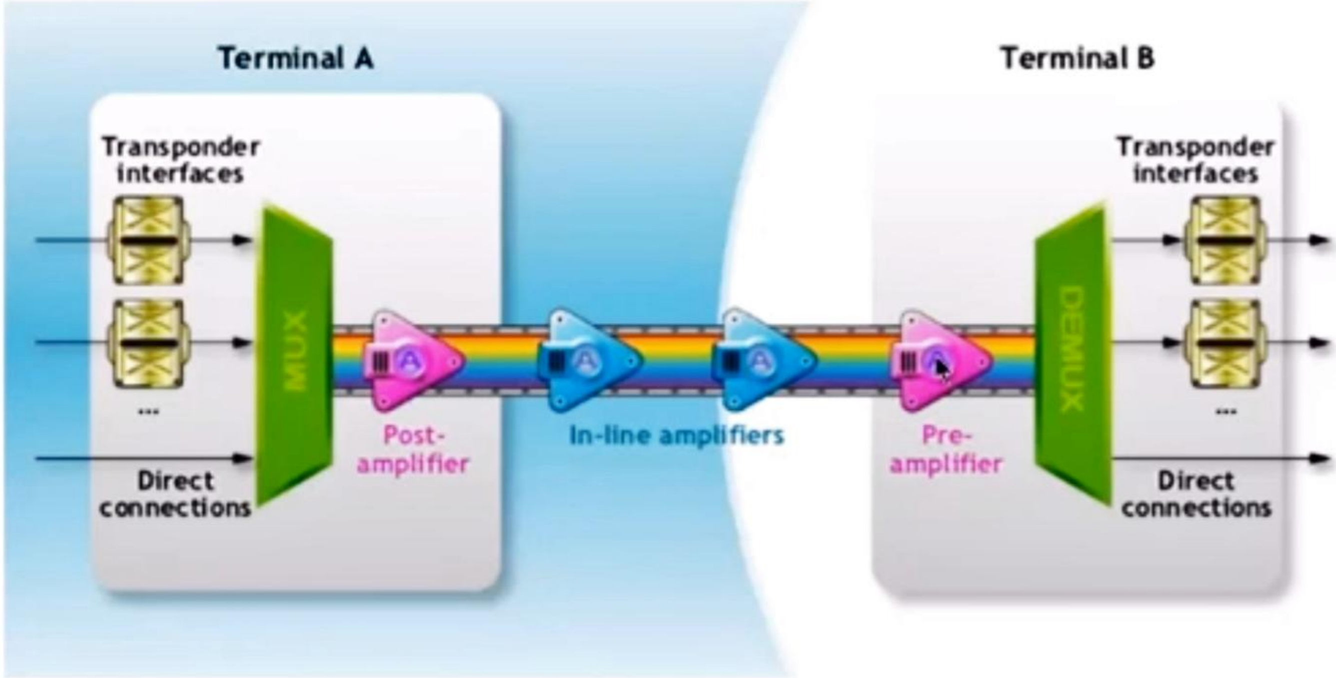
- Combining a number of independent information carrying wavelengths onto the same fiber
- Enables the use of multiple light wavelengths (or colors) to send data over the same medium
- Types
  - Coarse Wavelength Division Multiplexing
  - Dense Wavelength Division Multiplexing

Applications: all levels of communication links


Bit rate = 2.5Gbps
Incoming streams
Link rate = (2.5Gbps x 4 = 10Gbps)
Outgoing stream
(T)
(T)

Operational Principle of WDM




Terminal A
Terminal B
Transponder interfaces
MUX
Post-amplifier
In-line amplifiers
Pre-amplifier
DEMUX
Transponder interfaces
Direct connections
Direct connections

- WDM Standards
- Optical couplers
- Optical Couplers:
  - Combines & splits signals
  - Light couples from one waveguide to a closely placed waveguide because the propagation mode overlaps the two waveguides
  - Wavelength independent or selective Fabricated using waveguides in integrated optics