UNIT-6
ANALOG AND DIGITAL LINKS

INTRODUCTION:

→ Introduction of digital integrated circuit technology has set a trend to link telephone exchanges with digital circuits because of reliable & economic method of transmitting both voice & data signals.

→ Analog optical communication links are used in cable television distributed network, radio over fiber network & antenna remoting links.

→ The function of optical link in these systems is to provide a very linear & low noise transmission channel, retaining the fidelity of input signal as closely as possible.

Overview of Analog Links

Explain basic elements of analog link with different noise contribution. $\boxed{\text{9M June/July 2013}}$

Clearly explain the analog link with major noise contributions of each stage $\boxed{\text{10M June/July 2014}}$

Discuss basic elements of an analog link & major noise contributions of an analog link with a neat diagram $\boxed{\text{8M June/July 2011}}$

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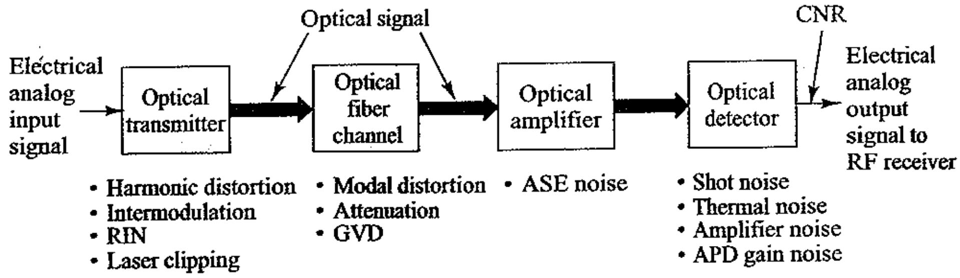

Fig: Basic elements of analog link & major noise contribitions

1. Transmitter

→ The transmitter contains either an LED or a laser diode optical source.

→ Setting bias point on the source approximately at midpoint of linear output region, the analog signal is then sent using several modulation techniques.

→ 2 methods may be used to transmit the message signal:

a) Direct Intensity Modulation :

This is the simplest form where the optical output from source is modulated by varying the current around the bias point.

The information signal is transmitted directly in the baseband.

b) AM/FM/PM Techniques:

More complex but efficient method is to translate baseband signal onto an electrical subcarrier prior to intensity modl^{n} of the source. This is done using amplitude modulation (AM), frequency modulation (FM) or phase modulation techniques.

→ Whichever method is used, careful attention must be paid to signal impairments in the optical source, these include harmonic distortion, intermodulation products, relative intensity noise & laser clipping.

2) Optical fiber channel

→ The fiber should have a flat amplitude & group delay response within the passband required to send the signal free of linear distortion.

→ Channel impairments include: Modal distortion
Attenuation
Group velocity Dispersion (GVD)

3) Optical amplifier:

It leads to additional noise known as amplified spontaneous emission (ASE)

4) Optical Detector:

This converts the light signal back to electrical analog signal.

Avlanche photodiode or pin photodiode can be used as detector.

The principal impairments are: quantum or shot noise, APD gain noise & thermal noise.

Carrier to Noise Ratio:

→ CNR is used to analyze the performance of analog systems.

→ CNR is defined as ratio of rms carrier power to rms noise power at the input of the RF reciever.

→ If CNR_i represents carrier to noise ratio related to a particular signal contaminant, then for N signal impairment factors the total CNR is given by:

$$\frac{1}{CNR} = \sum_{i=1}^{N} \frac{1}{CNR_i}$$

→ Links in which only a single information channel is transmitted, the signal impairments include laser intensity noise fluctuations, laser clipping, photodetector noise & optical amplifier noise.

→ when multiple message channels operating at different carrier frequencies are sent simultaneously over same fiber, then harmonic & intermodulation distortions arise.

Carrier Power:

→ The drive current through the optical source is sum of fixed bias current & a time varying sinusoid.

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→ The output optical power P(t) has the same form as input drive current.

→ If time varying analog drive signal is s(t), then

$$P(t) = P_t [1 + m\, s(t)] \quad \text{— (1)}$$

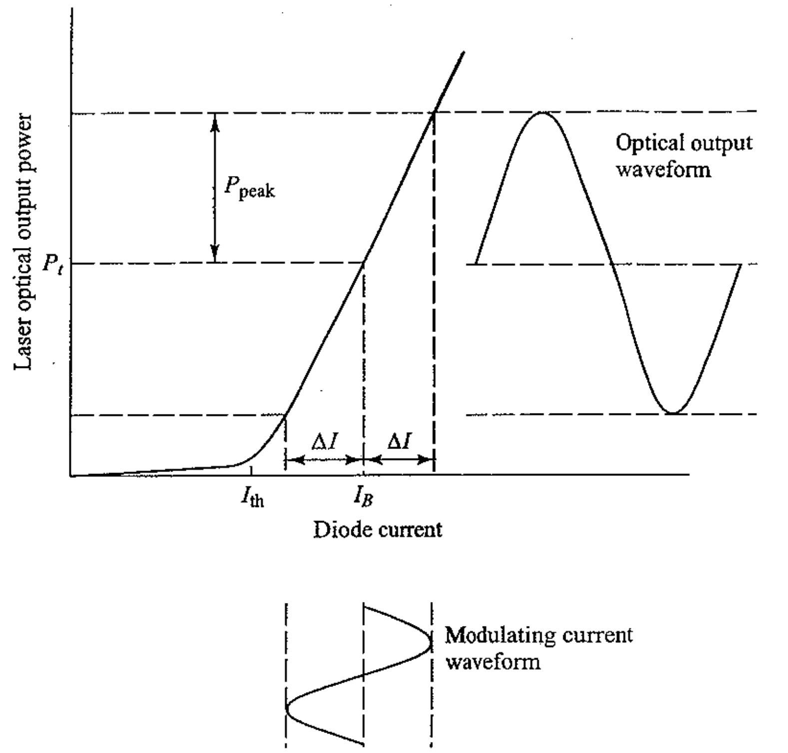

Fig: Biasing conditions of a laser diode & its response to analog signal modulation

From eqn (1) P_t → optical power at bias current level & m → modulation index

$$m = \frac{P_{peak}}{P_t}$$

Typical values of m for analog applications range from 0.25 to 0.50

→ For sinusoidal recieved sg, carrier power C at output of the reciever is:

$$C = \frac{1}{2}(m R M \bar{P})^2$$

R → unity gain responsivity of photo detector

M → photo detector gain

$\bar{P}$ → average recieved optical power

Photodetector and preamplifier Noises

Expression for photodiode noise is

$$\langle i_N^2 \rangle = \sigma_N^2 \approx 2q(I_P + I_D) M^2 F(M) B_e$$

$I_P = R_0 \bar{P}$ → primary photo current

I_D is the detector current

M is the photodiode gain

F(M) → Noise figure

B_e → reciever bandwidth

CNR for photodetector:

$$CNR|_{det} = \frac{C}{\sigma_N^2}$$

Preamplifier noise:

$$\langle i_T^2 \rangle = \sigma_T^2 = \frac{4K_B T}{R_{eq}} B_e F_t$$

R_{eq} → equivalent resistance of photodetector load & preamplifier

F_t → noise factor of preamplifier.

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$$CNR_{preamp} = \frac{C}{\sigma_T^2}$$

Relative Intensity Noise (RIN)

→ Fluctuations in amplitude or intensity of output produce optical intensity noise arise from temperature variations or from spontaneous emission contained in laser output.

→ The noise resulting from random intensity fluctuations is called relative intensity noise [RIN], defined in terms of mean-square intensity variations.

$$\langle i_{RIN}^2 \rangle = \sigma_{RIN}^2 = RIN(\mathcal{R}\bar{P})^2 B_e$$

→ CNR due to amplitude fluctuations:

$$CNR_{RIN} = \frac{C}{\sigma_{RIN}^2}$$

$$RIN = \frac{\langle (\Delta P_L)^2 \rangle}{\bar{P}_L^2}$$

$(\Delta P_L)^2$ → mean square intensity fluctuation of the laser output

$\bar{P}_L$ → average laser light intensity

→ Noise decreases as injection current level increases

$$RIN \propto \left(\frac{I_B}{I_{th}} - 1\right)^{-3}$$

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CNR for a single channel AM s/m:

$$\frac{C}{N} = \frac{\frac{1}{2}(m \mathcal{R} M \overline{P})^2}{RIN(\mathcal{R}\overline{P})^2 B_e + 2q(I_p+I_D)M^2 F(M) B_e + \left(\frac{4K_BT}{R_{eq}}\right) B_e F_t}$$

Reflection Effects on RIN

→ To implement high speed link, special precautions must be taken to minimize optical reflections back into the laser.

→ Back reflected signals can increase RIN by 10-20 dB

→ Feedback power ratio is amount of optical power reflected back into laser relative to the light output from the source.

Limiting Conditions

→ when optical power level at receiver is low, preamplifier circuit noise dominates the s/m noise

$$\left(\frac{C}{N}\right)_{limit\,1} = \frac{\frac{1}{2}(m \mathcal{R} M \overline{P})^2}{\left(\frac{4K_BT}{R_{eq}}\right) B_e F_t}$$

CNR here is α to square of recieved power

→ At intermediate power levels the quantum noise term of photodiode will dominate s/m noise

$$\left(\frac{C}{N}\right)_{limit\,2} = \frac{\frac{1}{2} m^2 \mathcal{R} \overline{P}}{2q\, F(M) B_e}$$

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→ If laser has a high RIN value, the reflection noise will dominate over other noise terms

$$\left(\frac{C}{N}\right)_{limit\ 3} = \frac{\frac{1}{2}(mM)^2}{RIN\ B_e}$$

MULTICHANNEL TRANSMISSION TECHNIQUES

→ In broadband analog applications like cable television supertrunks, one needs to send multiple analog signals over same fiber.

→ multiplexing can be applied where a number of base band signals are superimposed on set of N subcarriers that have different frequencies $f_1, f_2, \cdots f_N$

→ The modulated subcarriers are then combined electrically through frequency division multiplexing to form a composite signal that directly modulates a single optical source.

→ Methods for modulation are: frequency modl^n (FM)
vestigial sideband AM (VSB-AM)
subcarrier multiplexing (SCM)

→ AM is simplest & cost effective.

→ Although FM requires larger bandwidth than AM, it provides a higher SNR & less sensitive to source non-linearities.

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Multichannel Amplitude Modulation

- Explain multichannel AM technique employed in broadband analog applications [5M Dec 09 | Jan 10]
- with a diagram explain operation of multichannel AM briefly [6M Dec 10]
- Explain operation of multichannel amplitude modulation standard technique for frequency division multiplexing of N independent information bearing signals [7M June 12]
- Explain multichannel AM modulation technique with help of block diagram & relevant expressions. [6M Dec 13 | Jan 14]
- Explain multi AM technique employed in broadband analog application [8M Jan 14]

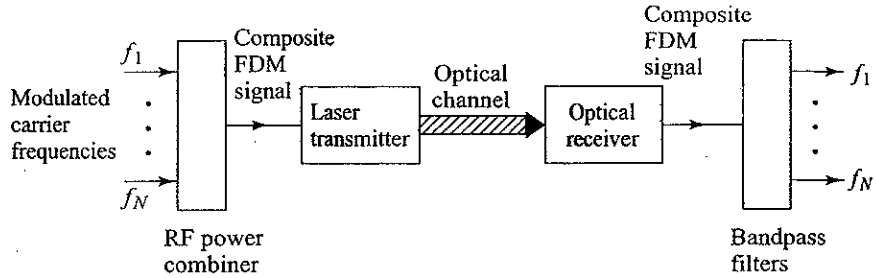

Fig: FDM of N independent information bearing signals

→ An information bearing signal on channel i amplitude-modulates a carrier wave that has frequency f_i, where i = 1, 2, 3 -- N.

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→ An RF power combiner then sums these N amplitude modulated carriers to get a composite frequency division multiplexed signal.

→ At RxR, bank of parallel band pass filters separates combined carriers back to individual channels

→ The individual message signals are recovered from carriers by standard RF techniques.

→ For n channels the optical modulation index m is related to per channel modulation index m_i

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

→ If each channel modulation index m_i has same value m_c, then

$$m = m_c N^{0.5}$$

→ when multiple carrier frequencies pass through a non linear device such as laser diode. Signal products other than original frequencies are produced. These are called Intermodulation products.

→ These intermodulation products result in degradation of transmitted signal

→ Generally only second order & third order products are considered.

→ The third order IM distortion products at frequencies $f_i + f_j - f_k$ are called triple beat frequencies.

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and $2f_i - f_j$ are called two tone third order IM products

→ If signal passband contains a large number of equally spaced carriers, then several IM terms will appear at or near same frequency. This is called <u>beat stacking</u>.

→ For N equally spaced equal amplitude carriers the number of third order IM products that fall right on r^{th} carrier:

$$D_{1,2} = \frac{1}{2}\left\{N - 2 - \frac{1}{2}\left[1 - (-1)^N\right](-1)^r\right\}$$

for two-tone terms of type $2f_i - f_j$

→ For triple beat terms of the type $f_i + f_j - f_k$

$$D_{1,1,1} = \frac{r}{2}(N - r + 1) + \frac{1}{4}\left\{(N-3)^2 - 5 - \frac{1}{2}\left[1 - (-1)^N\right](-1)^{N+r}\right\}$$

→ The result of beat stacking is composite second order [CSO] & composite triple beat (CTB)

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

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

Multichannel Frequency Modulation

→ The use of AM-VSB signals for transmitting multiple analog channels is simple but it has $\frac{C}{N}$ requirement at least 40 dB for each channel, which is very stringent requirement.

→ So alternative technique is frequency modulation (FM), where each subcarrier is frequency modulated by a message signal.

→ This method requires a wider bandwidth but yeilds improved SNR.

→ The $\frac{S}{N}$ o/p at FM detector is much larger the $\frac{C}{N}$ at i/p of detector. The improvement is given by:

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

B_e → required bandwidth

Δf_{pp} → peak to peak frequency deviation of modulator

f_v → highest video frequency

w → weighting factor that accounts for nonuniform eye pattern.

→ Reduced $\frac{C}{N}$ makes FM s/m less subjected to noise than AM s/m.

Subcarrier Multiplexing: [SCM]

- What is subcarrier multiplexing? Explain

[5M June/July 13]

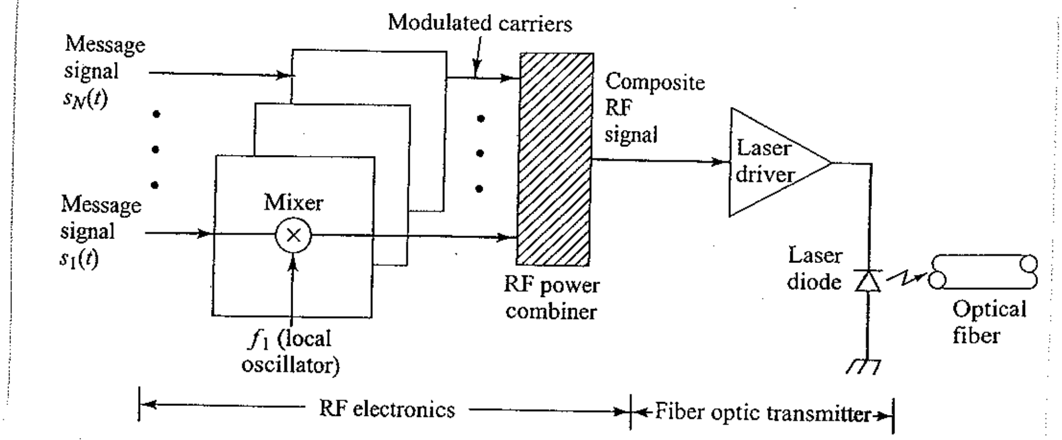

fig: Basic concepts of subcarrier multiplexing

→ subcarrier multiplexing is used to describe the capability of multiplexing both multichannel analog & digital signals within the same s/m.

→ Fig: shows the basic concept of an SCM s/m.

→ The input to TxR consists of a mixture of N independent analog & digital baseband signals which carry either voice, data, video, digital audio, high definition video or any other analog or digital information.

→ Each incoming signal $s_i(t)$ is mixed with local oscillator having frequency f_i.

→ The local oscillator frequencies employed in 2-8 GHz range are known as subcarriers.

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→ By combining modulated subcarriers a composite frequency division multiplexed signal is obtained.

→ At receiving end, optical signal is directly detected with a high speed pin photodiode & reconverted to microwave signal.

→ For long distance links, avalanche photo diode can be used.

RF OVER FIBER

• What is RF over fiber technique? Explain

5M Dec 09 | Jan10

→ Radio frequency signals at microwave range & millimeter wave frequencies are used in applications such as radars, satellite links, broadband terrestrial radios & cable TV networks.

→ The signal range includes 0.3 to 3 GHz ultra high frequency band (UHF), 3 to 30 GHz super high frequency (SHF) band & 30 to 300 GHz extremely high frequency (EHF) range.

→ Traditionally, RF systems used wireless or coaxial cables for transporting microwave signals from recieving element to signal processing center.

→ Advantages of optical fibers over coaxial cables like smaller size, lower losses, wider bandwidths & insensitivity to electromagnetic interference effects allow using fiber links over longer distances.

→ Thus, there has been must interest in developing & deploying high speed optical fiber links for transporting microwave & millimeter wave signals in their original analog format.

→ The methods for transmitting microwave analog signals over optical fiber link is known as RF over fiber techniques.

Key Link Parameters

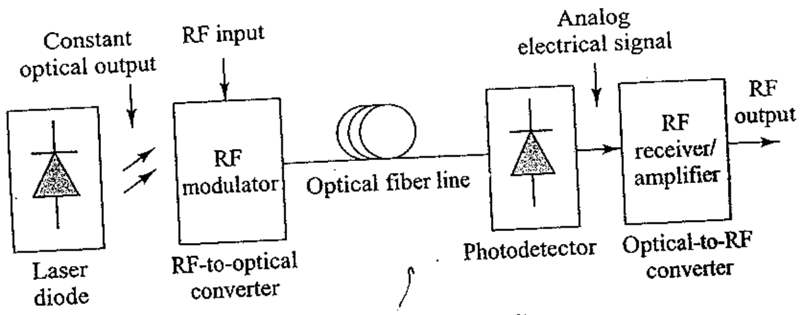

Fig: Basic constituents of generic RF-over fiber link

→ The 3 major modules are: RF to optical signal converting device at transmitting end, an optical-to-RF signal converting device at recieving end and an optical fiber that joins these 2 modules

→ The primary parameters to characterize the RF performance of optical link are:

- gain
- noise figure
- spur free dynamic range (SFDR)

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1. Gain

→ The link gain 'g' is defined as the ratio of the RF power P_{out} generated in photodetector load resistor to the RF power input P_{in} to the laser transmitter

→ For directly modulated link the gain is:

$$g = \frac{P_{out}}{P_{in}} = S_M^2 \eta_{LF}^2 T_F^2 \eta_{FD}^2 \mathcal{R}^2 \frac{R_{load}}{R_M}$$

S_M – slope efficiency of modulation
η_{LF} – laser to fiber coupling efficiency
T_F – fiber transmission efficiency
η_{FD} – fiber to detector coupling efficiency
$\mathcal{R}$ – photo detector responsivity
R_{load} – detector load resistance
R_M – modulator resistance

→ Gain values that are less than 1 represent a link loss

2. Noise figure (NF)

→ Noise figure represents a measure of the degradation in SNR between the input & output of the link.

$$NF = 10 \log \frac{SNR_{in}}{SNR_{out}} = 10 \log \frac{\bar{N}_{out}/B_e}{K_B T g} = 10 \log \frac{N_{out}}{K_B T g}$$

i/p noise → thermal noise power $T = 290°K$
K_B – Boltzmann Constant B_e – noise bandwidth
$\bar{N}_{out}$ → total output noise power

$\bar{N}_{out} \propto B$

N_{out} → noise power / unit bandwidth

→ At link output noise power is due to laser RIN, photodetector shot noise & thermal noise

$$N_{out,RIN} = I_p^2 RIN$$

$$N_{out,shot} = 2q I_p$$

$$N_{out,thermal} = \frac{4k_B T}{R_{Load}}$$

I_p is average photodiode current in RXR

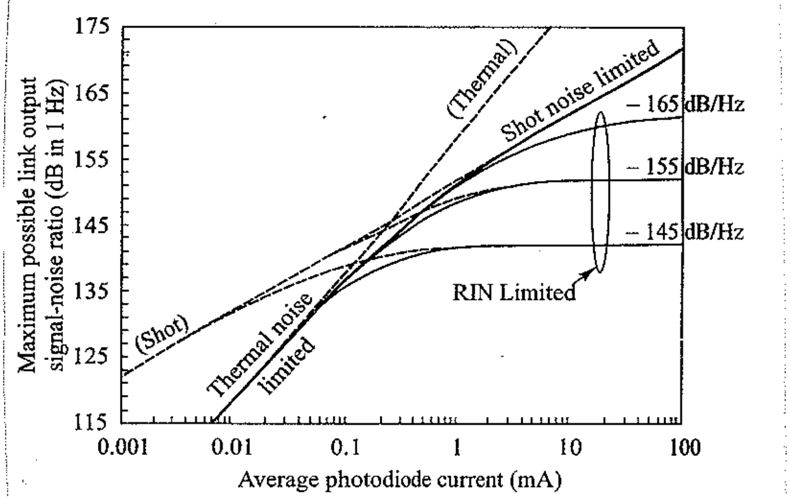

Fig: Limiting conditions due to noises on SNR

→ Thermal noise imposes poorly performing limit on SNR. RIN restricts SNR to an upper value that cannot exceed even if photodiode current is increased.

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3. Spur free dynamic range [SFDR]

→ Dynamic range of an analog link is defined in relation to two-tone third-order intermodulation frequencies.

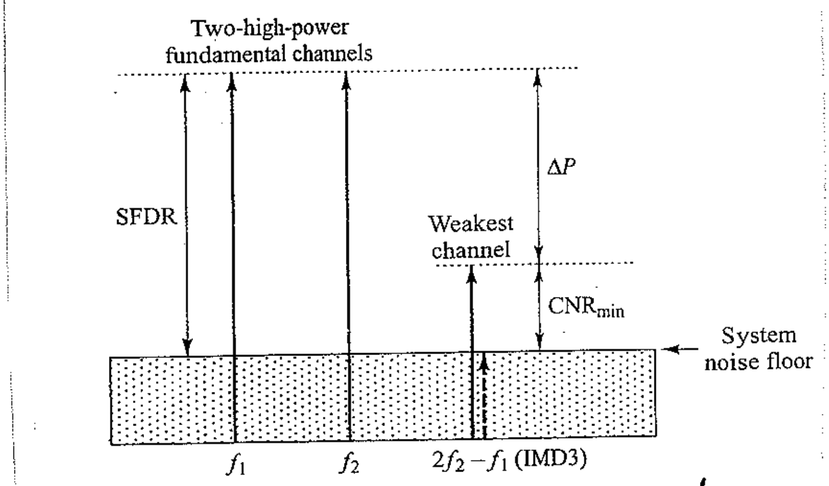

Fig : Relationship of 3rd order intermodulation products to s/m operating requirements

→ Consider 2 large equal power signals at fundamental frequencies f_1 & f_2.

→ These signals will produce second order intermodulation products : $2f_1$, $2f_2$ & $f_1 \pm f_2$

third order intermodulation products: $2f_1 \pm f_2$ & $2f_2 \pm f_1$

→ Second order terms fall outside pass band of the system, hence they are ignored

→ Third order products fall on signal frequency within s/m bandwidth & cannot be removed by simple filtering technique

→ Third order intermodulation product resulting from 2 fundamental carriers falls at frequency where

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weakest channel operates.

→ From the fig: Δp ⇒ power difference b/w strongest & weakest channels.

CNR_{min} ⇒ minimum required CNR for weakest signal

Intermodulation products resulting from strongest equal power fundamental carriers are equal to noise floor.

→ For standard analog link:

Third order intermodulation product distortion varies with cube of RF input power.

→ SFDR is defined as ratio b/w powers in fundamental carrier & 3rd order intermodulation at that power level where IMD_3 is equal to noise floor.

→ SFDR is usable dynamic range before noise interferes with or distorts the fundamental signal.

→ SFDR must be larger than $CNR_{min} + \Delta P$.

→ SFDR decreases significantly as frequency increases beyond 1GHz due to inherent distortion effects in laser.

Radio Over Fiber Links

- Explain radio over fiber concept of broadband wireless access n/w for interconnecting base station with central controlling office.

$\boxed{\text{7M Dec 10}}$

- Explain with a neat diagram the functioning of radio over fiber links of a broadband wireless access n/w $\boxed{\text{6M May 2010}}$
- Explain radio over fiber links with a concept of a broadband wireless access n/w for inter-connecting antenna base station with central controlling office. $\boxed{\text{6M June 2012}}$
- Explain & write the diagram of radio over fiber links. $\boxed{\text{10M Dec 12}}$
- write short notes on radio over fiber link. $\boxed{\text{10M Dec 13/Jan 14}}$

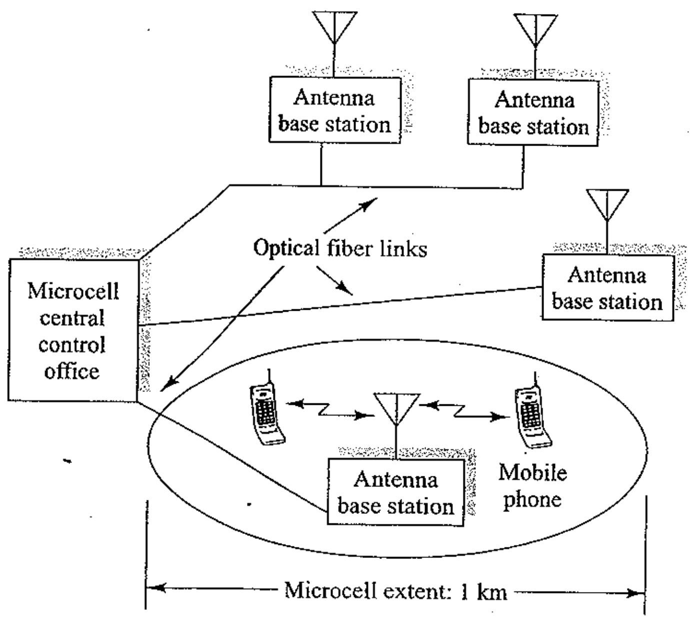

Fig: Radio over fiber concept of a broadband wireless access network.

→ Application of RF over fiber technology is in broadband wireless access n/w for interconnecting antenna base station with central controlling office.

→ collection of atenna base stations provide wireless connectivity to subscriber by means of millimeter-wave frequency.

→ Subscribers are located up to 1Km from a local base station (BS)

→ The transmission range around BS is called microcell, or a picocell or a hot spot.

→ The BSs are connected to microcell control office (CS) in central office.

→ CS is responsible for functions such as RF modulation, demodulation, channel control & switching & routing of customer calls.

→ Due to advantageous transmission characteristics of optical fibers, fibers are used to connect the base stations to central office.

→ Individual BSs can be independently connected to the microcell CS through wavelength Division Multiplexing (WDM) techniques by using a separate unique wavelength for each BS.

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Microwave Photonics:

• Explain microwave photonics

4M Dec 13/Jan 14

→ Microwave photonics is the study of applications of photonic devices operating at microwave frequencies.

→ The key components being developed & applied are:

a) High-frequency low-loss external optical modulators that have linear transfer function & withstand continous-wave optical power up to 60mW.

b) optical sources with high slope efficiencies & low RIN that can be modulated at tens of GHz

c) High speed photodiodes & optical RxRs that can respond to signal frequencies of 20 to 60 GHz

d) Microwave photonic filters that perform same tasks as standard RF filters.

→ Microwave photonics also address optical signal processing at microwave speeds & design & implementation of RF photonic transmission systems.

DIGITAL LINKS

Point to Point Links

- Explain with neat diagram, the simplex point to point links in optical fiber communication engineering. [6M June/July 15]
- with a simplex point to point link, explain the key system requirements which are needed in analyzing a link & how to fulfil these requirements [8M June/July 11]

→ The simplex transmission link has a transmitter at one end & a reciever at the other.

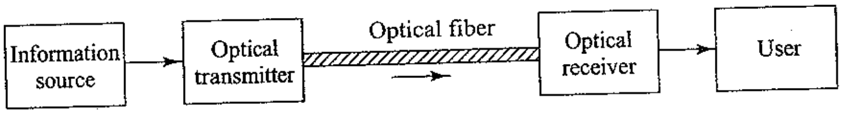

Fig: simplex point to point link

→ The design of an optical link involves many inter related variables among the fiber, source & photo detector operating characteristics.

→ Performance & cost constraints are very important factors in fiber optic communication links.

→ The designer must carefully choose the components to ensure the desired performance level can be maintained over expected life time without over specifying component characteristics.

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→ Following key system requirements are required in analyzing a link:

1. The desired transmission distance
2. The data rate or channel bandwidth
3. The bit-error rate. (BER)

→ To fulfill the above requirements the designer has choice of following components & their associated characteristics:

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 diodes
3. Pin or avalanche photodiode
   a) Responsivity
   b) operating wavelength
   c) speed
   d) sensitivity

→ Two analyses usually carried out to ensure that desired s/m performance can be met :
• link power budget • System rise time budget

→ Once the link power budget has been established, designer can perform a system rise time analysis to ensure that the desired overall system performance has been met.

System Considerations

→ In carrying out link power budget, first wave-length to transmit is decided & then other components are choosen to operate in that region.

→ The system performance of three major optical link building blocks are inter related; that is the RxR, TxR & optical fiber.

→ usually, designer chooses characteristics of two of these elements & then computes the third to meet the s/m requirements.

→ The procedure followed is: first select the photo-detector then choose an optical source & see how far data can be transmitted over a particular fiber before an amplifier is needed in line to boost up the power level of optical signal.

→ choosing photodetector:
• determine the minimum optical power that must fall on photodetector to satisfy the BER at specified data rate.

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- Design & cost complexity constraints must be taken into account.
- A pin photodiode RxR is simpler, stable with changes in temperature & less expensive than avalanche photodiode (APD).
- But advantages of pin photodiode can be overruled by increased sensitivity of APD.

→ S/m parameters involved in choosing LED or laser diode are: dispersion, data rate, transmission distance & cost.

- In 770 to 910 nm region, spectral width of an LED & dispersion characteristics of multimode silica fibers limit data rate distance product around 150 Mbps.
- For higher value, laser must be used @ these wavelengths
- Laser diodes couple more optical power than LED, greater repeaterless transmission distances are possible with a laser
- But laser diode itself is more expensive than LED & also TxR circuitry is more complex.

→ Optical fiber: choice b/w single mode & multimode fiber, either of which could have a step or a graded index core

- choice depends on type of light source used & amount of dispersion that can be tolerated.
- LED Tends to be used with multimode fibers

Link Power Budget

- Explain link power budget, with relevant diagram.

$\boxed{\text{7M June 12}}$

- what is link power budget? with an example, explain link power budget calculation.

$\boxed{\text{10M Dec 12}}$

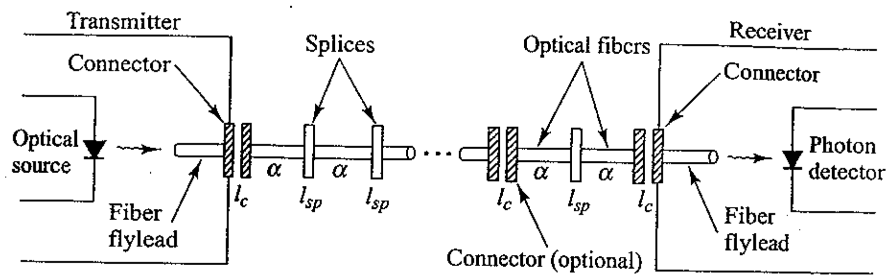

fig: optical power loss model for a point to point link

- Explain optical power loss model with neat diagram.

$\boxed{\text{10M June/July 14}}$

→ An optical power loss model for point to point link is shown in fig.

→ The optical power recieved at photo detector depends on amount of light coupled into fiber & losses occuring in fiber & at connector & splices.

→ Link power budget determines the power margin b/w optical TxR o/p & minimum RxR sensitivity to establish specified BER.

→ The link loss budget is derived from sequential loss contributions of each element in the link.

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→ Each of these loss elements is expressed in dB.

$$loss = 10 \log \left(\frac{P_{out}}{P_{in}}\right)$$

P_{out} & P_{in} are optical power leaving & entering the loss element.

→ In addition to link loss contributors, link power margin normally provided in the analysis allow for component aging, temperature fluctuations & losses occuring from components that might be added in future.

→ A link margin of 6-8dB is generally used for systems that are not expected to have additional components into the link in future.

→ Link loss budget considers the total optical power loss P_T allowed b/w source & photodetector & This loss is allocated to cable attenuation, connector loss, splice loss & s/m margin.

$$P_T = P_S - P_R$$
$$= 2l_c + \alpha L + \text{System margin}$$

P_S → optical power emerging from end of flylead attached to light source or source coupled connector.

P_R → reciever sensitivity.

l_c → connector loss

α → fiber attenuation L → transmission distance

System margin nominally taken at 6dB.

Example :

Date rate 20Mbps, BER 10^{-9} consider a pin photo diode operating at 850 nm. Required reciever i/p signal is −42dBm. Select LED that can couple 50μW (−13dBm) average power level into fiber flylead with 50 μm core diameter. Total allowable power loss 29dB. 1dB loss occurs at fiber flylead & 1dB connector loss. S/m margin is 6dB. $\alpha = 3.5\,dB/km$

$$P_T = P_S - P_R$$

$$29dB = 2l_c + \alpha L + \text{System margin}$$

$$29(dB) = 2(1dB) + 3.5L + 6dB$$

$$L = 6\,km$$

6 km is the transmission path possible.

→ Convinient procedure for calculating the power budget is to use a tabular or spreadsheet form.

Rise time Budget

- What is rise time budget analysis? Derive an expression for total system rise time budget in terms of TxR & RxR rise times. $\boxed{\text{10M Dec09/Jan10}}$

- What is rise time budget? Derive an expression for total S/m rise time (tsys) $\boxed{\text{7M Dec10}}$

→ Rise Time budget analysis is a convinient method for determining the dispersion limitation of an optical fiber link

→ used for digital slms

→ Total rise time t_{sys} of link is root sum square of rise times from each contribution t_i to the pulse rise time degradation.

$$t_{sys} = \left[\sum_{i=1}^{N} t_i^2\right]^{1/2}$$

→ Basic elements that limit slm speed are:

i) TxR rise time t_{tx}

ii) Group velocity Dispersion (GVD) rise time t_{GVD} of fiber

iii) Modal dispersion rise time t_{mod} of fiber.

iv) RxR rise time t_{rx}

→ Single mode fiber do not experience modal dispersion.

→ Rise time of TxR & RxR are generally known to designer.

→ TxR rise time is related to light source & drive circuitry

→ RxR rise time results from photodetector response time & 3dB electrical band width of RxR front end.

To find t_{rx} :

→ The response of RxR front-end is modelled by first order LPF having a step response

$$g(t) = [1 - \exp(-2\pi B_{rx} t)]\, u(t)$$

B_{rx} ⇒ 3dB electrical B.W. of RxR

$u(t)$ ⇒ unit step function which is 1 for $t \geq 0$ & 0 for $t < 0$.

t_{rx} ⇒ rise time of RxR i.e; interval between $g(t) = 0.1$ & $g(t) = 0.9$ (10 to 90% rise time)

If B_{rx} is given in MHz then t_{rx} is in ns

$$t_{rx} = \frac{350}{B_{rx}}$$

To find t_{GVD}

→ The fiber rise time t_{GVD} resulting from group velocity dispersion over length L.

$$t_{GVD} \simeq |D| L \sigma_\lambda$$

D ⇒ dispersion

σ_λ ⇒ Half power Band width of source

To find t_{mod}

→ Empirical relation for band width 'B_M' of link length L : $B_M(L) = \dfrac{B_0}{L^q}$

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where $0.5 < q < 1$

$B_0 \Rightarrow$ bandwidth of 1km length of fiber cable

→ B_M based on curve fitting of experimental data

$$\frac{1}{B_M} = \left[\sum_{n=1}^{N} \left(\frac{1}{B_n}\right)^{1/q}\right]^q$$

$B_n \Rightarrow$ bandwidth of fiber section

alternatively,

$$t_M(N) = \left[\sum_{n=1}^{N} (t_n)^{1/q}\right]^q$$

$t_M(N) \Rightarrow$ pulse broadening occuring over N cable sections in which individual pulse broadening is given by t_n

→ Relation b/w fiber rise time & 3dB bandwidth assuming optical power is gaussian response:

$$g(t) = \frac{1}{\sqrt{2\pi\sigma}} e^{-t^2/2\sigma^2}$$

$\sigma \Rightarrow$ rms pulse width

Taking the Fourier Transform:

$$G(\omega) = \frac{1}{\sqrt{2\pi}} e^{-\omega^2\sigma^2/2}$$

→ time $t_{1/2}$ required for pulse to reach half the maximum value:

$$g(t_{1/2}) = 0.5\, g(0)$$

$$t_{1/2} = (2\ln 2)^{1/2}\sigma$$

→ Full width half maximum :

$$t_{FWHM} = 2t_{1/2} = 2\sigma(\ln)^{1/2}$$

→ 3dB bandwidth is defined as modulation frequency f_{3dB} at which recieved optical power has fallen to 0.5 of zero frequency value.

$$f_{3dB} = B_{3dB} = \frac{0.44}{t_{FWHM}}$$

letting t_{FWHM} be the rise time resulting from modal dispersion

$$t_{mod} = \frac{0.44}{B_M} = \frac{0.44L^q}{B_0}$$

If t_{mod} is in ns & B_M is in MHz

$$t_{mod} = \frac{440}{B_M} = \frac{440L^q}{B_0}$$

→ t_{sys}

Total s/m rise time is given by:

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

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

all the times are in nanoseconds

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Short wavelength Band:

- Explain in brief short wavelength band.

3M Dec 13/Jan 14

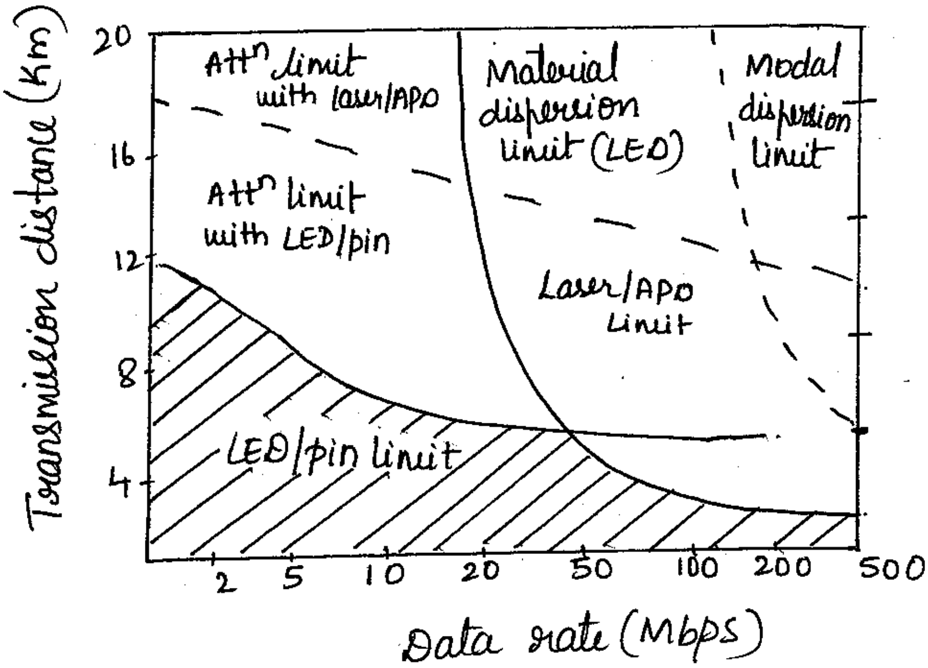

fig: Transmission distance limits as a function of data rate, combination of 800nm LED & 850nm Laser

→ The attenuation & dispersion limitation on repeaterless transmission distance as a function of data rate for short wavelength (770-910nm) LED/pin combination.

→ BER = 10^{-9} for all data rates.

→ The minimum optical power required at the Rxr for a given BER becomes higher for increasing data rates, the attenuation limitation curve slopes downward to the right.

→ Material dispersion at 800nm is taken as 0.07 ns/(nm.km) or 3.5 ns/km for an LED with a 50 nm spectral width.

→ The curve shown is material dispersion limit in the absence of modal dispersion. t_{mat} is taken as 70 percent of bit period.

→ Modal dispersion for a fiber with 800MHz.Km bandwidth-distance product & with $q=0.7$. t_{mod} is taken as 70% of bit period.

→ The acheivable transmission distances are those that fall below the attenuation limit curve & to the left of the line as indicated by shaded area.

→ Transmission distance is attenuation limited up to about 40Mbps after which it becomes material dispersion limited.

Power Penalities:

→ The optical power falling on the photo-detector is clearly defined function of time.

→ A number of signal impairments that are inherent in optical fiber transmission systems can degrade the link performance.

→ When any of these impairment effects are present in a link, there is reduction in SNR of the system.

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→ The reduction in SNR is known as power penalty for that effect.

→ If SNR_{ideal} & SNR_{impair} are SNR for ideal & impaired cases respectively, then power penalty PP_x for impairment x is given by

$$PP_x = -10 \log \frac{SNR_{impair}}{SNR_{ideal}}$$

→ In some cases one can increase optical power level at the reciever to reduce the power penalty

→ The main power penalties are due to chromatic & polarization mode dispersions, modal or speckle noise, mode partition noise, the extinction ratio wavelength chirp, timing jitter, optical reflection noise & non linear effects that arise when there is a high optical power level in a fiber link.

1. Chromatic Dispersion Penalty (D_{cD})

→ chromatic dispersion originates from the fact that each wavelength travels a slightly different velocity in a fiber & thus they arrive at different times at the fiber end.

→ The range of arrival times at the fiber end of spectrum of wavelengths will lead to pulse spreading.

→ The accumlated chromatic dispersion increases with distance along a link.

→ A transmission system has to be designed to tolerate total dispersion or some type of dispersion compensation method has to be employed.

→ A simple method to limit chromatic dispersion on link performance is to specify that accumlated dispersion should be less than a fraction ε of the bit period $T_b = \frac{1}{B}$ where B is bit rate.

$$|D_{CD}| L \sigma_\lambda < \varepsilon T_b$$

$$|D_{CD}| L B \sigma_\lambda < \varepsilon$$

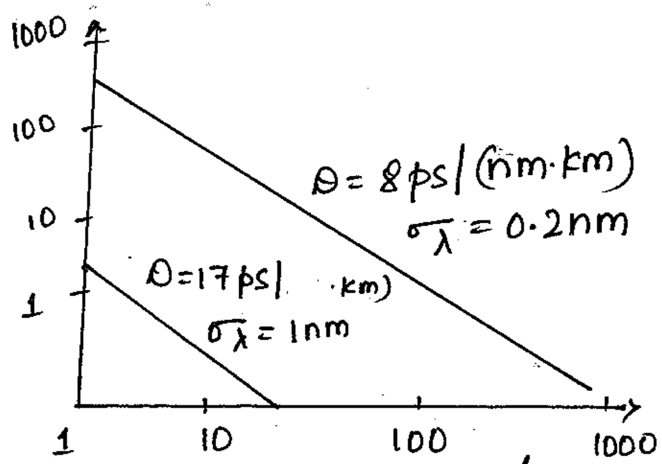

fig: chromatic dispersion limits for 2 different chromatic dispersion values

2. Polarization mode dispersion penalty (D_{PMD})

• Explain the polarization mode dispersion penalty in power penalties of a digital link.

$\boxed{\text{4M June/July 2011}}$

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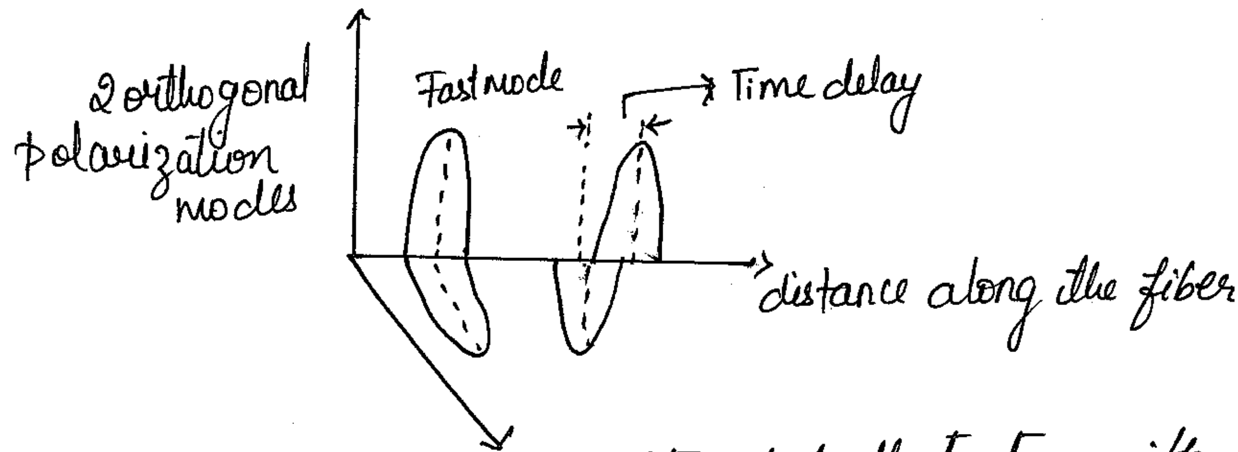
→ Polarization mode dispersion (PMD) results from the fact that light signal energy at a given wavelength in a single mode fiber occupies 2 orthogonal polarization states or modes.

→ PMD arises because 2 fundamental orthogonal polarization modes travel at slightly different speeds owing to fiber birefringence.

→ The resulting difference in propogation time b/w 2 orthogonal modes will result in pulse spreading.



→ PMD is not fixed quantity but fluctuates with time due to factors like temperature variations & stress changes on the fiber

→ PMD varies as square root of distance

→ A typical PMD value for a fiber is $D_{PMD} = 0.05$ ps/$\sqrt{km}$.

→ PMD value does not fluctuate wide for cables enclosed underground ducts or in buildings compared to cables that are suspended on poles.

→ To have power penalty less than 1dB, pulse spreading τ_{PMD} resulting from PMD must be on average less than 10 percent of a bit period T_b

$$\tau_{PMD} = D_{PMD}\sqrt{L} < 0.1\,T_b$$

3. Extinction Ratio Penalty:

→ The extinction ratio r_e in a laser is defined as ratio of optical power level P_1 for logic 1 to optical power level P_0 for logic 0

$$r_e = \frac{P_1}{P_0}$$

→ If extinction ratio is infinite there would be no power penalty

→ If P_{ave} is average power, $P_0 = 0$ & $P_1 = 2P_{ave}$

→ If P_{1-ER} & P_{0-ER} be the 1 & 0 power levels with non zero extinction ratio &

$$r_e = \frac{P_{1-ER}}{P_{0-ER}}$$

average power: $P_{ave} = \frac{P_{1-ER} + P_{0-ER}}{2} = P_{0-ER}\frac{r_e+1}{2}$

$$= P_{1-ER}\frac{r_e+1}{2r_e}$$

→ when reciever thermal noise dominates, 1 & 0 powers are equal & independent of signal level. $P_0 = 0$ & $P_1 = 2P_{ave}$, power penalty is given by:

$$PP_{ER} = -10 \log \frac{P_{1-ER} - P_{0-ER}}{P_1} = -10 \log \frac{r_e - 1}{r_e + 1}$$

4. <u>Modal Noise</u>:

→ when light from laser is launched into multi-mode fiber, number of propogating modes are excited.

→ As a result of construcTive & destructive interference between propogating modes the radiation pattern at the end of the fiber takes on the form of a speckle pattern.

→ As light travels along the fiber, a combination of mode dependent losses, changes in phase b/w the modes & fluctuation in energy among various modes change the modal interference & result in a different speckle pattern

→ Modal or speckle noise occurs when any losses that are speckle pattern dependent are present in a link.

→ losses that are speckle pattern dependent are: splices, connectors, microbends & photodetectors with non uniform responsivity.

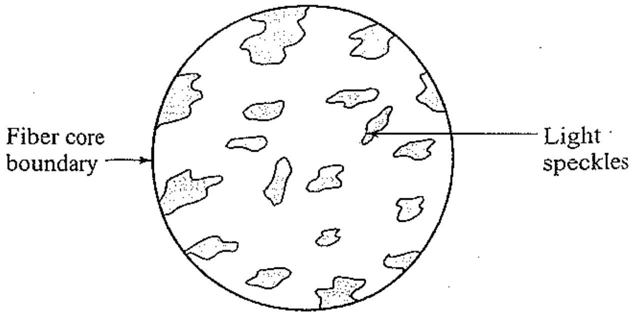


Fig: Speckle pattern when laser light is launched into a multimode fiber

→ The modal distortion resulting from interference between a single pair of modes will appear as a sinusoidal ripple frequency

$$\nu = \delta T \frac{d\nu_{source}}{dt}$$

$\frac{d\nu_{source}}{dt}$ → rate of change of optical frequency

δT → intermodal dispersion time.

→ Performance of laser based multimode fiber link is difficult to predict, since degree of modal noise depends on particular installation.

→ Steps to avoid modal noise are:

a) use LED's
b) use laser that has large number of longitudinal modes
c) use fiber with large NA, it supports large number of modes & gives greater number of speckles
d) use of single mode fibers (no modal dispersion)

5. Mode Partition Noise: [SM Dec 11]

→ Mode-partition noise is dominant noise in single mode fibers while using multimode devices (LASER)

→ Due to intensity fluctuations in the longitudinal modes of a multimode laser diode are not sufficiently suppressed.

→ Power distribution can vary within the pulse & from pulse to pulse.

→ Each of the longitudinal modes coupled into fiber has different attenuation & time delay as each is associated with slightly different wavelength.

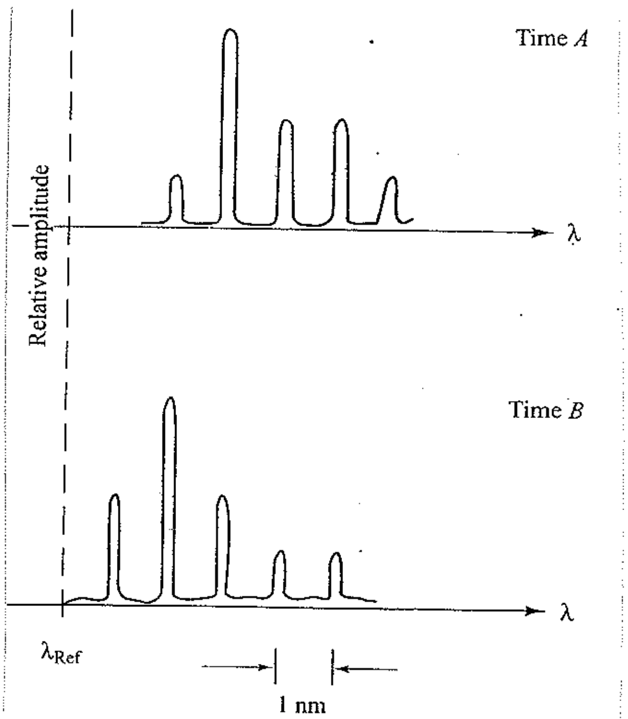


Fig: Different modes or groups of modes dominates optical o/p at different times

→ The power penalty caused by laser mode-partition noise is given by:

$$PP_{mpn} = -5\,\frac{x+2}{x+1}\log\left[1 - \frac{K^2Q^2}{2}(\pi B L D \sigma_\lambda)^4\right]$$

$x \Rightarrow$ excess noise factor
$B \Rightarrow$ bit rate
$Q \Rightarrow$ SNR factor
$L \Rightarrow$ fiber length
$D \Rightarrow$ fiber chromatic dispersion
$\sigma_\lambda \Rightarrow$ rms spectral width of source

→ Mode partition noise increases with increase in bit rates.

6. <u>Chirping</u>

• Write a short note on chirping [4M Dec 11] [5M Dec 13/Jan 14]

→ Chirping is a phenomenon, in which a LASER oscillating in a single mode under CW operation experiences dynamic line broadening, when injected current is directly modulated.

→ The line broadening is a frequency 'chirp' associated with modulation induced changes in the carrier density.

→ Laser chirping can lead to dispersion effects for intensity modulated pulses when laser emission wavelength is displaced from zero dispersion wavelength of the fiber.

→ The time dependent frequency change $\Delta v(t)$

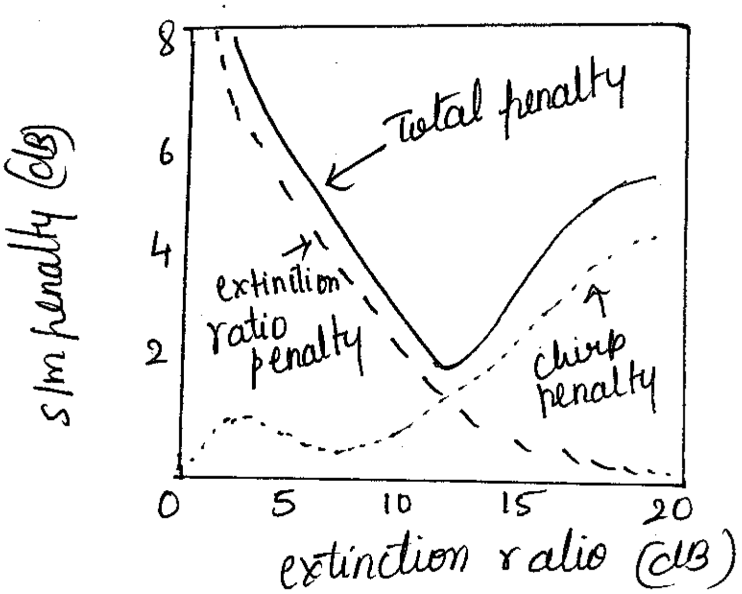
$$\Delta v(t) = \frac{-\alpha}{4\pi}\left[\frac{d}{dt}\ln P(t) + K\,P(t)\right]$$

α - line width enchancement factor

K - frequency independent factor

→ To minimize chirp is to increase the bias level of laser, this results in lower extinction ratio.

→ This leads to an extension ratio power penalty at the RxR



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→ when effect of laser chirp is small, eye closure value Δ is given by:

$$\Delta = \left(\frac{4}{3}\pi^2 - 8\right) t_{chirp}\, DLB^2\, \delta\lambda \left[1 + \frac{2}{3}\left(DL\delta\lambda - t_{chirp}\right)\right]$$

t_{chirp} - chirp duration

D - fiber chromatic dispersion

L - length of fiber

B - bit rate

$\delta\lambda$ - chirp included wavelength excursion

→ Power penalty estimated from SNR degradation due to signal amplitude decreases:

$$PP_{chirp} = -10 \log \frac{x+2}{x+1} \log(1-\Delta)$$

$x \Rightarrow$ excess noise ratio factor

7. <u>Reflection Noise</u>:

→ when light travels through a fiber link, some optical power gets reflected at R.I. discontinuities like splices, couplers & filters.

→ Reflected sgs degrade both TXR & RXR performance

→ Fig a) shows multiple reflection pts set up an interferometric cavity that feeds power back to laser cavity, converting phase noise into intensity noise.

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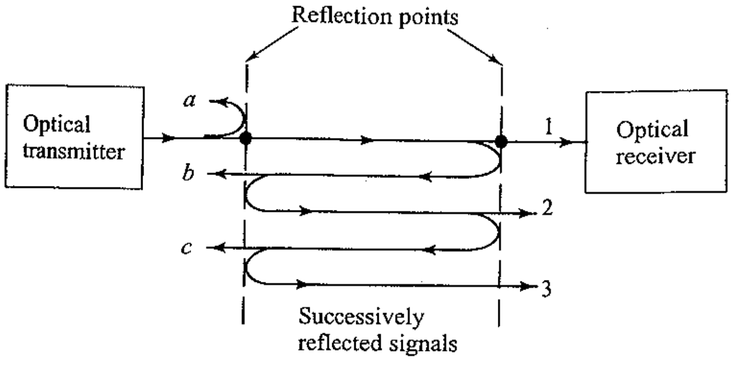
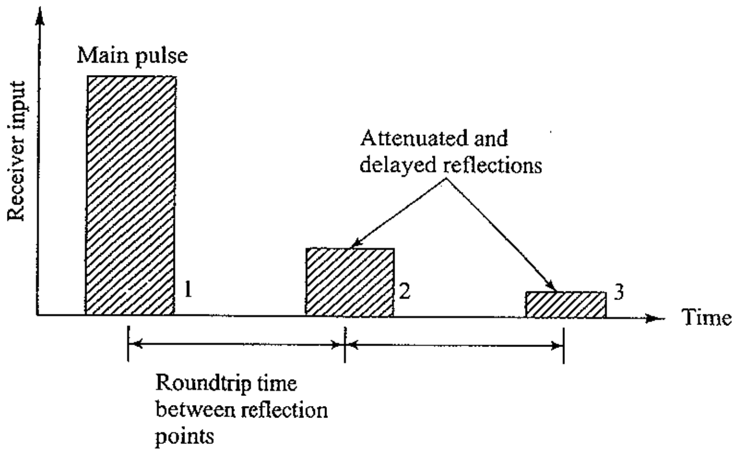


(a)

→ A second effect is created by multiple optical paths is appearence of spurious signals arriving at RXR with variable delays, causing ISI [inter symbol interference]

Fig b) illustrates this.



(b)

→ Techniques for reducing optical feedback include the following:

a) Prepare fiber end faces with curved surface relative to laser emitting facet. This directs reflected light away from fiber axis, so it does not re-enter the waveguide

b) use index matching oil or gel at air glass interfaces

c) Use connectors in which end faces make physical contact.

d) use optical isolator within the laser TXR module.

Problems

1. Following are parameters of pt to pt link
   - optical power launched : +5 dBm
   - sensitivity of detector : −30 dBm
   - Source/detector connector loss : 1 dB
   - Length of cable : 55 Km
   - cable attenuation : 0.3 dB/Km
   - Jumper cable loss ; 2.5 dB
   - connection loss @ each fiber joint : 1 dB

Assume 2 jumper cables & 2 cable joints. Compute power margin of the link. $\boxed{\text{8M May/June 10}}$

→

Parameter	o/p/sensitivity/loss	Power margin (dB)
Laser o/p	5 dBm	
APD sensitivity	−30 dBm	
Loss [5 − (−30)]		35
Source connector loss	1 dB	34
Jumper connector loss (T)	(2.5 + 1) dB	30.5
Cable attenuation	16.5 dB	14
Jumper connector loss (R)	(2.5 + 1) dB	10.5
RxR connector loss	1 dB	$\boxed{9.5}$
		Final margin

2. Following are different types of front end amplifiers in optical RXR; [6M June/July 13]

optical power launched: 3dBm
sensitivity of detector: -32dBm
Source/detector connector loss: 1dB
Length of optical cable: 60 km
cable attenuation: 0.3 dB/Km
Jumper cable loss: 3dB
connector loss at each fiber: 1dB

Assume 2 jumper cable joint. Compute power margin.

→

Parameter	O/P/Sensitivity/Loss	Power Margin (dB)
Laser O/P	3 dBm	
APD sensitivity	-32 dBm	
Loss [3-(-32)]		35
Source connector loss	1dB	34
Jumper connector loss (T)	(3+1) dB	30
Cable attenuation	18 dB	12
Jumper connector loss (R)	(3+1) dB	8
RXR connector loss	1 dB	7 power margin

3. In a multimode link using LED as source, material dispersion related rise time degradation is 20ns over 5km link. RXR has 30MHz

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bandwidth. Fiber has 500 MHz·Km bandwidth distance product with mode mixing parameter $q = 0.7$. Assuming LED with drive circuit has rise time 15ns. Calculate link rise time.

$\boxed{\text{6M May/June 10}}$

→ $t_{mat} = 20ns$

$B_{rx} = 20 \text{ MHz}$

$$t_{rx} = \frac{350}{B_{rx}}$$

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

S/m bandwidth :

$$BW = \frac{0.35}{t_{sys}}$$

$$t_{mod} = \frac{440}{B_M} = \frac{440 L^q}{B_0}$$

$$t_{mod} = \frac{440 \times (5)^{0.7}}{50 \times M} = 2.265 \times 10^{-9} \text{ sec}$$

$$t_{rx} = \frac{350}{30M} = 11.66 \times 10^{-6}$$

$$t_{sys} = \left[\sum_{i=1}^{N} t_{rx}^2 \right]^2$$

$$t_{sys} = \left[(20\times10^{-9})^2 + (11.66\times10^{-6})^2 + (2.265\times10^{-9})^2 + (15\times10^{-9})^2\right]^{1/2}$$

$$= 1.166\times10^{-5} \text{ sec}$$

S/m BW

$$BW = \frac{0.35}{t_{sys}} = \frac{0.35}{1.16\times10^{-5}} = \underline{30KHz}$$

---

4. For a multimode fiber link following parameters given:
   LED drive circuit has rise time 15ns
   LED spectral width = 40nm
   Material dispersion related rise time degradation = 21ns over 6km link
   Reciever Band width = 25MHz
   Modal dispersion rise time = 3.9nsec
   Calculate s/m rise time:

→

$t_{tx} = 15nsec$

$t_{mat} = 21nsec$

$t_{mod} = 3.9nsec$

$$t_{rx} = \frac{350}{B_{rx}}$$

$$t_{rx} = \frac{350}{25} = 14nsec$$

$$t_{sys} = \left[\sum_{i=1}^{N} t_{ri}^2\right]^{1/2}$$

$$= \left[15^2 + 21^2 + 3.9^2 + 1.4^2\right]^{1/2}$$

$$= 29.61 nsec$$

$$t_{sys} \simeq 30ns$$

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5. An optical link is found with below data, calculate the s/m rise time & BW for the link.

Components	Rise time	Bandwidth
TXR	1.45 ns	250 MHz
LED	2.9 ns	115 MHz
optical fiber cable	3.55 ns	98 MHz
Detector pin PD	1.3 ns	375 MHz
optical RXR	2.1 ns	200 MHz

→ $t_{sys} = \left[\sum_{i=1}^{N} t_i^2 \right]^{1/2}$

$$= \left[(1.45)^2 + (2.9)^2 + (3.55)^2 + (1.3)^2 + (2.1)^2\right]^{1/2}$$

$t_{sys} = 5.45\,ns$

$$\text{system bandwidth} = \frac{0.35}{t_{sys}}$$

$$= \frac{0.35}{5.45 \times 10^{-9}}$$

$$= 64.22\ MHz$$

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