Module-3

Q1. Describe the Basic elements of an analog link and the Major noise contributors at each stage with diagrams.

Sol:

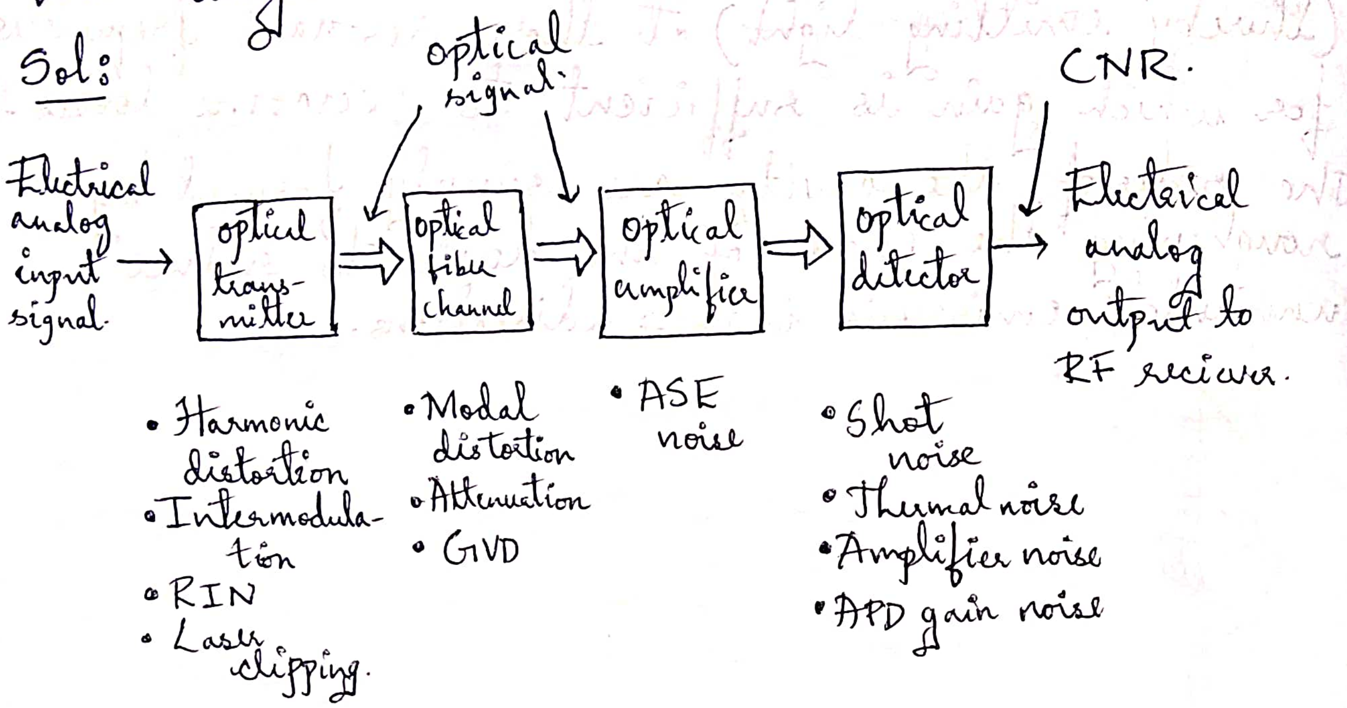

Fig: Basic elements of an analog link and the major noise contributors.

The above figure shows the basic elements of an analog link. The transmitter contains either an LED or a laser diode optical source. The simplest form for optical fiber links is direct-intensity modulation, wherein the optical output from the source is modulated simply by varying the ~~ac~~ current around the biase point in proportion to the message signal level. Thus, the information signal is transmitted directly in the baseband. A somewhat more complex but often more efficient method is to translate the baseband signal onto an electric subcarrier prior to intensity modulation of the source. This is done is standard amplitude-modulation (AM), frequency-modulation (FM), or Phase modulation (PM) techniques. Here the signal impairments include harmonic distortions,

intermodulation products, relative intensity ~~noise~~ noise (RIN) in the laser, and laser clipping.
In relation to the fiber-optic element as shown in figure, one must take into account the frequency dependance of the amplitude, phase and group delay in the fiber. Thus, the fiber should have a flat amplitude and group-delay response within the passband required to send the signal free of linear distortion. In addition, since modal distortion-limited bandwidth is difficult to equalize, it is best to choose a single mode fiber. The fiber attenuation is also important, since the carrier-to-noise performance of the system will change as a function of the recieved optical power.
The use of an optical amplifier in the link leads to additional noise, known as simplified spontaneous emission (ASE). In the optical reciever, the principal impairements are quantum or shot noise, APD gain noise, and thermal noise.

Q2. Derive the expressions for carrier to noise ratio of an analog optical fiber communication system under carrier power, Photo detector, Preamplifier noises and relative intensity noise (RIN).

Sol: Carrier Power

The optical source acts as a square-law device, so that the envelope of the output optical power P(t) has the same form as the input drive current. If the time-varying analog drive signal is s(t), then.

$$P(t) = P_t[1 + ms(t)]$$

P_t → optical output power at the bias current level and the modulation index m ~~is defined~~ In terms of optical power, the modulation index is given by

$$m = P_{peak}/P_t.$$

For a sinusoidal recieved signal, the carrier power C at the output of the reciever (in units of A^2) is

$$C = \frac{1}{2}(m R_0 M \bar{P})^2$$

where R_0 is the unity gain responsivity of the photo-detector, M is the photo-detector gain ($M = 1$ for pin photodiodes), and $\bar{P}$ is the average recieved optical power.

Photodetector and Preamplifier noises

The expressions for the photodiodes and preamplifier ~~noises are n~~ For the photodiode noise,

$$\{i_N^2\} = \sigma_N^2 \approx 2q(I_p + I_D)M^2 F(M) B.$$

I_D is the detector bulk dark current, M is the photodiode gain with $F(M)$ being its associated noise figure, and B is the reciever Bandwidth.

Then, the CNR for the photodetector only is

$$CNR_{det} = C/\sigma_N^2.$$

~~G~~ Generalizing equation of preamplifier noise,

$$\{i_T^2\} = \sigma_T^2 = \frac{4K_BT}{R_{eq}} BF_t.$$

Here, R_{eq} is the equivalent resistance of the photo-detector load and the preamplifier, and F_t is the noise factor for the preamplifier. Then, the CNR for the preamplifier only is

$$CNR_{preamp} = C/\sigma_T^2.$$

Relative intensity Noise (RIN)

Within a semiconductor laser, fluctuations in the amplitude or intensity of the output produce optical intensity noise. These fluctuations could arise from temperature variations or from spontaneous emissions contained in the laser output. The noise resulting from the random intensity fluctuations is called relative intensity noise (RIN), which may be defined in terms of mean-square intensity variations. The resultant mean-square noise current is,

$$\{i^2_{RIN}\} = \sigma^2_{RIN} = RIN(\mathcal{R}_0 \bar{P})B.$$

Then, the CNR due to laser amplitude fluctuations only is $CNR_{IN} = C/\sigma^2_{RIN}$

RIN measured in dB/Hz, is defined by noise-to-signal power ratio

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

where $\langle(\Delta P_L)^2\rangle$ is the mean-square intensity fluctuation of the laser output and $\bar{P}_L$ is the average laser light intensity. This noise decreases as the injection-current level increases according to the relationship,

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

Q3(i) Explain the Basic constituents of a generic RF over fiber link and with the help of diagram explain the Radio over fiber links.

Sol:

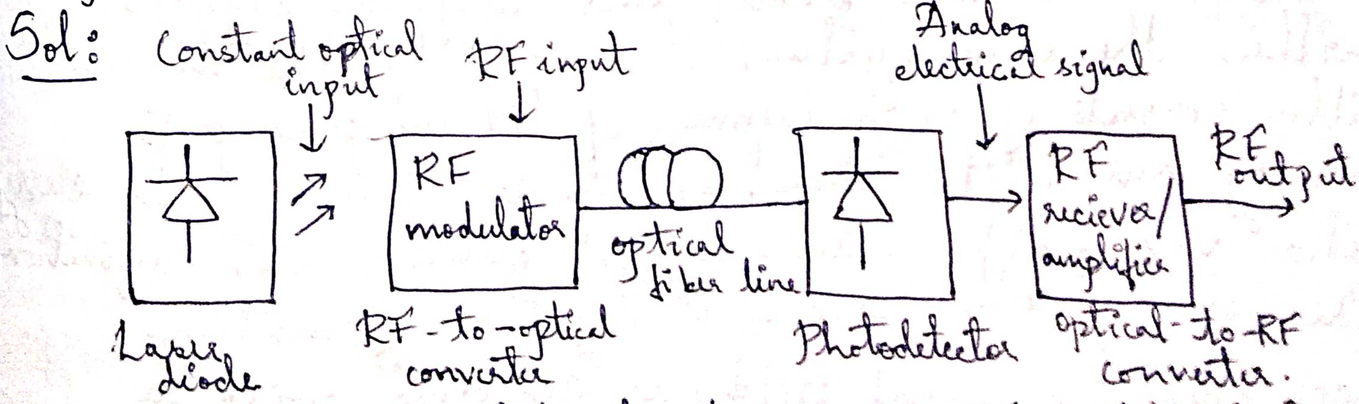

Fig: Basic constituents of a generic RF-over-fiber link

The above figure shows the constituents of a generic RF-over-fiber link. The ~~a~~ three major modules are an RF-to optical signal converting device at the transmitting end, an optical-to-RF signal converting device at the recieving end and an optical fiber that joins these two modules. The primary parameters used to characterize the RF performance of the optical link are the gain, noise figure, and spurious free dynamic range (SFDR). The link gain G_I is defined as the ratio of the RF power P_{out} generated in the photo-detector load resistor to RF power input P_{in} to the laser transmitter. Thus, for a directly modulated link, the gain is

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

where S_M is the slope efficiency of the modulation device η_{LF} is the laser-to-fiber sampling efficiency, T_F is the fiber transmission efficiency, η_{FD} is the fiber-to-detector coupling efficiency, R is the photodetector responsivity (amperes/watt), R_{Load} is the detector load resistance, and R_M is the modulator resistance.

(ii) With relevant diagram discuss the subcarrier multiplexing.

Sol: The term Subcarrier multiplexing (SCM) is used to describe the capability of multiplexing the multichannel analog and digital signals within the same system. The input to the transmitter consists of a minimum of N independent analog and digital baseband signals. These signals carry either voice, data, video, digital audio, high-definition video, or any other analog or digital information. Each incoming signal $S_i(t)$ is combined with a local oscillator (LO) having frequency f_i. The local oscillator frequencies employed are in the 8-GHz range and are known as the Subcarriers. Combining the modulated subcarriers gives a composite frequency-division-multiplexed signal, which is used to drive a laser diode.

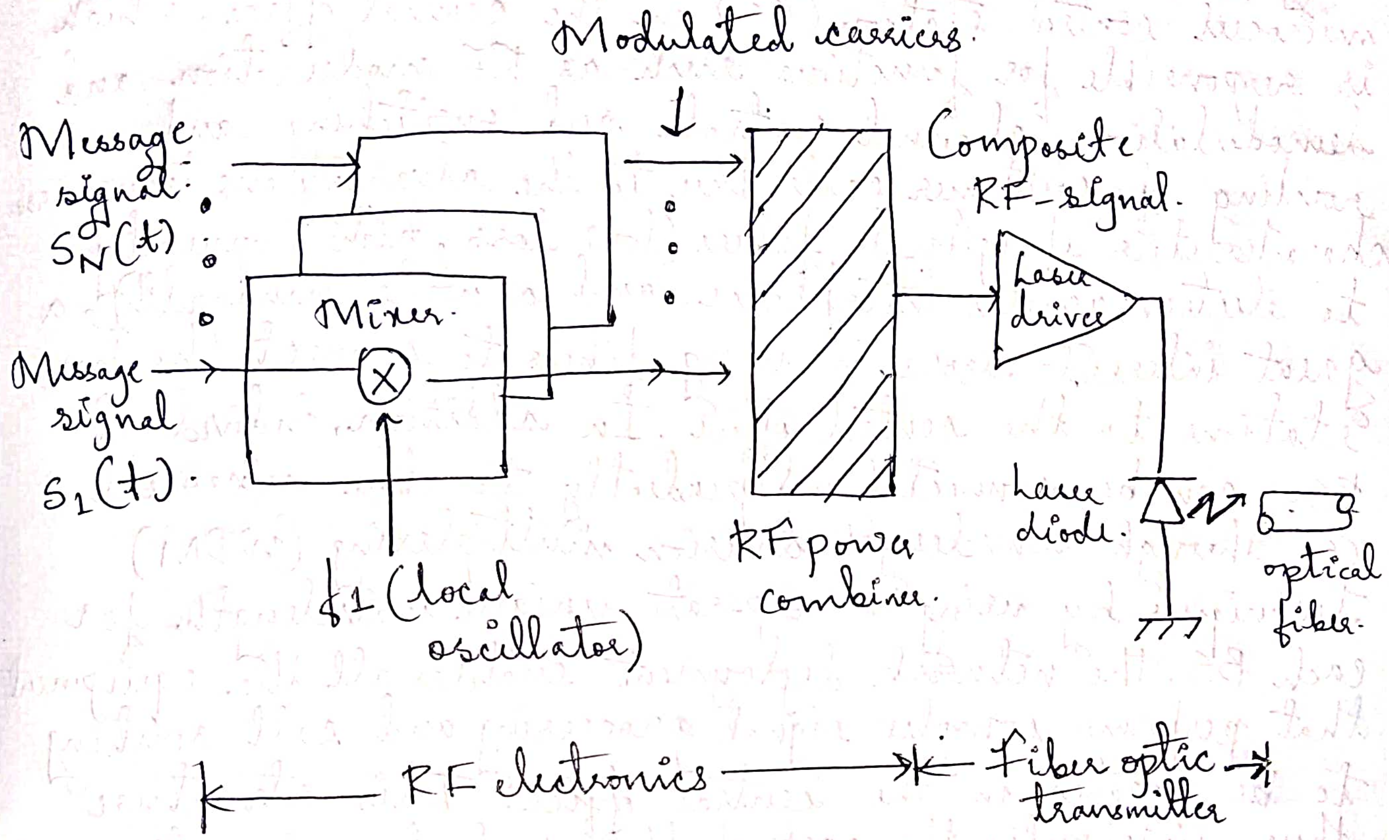

Figure: Basic concept of subcarrier multiplexing. One can send analog and digital signal simultaneously by frequency-division multiplexing them on different subcarrier frequencies.

Q4. With a neat diagram explain the Radio-over fiber concept of a broadband wireless access networks for interconnecting ~~at~~ antenna base station ROF network.

Sol: One application of RF-over-fiber technology is in broadband wireless access network for interconnecting antenna base stations (BSs) with the central controlling office. Figure(a) shows the basic networks architecture for such a scheme. Here a collection of antenna base stations provide wireless connectitivity to subscriber by means of millimeter-wave frequencies. Subscribers are located up to 1Km from a local base station. The transmission range around as BS is called a microcell (diameter less than 1Km) or a picocell or hotspot (cell ranging from 5 to 50m). The BSs are connected to microcell control station (CS) in the central office, which is responsible for functions such as RF modulation and demodulation, channel control, and switching and routing of customer calls. Due to the advantageous transmission characteristics of optical fibers (low loss, high immunity to electromagnetic interference, and a wide bandwidth), a great interest arose in using fibers to connect the base stations to the central office. In addition, individual BSs can be connected independently to the microcell CS through wavelength division multiplexing (WDM) techniques by using a seperate unique wavelength for each BS. The network deployment enables all the equipment that performs complex signal processing and call routing to be located in the central office. This structure thus distributes the cost of the central equipment among inexpensive base stations that need to do only amplification plus electrical-to-optical and optical-to-electrical signal conversion.

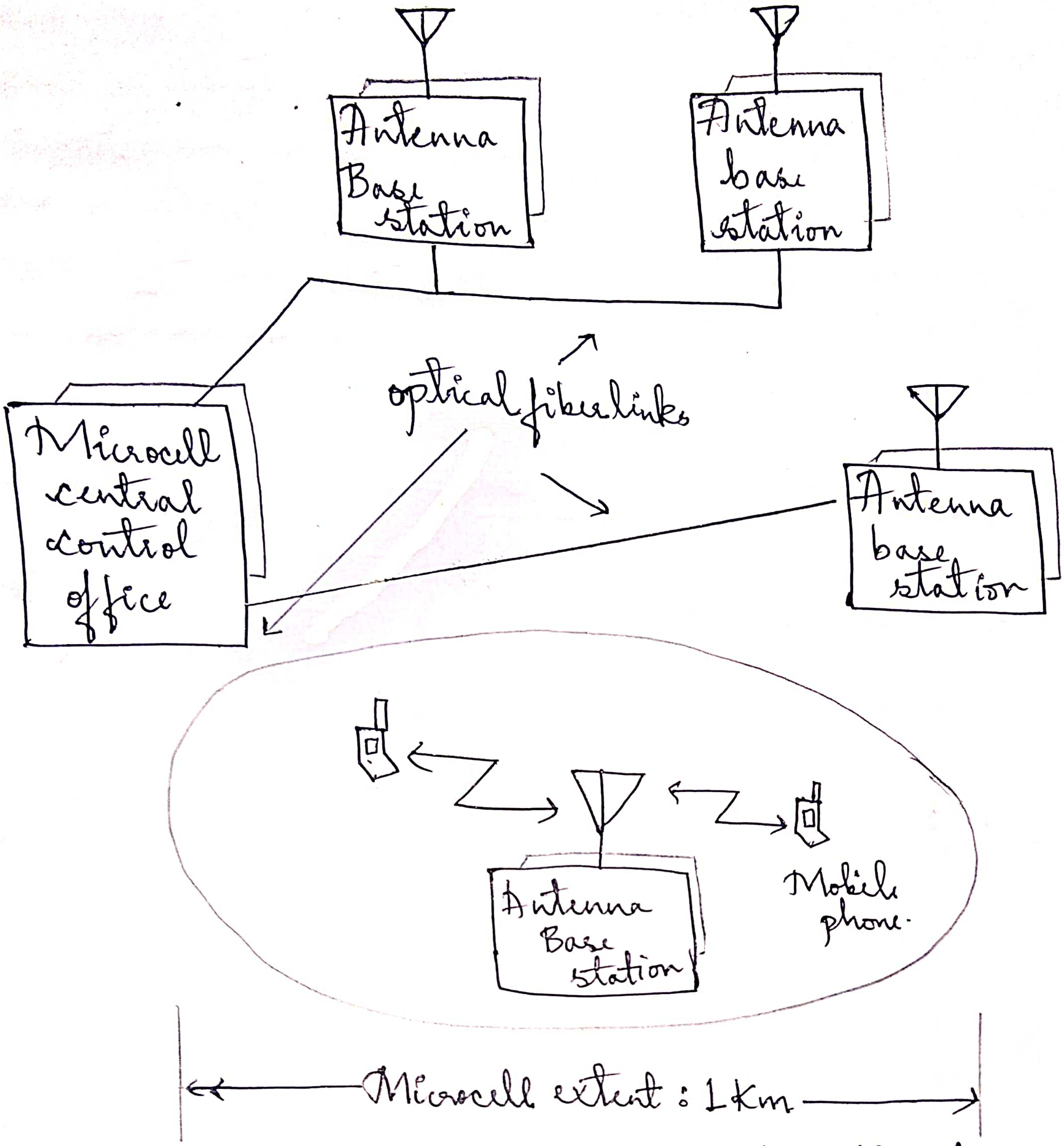

Fig (a) : Radio-over-fiber concept of a broadband wireless access network for interconnecting antenna base stations with the central controlling office.

5) Explain the operation of Multichannel amplitude modulation standard technique for frequency division multiplexing of N independent information bearing signals.

→ An information bearing signal on channel i amplitude modulates a carrier wave that has a frequency f_i, where $i = 1, 2, \cdots N$. An RF power combiner that sums thes N amplitude - modulated carriers to yield a composite frequency division - multiplexed (FDM) signal that intensity - modulates a laser diode. Following the optical receiver, a bank of parallel bandpass filters separates the combined carriers back into individual channel. The individual message signals are recovered from the carriers by standard RF techniques.

→ For large number of FDM carriers with random phases, the carriers add on a power basis. Thus for N channels optical modulation index m is related to per-channel modulation index m_i by

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

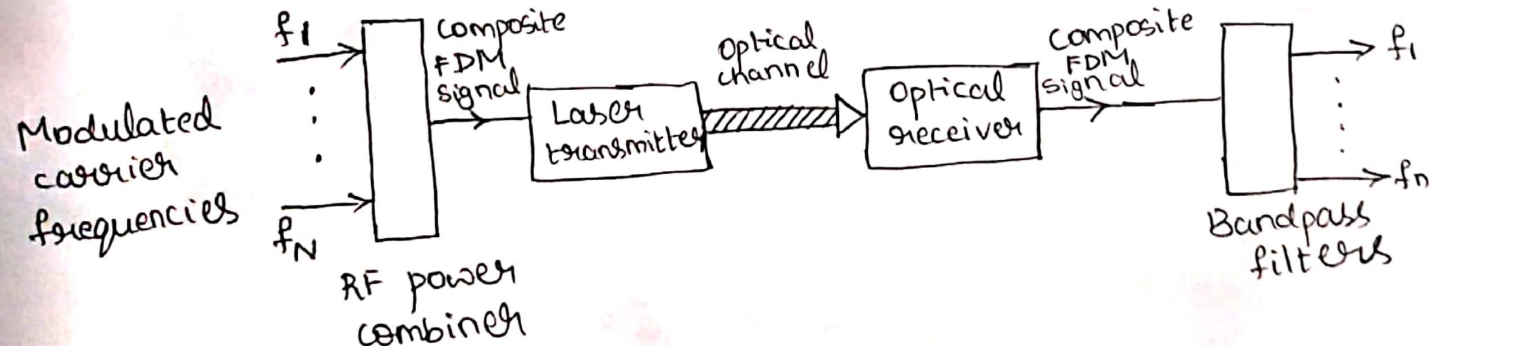

Fig : Standard technique for frequency - division multiplexing of N independent information bearing signals

→ In each channel modulation index m_i has the same value m_e, then $m = m_e N^{0.5}$

→ As a result, when N signals are frequency - multiplex and used to modulate a signal optical source, the carrier to-noise ratio of signal channel is degraded by 10 log N. If only a few channels are combined, the signals will add in voltage rather than power, so that degradation will have a 20 log N characteristic

→ When multiple carrier frequencies pass through a nonlinear device such as a laser diode, signal products other than the original frequencies can be produced. As noted in sec 4.4, these undesirable signals called intermodulation products, and they can cause serious interference in both in-band and out-band channels.

→ Among intermodulation products, generally only the second and third order terms are considered ~~based~~ because higher-order products tend to be significant smaller.

→ Third order intermodulation (IM) distortion products at frequencies $f_i + f_j - f_k$ (which are known as triple beat third order IM product) and $2f_i - f_j$ (Two-tone third order IM products) and are most dominant, ~~network~~ ~~operating~~ ~~over a standard~~ ~~frequency range of 5~~ since many of these fall within the bandwidth of multichannel system.

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

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

For Two-tone terms of type $2f_i - f_j$, and by

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

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

6) Discuss simplex point to point link and also explain the key system requirements which are needed in analyzing a link and how to fulfill these requirements.

→ The simplest transmission link is a point-to-point line that has a transmitter on one end and receiver on other, as shown in figure. This type of link places the least demand on optical fiber technology and thus sets the basis for examining more complex system architectures.

→ The design of an optical link involves many interrelated variables among fiber, source and photodetector operating characteristics, so that actual link design and analysis may require several iterations before they are completed satisfactorily. Since performance and cost constraints are very important factors in fiber optic communication links, the designer must carefully choose the components to ensure that the desired performance level can be maintained over the expected system lifetime without overspecifying the component characteristics.

The following key system requirements are needed in analyzing a link.

i) The desired (or possible) transmission distance.
ii) The data rate or channel bandwidth
iii) The bit-error rate (BER).

To fulfill these requirements the designer has to choice of following components and 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

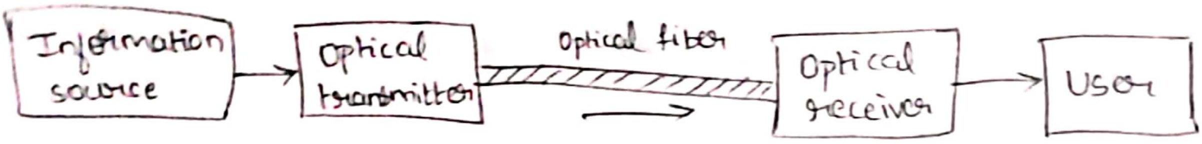

Fig: Simplex point-to-point link.

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

7) What is link power budget? With an example explain the link power budget calculation.

→ An optical power loss model for point-to-point link is shown in figure. The optical power received at the photodetector depends on the amount of light coupled into the fiber and losses occurring in fiber and at the connectors and splices. The link loss budget is derived from sequential loss contributions of each element in the link. Each of these loss elements is expressed in decibels (dB) as

$$loss = 10 \log \frac{P_{out}}{P_{in}}$$

→ In addition to the link loss contributions shown in figure, a link power margin is normally provided in the analysis to allow for components aging, temperature fluctuations, and losses arising from components that might be added at future dates. A link margin of 6-8 dB is generally used for systems that are not expected to have additional components incorporated into the link in the future.

→ The link loss budget simply considers total optical power loss P_T that is allowed between light source and photodector, and allocates this loss to cable attenuation, connector loss, splice loss, and system margin. Thus if P_s is the optical power emerging from end of fiber flylead attached to light source, and if P_R is receiver sensitivity, then

$$P_T = P_S - P_R$$
$$= 2 l_c + \alpha_f L + \text{system margin}$$

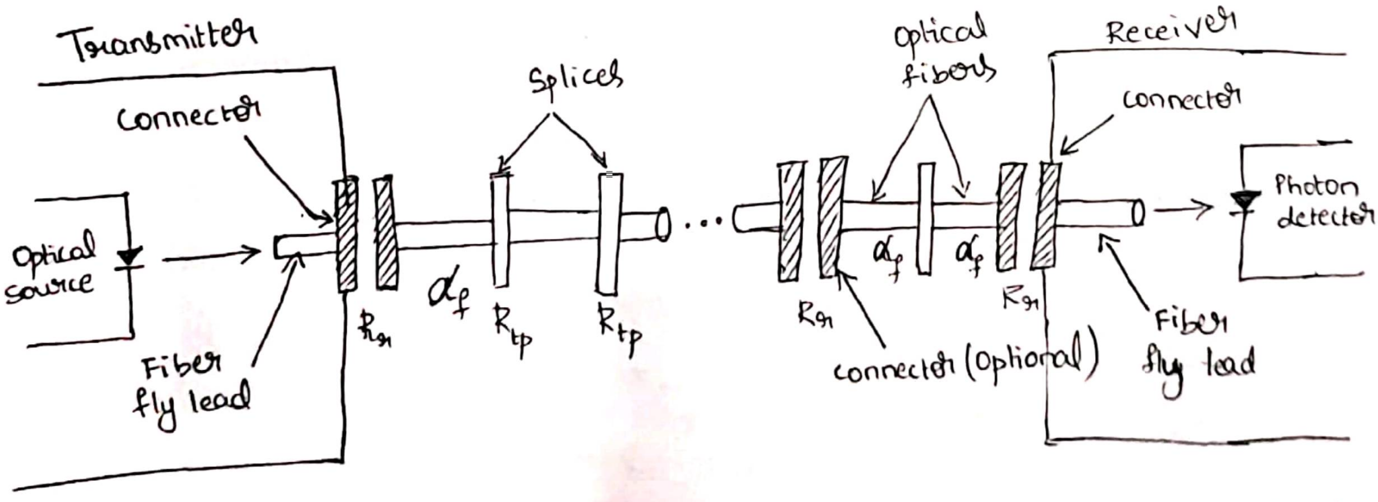

Fig: Optical power loss model for a point-to-point link. The losses occur at connectors (l_c), at splices (l_{sp}), and in fiber (α_f)

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

→Lists of components in column 1 and associated optical output sensitivity, or loss in Column 2. Column 3 gives the power margin available after subtracting component loss from total optical power loss that is allowed.

Example of spreadsheet for calculating an optical link power budget

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

Between light source and photodetector, which in this case is 35dB, Adding all losses results in a final power margin of 7dB.

8) What is rise time budget? Explain. Derive an ~~exp~~ expression for total rise or total system rise time.

→ A rise time budget analysis is a convenient method for determining the dispersion limitation of an optical fiber link. This is particularly useful for digital systems. In this approach, total rise time t_{sys} of the link is root sum square of rise times from each contributor t_i to the pulse rise-time degradation:

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

→ The four basic elements that may significantly limit the system speed are transmitter rise time t_{tx}, the group-velocity dispersion (GVD) rise time t_{GVD} of the fiber, modal dispersion rise time t_{mod} of fiber and receiver rise time t_{rx}.

→ Total ~~transm~~ transition - time degradation of digital link should not exceed 70 percent of an NRZ (non return to zero) bit period or 35 percent of bit period for RZ (Return to zero data.

→ The response of receiver front end can be modeled by first-order lowpass filter having a step response

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

where B_{rx} is 3 dB electrical bandwidth of receiver
$u(t)$ is unit step function which is $\begin{cases} 1 & \text{for } t \geq 0 \\ 0 & \text{for } t < 0 \end{cases}$

$g(t) = 0.1$ and $g(t) = 0.9$

Thus if B_{rx} is given in megahertz, then receiver front-end rise time in nanoseconds is ~~t~~

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

The fiber rise time t_{GVD} resulting from GVD over a length L can be approximated by

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

where σ_λ is half power spectral width of source, D - dispersion

→ Bandwidth B_M in a link of length L can be expressed to reasonable approximation by empirical relation

$$B_M(L) = \frac{B_0}{L^q}$$

Based on curve fitting of experimental data, is

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

B_n - Bandwidth of n^{th} fiber section.

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

$t_M(N)$ - pulse broadening occurring over N cable sections.

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

σ is rms pulse width

Fourier transform of function is

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

Time $t_{1/2}$ required for pulse to reach its half-maximum value.

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

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

If we define t_{FWHM} as full width of pulse at its half-maximum value, then

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

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

Resulting modal dispersion

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

If t_{mod} is expressed in nanosec and B_M is given in megahertz,

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

Subsituting in equation gives total system rise time of

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

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

where σ_λ - half power spectral width of source.