UNIT - 5

OPTICAL RECIEVERS

INTRODUCTION

An optical reciever consists of a photodetector amplifier, signal processing circuitary.

Reciever converts optical signal from end of fiber into an electric signal and then amplify the signal.

FUNDAMENTAL RECIEVER OPERAIION

- With a neat block diagram, explain digital signal transmission through an optical data link. 12M June/July 2014
- Draw basic block diagram of digital transmission link with relevant optical & electrical waveforms at each stage & explain 7M June/July 2015
- With a schematic diagram, explain working of an optical Reciever 6M Dec09/Jan10
- Draw the signal path through a digital link with relevant components & optical/electrical waveforms at every stage. 6M May/June 10

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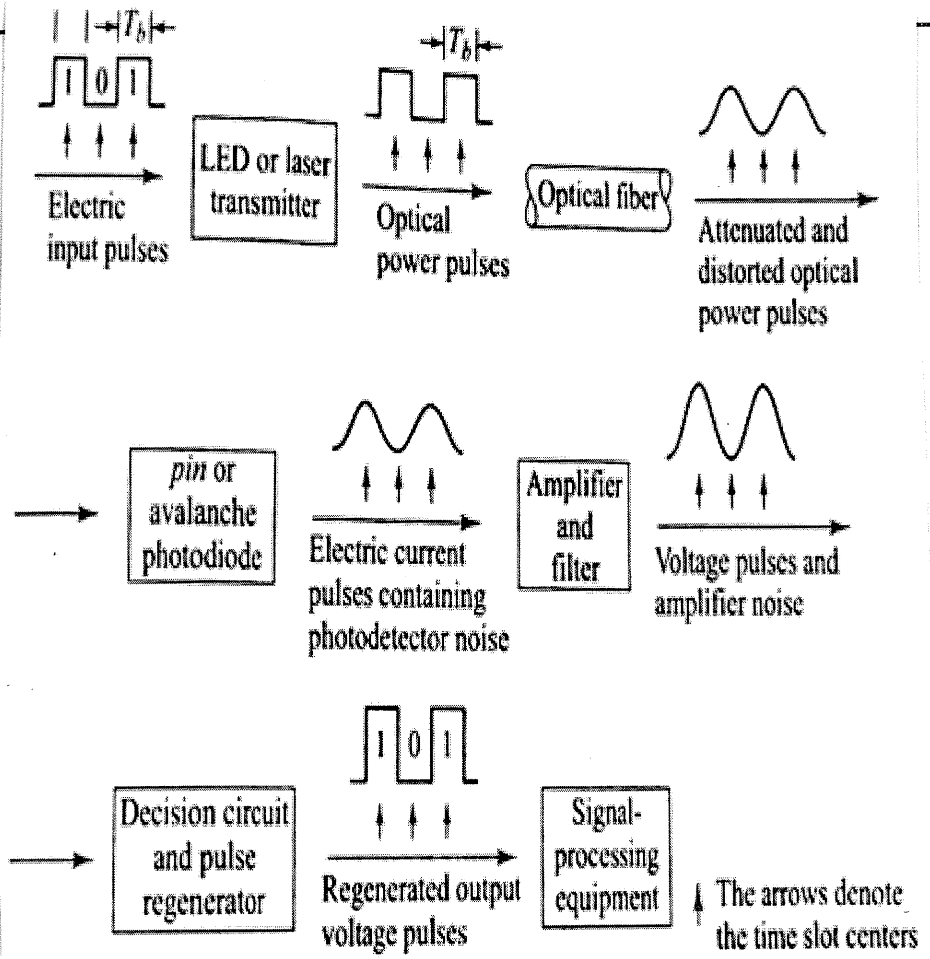

Fig: signal path through an optical data link

- The transmitted signal is a two-level binary data stream consisting of either 0 or 1 in a time slot of duration T_b.
- T_b time slot is a bit period.
- Simplest technique for sending binary data is amplitude shift keying (ASK) or on-off keying (OOK)
- Here, voltage level is switched between two values usually on or off.
- Resultant signal consists of a voltage pulse of amplitude V relative to zero voltage level when binary 1 occurs & a zero voltage space when binary 0 occurs.

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- Function of optical TxR is to convert the electric signal to an optical signal.
- This is done by directly modulating the light source drive current with infⁿ stream to produce a varying optical output power P(t).
- After arriving at the end of a fiber, a RxR converts the optical signal back to an electrical format.

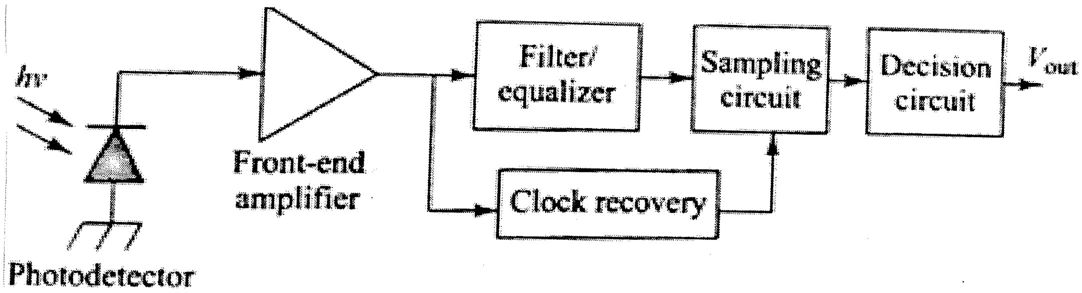

Fig: The basic sections of an optical reciever

- First element is either pin or an avlanche photodiode, which produces an electric current that is proportional to the recieved power level.
- The produced electric current is very weak, a front end amplifier boosts the signal level
- Once the signal is amplified, it is passed through a low-pass filter to reduce the noise
- This filter defines the RxR bandwidth and also minimizes the effects of inter symbol interference (ISI)
- The filter can reshape the pulses that are distorted. This function is called equalization.

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- Decision circuit samples the signal level and compares it with certain reference voltage known as the threshold level.
- If Rxd signal is greater than threshold level, 1 is recieved
- If voltage is below threshold level, 0 is recieved.
- To accomplish this bit interpretation, the RXR should know the bit boundaries.
- This is done by clock, which has periodicity equal to the bit interval. This is called as clock recovery or timing recovery.

ERROR SOURCES

- Briefly discuss possible sources of noise in optical fiber reciever. 6M Dec 13/Jan14
- What are noise sources and disturbances that arise in optical pulse detection mechanism? Explain 8M Dec 09/Jan 10

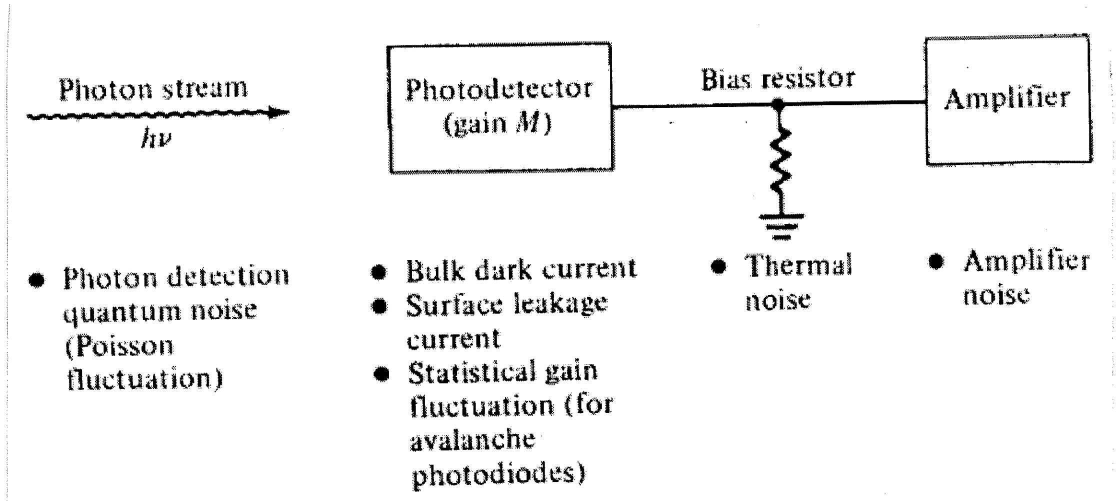

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Fig: shows noise sources & disturbances in an optical pulse detection mechanism.

- Errors arise from various noise & disturbances associated with system.
- Noise is unwanted components of electric signal that disturb the transmission & processing of signal in a system.
- Noise sources can be external or internal to the system.
- we consider internal noise associated with the system
- Noise is caused due to fluctuations of current or voltage in the circuit.
- common spontaneous fluctuations are shot noise & thermal noise.
- Shot noise arises due to discrete nature of current flow in the circuit.

  Thermal noise is due to random motion of e^- in the conductor.

  Quantum noise is caused by random arrival rate of photons at photodector.

  This depends upon the signal level.

If APD is used, additional shot noise occurs due to nature of multiplication process.

Noise level increases with larger avalanche gain M.

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- Additional photodetector noises come from dark current & leakage current.

- Thermal noise arising from detector load resistor & from amplifier dominate in applications with low SNR when pin photodiode is used.

- Average number of e^- & hole pairs $\bar{N}$, generated in a time τ is:

$$\bar{N} = \frac{\eta}{h\nu} \int_0^{\tau} P(t)\,dt = \frac{\eta E}{h\nu}$$

η = quantum efficiency
E = energy recieved in interval τ.
$h\nu$ = photon energy

- Actual num of e^- hole pairs 'n' that are generated, fluctuates from average according to Poisson distribution:

$$P_r(n) = \bar{N}^n \frac{e^{-\bar{N}}}{n!}$$

$P_r(n)$ = probability that n electrons are emitted in time interval τ.

- when Avlanche photo Diode (APD) is used, shot noise due to multiplication process is given by:

$$F(M) = KM + \left(2 - \frac{1}{M}\right)(1-K)$$

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F(M) = excess noise factor

K = ionization ratio

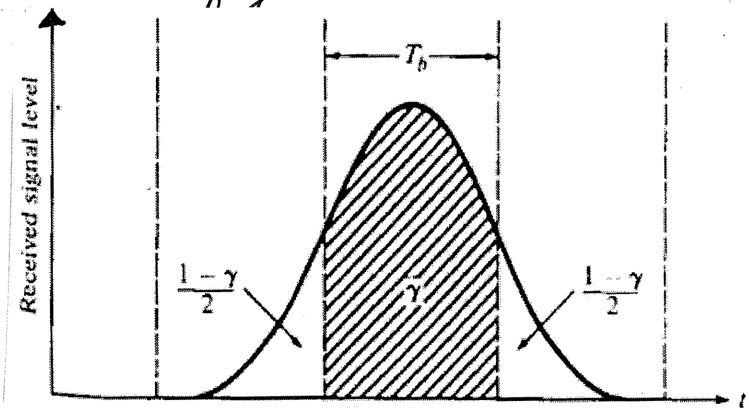
$$F(M) \simeq M^x$$

x ranges from 0 & 1 depending on PD material.

- Another error source is intersymbol interference (ISI), results from pulse spreading in optical fiber.

  when a pulse is transmitted in a given time slot, most of pulse energy will arrive in corresponding time slot at a reciever.

  As shown in fig below:



- Because of pulse spreading induced by the fiber, transmitted energy will spread into neighbouring time slots.

  The presence of this energy in adjacent time slots results in an interfering signal.

- γ determines fraction of energy in time slot T_b.

  $1-\gamma$ is fraction of energy that has spread into adjacent time slots.

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FRONT END AMPLIFIER

- Give classification of front end amplifier used in OFC. Explain any one of them

  | 8M June/July 14 |

- why preamplifiers are necessary in optical receivers ? List different types of preamplifier in use

  | 4M June/July 15 |

→ Front end amplifiers are used with a goal to maximize the receiver sensitivity while maintaining a suitable bandwidth.

→ Front end amplifiers used in OFC s/ms are of 2 categories: high impedance & transimpedance designs.

→ Thermal noise is inversely proportional to load resistance.
Thus R_L should be as large as possible to minimize the thermal noise.

High Impedance Amplifier:

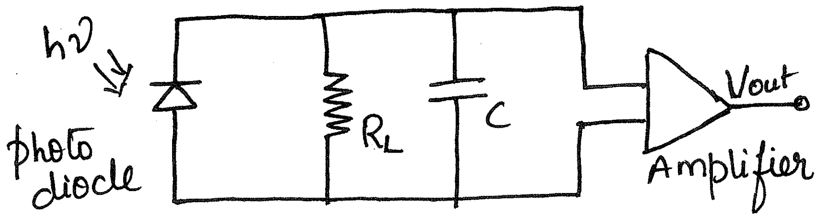

fig: Generic structure of high impedance amplifier

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→ Trade off is made between the noise & RxR bandwidth, since $B.W \propto \frac{1}{R_P}$

→ For high impedance amplifier, $R_P = R_L$.

→ A high load resistance results in low noise but gives low RxR bandwidth.

→ If bandwidth is much less than bit rate, such a front end amplifier cannot be used.

Transimpedance Amplifier:

→ Largely overcomes the drawback of high impedance amplifier.

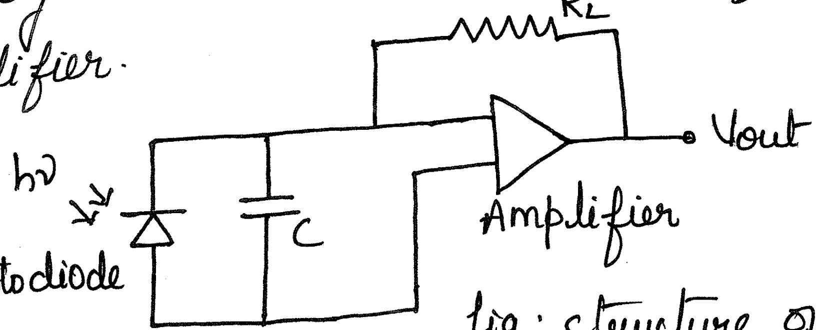

fig: structure of transimpedance amplifier

→ Here R_L is used as negative feedback resistor around an inverting amplifier.

→ R_L can be large, negative feedback reduces the effective resistance R_P by factor G.

$$R_P = \frac{R_L}{(G+1)}$$

G = gain of amplifier

→ Transimpedance bandwidth increases by a factor of G+1, for same R_L.

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→ Although thermal noise is more compared to high impedance amplifier, it can be tolerated.

→ In addition to thermal noise due to R_L, electronic components in front end amplifier also add thermal noise.

→ This noise increase given by amplifier noise figure. F_n

$$F_n = \frac{i/p\ SNR}{o/p\ SNR} \text{ of the amplifier.}$$

DIGITAL RECIEVER PERFORMANCE

→ The decision-circuit output signal voltage $V_{out}(t)$ would always exceed the threshold voltage a 1 is present & would less than threshold when no pulse is sent.

→ In actual systems, deviations from the average value of $V_{out}(t)$ are caused by various noises, interference from adjacent pulses & when light sources are not completely extinguished during bit '0'.

Probability of Error

→ To determine the rate of error occurences: Measure the bit error rate (BER)

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$$BER = \frac{N_e}{N_t} = \frac{N_e}{B_t}$$

N_e = number of errors occuring over certain time interval t

N_t = Number of pulses transmitted during time t.

$B = \frac{1}{T_b}$ bit rate

Eg: If error rate expressed as 10^{-9} ⇒ on average 1 error occurs for every billion pulses sent.

→ For OFC S/ms range from 10^{-9} to 10^{-12}. The error rate depends on SNR at the RxR.

→ To compute BER, the probability distribution of signal at equalizer o/p should be known. Decision is made as 1 or 0 is sent.

→ Probability that equalizer o/p vtg is less than v when logical 1 pulse is sent:

$$P_1(v) = \int_{-\infty}^{v} P(y|1)\,dy$$

→ Probability that o/p vtg exceeds v when logical 0 is txd.

$$P_0(v) = \int_{v}^{\infty} P(y|0)\,dy \quad — (1)$$

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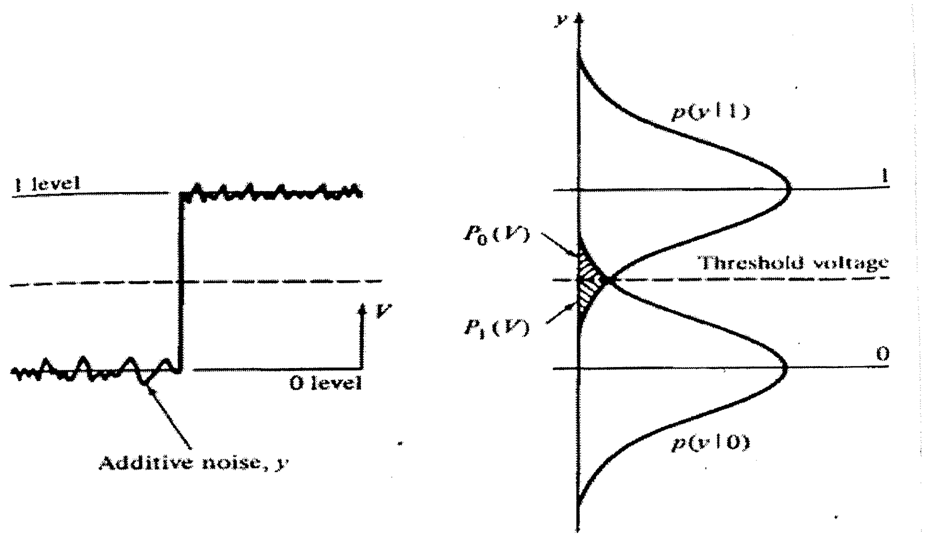
Fig: Different shapes of 2 probability distributions



→ This indicates noise power for a logical 0 is not same as that for logical 1.

→ This occurs because of signal distortion from transmission impairments & from noise and ISI contributions at the RxR.

→ $P(y|1)$, $P(y|0)$ ⇒ conditional probability distribution function

$P(y|x)$ → probability that o/p vtg is y, if x was transmitted.

→ If threshold voltage is V_{th}, error probability

$$P_e = a P_1(V_{th}) + b P_0(V_{th})$$

a & b ⇒ weighting factors, this determine distribution of the data.

→ To calculate the error probability mean square noise vtg (V_N^2) superimposed on sig @ decision time should be known

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Gaussian Method: when sequence of optical i/p pulses is known, the equalizer o/p vtg $V_{out}(t)$ is a Gaussian variable.

→ Assume sg 's' has Gaussian distribution with mean value m.

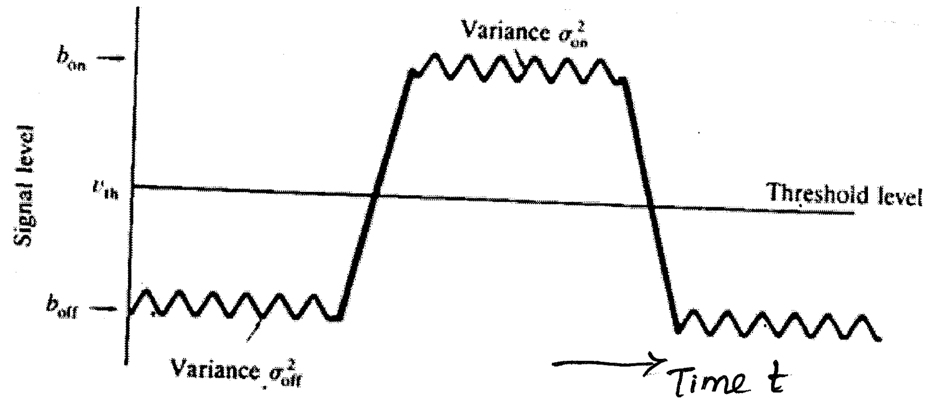
→ Sample sg vtg level s(t) at time t_1

→ probability that $s(t_1)$ falls in range s to s+ds:

$$f(s)\,ds = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-(s-m)^2/2\sigma^2} ds \quad -(2)$$

$f(s)$ → Probability Density function

σ^2 → variance $\sqrt{\sigma}$ → std deviation



→ The mean & variance for o/p 1 : b_{on} & σ_{on}^2

for o/p 0 : b_{off} & σ_{off}^2

→ If 0 is sent : PER ⇒ probability of noise that will exceed V_{th} & mistaken as 1.

$P_0(v)$ ⇒ probability of equalizer o/p V(t) falls b/w V_{th} & ∞

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using (1) & (2)

$$P_0(V_{th}) = \int_{V_{th}}^{\infty} P(y|0)\,dy = \int_{V_{th}}^{\infty} f_0(y)\,dy$$

$$= \frac{1}{\sqrt{2\pi}\,\sigma_{off}} \int_{V_{th}}^{\infty} \exp\left[-\frac{(V-b_{off})^2}{2\sigma_{off}^2}\right] dv$$

$|||^{ly}$ for 1

$$P_1(V_{th}) = \frac{1}{\sqrt{2\pi}\,\sigma_{on}} \int_{-\infty}^{V_{th}} \exp\left[-\frac{(b_{on}-V)^2}{2\sigma_{on}^2}\right] dv$$

→ If probability of 0 & 1 are equally likely

$a = b = 0.5$

$$\Rightarrow P_0(V_{th}) = P_1(V_{th}) = \tfrac{1}{2} P_e$$

$$BER = P_e(Q) = \frac{1}{\sqrt{\pi}} \frac{e^{-Q^2/2}}{Q}$$

$$Q = \frac{b_{on} - b_{off}}{\sigma_{on} + \sigma_{off}}$$

→ when $\sigma_{on} = \sigma_{off}$ $\Rightarrow$ $b_{off} = 0$ $b_{on} = V$

$V_{th} = \frac{V}{2}$ $Q = \frac{V}{2\sigma}$

Peak sg to noise ratio $= \frac{V}{\sigma}$

$$P_e(\sigma_{on} = \sigma_{off}) = \frac{1}{2}\left[1 - \operatorname{erf}\left(\frac{V}{2\sqrt{2}\,\sigma}\right)\right]$$

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Reciever Sensitivity

Explain RxR sensitivity of an optical RxR. Derive an expression for RxR sensitivity.

10M	June 12
6M	Dec 12

→ OFC s/ms use BER value to specify performance requirements for a particular transmission link application.

Eg: SONET/SDH network specify BER ⇒ 10^{-10} or lower

Gigabit ethernet BER not more than 10^{-12}

→ The minimum average optical power level that must arrive at photodetector to achieve desired BER, for a given data rate is called the RxR sensitivity.

→ Method of defining RxR sensitivity is using avg optical power incident on the photo detector ⇒ P_{ave} (dBm)

→ Alternatively, RxR sensitivity can be defined as an optical modulation amplitude [OMA] in terms of peak to peak current at photodetector o/p.

→ Reciever sensitivity gives: a) Measure of min average power
b) OMA needed to maintain a max BER at specific data rate.

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→ Signal currents @ 1 & 0 pulses & noise current variations :

$$Q = \frac{I_1 - I_0}{\sigma_1 + \sigma_0} \simeq \frac{I_1}{\sigma_1 + \sigma_0}$$ (assuming no optical power in zero pulse)

→ RxR sensitivity, $P_{sensitivity}$ found from avg power contained in bit period for specific data rate :

$$P_{sensitivity} = \frac{P_1}{2} = \frac{I_1}{2(RM)} = \frac{Q(\sigma_1 + \sigma_0)}{2(RM)} \quad \text{— (1)}$$

R = unity gain responsivity
M = gain of photodiode

→ If there is no amplifier in fiber transmission link, then thermal noise & shot noise are dominant in the RxR.

→ The noise variances for 0 & 1 pulses

$$\sigma_0^2 = \sigma_T^2 \qquad \sigma_1^2 = \sigma_T^2 + \sigma_{shot}^2$$

Shot noise variance for 1 pulse :

$$\sigma_{shot}^2 = 2q\, R P_1 M^2 F(M) B_e$$
$$= 4q\, R P_{sensitivity} M^2 F(M) \frac{B}{2}$$

F(M) = photodiode noise figure
B_e = bandwidth of RxR = half bit rate $\left(B_e = \frac{B}{2}\right)$

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Thermal noise variance :

$$\sigma_T^2 = \frac{4K_BT}{R_L} F_n \frac{B}{2}$$

F_n => noise figure of amplifier

Substitute $\sigma_1 = (\sigma_{shot}^2 + \sigma_T^2)^{1/2}$ & $\sigma_0 = \sigma_T$

in eqn (i)

$$\Rightarrow \boxed{P_{Sensitivity} = \frac{1}{\mathcal{R}} \frac{Q}{M}\left[\frac{q\,M\,F(M)\,BQ}{2} + \sigma_T\right]}$$

Quantum Limit :

→ For an ideal photodetector : a) unity quantum efficiency
b) no dark current i.e., no e⁻ hole pairs are generated in absence of an optical pulse.

→ In these given conditions, the minimum recieved optical power required for specific BER performance in a digital s/m is known as Quantum limit.

→ Sensitivity of RxRs is 20dB more than quantum limit because of non linear distortions & noise effects in transmission link.

→ $$P_r(0) = e^{-\bar{N}}$$

$\bar{N}$ => avg num of e⁻ hole pairs

$P_r(0)$ => error probability.

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EYE DIAGRAM

Explain general configuration of an eye diagram showing definitions of fundamental measurement parameters. Also explain noise margin & timing jitter parameters

7M June 12

Discuss how eye diagram is powerful measurement tool for assessing the data handling capability in digital transmission system.

8M Dec 13/Jan 14

Write a neat sketch, explain how system performance information can be obtained from eye diagram.

8M June/July 13

Write a short note on eye diagram.

5M June/July 15

→ Eye diagram is tool for assessing data handling ability of digital transmission s/m

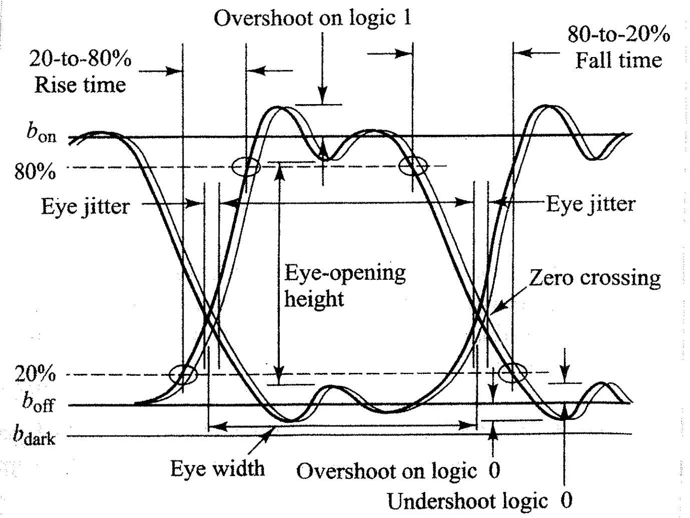

fig: General configuration of an eye diagram

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→ Eye pattern measurements made in time domain & allow effects of waveform distortion shown immediately on display screen of BER equipments.

→ Fig. shows display pattern known as eye pattern or eye diagram.

→ The basic upper & lower bounds are determined by logic 1 & 0 levels, bon & boff respectively.

→ System performance information can be deduced from the eye pattern display.

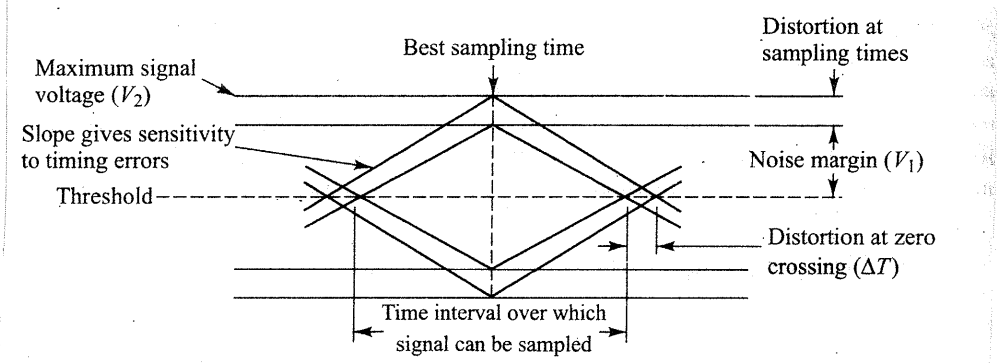

Fig: Simplified eye diagram with key performance parameters

- The width of the eye opening defines the time interval over which recieved signal can be sampled without error due to interference from adjacent pulses (ISI)
- Best time to sample recieved waveform is when height of eye opening is largest.

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The height reduces due to distortion in data sg.
The vertical distance b/w top of eye opening & max sg level is the degree of distortion.
The more eye closes, difficult to differentiate b/w 1's & 0's of the sg.

- The height of the eye opening at the specified sampling times shows the noise margin or immunity to noise.

$$\text{Noise margin} = \frac{\text{peak Vtg } V_1 \text{ for alternating bit sequence}}{V_2 \text{ measured from threshold level}}$$

$$\text{Noise margin} = \frac{V_1}{V_2} \times 100$$

- The rate at which eye closes as sampling time is varied determines the sensitivity of system to timing errors
- Timing jitter in OF S/m arises from noise in RxR & pulse distortion in optical fiber.
- Excessive jitter can produce uncertainities in clock timing. This timing uncertainity will cause RxR to lose synchronization with incoming bit stream incorrectly interpreting logic 1 & 0 pulses.

$$\text{Timing jitter} = \frac{\Delta T}{T_b} \times 100$$

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- Rise time is time interval: rising edge of sg reaches 10% of its final amplitude to time where it reaches 90% of its final amplitude.
- when measuring optical sgs, these points are often obscured by noise & jitter effects. so more distinct values 20% & 80% threshold points are measured.

conversion of 20-80% rise time to 10-90% rise time:

$$T_{10-90} = 1.25 \times T_{20-80}$$

similar approach to determine fall time.

BER & Q factor Measurements:

→ BER depends on: a) measurement time
b) factors that cause errors

→ If errors due to Gaussian noise: then measurement time in which about 100 errors occur may be needed to ensure BER.

→ For high speed commⁿ slms ⇒ BER = 10^{-12}

→ For 10Gbps links 10^{-12} BER means 1 bit error occurs every 100 seconds. Such errors are not acceptable.

→ standards which define acceptable BER are:
To.150 & O.201 Recommendations
ANSI T1.510

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→ Tests time can be very long.
Eg: To detect 100 errors for measuring BER of 10^{-12} in 10Gbps link will require 2.8 hours

→ Test times on installed links could be from 8 to 72 hours.

→ To reduce such costly & time consuming test periods, a Q-factor technique is used.

→ In this method, the reciever threshold is decreased, which increases the probability of errors & thus decreases test time.

→ It reduces test time to minutes instead of hours.

Coherent Detection:

Explain fundamental concept of a coherent light-wave s/m using coherent detection technique with help of fig & expressions **8M June/July 13**

List characteristic features of direct detection & coherent detection techniques in OFC. **4M June/July 15**

Explain with neat diagram the fundamental concept of coherent detection **6M May/June 10**

Difference b/w Heterodyne & Homodyne coherent detection schemes w.r.t. probability of error functions of BER.

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→ In this scheme, photodetector at the receiving end only responds to changes in power level that falls on it.

→ The photodetector then transforms optical power level variations back to electrical signal format. This method is known as intensity modulation with direct detection (IM/DD)

→ optical commn slms which use homodyne or heterodyne detection are called coherent optical commn slms, there implementation depends on phase coherence of optical signal.

→ In coherent detection techniques the light is treated as a carrier medium which can be amplitude, frequency or phase modulated

Fundamental concepts:

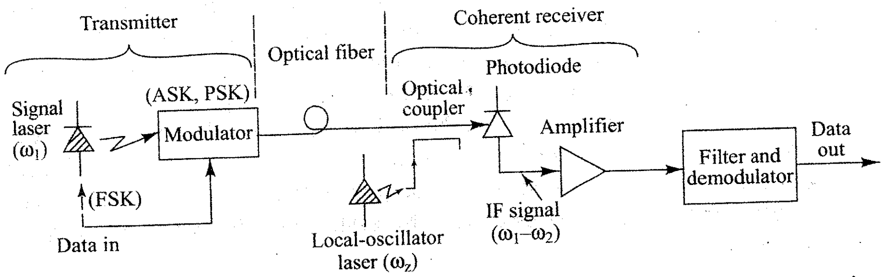

Fig: Fundamental concept of a coherent lightwave System

→ The key principle of coherent detection technique is to provide gain to incoming optical signal by combining or mixing it with locally generated continous wave (cw) optical field.

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→ Mixing means that when 2 waves with frequencies w_1 & w_2 are combined, resulting waves will have frequencies equal to $2w_1$, $2w_2$ & $w_1 \pm w_2$

→ For coherent lightwave s/ms, frequency components except $w_1 - w_2$, others are filtered out at the RxR.

→ Device used for creating CW sg is a narrow line-width laser called local oscillator (LO).

→ Electric field of transmitted optical sg considered to be a plane wave:

$$E_s = A_s \cos[w_s t + \phi_s(t)]$$

$A_s \rightarrow$ amplitude of the optical sg

$w_s \rightarrow$ optical sg carrier frequency

$\phi_s(t) \rightarrow$ phase of optical carrier

→ To send the infn, we can use any of the following modln techniques:

1. ASK (Amplitude shift keying) or On-off keying (OOK)
   Here ϕ_s is constant & sg amplitude A_s takes one of 2 values during each bit period.

2. FSK (Frequency shift keying)
   A_s is constant, $w_1 t$ or $w_2 t$ varied where frequencies w_1 & w_2 represent binary sg values.

3. PSK (phase shift keying)
   varying phase with a sine wave $\phi_s(t) = \beta \sin w_m t$
   $\beta \rightarrow$ modln index $w_m \rightarrow$ modln frequency

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Direct Detection

→ In a direct detection s/m the electrical sg coming into TxR amplitude modulates the optical power level of light source.

→ optical power is proportional to sg current level.

→ At the RxR, the incoming sg is converted directly into a demodulated electrical O/p.

→ Directly detected current ∝ intensity I_{DD} of optical sg

$$I_{DD} = E_S E_S^*$$
$$= \frac{1}{2} A_S^2 \left[1 + \cos(2w_s t + 2\phi_s)\right]$$

The term involving $\cos(2w_s t + 2\phi_s)$ gets eliminated from the RxR

→ ∴ For direct detection :

$$I_{DD} = E_S E_S^* = \frac{1}{2} A_S^2$$

→ At RxR, locally generated optical sg is mixed with recieved sg.

→ Based on type of mixing we determine : It's homodyne or heterodyne.

→ Local oscillator(LO) field is given by :

$$E_{LO} = A_{LO} \cos\left[w_{LO} t + \phi_{LO} t\right]$$

coherent intensity :

$$I_{coh}(t) = \left(E_S + E_{LO}\right)^2$$

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$$I_{con}(t) = \frac{1}{2}A_S^2 + \frac{1}{2}A_{LO}^2 + A_S A_{LO} \cos[(\omega_S - \omega_{LO})t + \phi t] \cos\theta t$$

$$\phi(t) = \phi_S(t) - \phi_{LO}(t)$$

phase difference

Polarization misalignment b/w sg & LO wave

$$\cos\theta(t) = \frac{E_S \cdot E_{LO}}{|E_S||E_{LO}|}$$

optical power $P(t)$ is given by:

$$P(t) = P_S + P_{LO} + 2\sqrt{P_S P_{LO}} \cos[(\omega_S - \omega_{LO})t + \phi(t)] \cos\theta t \quad \text{--- } (1)$$

P_S & P_{LO} are sg & local oscillator powers

$$P_{LO} \gg P_S$$

angular frequency difference:

$$\omega_{IF} = \omega_S - \omega_{LO}$$

Intermediate frequency

Homodyne Detection

→ when sg carrier & local oscillator frequencies are equal i.e; when $\omega_{IF} = 0$, its homodyne detection

Eqn (1) becomes

$$P(t) = P_S + P_{LO} + 2\sqrt{P_S P_{LO}} \cos\phi(t) \cos\theta(t) \quad \text{--- } (2)$$

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for 1 pulse, sgs are in phase

$$\bar{N}_1 = (A_{LO} + A_S)^2 T$$

→ Voltage seen by the decoder :

$$V = \bar{N}_1 - \bar{N}_0 = 4 A_{LO} A_S T$$

→ rms noise

$$\sigma = \sqrt{A_{LO}^2 T}$$

→ For homodyne PSK

$$A_{LO}^2 T = 9$$

avg of 9 photons/bit required to achieve BER of 10^{-9}.

→ $$\boxed{BER = \frac{1}{2} \operatorname{erfc}\sqrt{\eta \bar{N}_p}}$$

for PSK homodyne detection

4 Heterodyne Detection schemes

→ Analysis for heterodyne s/m is complicated, as photo detector o/p appears at an intermediate frequency ω_{IF}.

→ Heterodyne recievers can ~~empty~~ employ either synchronous or asynchronous detection

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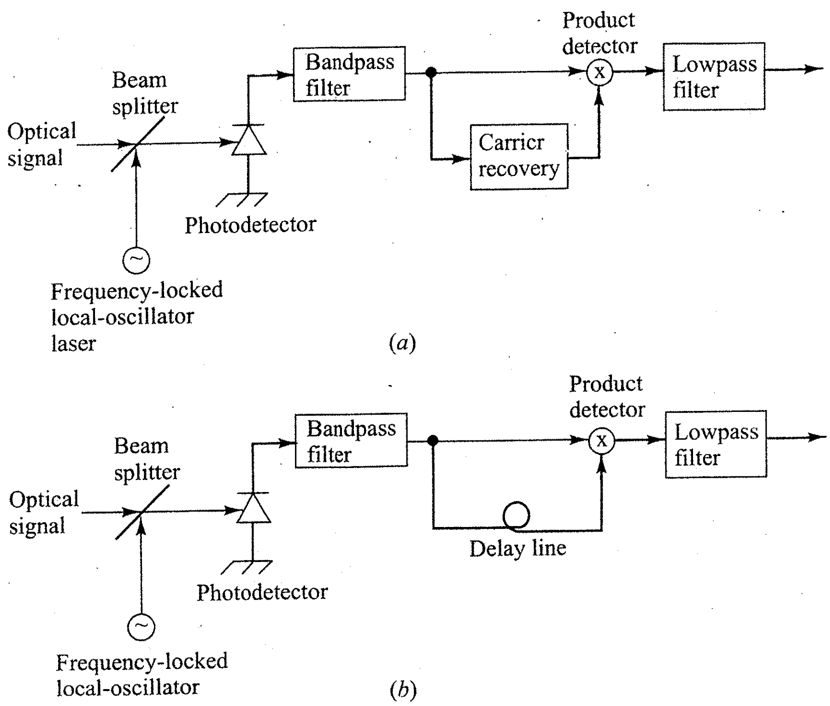

Fig: a) Synchronous heterodyne reciever
b) asynchronous heterodyne reciever

Synchronous Detection:

→ carrier - recovery circuit is used, usually a microwave phase - locked loop (PLL), to generate a local phase reference.

→ The ω_{IF} is recovered by mixing o/p of PLL with intermediate frequency sg.

→ Lowpass filter used to recover the baseband sg.

→ BER for synchronous heterodyne PSK:

$$\boxed{BER = \frac{1}{2} \operatorname{erfc} \sqrt{\eta \bar{N}_p}}$$

for ideal PSK RxR ⇒ 18 photons/bit for 10^{-9} BER

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→ Either OOK, ~~FSK~~, or PSK modl^n techniques can be used to transmit information.

→ $P_{LO} >> P_S$ & P_{LO} is constant

Last term of eq^n (2) contains the inf^n

→ The term increases with increase in laser power.

LO acts as sg amplifier.

This gives greater sensitivity then direct detection

→ Homodyne detection brings sg directly to baseband frequency.

→ Homodyne RxRs are difficult to build, since the local oscillator lasers to have same frequencies it should have phase locked loop (PLL).

Heterodyne Detection:

→ In this detection ω_{IF} is non zero & an optical phase locked loop is not needed.

$$\omega_{IF} \neq 0.$$

→ 3dB degradation in sensitivity compared to homodyne detection.

→ OOK, FSK or PSK modl^n techniques can be used to transmit inf^n

→ $P_{LO} >> P_S$, ignore P_S of eq^n (1)

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→ RxR o/p contains a dc term:

$$i_{dc} = \frac{\eta q}{h\nu} P_{LO}$$

→ time varying IF, term given by:

$$i_{IF}(t) = \frac{2\eta q}{h\nu} \sqrt{P_S P_{LO}} \cos[\omega_{IF} + \phi(t)] \cos\theta(t)$$

→ The dc current is filtered out in the RxR & IF current gets amplified.

BER Comparisons

1. Direct Detection OOK

- Here for, OOK s/m sequence of 1 & 0 pulses occur with equal probability.

$\bar{N} \Rightarrow e^-$ hole pairs for pulse 1

$0 \Rightarrow e^-$ hole pairs for pulse 0

- Avg number of photons per bit $\bar{N}_p$ for unity quantum efficiency is:

$$\bar{N}_p = \frac{1}{2}\bar{N} + \frac{1}{2}(0)$$

$$\Rightarrow \quad \bar{N} = 2\bar{N}_p$$

- Chance of making an error

$$\frac{1}{2} P_r(0) = \frac{1}{2} e^{-2\bar{N}_p}$$

$\Rightarrow$ 10 photons per bit required to get a BER of 10^{-9}

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Asynchronous Detection

→ This does not use PLL.
→ Technique used is differential PSK or DPSK.
→ Carrier recovery circuit is replaced by one-bit delay line.
→ PSK method infⁿ is encoded by means of changes in optical phase, mixer will produce '+ve or '-ve o/p depending on whether phase of rxd sg has changed from previous bit.
→ The txd infⁿ is thus recovered from this o/p.
→ BER is given by:

$$\boxed{BER = \frac{1}{2} \exp(-\eta \bar{N}_p)}$$

For OOK detection

Synchronous heterodyne OOK:

$$\boxed{BER = \frac{1}{2} \operatorname{erfc} \sqrt{\frac{1}{2} \eta \bar{N}_p}}$$

Asynchronous heterodyne OOK:

$$\boxed{BER = \frac{1}{2} \exp\left(-\frac{1}{2} \eta \bar{N}_p\right)}$$

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Burst Mode Recievers:

Explain operation of Burst mode RxR with recieved data.

6M	June/July 13
7M	Dec 12/Jan 13
6M	June 12

write a note on Burst mode RxRs.

6M	Dec 09/Jan 10

what is burst mode RxR? Explain.

6M	May/June 10

Passive optical N/w (PON)

→ Its a n/w that uses point to multipoint, fiber to end points
uses unpowered optical splitters to enable a single optical fiber to serve multiple points.

→ optical Line Terminal (OLT) present @ service provider's central office.
optical Network Terminal (ONT) near end users.

Operation:

→ PON/w differ significantly from conventional point to point links

→ This is due to amplitude & phase information packets recieved in successive time slots from different n/w user locations vary widely from packet to packet.

→ This is due to 20km possible distance variations of customers from central office.

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→ suppose, the closest & farthest customers attached to common optical power splitter are 20km apart & fiber attn is 0.5dB/km, then there is 10dB difference in sg amplitudes that arrive at OLT. from these users, if they have same upstream laser o/p level.

→ Fig: shows the consequence of this effect.

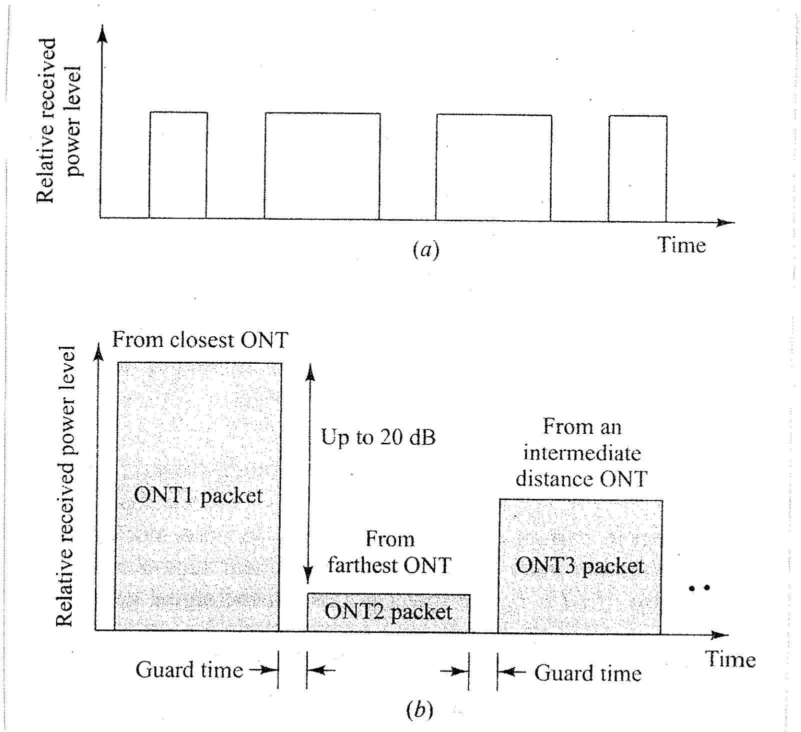

Fig: a) Rxd data pattern in conventional pt to pt links
b) optical sg level variations in pulses at an OLT

→ ONT in this fig refers to transiever equipment at customer location.

→ Fig a) shows data pattern rxd in conventional pt to pt links, sgs arriving at customer site from central office.

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Here there is no amplitude variation in the recieved logic 1's.

→ Fig b) gives optical pattern levels that arrive at OLT from various customers.
Here sg amplitude changes from packet to packet depending on distance of ONT from central office.

→ Guard time provides sufficient delay time to prevent collisions b/w successive packets.

Disadvantage of conventional optical RxR:

→ conventional optical RxR is not capable of handling rapidly changing differences in signal amplitude & clock phase alignment.

Burst mode RxR:

→ These are specially designed RxRs, quickly extract the decision threshold & determine sg phase from set of overhead bits placed at the beginning of each packet burst.

→ Key requirements of Burst mode RxR:

- High sensitivity
  sensitivity is important in relation to optical power budget
  Eg: 3dB sensitivity improvement can double the size of beam splitter, so more customers can be attached to PON.

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• wide dynamic range:
this is essential for achieving long n/w reach, i.e; accomodate users located both close & far away from central office.
• fast response time.

Analog Recievers:

write a note on analog recievers.

6M Dec 13/Jan 14

→ For analog recievers the performance is measured in terms of signal to noise ratio

$$SNR = \frac{\text{mean square sg current}}{\text{mean square noise current}}$$

→ while for digital RxRs performance measured in terms of error probability.
→ Simplest analog technique is amplitude modl^n.
→ Time varying sg s(t) is used to modulate an optical source. about some bias point defined by I_B as shown in fig.
→ The txd power P(t) is:

$$P(t) = P_t \left[1 + m\, s(t)\right]$$

P_t = avg txd optical power
s(t) = modulating sg m = modl^n index

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$$m = \frac{\Delta I}{I_B}$$

$\Delta I \rightarrow$ variation of current about bias point

→ To avoid distortion, modulation must be confined to linear region of light o/p source curve.

If $\Delta I > I_B$, lower portion of sg gets cut off & severe distortion occurs.

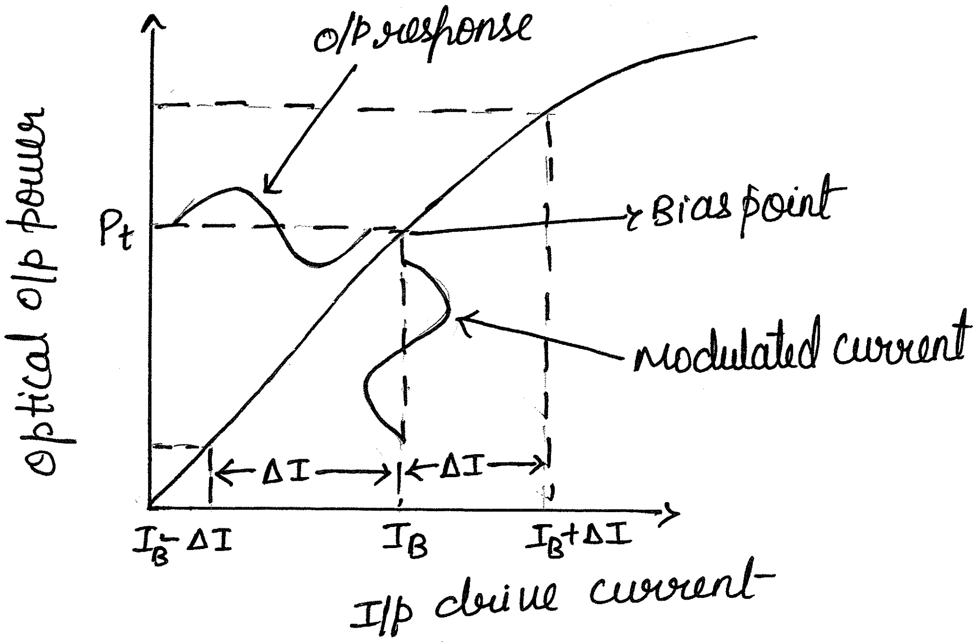

fig: Direct analog modl^n of LED source

→ At the RxR end, photocurrent generated by optical sg:

$$i_s(t) = R M P_r [1 + m\, s(t)]$$

$$i_s(t) = I_p M [1 + m\, s(t)]$$

$I_p = R P_r \Rightarrow$ primary photo current

M = photo detector gain

R = responsivity

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→ Sg current at photodetector o/p :

$$\langle i_S^2 \rangle = \frac{1}{2}(\mathcal{R} M m P_{or})^2 = \frac{1}{2}(M m I_p)^2$$

→ Noise current for a photodetector RxR is sum of mean square of quantum noise current, equivalent resistance thermal noise current, dark noise current & surface leakage noise current.

$$\langle i_N^2 \rangle = 2q(I_p + I_D) M^2 F(M) B_e + 2q I_L B_e + \frac{4 k_B T B_e}{R_{eq}} F_t$$

I_p - primary current
I_D - primary bulk dark current
I_L - surface leakage current
$F(M)$ - excess photo diode noise factor
B_e - effective RxR noise band width
R_{eq} - equivalent resistance of photodetector & amplifier
F_t - noise figure of baseband amplifier

→ Signal to noise ratio :

$$\frac{S}{N} = \frac{\langle i_S^2 \rangle}{\langle i_N^2 \rangle} = \frac{\frac{1}{2}(\mathcal{R} M m P_{or})^2}{2q(\mathcal{R} P_{or} + I_D) M^2 F(M) B_e + \frac{4 k_B T B_e}{R_{eq}} F_t}$$

$$= \frac{\frac{1}{2}(I_p M m)^2}{2q(I_p + I_D) M^2 F(M) B_e + \frac{4 k_B T B_e}{R_{eq}} F_t}$$

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→ For pin photo diode $M=1$,

$$\frac{S}{N} \simeq \frac{\frac{1}{2} m^2 R^2 P_r^2}{(4 K_B T B_e / R_{eq}) F_t}$$

→ For avalanche photo diode,

At low sg levels & low values of gain M, the circuit noise dominates

If the gain is increased SNR value also increases, then quantum noise is comparable to circuit noise. Beyond this if gain is increased, SNR decreases.

Thus, for given set of operations, there exists an optimum value of avalanche gain for which SNR is maximum.

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2. OOK Homodyne system

→ A 0 pulse of duration T is recieved, average number $\overline{N}_0$ of e⁻-hole pairs created is the number generated by local oscillator.

$$\overline{N}_0 = A_{LO}^2 T$$

→ For a 1 pulse, avg num of e⁻-hole pairs, $\overline{N}_1$:

$$\overline{N}_1 = (A_{LO} + A_S)^2 T \approx (A_{LO}^2 + 2 A_{LO} A_S) T$$

$$\because A_{LO}^2 \gg A_S^2$$

→ LO o/p power is much higher then rxd sg level. Vtg V seen by decoder in RxR during pulse 1 :

$$V = \overline{N}_1 - \overline{N}_0 = 2 A_{LO} A_S T$$

→ Associated rms noise σ

$$\sigma = \sqrt{\overline{N}_1} = \sqrt{\overline{N}_0}$$

$$P_e = BER = \frac{1}{2}\left[1 - \mathrm{erf}\left(\frac{V}{2\sqrt{2}\,\sigma}\right)\right]$$

$$= \frac{1}{2}\,\mathrm{erfc}\left(\frac{V}{2\sqrt{2}\,\sigma}\right)$$

$$= \frac{1}{2}\,\mathrm{erfc}\left(\frac{A_S T^{1/2}}{\sqrt{2}}\right)$$

$\mathrm{erfc}(x) = 1 - \mathrm{erf}(x)$ (complementary error function)

$A_S^2 T = 36$ → sg photons created per pulse

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Each pulse must produce 36 e⁻-hole pairs for homodyne detection.

$$\boxed{BER = \frac{1}{2} erfc\left(\sqrt{\eta \bar{N}_P}\right)}$$

$$BER \approx \frac{e^{-\eta \bar{N}_P}}{(\pi \eta \bar{N}_P)^{1/2}}$$

3. <u>PSK</u> <u>Homodyne</u> <u>system</u> :

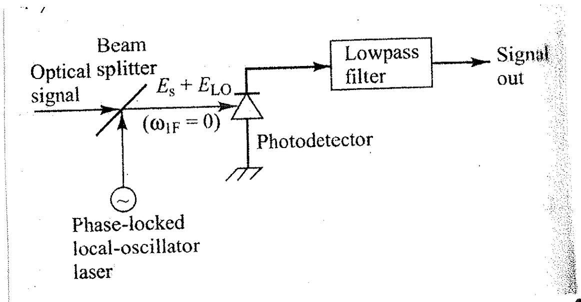

Fig: Fundamental set up of a homodyne RxR

→ Homodetection of PSK modlⁿ gives best RxR sensitivity but most difficult to implement.

→ The incoming signal is first combined with a strong optical wave being emitted from the local oscillator.

→ Combining the sgs is done using a partially reflecting plate called beam splitter.

→ For 0 pulse, sg & local oscillator are out of phase., num of e⁻ hole pairs:

$$\bar{N}_0 = (A_{LO} - A_S)^2 T$$

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Problems:

1. An InGaAs PIN photodiode has wavelength of 1300 nm, $I_D = 4nA$, $\eta = 0.9$, $R_L = 1000\,\Omega$ & surface leakage current is negligible. The incident power is 300 nW (-35 dBm) & RxR bandwidth is 20 MHz. Find various noise terms of the RxR.

→ Given: $\lambda = 1300\,nm$ $\quad R_L = 1K\Omega$

$I_D = 4nA$ $\quad P_{incident} = 300\,nW$

$\eta = 0.9$ $\quad B = 20\,MHz$

mean square Quantum noise:

$$I_q = \sqrt{\frac{q \cdot P_{incident}\,\eta}{h\nu}} = \sqrt{\frac{q \cdot P_{incident}\,\eta\,\lambda}{hc}}$$

$$= \sqrt{\frac{(1.69\times10^{-19})(300\times10^{-9})(0.9)(1300\times10^{-9})}{(6.626\times10^{-34})(3\times10^{8})}}$$

$$\boxed{I_q = 0.547\,mA}$$

mean^2 dark current noise:

$$I_d^2 = 2eBI_D$$

$$= 2(1.6\times10^{-19})(200\times10^{6})(4\times10^{-9})$$

$$\boxed{I_d^2 = 0.256\times10^{-19}\,A}$$

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Mean square thermal noise current

$$I_t^2 = \frac{4 k_B T B}{R_L}$$

$$T = (25^\circ + 273^\circ) = 298 K$$

$$I_t^2 = \frac{4 \times (1.38 \times 10^{-23}) \times (298)(20 \times 10^6)}{1000}$$

$$\boxed{I_t^2 = 3.28 \times 10^{-16} A}$$

2. A digital fiber optic link operating at 850nm requires a max BER of 10^{-9}. calculate
a) minimum energy, E b) min incidental power

→ a) Finding Quantum limit in terms of quantum efficiency

$$P_r(0) = e^{-\bar{N}} = 10^{-9}$$

$$\bar{N} = 9 \ln 10 = 20.7 \sim 21$$

⇒ avg 21 photons/bit required for BER 10^{-9}

$$E = 20.7 \frac{h\nu}{\eta}$$

b) Assume $\eta = 1$ & data rate 10Mbps

$$E = P_i \tau = 20.7 h\nu = 20.7 \frac{hc\tau}{\lambda}$$

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$$\frac{1}{\tau} = \frac{B}{2}$$

$$P_i = 20.7 \frac{hcB}{2\lambda}$$

$$= \frac{20.7\,(6.626\times10^{-34})\,(3\times10^{8})\,(10\times10^{6})}{2\times(850\times10^{-9})}$$

$$P_i = 24.2\,pW$$

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