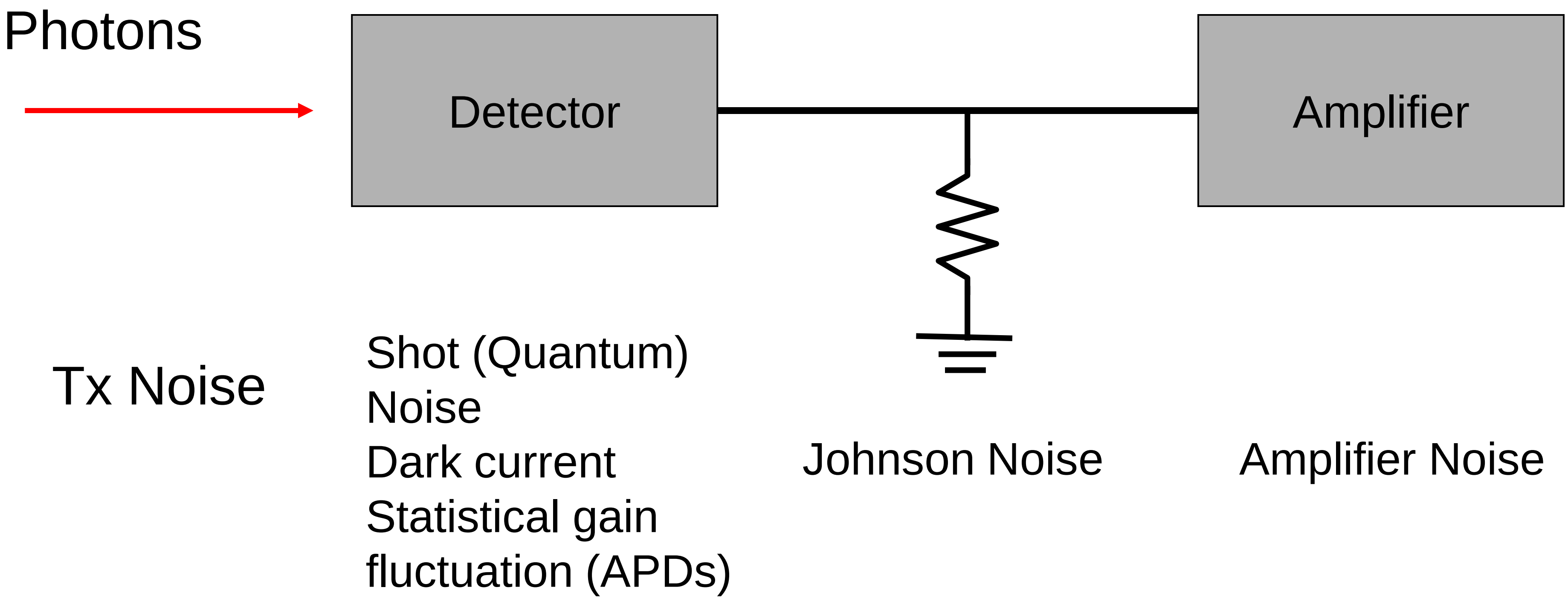
NOISE and BIT ERROR RATE (BER)

Noise
Bit Error Rate (BER) and Receiver Q

Error Sources - Noise



Noise at detector ultimately limits sensitivity of detector and so transmission distance

Noise

Shot Noise

Electric current is the flow of discrete electric charges – digital so statistical variations in current e.g. “rain on a tin roof”

Dark Current

Discussed for pin diodes– leakage currents due to;
-crystal defects & surface states
-Band-band tunnelling - ~exp(-cE_{gap})
-Not constant – quantum world

Noise (2)

Multiplication Noise

Discussed for APDs – variation in multiplication (gain) as it is a random process

Johnson Noise

Thermal or white noise – Noise voltage over any resistor – Gaussian with zero mean

1/f noise

Flicker noise, excess noise, pink noise - component dependent

(Pre-)Amplifier Noise

Amplifying components will add additional noise (see FET noise, etc)

Noise(3)

Transmitter Noise

For a directly modulated laser – many possibilities to have variation in output power

Self pulsation e.g. via Optical feedback, non-uniform current injection

Discrete and random spontaneous/stimulated emission – Quantum/shot noise (Relative Intensity Noise -RIN)

Also 1/f noise – laser is a resistor so has Johnson noise……

Noise results in a fluctuating signal at the receiver where a decision has to be made.

Bit-Error-Rate – Fluctuating signal at receiver

A bit error is registering a 1 when 0 was sent,
or a 0 when a 1 was sent

$BER = N_e/N_t = N_e/Bt$

N_e =Number of errors
N_t = Number of bits
B = Bit rate
t = time

Typical BER are $10^{-9} \sim 10^{-12}$

BER is equal to number of errors divided by total number of pulses (ones and zeros).
Total number of pulses is bit rate B times time interval.
BER is thus not really a rate, but a unitless probability.

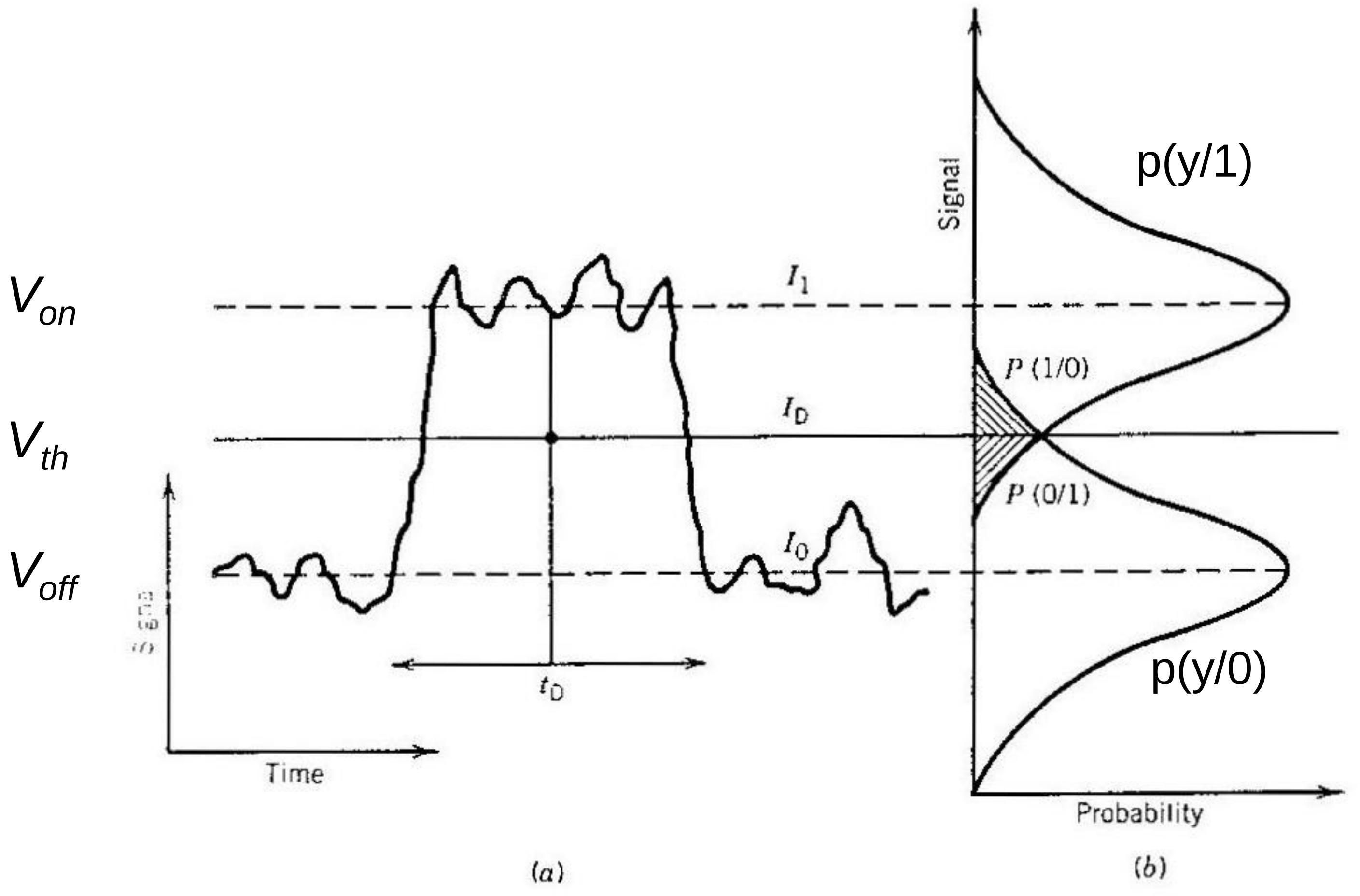
Need to know the probability distribution of the signal

$$P_1(v) = \int_{-\infty}^{v} p(y|1)\,dy \quad P_0(v) = \int_{v}^{\infty} p(y|0)\,dy$$

p(y/1) is probability that voltage is less than v when a 1 is sent
p(y/0) is probability that voltage exceeds v when a 0 is sent

P(1/0) is probability of detecting a 1 when a 0 was sent
P(0/1) is probability of detecting a 0 when a 1 was sent

For p-i-n photodiode main noise contribution is thermal
(Gaussian) noise and shot noise (~Gaussian)



The **Q** factor is widely used to specify receiver performance

Q = 6 often used as gives BER = 10^{-9}

Receiver Q Factor and BER

$$Q = \frac{V_{th} - V_{off}}{\sigma_{off}} = \frac{V_{on} - V_{th}}{\sigma_{on}}$$

$$BER = \frac{1}{2}\left[1 - erf\left(\frac{Q}{\sqrt{2}}\right)\right]$$

$$erf(x) = \frac{2}{\sqrt{\pi}}\int_0^x \exp\left(-y^2\right)dy.$$ - error function tabulated in maths books

- V_n – average level
- σ_n - standard deviation

V_{th}=threshold voltage used to determine a 0 or 1

BER vs. Q, continued

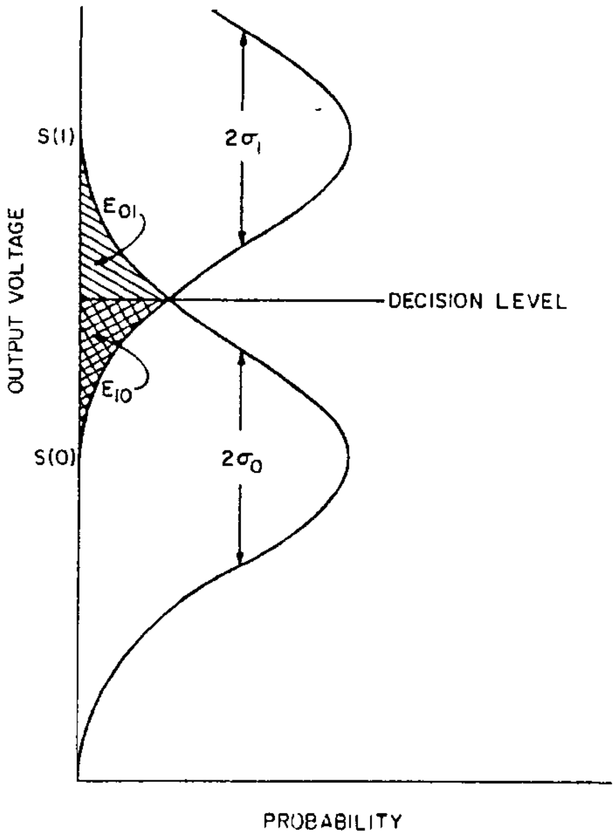
When $\sigma_{off} = \sigma_{on}$ and V_{off}=0 so that V_{th}=V/2, then Q=V/2σ. In this case,

$$BER = \frac{1}{2}\left[1 - erf\left(\frac{V}{2\sigma\sqrt{2}}\right)\right] \approx \frac{1}{\sqrt{2}}\frac{e^{-Q^2/2}}{Q}$$

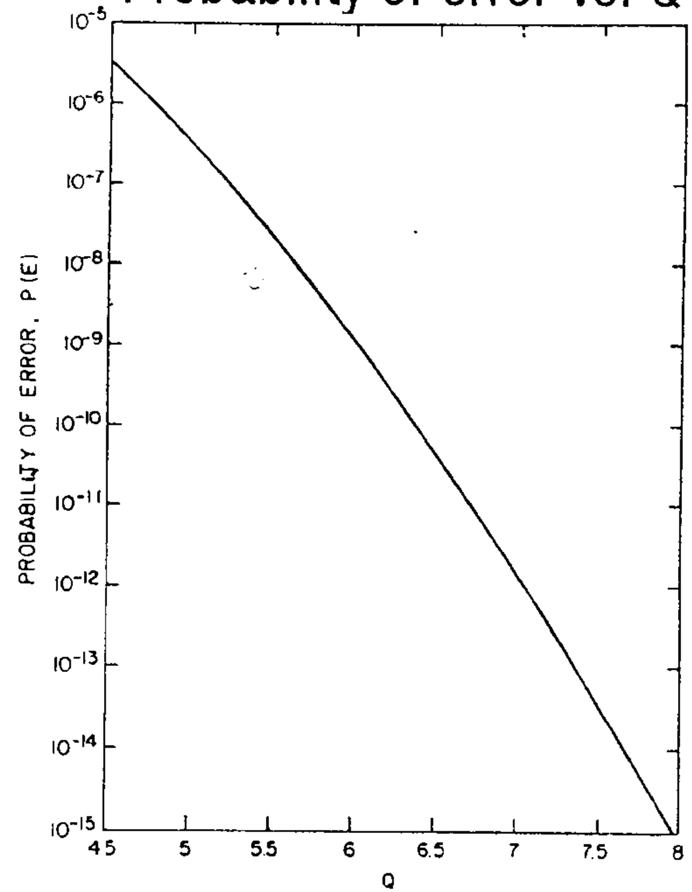
σ usually called the rms noise and V/ σ = peak signal to rms noise level.

Receiver Sensitivity

Probability of error distribution function



Probability of error vs. Q



(Smith and Personick 1982)

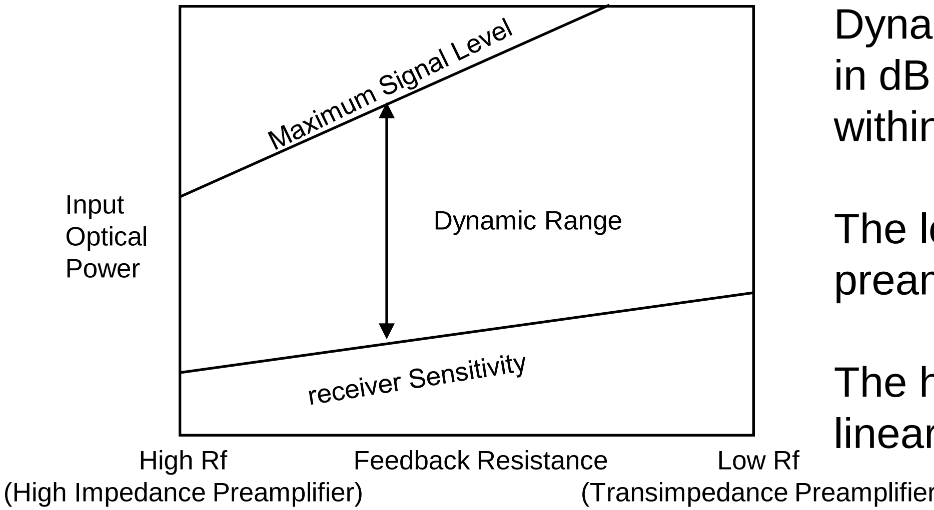
Sensitivity = average detected optical power for given BER

Sensitivity

The minimum optical power that still gives a bit error rate of 10^{-9} or below

Essentially the minimum power that can be received and still have reliable communication

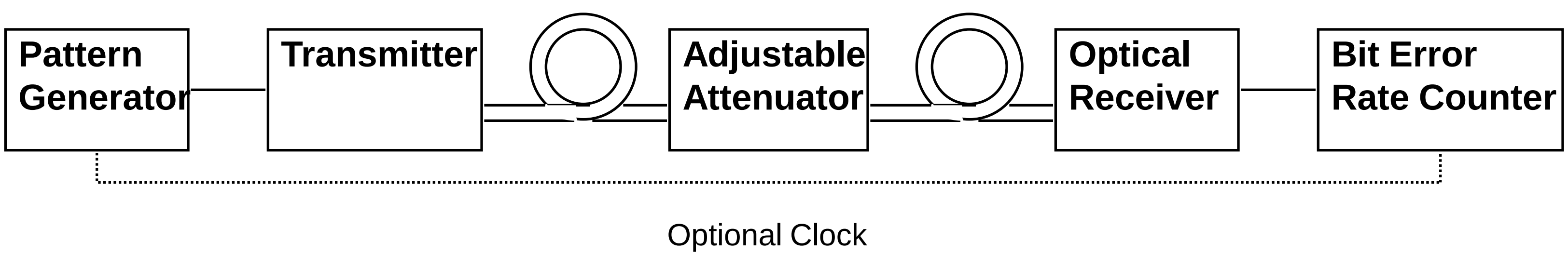
Dynamic Range and Sensitivity Measurement



Dynamic range is the Optical power difference in dB over which the BER remains within specified limits (Typically 10-9/sec)

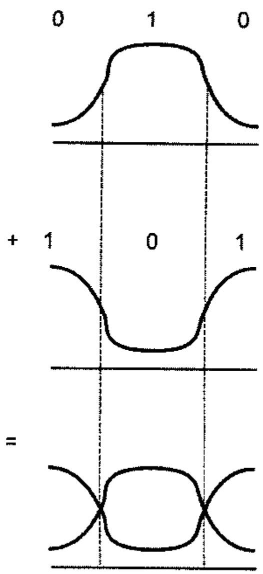
The low power limit is determined by the preamplifier sensitivity

The high power limit is determined by the non-linearity and gain compression

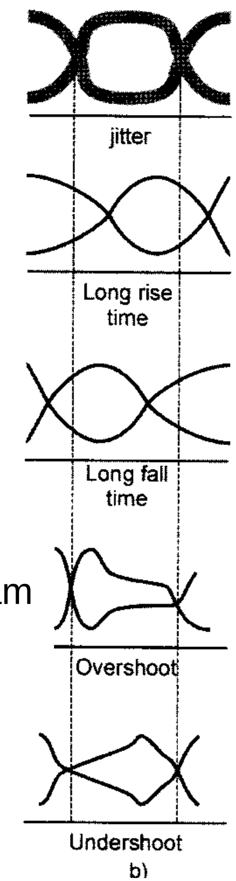


Experimental Setup

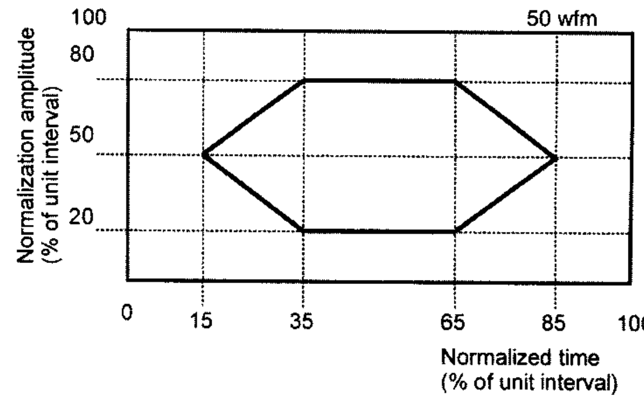
Eye Diagrams



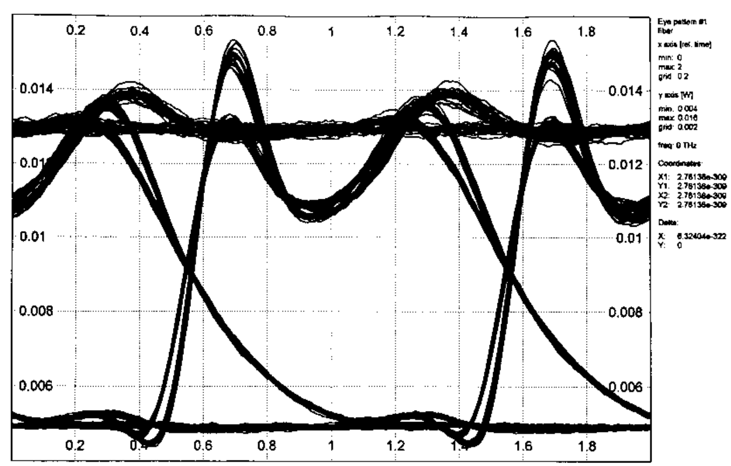
Formation of eye diagram
Overlay pulses
Use storage scope



Eye diagram
degradations



Transmitter
"eye" mask
determination



Computer Simulation of a distorted eye diagram

Extinction Ratio

Ideally a light source transmits no power when a 0 is being sent. In practice power is sent during a 0 pulse.

The extinction ratio (r_e) is the ratio of a digital signal generated by an optical source, e.g., a laser diode, where P_1 is the optical power level generated when the light source is "on," and P_0 is the power level generated when the light source is "off." The extinction ratio may be expressed as a fraction, in dB, or as a percentage

$$r_e = P_1/P_0 \qquad \text{(10-15dB)}$$

Since $P_0 \neq 0$ the signal level must be increased to maintain the BER – known as the Extinction ratio penalty

Summary

Noise at receiver – affects required receiver power to discriminate between “0” and “1”

Bit error rate (BER) is governed by probability function of received electrical signal

Main source of noise for p-i-n photodetector is thermal, plus some shot noise, APDs have additional noise due to gain fluctuations

Can map probability function, assume gaussian form and determine BER