VPI University Program

Photonics Curriculum Version 7.0

Lecture Series

BER and Q-factor

TaM2

Module Prerequisites

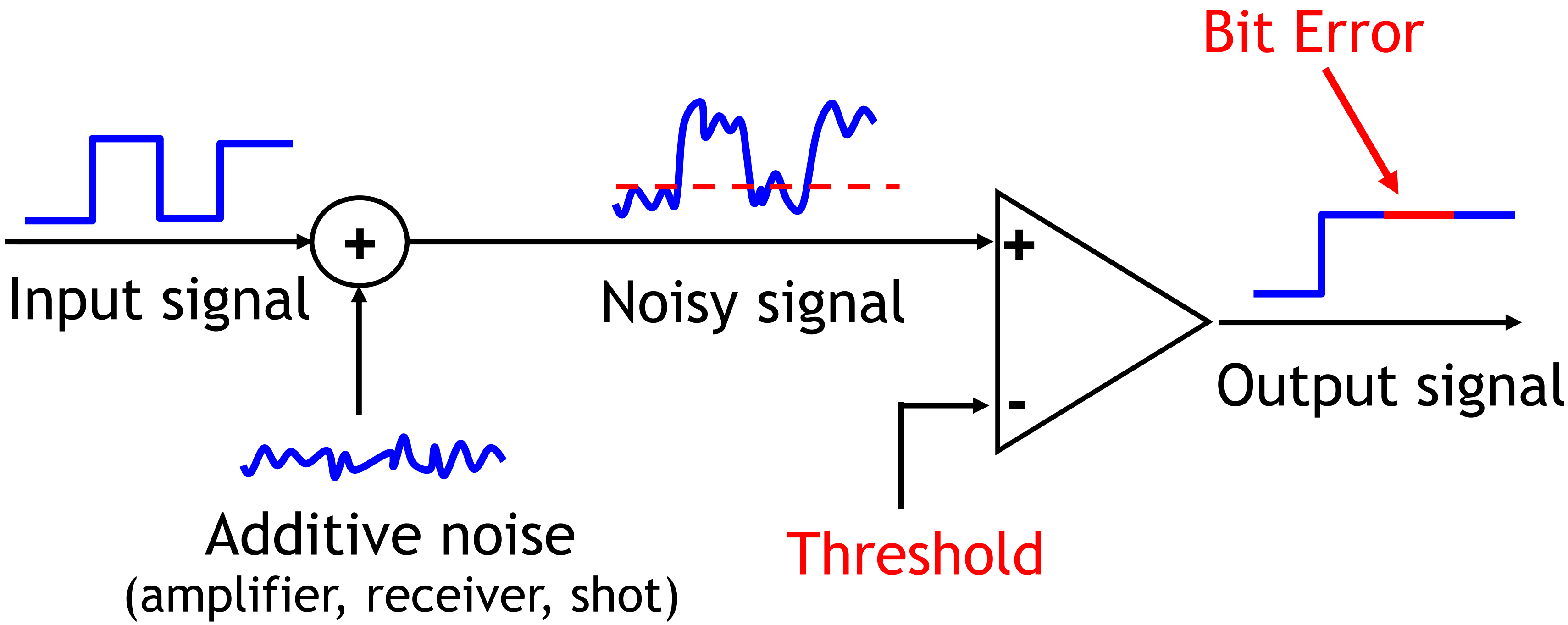
- Introduction to Fiber-Optic Communications I & II
- Basic Photonic Measurements

Module Objectives

- Introduce Bit Error Ratio (BER) concepts
  - BER and Q calculations
  - BER measurements
  - Interpreting BER curves
  - Statistical significance

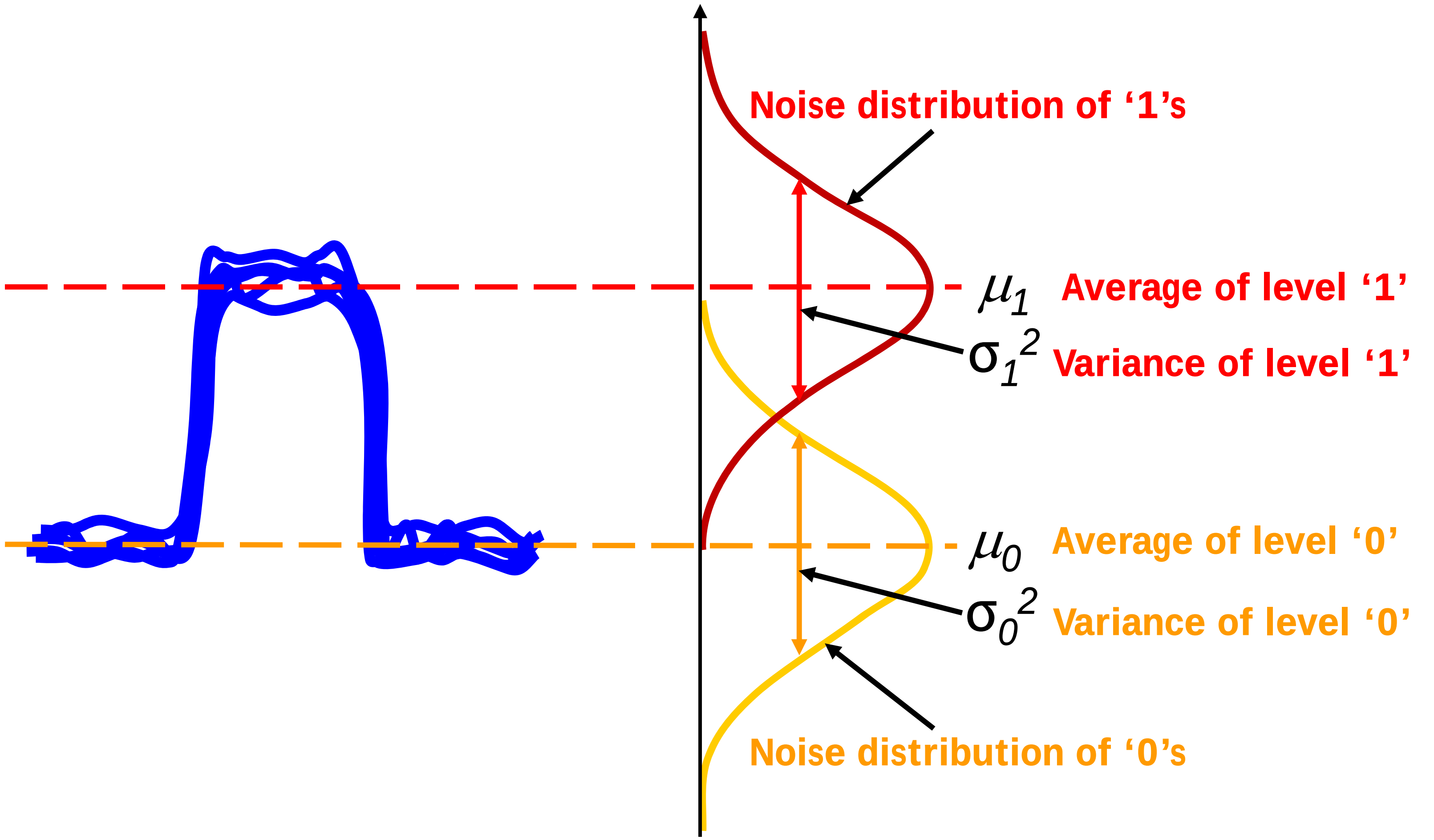
What Causes Bit-Errors?

- Incorrect decisions are made in a receiver due to the presence of noise on the digital signal



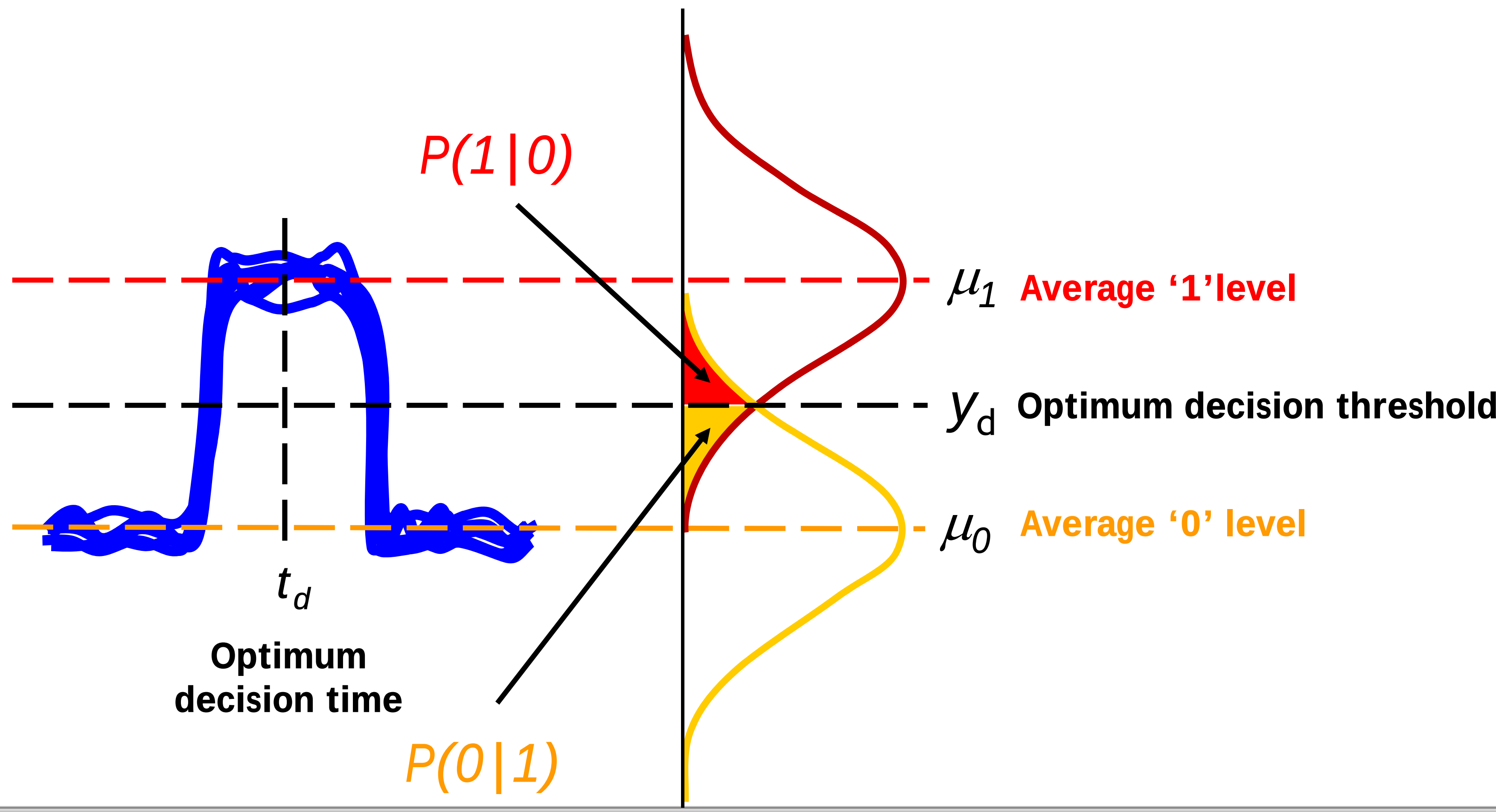
Bit Error Ratio Estimation

Consider two-level modulation only:



BER Estimation

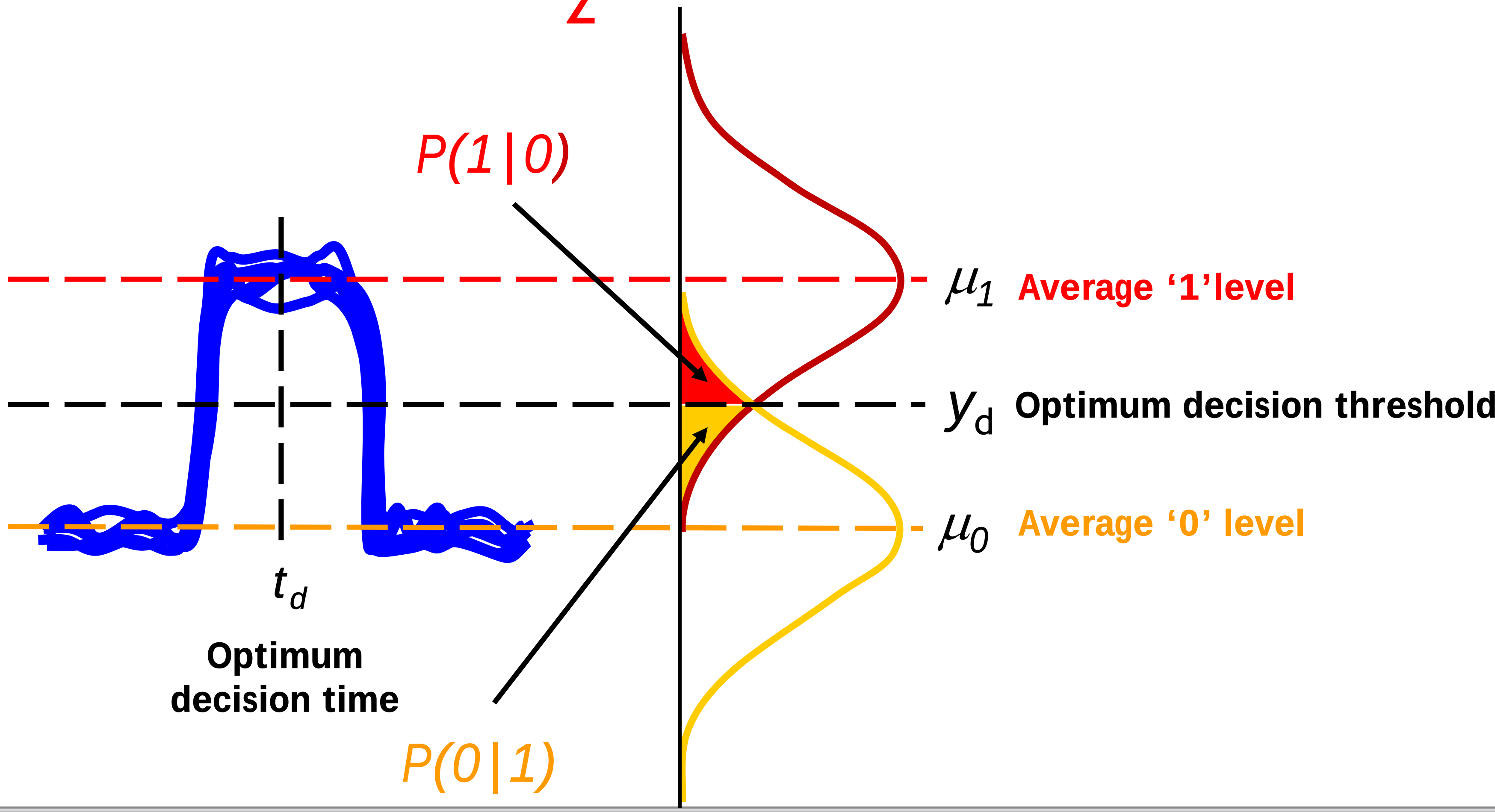
$$BER = p(1)\,P(0|1) + p(0)\,P(1|0)$$



BER Estimation

If the same number of ‘1’s as ‘0’s are sent

$$BER = \frac{1}{2}[P(0|1) + P(1|0)]$$



BER Estimation

If the noise distribution is Gaussian

$$p_1(y) = \frac{1}{\sqrt{2\pi}\sigma_1} \exp\left[- \frac{(y_d - \mu_1)^2}{2\sigma_1^2} \right]$$

$$p_0(y) = \frac{1}{\sqrt{2\pi}\sigma_0} \exp\left[- \frac{(y_d - \mu_0)^2}{2\sigma_0^2} \right]$$

$$P(1|0) = p(y > y_d \mid y \sim p_0) = \frac{1}{2} \mathrm{erfc}\left[\frac{y_d - \mu_0}{\sqrt{2}\,\sigma_0} \right]$$

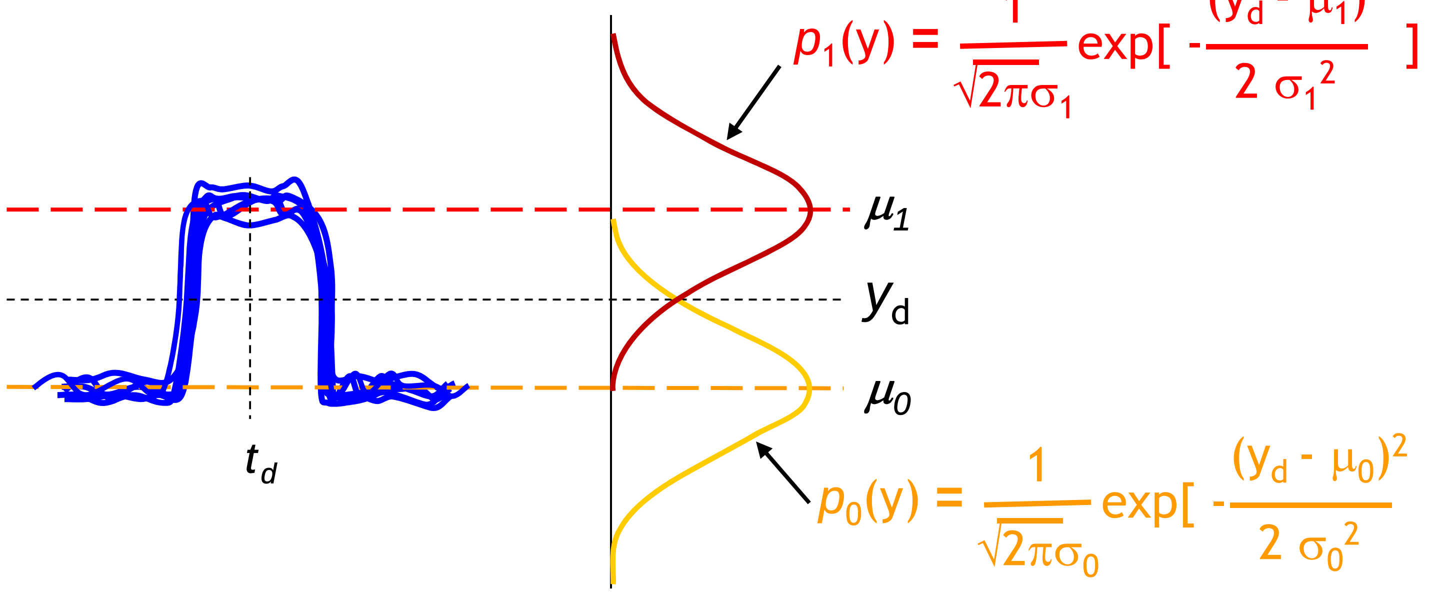
$$P(0|1) = p(y < y_d \mid y \sim p_1) = \frac{1}{2} \mathrm{erfc}\left[\frac{\mu_1 - y_d}{\sqrt{2}\,\sigma_1} \right]$$

WARNING: There is more than one common definition of *erfc(x)*!

BER Estimation

For Gaussian noise, the BER is given by

$$BER = \frac{1}{4}\left[\mathrm{erfc}\left(\frac{\mu_1 - y_d}{\sqrt{2}\,\sigma_1}\right) + \mathrm{erfc}\left(\frac{y_d - \mu_0}{\sqrt{2}\,\sigma_0}\right)\right]$$

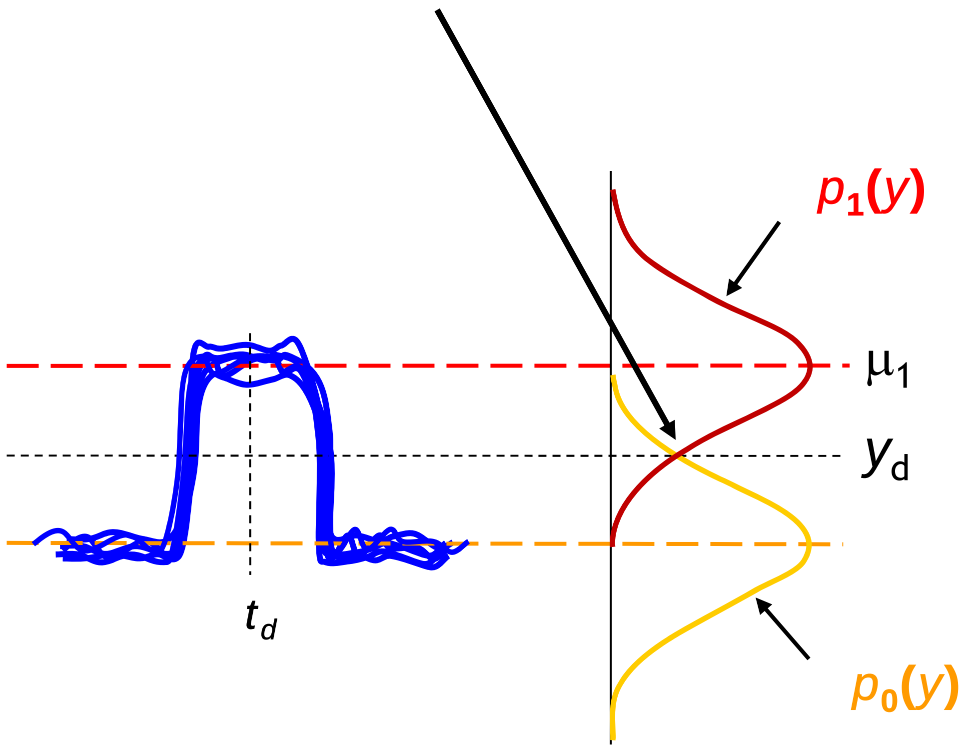


WARNING: There is more than one common definition of *erfc(x)*!

Optimum Threshold

Optimum y_d - gives minimum BER:

$$p_1(y_\mathrm{d}) = p_0(y_\mathrm{d})$$



Optimum Threshold and "Q"

- A common (but accurate) approximation is that for an optimum threshold

$$P(0|1) = P(1|0) \Rightarrow y_d = \frac{\sigma_0 \mu_1 + \sigma_1 \mu_0}{\sigma_0 + \sigma_1}$$

for which the *BER* is

$$BER = \frac{1}{2}\operatorname{erfc}\left(\frac{Q}{\sqrt{2}}\right) \approx \frac{1}{\sqrt{2\pi}\,Q}\exp\left[-\frac{Q^2}{2}\right]$$

where $Q = \dfrac{\mu_1 - \mu_0}{\sigma_0 + \sigma_1}$

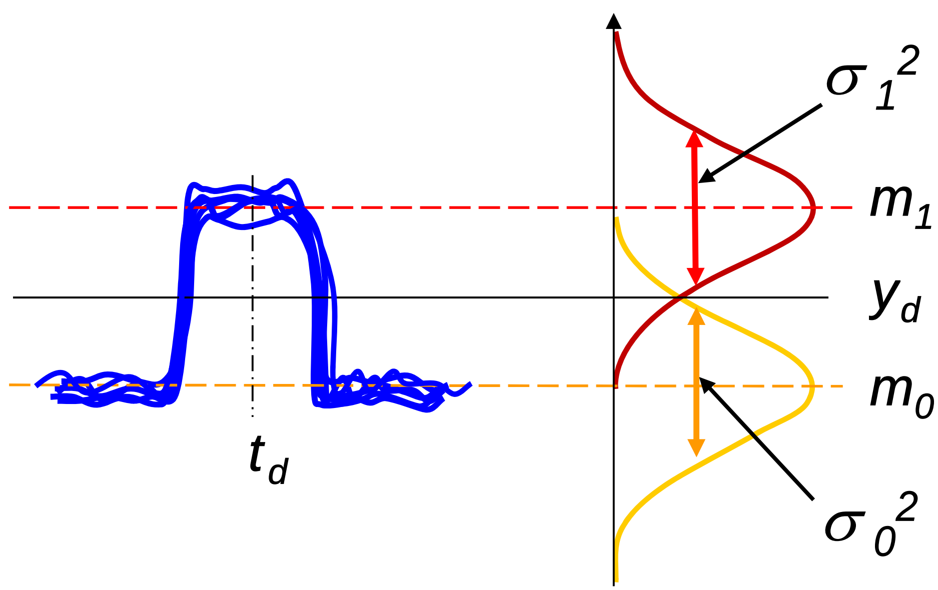
- If noise is Gaussian, *BER* is determined fully by *Q*

WARNING: There is more than one common definition of erfc(*x*)!

What is "Q"?

Q is a measure of the "quality" of any signal

- defined for any signal, for which mean "1" and "0" levels μ_1 and μ_0, and the noise powers σ_1^2 and σ_0^2 are defined



$$Q = \frac{\mu_1 - \mu_0}{\sigma_0 + \sigma_1}$$

What is "Q"?

In many cases of interest

- the plot *Q* against signal amplitude is a straight line
- to get a straight line for BER vs. signal amplitude, you can convert BER to an effective *Q*

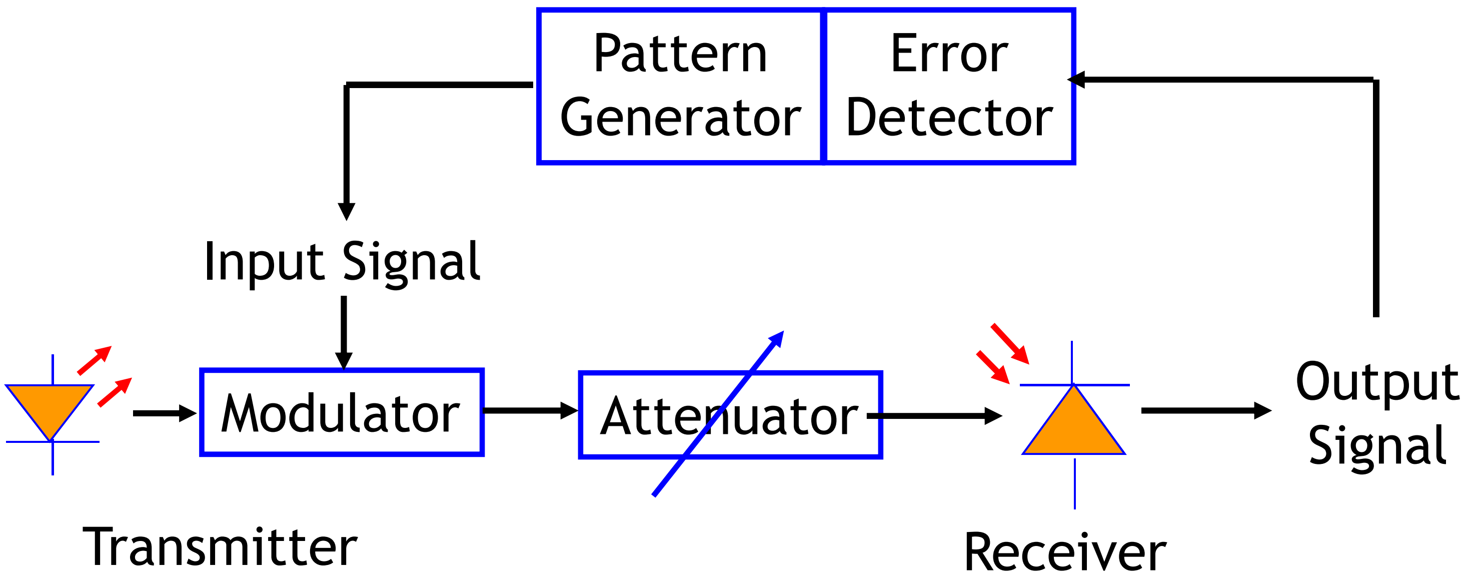
$$Q_{eff} = \sqrt{2}\ \{\log[\frac{1}{2}\mathrm{erfc}(\bullet)]\}^{-1}(x) \quad \text{where } x = \log(BER)$$

BER Measurement Techniques

- Traditionally, BER is measured as a function of the SNR
- In optical systems, BER is measured as a function of mean *received optical power (ROP)*

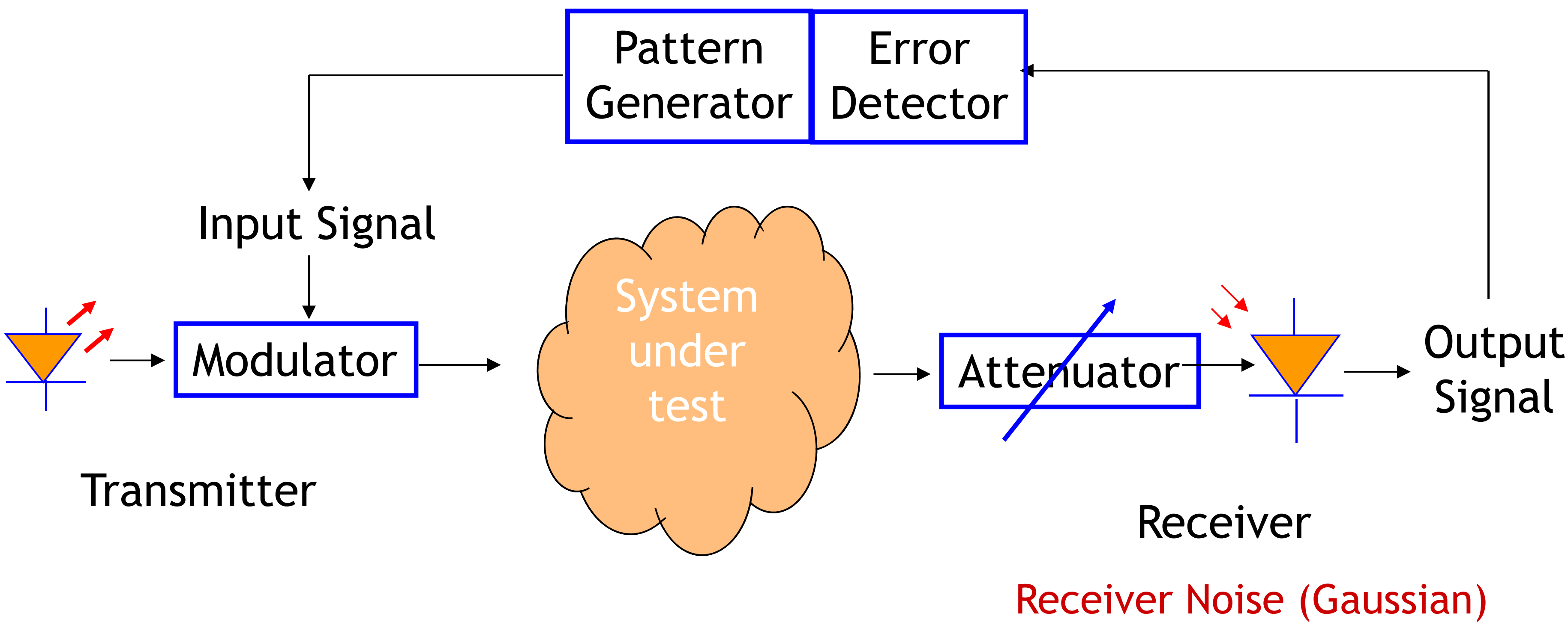
“Back-To-Back” Measurement

- BER test set – pattern generator and error detector
- Pattern is pseudo-random to mimic real traffic
- Errors are counted and then a BER is computed

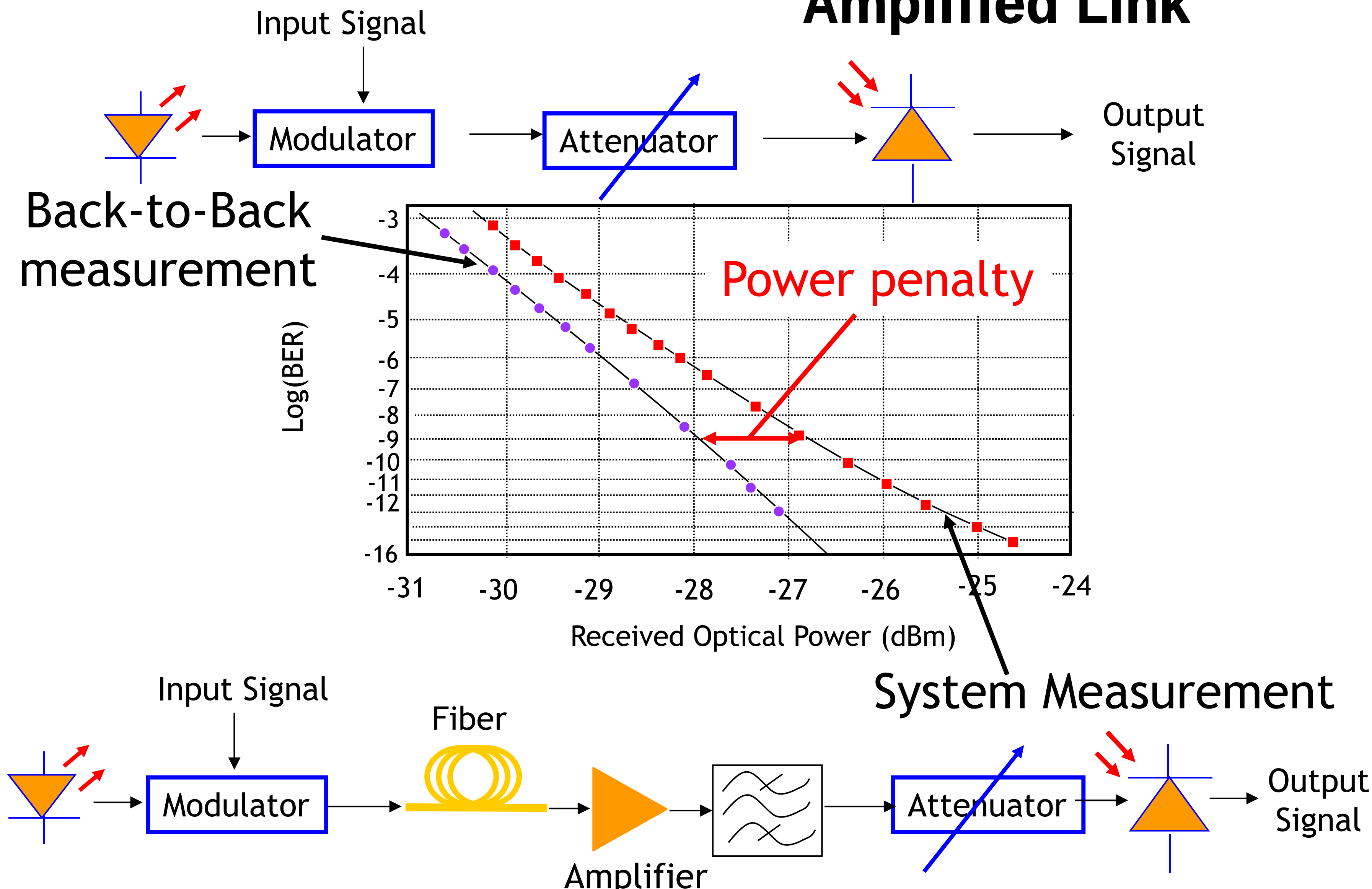


Receiver Noise (Gaussian)

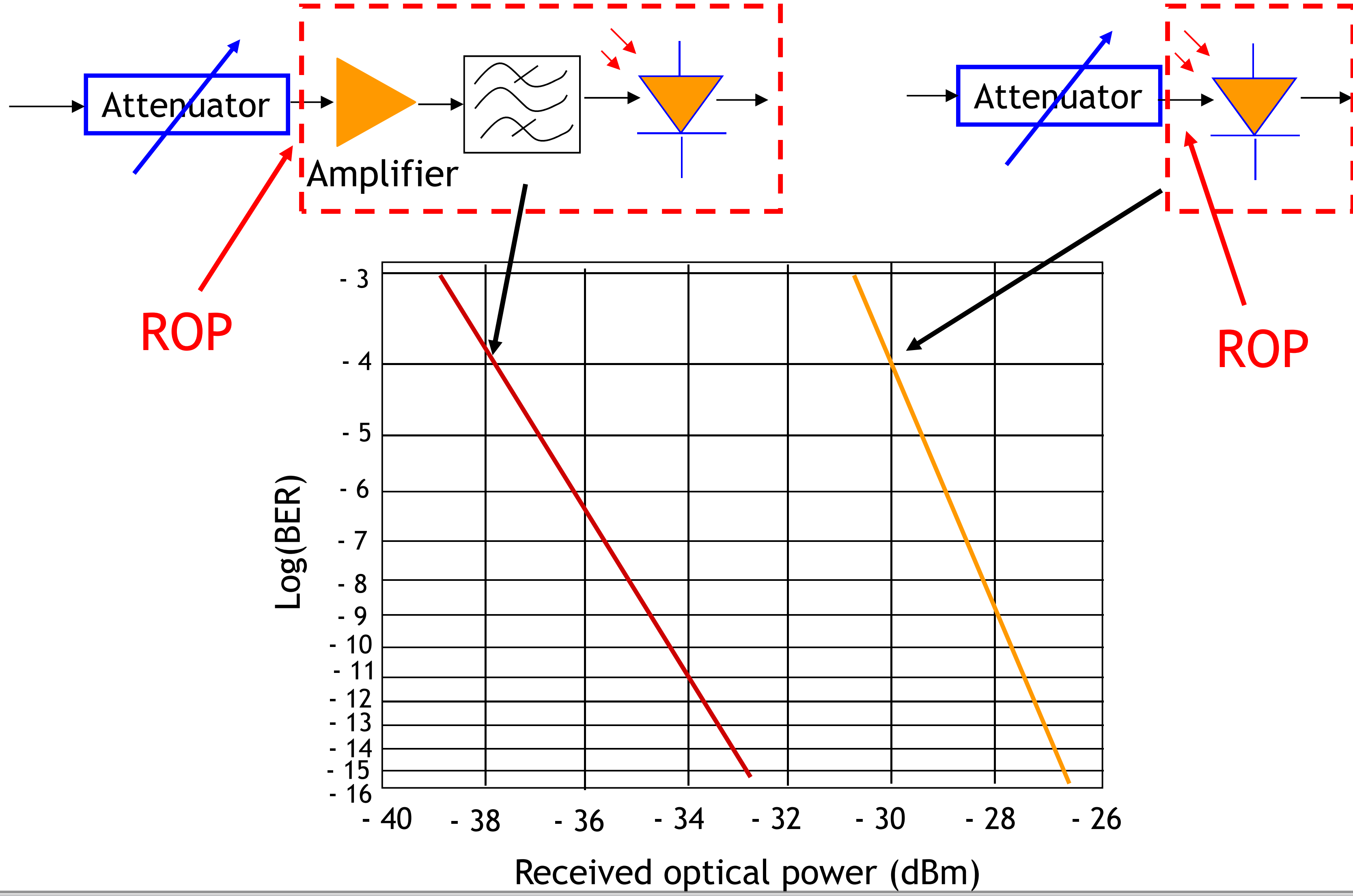
"System" Measurements



Example: An Optically-Amplified Link



Example: Optically-Preamplified Receiver



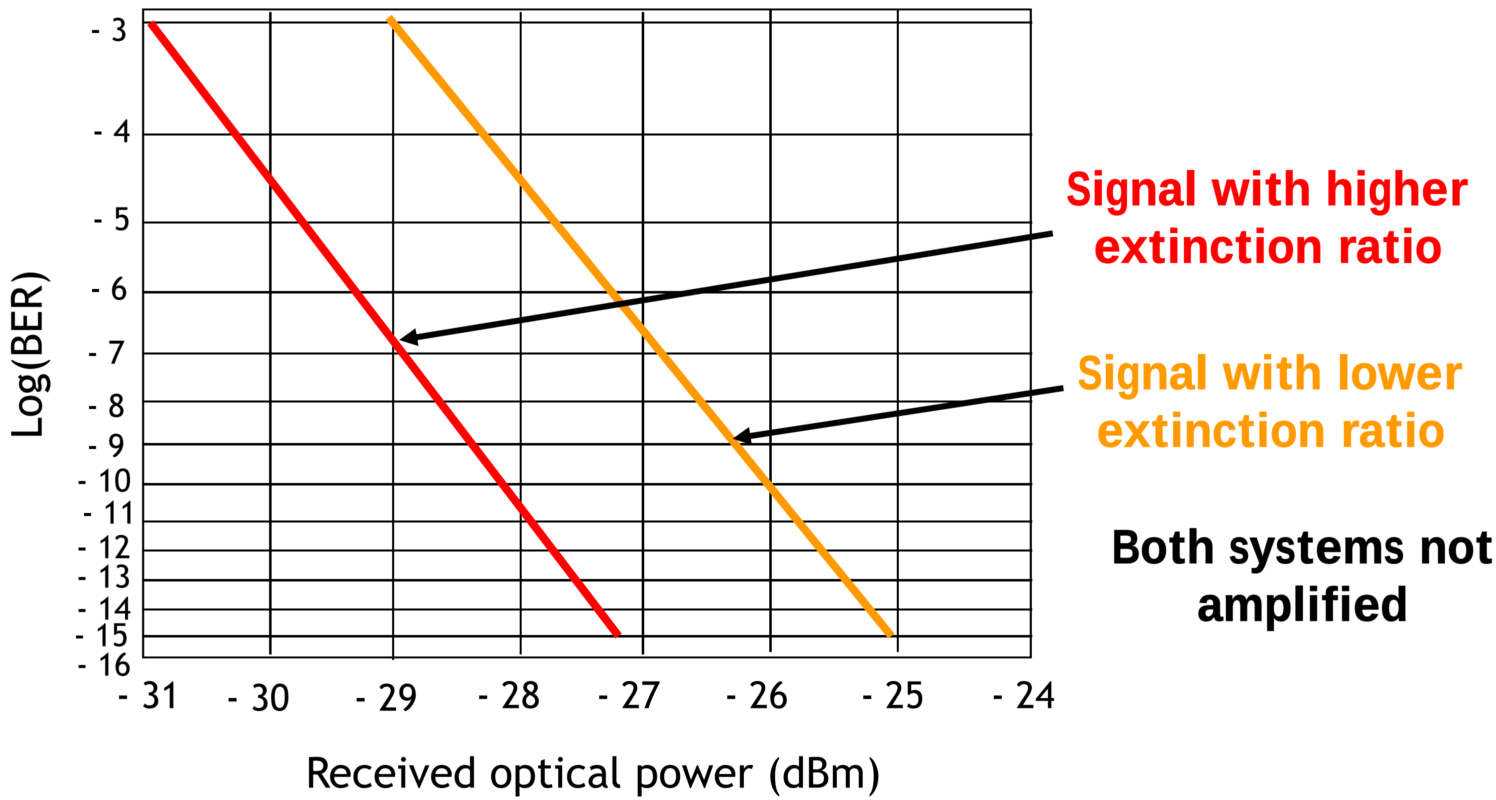
Interpreting BER Curves

- A BER measurement cannot tell you what physical mechanism resulted in a particular degradation of the received signal

- However, BER measurements can be very helpful in determining what type of degradation is occurring

- You can isolate or eliminate sources of degradation

Extinction Ratio Degradation

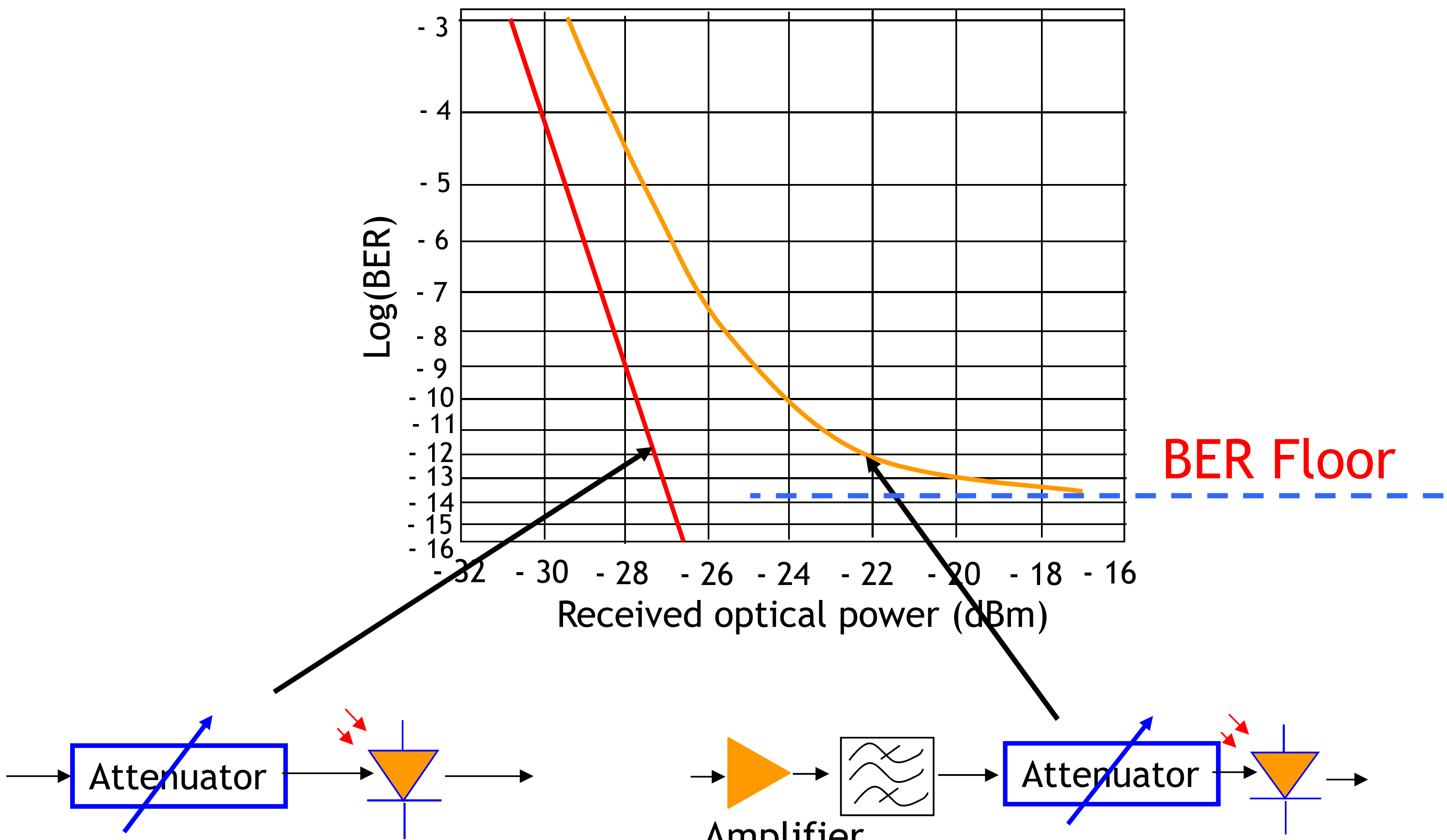


Both systems not amplified

The power penalty (PP) caused by poor extinction ratio is:

$$PP = 10\log_{10}\left[\frac{1 + r}{1 - r}\right],\ r = \frac{P_0}{P_1}$$

Additive Optical Noise



Back-to-Back measurement

System Measurement

Intersymbol Interference

- Intersymbol interference (ISI) in a single-channel system may result from a number of sources
- ISI may result in a power penalty and/or an error-rate floor
- A common signature of ISI is *pattern dependence* of the BER curve

Statistical Significance

In a BER measurement

Sent:

…10110010111010001011010001001 01…..

n_e

Received:

$$\underbrace{\ldots 1010001111001000100101001100111}_{N_b}\ldots..$$

$$BER \approx \frac{n_e}{N_b}$$

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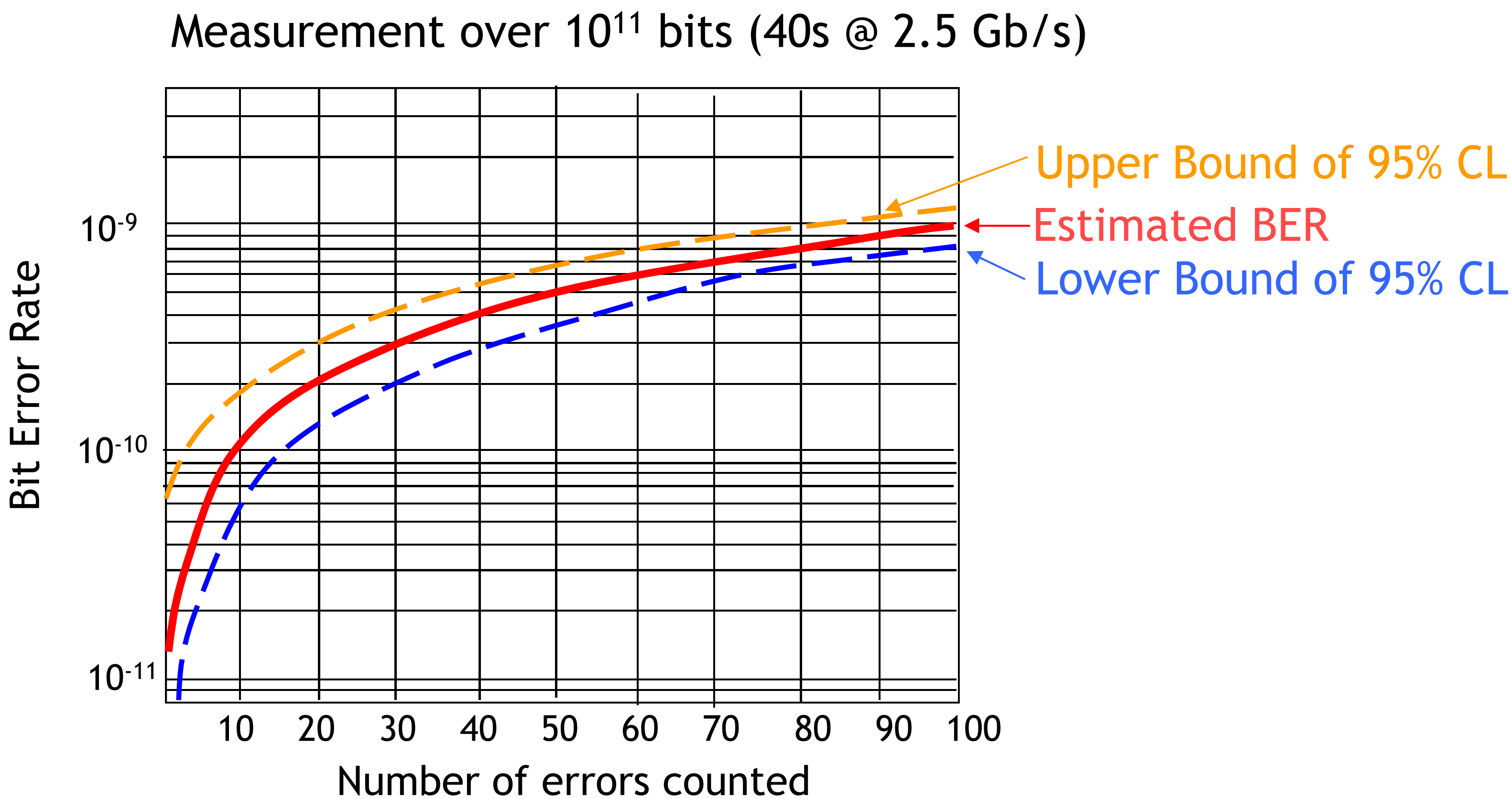
Statistical Significance

How many errors do you need to count?



40 s at 2.5 Gb/s (10^{11} bits) for 10^{-9} BER
approx. 11 hours (10^{15} bits) for 10^{-12} BER !!!

Summary

- What causes bit errors
- BER and Q calculations
- BER measurements and interpretation
- Statistical significance

Proceed with the *Interactive Learning Module*