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HUT Communications Laboratory

S-72.3340 Optical Networks Course

Lecture 3: Modulation and Demodulation

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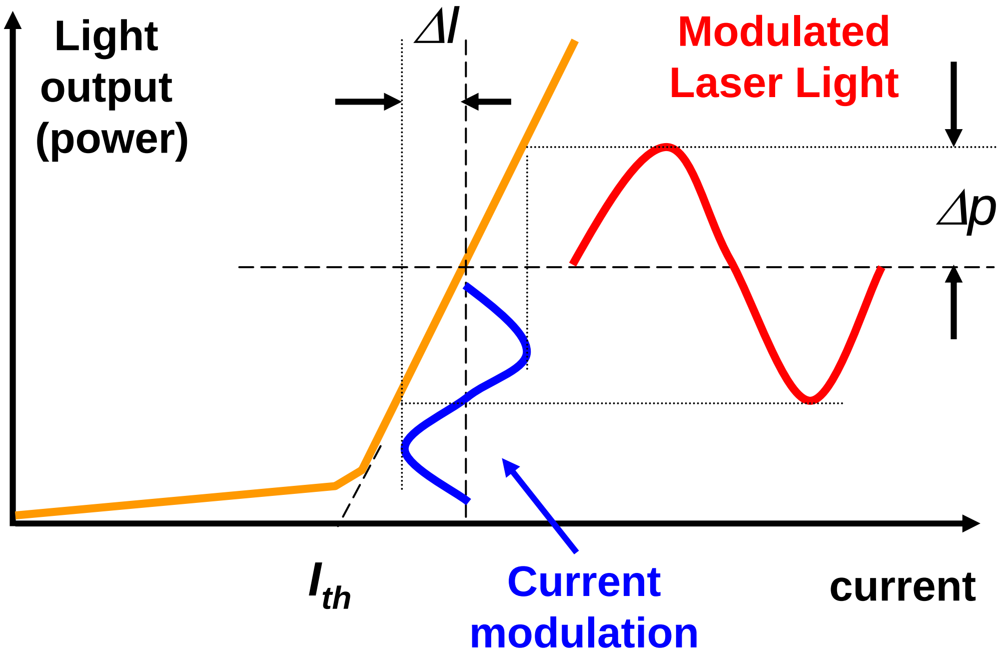
Lecture Outline

- Introduction
- Modulation
- Demodulation
- Link performance evaluation
- Performance improvements methods
- Conclusions

1. Introduction

- ☐ Modulation ⇒ Converting digital or analog data in electronic form to an optical signal suitable for fiber transmission
- ☐ Demodulation ⇒ reverse process of converting the optical signal to an electronic signal and extracting the data



1. Introduction

❑ Need for modulation
- Transferring signal to fiber “transmission windows” (850 nm, 1300 nm, 1550 nm)
- Prior to multiplexing ⇒ impress data signals on carriers of different frequencies
- Transfer data signal to a frequency where equipment design requirements are easily met
- Etc.

2. Modulation

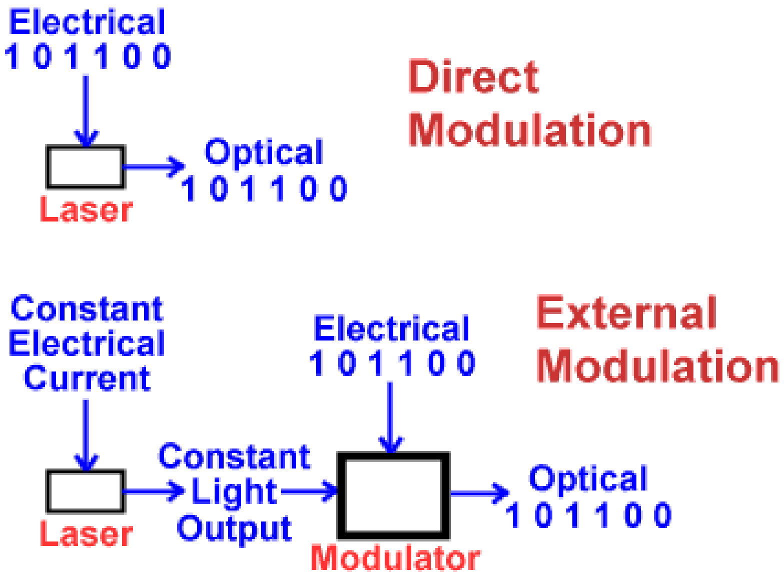
- ☐ Selection of optical modulation scheme
  - Data signal type, analog or digital?
  - Desired performance (tolerable errors, bandwidth usage etc.)
  - Link characterstics e.g. length, fiber type
  - etc.
- ☐ Two popular optical modulation schemes are described here
  - On-off keying modulation
  - Subcarrier modulation

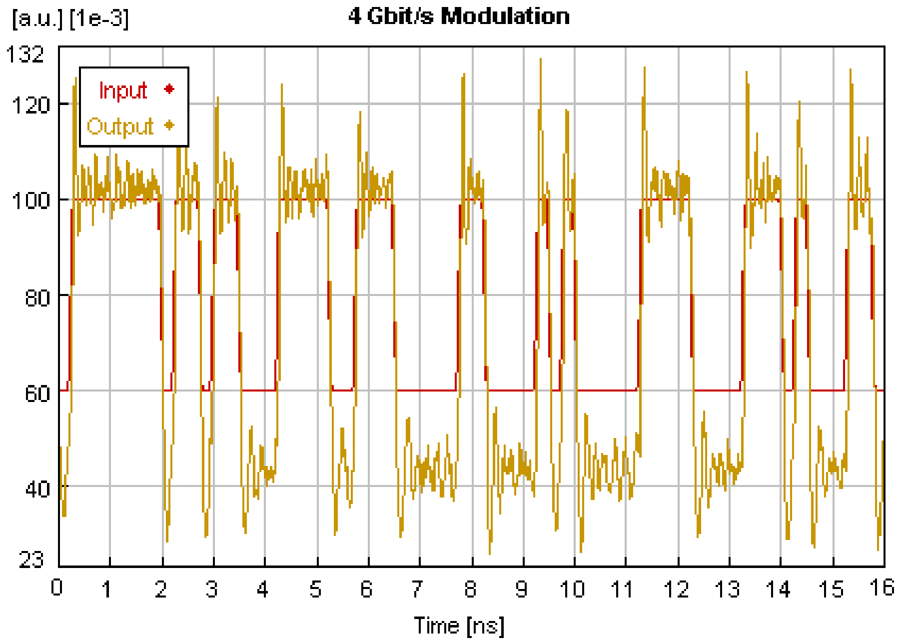
2.1 On-Off Keying (OOK) Modulation

- ❑ Most common digital modulation scheme in current optical communication systems
    - Also referred to as optical amplitude shift keying or intensity modulation
- ❑ Each bit is transmitted within a given time T ⇒ bit interval
    - T = 1/bit-rate
        - e.g. 1 Gbit/s bit rate, bit interval is 1 ns
    - “1” bits encoded by presence of light within bit interval
    - Light is absent (ideally) in a bit interval for a “0” bit

2.1 On-Off Keying (OOK) Modulation

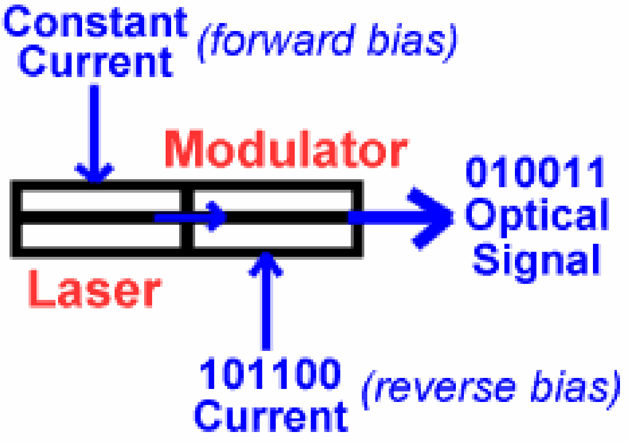
- ❑ It is possible to directly or externally modulate (i.e. turn off and on) a light source (laser or LED)
  - Direct modulation ⇒ simple, chirp
  - External modulation ⇒ more complex, less chirp





2.1 On-Off Keying (OOK) Modulation

- ❑ Example of external modulator ⇒ Electro-absorption modulator
  - Modulates light by changing optical absorption coefficient of modulator semiconductor material using reverse bias voltage
  - Can be monolithically integrated (same chip) with lasers ⇒ cheaper compact transmitters



Constant Current *(forward bias)*

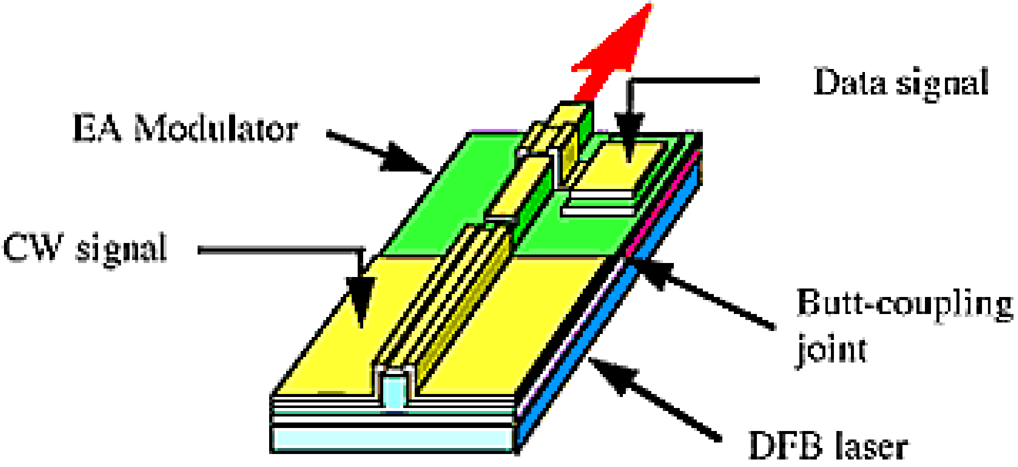
Modulator

Laser

010011 Optical Signal

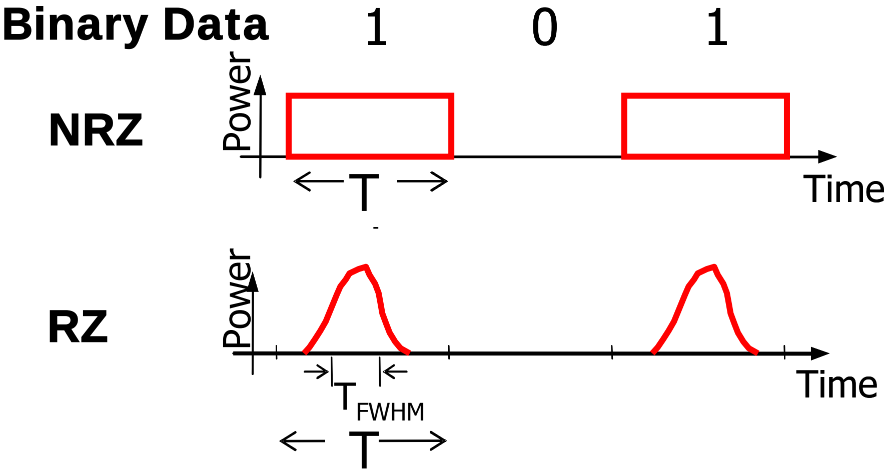
101100 Current *(reverse bias)*

Electro-Absorption Modulator



2.1 On-Off Keying (OOK) Modulation

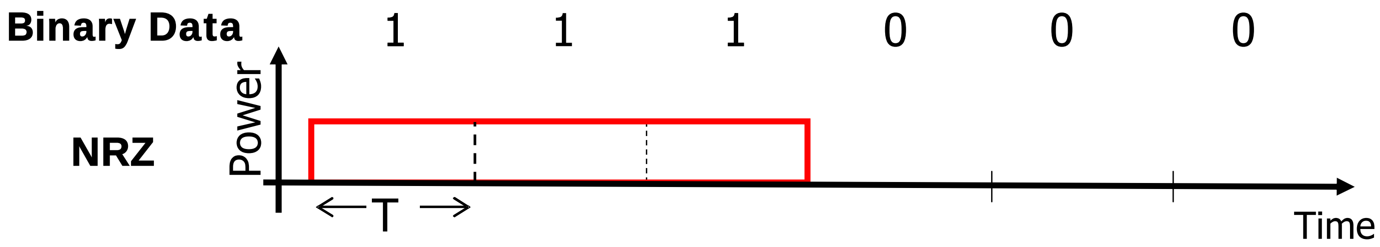
- Non-Return-to-Zero (NRZ) format
  - A '1' bit occupies entire bit interval
  - Bandwidth efficient
  - Used in most high-speed (155 Mb/s to 10 Gb/s) systems
- Return-to-Zero (RZ) format
  - A '1' bit occupies a fraction of the bit interval
  - Large bandwidth required
  - Used in certain long-range, high-bit-rate (≥10 Gb/s) systems



Duty Cycle = T_{FWHM}/T where T_{FWHM} is full width at half maximum of power

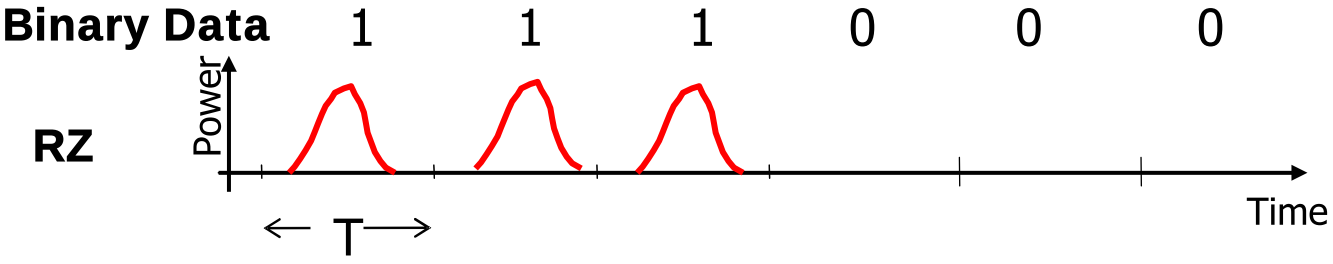
2.1 On-Off Keying (OOK) Modulation

- Clocks counted using 1 to 0 or 0 to 1 transitions in the received bit string
- There is lack of transitions when a consecutive string of ‘1s’ or ‘0s’ is sent
  - Makes acquisition of clock signal by receiver difficult



2.1 On-Off Keying (OOK) Modulation

- ❑ RZ solves the problem partially for strings of ’1s’

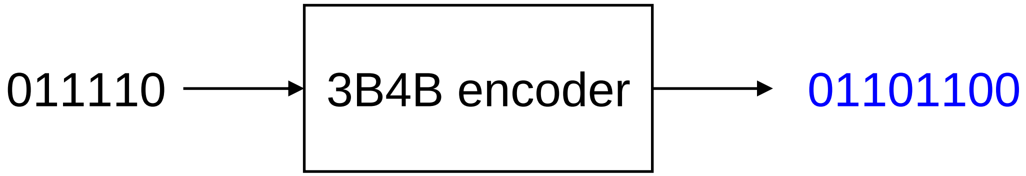


- ❑ Lack of ‘DC balance’ with NRZ and RZ formats
  - Average transmitted power is not constant
  - Average needed to set the decision threshold at the receiver
- ❑ Lack of transition and DC balance problems solved by line coding and/or scrambling

2.1 On-Off Keying (OOK) Modulation

❑ Line coding

- Produce encoded sequence with sufficient transitions and DC balance
- Performed prior to optical modulation
  - Example: 3B4B code used in low rate optical communications systems. Guarantees maximum 1s or 0s run length of 4.



- Requires extra bandwidth
  - Example: 3B4B code results in a large 25% overhead.
  - High rate systems use alternative coding schemes. Example 64B66B codes (3% overhead) used for some 10 Gbit/s systems.

2.1 On-Off Keying (OOK) Modulation

❑ Scrambling

- One-to-one mapping of the data stream into another stream before transmission
- Doesn't require extra bandwidth
- Possible DC imbalance and no guarantees on maximum run length of 0s and 1s

2.2 Subcarrier Modulation

- Subcarrier modulated (SCM) systems
  - Data signal first modulate an electrical microwave or millimeter-wave carrier (subcarrier) in 10 MHz-300 GHz frequency range
  - Modulated subcarrier then modulates the optical carrier

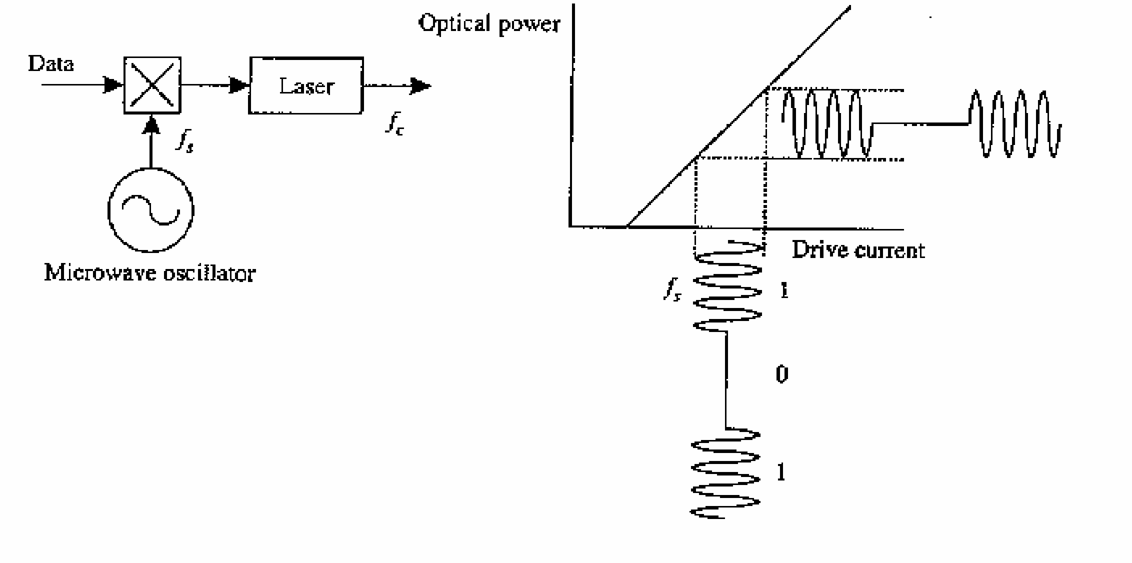
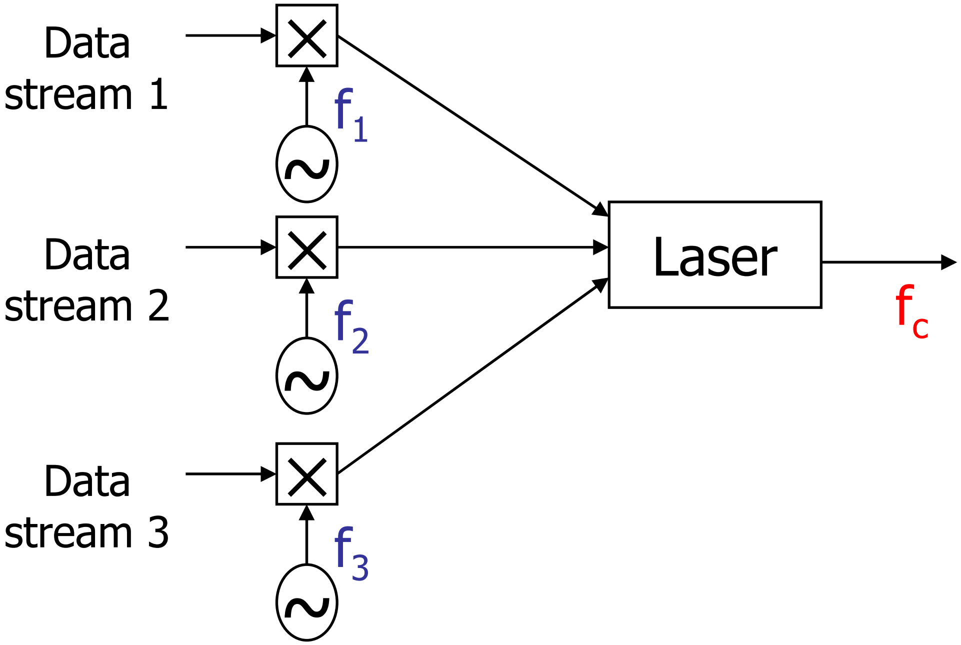


Figure 4.5 Subcarrier modulation. The data stream first modulates a microwave carrier, which, in turn, modulates the optical carrier.

2.2 Subcarrier Modulation

❑ Motivation for subcarrier modulation

- Multiplex multiple data streams onto one optical signal
- Each data stream assigned a unique subcarrier frequency
  ⇒ subcarrier multiplexing



Data stream 1

f_1

Data stream 2

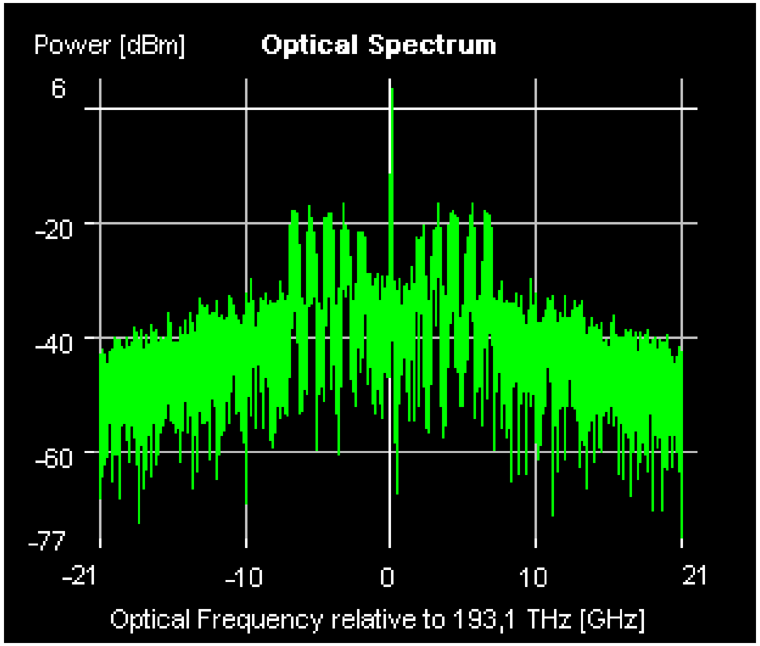
f_2

Data stream 3

f_3

Laser

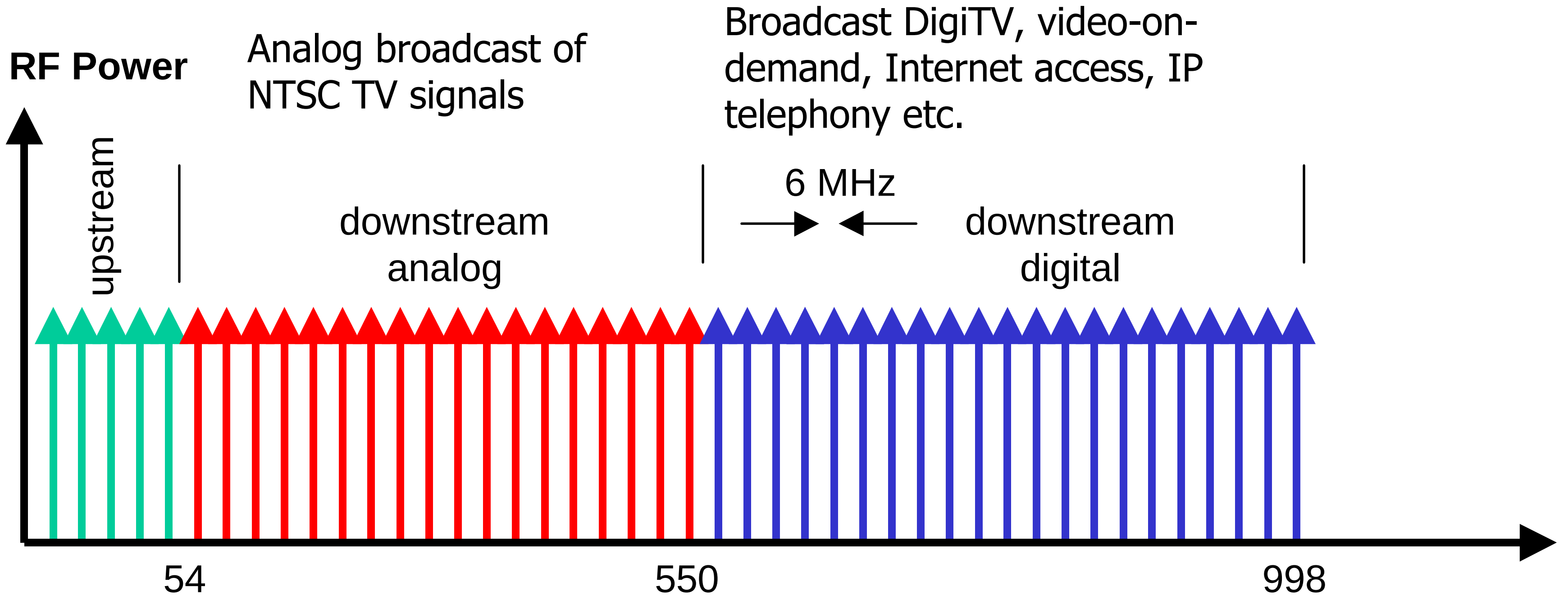
f_c



5 signal subcarrier multiplexing

2.2 Subcarrier Modulation

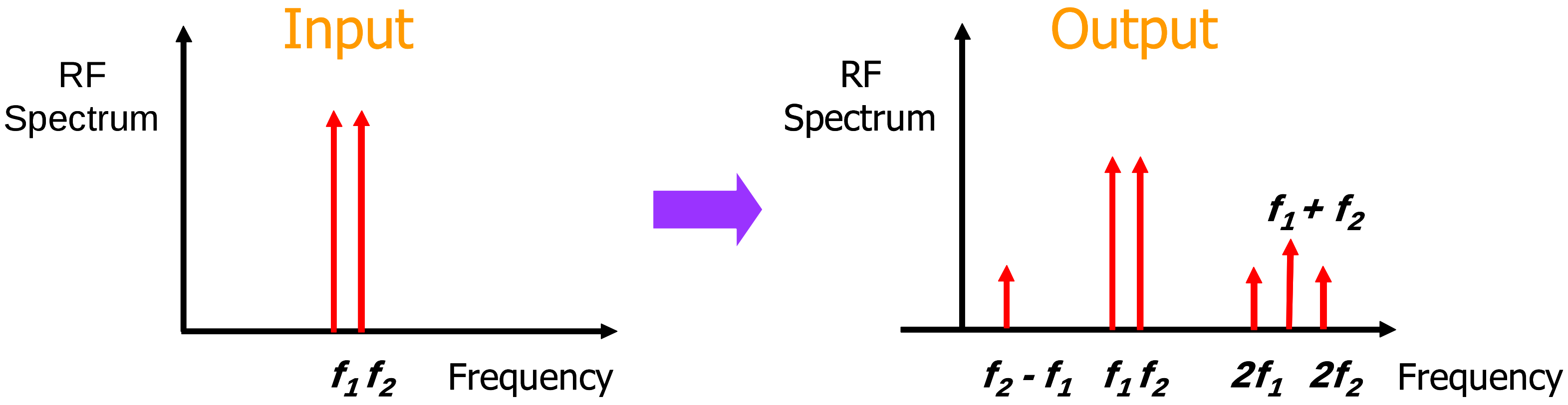
- Example SCM application:
  - Multichannel TV broadcast in CATV systems using single optical transmitters



The NTSC frequency plan

2.2 Subcarrier Modulation

- ❑ SCM performance sensitive to linearity of laser power vs drive current relationship
  - Laser nonlinearity produces intermodulation products ⇒ interferes with other channels
  - Must operate in higher optical power to keep intermodulation products low
  - Highly linear lasers required for SCM systems



2.2 Subcarrier Modulation

- Signal distortion in SCM systems also by clipping

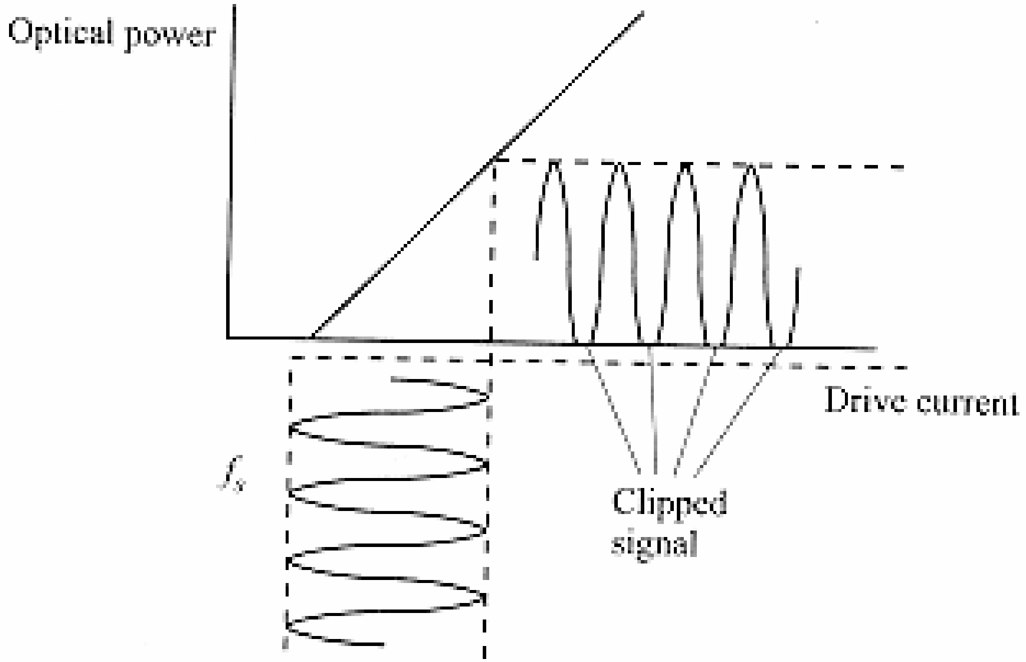


Figure 4.3 Clipping of a subcarrier modulated signal. When the drive current goes below a threshold, the laser output power goes to zero and the signal is said to be clipped.

3. Demodulation

❑ Received modulated signals

- Usually attenuated, dispersed and have added noise obscuring the desired signal
- Must be recovered with low bit error rate
  - Example: BER typically < 10^{-12}

❑ Data signal recovery is a two step process

(1) Recovering the clock

(2) Determining whether a “0” or “1” bit was sent in a bit interval ⇨ direct detection

3.1 Receiver Noise Components

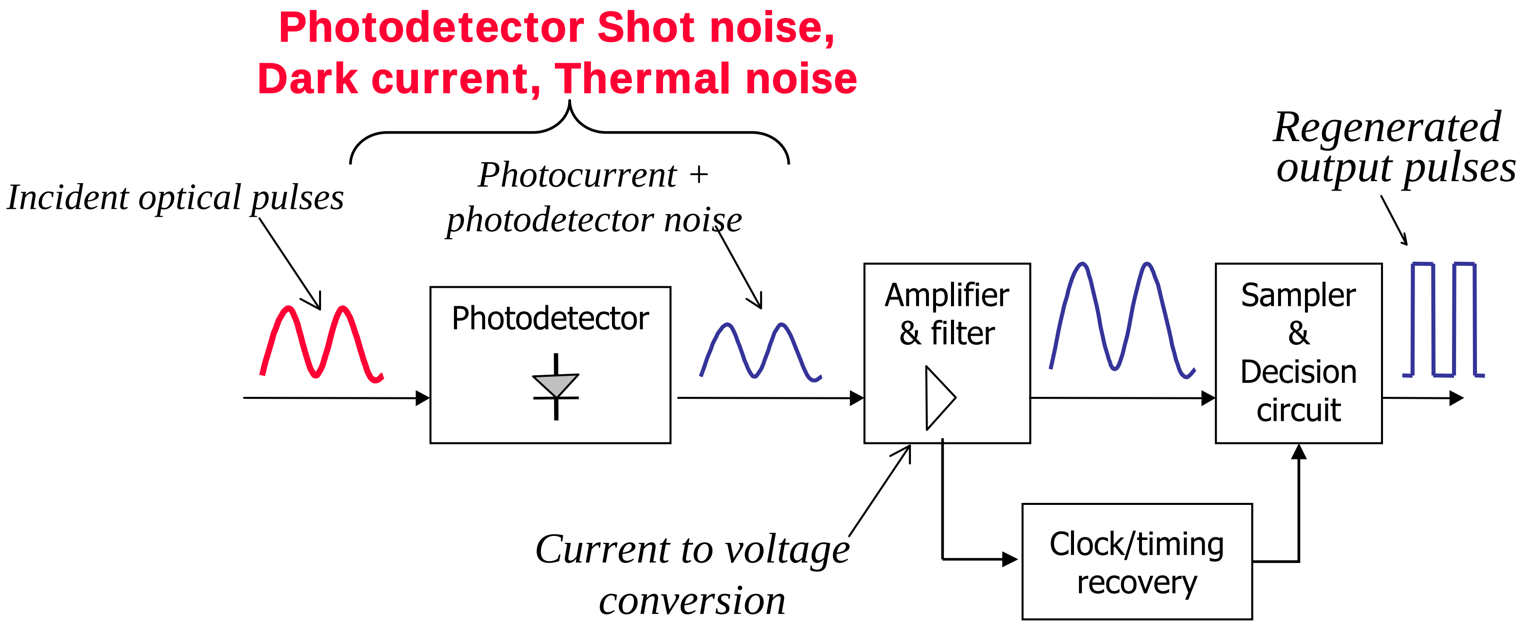
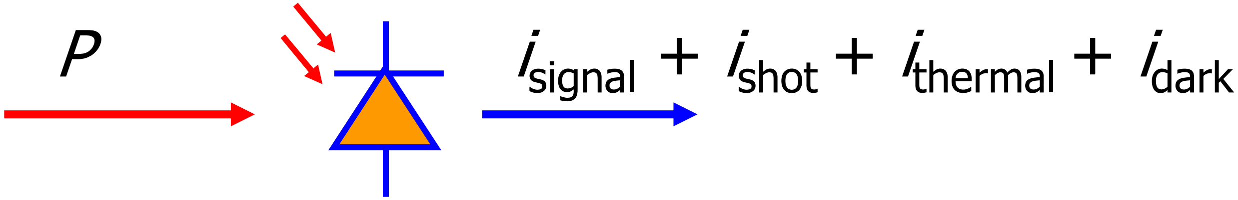


Figure: Block diagram showing various functions in a receiver

3.1 Receiver Noise Components

- ☐ Photocurrent produced from a received optical signal of power *P*
  - Results from the desired signal plus various noise components



  - If R is photodetector responsivity (in A/W) the signal photocurrent is:

$$i_{\text{signal}} = R \cdot P$$

  - Noise components are Gaussian random variables with variance equal to mean square of photocurrents they produce

$$\langle i^2_{\text{noise}} \rangle = \sigma^2_{\text{noise}}$$

3.1 Receiver Noise Components

- ❑ Thermal noise ⇒ noise resulting from the random motion of electrons in a conducting medium
  - Arises from both the photodetector and the load resistor in receiver circuitry
  - Independent of input signal
  - Limited by receiver electrical bandwidth B_e
- ❑ Thermal noise current i_{thermal} has variance

Boltzmann's Constant (1.38 × 10^{-23} J/K)

temperature

bandwidth

$$\sigma^2_{\text{thermal}} = \frac{4kTB_e}{R_L}$$

resistance

3.1 Receiver Noise Components

- ❑ Shot noise ⇒ due to random distribution of electrons generated by photodetection process
  - Convenient representation of variability of generated photocurrent
  - Dependent of received signal level
  - Shot noise current i_{shot} associated with a photocurrent I has variance

Generated photocurrent

$$\sigma^2_{\text{shot}} = 2eIB_e$$

Electron charge (e = 1.602×10^{-19} coulombs)

bandwidth

3.1 Receiver Noise Components

- ❑ Dark current ⇒ “ghost-like” current that flows when there is no incident light n the receiver
  - Independent of received optical signal
  - Smaller in magnitude compared to thermal and shot noise

3.1 Receiver Noise Components

- Shot, thermal and dark noise level reduced if B_e is small
  - In practice, $0.5B < B_e < B$ where B is bit rate, so as not to distort signal

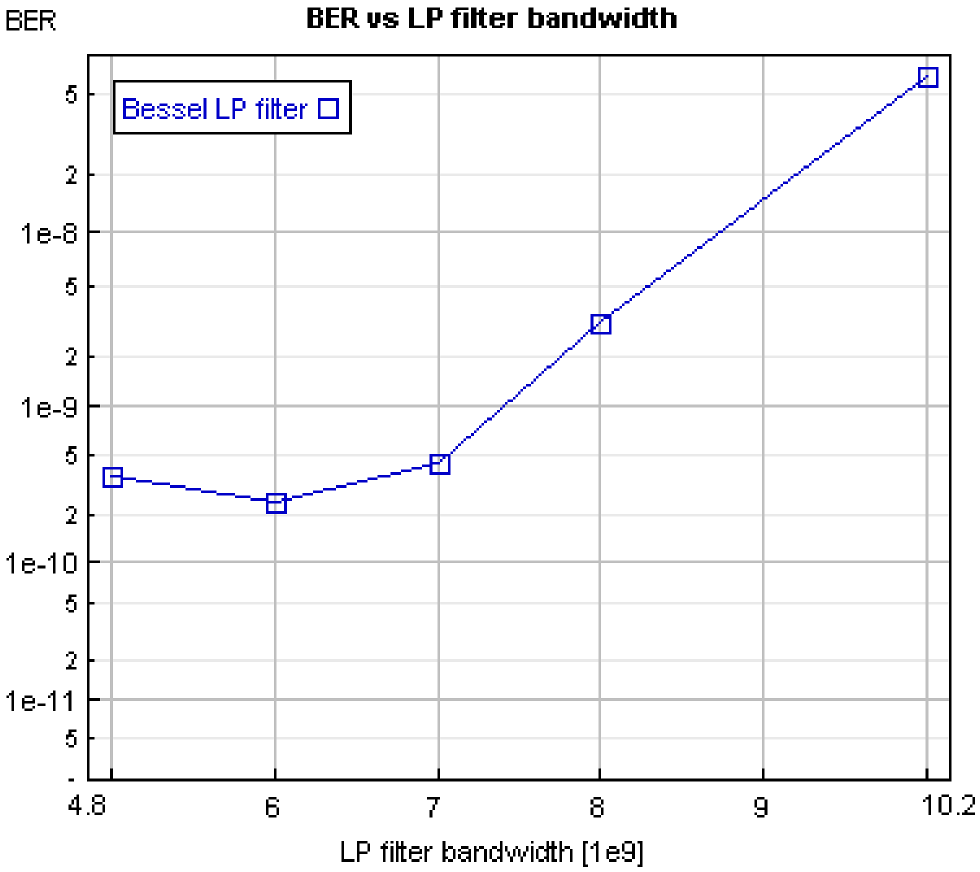


Figure: BER variation with bandwidth of a LP (4th order Bessel) filter for 10 Gb/s receiver

3.2 Clock Recovery

- ❑ At receiver clock extracted from received signal
  - By determining bit transitions
  - Clock period may be same to bit interval but out of phase
  - Clock periods may also vary
  - Causing timing jitter
    - Jitter suppression essential part of clock recovery circuit

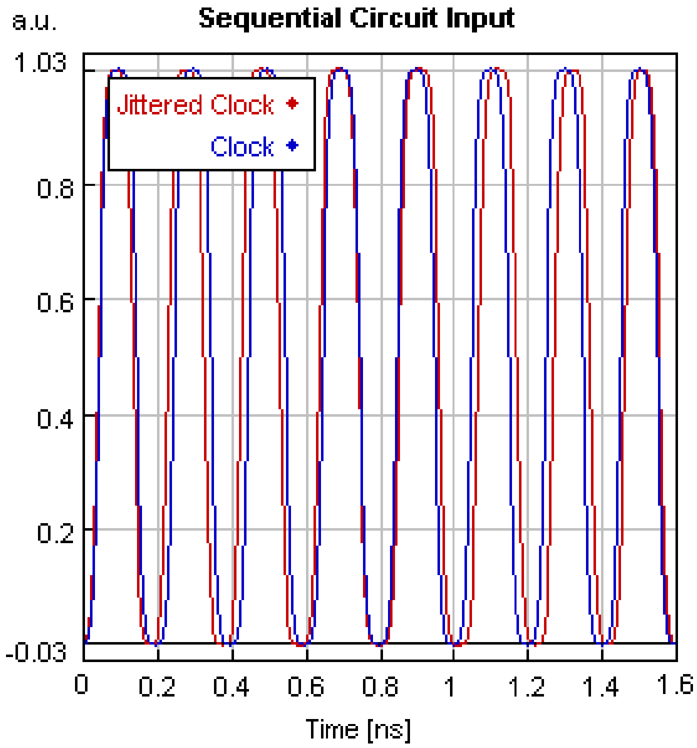
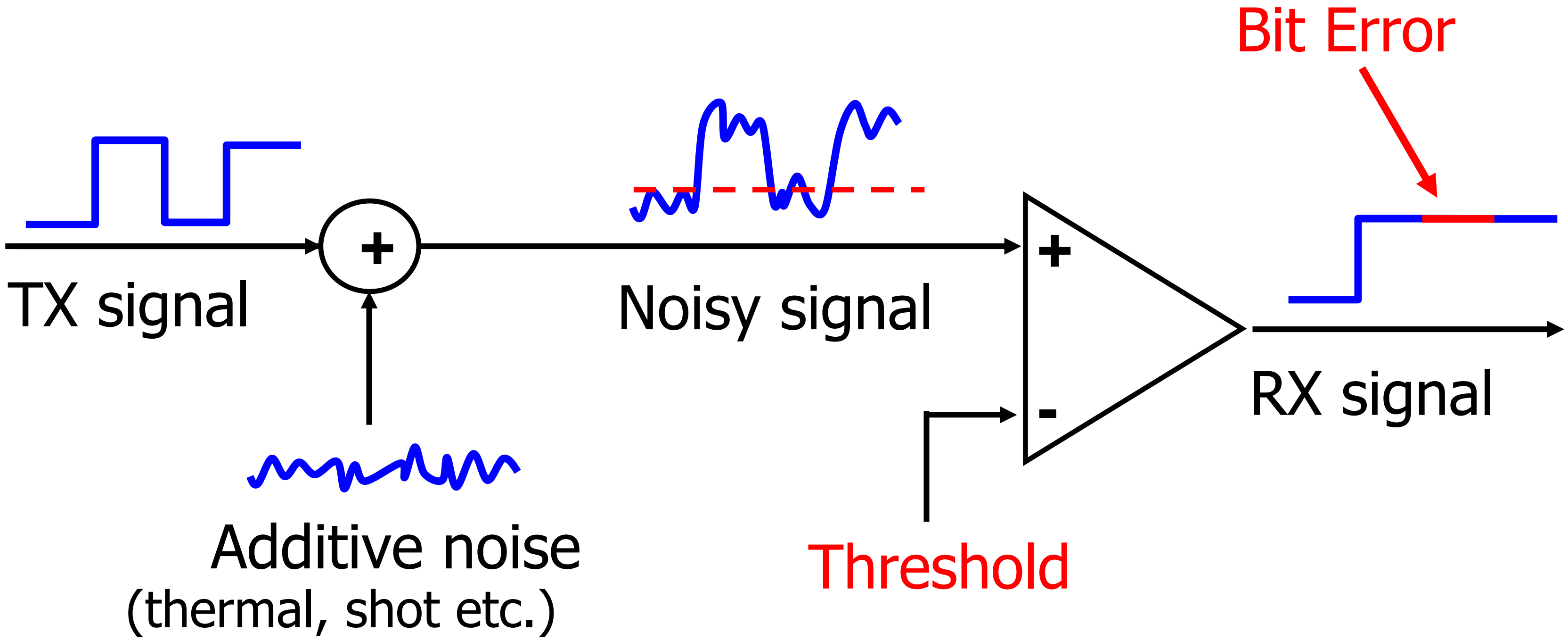


Figure: Timing jitter in a 10 Gb/s link.

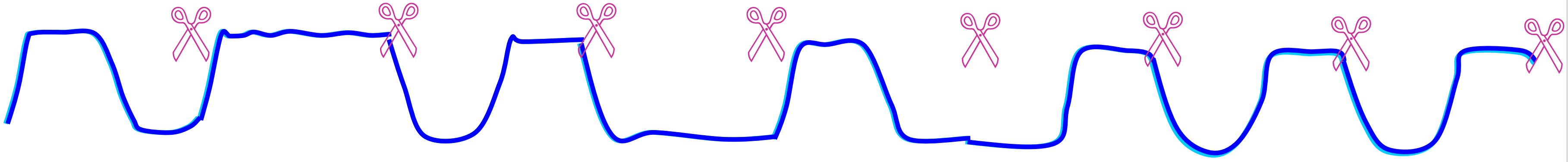
4. Link Performance Measures

- Errors will occur with incorrect decisions made in a receiver due to the presence of noise on the digital signal

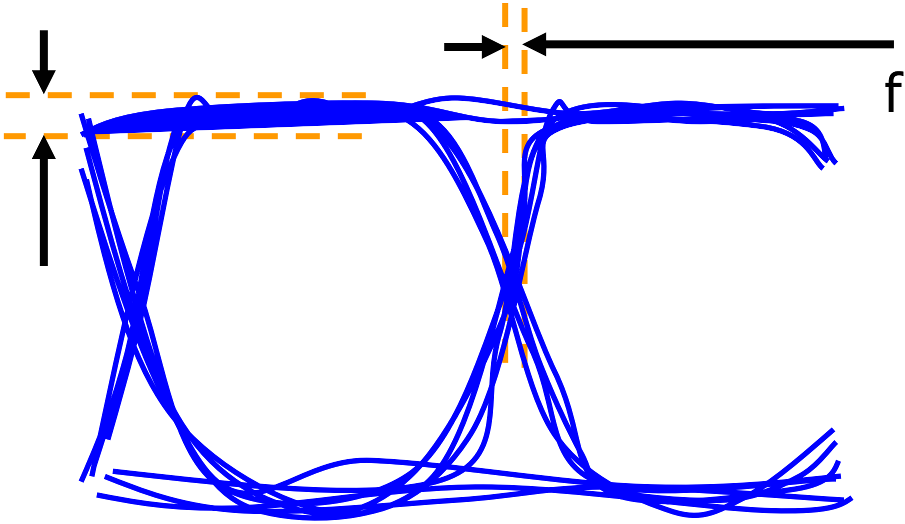


4.1 Eye Diagrams

- Eye diagrams used to determine the “goodness” of received signal ⇒ resembles human eye



Detected bit stream waveform



Intensity fluctuation

Timing fluctuation

Bits overlaid to form eye diagram

4.1 Eye Diagrams

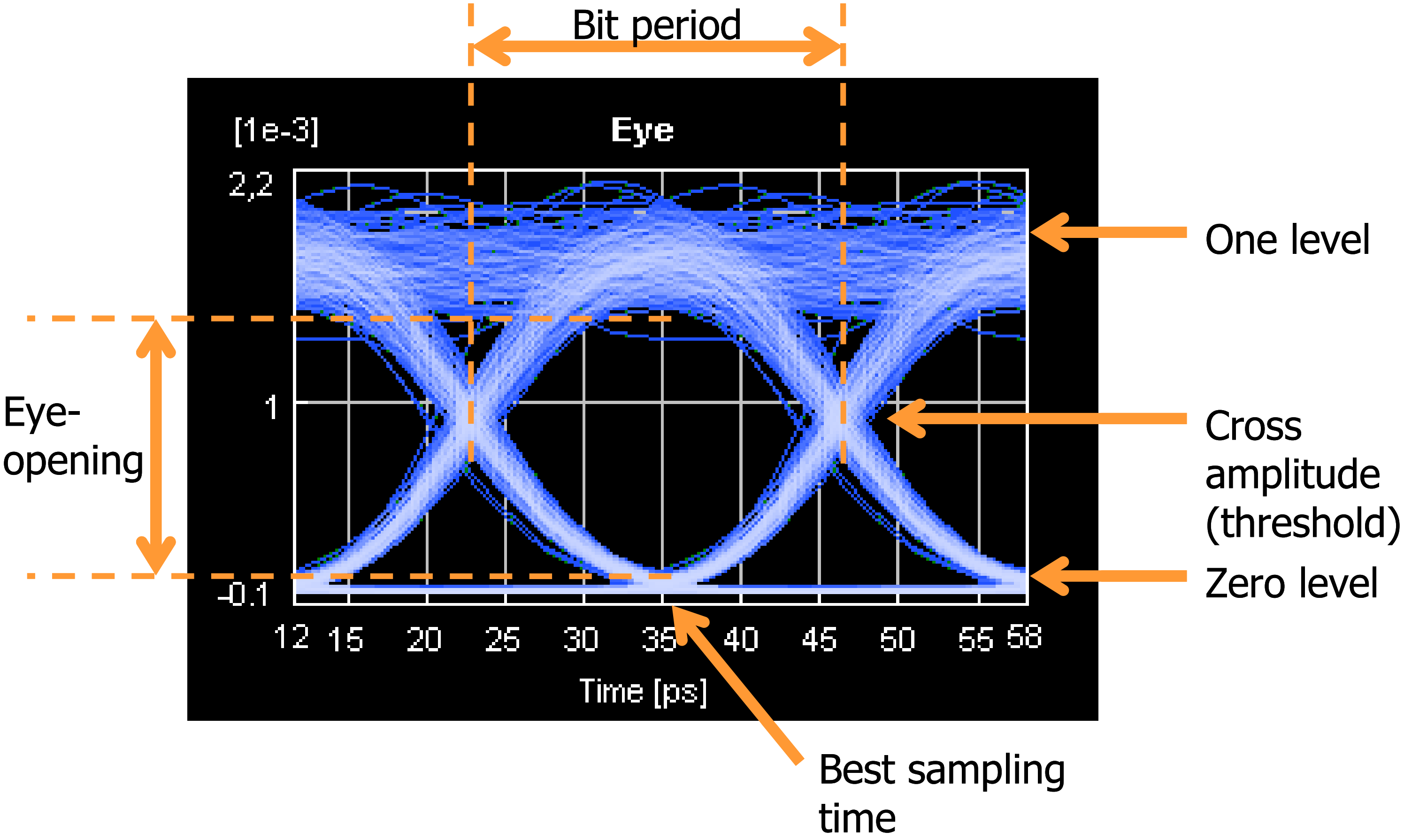


Figure: Fundamental eye (43 Gbit/s OOK-NRZ) parameters.

4.1 Eye Diagrams

- Eye opening penalty (EOP)

$$EOP = -10\log\left(\frac{EO_{\text{Test}}}{EO_{\text{Ref}}}\right)\text{dB}$$

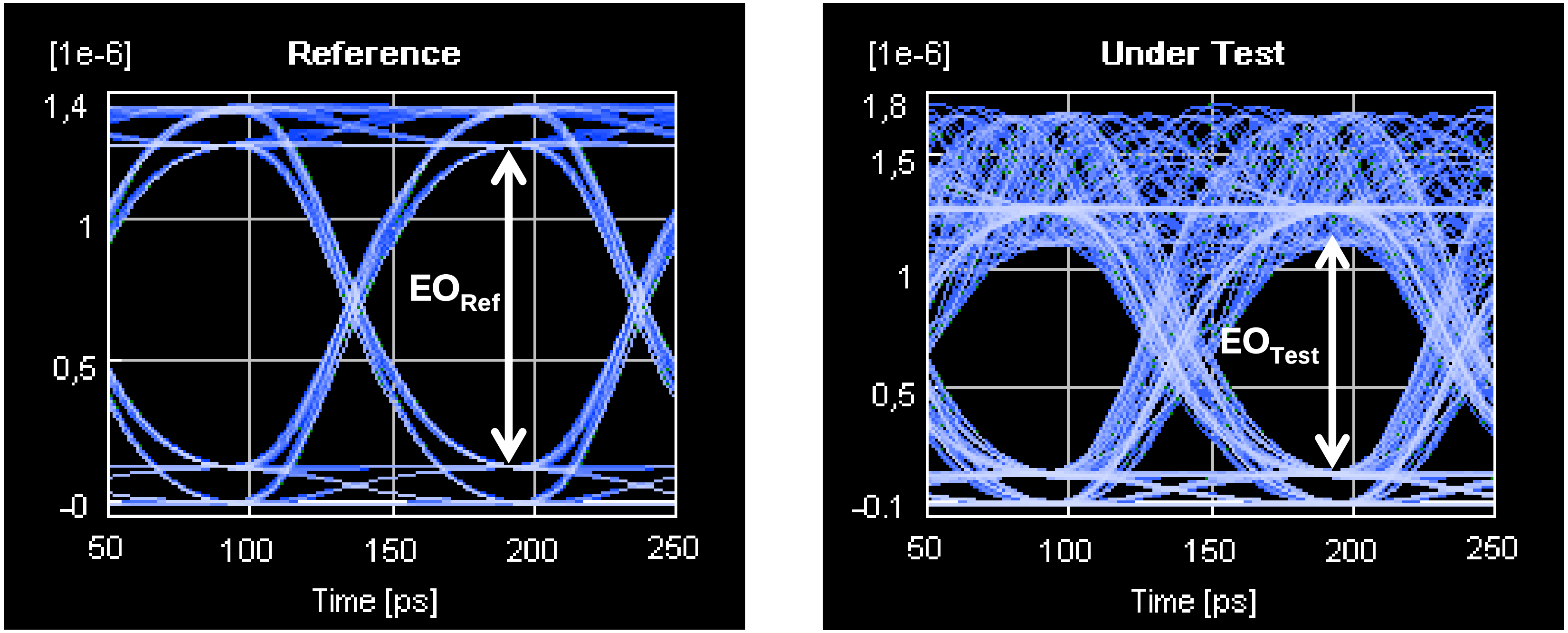
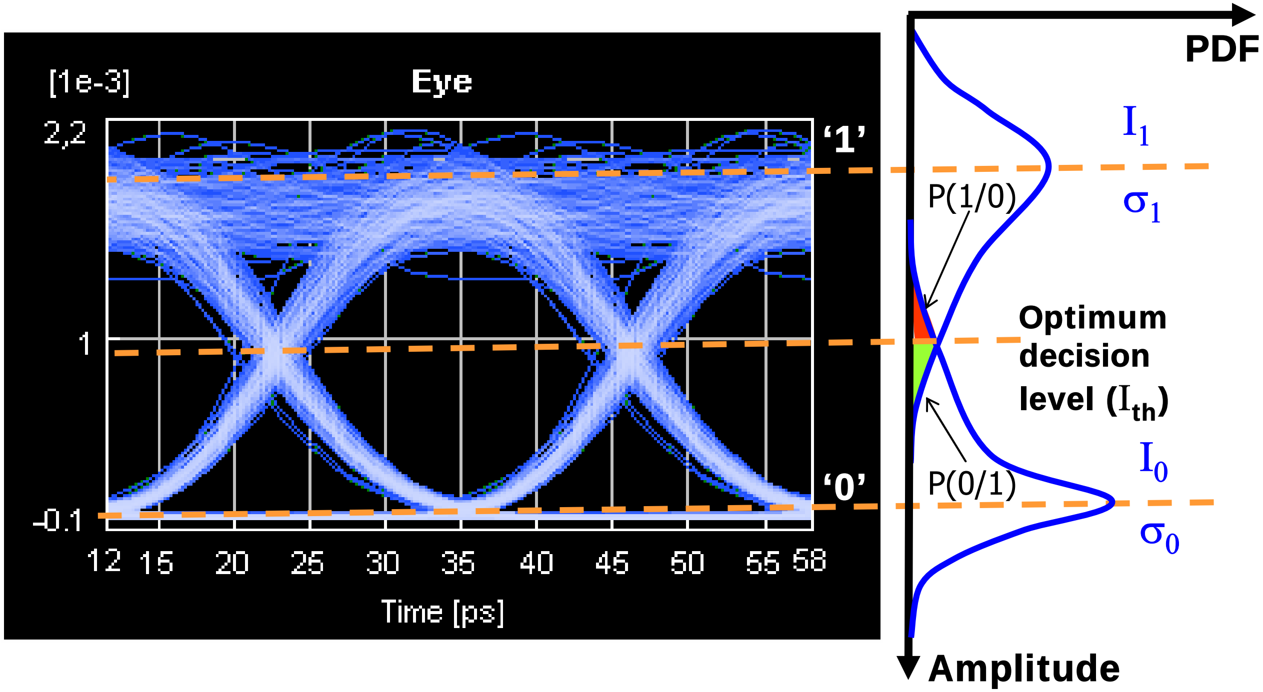


Figure : Eye diagrams from reference and test system setups with EOP = 0.68 dB

4.2 Bit Error Rate

- At receiver decision made on whether "0" or "1" was sent



$$I_{th} \approx \frac{\sigma_1 I_0 + \sigma_0 I_1}{\sigma_0 + \sigma_1}$$

$$\text{bit} = \begin{cases} 1 & \text{if } I \geq I_{th} \\ 0 & \text{otherwise} \end{cases}$$

Figure: Eye diagram (43 Gbit/s OOK-NRZ) and probability density functions (PDF) related to 1 and 0 levels. Mean I_z and variance σ_z^2 are photocurrent mean and noise variance respectively for a received "z" bit.

4.2 Bit Error Rate

❑ Gaussian assumption for noise distribution

- $Q(x)$ ⇨ Probability that a zero mean, unit variance Gaussian random variable exceeds value x

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_{x}^{\infty} e^{-y^2/2} dy$$

$$P[0\,|\,1] = Q\left(\frac{I_1 - I_{th}}{\sigma_1}\right) \qquad P[1\,|\,0] = Q\left(\frac{I_{th} - I_0}{\sigma_0}\right)$$

- If P[z] is probability of sending “z” bit, then bit error rate (BER) given by

$$\boxed{BER = P[0] \cdot P[1|0] + P[1] \cdot P[0|1]}$$

4.2 Bit Error Rate

- Assume P[0]=P[1]=½, it can be shown that:
  - If threshold I_{th} is optimum, BER is minimized

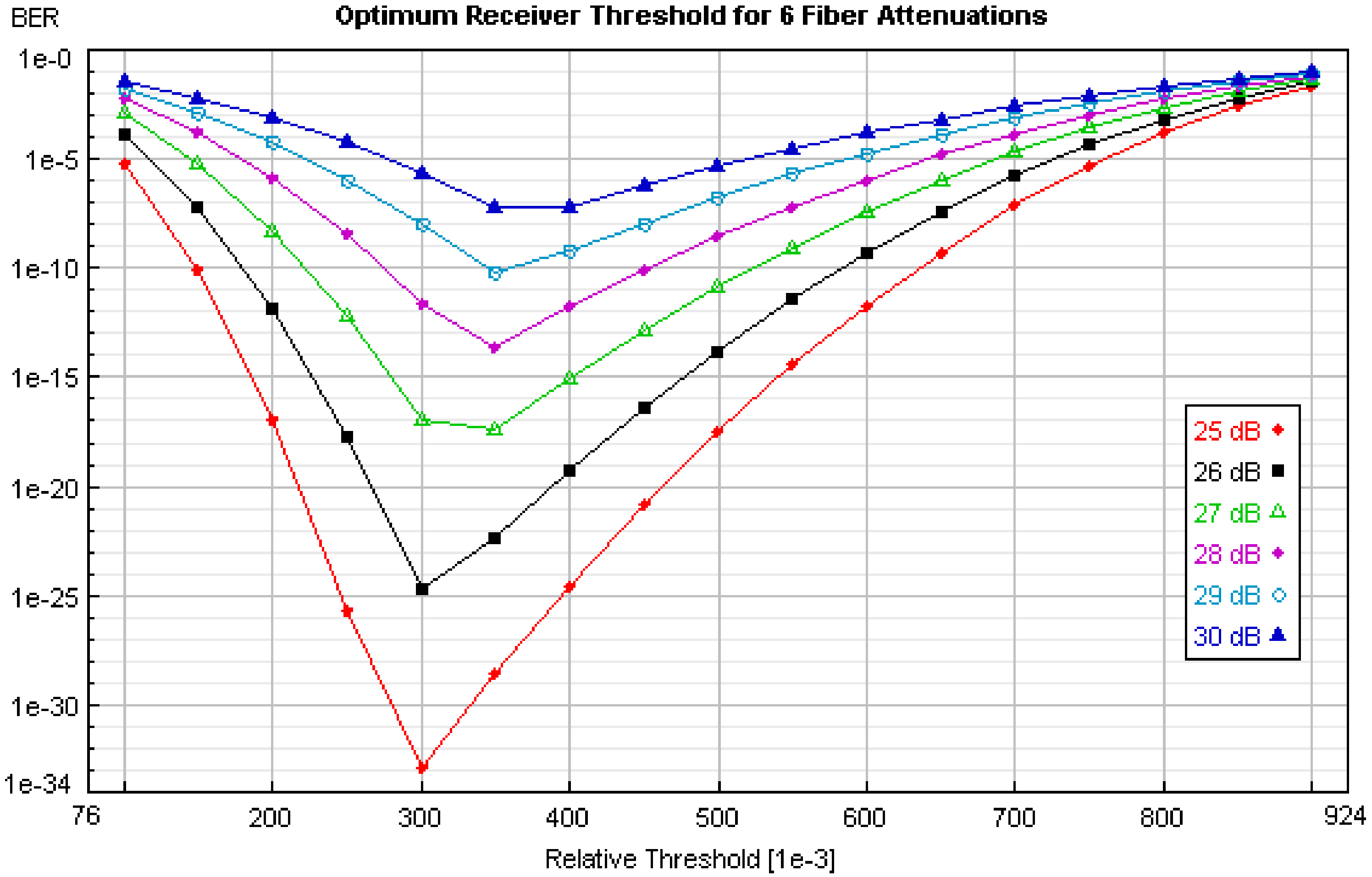
$$\boxed{BER = Q\left(\frac{I_1 - I_0}{\sigma_0 + \sigma_1}\right)}$$

  - Otherwise if threshold is just mean of I_1 and I_0 (relatively worse BER)

$$\boxed{BER = \frac{1}{2}\left[Q\left(\frac{I_1 - I_0}{2\sigma_1}\right) + Q\left(\frac{I_1 - I_0}{2\sigma_0}\right)\right]}$$

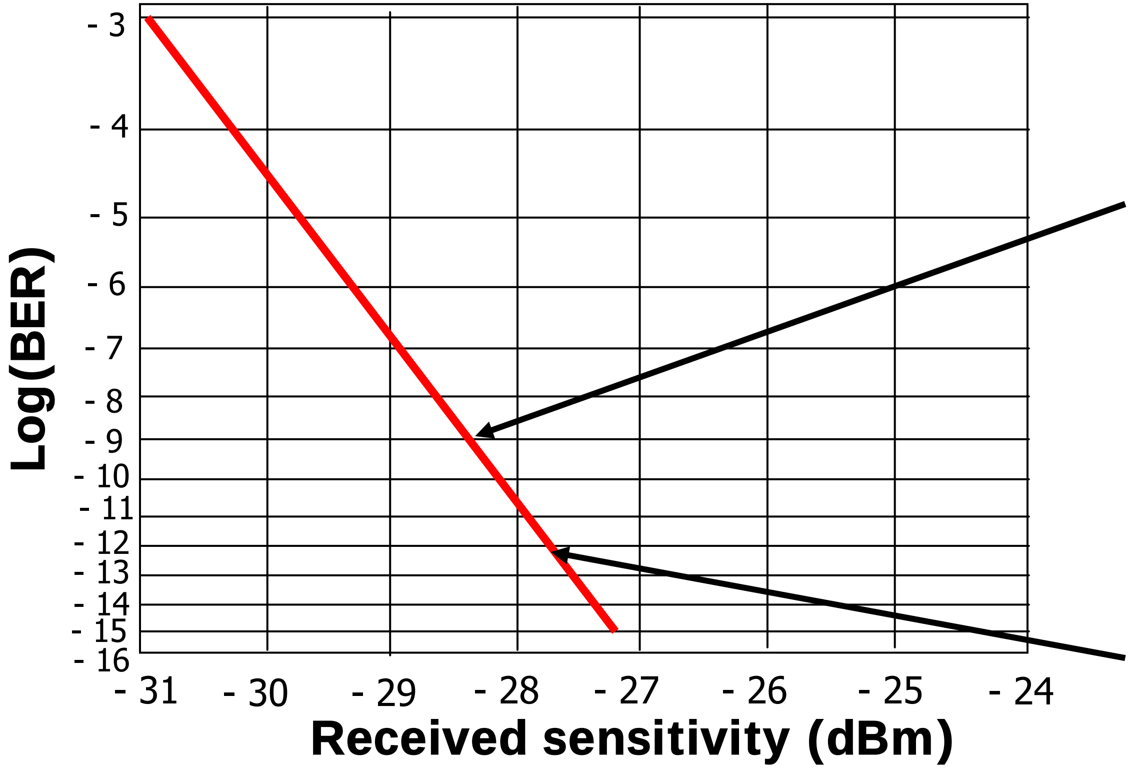
4.2 Bit Error Rates

- Example BER vs thresh. variations at different power levels



4.2 Bit Error Rate

- ❑ BER plotted vs mean received optical power or receiver sensitivity
  - Unlike most systems where BER is plotted vs SNR
  - Interest usually to determine receiver sensitivity required to achieve certain BER



Receiver sensitivity is -28.4 dBm for BER = 10^{-9}

Receiver sensitivity is -27.7 dBm for BER = 10^{-12}

4.3 Q-factor

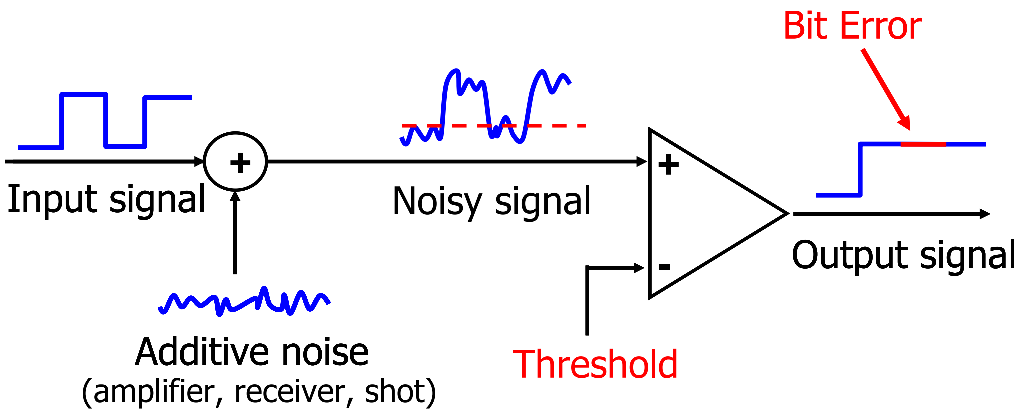
- ☐ Q-factor or simply Q
  - Measure of ”quality” of a signal
  - In some cases used as starting point to evaluate BER
    - Q = 7 or 16.90 dB ⇒ BER = 10^{-12}
  - Electrical SNR [$\mathrm{SNR}_{\mathrm{dB}}=20\cdot\log(Q)$]

$$\boxed{\text{Q-factor} = Q^{-1}\left(BER\right) = \frac{\left|I_1 - I_0\right|}{\sigma_0 + \sigma_1}}$$

$$\boxed{BER \cong \frac{\exp\left(-Q^2/2\right)}{Q\sqrt{2\pi}}}$$

5. Performance Analysis

- ☐ Optical link performance dependant on receiver type
  - Certain noise components will dominate over others for different receiver types ⇒ determines the noise level (σ_0^2 and σ_1^2)
  - Generated photocurrents I_1 and I_0 includes the signal plus error inducing photocurrents due to added noise



$$BER = \frac{1}{2}\left[Q\left(\frac{I_1 - I_0}{2\sigma_1}\right) + Q\left(\frac{I_1 - I_0}{2\sigma_0}\right)\right]$$

$$BER = Q\left(\frac{I_1 - I_0}{\sigma_0 + \sigma_1}\right)$$

5. Performance Analysis

❑ Analysis for the following will be illustrated

- Link with ideal receiver
- Link with *pin* photodetector receiver
- Link with avalanche photodetector (APD) receiver
- Link with optical preamplified receiver

5.1 Link With an Ideal Receiver

- Visualizing received optical signal as stream of photons arriving at receiver
  - Optical data bits arrive at receiver at a rate *B* bits/s
    - Let *P* be power of optical signal incident on receiver in a bit interval when a ”1” bit is transmitted
    - Assume 0 power (no light) when ”0” bit is transmitted
  - Recall hf_c is the energy of a single photon
    - where h=6.63×10-34 J/Hz is Planck’s constant and f_c is the signal frequency
  - The average number of photons received during 1 bit is then:

$$M = \frac{P}{hf_c \cdot B}$$

5.1 Link With an Ideal Receiver

- If all noise sources in amplifiers and receivers were switched off
  - Noise still present due to random nature of arrival of photons
  - Photon arrivals at receivers modeled as a Poisson random process

Prob[n photons received in $T=1/B$] = $\exp(-M)\cdot M^{n}/n!$

Prob[no photons ($n=0$) received in $T=1/B$] = $\exp(-M)$

5.1 Link With an Ideal Receiver

- If Prob[receiving a “1”] = Prob[receiving a “0”] = ½ then

BER = Prob[receiving a 1]×Prob[no photons received in T=1/B]

$$= \frac{\exp(-M)}{2}$$

- This expression represents the BER of an ideal receiver ⇨ quantum limit
  - Example: M = 27 photons/bit needed to guarantee BER = 10^{-12}

❑ However in practice receivers do have other noise sources

5.2 Link With *pin* Photodetector Receiver

- ❑ Total photocurrent *I* produced by *pin* receiver

$$\boxed{I = i_{\text{signal}} + i_{\text{shot}} + i_{\text{thermal}}}$$

  - Shot and thermal noise assumed to be independant
  - Photocurrent *I* can be modeled as Gaussian random process with a mean $<I> = i_{signal} = R \cdot P$ and variance

$$\boxed{\sigma^2 = \sigma_{\text{shot}}^2 + \sigma_{\text{thermal}}^2}$$

- ❑ Thermal noise dominates $\Rightarrow$ *pin* receivers are thermal noise limited

5.2 Link With *pin* Photodetector Receiver

- Now obtaining BER for pin receiver
  - Let P_1 be received signal optical power when ”1” bit was transmitted
  - Produced photocurrent mean and variance are

$$\boxed{I_1 = RP_1 \qquad \sigma_1^2 = 2eI_1B_e + \frac{4k_BTB_e}{R_L}}$$

and P_0 when ”0” bit was transmitted

$$\boxed{I_0 = RP_0 \qquad \sigma_0^2 = 2eI_0B_e + \frac{4k_BTB_e}{R_L}}$$

  - I_0=0 assumption used in most analysis

5.3 Link With APD Receiver

- ☐ APD have gain that enables larger photocurrents than *pin* photodetectors
- ☐ Random nature of avalanche multiplication gain of APDs increases shot noise current in APD receiver
  - Shot noise increased by a noise multiplication factor

$$\boxed{G_m^{2+x} \qquad 0 < x < 1}$$

where G_m is the average avalanche multiplication gain

  - A *pin* receiver is like an APD receiver with $G_m = 1$

5.3 Link With APD Receiver

- Therefore to evaluate BER for APD receivers:

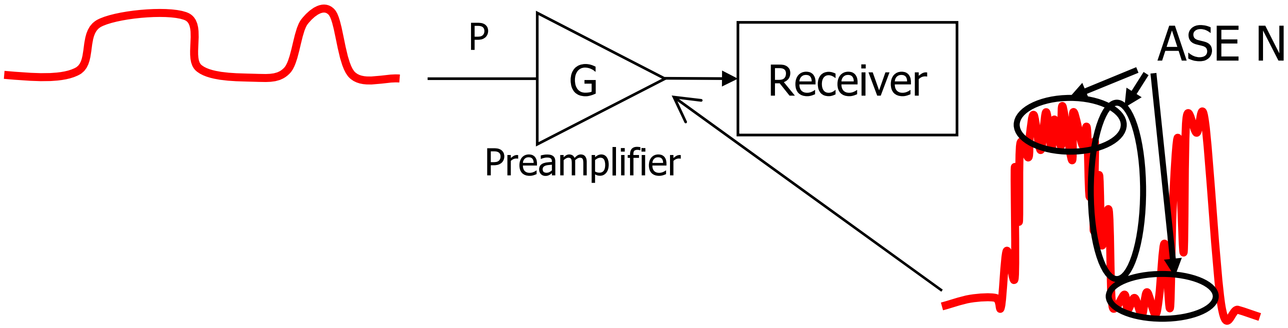
$$\boxed{I_1 = RP_1G_m \qquad \sigma_1^2 = 2eI_1B_e \cdot G_m^{2+x} + \sigma_{\text{thermal}}^2}$$

$$\boxed{I_0 = RP_0G_m \qquad \sigma_0^2 = 2eI_0B_e \cdot G_m^{2+x} + \sigma_{\text{thermal}}^2}$$

where $0 < x < 1$

5.4 Receiver with Optical Preamplifier

❑ Performance of thermal noise limited receivers can be boosted by deploying an optical preamplifier



- Desired signal photocurrent becomes $i_{signal} = RPG$
- Unfortunately optical amplifier also adds ASE noise
- Preamplified receivers are ASE noise limited when G > 10dB

5.4 Receiver with Optical Preamplifier

- Total ASE noise power given by

$$\boxed{P_{ASE} = 2n_{sp}hf_c\left(G-1\right)B_o}$$

where n_{sp} is the spontaneous emission factor, G is the amplifier gain and B_o bandwidth of optical filter at receiver

- Dependent on ASE noise filtering before receiver
  - Typically $B_o \geq 2B_e$
- Noise photocurrent i_{ASE} generated from ASE noise

$$\boxed{i_{ASE} = RP_{ASE}}$$

5.4 Receiver with Optical Preamplifier

- ❑ Amplifier noise usually expressed as noise figure F_N

$$\boxed{F_N = \frac{SNR_{in}}{SNR_{out}}}$$

- ❑ For preamplified receivers:

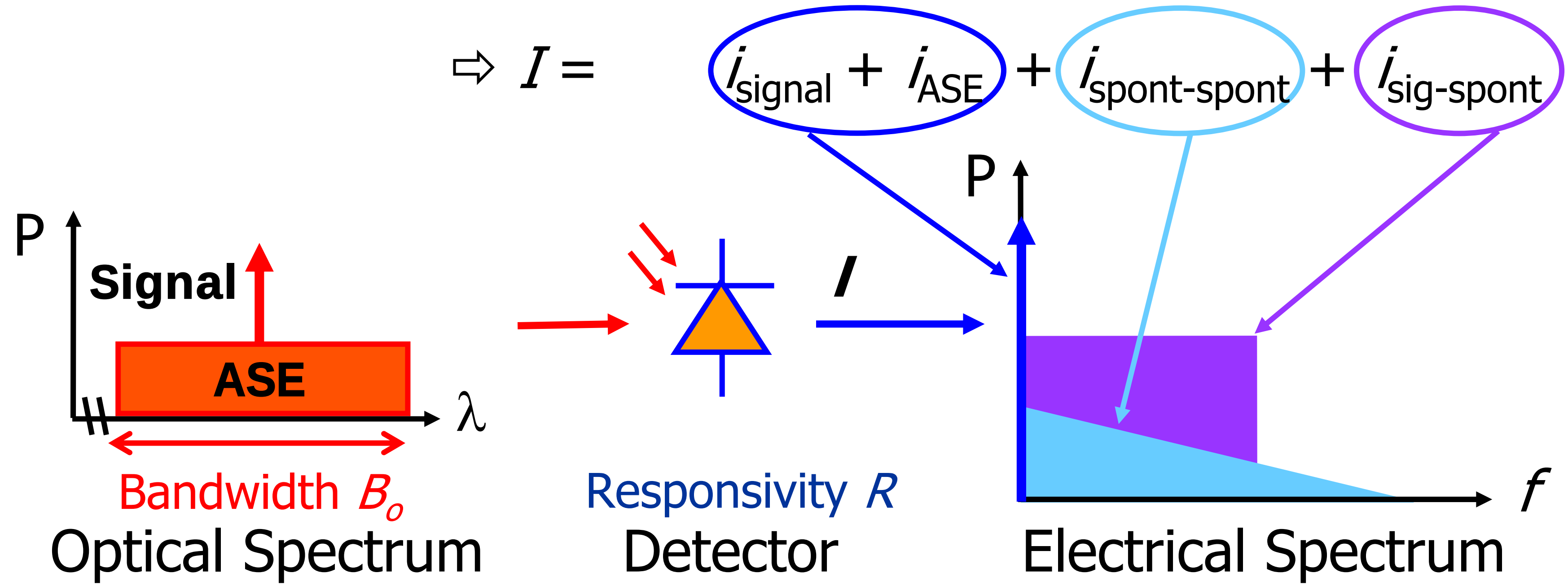
$$F_N = 2n_{sp}(G-1)/G \cong 2n_{sp}$$

  - Ideally, best-case noise figure F_N =3dB (where n_{sp} =1)
  - In practice, F_N is in the range of 4 dB to 7 dB (n_{sp} typically in range [2,5])

5.4 Receiver with Optical Preamplifier

- ☐ Further noise components produced by fields of signals mixing or beating with each other
  - ASE noise beats with desired signal to produce signal-spontaneous beat noise $i_{\text{sig-spont}}$
  - ASE noise beats with itself to produce spontaneous-spontaneous beat noise $i_{\text{spont-spont}}$

$$\Rightarrow I = i_{\text{signal}} + i_{\text{ASE}} + i_{\text{spont-spont}} + i_{\text{sig-spont}}$$



5.4 Receiver with Optical Preamplifier

- Beat noise variances are:

$$\sigma^2_{\text{sig-spont}} = 2\cdot RPG\cdot\frac{RP_{ASE}}{B_o}\cdot B_e = 2\cdot i_{\text{signal}}\cdot\frac{i_{ASE}}{B_o}\cdot B_e$$

$$\sigma^2_{\text{spont-spont}} = \frac{1}{2}\cdot\left(RP_{ASE}\right)^2\cdot\left(\frac{2B_e}{B_o}-\left[\frac{B_e}{B_o}\right]^2\right) = \frac{1}{2}\cdot i^2_{ASE}\cdot\left(\frac{2B_e}{B_o}-\left[\frac{B_e}{B_o}\right]^2\right)$$

5.4 Receiver with Optical Preamplifier

- ☐ Therefore to evaluate BER for preamplified receivers:

$$I_1 = RP_1G \qquad \sigma_1^2 = 2e\left(I_1 + i_{ASE}\right)B_e + 2 \cdot I_1 \cdot \frac{i_{ASE}}{B_o} \cdot B_e + \sigma_{spont-spont}^2 + \sigma_{thermal}^2$$

$$I_0 = RP_0G \qquad \sigma_0^2 = 2e\left(I_0 + i_{ASE}\right)B_e + 2 \cdot I_0 \cdot \frac{i_{ASE}}{B_o} \cdot B_e + \sigma_{spont-spont}^2 + \sigma_{thermal}^2$$

5.5 Receiver Performance Comparison

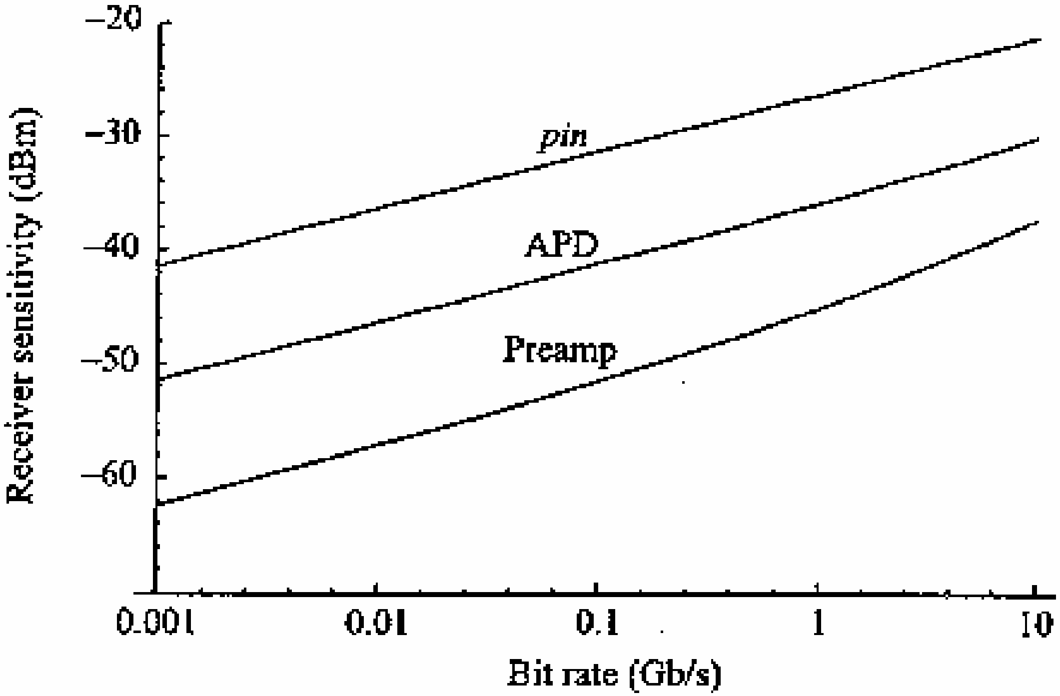


Figure 4.4 Sensitivity plotted as a function of bit rate for typical *pin*, APD, and optically preamplified receivers. The parameters used for the receivers are described in the text.

- For optically preamplified receiver, a noise figure of 6dB assumed
- Optical bandwidth B_o =50 GHz

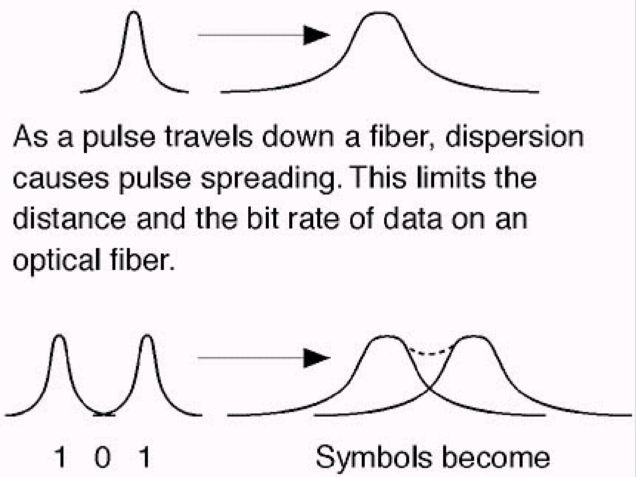
6. Performance Improvement Methods

- ❑ Major strides in electrical digital signal processing (DSP)
  - ▪ Pressure to squeeze out ever better performance from very bandwidth limited channels
    - Wireless channels
    - Copper twisted pair cables
- ❑ Same technologies now important for improving performance of optical communication systems
- ❑ Two examples presented here
  - ▪ Equalization
  - ▪ Error correction and detection

6.1 Equalization

❑ System performance affected by ISI due to fiber dispersion
  - Dispersion is linear effect ⇨ can be modeled by filter with transfer function $H_D(f)$
  - Equalization or transversal filter with $H_D^{-1}(f)$ response can cancel dispersion before decision circuit

Dispersion



As a pulse travels down a fiber, dispersion causes pulse spreading. This limits the distance and the bit rate of data on an optical fiber.

6.1 Equalization

- Tap weights and delays determine transfer function
  - Adjusted using adaptation algorithms (e.g. LMS) to cancel out dispersion-induced spreading

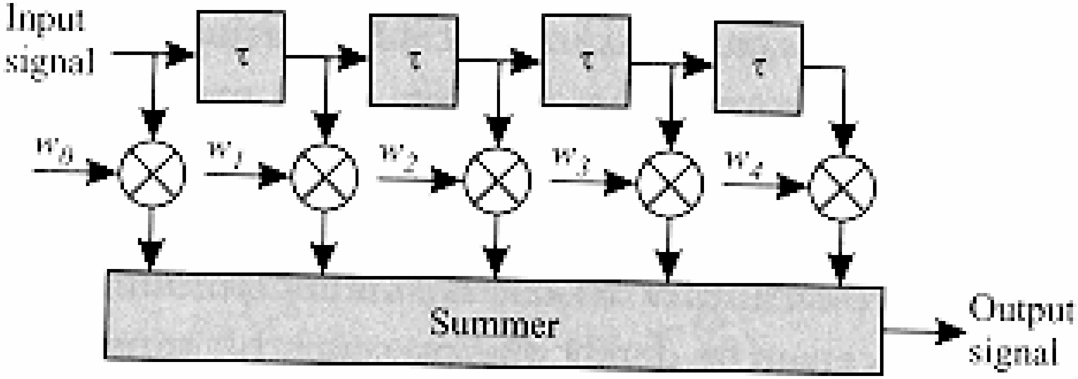
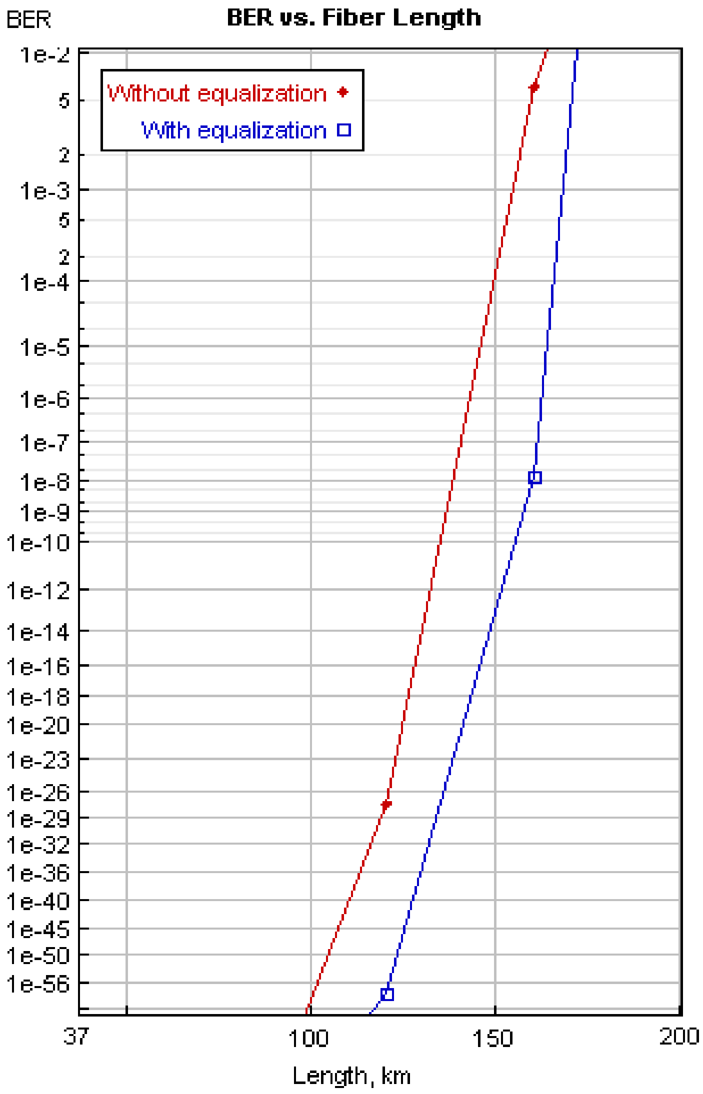


Figure 4.12 A transversal filter, a commonly used structure for equalization. The output (equalized) signal is obtained by adding together suitably delayed versions of the input signal, with appropriate weights.

6.1 Equalization



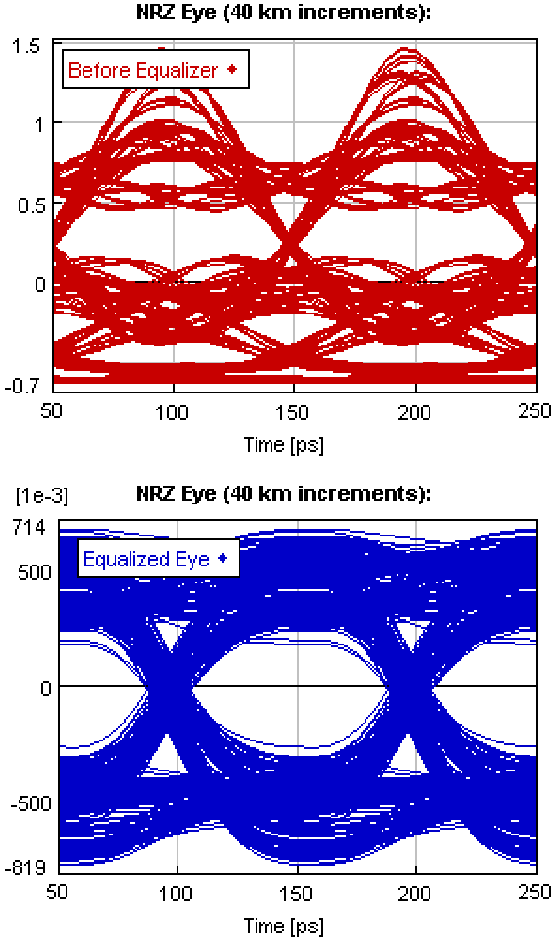


Figure: Example link performance without and with equalizers

6.1 Equalization

❑ Disadvantages

- Complex analog, digital or mixed-signal integrated circuits at higher rates (≥ 10 Gb/s)
- Usually locked to a particular bit rate and transmission format
- One needed per WDM channel

6.2 Error Detection and Correction

- Redundancy techniques for reducing BER on a communication channel
    - Transmitting additional overhead bits carrying information used by receiver to correct errors in data bits
    - Also known as forward error correction (FEC)
    - Smaller amount of redundancy could be used to just detect errors
        - For BER monitoring
        - Implementation of automatic repeat request (ARQ) schemes

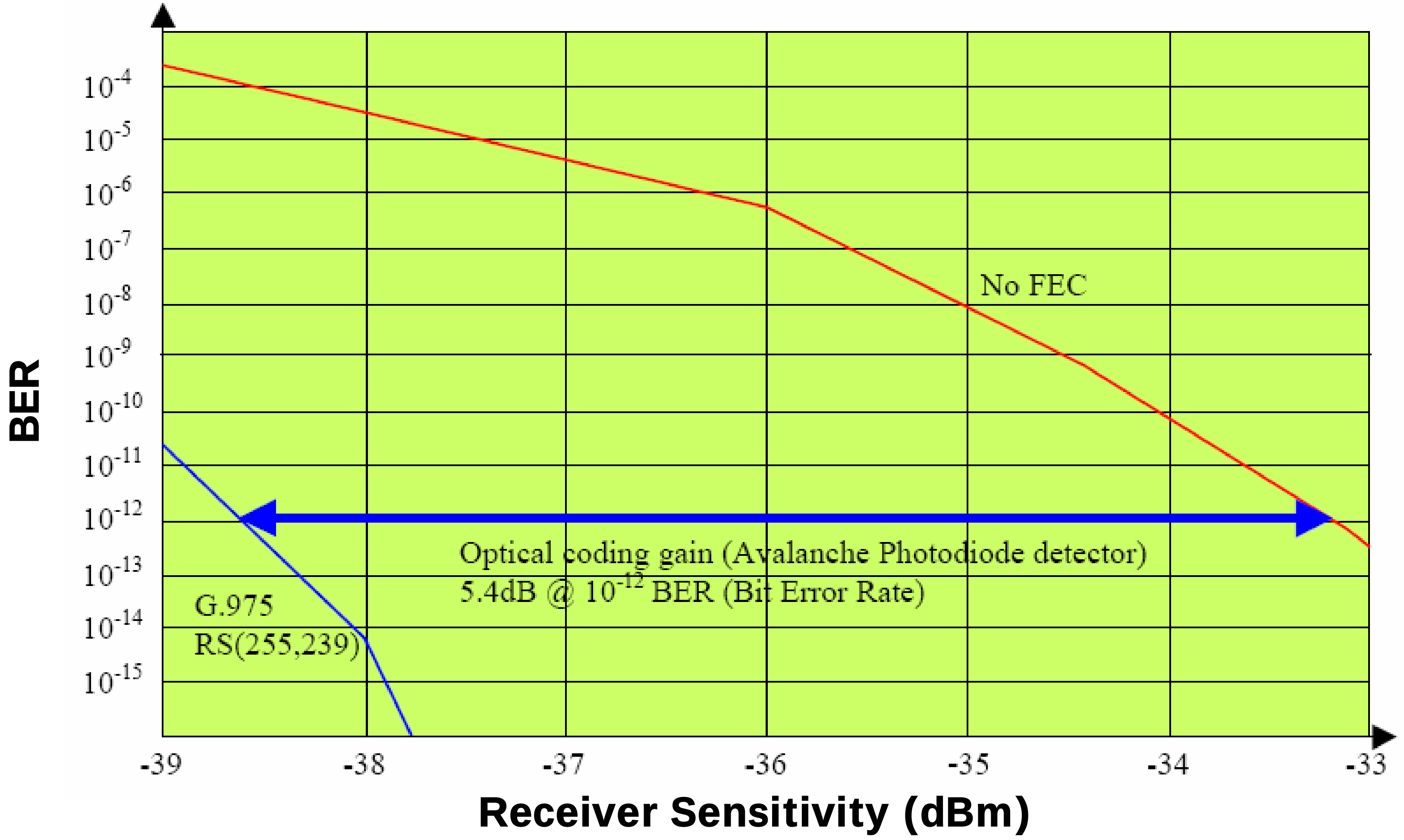
6.2 Error Detection and Correction

- FEC offers coding gain
    - Example: a 6 dB coding gain achieves the same effect as transmitting four times the optical power or using a receiver that is four times as sensitive
  - Enables longer links before regeneration is necessary
  - Less sensitive receiver may be used
  - Need for optical preamplification reduced
  - Eliminates BER floors due crosstalk from adjacent WDM channels
- Development of FEC for optical communication systems can be classified in three generations

6.2 Error Detection and Correction

- 1st generation ⇒ Reed–Solomon coding using RS(255, 239) code
  - Corrects up to 8 errored data symbols in a block of 239 data symbols (8 bits per symbol)
  - Adopted in the early 1990s in submarine transmission systems
  - Standardized (ITU-T G.975, G.709) and now widely used in DWDM networks

6.2 Error Detection and Correction



Optical coding gain (Avalanche Photodiode detector)
5.4dB @ 10^{-12} BER (Bit Error Rate)

Source: G. Barlow, "A G.709 Optical Transport Network Tutorial," Innocor white paper.

6.2 Error Detection and Correction

- 2nd generation of enhanced FECs
  - ITU-T G.975 amended to include several enhanced FECs
  - Provide coding gain of > 8 dB for 10 Gbit/s line rates
  - Example: concatenated coding of RS (239,223) + RS (255,239)
- 3rd generation powerful FECs
  - Current intensive research
  - Even stronger codes e.g. turbo codes or low-density parity check (LDPC) codes
  - Coding gain > 10 dB
  - Useful for ≥ 40 Gbit/s line rates

7. Conclusions

- ❑ Modulation procedures for optical communications systems were discussed in some detail
  - Modulation formats
  - Demodulation and noise sources
  - Performance metrics
  - Link performance analysis
  - Performance improvement methods

- ❑ Next lecture will focus on the engineering of whole optical communications systems

Thank You!