Fiber Optic Link Design

Basic Design - Governing Relationship

\[ P_T = P_R + C_L + M + \text{dispersion penalty (dB)} \]

*Transmit Laser Power* → *Receiver Sensitivity* → *System Margin*

*Total fiber, splices & connector losses*

Notes on each:

- \( P_T \) - depends on optical source type (LED or laser diode), drive levels, fiber type & coupling arrangements
  - typical values from say -16 dBm to +2 dBm

- \( P_R \) - a specification of the optical receivers measured or guaranteed performance at a required maximum BER, eg) "BER not worse than 10^-12 at -38 dBm"
  - is a \( P_R \) specification

- depends on: binary data rate, receiver noise
  - line coding used
  - Equivalent BW
  - Optical detector type: PIN, APD
  - Receiver shot noise, thermal noise, dark current noise
  - Extinction ratio from \( T_x \)
\[ C_L = \alpha_L \cdot L + \alpha_n + \alpha_s \text{ splices (dB)} \]

\[ \alpha_L = \text{base/\text{km of fiber used}} \]

\[ L = \text{length} \]

\[ M = \text{system design margin (dB)} \]

- Typical. This may be as much as 10-11 dB of "reserved" power margin to counteract or allow for:
  - Effects in clock recovery/timing performance
  - Unexpected extra splice or connector losses
  - Optical source degradation near end of life
  - Allowance for future insertion of optical mux/demux devices.
  - Etc.

**Additional Considerations in Modern Link Design**

- **Transmitter-Receiver may employ Forward Error Correction (FEC) Coding**
  - This is characterized by its "Coding Gain" as if it was an equivalent amount of added Tx power.
  - Typical values: 3 dB to 8 dB

- **Optical Amplifiers (OA)**
  - May be inserted at regular distances to offset accumulating fiber loss
However, optical amplifiers both boost signal and add noise. Overall effect is to (apparently) reduce the receiver sensitivity, but also affect oo.

Notes: "OIs" are different, importantly, from Regenerators—Regen's effect is clock timing recovery from the signal and noise. I/O decisions about each line transmission symbol and then regenerate a new optical signal.

- Regen go from optical-electrical-optical

Regen:

Optical Amplifier: (typical)

Rolled up "Erbium-doped fiber"

Pump laser

~ 980 nm

(high power)

Gain monitor & feedback
Optical Amplifiers:

- The "pump" laser creates a large population inversion in the ED fiber.
- The main signal (much weaker) causes stimulated emission from the inversion population, at its wavelength.
- Chirped optical signal bandwidth came out with
  20-40 dB gain
- Pump wavelength excess power is lost or filtered out.

- An OA amplifies an entire Waveband, not just a Single optical carrier frequency
  (See Density Figure 10.2)  \[ \Rightarrow \text{key inversion enabling "DWDM" (dense-wavelength division multiplexing)} \]

- A regen can only operate on or process one modulated carrier signal.

- OA is also "format agnostic": It is a linear analog amplifier - doesn't care about data rate & formats of signals

- A regen is always specific to a given data rate, like coding format, etc.
Dispersion Penalty to the link design:

If the link design becomes "dispersion-limited," then this is treated as an equivalent "penalty" on the receiver $\text{PR}$ sensitivity. (Pulses smearing together due to chromatic dispersion, causes "eye closure" at the decision element in the regenerator.)

**Example:**

- Transmitted data sequence (NRZ case)

- Open eye diagram at decision element after optimal receiver filtering. System may be noise-limited, but is not suffering from dispersion-induced "inter-symbol interference".

- Reduced "eye opening" at decision element due to smearing together of pulses in a sequence-dependent way when a significant dispersion penalty is present. Equivalent to so many "dB of eye closure."

**dd** = decision distance (volts)
When loss or power limited:

\[
L_{\text{loss}} = 10 \log \left( \frac{P_t}{P_0} \right) \text{mW/km}
\]

When dispersion limited, things get worse, faster:

\[
L_{\text{disp}} \approx \frac{k}{B/D_a}
\]

where

- \( k = \) fraction of the bit time where the receiver starts to have eye closure
- \( B = \frac{1}{f_s} = \) the bit or symbol time
- \( D = \) magnitude of the chromatic dispersion in the fiber used (ps/nm-km)
- \( \Delta \lambda = \) full width half maximum (FWHM) laser spectral width (nm)

\[ L [\text{km}] \]

for

BER < 10^{-12} (for example)

\[ \text{Bit rate} \left( f_s = \frac{1}{B} \right) \]

Range of feasible system designs

\( \approx \) dispersion limited performance (slope is ever increasing)

\( \approx \) loss limited performance (10 dB/decade)
Calculating Optical Receiver Sensitivity

The analysis framework is to consider the voltage signal plus noise as it appears at the sample timing at the decision element:

\[ P_{\text{error}} = \frac{1}{2} \left[ p(0|1) + p(1|0) \right] \]

Assuming the decision threshold is optimally placed:

\[ P_{\text{error}} = \text{BER} \approx \frac{1}{2} \text{erfc} \left( \frac{Q}{\sqrt{2}} \right) \]

Where \( Q \) is the "digital signal to noise ratio"

\[ Q = \left( \frac{V_1 - V_0}{\sigma_1 + \sigma_0} \right) \]

Typical values: \( Q = 7 \rightarrow \text{BER} \approx 10^{-12} \)

\[ 20 \log(7) = 16.9 \text{ dB} \]
Notes:

* In an optical (digital) receiver, the noise on a '1' is not the same as on a '0'.
  - Reason is fundamental quantum nature of light itself:
    - "shot noise" increases with optical power itself
      \[ \sigma_q^2 = 2qIPDf \]
    - Noise due to average photocurrent (photodetector current)
      \[ e^{-\Delta P} \]
    - Mean square noise current from a photodetector
  - Hence optimal decision threshold is not at 50% of "on" voltage, but lower than that in general.

* Other noise to take into account in receiver
  - Shot noise on '1' and '0'
  - Thermal noise of receiver
    \[ \frac{4k_B T Df}{R} = \sigma_T^2 \]
  - "Dark current" noise in photodetector

Q. Where/how does dispersion penalty, or say clock recovery offset come into the SNR calculation?

* These effects lower \( V_i \) and raise \( V_o \) at the decision element, so \( V_i - V_o \) is reduced by any dispersion-induced eye closure or sampling timing offset from dead centre on the eye.
Typically in digital receiver design, the overall bandwidth, through which the receiver admits noise to the decision element is characterized by its "noise-equivalent bandwidth" (NEBW).

In a well-designed system, Nyquist filtering pulse shaping results in:

\[
\text{NEBW} \approx \frac{f_s}{2} = \text{symbol rate} \left( \frac{b}{s} \right)
\]

And the noise power spectral density, from all sources, can be measured at the decision element. It is not necessarily always "flat."

Then \( \sigma_n^2 = \text{mean square noise voltage} \) in general can be calculated by:

\[
\sigma_n^2 = \int H(f)^2 \cdot n(f) \cdot df
\]

and if the noise p.s.d. is more or less "white" (flat) at \( \pi \) (watts/Hz)

\[
\sigma_n^2 \approx \pi \cdot \text{NEBW (volts)}^2
\]

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In actual situation:

**Equivalent situation:**