SYSTEM DESIGN

- The results from the previous analysis can be used to obtain an estimate for the overall system performance.

**Power Budget**

This is a simple bookkeeping method to keep track of the power in the system relative to the minimum power required at the receiver. Quantities are kept in terms of dB and dBm so that values can be added.

**Example:**
Assume the following parameters:

<table>
<thead>
<tr>
<th>Source Power</th>
<th>( \bar{P}_{\text{src}} )</th>
<th>0 dBm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Receiver sensitivity</td>
<td>( \bar{P}_{\text{Rx}} )</td>
<td>-21.9 dBm</td>
</tr>
<tr>
<td>System Margin</td>
<td>( M_s )</td>
<td>6 dB</td>
</tr>
<tr>
<td>Available Channel Loss</td>
<td>( C_L )</td>
<td>16 dB</td>
</tr>
<tr>
<td>Connector Loss</td>
<td>( \alpha_c )</td>
<td>0.2 dB</td>
</tr>
<tr>
<td>Fiber attenuation loss</td>
<td>( \alpha_f )</td>
<td>0.5 dB/km</td>
</tr>
<tr>
<td>Maximum fiber length</td>
<td>( L )</td>
<td>31.6 km</td>
</tr>
</tbody>
</table>

- An estimate for \( \bar{P}_{\text{Rx}} \) can be made by considering the minimum number of photons required to maintain the desired BER.

- For instance for a p-i-n photodiode about 5000 photons/bit is necessary for a BER < 10^{-9}. Using
  \[
  \bar{P}_{\text{Rx}} = \bar{N}_p h \nu B
  \]
  with \( B \) the bit rate. Assuming a 10 Gb/s bit rate \( \bar{P}_{\text{Rx}} = 6.41 \mu W = -21.9 \text{dBm} \)

- The Power Budget can be expressed as:
  \[
  \bar{P}_{\text{src}} = \bar{P}_{\text{Rx}} + C_L + M_s
  \]
• A system margin is usually assigned to allow for component degradation over time.

• Channel Loss accounts for all sources of power loss. For instance:

\[ C_L = \alpha_f L + \alpha_c + \alpha_{splice} \]

\[ 15 = 0.2 + 0.5 L \]

• Using known parameters for components and estimates for the system margin, the fiber length before amplification can be computed.

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**Rise-Time Budget**

• In addition to the power budget the effects of dispersion on system performance can be determined by setting up a rise time budget.

• As discussed previously the rise time (\(T_r\)) is related to the 3-dB BW (\(B_{3dB}\)) through the relation:

\[ T_r = \frac{0.35}{B_{3dB}} \]

• This expression provides a conservative estimate on the relation between these parameters.

• It is possible to relax this constraint by using particular coding formats.

• For instance the relation between \(B_{3dB}\) and the bit rate (\(B_R\)) depends on the coding format.

• For **RZ (return-to-zero) codes** → \(B_{3dB} = B_R\) and \(B_R T_R = 0.35\).

• **NRZ (non-return-to-zero) codes** → \(B_{3dB} \approx \frac{B_R}{2}\) and \(B_R T_R = 0.70\).

• The reason for this is the way the data is encoded.
The two of the most commonly used formats are illustrated below:

- In NRZ modulation formats the amplitude does not drop to zero between successive 1 bits.

- There are about $2 \times$ fewer on-off transitions. Therefore the number of bits per available bandwidth is greater than with NRZ formats.

- However NRZ formats require tighter control of the pulse width.

- If the optical pulse spreads during transmission bit pattern dependent effects can result.
**Total Rise Time:**

\[ T_r^2 = T_{Tx}^2 + T_f^2 + T_A^2 + T_{Rx}^2 \]

where \( T_{Tx} \) is the transmitter rise time, \( T_f \) is the fiber-rise-time, \( T_{Rx} \) the receiver rise time, and \( T_A \) is any additional rise time factor introduced by other elements of the system.

- For SMF

\[ T_f = T_{GVD} \approx |D|L\Delta\lambda, \]

with \( \Delta\lambda \) the spectral width of the source.

**Example:**
Consider a 1 Gb/s system operating at a wavelength of 1.3 \( \mu \)m in SMF. It has OE repeaters at 50 km.

\( T_{tx} = 0.25 \) ns and \( T_{Rx} = 0.35 \) ns
\( \Delta\lambda = 3 \) nm and \( D = 2 \) ps/(km-nm) at 1.3 \( \mu \)m.

For the 50 km length \( T_f = 0.3 \) ns and \( T_r = 0.524 \) ns

Note that this system cannot be used with RZ modulation formats since this would require a rise time budget \(< 0.35 \) ns. It can be used with NRZ since the restriction on this format is \(< 0.70 \) ns.

\[ 0.524 \text{ns} < 0.70 \text{ns} \text{ NRZ} \]
\[ 0.32 \text{ns} < 0.35 \text{ns} \text{ RZ} \]
Modulation

ON-OFF Keying - most commonly used modulation scheme (OOK)

Binary Data: 1 0 1 1 0 1
NRZ

RZ

ON-OFF Keying is accomplished either by inverting current modulation or with an external modulator.

NRZ

RZ

Most common forms of modulation for bits

In RZ format, the pulse occupies a large portion of the bit interval, i.e. ~30B-50B. Requires more BW + higher peak power within the pulse for same energy/bit. (Same BER as NRZ)

NRZ - Required BW is ~1/2 that required for RZ

Problem - Long strings of 1s or 0s make it difficult for the receiver to acquire a bit clock.

DC-Balance - OOK modulation has DC balance if all sequences of data bits that may have to be transmitted have the average power constant.

DC Balance for OOK modulation is necessary to set the decision threshold at the Rx.

D.C. Balance - can be achieved by line code or scrambling

Binary Block Line Code - encodes a block of (k) data bits into n > k bits

Scrambling - maps one data stream into another data stream before transmission

NRZ - Annually used upto 10 Gb/s with scrambling

RZ - can be used to minimize chromatic dispersion.
**EYE-DIAGRAMS**

- A very useful tool for evaluating link performance is an *eye-diagram*.
- It gets its name from the form of the resultant oscilloscope pattern.
- Measurements are made in the time domain.
- In order to generate the pattern the following devices/instruments are required:
  1. A wavegenerator to provide a high speed clock signal
  2. A pseudo random bit generator to provide a sequence of nearly randomly changing bit patterns
  3. The fiber system (Tx, fiber, EDFAs, Rx)
  4. A high speed oscilloscope.

A diagram of the system required to generate an eye-diagram is shown below:
• The PRSG transmits a set of randomized words. This forms all possible transitions (rising, falling, high, low) within a bit time period.

• For instance for a 3-bit word sequence the following NRZ combinations are possible.

**Eight Possible 3-bit Long NRZ Combinations**

![Diagram showing eight possible 3-bit NRZ combinations.]

• The sequence generator is designated in terms of the number of bits that are randomized. A 32 bit PRSG randomizes the sequence of 32 bits and then repeats.

• The eye pattern is formed by superimposing 3-bit-long sequences on an oscilloscope.

1. *Width of the eye opening* – defines the time interval over which the received signal can be sampled without error from intersymbol interference. The waveform should be sampled when the eye opening is largest. This results in the lowest BER.
2. *Height of eye opening* – reduced by distortion of the data signal. Closure increases BER.

3. *Noise Margin*—percentage of the signal voltage $V_1$ to the maximum voltage relative to the threshold voltage $V_2$.

$$NM(\%) = \frac{V_1}{V_2} \times 100\%$$

4. *Slope of eye pattern*—determines the sensitivity to timing errors.

5. *Timing jitter*—results from receiver noise and pulse distortion in the optical fiber. The timing jitter is the closure in the time that the bit pattern is open.

$$TJ(\%) = \frac{\Delta T}{T_b} \times 100\%$$

6. *Rise and Fall Times*—10-90% rise and fall times can be measured from the eye pattern. The $B_{3db}$ can also be determined.

7. *Nonlinearities*—of the channel transfer characteristics results in asymmetry to the eye pattern.
Spectral Efficiency:

The ultimate bandwidth available in fused silica optical fiber

\[ \approx 400 \text{nm} \quad \text{from} \quad 1.25 \mu m - 1.6 \mu m \quad \approx 50 \text{THz} \]

want to know the total capacity at which signals can be transmitted over optical fiber.

Spectral efficiency - for a digital signal is defined

\[ S.E. = \frac{\text{bitrate}}{\text{Bandwidth used by signal at the bit rate}} = \frac{B}{\Delta f} \]

S.E. depends on modulation type + coding method

* In theory OOK modulation can achieve \( \frac{1 \text{ bit}}{1 \text{Hz}} \) data rate

  \( \text{in practice} \quad S.E. \approx 0.4 \text{ bit/Hz} \) have been achieved

  \[ \text{LB} \approx 20 \text{ Tbps} \quad \text{maximum capacity of optical fiber instead of} \quad \text{50 Tbps} \]

S.E. can be improved with more sophisticated modulation and coding schemes.

Capacity limits of optical fiber systems:

Upper limit on SE and channel capacity is given by Shannon's theorem:

\[
\text{channel capacity} \quad C = B \log_2 \left(1 + \frac{S}{N} \right)
\]

where it is assumed that there is a binary symmetric channel with additive noise.

\[ B = \text{available BW} \]

\[ \frac{S}{N} = \text{signal - noise ratio} \]

\[ \text{e.g. } \text{SNR=100} \quad \rightarrow \quad C = 350 \text{Tbps} \]

\[ \log_2 100 \approx 7 \quad \frac{SE}{\Delta f} \approx 7 \text{bit/Hz} \]

\[ C = 50 \times 7 = 350 \text{Tbps} \]

Since only \( 50 \text{Tbps} \) of spectral BW is available.
Example: Time Division Multiplexing (TDM) System

- Individual channels are modulated at high data rates (Channels A-C, more would be used in an actual system).

- An Optical Pulse generator forms high-speed pulses at rates less than the period of the transmitted data.

- The bit period for these signals is compressed to T/N, multiplexed, and transmitted through optical fiber.

- A high-speed clock and regenerator demodulates the signals.

- All optical 3R regeneration processes (re-amplifying, re-shaping, and re-timing) can greatly extend the capability of this technique beyond 100 Gb/s. A demonstration of 1.28 Tb/s has been demonstrated (Nakazawa, et.al., Elect. Lett. 2000).
2. **Sub Carrier Multiplexing**

- Multiple digital signals are multiplexed onto one RF signal and then sent at one optical wavelength.
- MUX and DEMUX accomplished electronically not optically.
- Limited by BW of electrical and optical components.
- Can be combined with other multiplexing schemes such as SONET (Synchronous Optical Network) and DWDM to extend transmission capacity.
3. **CODE Division Multiplexing (CDM)**

- Each channel transmits its data bits as a coded channel specific sequence over available BW, wavelength, and time slots.

![Diagram of CDM](image)

4. **Space Division Multiplexing (SDM)**

- The channel routing path is determined by different spatial positions (fiber locations).

- High BW space switching matrix is formed.

![Diagram of SDM](image)
WAVELENGTH DIVISION MULTIPLEXING (WDM) Systems:

- A basic point-point communication configuration is illustrated below:

- For single frequency point-point links the bit rate is limited ~100 Gb/s due to dispersion. This is well below the capability of the optical carrier frequency.

- WDM can increase the total bit rate of point-to-point systems.

- For N channels with bit rates $B_1$, $B_2$, ..., $B_N$ transmitted simultaneously over a fiber of length $L$, the bit rate-length product becomes

$$B \cdot L = (B_1 + B_2 + \ldots + B_N) \cdot L$$
• Another type of network takes the form of broadcast and select and is illustrated below.

• This type uses a star coupler to mix signals of different wavelengths and wavelength tuneable filters to extract the information.

• Although the power is decreased by a factor of 1/N this loss can be offset with the use of an optical amplifier prior to the second star coupler.

• During the past few years dense WDM (DWDM) systems have been proposed and are being developed. These systems have wavelength separations on the order of 0.3 – 0.8 nm.
WDM Overview

Multiple wavelengths are individually modulated and then sent through a single fiber.

Multiplexing/De-multiplexing

Thin Film Filters

Fiber Bragg Gratings (FBGs)
Arrayed Waveguide Gratings (AWGs)

\[ \Delta \lambda = \frac{\lambda^2}{c} \Delta \nu \]

\[ \Delta \lambda = 0.8 \text{ nm} \rightarrow \Delta \nu = 1006 \text{ Hz} \]

\[ 0.4 \text{ mm} \rightarrow 50 \text{ GHz} \]

\[ 0.2 \text{ mm} \rightarrow 25 \text{ GHz} \]

DFB lasers - Distributed Feedback Laser = \( \Delta \nu_{\text{max}} = 20-50 \text{ MHz} \)

However, when injection current modulated the linewidth will broaden due to chirp. Possibly to 10 GHz.

This can be eliminated using an external modulator (Figure).

In this case, the laser output remains constant.

Even with an external modulator, the linewidth will increase proportionally to the modulation bandwidth.
Mach Zehnder Interferometer (MZI)

- Light from a fiber is coupled to an integrated optic interferometer.
- A phase shift is introduced between the optical signals in each arm of the interferometer by applying a voltage to an electro optic material.
- The phase shift modulates the intensity of the optical beam in the output waveguide.

Transfer Matrix for the MZI:

\[
\begin{bmatrix}
E_{\text{out}} \\
0
\end{bmatrix} = \frac{1}{2} \begin{bmatrix}
1 & j \\
-j & 1
\end{bmatrix} \begin{bmatrix}
\exp\left(j \frac{2\pi n_1 L_1}{\lambda_0}\right) & 0 \\
0 & \exp\left(j \frac{2\pi n_2 L_2 + \phi_0}{\lambda_0}\right)
\end{bmatrix} \begin{bmatrix}
1 & j \\
-j & 1
\end{bmatrix} \begin{bmatrix}
E_{\text{inc}} \\
0
\end{bmatrix}
\]
Fiber loss limit:

A minimum detectable power $P_{\text{min}}$ will provide a BER at a required level.

For Gaussian distributed signals:

$$ Q = \frac{I_i - I_o}{\sigma_i + \sigma_o} $$

$$ I_i = P_i R_i \quad \text{and} \quad I_o = P_o R_o $$

$$ P_{\text{min}} = \left( \frac{1+R}{1-R} \right) \frac{P_i}{\lambda} \frac{\sigma_i^2}{\sigma_o^2} $$

If fiber loss $\alpha = \text{loss/m}$

$$ L_{\text{fib}} = e^{-\alpha L} $$

$$ P_{\text{min}} = e^{-\alpha L} P_{\text{source}} $$

Similarly, when only a few photon arrive and detection is governed by Poisson statistics:

$$ P_{\text{min}} = N_r h v B $$

$N_r = \text{Average number of photons in 140 bits}$

*Typical Receiver sensitivities*

<table>
<thead>
<tr>
<th>Bit Rate</th>
<th>Type</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5 Gbs</td>
<td>PINFET</td>
<td>-33 dBm</td>
</tr>
<tr>
<td>0.5 Gbs</td>
<td>APD</td>
<td>-54 dBm</td>
</tr>
<tr>
<td>10 Gbs/s</td>
<td>PINFET</td>
<td>-14 dBm</td>
</tr>
<tr>
<td>15 Gbs/s</td>
<td>APD</td>
<td>-24 dBm</td>
</tr>
<tr>
<td>40 Gbs/s</td>
<td>PINFET</td>
<td>-7 dBm</td>
</tr>
</tbody>
</table>

Power Penalty: When the system performance degrades, a power penalty can be specified that expresses the loss in performance.

Assuming Gaussian statistics, optimized threshold, equal likelihood of $12+6$: 

$$ Q = \frac{I_i - I_o}{\sigma_i + \sigma_o} = \frac{R(P_i-P_o)}{\sigma_i + \sigma_o} \Rightarrow PP = -10 \log \left[ \frac{R(P_i-P_o)}{\sigma_i + \sigma_o} \right] $$
Dispersion limit on propagation distance

\[ \frac{\Delta T_{\text{prop}}}{B} \leq 10/1 \Delta \lambda < \left\{ \begin{array}{c}
\frac{1}{B} \text{ - max Tolerance possible} \\
\frac{1}{4} \text{ - practical limit}
\end{array} \right. \]

length-spectral dependent

10/1 includes all sources of dispersion

i.e. \( D_m + D_w = \frac{1}{T_0} = B_{m,w} < \frac{1}{4} \leq 10/1 \Delta \lambda \)

PMD must be considered separately since it has a different dependence.

\[ \langle \Delta T \rangle_{\text{PMD}} = D_{\text{PMD}} \sqrt{2} \]

\[ \Delta T_{\text{prop}} = \left\{ \Delta T_{\text{m,w}}^2 + \Delta T_{\text{PMD}}^2 \right\}^{1/2} \]

Frequency chirp:

When a semiconductor laser is modulated at a high frequency, the refractive index of the laser cavity will change in time due to the injection current induced nonlinear effects in index. Changing the refractive index results in a phase change and this results in a linear frequency chirp:

\[ \dot{\omega}(t) = -\frac{\partial \phi}{\partial t} = K \dot{t} \]

\[ \phi(t) \]

Chirp:

Linear time dependence

In order to eliminate this problem, external modulation schemes are often used.