Introduction to Optical Link Design

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OPTICAL FIBER SYSTEMS – BASIC CONSIDERATIONS
Optical fibre communication systems vary according to application, and can be categorised in many ways, e.g.

- **Topology** – in local area networks, for example, rings and stars are possible, while transatlantic links will be point-to-point.

- **Length** – from a few hundred metres in data centres through to thousands of km.

- **Modulation** – analogue or digital
  - If digital, this can be binary or multilevel pulse amplitude modulation
  - Modulation can be direct (applies to LEDs and lasers), or it can be external modulation of a laser
    - Direct modulation simply leads to modulation of optical power, and is called intensity modulation. Detection is then called direct detection.
    - External modulation can be used to modulate the optical phase, which then allows the use of coherent detection.

- **Wavelength** – can be a single wavelength system, or a wavelength division multiplexed (WDM) system (CWDM – coarse WDM, DWDM – dense WDM).
We will keep things simple for the moment, by considering links that are:

- Point-to-point
- Use direct intensity modulation and direct detection (IM/DD)
- Single wavelength
POINT-TO-POINT DIGITAL LINK DESIGN
• In digital communications, three key specifications are:

1. The length of the link (in km)
2. The bit rate (in Mb/s or Gb/s)
3. The bit error rate (BER).

• In addition, such considerations as component cost (per subscriber), environmental conditions and reliability also have to be taken care of. In satisfying the link specifications, a designer has a number of decisions to take, because ....
Bandwidth (bit rate) and repeater spacing are determined by:

- Transmitter (e.g. laser)
- Transmission Medium (Fibre)
- Receiver (photodiode)

- Power
- Attenuation
- Sensitivity

- Modulation bandwidth
- Dispersion
- Modulation bandwidth
The bit rate-transmission length grid

<table>
<thead>
<tr>
<th>Bit Rate</th>
<th>1-10 m</th>
<th>10-100 m</th>
<th>100-1000 m</th>
<th>1-3 km</th>
<th>3-10 km</th>
<th>10-50 km</th>
<th>50-100 km</th>
<th>&gt;100 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;10 Kb/s</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>VII</td>
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<tr>
<td>10-100 Kb/s</td>
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<td></td>
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<tr>
<td>100-1000 Kb/s</td>
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<tr>
<td>1-10 Mb/s</td>
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<td>V</td>
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<tr>
<td>10-50 Mb/s</td>
<td></td>
<td></td>
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<tr>
<td>50-500 Mb/s</td>
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<td></td>
<td>VI</td>
</tr>
<tr>
<td>500-1000 Mb/s</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt;1 Gb/s</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

I Region: BL ≤ 100 Mb/s SLED with SI MMF
II Region: 100 Mb/s ≤ BL ≤ 5 Gb/s LED or LD with SI or GI MMF
III Region: BL ≤ 100 Mb/s ELED or LD with SI MMF
IV Region: 5 Mb/s ≤ BL ≤ 4 Gb/s ELED or LD with GI MMF
V Region: 10 Mb/s ≤ BL ≤ 1 Gb/s LD with GI MMF
VI Region: 100 Mb/s ≤ BL ≤ 100 Gb/s LD with SMF
VII Region: 5 Mb/s ≤ BL ≤ 100 Mb/s LD with SI or GI MMF

SI: step index, GI: graded index, MMF: multimode fiber, SMF: single mode fiber
A. Choice of operating wavelength

- Short haul links (e.g. LANs) :- use short wavelengths (e.g. 0.85 mm). Moderate fibre losses can be tolerated and the technology is cheap. By using multimode fibre, connectors are more rugged than for single mode.

- Long haul links (e.g. transatlantic) :- use long wavelengths where attenuation and dispersion are low. (e.g. 1.3 μm - gives dispersion minimum, or 1.55 μm - has attenuation minimum and is compatible with optical amplifiers; dispersion-shifted fibre also available).
Loss of modern fibres

- Transmitter (e.g. laser)
- Power
- Modulation bandwidth
- λ ( attenuation
- λ (dispersion
- λ (modulation bandwidth
- Transmission Medium (Fibre)
- Receiver (photodiode)
- Sensitivity
- First window
- Standard fiber
- Second window
- Third window
- AllWave® fiber

Wavelength (nm)
Dispersion for a standard silica single-mode fibre
B. Choice of source

- **Power** :- laser couples more power into single mode fibre than LED, but high-bit rate versions can be expensive and require temperature and optical power control. This makes them unsuitable for short links, unless VCSELs are considered (vertical cavity surface emitting laser).

- **Spectral width** :- at short wavelengths (high material dispersion) LEDs with large spectral widths might cause problems with inter-symbol interference. At 1.3 μm, we have very low dispersion fibre, which combined with low spectral width lasers allows high bit rates (e.g. 10 Gb/s and above), while dispersion management is possible at 1.55 μm
Comparison of spectral widths

- **LED**
  - Wavelength: 50 to 100 nm
  - Relative Power Density

- **Fabry-Perot Laser Diode**
  - Wavelength: 3 to 6 nm
  - Relative Power Density
  - < 1 pm

- **Single-Mode Laser Diode**
  - Wavelength: ~< 1 pm
  - Relative Power Density

- **Transmitter (e.g. laser)**
- **Transmission Medium (Fibre)**
- **Receiver (photodiode)**
- **Power**
- **Attenuation**
- **Sensitivity**
- **Modulation bandwidth**
- **Dispersion**

**Modulation bandwidth**

- **Single-Mode Laser Diode**
Source Bandwidth:

- LEDs: 3 dB bandwidth of a few hundreds of MHz available from commercial devices.
- Laser diodes: up to a few tens of GHz
- External modulation (e.g. Mach-Zehnder modulator plus laser) to more than 100 GHz has been demonstrated.
C. Choice of fibre

- **Multimode**:
  - modal dispersion limited
  - can be used with LEDs and laser diodes (esp. VCSELs)
  - graded index multimode fibre can achieve reasonable reduction in modal dispersion.

- **Single-mode**:
  - no modal dispersion problems
  - only used with laser diodes (high tolerance coupling)
  - can support > 1 Tb/s (using WDM)
  - small core diameter (8μm) leads to high tolerance (high price) connectors.
**Example:**

<table>
<thead>
<tr>
<th>GBIC</th>
<th>Wavelength (nm)</th>
<th>Fiber Type</th>
<th>Core Size (Micron)</th>
<th>Modal Bandwidth (MHz/km)***</th>
<th>Cable Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cisco 1000BASE-SX</td>
<td>850</td>
<td>MMF</td>
<td>62.5</td>
<td>160</td>
<td>722 ft (220 m)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>62.5</td>
<td>200</td>
<td>902 ft (275 m)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>50.0</td>
<td>400</td>
<td>1640 ft (500 m)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>50.0</td>
<td>500</td>
<td>1804 ft (550 m)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2000</td>
<td>3281 ft (1000 m)</td>
</tr>
<tr>
<td>Cisco 1000BASE-LX/LH</td>
<td>1310</td>
<td>MMF*</td>
<td>62.5</td>
<td>500</td>
<td>1804 ft (550 m)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>50.0</td>
<td>400</td>
<td>1804 ft (550 m)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>50.0</td>
<td>500</td>
<td>1804 ft (550 m)</td>
</tr>
<tr>
<td></td>
<td>SMF</td>
<td>9/10</td>
<td>N/A</td>
<td>6.2 miles (10 km)</td>
<td></td>
</tr>
<tr>
<td>Cisco 1000BASE-ZX</td>
<td>1550</td>
<td>SMF</td>
<td>9/10</td>
<td>N/A</td>
<td>43.4 to 62 miles (70 to 100 km)**</td>
</tr>
</tbody>
</table>
D. Choice of photodetector

- **PIN** :-
  - simpler construction than APD
  - relatively low sensitivity
  - available for short and long wavelengths
  - higher bandwidths achievable compared to APDs (up to 100 GHz)

- **APD** :-
  - better receiver sensitivity
  - temperature sensitive
  - high bias voltages
Typical receiver sensitivities vs bit rate:

- **Si pin** (800–900 nm)
- **Si APD** (800–900 nm)
- **InGaAs pin** (1300 nm)
- **InGaAs APD** (1550 nm)
LINK POWER BUDGET
Link Power Budget

• Put simply, the link power budget is an "accounting" procedure in which one calculates how much power can be lost between the transmitter and the receiver for a given receiver sensitivity (which depends on the bit rate) and transmitter power output. The resulting budget is allocated to connector losses, splice losses, fibre losses and a safety margin (system margin).

• dB and dBm units are used in the link power budget.
dB and dBm

- Advantage of this approach is that it replaces multiplication & division with addition/subtraction in calculation of link gain/link loss.

\[
P_{\text{out}} \text{(dBm)} = P_{\text{in}} \text{(dBm)} + G \text{ (dB)}
\]

\[
P_{\text{out}} \text{(dBm)} = P_{\text{in}} \text{(dBm)} - \alpha L \text{ (dB)}
\]
The power link budget is given by:

\[ \alpha L_{\text{max}} = P_S - P_R \]
Laser-to-fibre coupling loss; can be minimised using lenses.

Fibre pigtails: very short, negligible loss.

Fibre splice (permanent connection) introduces splice loss.

Loss due to fibre connector.
Distance along link (km)

Power level (dBm)

Total link loss

$M_a$
• In practical applications, we often use components that have connectors attached. Fibre with one connector is known as a *fibre pigtail*. A length of fibre with connectors on both ends is called a *patchcord*.

• In many link budgets, the splice loss is often combined together with the fibre loss.

• We also include a safety factor known as the *system margin* ($M_a$) to account for component degradation. A typical value for $M_a$ is 6 dB.
Example

- Calculate maximum link length for a system with:
  - a connectorised laser transmitter \( P_S = 3 \text{ dBm} \)
  - a connectorised receiver with sensitivity \( P_R = -40 \text{ dBm} \)
  - a fibre patchcord \( \alpha_F = 0.5 \text{ dB/km, including splice losses} \)
  - connector losses of \( \alpha_C = 1 \text{ dB} \) and system margin of 6 dB

\[
\text{Total link loss (dB)} = P_S - P_R = \alpha_F L + 2 \alpha_C + M_a
\]
\[ \alpha_F L = P_S - P_R - 2 \alpha_C - M_a = 35 \text{ dB} \]

Hence \( L_{\text{max}} = 35 / 0.5 = 70 \text{ km} \)

N.B. Not to scale!

\[ P_S = 3 \]
\[ P_R = -40 \]

Power level (dBm)

Distance (km)
LINK RISE-TIME BUDGET
Digital link design: Rise time budget

• In the previous section, we saw how the maximum link distance is affected by the fibre attenuation and also the source power and the photoreceiver sensitivity for a given bit rate; this gave us the link power budget.
However, recall that bit rate and repeater spacing are also determined by rise-time considerations:

- **Transmitter (e.g. laser)**
- **Transmission Medium (Fibre)**
- **Receiver (photodiode)**

- **Power**
- **Attenuation**
- **Sensitivity**

- **Modulation bandwidth**
- **Dispersion**
- **Modulation bandwidth**
\[ t_{\text{sys}} = \sqrt{t_{\text{TX}}^2 + t_{\text{mat}}^2 + t_{\text{mod}}^2 + t_{\text{RX}}^2} \]
Concept of rise-time

- Any real-life system with an input/output will have a finite bandwidth.
- For example, consider typical modulation response of a laser diode:
• Previous diagram relates to sinusoidal ($j\omega$) response.
• The corresponding step-response shows that it takes a finite time to reach the steady-state, and that in some cases there may even be relaxation oscillations:

![Diagram](image)

Typical step-response of a laser diode, showing turn-on delay and relaxation oscillations (due to low damping factor)
Similarly, a photodiode will take a finite time to respond to step-changes in the incident optical power, as shown below for the case of a pulse input:

Note: Output current pulse shape depends on the device capacitance and also the width of the depletion region. The above response is quite poor due to large junction capacitance.
- Finally, the optical fibre itself will exhibit its own rise time due to the effects of dispersion.

  - In the case of single-mode fibres, this is entirely due to intramodal dispersion, with the main contribution to this being being material dispersion.
  - In multimode fibres, the dominant effect is intermodal dispersion. (Although material dispersion also exists, it is negligible in comparison).
  - Although attenuation is important, it does not have an impact on rise-time. It affects the link power budget instead.
• So, not surprisingly, the optical fibre link as a whole will have a rise-time (and fall-time) in response to a rectangular pulse input:

\[
\begin{align*}
    i_{in}(t) & \rightarrow p_{LD}(t) \rightarrow \text{FIBRE} \rightarrow p_{PD}(t) \rightarrow i_{out}(t)
\end{align*}
\]
Definition of rise-time and fall-time

N.B. y-axis is voltage, current or optical power as appropriate

- **Rise-time**: time taken to rise from 10% to 90% of the steady-state value of the pulse.
- **Fall-time**: time taken to fall from 90% to 10% of the steady-state value of the pulse.
• Put simply, the rise-time budget is an "accounting" procedure in which one calculates how much pulse spreading can be tolerated between the transmitter and the receiver for a given transmitter rise-time, photoreceiver rise-time and dispersion due to the fibre (both modal and chromatic, as appropriate).
Rise-time Budget

- The total rise-time of the fibre-optic link is known as the system rise time $t_{sys}$.
- It depends on the rise-times of the individual systems components, and assuming these are independent of one another, they affect $t_{sys}$ as follows:

$$t_{sys} = \sqrt{t_{TX}^2 + t_{mat}^2 + t_{mod}^2 + t_{RX}^2}$$
• \( t_{TX} \) = optical transmitter rise-time
• \( t_{RX} \) = optical receiver rise-time
• \( t_{mat} \) = material dispersion rise-time
• \( t_{mod} \) = modal dispersion rise-time (for multimode fibre only)

• The usual requirement on \( t_{sys} \) is:

\[
    t_{sys} < 0.7 \, \tau
\]

where \( \tau \) is the pulse duration.
• The pulse duration depends on the data format.

• Two main data formats are used: NRZ and RZ
Consider an NRZ stream composed of alternating “0”s and “1”s, and an RZ stream composed entirely of “1”s:

For NRZ signalling, $\tau_{NRZ} = 1/B_T$, hence:

For RZ signalling, $\tau_{RZ} = 1/2B_T$, hence:
$t_{mat}$: material dispersion rise-time

- due to *material dispersion*
- significant in single-mode fibres

\[ t_{mat} = D_{mat} \sigma_\lambda L \]

- $D_{mat}$ = material dispersion parameter (ps/nm.km)
- $\sigma_\lambda$ = spectral width of optical source (in nm or $\mu$m)

- $t_{mat}$ can usually be neglected if the spectral width is narrow (e.g. in DFB lasers) or if operation is at 1.3 $\mu$m.
\( t_{\text{mod}} \): modal dispersion rise-time

- due to (inter)modal dispersion
- dominant in multimode fibres
- In theory, \( t_{\text{mod}} \) is proportional to fibre length. In a real system, pulse distortion increases less rapidly after a certain initial length because of mode coupling.
• It can be shown that $t_{\text{mod}}$ in ns is given by:

$$t_{\text{mod}} = \frac{0.44L^q}{B_0}$$

where $q$ is between 0.5 and 1.0 (depends on amount of mode coupling), $L$ is the fibre length (km) and $B_0$ is the 3dB electrical bandwidth (in GHz) of 1 km of fibre.
\( t_{RX} : \text{photoreceiver rise-time} \)

- Assuming a simple low-pass RC characteristic for the frequency response of a photoreceiver, then we can relate \( t_{RX} \) (in ns) to the 3 dB receiver bandwidth (\( B_{RX} \) in units of GHz) as follows:

\[
t_{RX} = \frac{0.35}{B_{RX}}
\]

A simple photodiode model; high frequency versions also include parasitics due to the packaging.
$t_{TX}$ : optical transmitter rise-time

- This is a function of both the intrinsic frequency response (of either the LED or the laser diode) along with any drive electronics.
- LED and laser diode data sheets usually specify the device rise time.
Finally....

Although the above equations/analysis may appear to be straightforward, be VERY careful in using units.

Bandwidths of laser diodes, for example, tend to be in the GHz range, so rise-times tend to be quoted in ns.

However, it is possible to encounter a mix of units when performing rise-time calculations.

If in any doubt, convert all quantities to SI units, and perform calculations in SI units, before converting to ns at the end.