SYSTEM ARCHITECTURES

- **Point-to-point links**
  - Point-to-point links constitute the simplest kind of lightwave systems.
  - The link length can vary from less than a kilometer (short haul) to thousands of kilometers (long haul), depending on the specific application.

- **Broadcast and distribution networks**
  - Networks designed for distribution of a wide range of services, including telephone, facsimile, computer data, and video broadcasts.

- **Local-area networks**
  - Local-area networks (LANs) are the networks in which users within a local area (e.g., a university campus) are interconnected in such a way that any user can access the network randomly to transmit data to any other user.

The fiber loss can be compensated by:
- repeaters which detect the incoming optical signal, recovers the electrical bit stream, and then converts it back into optical form by modulating the optical source. This devices are often called regenerators because they regenerate the optical signal.
- optical amplifiers, which amplify the optical bit stream directly without requiring conversion of the signal to the electric domain.

The bit rate-distance product, BL, is generally used as a measure of the system performance for point-to-point link.
- The first three generations of lightwave systems correspond to three different operating wavelengths, near 0.85, 1.3, and 1.55 μm with the BL product in the range of 1 (Gb/s)-km (0.85 μm) up to 100 (Tb/s)-km (1.55 μm).
Broadcast and distribution networks

- Star or hub topology
  - A dedicated fiber is used for each office
  - Telephone networks employ hub topology for distribution of audio channels within a city
- Bus topology
  - Several offices share the same fiber
  - Signal loss increases exponentially with the number of taps

Transmission distances are relatively short ($L < 50$ km), but the bit rate can be as high as 10 Gb/s for a super-broadband ISDN.

Local-Area Networks

- Ring topology
  - Fiber distributed data interface (FDDI)
- Star topology
  - Passive and active star topology
DESIGN GUIDELINES

The choice of operating wavelength is a major design issue.

Loss-Limited Lightwave Systems

the maximum transmission distance is limited by

\[ L = \frac{10}{\alpha_f} \log_{10} \left( \frac{P_{tr}}{P_{rec}} \right) \]

where \( \alpha_f \) is the net loss (in dB/km) of the fiber cable, including splice and connector losses, \( P_{tr} \) is an average input power, \( P_{rec} \) is a minimum average power required for the normal operation of the receiver.

Remark: for a shot noise limited receiver

\[ SNR = \frac{\eta \cdot P_{in}}{2 \cdot h \cdot \omega \cdot \Delta f} = \eta \cdot N_p \]

\( P_{rec} \) depends on the bit rate \( B \), since \( P_{rec} = N_p h v B \), where \( h v \) is the photon energy

For a fixed SNR the maximum transmission distance will be

\[ L = \frac{10}{\alpha_f} \log_{10} \left( \frac{P_{tr}}{N_p h v B} \right) \]

Loss limits and dispersion of fiber and coaxial cables

The transmitted power is taken to be \( P_{tr} = 1 \text{ mW} \) at the three wavelengths, whereas \( N_p = 300 \) at 0.85 μm and \( N_p = 500 \) at 1.3 and 1.55 μm.

Solid lines show the dependence of \( L \) on \( B \) for three wavelengths of 0.85, 1.3, and 1.55 μm, whereas it was assumed \( \alpha_f = 2.5, 0.4, \) and 0.25 dB/km, respectively. a repeater spacing of more than 100 km is possible for lightwave systems operating near 1.55 μm. The dotted line shows the performance of coaxial-cable systems. Filled circles denote terrestrial commercial lightwave systems; empty circles correspond to undersea transmission systems; triangles denote laboratory experiments.

The dashed lines show the dispersion-limited transmission distance as a function of the bit rate.
Dispersion-Limited Lightwave Systems

When the dispersion-limited transmission distance is shorter than the loss-limited distance, the system is said to be dispersion-limited.

Bit rate of dispersion limited systems

- Multimode step-index fibers
  \[ BL < \frac{n_2}{n_1^2} \frac{c}{\Delta} \]
  \[ \Delta = \frac{n_1 - n_2}{n_1} \]
  \[ n_1 n_{nc} - n_2 = \Delta < 0 \]
  
  Bit rate: \( 1 \text{ Mb/s} \)

- Multimode graded-index fibers
  \[ BL < \frac{8c}{n_1 \Delta^2} \]

  Bit rate: \( 100 \text{ Mb/s} \)

- Second generation systems with monomode fiber and large source spectral width
  \[ BL |D| \sigma_\lambda < 1/4 \]

  Bit rate: \( 1 \text{ Gb/s} \)

- Third generation systems with monomode fiber and a single longitudinal mode laser
  \[ B \leq \frac{1}{4 \sqrt{\beta_2 L}} \]

  Bit rate: \( 5-20 \text{ Gb/s} \)

Long-Haul Systems

Fiber loss are compensated by inserting in-line amplifiers periodically in a long-haul fiber link.

The effects of group-velocity dispersion can be reduced either by operating close to the zero-dispersion wavelength of the fiber or by using a dispersion-compensation techniques.

What does limit the performance of amplified fiber link?

- The most important limiting factors in the design of fiber links with amplifiers are nonlinear effects in optical fibers.
- When optoelectronic regenerators are used, the nonlinear effects accumulate only over one repeater spacing (typically, < 100 km) and are of little concern if the launch power \( P_{tr} < 45 \text{ mW} \).
- By contrast, the nonlinear effects accumulate over long lengths (~ 1000 km) when in-line amplifiers are used periodically for loss compensation.
- Typically, the link length is limited to below 1000 km even for \( P_{tr} = 1 \text{ mW} \).
- The dispersive and nonlinear effects act on the optical signal simultaneously and their mutual interplay becomes quite important.
SYSTEM DESIGN

The performance criterion is specified through the bit-error rate (BER), a typical requirement being BER < 10^{-9}.

The system requirements typically specified in advance are the bit rate B (rise time budget) and the transmission distance L (power budget).

The operating wavelength
Selection of appropriate transmitters, receivers, and fibers
Compatibility of various components
Cost versus performance
System reliability and upgradability.

The cost of components is lowest near 0.85 µm and increases as wavelength shifts toward 1.3-1.6 µm.

A fiber-optic link can operate near 0.85 µm if B < 100 Mb/s and L < 20 km.

Power Budget

The purpose of the power budget is to ensure that enough power will reach the receiver to maintain reliable performance (within a specified BER) during the entire system lifetime.

The power budget in decibel units can be represented as

\[
P_{tr} = P_{rec} + C_L + M_s
\]

where \(P_{rec}\) is the receiver sensitivity (minimum average power required by the receiver)
\(P_{tr}\) is the average launch power
\(C_L\) is the total channel loss and \(M_s\) is the system margin

A system margin of 6-8 dB is generally allocated during the design process to offset power penalty that may develop during system lifetime because of component degradation or other unforeseen events

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

\(\alpha_f\) is the fiber loss in dB/km, \(\alpha_{con}\) and \(\alpha_{splice}\) are the connector and splice losses
Consider the design of a fiber link operating at 50 Mb/s and transmission distance of 8 km. Such a system can be designed to operate near 0.85 \( \mu \text{m} \) provided that graded-index multimode fiber is used for the fiber cable. The operation near 0.85 \( \mu \text{m} \) is desirable from the economic standpoint.

The GaAs transmitter can be a semiconductor laser (1 mW) or a LED (50 \( \mu \text{W} \)). A p-i-n receiver requires about 5000 photons/bit on average to operate reliably with a BER below 10\(^{-9}\).

\[
\overline{P}_{\text{rec}} = \overline{N}_p h v B = 5 \cdot 10^3 \cdot h v \cdot 5 \cdot 10^7 \approx -42 \text{dBm}
\]

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Laser</th>
<th>LED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmitter power</td>
<td>( P_t )</td>
<td>0 dBm</td>
<td>-13 dBm</td>
</tr>
<tr>
<td>Receiver sensitivity</td>
<td>( P_{\text{rec}} )</td>
<td>-42 dBm</td>
<td>-42 dBm</td>
</tr>
<tr>
<td>System margin</td>
<td>( M_s )</td>
<td>6 dB</td>
<td>6 dB</td>
</tr>
<tr>
<td>Available channel loss</td>
<td>( C_L )</td>
<td>36 dB</td>
<td>23 dB</td>
</tr>
<tr>
<td>Connector loss</td>
<td>( \alpha_{\text{con}} )</td>
<td>2 dB</td>
<td>2 dB</td>
</tr>
<tr>
<td>Fiber cable loss</td>
<td>( \alpha_f )</td>
<td>3.5 dB/km</td>
<td>3.5 dB/km</td>
</tr>
<tr>
<td>Maximum fiber length</td>
<td>( L )</td>
<td>9.7 km</td>
<td>6 km</td>
</tr>
</tbody>
</table>

The transmission distance is limited to 6 km for the case of LED based transmitters and up to 9.7 km for more expensive laser transmitters.

The rise time \( T_r \) of a linear system is defined as the time during which the response increases from 10\% to 90\% of its final output value when the input is changed abruptly (a step function).

The concept of rise time is used to allocate the bandwidth among various components.

The purpose of the rise-time budget is to ensure that the system is able to operate properly at the intended bit rate.

Even if the bandwidth of the individual system components exceeds the bit rate, it is still possible that the total system may not be able to operate at that bit rate.
Bandwidth and the Rise time

\[ V(t) = V_0 \left[ 1 - \exp\left( -t / RC \right) \right] \]

\[ V_0 \left[ 1 - \exp\left( -t_0 / RC \right) \right] = 0.1V_0 \]

\[ V_0 \left[ 1 - \exp\left( -t_1 / RC \right) \right] = 0.9V_0 \]

\[ T_r = t_1 - t_0 = \ln(0.9)RC - \ln(0.1)RC = \ln(9)RC \]

\[ \Delta f_{3dB} = \left( 2\pi RC \right)^{-1} \]

\[ T_r \Delta f_{3dB} = \frac{\ln(9)}{2\pi} = 0.35 \]

One expects an inverse relationship between the rise time and the bandwidth to hold for any linear system, but the product \( T_r \Delta f_{3dB} \) would generally be different than 0.35.

In the design of optical communication systems it is common to use \( T_r \Delta f_{3dB} = 0.35 \) as a conservative guideline.

Bandwidth and the bit rate B

The relationship between the bandwidth \( \Delta f \) and the bit rate \( B \) depends on the digital format and respectively the specified bit rate imposes an upper limit on the maximum rise time that can be tolerated

\[ T_r \leq \begin{cases} 
0.35 / B & \text{for RZ format} \\
0.7 / B & \text{for NRZ format} 
\end{cases} \]

The total rise time of a fiber-optic communication system depends on the rise times of its components

\[ T_r^2 = T_{tr}^2 + T_{fiber}^2 + T_{rec}^2 \]

where \( T_{tr} \), \( T_{fiber} \), and \( T_{rec} \) are the rise times associated with the transmitter, fiber, and receiver, respectively.

\( T_{tr} \sim 5 \text{ ns (LED)} - 0.1 \text{ ns (Laser Diode)}; \)

\( T_{rec} \) is determined by the bandwidth of the receiver, typically \( 0.05 - 2 \text{ ns} \).
The fiber rise time

The fiber rise time \( T_{\text{fiber}} \) includes the contributions of modal and group-velocity dispersions

\[
T_{\text{fiber}}^2 = T_{\text{modal}}^2 + T_{\text{GVD}}^2
\]

For single-mode fibers, \( T_{\text{modal}} = 0 \) and \( T_{\text{fiber}} = T_{\text{GVD}} \).

The contribution of modal dispersion is difficult to calculate since a variety of factors must be taken in account (mode mixing, many concatenated fiber sections with different dispersion characteristics).

In a phenomenological approach, \( T_{\text{modal}} \) for a step-index cable can be approximated by the time delay \( \Delta T \) in the absence of mode mixing, i.e.,

\[
T_{\text{modal}} \approx \Delta T = \frac{L}{c} \left( \frac{1}{\sin \phi_e} - 1 \right) = \frac{L}{c} n_1^2 \Delta \approx \frac{L}{c} n_1 \Delta
\]

For a graded-index cable

\[
T_{\text{modal}} \approx \frac{L}{8c} n_1^2 \Delta^2
\]

The effect of mode mixing is included by changing the linear dependence on \( L \) by a \( L^q \), where \( q \) has a value in the range 0.5-1, depending on the extent of mode mixing.

Time rise contribution of GVD

The contribution \( T_{\text{GVD}} \) can also be approximated by \( \Delta T \) given by

\[
T_{\text{GVD}} \approx |\Delta T| = |D| L \Delta \lambda
\]

where \( \Delta \lambda \) is the spectral width (FWHM) of the optical source. The dispersion parameter \( D \) may change along the fiber link if different sections have different dispersion characteristics; an average value should be used in the equation above.

Example

Consider a 1.3-\( \mu \)m system designed to operate at 1 Gb/s over a single-mode fiber with a repeater spacing of 50 km. The rise times for the transmitter and the receiver have been specified as \( T_{\text{tr}} = 0.25 \) ns and \( T_{\text{rec}} = 0.35 \) ns. The source spectral width is specified as \( \Delta \lambda = 3 \) nm, whereas the average value of \( D \) is 2 ps/(km-nm) at the operating wavelength.

For a link length \( L \) of 50 km

\[
T_{\text{GVD}} \approx |D| L \Delta \lambda = 2 \cdot 50 \cdot 3 = 0.3 \text{ ns}
\]

Modal dispersion in single-mode fibers \( T_{\text{modal}} = 0 \). Hence, \( T_{\text{fiber}} = 0.3 \) ns. The system rise time is found to be

\[
T_r = \sqrt{T_{\text{tr}}^2 + T_{\text{fiber}}^2 + T_{\text{rec}}^2} = 0.524 \text{ ns}
\]

Therefore, such a system cannot be operated at 1 Gb/s when the RZ format is employed for the optical bit stream. However, it would operate properly if digital format is changed to the NRZ format.
Sources of Power Penalty
At low bit rates (B < 100 Mb/s), most lightwave systems are limited by fiber loss rather than fiber dispersion.
At high bit rates (B > 500 Mb/s) fiber dispersion begins to dominate system performance.
The sensitivity of the optical receiver is affected by several physical phenomena:
• modal noise
• dispersion broadening and intersymbol interference
• mode-partition noise
• frequency chirp
• reflection feedback.
The combination of these phenomena with the fiber dispersion may degrade the signal-to-noise ratio.
Power penalty resulting from the degradation of the receiver sensitivity affects the system performance.

Modal Noise
The non-uniform intensity distribution at the receiver due to interference among various modes in a multimode fiber fluctuates with time. These fluctuations are due to some mechanical disturbances such as vibrations and microbends.
Splices and connectors act as spatial filters. Any temporal changes in spatial filtering change the mode content and enhance the fluctuations of the optical power at the fiber end.
The fluctuations in the received power degrade the SNR. Such fluctuations are referred to as modal noise.
Modal noise is strongly affected by the source spectral bandwidth $\Delta \nu$ since mode interference occurs only if the coherence time ($T_c \sim 1/\Delta \nu$) is longer than the intermodal delay time $\Delta T$ given by
$$\Delta T = \frac{L}{c} \frac{n_2}{n_1} \Delta$$
For LED-based transmitters $\Delta \nu$ is large enough ($\Delta \nu \sim 10$ THz) that the condition above is not satisfied. Most lightwave systems that use multimode fibers also use LEDs to avoid the modal-noise problem.
Lasers in combination with multimode fibers

Modal noise becomes a serious problem when semiconductor lasers are used in combination with multimode fibers.

Power penalty at a BER of $10^{-12}$ calculated for a 1.3-µm lightwave system operating at 140 Mb/s.

The graded-index fiber has a 50-µm core diameter and supports 146 modes. The power penalty depends on the mode-selective coupling loss occurring at splices and connectors. The parameter $M$ is the total number of longitudinal modes whose power exceeds 10% of the peak power.

Power penalty decreases as the number of longitudinal modes increases because of a reduction in the coherence time of the emitted light.

Modal noise in special cases

Modal noise can occur in single-mode systems if short sections of fiber are installed between two connectors or splices. A higher-order mode will be excited at the fiber discontinuity.

Since a higher-order mode cannot propagate far from its excitation point, this problem can be avoided by ensuring that the spacing between two connectors or splices exceeds 2 meters.

Short-haul optical data links employing the vertical-cavity surface-emitting laser (VCSEL) in combination with multimode fibers is of considerable interest because of high bit rates (several Gb/s) and low cost of a multimode fiber.

Bit rates of several Gb/s have been demonstrated in laboratory experiments with plastic-cladded multimode fibers.

However, VCSELs have a long coherence length as they oscillate in a single longitudinal mode. The BER measurements show an error floor at a level of $10^{-7}$ even for a 1-dB mode-selective loss.
Dispersion Broadening

The use of single-mode fibers for lightwave systems nearly avoids the problem of intermodal dispersion and the associated modal noise. However, the group-velocity dispersion still limits the bit rate-distance product $BL$ by broadening pulses. Dispersion-induced pulse broadening affects the receiver performance in two ways:

1) A part of the pulse energy spreads beyond the allocated bit slot and leads to intersymbol interference (ISI).
2) The pulse energy within the bit slot is reduced when the optical pulse broadens.

Such a decrease in the pulse energy reduces the SNR at the decision circuit.

An exact calculation of power penalty ($\delta_d$) in the case is difficult, as it depends on many details, such as the extent of pulse shaping at the receiver.

Gaussian Pulses

A rough estimate of $\delta_d$ can be obtained for Gaussian pulses

$$A(t) = A_0 \exp \left(-\frac{1 + jC}{2} \left( \frac{t}{T_0} \right)^2 \right)$$

The optical pulse peak power of the output pulse is reduced by a pulse-broadening factor

$$f_b = \frac{\left| T_1 \right|}{T_0} = \sqrt{\left(1 + \frac{C\beta_2 z}{T_0} \right)^2 + \left( \frac{\beta_2 z}{T_0} \right)^2}$$

If we define the power penalty $\delta_d$ as the increase (in dB) in the received power that would compensate the peak-power reduction, $\delta_d$ is given by

$$\delta_d = 10 \log_{10} \left( \frac{\left| T_1 \right|}{T_0} \right) = 10 \log_{10} (f_b)$$
Wide source spectrum

The broadening factor \( f_b \) for a wide spectrum source is given

\[
f_b = \frac{\sigma}{\sigma_0} = \left[ 1 + \left( \frac{D \lambda \sigma}{\sigma_0} \right)^2 \right]^{1/2}
\]

The intersymbol interference is minimized when the bit rate \( B \) is such that

\[
4B \sigma < 1, \text{ as little pulse energy spreads beyond the bit slot (} T_B = 1/B \text{)}
\]

\[
\sigma = \frac{1}{4B} \bigoplus f_b \sigma_0 = \sigma \quad \sigma_0 = \frac{1}{4B f_b} \quad f_b = \left[ 1 + (4B f_b D \lambda \sigma)^2 \right]^{1/2}
\]

\[
f_b^2 = \frac{1}{1 - (4B D \lambda \sigma)^2}
\]

Therefore the power penalty for a system with a single mode fiber and wide spectrum source will be

\[
\delta_d = 10 \log_{10} (f_b) = -5 \log_{10} \left( 1 - (4B D \lambda \sigma)^2 \right)
\]

The power penalty is negligible (\( \delta_d = 0.38 \text{ dB} \)) for \( B \lambda D \sigma = 0.1 \).

It increases to 2.2 dB when \( B \lambda D \sigma = 0.2 \) and becomes infinite when \( B \lambda D \sigma = 0.25 \).

Most lightwave systems are designed such that \( B \lambda D \sigma < 0.2 \), so that the dispersion penalty is below 2 dB. It should be stressed that we provide a rough estimate only based on several simplifying assumptions, such as a Gaussian pulse shape and a Gaussian source spectrum. These assumptions are not always satisfied in practice.

Dispersion-induced power penalty for a Gaussian pulse as a function of \( B \lambda D \sigma \). Source spectrum is also assumed to be Gaussian, with an RMS width \( \sigma_\lambda \).
Transmitter associated noise

- Noise sources
  - Shot noise - occurs in all electronic devices
  - Spontaneous emission noise
    - Spontaneous emission events produce a light at a wavelength supported by the cavity but with a random phasor
  - Mode partition noise
    - In reality any laser a number of modes (with different amplitudes). Power switches randomly back and forth among the modes. Due to their slightly different frequencies these modes will not arrive in synchronism at the receiver end providing some fluctuating interference power pattern.

Spontaneous emission noise

Spontaneous emission events occur in time and space. Those events that produce a light at a wavelength supported by the cavity add a random phasor to the coherent light produced by stimulated emission. Thus random amplitude and random phase fluctuations added to the ideal coherent light.

\[
\Delta N_{ph} = N_{ph} - \bar{N}_{ph}
\]

Intensity and phase show variations over a short time as 100 ps. The term relative intensity noise (RIN) is used to define the fluctuations in power level. Let the fluctuations in photon density be \( \Delta N_{ph} = N_{ph} - \bar{N}_{ph} \).

The normalized auto-correlation function of the photon density, and hence of the light fluctuation intensity is

\[
C_f(\tau) = \frac{\langle \Delta N_{ph}(t) \cdot \Delta N_{ph}(t + \tau) \rangle}{\bar{N}_{ph}^2}
\]
Relative intensity noise spectrum

The Fourier transform of the auto correlation function gives the power spectrum

$$RIN(\omega) = \int C_\tau(\tau) \exp(-j\omega\tau) d\tau$$

Calculated RIN spectra at several power levels for a typical 1.55 µm InGaAsP laser. The RIN is considerably enhanced near the relaxation-oscillation frequency. It decreases with the power of emitted light as $P^{-3}$ at lower laser power, while this behavior changes to $P^{-1}$ at higher powers.

Mode partition noise

Various longitudinal modes fluctuate in such a way that individual modes exhibit large intensity fluctuations even though the total intensity remains relatively constant.

Different modes have slightly different frequencies and travel at different speeds inside the fiber because of group-velocity dispersion. At the receiver end the modes will interfere producing fluctuations of the received optical power. As a result the receiver current exhibits additional fluctuations, and the SNR at the decision circuit becomes worse than that expected in the absence of MPN.

A power penalty must be paid to improve the SNR to the same level as it was in the absence of mode partition noise.

For multimode semiconductor lasers, the power penalty can be calculated by following an approach used in estimation of power penalty in Section 4.6

$$\delta_{\text{mpn}} = -5 \log_{10} (1 - Q^2 r_{\text{mpn}}^2)$$

where $Q$ is the BER parameter (see Section 4.5), and $r_{\text{mpn}}$ is the relative noise level of the received power in the presence of mode partition noise.
MPN induced power penalty

Assuming that laser modes fluctuate in such a way that the total power remains constant under CW operation, the following expression for $r_{mpn}$ can be derived.

$$ r_{mpn} = \left( k / \sqrt{2} \right) \left( 1 - \exp \left[ -(\pi BLD \sigma \lambda)^2 \right] \right). $$

The model assumes that mode partition can be quantified in terms of a single parameter $k$ (mode-partition coefficient) with values in the range $0-1$.

$$ k = \sqrt{1 - \gamma_{cc}} \quad \gamma_{cc} = \frac{\langle N_{ph}^{(1)} N_{ph}^{(1)} \rangle}{\langle N_{ph}^{(1)} \rangle^2} $$

For a given value of $k$ the power penalty increases rapidly with an increase in $BLD \sigma \lambda$ and becomes infinite when $BLD \sigma \lambda$ reaches a critical value.

The MPN-induced power penalty can be reduced to a negligible level ($\delta_{mpn} < 0.5$ dB) by designing the optical communication system such that $BLD \sigma \lambda < 0.1$.

Example

Consider a 1.3µm lightwave system. If we assume that the operating wavelength is matched to the zero-dispersion wavelength to within 10 nm, $D \sim 1$ ps/(km-nm). A typical value of $\sigma \lambda$ for multimode semiconductor lasers is 2 nm.

The MPN-induced power penalty would be negligible if the $BL < 0.1 / (D \sigma \lambda)$ or $BL < 50$ (Gb/s)-km. At $B = 2$ Gb/s the transmission distance is then limited to 25 km.

The situation becomes worse for 1.55-µm lightwave systems for which $D \sim 16$ ps/(km-nm) unless dispersion-shifted fibers are used.

In general, the MPN-induced power penalty is quite sensitive to the spectral bandwidth of the multimode laser and can be reduced by reducing the bandwidth.

Most 1.55-µm lightwave systems make use of DFB semiconductor lasers to solve the dispersion problem. However it was discovered in many experiments that even in this case MPN can not be avoided completely.

The reason is that the main mode of any DFB laser is accompanied by several side modes of much smaller amplitudes.
**MPN in DFB lasers**

Effect of MPN on bit-error rate of DFB lasers for several values of mode-suppression ratio (MSR). Intersection of the dashed line with the solid curves provides MPN-induced power penalty.

The power penalty becomes infinite for MSR values below 42. The penalty can be reduced to a negligible level (< 0.1 dB) for MSR values in excess of 100 (20 dB).

The experimental measurements of the BER in several transmission experiments show that a BER floor above the 10^{-9} level can occur even for DFB lasers which exhibit a MSR in excess of 30 dB (under CW operation). It is due to the side-mode excitation under transient conditions.

**Frequency chirping**

Frequency chirping is known to limit the performance of 1.55-µm lightwave systems even when a DFB laser with a large MSR is used to generate the digital bit stream.

As a result of the frequency chirp imposed on an optical pulse, its spectrum is considerably broadened. Such spectral broadening affects the pulse shape at the fiber output because of fiber dispersion and degrades system performance.

In a simple model the chirp-induced power penalty is given by

\[ \delta_c = -10 \log_{10}(1 - 4BLD\Delta \lambda_c), \]

where \( \Delta \lambda_c \) is the spectral shift associated with frequency chirping. This equation applies as long as \( LDA_\lambda_c < t_c \), where \( t_c \) is the chirp duration.

Typically, chip duration \( t_c \) is 100-200 ps. By the time \( LDA_\lambda_c \) equals \( t_c \) the power penalty stops increasing because all the chirped power has left the bit interval. For \( LDA_\lambda_c > t_c \) the product \( LDA_\lambda_c \) in the equation above should be replaced by \( t_c \).
Chirp-induced power penalty

Bt, which is a measure of the fraction of the bit period over which chirping occurs.

The length of the bit will determine the maximum time during which the frequency will change.

Power penalty versus BLDΔλc, for several values of the parameter Bt.

Power penalty versus extinction ratio

The effect of chirp can be reduced by biasing the semiconductor laser above threshold. However, above-threshold biasing increases the extinction ratio.

The total system performance can be optimized by designing the system so that it operates with an optimum value of r_{ex} that takes into account the trade-off between the chirp and the extinction ratio.

An alternative approach eliminates the laser-chirp problem completely by operating the laser continuously and using an external modulator to generate the bit stream.
Reflection Feedback and Noise

Even a relatively small reflections of light because of refractive-index discontinuities occurring at splices, connectors, and fiber ends affect the operation of semiconductor lasers and can lead to excess noise in the transmitter output.

The reason behind such a sensitivity is related to the fact that the phase of the reflected light can perturb the laser phase significantly even for relatively weak feedback levels.

There are several mechanisms through which the relative intensity noise (RIN) of a semiconductor laser can be enhanced by the external optical feedback.

BER measurements for a VCSEL operating at 958 mn and 500 Mb/s.