9 Optical point-to-point Communication Systems

1.28 Tb/s (10 Gb/s x 64 x 2) over 70 km OTDM-Transmission (Transmitter-Fiber-Receiver)

Tb/s Signal Processing by optical Nonlinear Material properties (eg. nonlinear optical fibers)
Goals of the chapter:

- Analysis of signal distortion between transmitter and receiver in a simple fiber-optic point-to-point link with respect to attenuation and pulse dispersion
- Qualitative estimate of the maximum transmission distance $L$ at a given signal data rate
- Quantitative characterization of the signal detection process and definition of the minimal detectable optical power for a particular type of signal distortion with respect to a detection error criterion

Methods for the Solution:

- Fiber attenuation $\alpha$ and addition losses $k$ or fiber dispersion $D$ define a maximum fiberlength $L_{\text{max}}$ for a given minimal received optical power $P_{\text{rec, min}}$
- For digital signals and only simple on-off keying with threshold detection we calculate analytically the minimal received optical power $P_{\text{rec, min}}$ as a function of a tolerated Bit-Error Rate (BER) under the influence signal- and receiver noise, dispersion, timing-jitter etc.
9 Electrical Time-Division Multiplex (ETDM):

The following basic building blocks form the elements of complex fiber-optic networks:

- **Optical fibers** and waveguides to guide the optical waves from transmitter to receiver
- **Laser** and **LED** for the generation (current modulation) of optical fields
- **Optical Amplifier** for simultaneous amplification of several optical waves with THz-bandwidth
- **Modulators** for modulating amplitude, phase and frequency of the optical carrier
- **Photodetectors** for efficient conversion between optical signal into electrical signals

Connecting these components into systems rises questions like:

- Transmission concept, transmission format and **network architecture**
- Transmission performance, **bandwidth** and **transmission distance**
- **Usage of available** transmission medium
- **Modulation techniques and formats**
- Economic and technological boundary conditions, extendibility, transmission guaranty and efficiency of the system

This chapter addresses some basic transmission concepts and techniques less on a system level, but in the context of the elementary **point-to-point-transmission** with the following goals:

**Goals:**

- Basic considerations of electrically multiplexed (time or frequency) optical point-point links with **incoherent** detection (intensity detection with PD)
- Quantitative limitations of transmission distance and data rates (Bit-Error Rates (BER) as a figure of merit)
- Signal power budgets of fiber optic links
Systems for transmission and distribution of information are **optical carrier frequency system**, where the base-band information is modulated incoherently or coherently onto an optical carrier. Optical waveguide obviously can not transmit baseband signals.

**RF and optical carrier frequency:**

Optical communication networks are constructed similar to wired and RF-networks from **elementary fiber-optic point-to-point links**:

**Communication networks**

consist of sub-networks:

1) Point-to-point links,

2) Star-

3) Bus- and

4) Ring-networks

Signal multiplexing can be in the time domain (TDM) or in the wavelength domain (WDM)
In analogy to RF-carrier-systems we classify optical carrier-frequency systems as:

- Analog or digital signal representation
- Incoherent (Intensity-) or coherent AM-, FM- and PM-signal modulation, resp. demodulation
- Digital (NRZ, RZ) coding
- Single- or multiple wavelength optical systems

In the following we consider only optical single frequency (wavelength)-systems, where the different signal-channels are multiplexed in the electrical time- or frequency domain.
Schematic Representation of a 40 Gb/s-ETDM-Systems: (typical)

Point-to-point links based on the incoherent intensity modulation / detection comprise the following generic link-elements:

- **Current - or external modulated laser source** (transmitter, regenerator)
- **Fiber-media (MM-, SM-fibers)**
- **Optical amplifiers** (optional)
- **Fiber- and waveguide components** (isolators, splitters and combiners, fiber-splicing, connectors, couplers, filters, polarizers, etc.)
- **Photodetection** (photoreceivers, regenerator)
- **Processing Electronics** (amplifiers, clock-extraction, data-detection (thresholding), …)

The whole MUX/DEMUX-Operation takes place in the electrical domain – the signal processing is carried out electronically and is limited by current IC-speed of about 40 Gb/s → 80 Gb/s (approaching 120 Gb/s in near future).
Electronic Bottle-Neck in MUX / DEMUX-functions:

It is obvious that the following electronic components in the ETDM configuration have to operate at the maximum data rate and are speed critical:

- Multiplexer (on the transmitter side)
- Modulator driver / Laser driver
- Preamplifier / Limiting-amplifier
- Clock-Extraction Circuit
- Threshold-Gate
- Demultiplexer

The fastest electronic ICs (only partially commercial) reach data rates of 40 Gb/s digital, resp. analog bandwidth ~30-40 GHz. These High Speed ICs are based on SiGe, InP or GaAs-transistors.

For data rates of 80-100 Gb/s there have been a only a few demonstrations-ICs realized in research labs.

80 Gb/s MUX with HEMT-Transistors:  (hero-experiment: 150Gb/s divider circuit)
Fiber optic systems evolved during the last 30 years through 5 system-generations characterized by different optical wave lengths, spectral source characteristics, fiber types and transmission formats:

**Evolution of fiberoptic System-Generations: BL-product vers. year**

<table>
<thead>
<tr>
<th>Generation</th>
<th>Light Sources</th>
<th>Wavelength (nm)</th>
<th>Fiber Attenuation (dB/km)</th>
<th>Fiber Dispersion</th>
<th>Detection</th>
</tr>
</thead>
<tbody>
<tr>
<td>First</td>
<td>GaAs LED and FP LD</td>
<td>800–900</td>
<td>&gt;5</td>
<td>Large</td>
<td>Incoherent</td>
</tr>
<tr>
<td>Second</td>
<td>III–V FP LD</td>
<td>1300</td>
<td>1 at 1330 nm</td>
<td>Minimal at 1300 nm</td>
<td>Incoherent</td>
</tr>
<tr>
<td>Third</td>
<td>III–V DFB LD</td>
<td>1300 and 1550</td>
<td>0.2 at 1550 nm</td>
<td>Minimal at 1300 nm</td>
<td>Incoherent</td>
</tr>
<tr>
<td>Fourth</td>
<td>III–V DFB and DBR LD</td>
<td>1300 and 1550</td>
<td>0.2 at 1550 nm</td>
<td>Dispersions shifted fiber for zero dispersion at 1550 nm</td>
<td>Incoherent</td>
</tr>
<tr>
<td>Fifth</td>
<td>III–V DFB and DBR LD</td>
<td>1300 and 1550</td>
<td>0.5 at 1300 nm</td>
<td>Optical amplifiers</td>
<td>Optical solitons</td>
</tr>
</tbody>
</table>

**9.1 Point-to-point links: general system considerations**

In the following we assume that the data format for modulation and detection is incoherent envelop (intensity)-modulation of the single- or multi-frequency optical carrier wave.

→ **Intensity-Modulation/Detection (ID)**; no information on optical phase used

\[ i_{ph}(t) \alpha E(t)E^*(t)_{Kurzzeit-MiWe} \neq f(\omega_{opt}, \phi_{opt}) \]
9.1.1 Point-to-point links (Prototype-structure, Intensity-modulation / detection)

Performance dominating are maximum the values, resp. the product of:

- **Data rate** $B_{ch}$ and
- **Fiber length** $L$

If the signal transmission or extraction is disturbed (noise, dispersion, attenuation, etc.) the received information will contain bit-errors (BE) at the receiver.

**Definition Bit Error Rate (BER):**

The figure of merit for signal disturbance in a transmission is the so called **Bit-Error-Rate (BER)** defined as **number of erroneous bits per unit time at a certain data rate** $B$, or equivalently the **probability that a bit is transmitted erroneously multiplied by the data rate** $B$.

**Main parameters influencing the BER:**

- **Signal-Distortion in the source / modulator:** (linear, nonlinear)
  - bandwidth, RIN and time-jitter of the diode laser / modulator / driver electronic

- **Signal-attenuation:**
  - Fiber attenuation $\alpha$, fiber length $L$
  - coupling losses Laser-Fiber, Laser-Modulator-Fiber, Fiber-optical amplifier and fiber-photodetector
Signal-dispersion:
- Fiber dispersion $D$, pulse broadening
- (dispersion in frequency selective components)
- (optical nonlinearity in fibers)
- (polarization effects in fibers and components)

Signal-Distortions in photoreceiver (mostly linear)
- Responsivity $R$ and frequency response of the photodetector, electronic pre-, main- and limiting amplifier
- Time-Jitter in the Clock- and Data-Extraction Circuit

Signal degradation by noise:
- Source noise: AM- and FM-noise from the SC-Laser (light intensity noise characterized by RIN)
- Noise of optical in-line and pre-amplifiers (characterized by noise figure $F$)
- Noise of the photodetector (shot-noise, APD-excess-noise)
- Noise of the electronic amplifier chain (gain: 1000-10’000) (opt. $P_{\text{in}} \sim \mu W$, elect. $P_{\text{out}}: \sim 10\text{mW}$)

To guarantee a certain maximum BER in a digital transmission with a data rate $B_{\text{ch}}$ several limiting requirements of the following characteristics are necessary to be met:

**Total analog System-Bandwidth $B \sim 0.7-0.8xB_{\text{ch}}$**

**Maximum total attenuation of the transmission length ($\alpha_{\text{eff}}L$) and minimal source power ($P_{\text{opt,in}}$)**

**Total-Noise budget (source, receiver)**

**Minimal received Signal Power $P_{\text{rec,min}}$ at BER at the receiver**
### 9.1.2 Power budget in a fiber-optic link (schematic)

Considering a simple point-to-point-link (without amplifier), we find the following **component power losses** \( k = \frac{P_{out}}{P_{in}} \):

- **Attenuation losses** of the fiber (proportional to the fiber length \( L \), \( k_{\text{faser}} = e^{-\alpha L} \))
- **Coupling losses (input)** Laser-Fiber (\( k_{\text{LF}} \))
- **Insertion loss** of an external modulator (\( k_{\text{MOD}} \)) (optional)
- **Total Fiber-Splice losses** (\( k_{\text{SPLICE}} \), mostly proportional to \( L \))
- **Coupling losses (output)** Fiber-Photodetector (\( k_{\text{PD}} \))

- **Amplification** in optical amplifiers (\( G_{\text{tot}} \))
- **Responsivity of the photodiode** (\( R \))

\( P_{s,\text{in}} \) is the modulated optical power emitted by the source. We determine the power on the receiving photodiode as \( P_{\text{out}} \):

\[
P_{\text{out}} = P_{s,\text{in}} (0) k_{\text{faser}} (L) k_{\text{LF}} k_{\text{MOD}} k_{\text{SPLICE}} k_{\text{PD}} G_{\text{tot}} = P_{\text{rec}} (L) > P_{\text{rec,min}} (BER, B_{\text{ch}})
\]

with

\[
P_{\text{out}} = P_{s,\text{in}} e^{-\alpha_{\text{faser}} L} e^{-\alpha_{\text{loss}} L} \quad \text{with} \quad \alpha_{\text{loss}} = \frac{1}{L} \ln \left( k_{\text{LF}} k_{\text{MOD}} k_{\text{SPLICE}} k_{\text{PD}} G_{\text{tot}} \right) \quad \text{(equivalent loss per unit length)}
\]

\( \alpha_{\text{loss}} \) are local losses, represented formally as distributed losses over the distance \( L \).

Depending on

1) the requested BER
2) the necessary signal bandwidth \( B_{\text{ch}} \)
3) and the noise properties of the receiver

the receiver is characterized by its **sensitivity**, resp. a minimal optical power \( P_{\text{rec,min}} \) required at its input (\( P_{\text{out}} > P_{\text{rec,min}} \)).
9.1.3 Attenuation Limit (loss limited BL-Product)

Transmission at low data rates $B_{ch}$ are usually not dispersion, but power limited. We get from the above relations the following value for a maximal fiber length $L_{\text{max,att}}$:

$$P_{s,\text{in}} e^{-\alpha_{\text{faser}}L_{\text{max,att}}} (k_{LF}k_{\text{MOD}}k_{\text{SPLICE}}k_{PD}) \geq P_{\text{rec,min}} (B_{ch}, \text{BER})$$

$$\rightarrow \quad L_{\text{max,att}} \leq \frac{1}{\alpha_{\text{faser}}} \ln \left\{ \frac{P_{s,\text{in}}}{P_{\text{rec,min}} (B_{ch}, \text{BER})} (k_{LF}k_{\text{MOD}}k_{\text{SPLICE}}k_{PD}) \right\}$$

We will show in this chapter, that $P_{\text{rec,min}}$ for a required BER and for the situation, where the signal-to-noise ratio (SNR) is determined by the noise of the photoreceiver, is given by the following relation

$$P_{\text{rec,min}} = Q(\text{BER}) \sigma / R$$

From the desired BER-value we get the following so called Q-factor (eg. BER=10^{-9} → Q=6)

$$Q(\text{BER}) = \frac{I_l}{2\sigma} = \frac{2RP_{\text{rec,min}}}{2\sigma}$$

$$\sigma = \sqrt{\text{RMS}} - \text{value of the equivalent current noise at the amplifier input}$$

$I_l = \text{photocurrent of the 1-Bit, with: } I_l = 2RP_{\text{rec,min}}$

$$\sigma^2 = k B_{ch} \rightarrow \text{noise power is proportional to the signal bandwidth}$$

$R = \text{responsivity of the photodetector [A/W]}$

Expressing the receiver noise:

$$Q = \frac{I_l}{2\sigma} = \frac{RP_{\text{rec,min}}}{\sqrt{k} \sqrt{B_{ch}}}$$

(without proof here) →

$$P_{\text{rec,min}} = Q(\text{BER}) \frac{\sqrt{k} \sqrt{B_{ch}}}{R} \approx k' \sqrt{B_{ch}} \quad \text{minimum required power at the receiver for a given BER}$$
We see $P_{rec,min}$ increases only with $\sqrt{B_{ch}}$, as a consequence $L_{max,att} \sim \ln\left(1/\sqrt{B_{ch}}\right)$ decreases relatively moderate with increasing data rates $B_{ch}$:

$$L_{max,att} \leq \frac{1}{\alpha_{faser}} \ln\left(\frac{P_{s,in}}{P_{rec,min}\left(B_{ch}, \text{BER}\right)} \left(k_{LF}k_{MOD}k_{SPLICE}k_{PD}\right)\right) = \frac{1}{\alpha_{faser}} \ln\left(\frac{P_{tot}}{P_{rec,min}\left(B_{ch}, \text{BER}\right)}\right)$$

Nonamplified Transmission distance $L$ versus Bit-Rate $B$ for different optical fibers:

![Diagram showing nonamplified transmission distance vs. bit rate for different fiber types](image-url)

- Attenuation limited
- Dispersion limited
9.1.4 Dispersion-Limitations (pulse broadening)

In chap.2 we considered the pulse broadening $\Delta t$ caused by the material-dispersion $D_{\text{mat}}$. In fibers there is an additional dependence of the propagation vector $\beta(\omega)$ of the fiber mode on the fiber geometry leading to mode-dispersion $D_{\text{mode}}$ (chap.3). The total dispersion is approximated by the sum of the dispersions:

$$D_{\text{fiber}} = D_{\text{mat}} + D_{\text{mode}}$$

The maximal allowable pulse broadening $\Delta T$ for a data rate $B_{ch}$ is:

$$\Delta T \leq k T_{\text{puls}} = 1 / B_{ch} \rightarrow \text{using } \Delta T = L_{\text{max,disp}} \left| D \Delta \lambda \right| \text{ and } k = 1 / 4 - 1 \text{ (typ.)}$$

$\Delta \lambda = \text{spectral optical width of the signal}$, $L_{\text{max,disp}} = \text{maximal, dispersion limited fiber length}$ with $k=1$

$$B_{ch} L_{\text{max,disp}} \left| D_{\text{fiber}} \right| \Delta \lambda \leq 1 \rightarrow$$

$$L_{\text{max,disp}}(B_{ch}) \text{ Maximum dispersion limited (ISI) fiber length}$$

(in a log L-log B-representation the curve $L_{\text{max,disp}}(B_{ch})$ decreases with $-10 \text{dB/DB}$)

Depending on the system generation the spectral width $\Delta \lambda$ of the source is dominated
a) by the large spectral width of the source (MM-FP-lasers) (older systems $\Delta \lambda \gg B_{ch} \lambda^2 / c$ Fourier-limited spectrum of the optical pulse)
b) or by the Fourier-limited pulse spectrum $\Delta \lambda \approx B_{ch} \lambda^2 / c$, resp. $\Delta \omega = B_{ch}$ (new systems with SM-DBR-lasers).

**System of the 1. Generation:** ($0.8 \mu m$ MM-FP-LD, Multimode-Fiber, $\Delta \nu = \frac{c}{\lambda^2} \Delta \lambda \gg B_{ch}$)

The bandwidth $\Delta \lambda$ of the laser source (multi-mode LD, opt. carrier) is much larger than the Fourier-transform of the digital signal (envelop) $B_{ch}$. The fibers have been multimode-fibers with very high mode dispersion.

**System of the 2. Generation:** ($1.3 \mu m$ MM-FP-LD, Singlemode-Fiber, Multimode Source Spectrum $\Delta \nu = \frac{c}{\lambda^2} \Delta \lambda \gg B_{ch}$)

Use of standard single-mode fibers with a dispersions-minimum at $1.3 \mu m$ and $1.3 \mu m$ multi-longitudinal mode FP-diode lasers.
$\Delta \lambda \sim 2\text{-}3\text{nm} \ (\Delta \nu \rightarrow 200\text{-}400 \text{GHz}) , \ \lambda = 1.35 \mu \text{m}, \ D \sim 0\text{-}10 \text{ps/km/nm}$

$$BL \bigg| D \bigg| \Delta \lambda \leq 1 \quad \rightarrow \quad L_{\max} = \frac{1}{B_{ch} \bigg| D \bigg| \Delta \lambda} \sim \frac{1}{B_{ch}} \quad (-10 \text{dB} / DK)$$

**System of the 3. Generation:** (1.3μm SM-DBR-LD, SM-fiber and singlemode source)  
$\delta \nu = \frac{c}{\lambda^2} \delta \lambda \ll B_{ch}$

The bandwidth $\delta \lambda$ of the unmodulated laser source (DBR-laser) is much smaller than the Fourier-transform of the digital signal $B_{ch} = \Delta \nu$. Use of dynamically stable DFB-diode laser and standard fibers operated in the dispersion minimum at 1.3μm.

$\delta \lambda \sim 0.01 \text{ nm} \ (\rightarrow \nu_{opt} \sim 1\text{-}2 \text{ GHz}) , \ \lambda = 1.35 \mu \text{m} \ (\text{operation close to the dispersion minimum}), \ D \sim 0 - 5\text{-}10 \text{ps/km/nm}$

$$\nu = \frac{c}{\lambda} \rightarrow \Delta \nu = B_{ch} = -\frac{c}{\lambda^2} \Delta \lambda$$

$$B_{ch} L_{\max,\text{disp}} \bigg| D \bigg| \Delta \lambda \leq B_{ch}^2 L_{\max,\text{disp}} \bigg| D \bigg| \frac{\lambda^2}{c} \leq 1 \quad \rightarrow \quad L_{\max,\text{disp}} = \frac{1}{B_{ch}^2 \bigg| D \bigg| \frac{\lambda^2}{c}} \sim \frac{1}{B_{ch}^2} \quad (-20 \text{DK} / DK)$$

**System der 4. Generation:** (1.55μm SM-DBR-LD, SM-fiber and narrow band sources)  
$\delta \nu = \frac{c}{\lambda^2} \delta \lambda \ll B_{ch}$

The bandwidth $\delta \lambda$ of the lasers source (DBR-laser) is much smaller than the Fourier-transform of the digital system $B_{ch} = \Delta \nu_{opt}$. Use of optical amplifiers, external modulators and WDM-concepts (optical multi-carrier systems).

$\delta \lambda \sim 0.01 \text{ nm} \ (\rightarrow \nu_{opt} \sim 1\text{-}2 \text{ GHz}) , \ \lambda = 1.55 \mu \text{m}, \ D \sim 5 \text{ps/km/nm} \ (\text{Increasing use of dispersion-shifted fibers at 1.55μm})$
Dispersion at the „Dispersions-minimum $\lambda_{ZD}$“:

Because of the finite spectral width $\Delta\lambda \geq B_{ch}\lambda^2/c$ of any optical signal and because of the frequency dependence of the dispersion $D(\lambda)$ the dispersion only becomes zero for one precise wavelength $\lambda_0 = \lambda_{ZD}$: Therefore the signal dispersion can be minimized, but does not vanish completely:

Average dispersion $\overline{D} = 2\Delta D$ for a signal spectrum $\Delta \lambda$:

$$D(\lambda) = D(\lambda_{ZD}) + \frac{\partial D}{\partial \lambda} \mid_{\lambda_{ZD}} \Delta \lambda \Delta \lambda + \left[ \frac{\partial^2 D}{\partial \lambda^2} \right]_{\lambda_{ZD}} \Delta \lambda^2 + \ldots \right) = \Delta D = S \Delta \lambda = 2\overline{D}$$

We define $S = \frac{\partial D}{\partial \lambda} \mid_{\lambda_{ZD}}$

with $B_{ch} = \Delta v$, $\lambda = \frac{c}{\nu}$ $\rightarrow \Delta \lambda = -\frac{\lambda^2}{c} B_{ch}$ (fourier-limited)

$$B_{ch} L_{\text{max,disp}} \mid \Delta \lambda \geq B_{ch} L_{\text{max,disp}} \mid S \mid \Delta \lambda^2 = B_{ch}^3 L_{\text{max,disp}} \mid S \mid \left( \frac{\lambda^2_{ZD}}{c} \right)^2 \leq 1$$

$$\rightarrow L_{\text{max,disp}} = \frac{1}{B_{ch}^3 S} \left( \frac{\lambda^2_{ZD}}{c} \right)^{-2} \sim \frac{1}{B_{ch}^3}$$

Dispersion at the Dispersion minimum $\lambda_{ZD}$

System of the 5. Generation: (1.55$\mu$m SM-DBR-LD, SM-Fiber, single mode source $\delta \nu = \frac{c}{\lambda^2} \delta \lambda \ll B_{ch}$, and optical amplification)

Similar to the 4. Generation but including WDM and optical amplifiers.
9.2 Noise properties of optical receivers

9.2.1 3-R-receiver concept

Optical signals are corrupted during generation, transmission, detection and signal processing by attenuation of the amplitude, pulse-broadening and addition of noise (source-, amplification-, detection-noise and noise from the electronic processing).

To restore the signal amplitude the attenuation must be compensated by electronic gain. This „reamplification“ (R) restores the signal amplitude, but not the pulse form (eg. pulse width T) and does not eliminate noise.

Before the pulse broadening becomes to excessive leading to symbol-interference, or the pulse amplitude comparable to the system noise the pulses have to be electronically regenerated in so called repeater circuits (3R-regeneration)

- reamplification (R₁)
- regeneration of pulse form (R₂) and
- resynchronisiert (R₃) of the pulses to the bit-clock of the system

Schematic electronic 3R-Regenerator circuit:

![3R-Regenerator circuit diagram](image)

CL = Clock-signal

Today the functions R₂ and R₃ are still realized electronically, which limits data rates to the speed of digital high speed ICs.
9.2.2 Concept of Detections (Digital RZ or NRZ-transmission)

If we could consider the whole transmission chain “driver current-source-laser-fiber-detector-amplifier-detection filter” as a linear system with the input-output-frequency response $H_T(\omega)$ and the total impulse response $h_T(t)$, then the general signal response is the convolution-operation between $i_{LD}(t)$ and $h_T(t)$:

$$v_{out}(t) = \int_{-\infty}^{+\infty} i_{LD}(t') h_T(t - t') dt'$$

$$V_{out}(\omega) = I_{LD}(\omega) \cdot H_T(\omega) = I_{LD}(\omega) \cdot H_{Laser}(\omega) \cdot H_{Fiber}(\omega) \cdot H_{PhotoDetector}(\omega) \cdot H_{Amplifier}(\omega) \cdot H_{Filter}(\omega)$$

with:

$v_{out} = \text{amplifier output voltage}$

$i_{LD} = \text{laser current}$

$h_T = \text{total impulse response}$

**Signal Eye-diagram of $v_{out}(t)$:**

For digital signal transmission of random bit-sequences the so called eye-diagram as the superposition of all possible $v_{out}(t)$ in a particular bit-time slot $T$ for all possible bit-pattern of $i_{LD}(t)$ characterizes the transmission with respect to pattern-distortion and noise.
Schematic NRZ-eye-diagram: NRZ-eye-diagram 1) ideal and 2) with attenuation and dispersion:

\[ t_D = \text{Sampling time} \]

Ideal \((\alpha=0, D=0, \text{component bandwidth } B=\infty)\)

With attenuation (reduced amplitude) and pulse broadening (symbol-interference) \(\Rightarrow\) but not BER

Reduction of the **eye-opening** in amplitude and pulse width and on-set of symbol-interference from neighboring bit-slots.

NRZ-eye-diagram with **attenuation, dispersion, time-jitter and noise**:

Jitter results in a stochastic time shift \((\delta t)\) of the bits, resp. level-transitions.
Noise leads to a stochastic variation of the actual signal value. Both effects reduce the „eye-opening with high error-free detection probability“.

In the ideal case one would chose the **signal sampling time** \(t_D\) for detection of \(v_{out}(t)\) at \(t_D=(m+1/2)T, m=0,1,2, \ldots\) (activation of the threshold switch) and the **decision-level** \(V_D\) at \((v_{1\text{-Bit}}+v_{0\text{-Bit}})/2\).
For ideal eye-diagrams the sampling time and the decision level are in the centre of the maximal eye-opening.

The presence of attenuation, dispersion, jitter and noise reduces the „eye-opening“ and the position of the sampling time and decision level has to be optimized (eg. dynamically, if the noise sources change) for minimum BER.

In a statistical sense the eye-opening represents the „sampling area with low bit-errors“ and should be as large as possible.

### 9.2.3 Detector- and Receiver Noise

The above eye-diagram of $v_{out}(t)$ shows that at the sampling time $t_D$ the amplitudes of the 1- and 0-level fluctuate due to the noise processes around an average value:

**1-Level:**

$$
 v_{out,1}(t_D) = \overline{v}_{out1} + \Delta v_{out1}(t_D)
$$

**0-Level:**

$$
 v_{out,0}(t_D) = \overline{v}_{out0} + \Delta v_{out0}(t_D)
$$

For simplicity reasons we consider in the following the input signal currents $I(t)$ at the transimpedance amplifier input (because $v_{out}(t)=R_{tr}I(t)$). All noise currents are referenced to this input:

$$
 I_D(t_D) = \overline{I}_D + i_{n,D}(t_D) \quad 1\text{-Bit}
$$

$$
 I_0(t_D) = \overline{I}_0 + i_{n,0}(t_D) \quad 0\text{-Bit}
$$

instantaneous value=average value+noise

Assuming that the variables $i_n(t)$ of the current noise processes are ergodic = sample average = time average:

\[
\sigma^2 = \lim_{T \to \infty} \frac{1}{T} \int_{0}^{T} i_n^2(t) dt = \int_{-\infty}^{\infty} i_n^2 p(i_n) di_n = \int_{0}^{B} i_n^2 (f) df
\]

$\sigma=variance$, $i_n^2(f) =$ noise power spectral density, $B= detection bandwidth$

$\sigma^2=average power in bandwidth B$

$p(i_n(t)) =$ probability density of finding $i_n(t)$ in the interval $i_n \pm di_n / 2$
We assume a Gaussian noise process, which a Gaussian amplitude-distributions for $i_n$

$$p(i_n) = \frac{1}{\sqrt{2\pi} \sigma} \exp\left(-\frac{i_n^2}{2\sigma^2}\right)$$

**Noise sources of the receiver:**

**A) Photodetection – Noise (Shot-noise):**

As discussed in chap.7 the photodetection is a statistical process of quantized events leading to shot-noise and a shot-noise current $i_{ph,n}$ in the photocurrent $i_{ph}(t) = \overline{i}_{ph} + i_{ph,n}(t)$. For photon fluxes which are not extremely small the detection noise process can be approximated by a Gaussian random process.

Spectral noise power density of the photocurrent: (no noise of the optical source RIN=0)

$$i_{ph,n}^2(f) = 2e\overline{i}_{ph}$$

related to the noise power $\sigma_{ph}^2$ in a bandwidth $B$ by: 

$$\sigma_{ph}^2 = \lim_{T\to\infty} \frac{1}{T} \int_0^T i_{ph,n}^2(t) \, dt = \int_0^B i_{ph,n}^2(f) \, df = 2e\overline{i}_{ph}B$$

$i_{ph,n}^2(f)$= noise power density spectrum of $i_{ph,n}(t)$

$B$=receiver bandwidth (resp. effective noise bandwidth)

**B) Amplifier – Noise (thermal noise and shot-noise):**

Transistors in circuits produce thermal and shot-noise, similar ohmic resistors produce thermal noise.

Globally the effect of all internal noise sources in the amplifier circuit after the PD can be reproduced by two equivalent input noise sources $i(t)$, $u(t)$ and a noise-free circuit. The two correlated input noise-sources are the equivalent current- and voltage-noise sources $i(t)$ and $u(t)$, described by their variances:

$$\sigma_i^2 = \lim_{T\to\infty} \frac{1}{T} \int_0^T i_r^2(t) \, dt = \int_0^B i_r^2(f) \, df ; \quad \sigma_u^2 = \lim_{T\to\infty} \frac{1}{T} \int_0^T u_r^2(t) \, dt = \int_0^B u_r^2(f) \, df$$
Thermal noise of feedback $R = R_n$:

$$i_{n,R}^2(f) = 4kT/R$$

The values of these equivalent noise sources are a figure of merit of the noise properties of a circuit and are usually independent from the input signal. (for details see: course of Ellinger and Jäckel: Integrated Circuits for High Speed Communications)

**Example:** simple transimpedance circuit with OP-Amps: (see exercise)

Transimpedance Amplifier $v_{out} = -RI_{ph}$:

$$v_{out} = -RI_{ph}$$

Transimpedance-circuit with Internal noise sources:

$$v_{out} = -RI_{ph} - i_{eq,n}(t)$$

noise-free circuit with external equivalent noise sources:

$$v_{out} = -RI_{ph}$$

Concept:

$i_{eq,n}(t)$ should produce the same output noise $v_{out,n}^2$ as $u_r(t)$, $i_r(t)$ and $i_{nR}(t)$.

$$R_n \to 0$$

Signal amplification:

$$v_{out}(t) = -RI_{ph}(t)$$

Equivalent input noise current (noise current density):

$$v_{out,n} = Ri_{eq,n}(t) = i_{n,R}(t)R + i_r(t)R + u_r(t) \to i_{eq,n}(t) = i_R(t) + i_r(t) + u_r(t)/R$$

→ autocorrelation / Fourier - transform

noise power spectrum:

$$i_{eq,n}^2(f) = 4kT/R + i_r^2(f) + u_r^2(f)/R^2 + 2\text{Re}\left(i_ru_r^*(\omega)\right)/R = S_n(f)$$

correlation neglected
9.2.4 Receiver Sensitivity and Bit-Errors

Signal/Noise-Ratio (SNR) and Bit-Error Probability:

For analog signal processing the previous noise analysis provided the spectral noise power density $S_n(f) = i_{eq,n}^2(f)$, resp. the signal/noise-ratio $SNR = \frac{i_{ph}^2}{(i_{eq,n}^2(f)B)} = \frac{i_{ph}^2}{\sigma_n^2}$ of a circuit block.

Practically we are interested in the following question with regard to analog signals:

**If we tolerate a signal error in a measurement, then what is the probability to exceed the tolerated error ($\Delta\%$)?**

For digital signals with only 2 discrete signal-levels 0 or 1, the question is modified to:

**What is the probability, that a certain bit current superposed by noise is detected erroneously by a sampled ($t_D$) threshold $I_D$ detection, eg. a 0-level $I_0(t_D)$ is detected as a 1-level, or vice-versa?**

It is plausible that in the presence of noise a bit-error probability appears, resp. a bit-error-rate (BER=bit error rate). Intuitively we expect that the BER increases with decreasing SNR, because the signal is masked by more noise. We are looking for the functional relationship between BER and SNR.

It should not be overlooked that there are signal-dependent (source noise RIN, shotnoise of PD) or signal-independent (eg. amplifier noise) parts in the noise spectrum.

Digital Signal Processing:

(schematic):

- $t_d = $ sampling time
- $I_D = $ threshold current
Assumptions:

We are considering two discrete 1 and 0 signal levels $I_1, I_0$ with noise $i_{n,1}(t), i_{n,0}(t)$ and $l_0(t) \equiv \text{"0"}$, which are sampled at the time $t_D$ within the bit-time slot $T$ and compared with a noise-free threshold value $I_D$:

$$I_1(t_D) = I_1 + i_{n,1}(t_D) > I_D \rightarrow \text{Detection "1" right decision}$$

$$I_1(t_D) = I_1 + i_{n,1}(t_D) < I_D \rightarrow \text{Detection "0" wrong decision (bit error) due to } i_{n,1}(t_D)$$

$$I_0(t_D) = I_0 + i_{n,0}(t_D) > I_D \rightarrow \text{Detection "1" wrong decision (bit error) due to } i_{n,0}(t_D)$$

$$I_0(t_D) = I_0 + i_{n,0}(t_D) < I_D \rightarrow \text{Detection "0" right decision}$$

$i_{n,1}(t), i_{n,0}(t)$ are the momentary noise signals of level 1 and 0. The noise amplitudes are assumed to show a Gaussian amplitude statistic $P(i_n)$, characterized by:

**Noise average:** $\overline{i_n(t)} = 0$

**Noise power spectral density:** $S_n(f) = i_{eq}(f) \geq 0$ (known)

**Noise square average, variance:** $\overline{i_{n,1}(t)^2} = \sigma_n^2 = \int_{-\infty}^{+\infty} S_n(f) df \approx S_nB$

**Gaussian probability distribution:** $p(i_n) = \frac{1}{\sigma_n \sqrt{2\pi}} e^{-\frac{(i_n)^2}{2\sigma_n^2}}$
Graphical Representation of the Amplitude Statistics:

Probability \( P(1/0) \) of a bit-error at 1-bit: (detecting 0 instead of 1)

using \( i_{n1} = I_1 - \bar{I}_1 \)

\[
P(1/0) = \frac{1}{\sigma_{n1}\sqrt{2\pi}} \int_{-\infty}^{I_D-I_1} \exp\left(-\frac{(i_{n1})^2}{2\sigma_{n1}^2}\right) di_{n1} = \frac{1}{\sigma_{n1}\sqrt{2\pi}} \int_{-\infty}^{I_D} \exp\left(-\frac{(I_1 - \bar{I}_1)^2}{2\sigma_{n1}^2}\right) dI_1 = \frac{1}{2} \text{erfc}\left(\frac{I_1 - I_D}{\sqrt{2}\sigma_{n1}}\right)
\]

\( \text{erfc} \) = complementary errorfunction

Probability \( P(0/1) \) of a bit-error at 0-bit: (detecting 1 instead of 0)

\[
P(0/1) = \frac{1}{\sigma_{n0}\sqrt{2\pi}} \int_{I_D-I_0}^{\infty} \exp\left(-\frac{(i_{n0})^2}{2\sigma_{n0}^2}\right) di_{n0} = \frac{1}{\sigma_{n0}\sqrt{2\pi}} \int_{I_D}^{\infty} \exp\left(-\frac{(I_0 - \bar{I}_0)^2}{2\sigma_{n0}^2}\right) dI_0 = \frac{1}{2} \text{erfc}\left(\frac{I_D - I_0}{\sqrt{2}\sigma_{n0}}\right)
\]

If in a bit-sequence the 1-bit appears with a probability \( p(1) \) and the 0-bit with \( p(0) \) then their bit-error probability BEP is:

\[\text{BEP} = p(0)P(0/1) + p(1)P(1/0) \quad \text{with} \quad p(1) + p(0) = 1\]
If 0- and 1-bits have equal probabilities:

\[ p(1) = p(0) = 1/2 \]

\[
Ber = \frac{1}{2} \left[ P(0/1) + P(1/0) \right] = \frac{1}{4} \left[ \text{erfc} \left( \frac{I_1 - I_D}{\sqrt{2} \sigma_{n1}} \right) + \text{erfc} \left( \frac{I_D - I_0}{\sqrt{2} \sigma_{n0}} \right) \right] = f \left( I_D, \sigma_{n1}, \sigma_{n0}, I_1, I_0 \right)
\]

Because the optimal detection threshold \( I_D \) is not yet determined, we choose \( I_D \) in such a way, that BEP becomes minimal:

\[
\frac{\partial Ber}{\partial I_D} = 0 \rightarrow \frac{I_1 - I_D}{\sigma_{n1}} = \frac{I_D - I_0}{\sigma_{n0}} = Q \quad \text{resp.} \quad I_D = \frac{\sigma_{n0} I_1 + \sigma_{n1} I_0}{\sigma_{n0} + \sigma_{n1}}
\]

This requirements results in the optimal BER of:

\[
Ber = \frac{1}{2} \left[ \text{erfc} \left( \frac{Q}{\sqrt{2}} \right) \right] \approx \frac{1}{Q \sqrt{2\pi}} \exp \left( -\frac{Q^2}{2} \right) \quad \text{with the definition of} \ I_D : \ Q = \frac{I_1 - I_0}{\sigma_{n0} + \sigma_{n1}} \quad \text{(with optimal threshold)}
\]

Graphical Representation of BER(Q):

![Graphical Representation of BER(Q)](image)

<table>
<thead>
<tr>
<th>Noise ( \sigma ) ↑</th>
<th>Q ↓</th>
<th>BER ↑</th>
<th>Amplifier-, source, jitter</th>
</tr>
</thead>
<tbody>
<tr>
<td>I₁ ↑</td>
<td>Q ↑</td>
<td>BER ↓</td>
<td>Source power, attenuation, losses, dispersion</td>
</tr>
<tr>
<td>I₀ ↑</td>
<td>Q ↓</td>
<td>BER ↓</td>
<td>On-off ratio, dispersion</td>
</tr>
</tbody>
</table>

Solution Procedure:

\[ BER = 10^{-12} \rightarrow Q = 7 \]

\[ BER = 10^{-9} \rightarrow Q = 6 \]

given: BER → Q → \( \frac{I_1 - I_0}{\sigma_{n0} + \sigma_{n1}} \) I₁, I₀, I_D → \( P_{\text{rec,min}} \)
The Q-value only depends on the noise variance and signal \( \sigma_n \) and \( I \), resp. of the \( \text{SNR} = I^2 / \sigma^2 \) of the two signal levels. We only get a simple relation for the ideal case, when the 0-level is ideal 0 and the noise is independent of the signal level:

\[
\sigma_0 = \sigma_1 = \sigma_n, \quad I_0 = 0 \quad \rightarrow \quad Q = \frac{I_i}{2\sigma_n} = \frac{1}{2} \sqrt{\text{SNR}} \quad \rightarrow \quad I_i = 2Q \sigma_n
\]

The non-ideal cases, where eg. the noise level of the detection system is signal dependent, has to be discussed for the particular case. Practically the BER is given and the SNR, resp. the required minimal signal power \( P_{\text{rec},\text{min}} \) is the quantity we are looking for.

**Receiver-sensitivity, minimal detectable power:**

With a given BER we get \( Q(\text{BER}) \) and the minimal detectable average power \( P_{\text{rec},\text{min}} \) gives \( P_{\text{l},\text{min}} R = 2P_{\text{rec},\text{min}} R = I_{\text{l},\text{min}} \). \( R \) is the responsivity of the photodetector and \( B_{\text{ch}} \) is the bandwidth of the receiver (assuming a 50% ratio between 1's and 0's):

\[
2\sigma_n Q(\text{BER}) = RP_{\text{l},\text{min}} = 2RP_{\text{rec},\text{min}} \rightarrow \frac{P_{\text{rec},\text{min}}}{R} = \frac{\sigma_n}{\sqrt{\sigma_n^2 B_{\text{ch}}}} Q(\text{BER}) \equiv \frac{Q(\text{BER})}{\sqrt{S_n B_{\text{ch}}}}
\]

**Minimal received power for** \( \sigma_0 = \sigma_1 = \sigma_n, \quad I_0 = 0 \) and frequency and signal independent \( S_n \)

- The minimal received power increases with noise and for lower BER
- For systems limited by receiver noise: \( P_{\text{rec},\text{min}} \sim \sqrt{B_{\text{ch}}} \)
- For the attenuation limit \( L_{\text{max}} \sim 1/P_{\text{rec},\text{min}} \)
- For dispersion limited systems \( P_{\text{rec},\text{min}} \) is modified by the details of the pulse distortion mechanisms (jitter, etc.)
9.2.5 Additional Mechanisms for BER-Degradation

Additional noise processes increase the minimal detectable power $P_{\text{rec,min}}$ and are characterized by the ratio of the minimal detect. powers with and without the particular noise effect (power penalty, increased $P_{\text{rec,min}}$)

$$\frac{P_{\text{rec,min}} (\text{with noise effect})}{P_{\text{rec,min}} (\text{without noise effect})} > 1$$

assuming that in both cases the BER, resp. the Q-factor must be the same.

9.2.5.1 Intrinsic Noise-Limit by Quantum-Noise - Detection Limit

In the most ideal case of a noise-free preamplifier there is only inherent shotnoise of the detection process itself (+ source noise): (here the detection noise is signal dependent!)

$N_p =$ number of photons per bit, 1-level: $N_p$ photons with shot noise, 0-level: $N_p=0$ photons with no shot noise,

$\eta =$ quantum efficiency of the photodetector (electrons per photon)

$T = 1/B =$ bit time-slot

$$P_{\text{opt,1}} = \frac{N_p}{T} \ h \omega \quad ; \quad I_1 = eN_p \eta / T \quad ; \quad I_0 = 0 \quad \eta =$ detector efficiency

$$Q = \frac{I_1}{\sigma_n} = \sqrt{\text{SNR}} = \frac{I_1}{\sqrt{2eI_1}\Delta f} = \frac{e\eta \frac{N_p}{T}}{\sqrt{2e^2\eta \frac{N_p}{T}}} = \sqrt{\eta \frac{N_p}{T} / (2B)} = \sqrt{\eta \frac{N_p}{2}} \rightarrow N_p \eta = 2Q^2$$

$$BER = \frac{1}{2} \text{erfc} \left( \frac{Q}{\sqrt{2}} \right) = \frac{1}{2} \text{erfc} \left( \sqrt{\eta \frac{N_p}{4}} \right)$$

quantum-noise for intensity detection (not heterodyne)

Example: eg. $\text{BER}=10^{-9} \rightarrow Q=6 \rightarrow \eta \ N_p > 72$ photons!
9.2.5.2 BER-Reduction due to the finite Extinction Ratio (qualitative)

If the intensity of the 0-level is not ideally zero, that is \( I_0 > 0 \), this results in a reduction of the eye-opening and an increase of the BER due to the reduced on-off-ratio \( I_i / I_0 = P_{on} / P_{off} = 1 / r_{ex} \).

To keep the BER identical the power of the 1-level has to be increase accordingly (without proof):

\[
\text{The increase of the extinction ratio } r_{ex} \text{ would lead to a reduction of the factor } Q, \text{ resp. to the increase in the BER.}
\]

The increased \( P_{rec,min}(r_{ex}>0) \), resp. the increase in the of the average signal power \( P_{rec} \), compared to the ideal situation \( P_{rec,min}(r_{ex}=0) \), defines the power penalty, compensating the decrease of \( Q \).

\[
r_{ex} = P_0 / P_1 \quad \text{extinction ratio} \\
\frac{I_i}{\sigma_{n1} + \sigma_{n0}}_{r_{ex}=0} = \frac{R P_1(r_{ex}=0)}{\sigma_{n1} + \sigma_{n0}} = Q \quad \text{from eg. p.9–26} \\
\frac{I_i - I_0}{\sigma_{n1} + \sigma_{n0}}_{r_{ex}=0} = \frac{R P_1(r_{ex}>0) - R P_0(r_{ex}>0)}{\sigma_{n1} + \sigma_{n0}} = 1 - r_{ex} \\
\frac{2R P_{rec}(r_{ex}>0)}{\sigma_{n1} + \sigma_{n0}}_{non–ideal, r_{ex}>0} = \frac{1}{2} \text{ with } P_{rec} = \frac{P_1 + P_0}{2}
\]

1dB penalty \( \rightarrow \approx 0.1 \text{ extinction ratio} \)
9.2.5.3 BER-Reduction due to intensity noise of the source (qualitative)

Laser sources also exhibit intrinsic noise in the emitted power, which is described as Relative Intensity Noise (RIN) defined as \( RIN(\omega) = \frac{I_{\text{opt}}^2(\omega)}{I_{\text{opt}}^2} = \frac{P_{\text{opt}}^2(\omega)}{P_{\text{opt}}^2} \), resp. \( \sigma_{\text{RIN}}^2 = \frac{\sigma_{\text{RIN}}^2}{2\pi} \int_0^B RIN(\omega) d\omega \).

For the detection process the RIN-noise is treated as part of the optical modulation signal.

As the 1- and 0-level have different RIN-values, \( RIN(P_{\text{on}}) \) and \( RIN(P_{\text{off}}) \), this results in an increase of the total variances \( \sigma_{n1} \) and \( \sigma_{n0} \) of the 1- and 0-level. This causes an increase in the BER, resp. the minimal received power for keeping BER constant and a loss in maximal transmission distance \( L_{\text{max}} \).

This degradation can be described by a power penalty:
\[ \sigma_{1,\text{tot}} = \sqrt{\sigma_{1,\text{RIN}}^2 + \sigma_i^2} = \sqrt{R^2 P_i^2 \left\{ \frac{1}{2\pi} \int \text{RIN}(\omega) d\omega \right\} + \sigma_i^2} \quad \text{with } \sigma_i^2 = \text{detector-shot noise and thermal noise of the receiver for the 1-level} \]

\[ \sigma_{0,\text{tot}} = \sqrt{\sigma_{0,\text{RIN}}^2 + \sigma_0^2} = \sqrt{R^2 P_0^2 \left\{ \frac{1}{2\pi} \int \text{RIN}(\omega) d\omega \right\} + \sigma_0^2} \quad \text{with } \sigma_0^2 = \text{detector-shot noise and thermal noise of the receiver for the 0-level} \]

Simplifying, if \( P_0 = 0 \rightarrow \)

\[ Q = \frac{2R P_{\text{rec}} (\text{RIN} > 0)}{\sigma_{1,\text{tot}} + \sigma_0} = \frac{2R P_{\text{rec}} (\text{RIN} = 0)}{\sigma_i + \sigma_0} \rightarrow \text{with some simple algebra} \]

Intensity noise power penalty:

\[ \delta_{\text{RIN}}(Q) = 10 \log \left( \frac{P_{\text{rec}} \left\{ \frac{1}{2\pi} \int \text{RIN}(\omega) d\omega \right\}}{P_{\text{rec}} (\text{RIN} = 0)} \right) = -10 \log \left( 1 - Q^2 \frac{1}{2\pi} \int \text{RIN}(\omega) d\omega \right) \]

(without proof, see Agrawal)

Observe that for \( \frac{1}{2\pi} \int \text{RIN}(\omega) d\omega = 1/Q^2 \) \( \delta_{\text{RIN}} \) becomes infinite, meaning that even infinite signal power does not decrease the BER anymore which results in a so called “noise-floor”.

### 9.2.5.4 BER-Reduction due to time-jitter (qualitative)

Dynamic processes in the modulated source, the driver- and detection electronic, as well as in the fiber result in time fluctuations \( \delta t \) of the arrival time of the pulses in their associated time slots.

Assuming that the fluctuations \( \delta t \) are represented by a Gaussian process with known \( \overline{\delta t} = 0, \quad \sigma_{\delta t} > 0 \), then, as the following figure shows qualitatively, this jitter leads to a reduction of the “vertical” eye-opening at a fixed detection time \( t_d \).
The effective reduction of the eye-opening and the resulting effective increase of the level-noise, increases the BER described by a power penalty $\delta_{\text{jitter}}$.

$\delta_{\text{jitter}}$ causes an increase of the minimal received power or a loss in maximal transmission distance $L_{\text{max}}$.

Assuming a particular signal shape, then $\delta I_{\text{on}}(\delta t)$ can be determined, with the Bit-time $T=1/B$

For cos$^2$ – Pulse: $h(t) = \cos^2 \left( \pi B t / 2 \right) = \cos^2 \left( \pi t / (2T) \right)$

follows for the jitter – Power – Penalty:

$$\delta_{\text{jitter}} = 10 \log \left( \frac{P_{\text{rec}}(b)}{P_{\text{rec}}(0)} \right) = 10 \log \left( \frac{1-b/2}{(1-b/2)^2 - b^2 Q^2 / 2} \right)$$

$\overline{\delta^2 t} = \tau_{\text{jitter}}^2$ with $\tau_{\text{jitter}} =$ rms-value of the timing-jitter

$$b = \frac{4}{3} \left( \pi^2 - 6 \right) B^2 \tau_{\text{jitter}}^2$$

Jitter of more than 13% of the Bit-timeslot $T$ lead to a power penalty larger than 1dB!
We omitted the coherent optical modulation techniques, which realize in comparison to the considered intensity modulation format slightly better SNR, but are not frequently use to-day because of their considerable requirements (frequency stability of laser sources) on the optical components (see Kap.11 Appendix).

Optical single wavelength systems are mostly limited by the bandwidth (< 40-100 GHz) of electronics, laser modulators and photodetectors. The usage of the available fiber bandwidth of ~10 THz is very modest. Transmitting several different carrier wavelength through the same fiber (OWDM=optical wavelength multiplexing) will improve the total data rate and bandwidth usage considerably.

Conclusion / Summary:

- Depending on data rate, spectral width of the source $\Delta \lambda$, dispersion $D$, attenuation $\alpha$ and fiber length $L$ optical links are attenuation or dispersion limited
- At low data rates $B$ the attenuation and the noise properties of the receiver dominate the maximum transmission distance $L_{\text{max}}$
- At high data rates $B$ fiber dispersion and receiver noise become dominant
- As a practical figure of merit for the whole link or for the receiver alone the bit-error-rate BER is used, which defines for a given bit rate $B$ the necessary optical power at receiver $P_{\text{rec, min}}$
- Additional effects such as timing-jitter, finite on-off ratio etc reduce the BER and are commonly characterized by the power penalty $\delta$ for the $P_{\text{rec, min}}$. 