3. Design of single-channel IM/DD systems

Optical Communication Systems and Networks
BIBLIOGRAPHY

- **Theory:**
  
  Fiber-Optic Communications Systems  

- **Problems:**
  
  Fiber-Optic Communications Systems  

  Lightwave Technology. Telecommunication Systems  

  Problemas de Comunicaciones Ópticas  
Two conditions must be satisfied in order to guarantee the correct performance of optical links:

- **Power budget**
  - Guarantees that optical power levels at the receiver are proper to satisfy quality parameters such as: OSNR, BER, SNR, Q ... 

- **Time budget (rise or fall time)**
  - Guarantees that the set composed by optical source + optical medium + optical receiver perform fast enough to follow variations associated to the conveyed signal without introducing any kind of distortion.
A set of requisites is imposed and must be taken into consideration during the design stage of an optical communication system:

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They must guarantee specific values of BER or SNR along a distance $L$ and a bit rate $B$
Optical Power Budget

Optical power at the receiver must be equal or higher than the photodetector sensitivity $S$ (*minimum power detected*) to assure quality criteria (BER, SNR, ...)

$$S, P_{RX_{min}} \text{(dBm)} \leq P_{TRX} \text{(dBm)} - L_c - SM$$

Power at the receiver is determined by: channel losses $L_c$, and the security margin $SM$

*SM*: Security margin is a value in dB introduced in the power budget in order to assure the correct performance in case of arising not foresable events (losses, degradation, derives ... in employed optical devices). SM takes values ranged between 4 and 12 dB. SM is usually considered about $MS = 6$ dB.
Channel losses, $L_c$

$$L_c = L_{\text{source}_\text{fiber}} + \alpha \cdot L + N_e \cdot \alpha_e + N_c \cdot \alpha_c + L_{\text{fiber}_\text{detector}} + L_{\text{topol}} + L_{\text{penal}}$$

(1) and (5) collect coupling losses, on one hand, between the optical source and the optical fiber, and on the other hand, between the fiber and the detector.

(2) represents losses caused by the attenuation coefficient [dB/km] along a link $L$ [km] long.

(3) And (4) collect losses produced by splices and connectors distributed along the link: $N_c$ and $N_e$ are the number of splices and connectors, respectively. $\alpha_e$ and $\alpha_c$ represent losses per splice or connector, respectively.

(6) Takes into account losses produced by distribution or intermediate points (insertion losses, typically) due to the presence of couplers, passive stars, add-drop multiplexers, taps, splitters...

(7) Power penalties are defined to introduce indirectly the effect caused by different phenomena along the optical length.
Power Penalties

The optical receiver sensitivity is affected by physical phenomena which, in combination with fiber dispersion, degrade the SNR.

It is needed to define power penalties in order to take into account effects degrading the receiver sensitivity.

Power penalties are considered to increase the power level at the receiver input so that degradation effects are compensated in order to guarantee a quality criterion.

Power penalty is defined as follows:

\[
\text{Penalty} = 10 \log_{10} \left( \frac{\text{Power in presence of degradation}}{\text{Power in absence of degradation}} \right) \text{ [dB]}
\]
Power Penalties

The most common power penalties considered in the power budget are:

- Relative intensity noise, RIN
- Modal partition noise, MPN
- Modal noise
- Extinction ratio
- Dispersion broadening
- Mode-partition noise
- Frequency chirp
- Jitter
- Reflection feedback
Relative Intensity Noise

- The output of a semiconductor laser presents fluctuations in intensity, phase, and frequency even when the laser is biased at a constant current with negligible current fluctuations.
  - Intensity fluctuations lead to a limited signal-to-noise ratio
  - Phase fluctuations lead to a finite spectral linewidth (laser biased with a constant current)

- There are two main noise sources: spontaneous emission processes (dominant) and noise due to the pairs e/h recombination
  - Each photon emitted spontaneously adds a small field component with random phase to the coherent field generated from stimulated emission processes
  - These effects occurred at high rates (~$10^{12}$ s$^{-1}$) due to the high rate of spontaneous recombination in semiconductor lasers
  - As a result, the signal phase and intensity present temporal fluctuations of the order of 100 ps

These effects can modify operation conditions in optical communication systems so power penalties are introduced in the design stage
Relative Intensity Noise

- The receiver converts power fluctuations into current variations
  - additional electrical noise is added to shot and thermal noise causing the SNR degradation.
- \( r_I \) parameter indicates a noise level measurement of the incident optical signal, and it is related to the RIN (relative intensity noise) of the transmitter
  - The power penalty is related to the Q (directly related to BER).

\[
\begin{align*}
\delta_I &= 10 \log_{10} \left( \frac{P(r_I)}{P(0)} \right) = 10 \log_{10} (1 - r_I^2 Q^2) \\
\end{align*}
\]

\[
\begin{align*}
\frac{r_I^2}{2} = \frac{1}{2\pi} \int_{-\infty}^{\infty} RIN(\omega) d\omega \\
\end{align*}
\]
Relative Intensity Noise

- Typical values are below $r_I < 0.01$ for most optical transmitters, which corresponds to a RIN penalty lower than 0.02 dB, which is considered negligible.
Relative Intensity Noise

- The previous analysis assumes that intensity noise in the receiver is same as that generated by the transmitter.

- In practice, **RIN can be enhanced** as the optical signal propagates through the optical fiber due to several factors:
  - Intensity **noise** introduced by optical amplifiers (following a "in line configuration") limits this factor in long distance systems.
  - Feedback from optical **undesired reflections** produced by optical elements: connectors, devices ...
  - The use of multimode semiconductor lasers (eg Fabry-Perot) in a dispersive medium such as the optical fiber, may cause quality degradation signal through the arising of **partition modal noise**.
Modal Partition Noise

Multimode semiconductor lasers present **modal partition noise, MPN**

Longitudinal modes fluctuate in time, interchanging energy among them, in such a way that several modes can present **intensity fluctuations** whereas the total power remains constant.

In absence of dispersion, this variation can be harmless since different modes would be "synchronized" during transmission and detection.

In practice, they travel at different group velocities due to the presence of dispersion:
- Causing additional fluctuations
- Reducing SNR in reception

In multimode lasers, **modal partition noise penalty** $\delta_{\text{mpn}}$ is given by:

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

Where $r_{\text{mpn}}$ is the relative noise associated to the received power.
When a laser present a linewidth $\sigma_\lambda$, the $r_{mpn}$ factor is given by:

$$r_{mpn} = \frac{k}{\sqrt{2}} \left\{ 1 - e^{-[\pi BLD\sigma_\lambda]^2} \right\}$$

- $B$ is the bit rate, $L$ is the link length, $D$ is the dispersion parameter, $\sigma_\lambda$ is the source's linewidth, and $k$ is the modal partition noise coefficient (statistical correlation among different modes).
- $k$ varies from laser to laser. Experimental measurements provide values of $k$ in the range 0.6–0.8.

It is assumed that modes fluctuate in such a way that the total power remains constant in CW.
Modal noise

Interference among various propagating modes in a multimode fiber creates a *speckle pattern* at the photodetector.

This pattern usually fluctuates over time, and the presence of fluctuations in the received power, called *modal noise*, degrade the SNR.

Modal noise is strongly affected by the source spectral bandwidth $\Delta \nu$:

- mode interference occurs only if the coherence time, $T_c \approx 1/\Delta \nu$, is longer than the intermodal delay time $\Delta T$: $T_c > \Delta T$
- For the particular case of using LEDs as transmitters, $\Delta \nu$ is large enough ($\Delta \nu \sim 5$ THz) so that $T_c > \Delta T$ is not satisfied.

Modal noise becomes a serious problem when semiconductor lasers are used as source in optical systems in combination with multimode fibers. For this reason, most optical systems based on multimode fibers use LEDs to avoid the modal-noise (in short reach applications).
Speckle patterns

Dotted circles represent photodetector surface

The pattern displacement causes variations in the generated photocurrent, since big light dots are lost over the detector’s surface.

When the pattern is uniform, the amount of lost light is reduced producing a low level of noise in the generated photocurrent.
Modal noise

- In systems based on single-mode fibers, modal noise does not degrade quality signal.

- The use of vertical-cavity surface-emitting lasers (VCSEL) in short links in combination with multimode fibers leads to a high modal noise penalty.

- This is a result of having a long coherence length and oscillating in a single longitudinal mode.

- This problem can be reduced by using larger-diameter VCSELs which oscillate in several transverse modes and have a shorter coherence length.

Descriptive behavior of Modal Noise Penalty as a function of mode selective losses

N = longitudinal modes exceeding a % of the peak power.
 Dispersion penalty

- Dispersion-induced pulse broadening can also affect the receiver performance:
  1. An amount of the pulse energy spreads beyond the bit slot causing intersymbol interference (ISI)
  2. Pulse amplitude is reduced when the optical pulse broadens causing a decrease of the SNR at the decision circuit

- SNR must remain constant during the system performance. Under these conditions, the receiver could require a higher average power

→ As a result, the introduction of a dispersion penalty is required in the power budget, and is given by $\delta_d = 10 \log_{10} f_b$, where

$$f_b = \left[ 1 + \left( \frac{DL\sigma_\lambda}{\sigma_0} \right)^2 \right]^{1/2}$$

Where $f_b$ is the broadening factor
Pulse’s broadening factor $f_b$:

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

Where: $\sigma$ is the pulse duration (rms) at the output, $\sigma_0$ is the pulse duration (rms) at the input and $\sigma_\lambda$ is the source’s linewidth (rms), $D$ is the dispersion parameter and $L$ is the length of the link.

A common criterion used to evaluate the broadening effect corresponds to:

$$\sigma \preceq \frac{T_{bit}}{4} = \frac{1}{4B}$$

Taking into consideration $f_b$

$$f_b^2 = 1 + (4BLD\sigma_\lambda f_b)^2 = 1 + (4\sigma_D f_b)^2$$

Then, the dispersion penalty is given by:

$$\delta_d = -5 \log_{10} \left(1 - (4\sigma_D)^2\right)$$
Chirp penalty

- When a semiconductor laser is directly modulated by a high capacity IM/DD signal, variations are responsible for a spectrum broadening
  - **Chirp** arises as a result of changes in the medium refractive index due to variations in the carrier density in the laser cavity where laser emission is produced

**Consequences:**

1. Source’s spectral width can be increased due to a phase modulation effect
2. This effect combined with dispersion can impose severe limits in the maximum bit rate transmitted (particularly in 3rd window systems operating with standard single-mode fiber, SMF)

- The power penalty calculation by chirp is complex due to the combination of aspects to consider such as the shape and the duration of transmitted pulses
Chirp penalty

- A change in the refractive index will involve a change in the phase of the signal propagating through the optical medium

\[
\delta v(t) = -\frac{1}{2\pi} \frac{\partial \phi}{\partial t} = \frac{1}{2\pi} \frac{C}{T_0^2} t
\]

The temporal variation in the phase produces a variation in the frequency, where \( C \) is the frequency offset parameter or chirp, \( T_0 \) is the half width intensity at 1/e (Gaussian pulse)

- Penalty for the simplest chirp effect (ignoring the pulse shape) is given by:

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

where the spectral shift is associated with a frequency shift caused by \( C \)

- This expression is valid provided that the duration of \( t_c \) frequency shift is less than:

\[
t_c > (LD\Delta \lambda_c)
\]

(typical values of \( t_c \) ranges from 100 and 200 ps)
Chirp penalty

- Usually, the previous condition is not satisfied in high capacity systems (B>2Gbps)
- When the shape of pulses is assumed Gaussian and chirp is considered linear, keeping the $4\sigma \leq 1/B$ criterion, chirp penalty is defined as:

$$\delta_c = 5\log_{10}[(1 + 8C\beta B^2L)^2 + (8\beta B^2L)^2]$$

$$= 5\log_{10}[(1 + 8C\sigma_d)^2 + (8\sigma_d)^2], \sigma_d = \text{dispersion parameter}$$
Extinction ratio

- The **extinction ratio** is used to describe the performance of an optical transmitter in a IM/DD system.
- It corresponds to the ratio of the energy (power) used to transmit a logic level ‘1’ to the energy used to transmit a logic level ‘0’, and it is defined as:

\[ r_{\text{ext}} = \frac{P_0}{P_1} \]

- Ideally \( P_{\text{0}} = 0 \), although in practice \( P_{\text{0}} \neq 0 \).
- This behavior depends on:
  1. Spontaneous emission noise
  2. Bias /pol. Intensity (above threshold current, \( I_{\text{th}} \))

This pushes to consider the **extinction ratio penalty**

\[ \text{Penalty} = 10 \log_{10} \left( \frac{1 + r_{\text{ext}}}{1 - r_{\text{ext}}} \right) \]

Ideally \( r_{\text{ext}} = 0 \), but usually \( r_{\text{ext}} > 0 \).
Extinction ratio

- When the ratio $r_{\text{ext}}=0.12$, a extinction penalty of 1 dB is obtained.

- In practice, extinction ratios are neglected when lasers presenting ratios of $r_{\text{ext}}$ lower than 0.05 ($P_{0}$ is the 10% of $P_{1}$).
Extinction ratio and Chirp-induced effect

In practice, the chirp power penalty depends on many system variables:

- Chirp can be reduced by biasing the semiconductor laser above threshold → the extinction ratio $r_{ex}$ is increased
Timing jitter penalty

- Receiver sensitivity is considered when the signal is sampled at the peak of the voltage pulse.

- In practice, the decision instant is determined by the clock-recovery circuit and by the sampling time which can fluctuate from bit to bit producing timing jitter.
  - This effect usually leads to a SNR degradation of the system.

- When the bit is not sampled at the center of the bit time interval, the sampled value is reduced which depends on the timing jitter $\Delta t$.

- $\Delta t$ is a random variable, so the reduction in the sampled value is also random.

SNR can be maintained by increasing the received optical power through the introduction of a power penalty induced by timing jitter in the power budget.
Timing jitter penalty

- In an optical system in which receiver consist of a pin photodiode dominated by thermal noise $\sigma_T$, assuming a zero extinction ratio and $I_0 = 0$, the parameter $Q$ is given by

$$Q = \frac{I_1 - \langle \Delta i_j \rangle}{(\sigma_T^2 + \sigma_j^2)^{1/2} + \sigma_T}$$

where $\Delta i_j$ is the average value of the photogenerated current, and $\sigma_j$ is the RMS value of the current fluctuation $\Delta i_j$ induced by timing jitter $\Delta t$.

- $\sigma_j$ depends on the shape of the signal pulse at the decision current
- $\Delta t$ uses to be much smaller than the bit period $T_B = 1/B$, then $\Delta i_j$ can be approximated as follows:

$$\Delta i_j = (2\pi^2/3-4)(B\cdot \Delta t)^2 I_1$$

Defining the parameter $b$ as:

$$b = (2\pi^2/3-4)(B\cdot \tau_j)^2$$

where $\tau_j$ is the RMS value (standard deviation) of $\Delta t$
Knowing $I_1 = 2 R P_{\text{rec}}$, where $R$ is the responsivity, the receiver sensitivity is:

$$
\bar{P}_{\text{rec}}(b) = \left( \frac{\sigma_T Q}{R} \right) \frac{1 - b/2}{(1 - b/2)^2 - b^2 Q^2 / 2}
$$

The **timing jitter penalty** is given by:

$$
\delta_j = 10 \log_{10} \left( \frac{\bar{P}_{\text{rec}}(b)}{\bar{P}_{\text{rec}}(0)} \right) = 10 \log_{10} \left( \frac{1-b/2}{(1-b/2)^2 - b^2 Q^2 / 2} \right)
$$
Reflections penalty

- Different reflection sources can appear as a result of connections between two components in a communication link:
  - Refractive index differences (causing Fresnel reflections)
  - Noise produced by the injection of a small amount of feedback power inside the laser cavity
  - Connections between fiber and devices
  - Connectors/splices between fibers (angular, lateral and longitudinal deviations, different diameters and ANs, ...)

- Main problem: Feedback reflections

- Possible solutions:
  - Using a liquid/gel for matching the refractive index between media (elimination/reduction of Fresnel reflections)
  - Introducing optical isolators (block optical signals which are "reflected" and transmitted in the opposite direction of propagation).
Rise-Time Budget

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

- In a linear system, the rise time $T_r$ 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.

Optical transmitter and receiver are bandwidth limited. This affects to the time response.

Optical fiber can limit the minimum broadening of transmitted pulses as a result of dispersion.

\[ V_{out}(t) = V_o \left(1 - e^{-t/RC}\right) \]

The bit rate can not exceed the speed of the overall response: SOURCE + FIBER + RECEIVER.
Rise-Time Budget

- An **inverse relationship** exists between the **bandwidth** $\Delta f$ and the **rise time** $T_r$ associated with a linear system.

  - Taking a simple $RC$ circuit, the input voltage changes instantaneously from 0 to $V_0$.

    Then, the output voltage changes as $V_{\text{out}}(t) = V_0 [1 - \exp(-t/RC)]$

    The rise time is given by $T_r = (\ln 9) RC \approx 2.2 RC$

- The **transfer function** $H(f)$ of the $RC$ circuit is obtained by taking the Fourier transform:

  $$H(f) = (1 + i2\pi fRC)^{-1}$$

- Then, the **bandwidth** $\Delta f$ of the $RC$ circuit corresponds to $\Delta f = (2\pi RC)^{-1}$

- $\Delta f$ and $T_r$ are related according to:

  $$T_r = 2.2 \cdot 2\pi \Delta f = 0.35 \cdot \Delta f$$
Rise-Time Budget

- The relationship between the bandwidth $\Delta f$ and the bit rate $B$ depends on the digital format:
  - Return-to-zero (RZ) format: $\Delta f = B$
  - Non return-to-zero (NRZ) format: $\Delta f \approx B/2$

Then, $BT_r = 0.35$ in the RZ case, and by contrast, $BT_r = 0.7$ in the NRZ case.

- During the design stage of an optical communication system must be ensured that **system rise time** $T_r$ must be below or equal to the maximum value imposed by the bit rate $B$:

$$T_r \leq \begin{cases} 
0.35 & \text{for RZ format} \\
\frac{0.70}{B} & \text{for NRZ format}
\end{cases}$$
Rise-Time Budget

\[ T_{r \text{sys}} = \sqrt{T_{r \text{TX}}^2 + T_{r \text{OF}}^2 + T_{r \text{RX}}^2} \]

The bit rate can not exceed the speed of the overall response: SOURCE + FIBER + RECEIVER

\[ B \propto \frac{1}{T_r} \]

- \( T_{r \text{TX}} \): Transmitter rise time
- \( T_{r \text{OF}} \): Optical fiber rise time
- \( T_{r \text{RX}} \): Receiver rise time
- \( T_{r \text{sys}} \): System rise time
Rise-Time Budget

- Assuming a linear behaviour again, transmitter’s and receiver’s rise time, $T_{r_{TX}}$ and $T_{r_{RX}}$, are related to their operation bandwidth as:

\[
T_{r_{TX}} = \frac{0.35}{\Delta f_{TX}} \quad \text{and} \quad T_{r_{RX}} = \frac{0.35}{\Delta f_{RX}}
\]

where $\Delta f_{TX}$ and $\Delta f_{RX}$ are the transmitter and receiver bandwidths, respectively.

- And the optical fiber rise time $T_{r_{OF}}$ taking into account contributions of Intermodal $T_{inter}$, chromatic $T_{chrom}$ and polarization mode dispersion $T_{PMD}$:

\[
T_{r_{OF}} = \sqrt{T_{r_{inter}}^2 + T_{r_{chrom}}^2 + T_{r_{PMD}}^2}
\]

Depending on the type of fiber considered and parameters as length and transmitter features.
Rise-Time Budget

- In **Multimode Fibers**:

  In this type of fibers, the magnitude of intermodal dispersion makes the chromatic contribution negligible. Then:

  $$T_{r\,OF} \approx T_{r\,modal}$$

  Depending on the fiber and assuming that refractive index of the cladding and the core are very similar ($n_1 \approx n_2$), modal dispersion is given by:

  - **step index profile**:
    $$T_{r\,modal} \approx (n_1\Delta/c)L$$

  - **graded index profile**:
    $$T_{r\,modal} \approx (n_1\Delta^2/8c)L$$

  ($\Delta$ is the relative index difference and $L$ is the optical link length)
Rise-Time Budget

- In Single-mode Fibers:

The rise time in single-mode fibers is produced by the chromatic dispersion $D$ and modified according to the spectral characteristics of the optical source, $\Delta \lambda$ along an optical fiber of $L$ long:

$$T_{r\ OF} \approx T_{r\ chromatic}$$

Where: $T_{r\ chromatic} = |\Delta \lambda| \cdot D \cdot L$, and if the linewidth was negligible (also operating in 3rd window):

$$T_{r\ chromatic} = \sqrt{\frac{\beta_2 L}{2\sigma_0}}$$, where $\sigma_0$ is the initial duration of the optical pulse

Furthermore, in case of long distance and high rate systems, an additional dispersive term caused by polarization mode dispersion becomes important

$$T_{r\ OF} \approx T_{r\ chromatic} + T_{r\ PMD}$$

Where: $T_{r\ PMD} = D_{PMD} \sqrt{L}$
Proposed problem
Design of a Passive Optical Network

It is intended to design a fiber optic network operating at 1550 nm and based on technology MI / DD to provide TV service to a residential area consisting of 16 user premises. RZ coding is employed with a duty cycle of 25%. The units are distributed within an area, whose maximum length with regard to the emitting source is 10 km, as shown schematically in the figure.

It is based on a topology determined by the use of passive stars (1 x 4 symmetrical optical splitters), employing at all joint points connectors FC / APC with typical losses of 0.2 dB. As far as the type of optical fiber is concerned, standard single-mode fiber 9/125 (D = 18 ps / km • nm and $\alpha = 0.2$ dB / km at 1550 nm) is used.
Proposed problem
Design of a Passive Optical Network

As an optical source, an FP-diode laser is used with a spectral width of 4 nm. Its intensity is modulated by pulses with a initial duration of 2 ns, so that the power associated to the "0" is a 25% of that corresponding to "1". The coding process is done so that the bits "0" and "1" are equiprobable. The laser has a spectral density of relative intensity noise (RIN) of -115 dB/Hz, which remains constant in the spectral range in which the detector operates.

The access to the user premises is via an optical network unit (ONU). The optical receiver is inside, and it consists of a PIN photodiode dominated by thermal noise (operation temperature, T = 27° C), and presents a quantum efficiency of 0.8, a load resistor of 50 Ω, and a bandwidth of 1GHz.

Additional requirements to take into account:

(1) It is recommended a safety margin of 6 dB.
(2) Consider the source spectral width and pulse duration initial in terms of RMS.
(3) Assume negligible effects caused by modal partition noise and jitter.