Optical Transmission – Lecture 2

Propagation impairments
Do you speak dB (deciBels) ?

• We often express ratios in dB (logarithmic) scale

\[ X = \frac{A}{B} \implies X_{dB} = 10 \log_{10} (X) \]

• 1x ↔ 0dB, 2x ↔ 3dB, 10x ↔ 10dB

• Product of ratios = sum in dB

\[ 10 \log_{10}(X_1 \ast X_2) = X_{1,dB} + X_{2,dB} \]
Do you speak dB?

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- 1 ↔ 0 dB, 2 ↔ 3 dB, 10 ↔ 10 dB

- Product of ratios = sum in dB

  \[ 10 \log_{10}(X_1 \cdot X_2) = X_{1,\text{dB}} + X_{2,\text{dB}} \]
  \[ 10 \log_{10}(X_1 / X_2) = X_{1,\text{dB}} - X_{2,\text{dB}} \]

- We also express powers in dBm

  \[ P_{\text{dBm}} = 10 \cdot \log_{10} \left( \frac{P_{\text{Watt}}}{10^{-3}\text{Watt}} \right) \]

- Product of power \( P_1 \) by ratio \( X \)

  \[ P_{2,\text{dBm}} = P_{1,\text{dBm}} + X_{\text{dB}} \]

- ! We can sum Watts, not dBm
Capacity = \( N_{\text{spatial modes}} \times N_{\text{wavelengths}} \times N_{\text{polar}} \times N_{\text{bit/symbol}} \times \frac{\text{Symbol Rate}}{\text{Overhead (FEC, signaling)}} \)

- Software-defined “Coherent” transceivers
  - Linear receiver assisted by high rate Digital Signal Processing enables mitigation of line impairments…
  - and adaptation of bit-rate (modulation) to Quality of Transmission (distance, signal to noise ratio)
One transmission line, multiple sources of signal impairments

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One transmission line, multiple sources of signal impairments

### Physical effects and Mitigation

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**Diagram:**

- **Laser + Modulator 1**
- **Laser + Modulator 2**
- **Laser + modulator N-1**
- **Laser + Modulator N**
- **Multiplexer**
- **Optical Amplifier**
- **Fibre**
- **Demultiplexer**
- **Receiver 1**
- **Receiver 2**
- **Rx. (N-1)**
- **Rx N**
### Physical effect  | Impact                  | Mitigation                                      | Limitations, metrics                  
--- | --- | --- | --- 
Attenuation  | Undetectable Signal     | Optical amplification                           | Amplifier noise, SNR<sub>ASE</sub>    
Chromatic Dispersion Frequency dep. Speed  | Pulse broadening       | Inline-optical Electronic Dispersion compensation | Imperfect compensation               
Kerr effect (power → phase)  | Power-dep. Distortions | Dispersion management, electronic mitigation    | Repeater count & power
### One transmission line, multiple sources of signal impairments

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<td>Phase &amp; polar shifts</td>
<td>Temperature = 0 K …</td>
<td>Length, Effective area</td>
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**Diagram Description**

- **Laser + Modulator 1**
- **Laser + Modulator 2**
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- **Rx N**

**Key Terms**

- **ASE**: Amplifier spontaneous emission noise
- **SNR**: Signal-to-noise ratio
- **Dispersion compensation**: Methods to correct for frequency-dependent speed
- **Power-dep. distortions**: Distortions caused by power variations
- **Dispersion-management**: Techniques to manage dispersion effects
One transmission line, multiple sources of signal impairments

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<td>Time-varying distortions</td>
<td>Electronic mitigation</td>
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Impact of fiber attenuation

Fiber attenuation is low (0.15dB/km) but not enough to reach 1000 km.
From optical amplification to amplifier noise

Optical amplifier: **Erbium Doped Fiber Amplifier** (EDFA)
Amplification by Stimulated Emission

Limitation: **Amplified Spontaneous Emission** (ASE)
Principles of optical amplification

Energy of a photon: \( \frac{h \cdot c}{\lambda} = h \nu \)

Level 1: Fundamental

Level 2: \( E_2 \leftrightarrow 1550\, \text{nm} \) (193THz)

Level 3: \( E_3 \leftrightarrow 980\, \text{nm} \) (306 THz)

All Erbium ions in the fundamental state
Principles of optical amplification
Optical pumping

Energy of a photon: \( \frac{h \cdot c}{\lambda} = h \nu \)

Energy states of Erbium

Level 1: Fundamental
Level 2: \( E_2 \leftrightarrow 1550\text{nm} \) (193THz)
Level 3: \( E_3 \leftrightarrow 980\text{nm} \) (306 THz)

1. Pump photon absorption
2. Fast transition (µs)

Erbium ions

Pump photons transfer Erbium ions into an excited state
Principles of optical amplification

Optical pumping

Energy states of Erbium

1. Fundamental
2. $E_2 \leftrightarrow 1550\text{nm}$ (193THz)
3. $E_3 \leftrightarrow 980\text{nm}$ (306 THz)

Erbium ions

Energy of a photon: $\frac{hc}{\lambda} = h\nu$

Pump photons transfer Erbium ions into an excited state
Principles of optical amplification
Population inversion

Energy states of Erbium

- Fundamental Level 1
- Level 2: $E_2 \leftrightarrow 1550\text{nm}$
- Level 3: $E_3 \leftrightarrow 980\text{nm}$

Energy of a photon: $\frac{h \cdot c}{\lambda}$

Strong pump power: almost all ions in level 2
Ready for signal amplification!
Principles of optical amplification

Incoming signal photons in presence of population inversion

Energy states of Erbium

Energy of a photon: $\frac{h \cdot c}{\lambda}$

Level 3: $E_3 \leftrightarrow 980\text{nm}$
Level 2: $E_2 \leftrightarrow 1550\text{nm}$
Fundamental Level 1

Competition between stimulated (+spontaneous) emission and absorption
Population inversion $\Rightarrow$ Amplification (+ spontaneous emission noise)
Principles of optical amplification with EDFA
Wideband amplification

Energy states of Erbium

1568nm
1530nm

1530-1610nm
980nm

Energy of a photon: $\frac{h \cdot c}{\lambda}$

Level 3: $E_{13} \leftrightarrow 980$nm
Level 2: $E_{12} \leftrightarrow 1530$-1610nm

Fundamental Level 1

Stark effect: myriad of sublevels $\rightarrow$ amplification over wide range of wavelengths
Gain and population inversion

\[ G(\lambda_s) = \sigma_e(\lambda_s)N_2 - \sigma_a(\lambda_s)N_1 \]

\[ N_1 + N_2 = N_t \]

Whatever the inversion, the gain is not flat!

With a constant gain (population inversion) one can control the spectral profile using a fixed equalization optical filter.
Typical optical amplifier with optical equalization

Typical features of subsea repeaters

- Total output power: up to 21dBm
- Equalizing filter adapted to fixed inter-amplifier section (span)
- Flatness within ±0.1dB over up to 5THz (40nm)
- Noise figure ~ 4-5 dB
Quality of transmission parameter: OSNR

Amplified Spontaneous Emission (ASE)
  - Additive Gaussian Noise
  - Broadband noise: >4THz, 30nm

Optical Signal to Noise Ratio (OSNR)

\[
\text{OSNR}_{B_{ref}} = \frac{P_{\text{signal per channel}}}{P_{\text{noise,2 polars}},B_{ref}}
\]

Expressed in dB, generally w/in 0.1nm (12.5GHz)
Amplifier characteristics:
Total Output Power (TOP), noise figure (NF)

- Generated ASE noise:
  $$P_{ASE, B_{ref}} = NF \times G \times \frac{hc}{\lambda} \times B_{ref}$$

- OSNR after 1 amplifier
  - Depends on input power
  $$OSNR_{B_{ref}} = \frac{P_{in per channel}}{NF} \times K, \text{ with } K = \frac{\lambda}{hc*B_{ref}}$$
Amplifier characteristics:
Total Output Power (TOP), noise figure (NF)

• Generated ASE noise:
  \[ P_{\text{ASE,ref}} = NF \times G \times \frac{hc}{\lambda} \times B_{\text{ref}} \]

  - Noise Figure (ITU)
  - Amplifier gain
  - Photon energy

• OSNR after 1 amplifier
  • Depends on input power

  \[ OSNR_{\text{B,ref}} = \frac{P_{\text{in per channel}}}{NF} \times K, \quad \text{with} \quad K = \frac{\lambda}{hc\times B_{\text{ref}}} \]

  \[ OSNR_{0.1\text{nm,dB}} = 58 + P_{\text{tot,in,dBm}} - N_{b\text{channels,dB}} - NF_{dB} \]
Cascade of N identical repeaters

- Generated ASE noise:
  - \( \ast \cdot N \)

- OSNR after N amplifiers
  - Assuming same signal input power

\[
OSNR_{dB,0.1nm} = 58 + P_{tot,out,dBm} - Loss_{dB} - Nb_{channels,dB} - NF_{dB} - N_{dB}
\]
Application: reach of terrestrial vs submarine systems

- $OSNR_{dB,0.1nm} \approx 58 + P_{out,total,dBm} - #channels_{dB} - Loss_{dB} - NF_{dB} - N_{repeaters,dB}$
- $SpanLoss_{dB} = Attenuation_{dB/km} \ast Repeater-spacing_{km}$

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OSNR in open cables: conventional vs natural bandwidth

• Convention: 0.1nm → OSNR depends on terminal (# channels)
• Natural: channel spacing → OSNR does not depend on terminal

\[
SNR_{ASE} = \frac{P_{signal,channel}}{P_{noise,channel \ spacing}} = \frac{P_{signal,total}}{P_{noise,total}}
\]
OSNR in open cables: conventional vs natural bandwidth

• Convention: 0.1nm → OSNR depends on terminal (# channels)
• Natural: channel spacing → OSNR does not depend on terminal
• Conversion:

\[ SNR_{ASE,dB} = OSN R_{ASE,B_{ref},dB} + 10 \times \log_{10} \left( \frac{B_{ref}}{\text{Channel spacing}} \right) \]

or

\[ SNR_{ASE,dB} \approx 38.9 + P_{out,tot,dBm} - Loss_{dB} - NF_{dB} - N_{rep,dB} - 10 \log_{10}(Ampl. Band_{THz}) \]
General formula of a cascade of amplifiers (1/3)

• OSNR degradation in presence of existing noise ($\text{OSNR}_{\text{in}}$)

$$\frac{1}{\text{OSNR}_{\text{out}}} = \frac{\mathbf{P}_{\text{sig, in}}}{\mathbf{P}_{\text{ASE, in}}} + \mathbf{P}_{\text{ASE, local}}$$
General formula of a cascade of amplifiers (2/3)

• OSNR degradation in presence of existing noise ($OSNR_{in}$)

$$\frac{1}{OSNR_{out}} = \frac{1}{OSNR_{in}} + \frac{1}{OSNR_{local}}$$
General formula of a cascade of amplifiers (3/3)

- OSNR degradation in presence of existing noise ($\text{OSNR}_{\text{in}}$)

\[
\frac{1}{\text{OSNR}_{\text{out}}} = \sum_{k=1}^{N} \frac{1}{\text{OSNR}_{\text{local},k}}
\]

- Depends on $P_{\text{sig,in},k}$
Exact OSNR with constant power amplifiers: signal & ASE droop

- Submarine repeaters = constant output power

- A fraction of total power is converted into noise
- The proportion of input signal decreases $\Rightarrow$ attenuation / droop

\[
\frac{P_{\text{total}}}{P_{\text{signal}}} = \frac{P_{\text{signal}} + P_{\text{noise}}}{P_{\text{signal}}} = 1 + \frac{1}{SNR_{\text{ASE}}}
\]

(SNRs expressed in channel spacing band)
Exact SNR after a cascade of repeaters

- Cascade of fixed power amplifiers: product of attenuations matters
  \[ 1 + \frac{1}{SNR_{ASE}} = \prod_{k} \left( 1 + \frac{1}{SNR_k} \right) \]
  Generalized droop (of signal and ASE)

- 1\textsuperscript{st} order approximation:
  \[ SNR_{Droop,1st\ order} = SNR_{theo} - \frac{1}{2} \quad \text{(for SNR>2dB)} \]
  \[ OSNR_{Droop,1st,B_{ref}} = OSNR_{theo,B_{ref}} - \frac{1}{2} \cdot \frac{\text{Ch.spacing}}{B_{ref}} \]

[J.-C. Antona et al, Mo1J.6, OFC’19]
C+L wide-band amplification

• Most amplifiers operate in the C-band
  • 1528-1570nm
  • High gain => short EDF

• Possible operation in the L-band
  • 1570-1610nm
  • Low gain ➔ long EDF

• Wideband C+L amplifiers
  • Separate amplifiers and band Demux/Mux
  • Higher bandwidth, with a price to pay…
(Distributed) Raman amplification

- Erbium process enables constant power operation
- Yet Raman amplification
  - bandwidth and gain shape are tunable
  - can be distributed along the line fiber → low NF

Stimulated process

Molecular vibrations of SiO₂

13THz (~100nm)

Resulting gain shape

Gain by pump 2

Gain by pump 1

(Dynamic) gain tilt management possible.
Raman-assisted amplification schemes

Conventional backward scheme

Bidirectional scheme

Second-order backward pumping

(Naturally, (b) and (c) may be combined...)

(Example: 15dB total Raman gain in all configurations)
Refinement: Wavelength dependence Gain

- Despite filter at amplifiers + periodic Equalizers along the line
- Wavelength-dependent OSNR \(\Rightarrow\) reduction of average OSNR
- Coping with that:
  - Today: (O)SNR equalization by channel power adjustment (pre-emphasis)
  - Future ?: wavelength-dependent bit-rate
## One transmission line, multiple sources of signal impairments

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### Diagram:

- **Laser + Modulator 1**
- **Laser + Modulator 2**
- **Laser + Modulator N-1**
- **Laser + Modulator N**
- **Multiplexer**
- **Fibre**
- **Optical Amplifier**
- **Demultiplexer**
- **Receiver 1**
- **Receiver 2**
- **Rx. (N-1)**
- **Rx N**

- **Laser + Modulator**
- **Multiplexer**
- **Optical Amplifier**
- **Demultiplexer**
- **Receiver**

### Optical Amplifier Components:

- Laser + Modulator
- Multiplexer
- Optical Amplifier
- Demultiplexer
- Receiver

### Mitigation Methods:

- Optical amplification
- Inline-optical Electronic Dispersion compensation

### Limitations:

- Amplifier noise, SNR$_{ASE}$
- Imperfect compensation
Chromatic dispersion (or Group velocity dispersion)

- Origin: wavelength dependence of refractive index

- Thus group velocity depends on wavelength

- Chromatic dispersion (or group velocity dispersion, GVD)

\[
D = \frac{\partial}{\partial \lambda} \left( \frac{1}{v_g} \right) \text{(ps/nm/km)} \quad \text{ou} \quad \beta_2 = \frac{\partial}{\partial f} \left( \frac{1}{v_g} \right) \text{(ps}^2/\text{km)}
\]

Notation from Optics world \hspace{1cm} Notation from Physics world
Chromatic dispersion

Pulse spectrum has a given bandwidth

The different pulse wavelengths travel at different group velocities

A arrival, pulse is broadened because of chromatic dispersion

• Dispersion D is expressed in (ps/(nm.km))

\[ D \text{ gives the arrival time after 1km fiber between two 1nm-spaced spectral components.} \]

From 10 to 100Gbaud: 100 times more stringent !!!
Evolution of dispersion maps in submarine cables

2000: NZDSF dispersion map

2005: DMF dispersion map

2010: Coherent dispersion map

• “Coherent” systems
  • Electronic mitigation
  • D+ fiber only:
    • Low attenuation, high effective area, high dispersion
    • ~ 0.15 dB/km 80-150µm²  ~ 21 ps/nm/km
## One transmission line, multiple sources of signal impairments

### Physical effect | Impact | Mitigation | Limitations
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Attenuation | Undetectable Signal | Optical amplification | Amplifier noise, \( \text{SNR}_{\text{ASE}} \)
Chromatic Dispersion Frequency dep. Speed | Pulse broadening | Inline-optical Electronic Dispersion compensation | Imperfect compensation
Kerr effect (power \(\rightarrow\) phase) | Power-dep. distortions | Dispersion management, electronic mitigation | Repeater count & power
Origin of Optical nonlinearities

• Main limitation = ASE noise ➔ need higher optical powers…

• But not too much, please
  • Low optical powers
  • Low core effective area ➔ High optical intensity:
    ~ 20dBm (100mW)
    ~ 100µm²
    1 billion W/m²

• 10 000 x solar radiation at top of Earth’s atmosphere
Nonlinear Kerr effect

1/ High optical power variations modulate fiber refractive index
   • $n = n(\omega) + n_2 \cdot \frac{P(t)}{A_{\text{eff}}}$

2/ the refractive index modifies the local phase of total optical field

3/ interplay with chromatic dispersion $\Rightarrow$ phase and intensity modulation $\Rightarrow$ mess

Impact on one channel:
   • intra-channel or inter-channel effect, nonlinear signal noise interaction
When $P_0$ or distance (N) increase, non-linear effects increase and degrade signal.

Accumulation depends on cumulated dispersion at each section input… Non obvious.
Nonlinear impairments as an additive Gaussian noise

- With current systems
  - High modulation rate
  - Complex modulations
  - Coherent detection

Additive Gaussian noise $\Rightarrow$ noise variance, $(O)\text{SNR}_{NL}$ matter

\[
\text{Variance} \propto N_{\text{spans}}^{1+\epsilon} \left( \frac{P_{\text{span input}}}{A_{\text{eff}}} \right)^2 P_{Rx}
\]

\[\epsilon \sim 0\] for coherent dispersion maps, $\sim 1$ when inline dispersion compensation

\[\propto: \text{analytical derivation in perturbative models (GN model...)}\]
Practical cases

$$SNR_{NL} \propto \frac{1}{N_{spans} \cdot P_{ch}^2}$$
i.e.

$$SNR_{NL,dB} = K - N_{spans,dB} - 2 \cdot P_{ch,dBm}$$

Combined with (O)SNR$_{ASE}$

$$P_{ASE+NL} \approx P_{ASE} + P_{NL}$$

Optimum power: ASE noise $= 2 \times$ NL noise
Practical cases

\[ \text{SNR}_{NL} \propto \frac{1}{N_{\text{spans}} \cdot P_{ch}^2} \]

i.e.

\[ \text{SNR}_{NL,dB} = K - N_{\text{spans},dB} - 2 \cdot P_{ch,dBm} \]

Combined with (O)SNR_{ASE}

\[ \frac{P_{ASE+NL}}{P_{\text{signal}}} \approx \frac{P_{ASE}}{P_{\text{signal}}} + \frac{P_{NL}}{P_{\text{signal}}} \]

Optimum power: ASE noise = 2x NL noise
Practical cases

\[
SNR_{NL} \propto \frac{1}{N_{\text{spans}} \times P_{ch}^2}
\]
i.e.

\[
SNR_{NL,dB} = K - N_{\text{spans,dB}} - 2 \times P_{ch,dBm}
\]

Combined with \((O)SNR_{ASE}\)

\[
\frac{1}{SNR_{ASE+NL}} \approx \frac{1}{SNR_{ASE}} + \frac{1}{SNR_{NL}}
\]

Optimum power: \(ASE\) noise = \(2x\) \(NL\) noise
Application: reach of terrestrial vs submarine systems

- \( OSNR_{dB,0.1nm} \approx 58 + P_{out,total,dBm} - \#channels_{dB} - Loss_{dB} - NF_{dB} - N_{repeaters,dB} \)
- \( \text{SpanLoss}_{dB} = \text{Attenuation}_{dB/km} \times \text{Repeater-spacing}_{km} \)

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Signal impairments in the cable: Additive Gaussian noise models

- Nonlinear (NL) noise due to high power density: (< 30% of impairments)

\[
SNR_{NL} \approx \frac{K_{models} * A_{eff}^2}{N_{spans}^\epsilon} * \frac{1}{N_{spans} * Power^2} - 1
\]

- Coming: partial mitigation of NL at transceiver

\[
SNR_{ASE+NL} = SNR_{ASE} + SNR_{NL}
\]
Signal impairments in the cable: Additive Gaussian noise models

• More on Nonlinear (NL) noise

• The higher the chromatic dispersion, the better

• The flatter the power spectral density, the better
  • Why? Peaks of power (in time / frequency) are detrimental
  • Channel rate as close as possible to channel spacing

• Details: NL noise seen by a channel stems from intra- and interchannel nonlinear effects, following:
  • $\sigma_{NL,tot}^2(ch \#i) = A_{NL} * P_{ch \#i}^2 + B_{NL} * \sum_{ch \#j \neq i} p_{ch \#i}^2 \frac{P_{ch \#j}^2}{|\lambda_j - \lambda_i|} \Rightarrow$ Less channels @ constant TOP and channel type = ☹

Difference in wavelengths/frequencies
# One transmission line, multiple sources of signal impairments

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<tr>
<th>Physical effect</th>
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Guided Acoustic Wave Brillouin Scattering (GAWBS)
[M. Bolshtyanski et al., M4B.3, OFC’18]

Spontaneous generation of transverse acoustic modes

Scatters incoming light in the forward direction, with small frequency shifts

$P_{GAWBS} \propto \frac{\text{Distance}}{A_{\text{eff}}} \ast P_{\text{ch}}$

characterized in M4B.3, OFC’18

$X \sim 1$
Guided Acoustic Wave Brillouin Scattering (GAWBS)

[M. Bolshtyanski et al, M4B.3, OFC’18]

\[ SNR_{GAWBS} \propto \frac{A_{\text{eff}}^x}{\text{Distance}} \]

Scatters incoming light in the forward direction, with small frequency shifts → Crosstalk noise

characterized in M4B.3, OFC’18
Joint SNR, Line SNR, Gaussian SNR, Generalized SNR

• Most signal distortions coming from the line can be captured by the joint G-SNR:

\[
\frac{1}{G - SNR} = \frac{1}{SNR_{ASE}} + \frac{1}{SNR_{NL}} + \frac{1}{SNR_{GAWBS}}
\]

• We expect here that chromatic dispersion and PMD are compensated by transceiver
Aggregation of impairments: Cable SNR, GSNR

\[
\frac{1}{GSNR} \approx \frac{1}{SNR_{ASE}(P)} + \frac{1}{SNR_{NL}(P)} + \frac{1}{SNR_{gawbs}}
\]

Optimum power $P$ only depends on ASE and NL noises.
### One transmission line, multiple sources of signal impairments

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<td>ASIC implementation</td>
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**Diagram:**

- **Laser + Modulator 1**
- **Laser + Modulator 2**
- **Laser + Modulator N-1**
- **Laser + Modulator N**
- **Multiplexer**
- **Optical Amplifier**
- **Fibre**
- **Demultiplexer**
- **Receiver 1**
- **Receiver 2**
- **Rx. (N-1)**
- **Rx N**
Polarization Mode Dispersion (PMD)

• Origin:
  • Fibre is a cylindrical medium with a quasi-circular section
  • Small imperfections from construction and conditions of deployment (torsions, pressure, trains…)

• 3 consequences
  • 1. Slight birefringence.
  • 2. This birefringence evolves along fiber line
  • 3. and with time

• Which impact over signal ?
Polarization Mode Dispersion (PMD)

• Fiber can be seen as a cascade of birefringent sections
In summary: transmission line = multiple sources of impairments modeled as Additive Gaussian noises

1. Amplifier noise (> 60% of impairments)
   - $SNR_{ASE,dB} \approx 38.9 + P_{out,tot,dBm} - Loss_{dB} - NF_{dB} - N_{rep,dB} - 10 \log_{10}(Ampl.Band_{THz})$
   - Correction with constant output power repeaters: -1/2 in linear scale
   - Extra-penalty expected with line non flatness

2. Nonlinear noise due to high power density: (< 30% of impairments)
   - At optimized power (max QoT), ASE noise = 2 x Nonlinear noise power

3. GAWBS: (< 10% of impairments)

4. Plus other sources of degradations, minor or significantly mitigated by transceiver

Aggregation into a line SNR: $\frac{1}{GSNR} \approx \frac{1}{SNR_{ASE}} + \frac{1}{SNR_{NL}} + \frac{1}{SNR_{gawbs}}$
Next: Design of an end to end system

• End to end performance model including transceiver

• Typical experiments to validate models / systems

• Power budget table

• Design of standard / SDM systems
Thank you