Optical Transmission – Lecture 3

From physics to system design
Back to propagation effects in the cable
Signal impairments in the cable: Additive Gaussian noise models

1. **Amplifier noise** (ASE) (> 60% of impairments)

\[
SNR_{ASE} \approx \frac{P_{out,tot}}{Gain \times NF \times N_{rep} \times Amplifier\ Band \times \frac{\lambda}{hc}}
\]

**Concatenation:**

\[
\frac{1}{SNR_{1 \rightarrow N,lin}} \approx \frac{1}{SNR_{1,lin}} + \ldots + \frac{1}{SNR_{N,lin}}
\]

**Refinements**

- **Constant total output power:** \( SNR_{signal\ droop,lin} - SNR_{basic,lin} \approx -\frac{1}{2} \times \frac{Ch.spacing}{Ref.Band_{SNR}} \)
- **Extra-penalty expected due to spectral non flatness**
Signal impairments in the cable: Additive Gaussian noise models

1. **Amplifier noise** (ASE) (> 60% of impairments)

\[
SNR_{ASE,\text{dB}} \approx 38.9 + P_{out,tot,\text{dBm}} - Gain_{\text{dB}} - NF_{\text{dB}} - N_{\text{rep},\text{dB}} - 10 \times \log_{10}(\text{Bandwidth}_{\text{THz}})
\]

\[\text{Loss} = \text{Gain} \times N\]

From OSNR\(_{0.1\text{nm},\text{dB}}\) to SNR\(_{\text{dB}}\):

\[
SNR_{\text{dB}} = OSNR_{dB,0.1\text{nm}} + 10 \times \log\left(\frac{12.5 \text{ GHz}}{\text{Channel spacing}}\right)
\]

12.5GHz corresponds to 0.1nm at 1550nm
Signal impairments in the cable: Additive Gaussian noise models

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

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

At optimized power (max Quality of Transmission),

- **ASE noise** = 2 x Nonlinear noise power
  \[ SNR_{ASE, dB} = SNR_{NL, dB} - 3 \text{dB} \]

- Coming: partial mitigation of NL at transceiver

- Often neglected
Signal impairments in the cable: Additive Gaussian noise models

• More on Nonlinear (NL) noise
  
  • The higher the local chromatic dispersion, the better
  
  • Increases with high cumulated chromatic dispersion, with quick saturation
  
  • 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
Guided Acoustic Wave Brillouin Scattering (GAWBS)

\[ P_{GAWBS} \propto \frac{\text{Distance}}{A_{eff}^x} \times P_{ch} \]

characterized in M4B.3, OFC’18

\[ X \sim 1 \]
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

→ Crosstalk noise

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

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

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

Optimum power P only depends on ASE and NL noises
GSNR and distance (constant repeater spacing)

\[
\frac{1}{\text{GSNR}} \approx \frac{1}{\text{SNR}_{\text{ASE}}} + \frac{1}{\text{SNR}_{\text{NL}}} + \frac{1}{\text{SNR}_{\text{gawbs}}}
\]

All the terms are almost proportional to distance

GSNR scales like 1/distance (-1dB/dB), with almost same optimum power
From GSNR to end to end performance

- Possible interconnection of cables with terrestrial sections, terminals through portals

- Same physics applies:
  - model impairment as an equivalent SNR, sum the inverse (G)SNRs…
Quality of Transmission (QoT) between 2 transceivers

• A usual metric is the **Bit Error Rate (BER)** before FEC decoding

  • or its translation into **Q-factor**, more precisely \( Q_{dB}^2 = 10 \times \log_{10}(Q^2) \)
    • With Q defined from relation: \( BER = \frac{1}{2} \text{erfc}\left(\frac{Q}{\sqrt{2}}\right) \)
    • Interest: \( Q^2 \) is usually proportional to electrical SNR

• **BER** is a function of the **electrical SNR** integrated in receiver band

  \[
  BER \approx x \times \text{erfc}\left(\sqrt{K \times SNR_e}\right)
  \]

  \( x, K \) depend on the modulation
Physical limitations at modem side

Transmission independent
- Thermal, shot noises
- Bandwidth of E/O components
- Assembly / alignment

Model: Additive Gaussian noise

Back to back measurements:
QoT vs external source of SNR
Physical limitations at modem side

Transmission dependent

- Av. impact of PDL / PMD
- Imperfect mitigation of chromatic dispersion due to
  - Resolution of implemented DSP
  - Laser linewidth

Characterization requires reliable emulation of impairment / model / simulations

Basic fit for $QoT = Q^2$ or $\text{SNR}_e$:

$$\eta_{QoT} = \frac{1}{\text{SNR}_{\text{line}}} + \frac{1}{\text{SNR}_{\text{TRx}}}$$
End to end Gaussian noise model

1. Back to back characterization
   - Transponder tolerance to Gaussian noise (ASE noise)
     \[ QoT = f_{btb}(O-SNR) \]
   - With possible refinements

2. Model transmission impairments as Gaussian noises
   - ASE noise, nonlinear effects, GAWBS,
   - G-(O)SNR matters

3. Infer end to end QoT using the back to back calibration
   \[ QoT_{predicted} = f_{btb}(GOSNR) \]
Performance prediction relies in three pillars

- Numerical simulations
- Physical models
- Experiments
Performance of Open Cable: From Modeling to Wide Scale Experimental Assessment

Name: Jean-Christophe ANTONA
Company: Alcatel Submarine Networks
Parametric study
Experimental set-up

• 36nm loop testbed
  - CSF1 (110µm² fiber)
• Real-time tribis, calibrated in back to back
• Various configurations:
  - Measurements of average OSNR_{ASE} and Q² factor over the full C-band
  - Comparisons with Q² factor predictions, aware of OSNR_{ASE} measures
Performance prediction accuracy

+ Additional cases: 45, 69Gbaud, QPSK, TPCS, 16 000km

Nonlinear noise: coherent GN model, signal depletion
GAWBS, CD limitations. Aggregation of noise: Gen. Droop

Accurate prediction whatever the configuration
Enough models and labs, let’s design a cable
Main expectations from a customer

**Turn-key system**

- Guarantee capacity “per fiber” over 25 years
  - Incl. manuf. Margins, time-fluctuations, repairs, customer margins
- Demonstrate capacity at commissioning, with terminals

**Open cable**

- Commit on agreed cable characteristics that will enable further interconnection with SLTE: $\text{OSNR}_{\text{ASE}}, \text{GOSNR (NL?)}, \text{flatness}$, expectable capacity over time
- Demonstrate OSNR / GOSNR at commissioning
Examples of characteristics to provide

<table>
<thead>
<tr>
<th>DLS</th>
<th>Site A to Site B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber Pair Number</td>
<td>Z</td>
</tr>
</tbody>
</table>

### Commissioning Parameters

- \( \text{SNR}_{\text{avg}} \) [dB] (Average & WC, under X conditions)
- \( \text{GSNR} \) [dB] (Average & WC, under X conditions)
- Slope of Tilt [dB/THz] (under Flat Tx conditions)
- Max Gain Deviation [dB] (under Flat Tx conditions)

### System Specification

- System Length [km]
- Nominal Span Length [km]
- Span Loss [dB]
- Accumulated Dispersion [ps/nm]
- Mean PMD [ps/\( \sqrt{\text{km}} \)]
- Mean PDL [dB]
- Number of Repeaters

### Repeater Specification

- Repeater TOP [dBm]
- Repeater Noise Figure [dB]
- Repeater Gain [dB]
- Data Passband [GHz]

### Fiber Specification

- Fiber Effective Area [\( \mu \text{m}^2 \)]
- Fiber Dispersion @ 1550nm [ps/nm/km]
- Fiber Loss (Cabled) [dB/km]
- Fiber Dispersion Slope @ 1550nm [ps/nm²/km]
- Fiber Nonlinear Index [m²/W]

### Repair Assumptions (BOL to EOL)

- Total \( \text{SNR}_{\text{avg}} \) penalty for Deep Water Repairs [dB]
- Total \( \text{SNR}_{\text{avg}} \) penalty for Shallow Water Repairs [dB]
Different $\text{SNR}_{\text{ASE}}$

- Average $\text{SNR}_{\text{Design}}$
- ROADM-Penalties, signal droop
- Average $\text{SNR}_{\text{Nominal}}$
- Manufacturing
- Average $\text{SNR}_{\text{Commissioning}}$
- From Average to Worst
- Worst $\text{SNR}_{\text{Commissioning}}$
Different GSNR

GSNR (dB)

Average GSNR\textsubscript{Commissioning}

From Average to Worst

Worst GSNR\textsubscript{Commissioning}
End of life considerations

• Possible $SNR_{ASE}$ degradations due to

  • Fiber ageing: typ. 0.002dB/km over 25 y

  • Pump failure:
    • Typ. 5% repeaters
    • 2pumps / FP => 3dB extra loss

• Repairs
  • Deep sea: one repair every 1000km: splice loss + 2-3 times water-depth * attenuation
  • Shallow water: one repair every … 20km. Typical 0.5dB loss.
MASTERCLASS: OPEN SUBMARINE NETWORKS

Name: Brian LAVALLEE, Pascal PECCI
Company: Ciena, Alcatel Submarine Networks
OPEN system

- Power Feed Equipment
- Cable
- Branching Units / R-OADM
- Wet Repeater / Amplifiers
- Power Feed Equipment

Survey, Lay, Maintain

Cable Landing Station

Open Portal
OSNR  GOSNR  SNR  GSNR

E2E design

# rep ?  TOP ?

Open Portal

Wet Repeater / Amplifiers

Open Portal

Cable Landing Station

Survey, Lay, Maintain

Cable Landing Station

E2E design
OUTLINES

- Many solutions to reach it
  - SNRASE
  - Capacity upper bound limit

- Definition
- Comparison of 3 solutions
- Optimums

Fibre capacity

OSNRASE
Upper bound limit

GOSNR
Lower bound limit

SDM

- Fibre
- Repeaters
- Conductor

Cable capacity
OSNR_{ASE} and SNR_{ASE}

\[ \text{OSNR}_{ASE} = 18.0 \text{ dB/0.1nm for 120ch} \]

\[ \text{SNR}_{ASE} = 13.2 \text{ dB} \]

\[ 10 \log (37.5/12.5) \]

BW is chosen to be 4500 GHz or 36nm
SNR\textsubscript{ASE}: Capacity upper bound limit

\[ C_{\text{upperbound}}(Tb/s) = 2.B(\text{THz}) \cdot \log_2[1 + \text{SNR}_{\text{ASE}}(\text{lin})] \]

with

\[ \text{SNR}_{\text{ASE}}(dB) = 38.9 - 10 \times \log(BW_{\text{THz}}) + \text{TOP} - \text{G} - \text{NF} - \text{NR} \]

0.1nm = 12.5GHz @ 1550nm

All WET parameters considered in the upper bound capacity: TOP, G, NR, NF, BW
SNR\textsubscript{ASE}: Capacity upper bound limit

SNR\textsubscript{ASE} = 13.2 dB

C_{upperbound} = 40.2 \text{ Tb/s per fiber}

SE = C / BW = 8.9 \text{ b/s/Hz}
Different solutions to reach the same $SNR_{ASE}$

$SNR_{ASE} (dB) = 38.9 - 10 \times \log(BW_{THz}) + TOP - G - NF - N_R$

$SNR_{ASE} (dB) 13.2 \text{ dB}$

Distance = 13 000 km
Fibre losses = 0.156 dB/km
16.0 dBm < TOP < 22.5 dBm
NF = 4.0 dB (constant)

Many solutions: 120 < N < 310 & 6.5 < Gain < 17.0 dB
Different solutions to reach the same $SNR_{ASE}$

$SNR_{ASE}(dB) = 13.2$

<table>
<thead>
<tr>
<th></th>
<th>TOP (dBm)</th>
<th># rep</th>
<th>Gain (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High TOP</td>
<td>22.5</td>
<td>120</td>
<td>16.9</td>
</tr>
<tr>
<td>Medium TOP</td>
<td>19.0</td>
<td>170</td>
<td>11.9</td>
</tr>
<tr>
<td>Low TOP</td>
<td>16.2</td>
<td>310</td>
<td>6.5</td>
</tr>
</tbody>
</table>

3 solutions will be studied. How can we differentiate them?
OUTLINES

- Many solutions to reach it
  - SNR\textsubscript{ASE}
  - Capacity upper bound limit

- Definition
- Comparison of 3 solutions
- Optimums

Fibre capacity

- Fibre
- Repeaters
- Conductor

GOSNR Lower bound limit

OSNR\textsubscript{ASE} Upper bound limit

SDM

Cable capacity
Different solutions to reach the same $\text{SNR}_{\text{ASE}}$

- **High TOP**
  - $\text{TOP} (\text{dBm})$: 22.5
  - # rep: 120
  - Gain (dB): 16.9

- **Medium TOP**
  - $\text{TOP} (\text{dBm})$: 19.0
  - # rep: 170
  - Gain (dB): 11.9

- **Low TOP**
  - $\text{TOP} (\text{dBm})$: 16.2
  - # rep: 310
  - Gain (dB): 6.5

**OSNR_{ASE}=18\text{dB/0.1nm} - SNR_{ASE}=13.2\text{dB}**
Design rule

Define a \( SNR_{ASE} \)

Define the max amount of NLE based on the amount of NLE that transponders will compensate in \( X \) years

\[ \rightarrow \text{Only one solution} \]
Define an SNR\textsubscript{ASE}
Define the max level of NLE
--> Only one solution

<table>
<thead>
<tr>
<th>13.2 dB</th>
<th>TOP (dBm)</th>
<th>N</th>
<th>Gain (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opt TOP</td>
<td>20.8</td>
<td>14</td>
<td>14.5</td>
</tr>
</tbody>
</table>
Shannon capacity: Lower and upper bounds

\[ GSNR = GOSNR + 10 \cdot \log(12.5/37.5) \]

Upper and lower capacities can characterize the WET part of submarine network

\[ C_{\text{upper bound}}(Tb/s) = 2 \cdot B \cdot \log_2 [1 + SNR_{ASE}] \]

\[ C_{\text{lower bound}}(Tb/s) = 2 \cdot B \cdot \log_2 [1 + GSNR] \]
**Optical Design reached**

**Inputs:**
- 13 000 km
- $\text{SNR}_{\text{ASE}} = 13.2$ dB
- $\text{BW} = 4500$ GHz or 36nm
- Max level of NLE = 3 dB
- $150 \mu m^2 / 0.156$ dB/km

**Outputs:**
- 140 repeaters
- $\text{TOP} = 20.8$ dBm
- Gain = 14.5 dB
- Capacity per FP = 32.4 Tb/s

**Hypothesis:**
Today’s SLTE can reach 60% of Shannon capacity.
Our cable is a 5FP cable.

**Cable capacity:**
Cable capacity = $5 \times 60\% \times 32.4T$

Cable capacity $\sim 100$ Tb/s

What about power efficiency?
INCREASING SYSTEM CAPACITY & EFFICIENCY WITH SDM

How can SDM be achieved?

- Multicore
- Multicore & Multimode
- Multimode
- Multiple Standard single mode Fibre
WHY SDM? Capacity evolution – soon 1Pb/s

- Pre-coherent vs Coherent

- SDM per cable vs per fibre

- Channel card

- Timeline:
  - 1989: 560M
  - 1999: 2,5G
  - 2009: 10G
  - 2019: 100G, X00G, 1T

- Technology:
  - Pre-coherent
  - Coherent
  - WDM
  - SDM

- Growth in Gb/s, Tb/s, Pb/s
**WHY SDM?**
Higher capacity for the same power

Cable with 1 fibre pair

\[ A_{eff} 150\mu m^2 \]

- 20Tb/s

**Without NLE**
**With NLE**

What are the options to increase capacity by doubling the # of pumps?
WHY SDM?
Higher capacity for the same power

Option 1:
Increase the Power (TOP, OSNRASE)

→ +20% fibre capacity (best case)
WHY SDM?
Higher capacity for the same power

Cable with 2 fibre pairs
$A_{eff} \ 150\mu m^2$

40Tb/s

Option 2a:
+ Add a fibre

$\rightarrow$ +100% fibre capacity (best case)
WHY SDM?
Higher capacity (+50%) for the same power

Option 2b:
+ Add a fibre
+ Change type of fibre

→ +85% fibre capacity (best case)
WHY SDM?
Same capacity for lower power (-50%)

Cable with 2 fibre pairs

\[ A_{\text{eff}} 80\mu m^2 \]

\[ \bullet 24\text{Tb/s} \]

Option 3:
+ Add a fibre
+ Change type of fibre
+ Share the pump power
+ Reduce the current
→ same cable capacity
WHY SDM?
Extension to POP

Standard - 8FP – 160 T cable

SDM - 12FP – 160 T cable

400km: 4x100km (22dB)

6600km

400km: 4x100km (22dB)
SDM Benefits

• Optimised $/bit compared to traditional approach (max OSNR per fiber pair)

• Technical: Extend the limit of traditional approach
  • Cable capacity increase
  • Higher reachable distance
  • Increase speed of manufacturing

• Business
  • Fiber pair as a new granularity: Easier to swap/sell/manage
  • POP to POP connectivity

More fibres  Lower Effective Area
Pump farming  Less conductor
Future challenges of subsea optical cables

- Higher and higher capacities
- At reduced cost / bit
- Power efficiency
- Spatial parallelism
- Integration
- More monitoring and automation

- Global optimization: wet + dry + marine + …

Zero loss “fibers”
Zero margin operation
Zero nonlinearities
Thank you
Constant total power vs constant gain amplifiers

Case study: 100 repeated sections, 3dB extra loss at first section

Gain mode amplifiers

- **Nominal**: 
  - Constant signal power
  - \( \text{SNR}_{\text{ref,dB}} = K + P_{\text{dBm}} - 20\text{dB} \)

- **Degradation at span 1**
  - Signal power -3dB at each span
  - Doubled noise per span
  - SNR penalty = 3dB
Constant total power vs constant gain amplifiers

Case study: 100 repeated sections, 3dB extra loss at first section

Gain mode amplifiers

- **Nominal**:  
  - Slight signal + ASE droop  
  - \( \text{SNR}_{\text{power}} = \text{SNR}_{\text{gain}} - 0.5 \)  
  - Typically 0.1dB penalty

- **Degradation at span 1**  
  - Signal power -3dB at 1\textsuperscript{st} ampli  
  - Equivalent to 1 more section  
  - \( Pen = 10 \times \log\left(\frac{101}{100}\right) = 0.04dB \)
The portal is the frontier between the open cable from one vendor
And terminals, extensions from other vendors

Primary mission: supervision of the cable, (band loading with ASE)
Can be adapted to multi-terminals per cable/fiber, extensions