Further discussion of DGD penalty and specification for 800G LR4

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Outline

1) Further discussion of G.652.B/D PMD specifications
   • Extended fiber manufacturer overview
   • Impact of segmented cables on fiber PMD

2) Follow up on DGD penalty assessment for 200G PAM4
   • DGD penalty verified by measurements
   • Combined penalty of CD+DGD (numerical)
**DGD_{max} Evolution in IEEE standards**

- The last major change in PMD specifications happened for 100G/lane PAM4 when G.652.A/C fibers were removed from consideration.
- **anslow_3cu_01_0519** derived a hypothetical worst case distribution for a single section cable to match $\text{PMD}_Q = 0.2\text{ps}/\sqrt{\text{km}}$ (link design value for 20 fiber segments).
- The maximum individual fiber PMD coefficient for G.652.B/D was assumed to be $0.43\text{ps}/\sqrt{\text{km}}$.

<table>
<thead>
<tr>
<th>Standard</th>
<th>$\text{PMD}_Q$ [ps/$\sqrt{\text{km}}$]</th>
<th>$\text{PMD}_{\text{max}}$ [ps/$\sqrt{\text{km}}$]</th>
<th>$\text{DGD}_{\text{max}}$ [ps]</th>
<th>Penalty</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>10GBASE-LR</td>
<td>0.5</td>
<td>0.8</td>
<td>10</td>
<td>0.1 dB</td>
<td>P802.3ae Equalization Ad Hoc</td>
</tr>
<tr>
<td>40GBASE-LR4</td>
<td>0.5</td>
<td>0.8</td>
<td>10</td>
<td></td>
<td>Anslow_04_1108</td>
</tr>
<tr>
<td>100GBASE-LR4</td>
<td>0.5</td>
<td>~0.7</td>
<td>10–8</td>
<td>0.4 dB → 0.2 dB</td>
<td></td>
</tr>
<tr>
<td>100GBASE-LR, 200GBASE-LR4, 400GBASE-LR8</td>
<td>0.5</td>
<td>~0.7</td>
<td>8</td>
<td>/</td>
<td></td>
</tr>
<tr>
<td>100GBASE-LR, 400GBASE-LR4</td>
<td>0.5</td>
<td>~0.7</td>
<td>8</td>
<td>0.6 dB → 0.25 dB</td>
<td>anslow_3cu_01_0519</td>
</tr>
<tr>
<td>100GBASE-FR, 400GBASE-FR4</td>
<td>0.2</td>
<td>0.43</td>
<td>2.3</td>
<td>~0 dB</td>
<td>Lewis_3cu_02_0719</td>
</tr>
<tr>
<td>4×200G FR4</td>
<td>0.2</td>
<td>0.43</td>
<td>2.28</td>
<td>&lt;0.2 dB</td>
<td>kuschnerov_3df_01b_221012</td>
</tr>
<tr>
<td>4×200G LR4</td>
<td>0.2</td>
<td>0.43</td>
<td>5</td>
<td>&lt;0.7 dB</td>
<td>kuschnerov_3df_01b_221012</td>
</tr>
</tbody>
</table>

$\text{DGD}_{\text{max}} = \text{PMD}_{\text{max}} \times \sqrt{\text{Lkm}} \times 3.75$
## G.652.B/D fiber PMD overview*

Based on publicly available information

<table>
<thead>
<tr>
<th>Supplier</th>
<th>Country</th>
<th>Fiber type</th>
<th>( \text{PMD}_3 ) ([\text{ps}/\sqrt{\text{km}}])</th>
<th>Max PMD individual fiber ([\text{ps}/\sqrt{\text{km}}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corning</td>
<td>US</td>
<td>SMF-28 ULL</td>
<td>( \leq 0.04 )</td>
<td>( \leq 0.1 )</td>
</tr>
<tr>
<td>Corning</td>
<td>US</td>
<td>SMF-28e+</td>
<td>( \leq 0.06 )</td>
<td>( \leq 0.1 )</td>
</tr>
<tr>
<td>YOFC</td>
<td>China</td>
<td>FullBand Ultra LL</td>
<td>( \leq 0.06 )</td>
<td>( \leq 0.1 )</td>
</tr>
<tr>
<td>OFS</td>
<td>Japan</td>
<td>AllWave Low Loss</td>
<td>( \leq 0.04 )</td>
<td>( \leq 0.1 )</td>
</tr>
<tr>
<td>OFS</td>
<td>Japan</td>
<td>AllWave</td>
<td>( \leq 0.06 )</td>
<td>( \leq 0.1 )</td>
</tr>
<tr>
<td>Hengtong</td>
<td>China</td>
<td>BoneCom LL G.652.D</td>
<td>( \leq 0.06 )</td>
<td>( \leq 0.1 )</td>
</tr>
<tr>
<td>Hengtong</td>
<td>China</td>
<td>BoneCom mini-G.652.D</td>
<td>( \leq 0.1 )</td>
<td>( \leq 0.2 )</td>
</tr>
<tr>
<td>Fiber Home</td>
<td>China</td>
<td>FiberHome ULL</td>
<td>( \leq 0.04 )</td>
<td>( \leq 0.1 )</td>
</tr>
<tr>
<td>Prysmian</td>
<td>Italy</td>
<td>BendBright-XS</td>
<td>( \leq 0.06 )</td>
<td>( \leq 0.1 )</td>
</tr>
<tr>
<td>Prysmian</td>
<td>Italy</td>
<td>G.652.D</td>
<td>( \leq 0.08 )</td>
<td>( \leq 0.15 )</td>
</tr>
<tr>
<td>Fujikura</td>
<td>Japan</td>
<td>FutureGuide</td>
<td>( \leq 0.04 )</td>
<td>( \leq 0.1 )</td>
</tr>
<tr>
<td>HFCL</td>
<td>Pakistan</td>
<td>Flexi ZWP</td>
<td>( \leq 0.06 )</td>
<td>( \leq 0.2 )</td>
</tr>
<tr>
<td>Draka (legacy)</td>
<td>US</td>
<td>SMF G652.B</td>
<td>( \leq 0.08 )</td>
<td>( \leq 0.2 )</td>
</tr>
</tbody>
</table>

*Extended from [kuschnerov_3df_01b_221012](#)
G.652.B/D PMD fiber specifications

• The overview of PMD specifications for G.652.B/D fibers shows that the link design value \( \text{PMD}_Q \) complies with \( \leq 0.1 \text{ps/√km} \) (vs. \( 0.2 \text{ps/√km} \) specified now)

• Regarding the maximum individual fiber PMD, all G.652.B/D specifications available to the authors for review complied with \( \leq 0.2 \text{ps/√km} \) (vs. \( 0.43 \text{ps/√km} \) assumed now)

• **Note**: Parameters specified by the fiber manufacturers are given for spooled fibers

• It was discussed in [kuschnerov 3df 01b 221012](#) that cabling doesn’t necessarily increase the worst case PMD statistics and can actually decrease it

➔ We believe that the PMD coefficient assumption of \( \leq 0.2 \text{ps/√km} \) for an individual fiber cable serves as good basis for further discussion and a continuing analysis of cabled fiber PMD specifications seems justified
Segmented fiber cable impact on fiber PMD

- So far, short reach Ethernet specifications assumed a *single section cable*, which is the worst case scenario regarding the maximum DGD statistics.
- *johnson_3df_optx_01_220414* suggested that ~5km is a typical maximum cable segment length for pulling through underground ducts or aerial installation.
- Cabling statistics vary depending on the operator, country regulations, deployment region (access vs. back bone) and brownfield vs. greenfield deployment.
- Splicing of several fibers for a longer fiber cable reduces the maximum PMD coefficient in the fibers according to the law of large numbers.
Operator fiber deployment statistics

• Initial survey of tier 1 operators indicates following design rules:
  o Operator 1: ≤3km cable length
  o Operator 2: ≤5km cable length (see figure)
  o Operator 3:
    ▪ ≤2.4km cable length in access networks
    ▪ ≤4.8km cable length in backbone networks
  o Operator 4: ~6km cable length (Backbone LEAF, deployment in 2000)
  o Operator 5: ≤3km cable length
  o Operator 6: ≤2km cable length
  o Operator 7: ≤6km cable length in metro core (2-3km typ)

• Assumption: A 10km single section cable assumption might be an unrealistic scenario for access/LR links

⇒ The initial data suggests a further study on access vs. backbone networks and information gathering from more operators

Figure taken from:

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Impact of multi-segment links on $\text{DGD}_{\text{max}}$

- The concatenation of several fiber cables leads to a reduction of the maximum DGD in the fiber link due to averaging of the PMD coefficient.
- Figures on the right show a single cable statistic approximately modelled after `anslow_3cu_01_0519`.
- A concatenation of 2 or 3 cables is able to reduce $\text{DGD}_{\text{max}}$ accordingly.

$\Rightarrow$ This analysis could be combined with a more realistic maximum individual fiber PMD coefficient.

<table>
<thead>
<tr>
<th>10km</th>
<th>1 section</th>
<th>2 sections</th>
<th>3 sections</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{PMD}_{\text{max}}$</td>
<td>$\sim0.4\text{ ps}/\sqrt{\text{km}}$</td>
<td>$0.33\text{ ps}/\sqrt{\text{km}}$</td>
<td>$0.29\text{ ps}/\sqrt{\text{km}}$</td>
</tr>
<tr>
<td>$\text{DGD}_{\text{max}}$</td>
<td>4.7 ps</td>
<td>3.9 ps</td>
<td>3.4 ps</td>
</tr>
</tbody>
</table>
224G PAM4: DGD measurement setup

- To study the measured effect of DGD, the setup below is used.
- Since the PMD emulator could only work with C-band optics, a Tx with ECL+MZM in C-band is used.
- DGD emulation was characterized using NRZ eye diagrams.

![Diagram of DGD measurement setup](image)

100 Gbaud NRZ with DGD

DGD emulator characterization
Measured DGD penalty for 224G PAM4

- At DGD=5ps a penalty of ~0.62dB was measured for the FFE+MLSE receiver
- This corresponds well with the simulations in kuschnerov_3df_01b_221012 where a penalty of <0.7dB was derived for 224Gbit/s PAM4 for several component bandwidth assumptions

➔ Overall, we believe that this further solidifies the current link budget assumptions for 800G LR4
Combined DGD+CD penalty for 200G PAM4

• During the discussion of kuschnerov_3df_01b_221012 a question was raised whether the penalties of CD and DGD can be added up linearly
• As it is shown on the figure, varying CD doesn’t change the baseline DGD penalty
• For very large CD penalty, the CD+DGD penalty becomes less than additive
➔ Adding CD and DGD penalties doesn’t underestimate the system impact
Conclusions

• A further analysis of cabled fiber PMD is justified
• More feedback is sought from operators regarding individual cable length statistics before splicing, which could reduce the maximum DGD specification for the 800G LR4 and 1.6T LR8 scenarios
• Numerical verification of DGD penalty for 200G PAM4 was confirmed in measurements
• Adding CD and DGD penalties [dB] doesn’t underestimate the system impact of these two impairments for PAM4 in the CD range of interest
Thank you.