SMF Optical Channel Model Proposal

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- This presentation is a proposal for an optical channel model to use in DR, FR and LR4 applications

- This presentation does not provide spec on 800G-LR4 (or other PMD), it proposes how to build a channel model

- This presentation also reviews recently received ITU-T liaison response
References

Previous IEEE discussions on developing statistical fiber channel model:

Statistical analysis on fiber zero dispersion wavelength (ZDW) and slope:
  • cole_3dj_01b_2305
  • ferretti_3dj_optx_01b_230615
  • parsons_3df_01a_2211
  • johnson_3dj_01a_2307
  • liu_3dj_01a_2307

Optical link segmentation:
  • liu_3dj_optx_01_230615
  • liu_3dj_01a_2307
How is Dispersion currently specified?

Formula to calculate Dispersion$_{\text{min}}$:
\[ \text{distance} \times (S_{0_{\text{max}}} / 4) \times \lambda \times [1 - (ZD W_{\text{max}} / \lambda)^4] \]

where $S_{0_{\text{max}}}$ = 0.092 ps.nm$^2$km and $ZD W_{\text{max}}$ = 1324nm from ITU-T fiber attributes

Until now, dispersion spec scales linearly with distance.
i.e.: LR equation is 5 times FR equation (No link segmentation)
• FR : $2 \times 0.023 = 0.046$
• LR: $10 \times 0.023 = 0.230$
How is Dispersion currently specified: Graphical representation.

IEEE specifies dispersion by the intersection of of $ZD_{W\text{max}}$ and $\text{slope}_{\text{max}}$. 

Current IEEE channel specification:

$\left(\frac{S_{0\text{max}}}{4}\right) \times \lambda \times \left[1 - \left(\frac{ZD_{W\text{max}}}{\lambda}\right)^2\right]$
Why IEEE channel model dispersion could be improved?

- Dispersion is a function of ZDW and slope, with each expecting to follow a gaussian-like distribution.
- Therefore, Dispersion is expected to have a multivariate normal distributions (ellipse-shape confidence region)

For illustration purposes only, ZDW distribution used my ITU liaison annex and slope from johnson_3dj_01a_2307

- Using the rectangle corner results on an overly pessimistic corner case spec
- We are fitting a square peg into a round hole
- This triggered the IEEE to collect data to build a statistical channel model, and to write a Liaison to ITU last November for statistical data
ITU-T liaison review

- ITU provided a min/max dispersion fitting function for 2, 10, 20, 30, and 40 km

- This presentation focus on 2 and 10km since these are the current IEEE .3dj objectives
- 2km fitting is based on a single segment link
- 10km fitting is based on four segments of 2.5km
- Fitting function is done for a 99.99% confidence
ITU-T liaison review: Single segment fitting

- 99.99% confidence
- single segment link

- 100% < 99.99%, therefore some reduction was expected. ITU-T fitting does not show it
- **ITU fitting does not meet its own spec**: ZDW range outside 1300-1324nm
- This is a clear problem in the methodology that we should ask to fix in the Liaison
ITU-T liaison review: Single segment fitting

- 99.99% confidence
- single segment link

Single segment ITU statistical fitting does not meet ITU own spec
Still fitting a square peg on a round hole
Can IEEE define an optical channel model...

1) ... based on ITU-T fiber specs, but still reasonable according to physics (multivariate normal distribution)
2) ...for high volume datacenter specifications to best supports Ethernet applications
3) ... transparent, with input parameters that are PMD dependent, i.e. wavelengths, link segmentation, confidence level
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Previously proposed models:

ITU Liaison annex:
- Applied to LR4 PMD: liu_3dj_01a_2307

cole_3dj_01b_2305
- In FR4 PMD: johnson_3dj_01a_2307
- In LR4 PMD: liu_3dj_01a_2307

- Simple
- underestimate when segments from same vendor
- Accounts for same vendor segments
- A bit more complex
- Not as conservative as ITU-T limits
Can IEEE define an optical channel model...

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This proposal:
Single distribution for ITU-T worst case ZDW and Slope at 4 sigma (~99.99%)

- Simple
- Accounts for same vendor segments
- A bit more complex
- Not as conservative as ITU-T limits

\[\text{Minimum Dispersion @ 1294.56nm (ps/(nm km))} \]

\[\text{Zero dispersion wavelength (nm)} \]

\[\text{Slope (ps/(nm2 x km))} \]

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\[\text{Slope (ps/(nm2 x km))} \]
The Proposed Channel Model:

- Is a multivariate normal distribution, not a rectangle with a corner
- Has two distributions, to account for vendors with a shifted distribution in opposite directions
- The distribution is pushed all the way to max/min ZDW and Slope spec with 99.99%

For Minimum dispersion:
- ZDW: mean= 1316, std= 2
- Slope: mean= 0.084, std= 0.002

For Maximum dispersion:
- ZDW: mean= 1308, std= 2
- Slope: mean= 0.084, std= 0.002
Optical links with Link Segmentation
Link segmentation: When? Improves what?

- Longer optical links are built in segments
- Link segmentation reduces the dispersion variance
- Dispersion reduction depends on standard deviation. See annex for more.
How to apply link segmentation with channel model?

Example steps to calculate minimum dispersion spec:
1. MonteCarlo analysis with the proposed ZDW and Slope multivariate normal distribution
2. Calculate dispersion for shortest/longest wavelength in the plan. i.e: 1294.56nm for LWDM4
3. Average dispersion among number of segments
4. Select minimum value within 99.99%

i.e: 800G-LR4 Dispersion_{min}:
-21.9 ps/nm for 99.99%
-21.3 ps/nm for 99.9%
ITU-T liaison review: 4x2.5km fitting

- 99.99% confidence
- Link segmentation: 4 x 2.5km segments

ITU-T fitting, even after averaging effect of link segmentation, does not completely meet ITU own specs
This proposal:  
- Fixes the problems the ITU fitting has regarding ZDWmax out of spec  
- Show a modest expected reduction in dispersion due to 99.99% confidence
Results comparison: four segments

This proposal for a **four-segment** link

Current ITU worst-case
This proposal single segment
This proposal four segments

ITU statistical fitting for a **four-segment** link

Current ITU worst-case
ITU fitting single segment
ITU fitting four segments

This proposal:
- Fixes the problems the ITU fitting has regarding ZDWmax out of spec
- Show a modest expected reduction in dispersion due to 99.99% confidence and additional improvement due to link segmentation
How can we specify it?

Using same approach than in stassar_3dj_01_2401 we can calculate effective ZDW and slope to reuse specification format

Effective $Z_{DW_{\text{min}}}$ = 1300.8 nm
Effective $Z_{DW_{\text{max}}}$ = 1323.4 nm
Effective $S_0_{\text{max}}$ = 0.086 ps/(nm² km)

Effective $Z_{DW_{\text{min}}}$ = 1304.5 nm
Effective $Z_{DW_{\text{max}}}$ = 1319.7 nm
Effective $S_0_{\text{max}}$ = 0.085 ps/(nm² km)

The effective ZDW and $S_0$ are used in the IEEE spec to obtain statistical distribution values while reusing specification methodology.
What all comes down to writing the spec

For every PMD, IEEE specifies in a subclause the zero-dispersion wavelength range to derive dispersion.

Comparison of this approach vs ITU fitting

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<tr>
<th>Distance [km]</th>
<th>Peter analysis of ITU</th>
<th>This Proposal</th>
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<tbody>
<tr>
<td>2</td>
<td>0.0864</td>
<td>0.086</td>
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<tr>
<td>10</td>
<td>0.0856</td>
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Slope S0 for min CD | ZDWmax for min CD | Slope S0 for max CD | ZDWmin for max CD

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Very similar values, expect for those that ITU fitting would require for the IEEE writing fiber spec that violates ITU spec ZDW (1300-1324nm)
800GBASE-LR4 specs

The proposed optical channel would result in a spec dispersion limits for 800GBASE-LR4 of:

**Option A:** Independent ZDW and Slope

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<th>Maximum</th>
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<td>-21.9</td>
<td>4.9</td>
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**Option B:** Alternatively, even a more conservative approach could be adopted using positive correlation of ZDW and Slope

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<td>-22.4</td>
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Conclusions

- This presentation proposes an IEEE statistical model for optical channels based on ITU-T ZDW and slope limits, while proving a transparent model for the task force to drive its own analysis.

- Presents a complete step-by-step methodology to evaluate any wavelength plan for a given fiber length, link segmentation and confidence level.

- Calculates the effective ZDW and Slope values to continue using current specification format.

- If further data from ITU-T is received, this model is clear, and can be easily updated based on any new input.
Appendix
Analysis of Link segmentation improvement. Part 1

Link segmentation improvement depends on the ZDW and Slope standard distributions

ZDWstd = 3.5 nm
ZDWmean = 1312 nm

ZDWstd = 2 nm
ZDWmean = 1312 nm

ZDWstd = 1 nm
ZDWmean = 1312 nm
Analysis of Link segmentation improvement. Part 2

ITU fitting for 10km min dispersion shows:

- Dispersion$_{\text{min}}$ of $\sim-2.6$ ps/(nm km) @1294.56nm with 99.99% confidence
- Dispersion$_{\text{min}}$ increase due to link segmentation of $\sim0.2$ps/(nm km)
- This would be achieved with a ZDW$_{\text{std}}$ = 1nm and ZDW$_{\text{mean}}$ = $1320 – 1322.5$ nm

ZDW: mean = 1322.5 nm and std = 1 nm
Slope: mean = 0.0825 nm and std = 0.002

ZDW: mean = 1320 nm and std = 1 nm
Slope: $Slope_{\text{max}} = 0.092$
Impact of ZDW – slope correlation. Part 1

Based on liu_3dj_01_2401, ZDW and S0 have a inverse correlation of -0.75
Impact of ZDW – slope correlation. Part 2

Just for curiosity, these would be simulation results on a worse case scenario if the ZDW and Slope had positive correlation.
Maximum dispersion for LWDM

Maximum dispersion values for the longest LWDM4 wavelength. The results is even slightly larger then ITU-T fitted function.
Maximum dispersion for LWDM. Part2

Available data indicates ZDW fiber distributions tend to be towards the longer wavelength, therefore, assuming a 5-sigma margin (instead of 4) to the shortest ITU ZDW$_{\text{min}}$ could be reasonable.