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 $Dispersion_{min}$:

$$\text{distance} \times (S0_{max} / 4) \times \lambda \times [1 - (ZDW_{max} / \lambda)^4]$$

where $S0_{max}$ = 0.092 $ps.nm^2km$ and ZDW_{max}= 1324nm from ITU-T fiber attributes

Table 140–10a—Transmitter compliance channel specifications

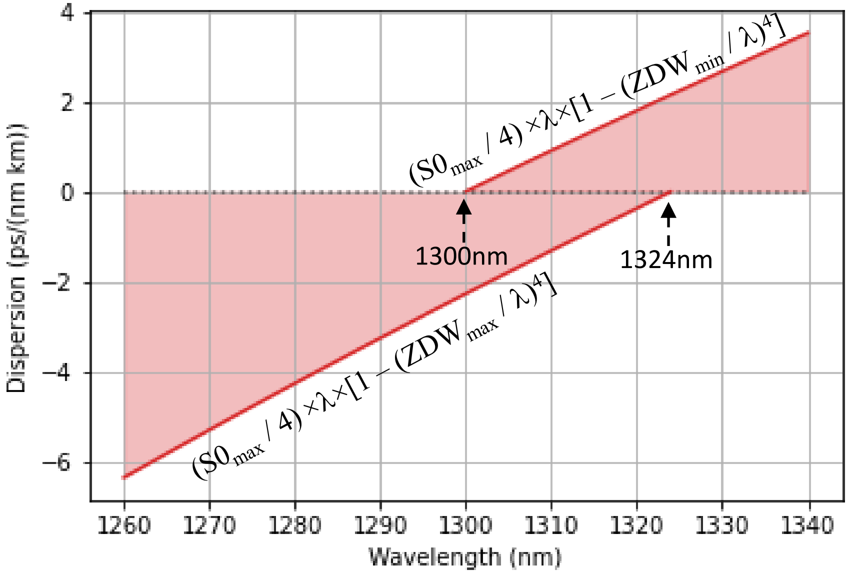
PMD type	Dispersion[a] (ps/nm)		Insertion loss[b]	Optical return loss[c]	Max mean DGD
	Minimum	Maximum			
100GBASE-DR	$0.011625 \times \lambda \times [1-(1324 / \lambda)^4]$	$0.011625 \times \lambda \times [1-(1300 / \lambda)^4]$	Minimum	15.5 dB	0.5 ps
100GBASE-FR1	$0.046 \times \lambda \times [1-(1324 / \lambda)^4]$	$0.046 \times \lambda \times [1-(1300 / \lambda)^4]$	Minimum	17.1 dB	0.8 ps
100GBASE-LR1	$0.230 \times \lambda \times [1-(1324 / \lambda)^4]$	$0.230 \times \lambda \times [1-(1300 / \lambda)^4]$	Minimum	15.6 dB	0.8 ps

[a] The dispersion is measured for the wavelength of the transmitter under test (λ in nm). The coefficient assumes 500 m for 100GBASE-DR, 2 km for 100GBASE-FR1, and 10 km for 100GBASE-LR1.

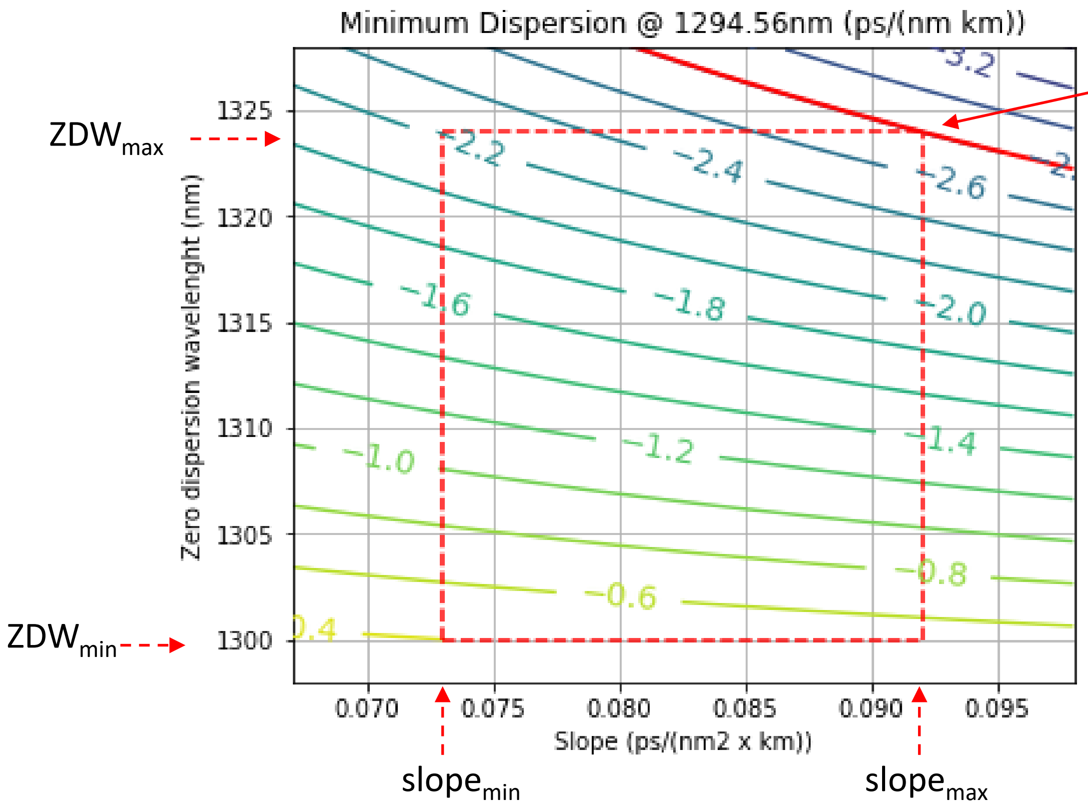
Until now, dispersion spec scales linearly with distance.
i.e.: LR equation is 5 times FR equation (No link segmentation)

- FR : **2** x 0.023 = 0.046
- LR: **10** x 0.023 = 0.230

Graphical representation of the dispersion formula



How is Dispersion currently specified: Graphical representation.



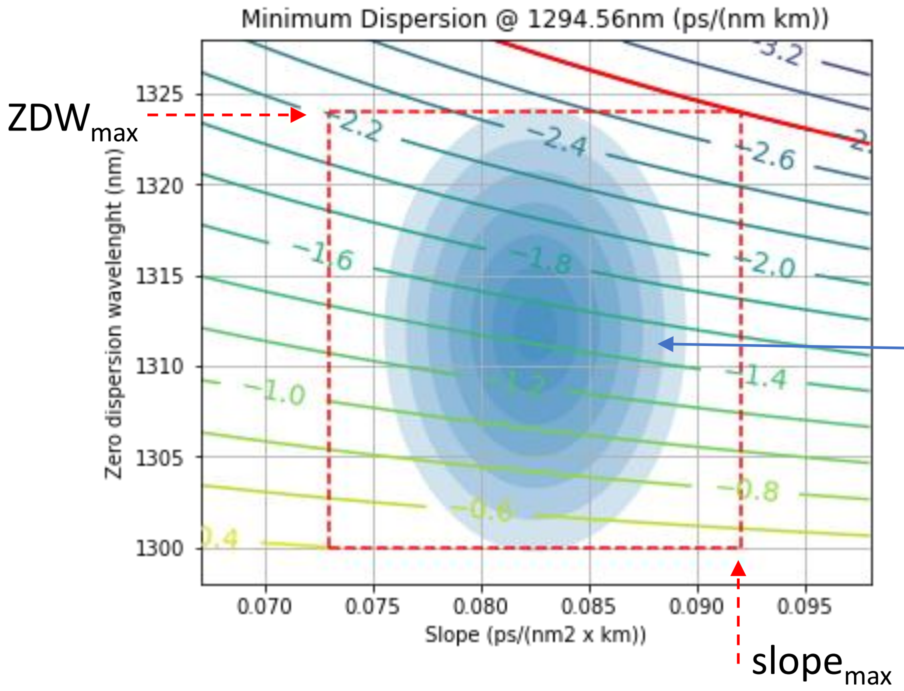
Current IEEE channel specification:

$(S0_{max} / 4) \times \lambda \times [1 - (ZDW_{max} / \lambda)^4]$

IEEE specifies dispersion by the intersection of of ZDW_{max} and $slope_{max}$

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

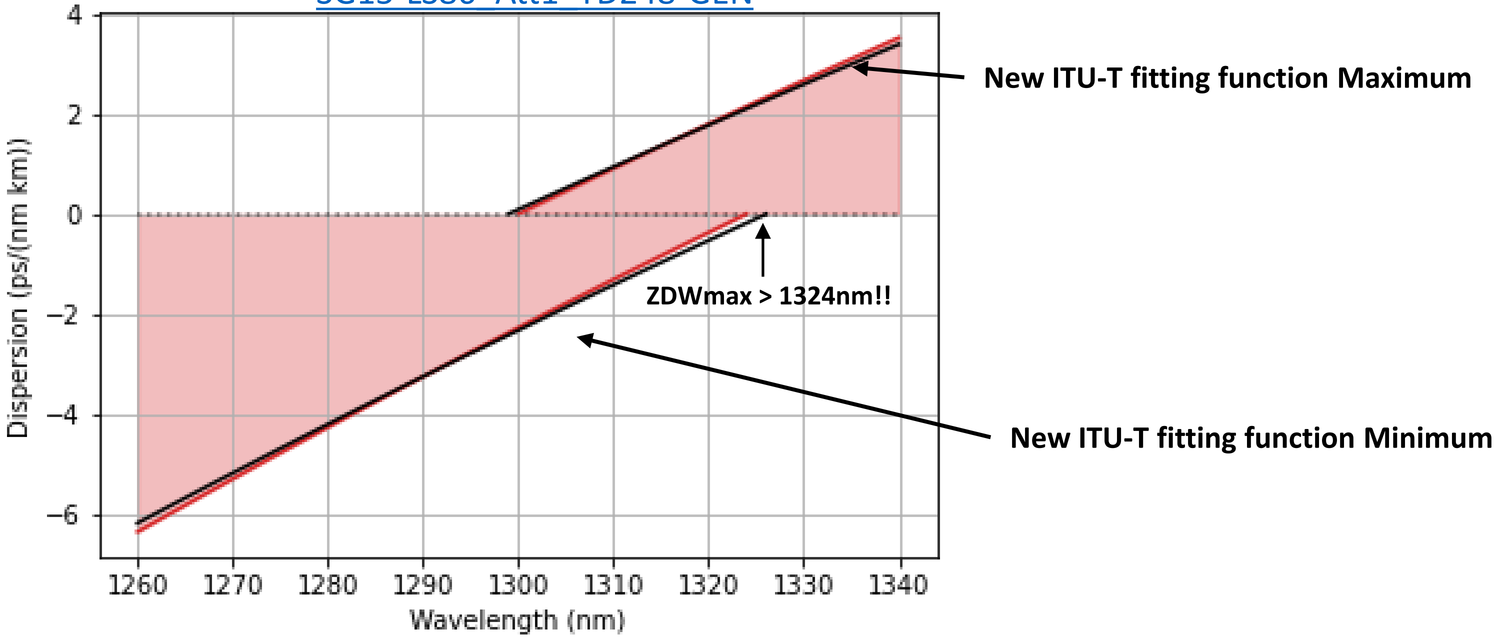
- ITU provided a min/max dispersion fitting function for 2, 10, 20, 30, and 40 km SG15-LS86_Att1_TD248-GEN

- 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

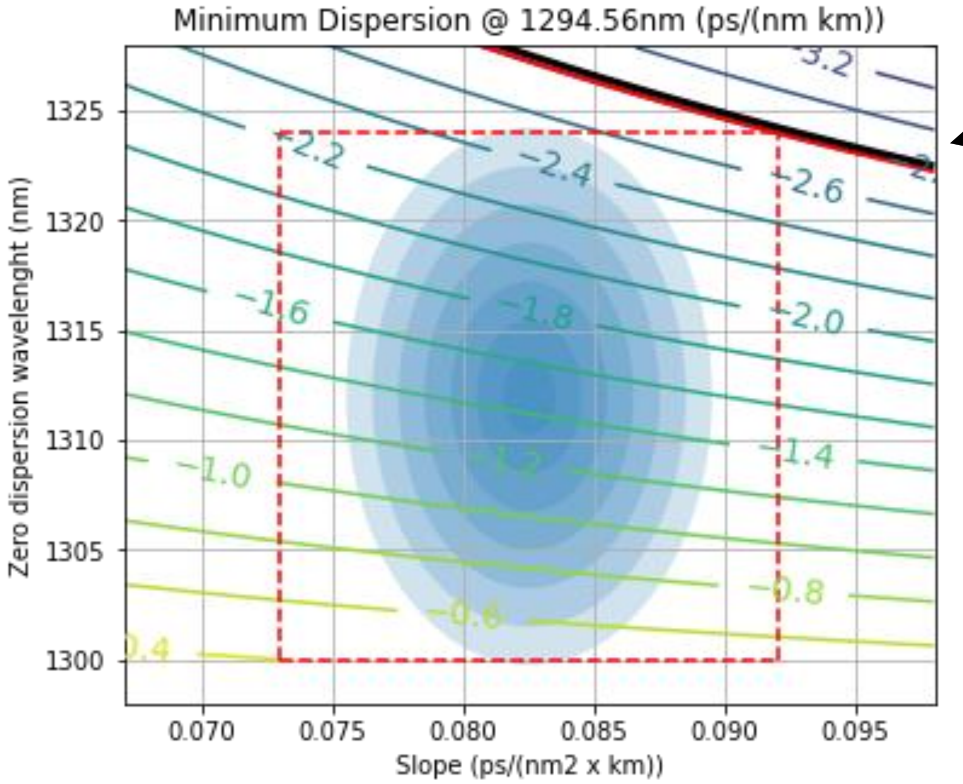
Normalized Dispersion based on 2km fitting in
[SG15-LS86_Att1_TD248-GEN]



- 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



Based on New ITU-T fitting function Maximum
SG15-LS86_Att1_TD248-GEN

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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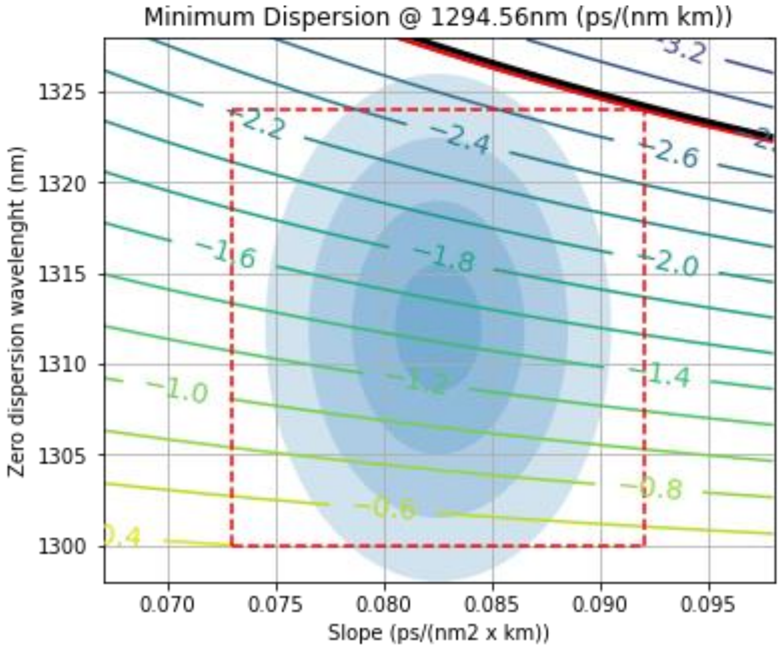
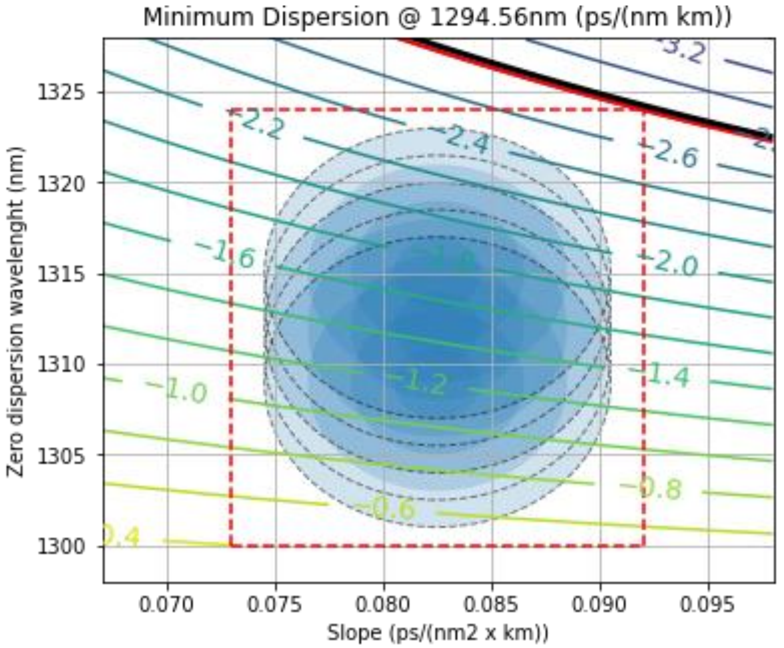
Previously proposed models:

ITU Liaison annex:
- Applied to LR4 PMD: liu_3dj_01a_2307



- Simple
- underestimate when segments from same vendor

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



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

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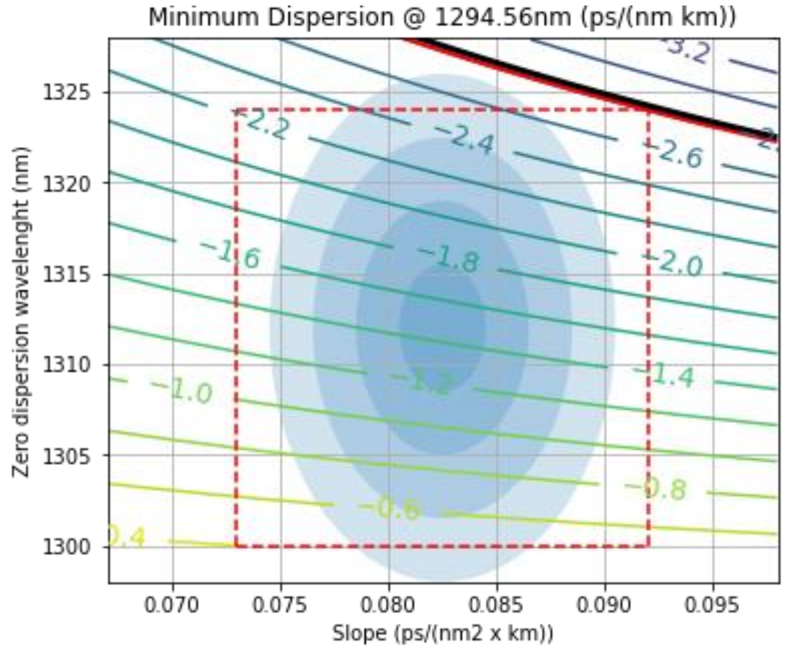

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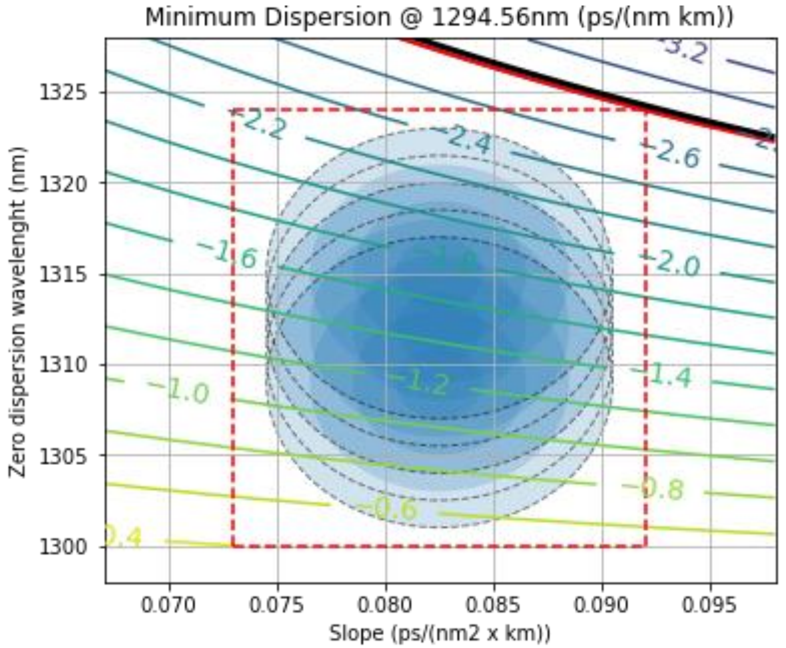
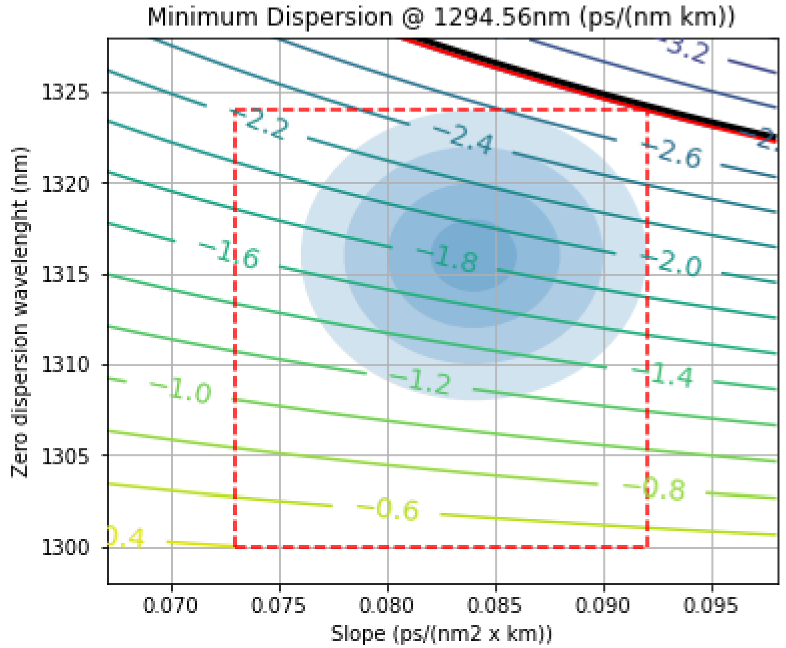


- Accounts for same vendor segments
- A bit more complex
- Not as conservative as ITU-T limits

This proposal:

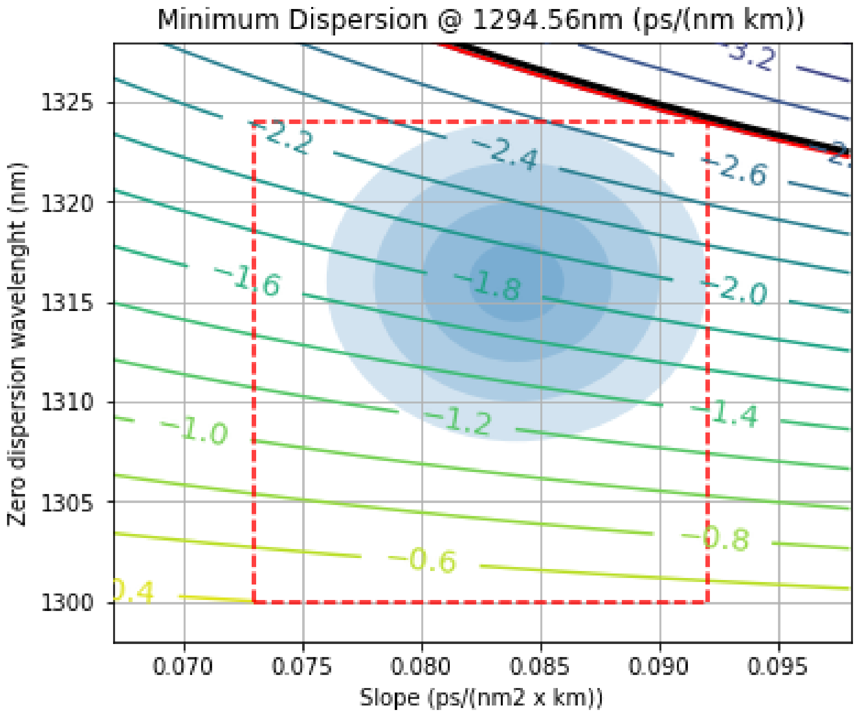
Single distribution for ITU-T worst case ZDW and Slope at 4 sigma (~99.99%)

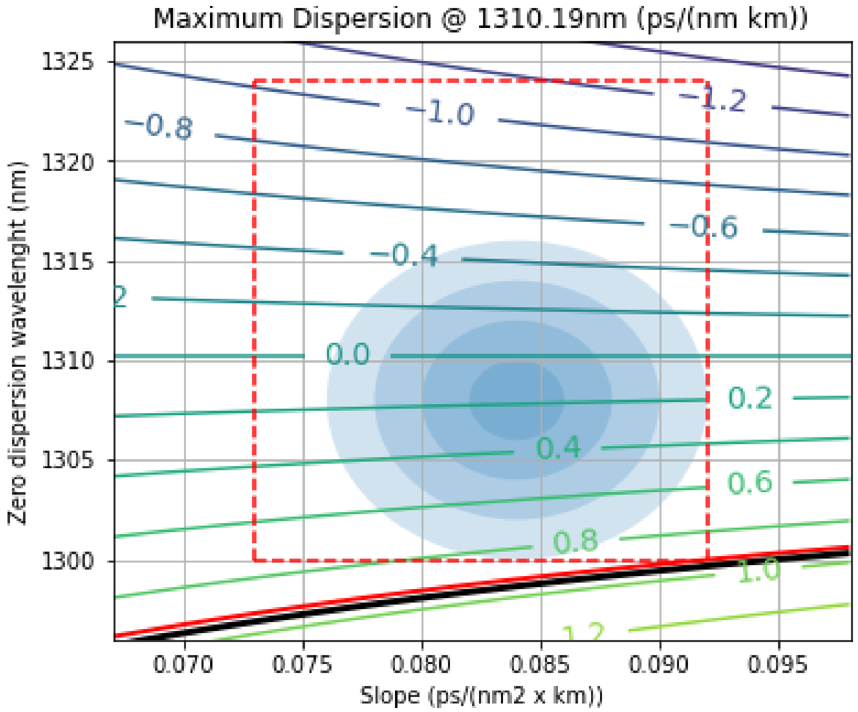


- Simple
- Same ITU-T ZDW and slope specs with 99.99% (~4 sigma)

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

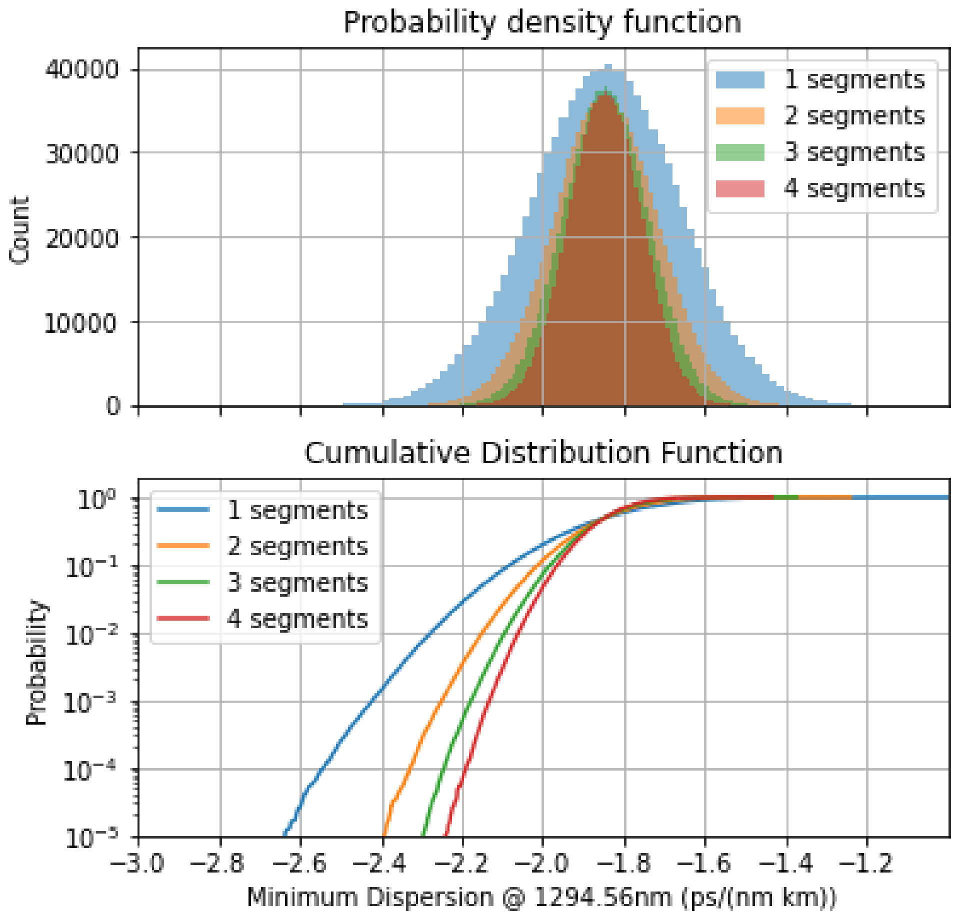
For Maximum dispersion:

- ZDW: mean= 1308, std= 2
- Slope: mean= 0.084, std= 0.002

Optical links with Link Segmentation

Link segmentation: When? Improves what?

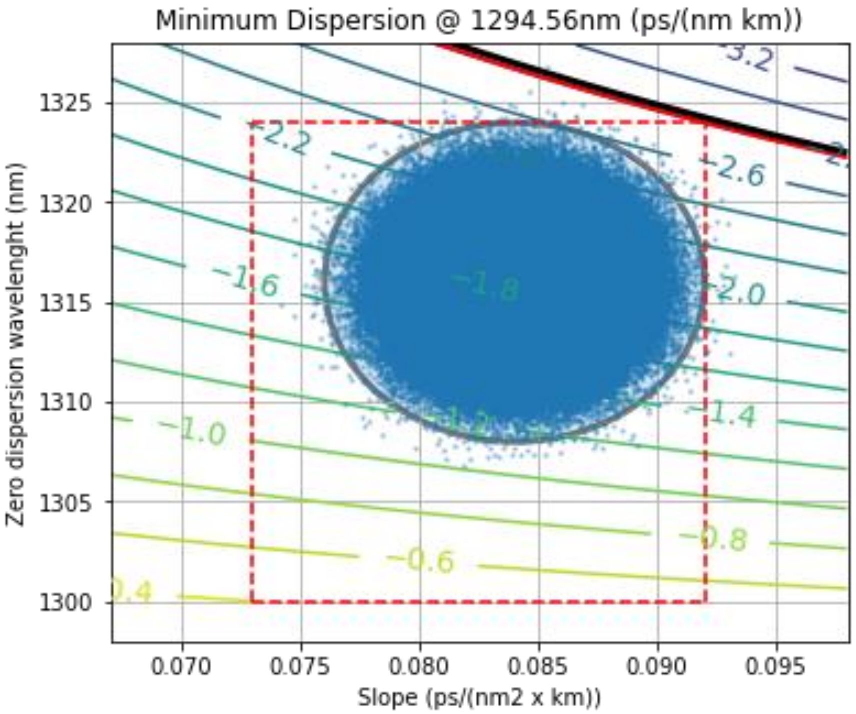
- Longer optical links are built in segments
- Link segmentation reduces the dispersion variance
- Dispersion reduction depends on standard deviation. See annex for more.

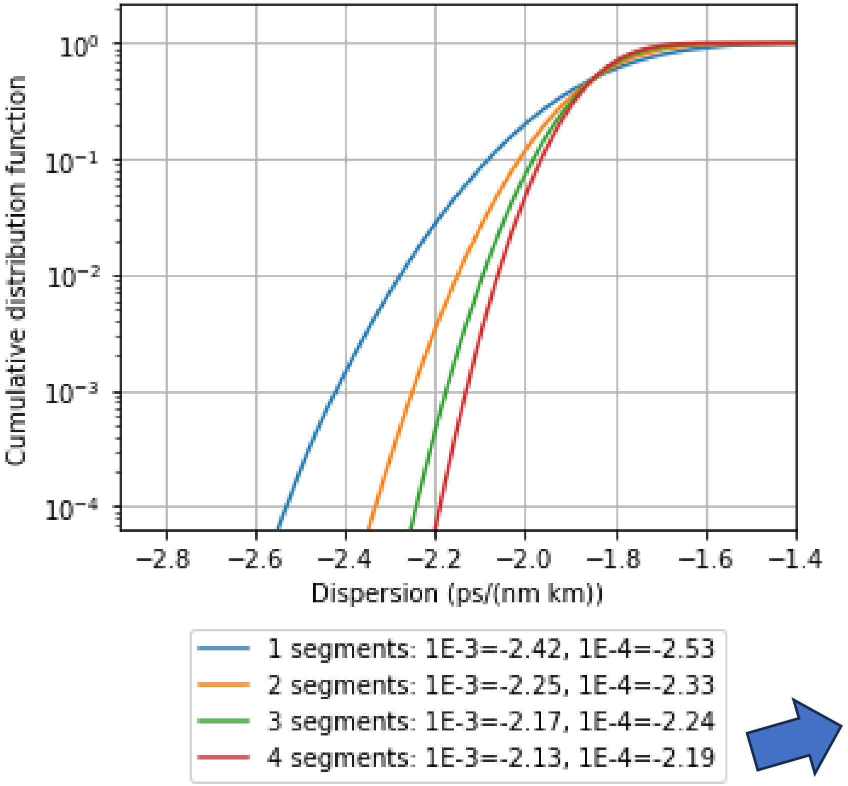


How to apply link segmentation with channel model?

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%



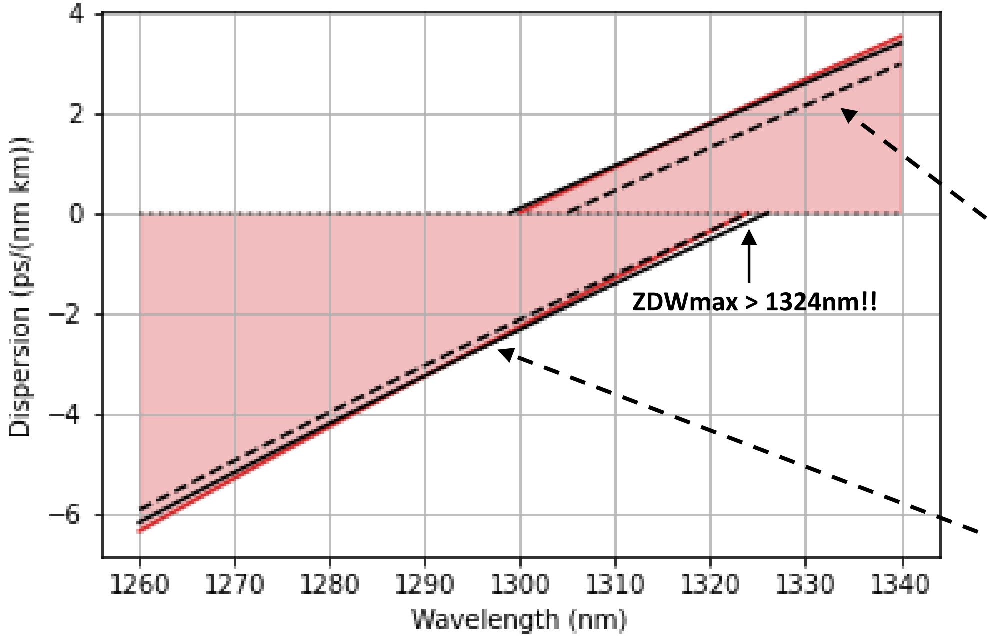


i.e: 800G-LR4 $Dispersion_{min}$:
-21.9 ps/nm for 99.99%
-21.3 ps/nm for 99.9%

ITU-T liaison review: 4x2.5km fitting

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

Normalized Dispersion based on 10km fitting in
SG15-LS86_Att1_TD248-GEN



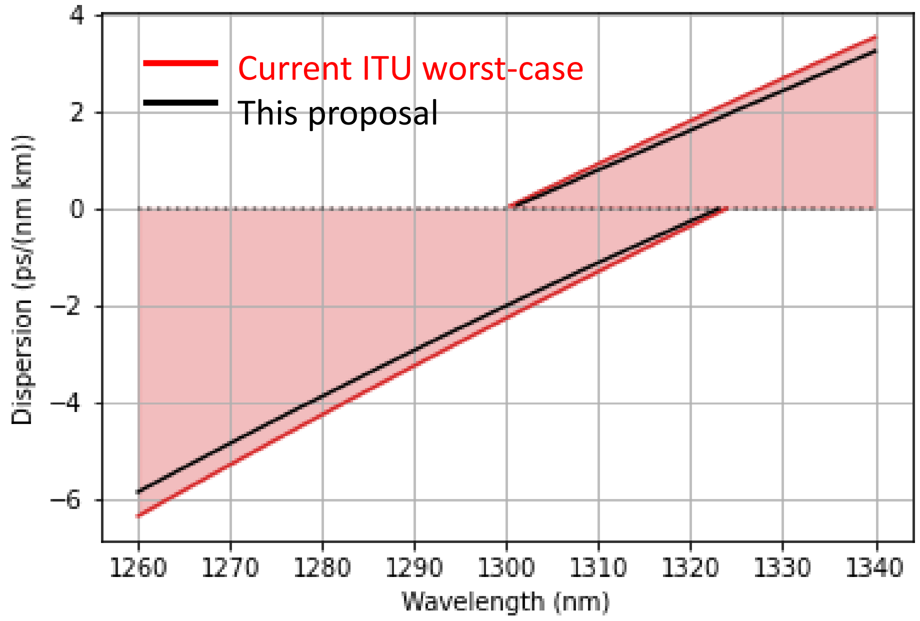
New ITU-T fitting function Maximum with 4 segments
SG15-LS86_Att1_TD248-GEN

New ITU-T fitting function Minimum with 4 segments
SG15-LS86_Att1_TD248-GEN

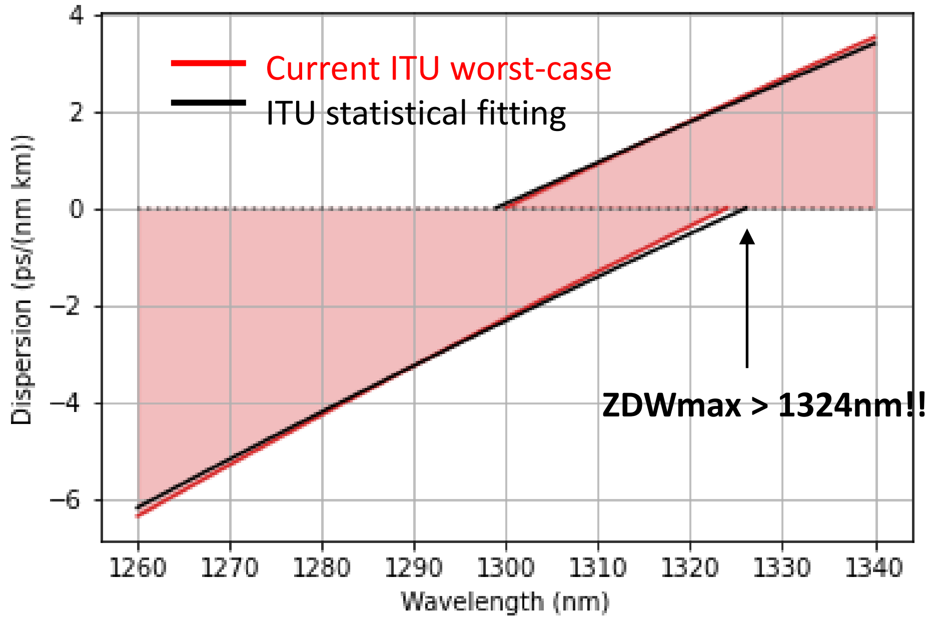
ITU-T fitting, even after averaging effect of link segmentation, does not completely meet ITU own specs

Results comparison: single segment

This proposal for **single segment** link



ITU statistical fitting for **single segment** link

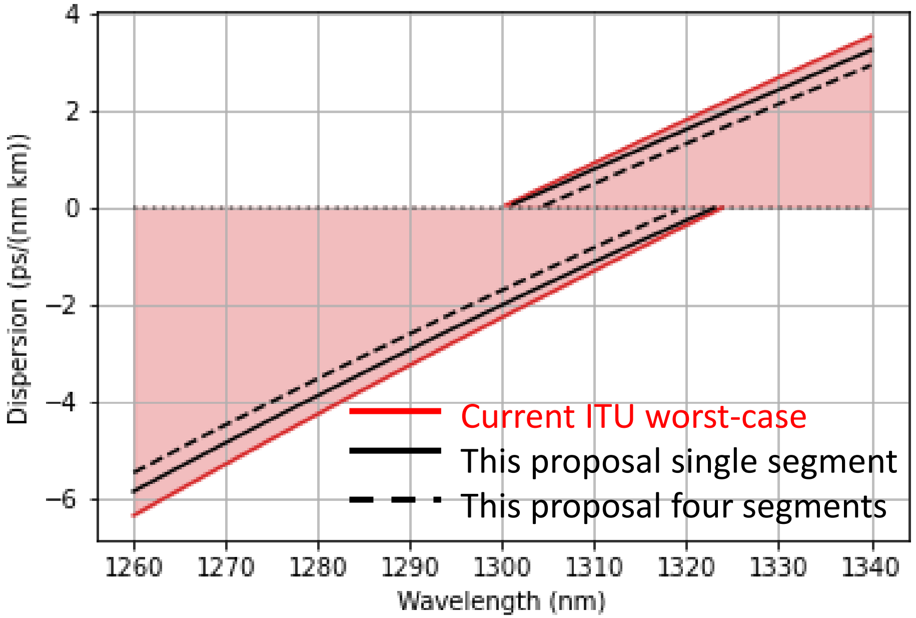


This proposal:

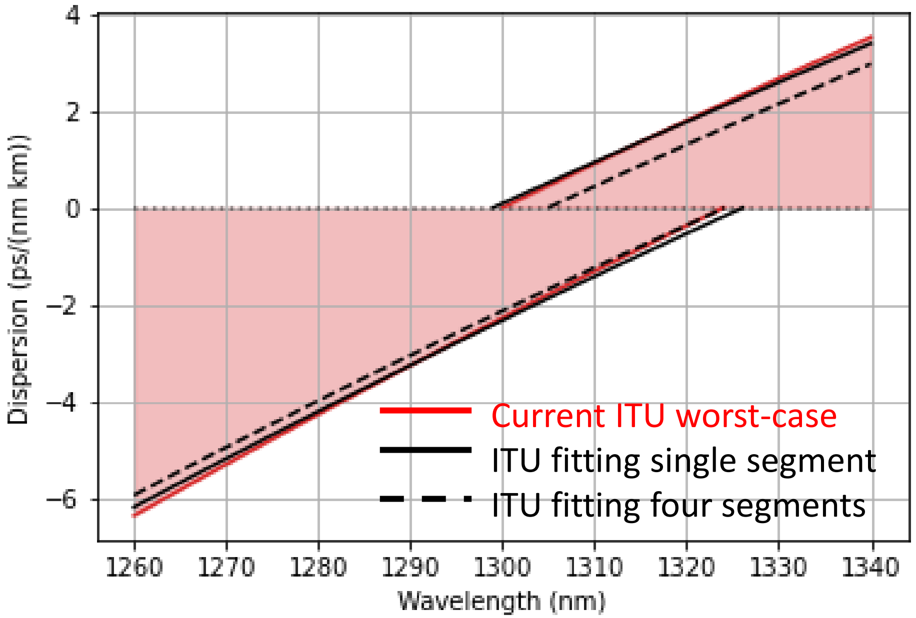
- Fixes the problems the ITU fitting has regarding ZDWmax out of spec
- Show a modest expected reduction in dispersion due to 99.99% confidence

Results comparison: four segments

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



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

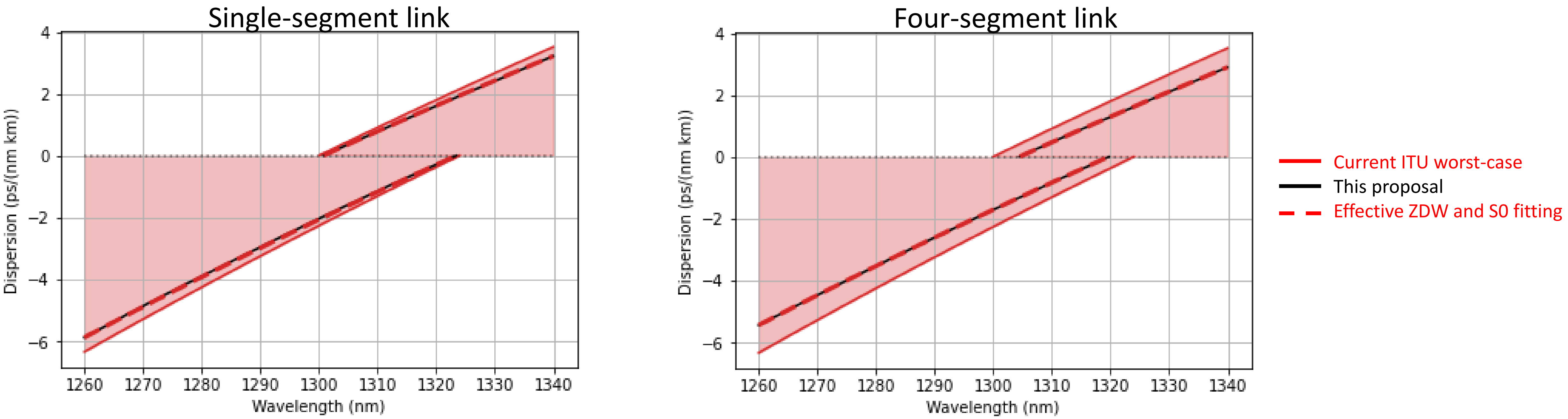


This proposal:

- 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 ZDWmin= 1300.8 nm
Effective ZDWmax= 1323.4 nm
Effective S0max = 0.086 ps/(nm2 km)

Effective ZDWmin= 1304.5 nm
Effective ZDWmax= 1319.7 nm
Effective S0max = 0.085 ps/(nm2 km)

The effective ZDW and S0 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

Peter ITU analysis in stassar_3dj_01_2401

Distance [km]	Slope S_0 for min CD [ps/nm^{2}km]	ZDW/λ_0 [nm]	Slope S_0 for max CD [ps/nm^{2}km]	ZDW/λ_0 [nm]
Current	0.092	1324	0.092	1300
2	0.0864	1326.1	0.0864	1299.0
10	0.0856	1324.2	0.088	1305

Comparison of this approach vs ITU fitting

2km	Slope S0 for min CD	ZDWmax for min CD	Slope S0 for max CD	ZDWmin for max CD
Peter analysis of ITU	0.0864	1326.1	0.0864	1299.0
This Proposal	0.086	1323.4	0.086	1300.8

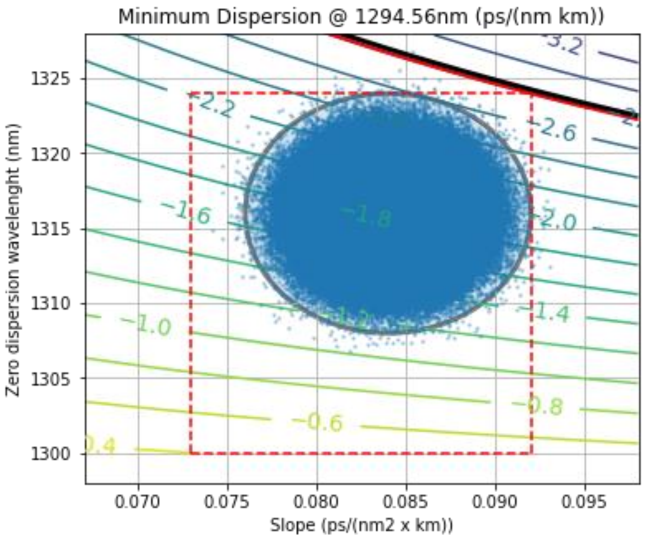
10km	Slope S0 for min CD	ZDWmax for min CD	Slope S0 for max CD	ZDWmin for max CD
Peter analysis of ITU	0.0856	1324.2	0.088	1305
This Proposal	0.086	1319.7	0.086	1304.5

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

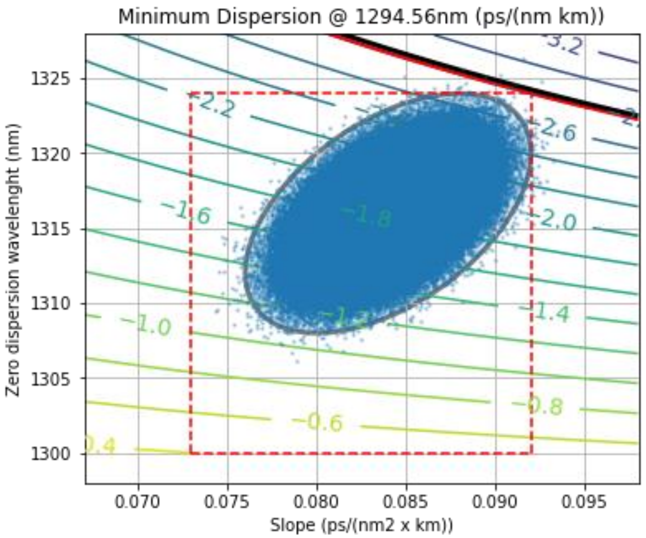
The proposed optical channel would result in a spec dispersion limits for 800GBASE-LR4 of:

Option A: Independent ZDW and Slope



PMD type	Dispersion (ps/nm)	
	Minimum	Maximum
800GBASE-LR4	-21.9	4.9

Option B: Alternatively, even a more conservative approach could be adopted using positive correlation of ZDW and Slope



PMD type	Dispersion (ps/nm)	
	Minimum	Maximum
800GBASE-LR4	-22.4	4.9

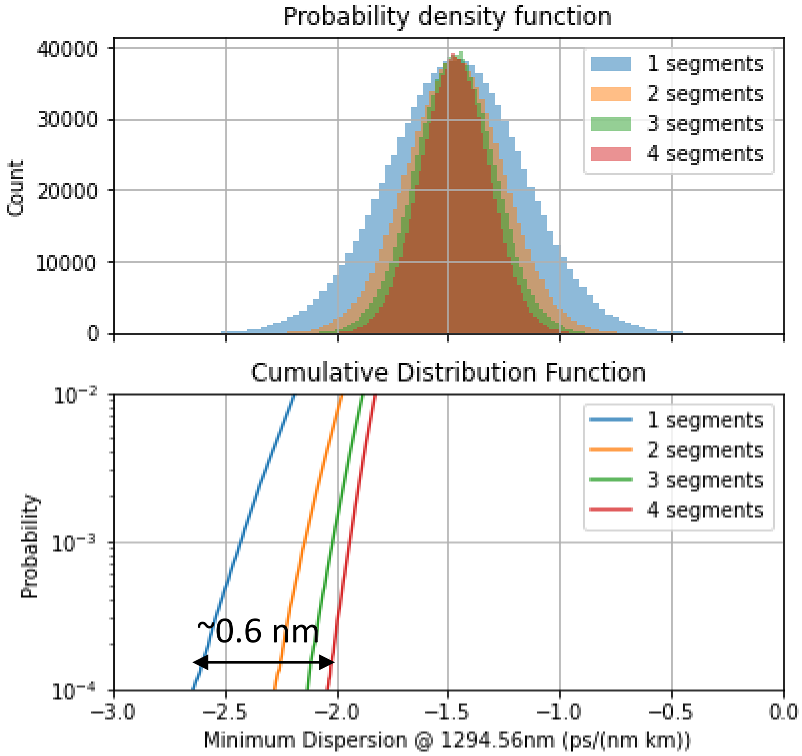
Conclusions

- 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

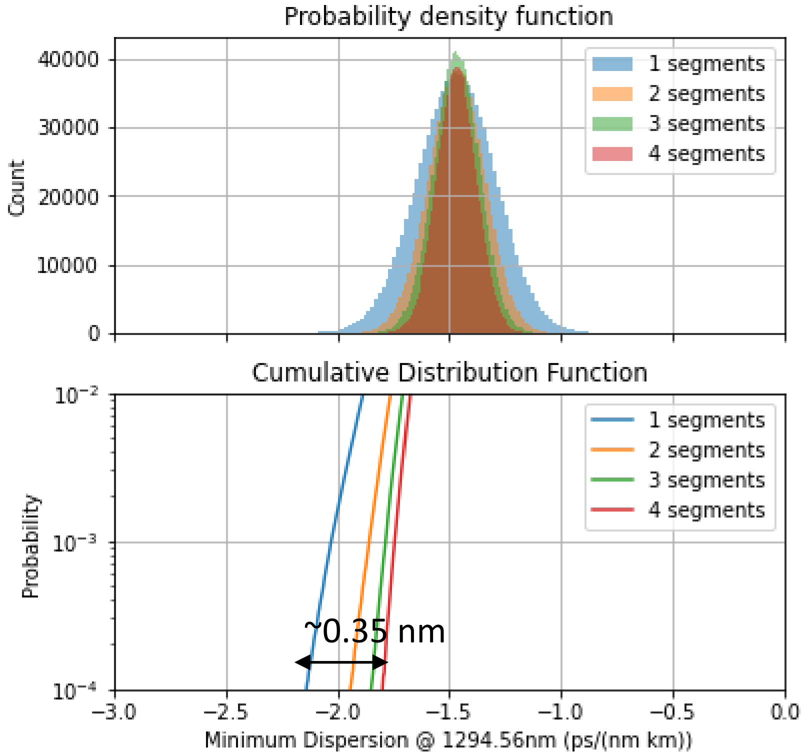
Analysis of Link segmentation improvement. Part 1

Link segmentation improvement depends on the ZDW and Slope standard distributions



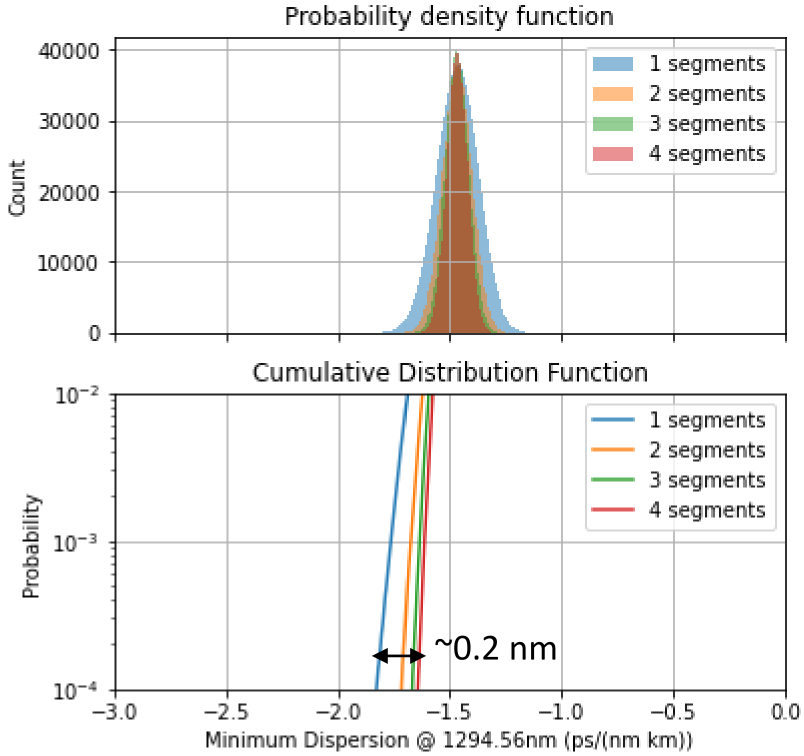
ZDWstd = 3.5 nm

ZDWmean = 1312 nm



ZDWstd = 2 nm

ZDWmean = 1312 nm



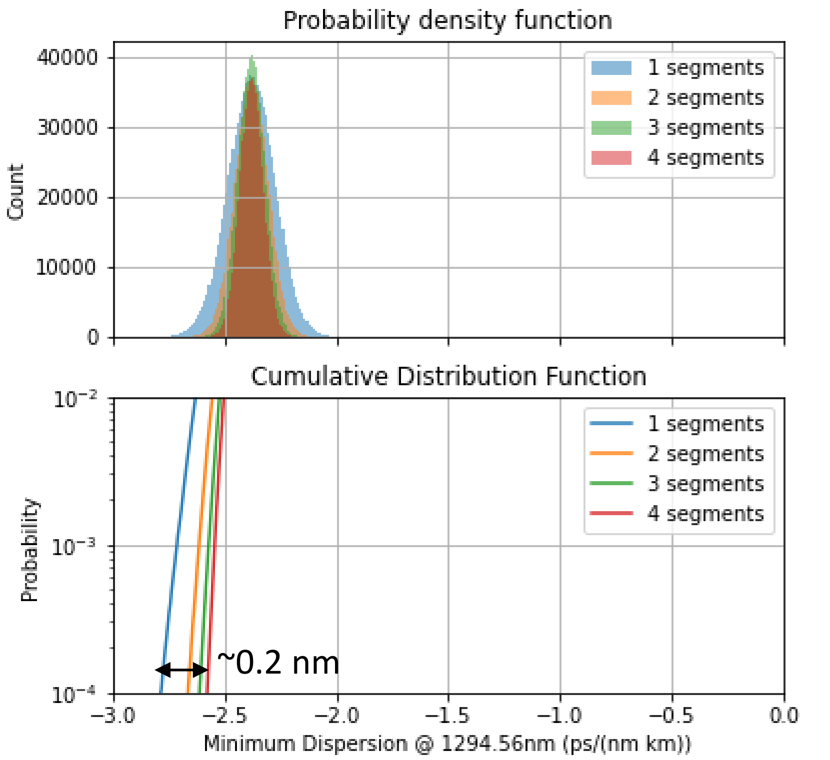
ZDWstd = 1 nm

ZDWmean = 1312 nm

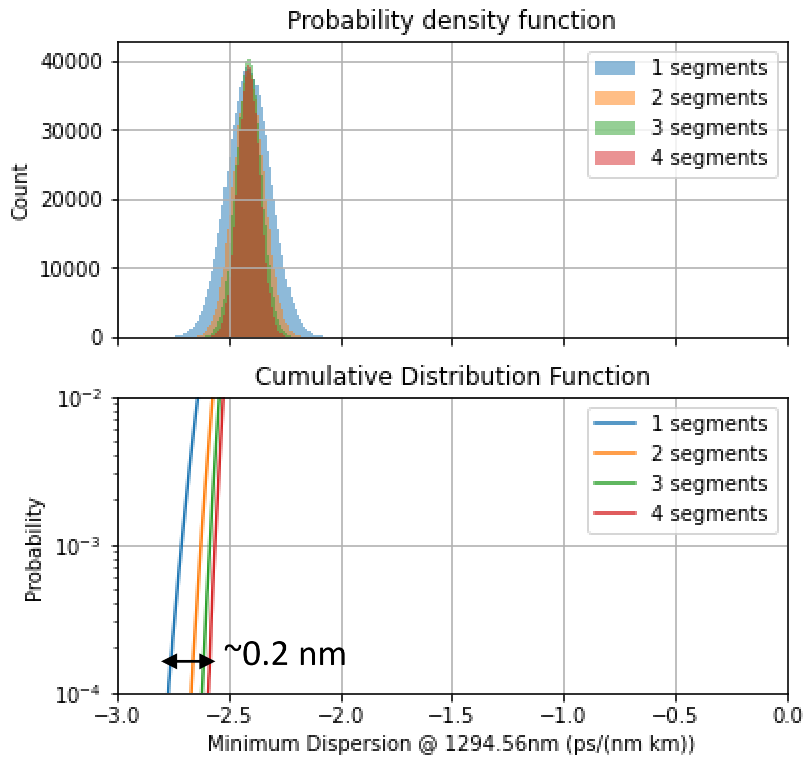
Analysis of Link segmentation improvement. Part 2

ITU fitting for 10km min dispersion shows:

- Dispersion_{min} of ~-2.6 ps/(nm km) @1294.56nm with 99.99% confidence
- Dispersion_{min} increase due to link segmentation of ~0.2ps/(nm km)
- This would be achieved with a ZDWstd = 1nm and ZDWmean = 1320 – 1322.5 nm



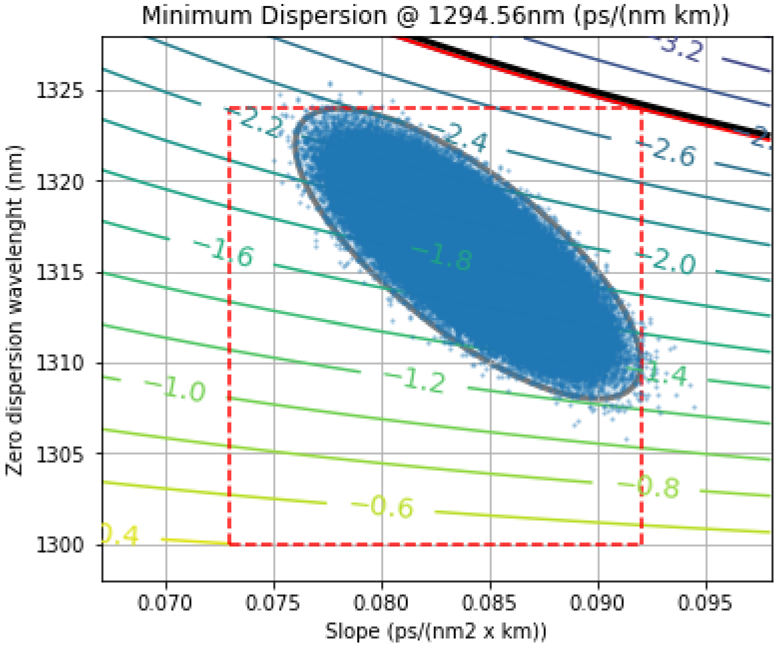
ZDW: mean= 1322.5 nm and std = 1 nm
Slope: mean= 0.0825 nm and std = 0.002

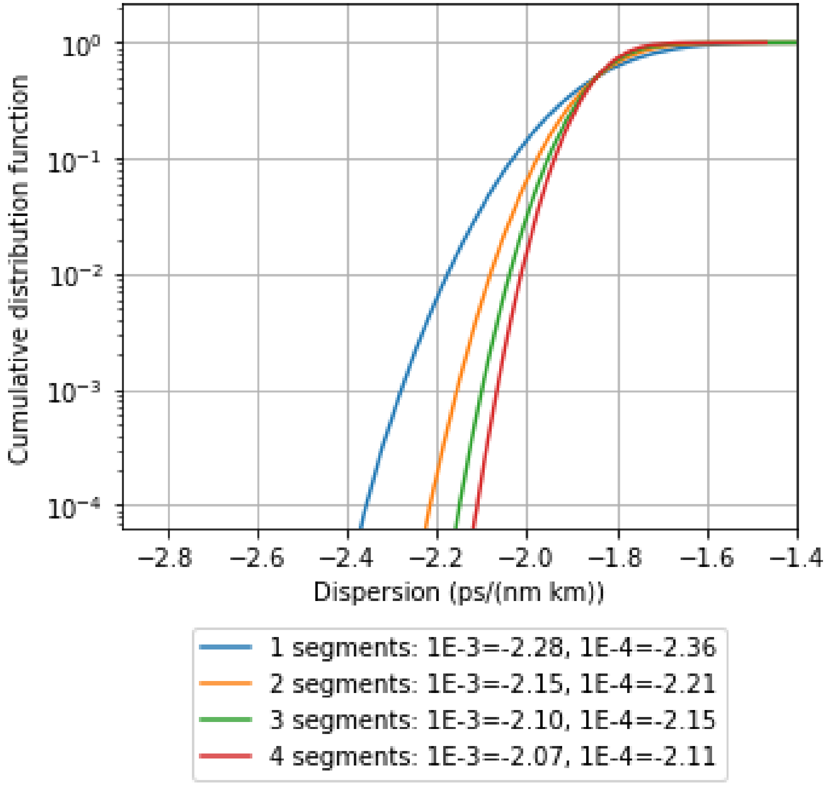


ZDW: mean= 1320 nm and std = 1 nm
Slope: Slope_{max}= 0.092

Impact of ZDW – slope correlation. Part 1

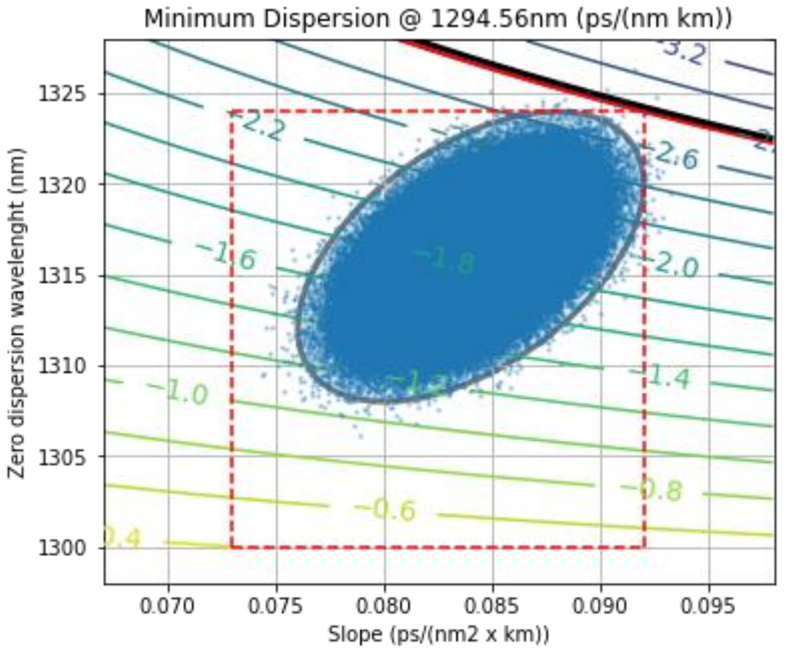
Based on liu_3dj_01_2401, ZDW and S0 have a inverse correlation of -0.75

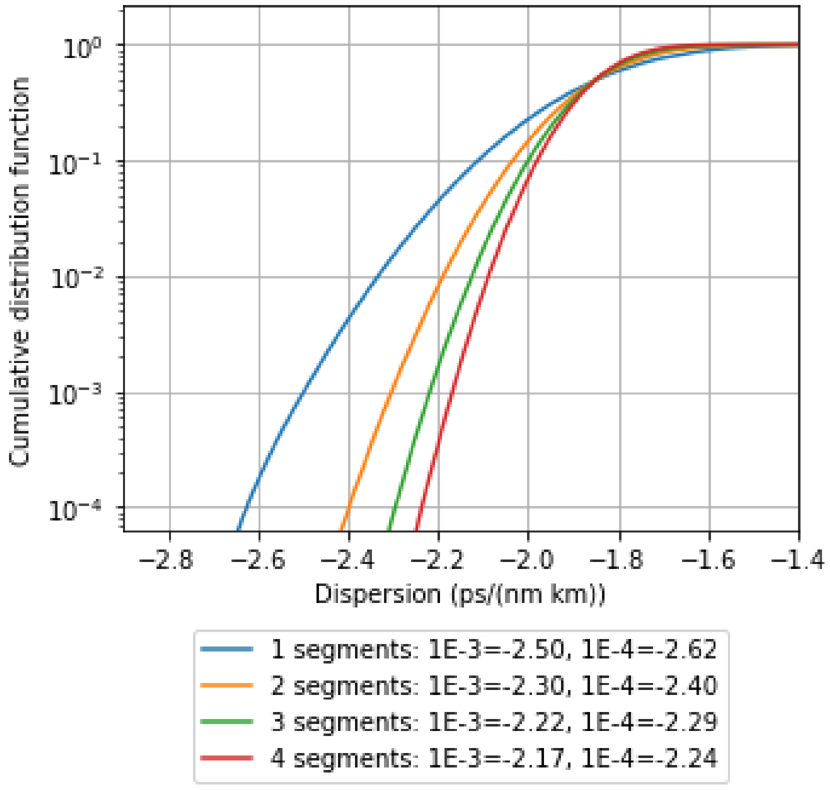




Impact of ZDW – slope correlation. Part 2

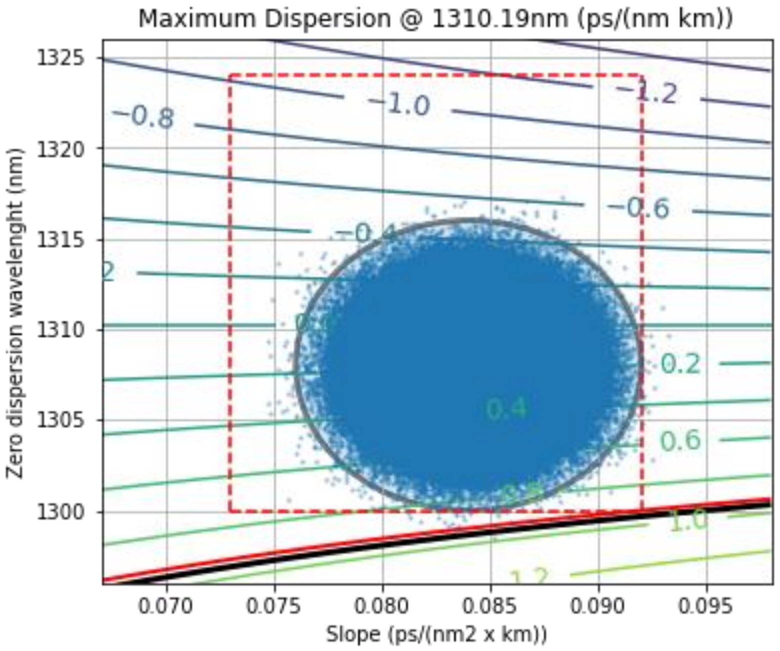
Just for curiosity, these would be simulation results on a worse case scenario if the ZDW and Slope had positive correlation

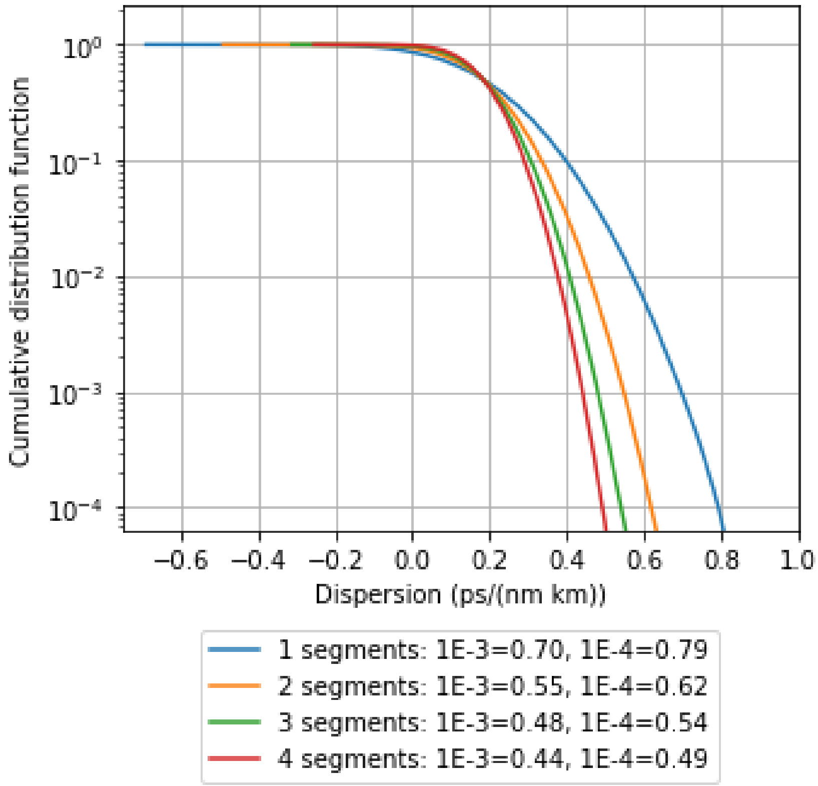




Maximum dispersion for LWDM

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 tent to be towards the longer wavelength, therefore, assuming a 5-sigma margin (instead of 4) to the shortest ITU ZDW_{min} could be reasonable