25 Gbaud PAM-4 transmission and mode partition noise
RE: comments 4 & 10 against D1.1

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IEEE P802.3cm 400 Gb/s MMF Task Force

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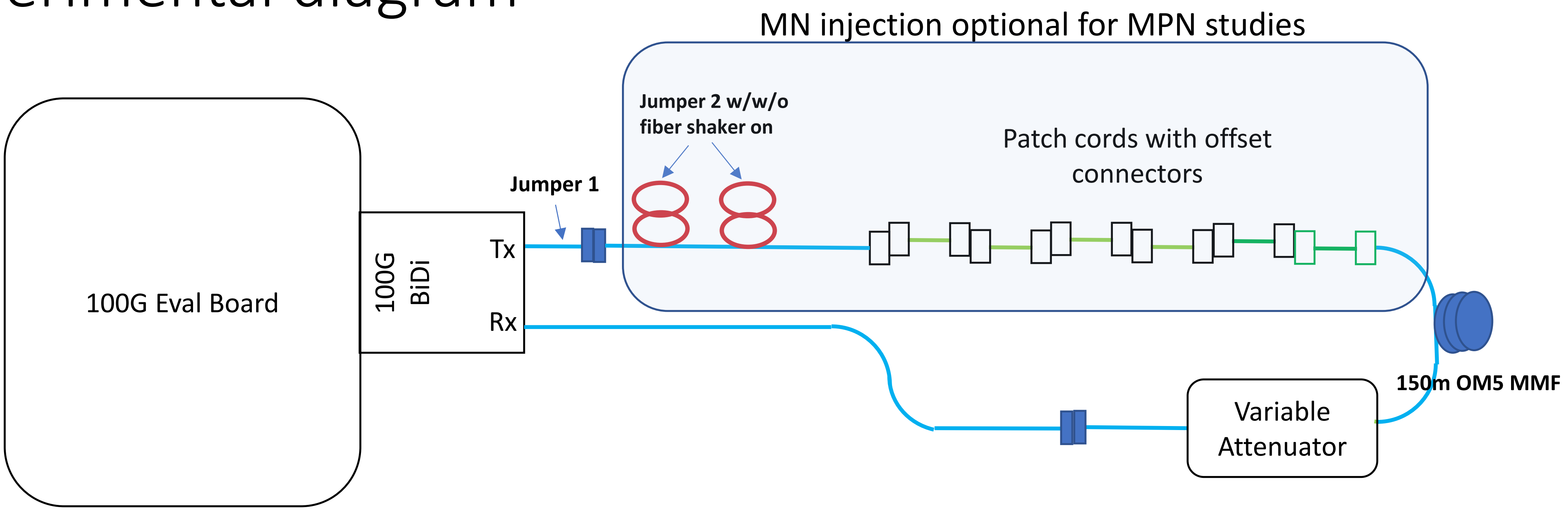
Motivation

- This is not a thorough study of MPN with 25 Gbaud PAM-4 VCSELs
- Some arguments from modeling have been presented, raising the question whether the power budget for SR4.2 sufficiently accounts for the MPN penalty (and associated Pcross) at 150m reach.
- It may be noted that those with access to the most detailed device & link models have not raised this concern.
- In the absence of experimental data showing that MPN is in fact a challenge to the budget for SR4.2 at 150m, we believe that showing robust performance of 25 Gbaud PAM-4 BiDi technology in a link that seeks to approximate worst case with available parts is sufficient to allay concerns.

MPN Experimental Setup

- 100G BiDi transceiver on eval board
- 2 wavelengths, 850 and 910 nm with 50 Gbit/s PAM4
- Test at 10^{o}C and 31^{o}C
- Transmission measurements over OM5 fibers with EMB values as close to OM5 limits as could readily be found
- Links up to 350 m over OM5
- Compare total transmission penalty to MPN penalty predicted by analytic models

Experimental diagram



Errors estimated by FEC decoder
Received power is measured by the power detector built into Rx (also by an external power meter)

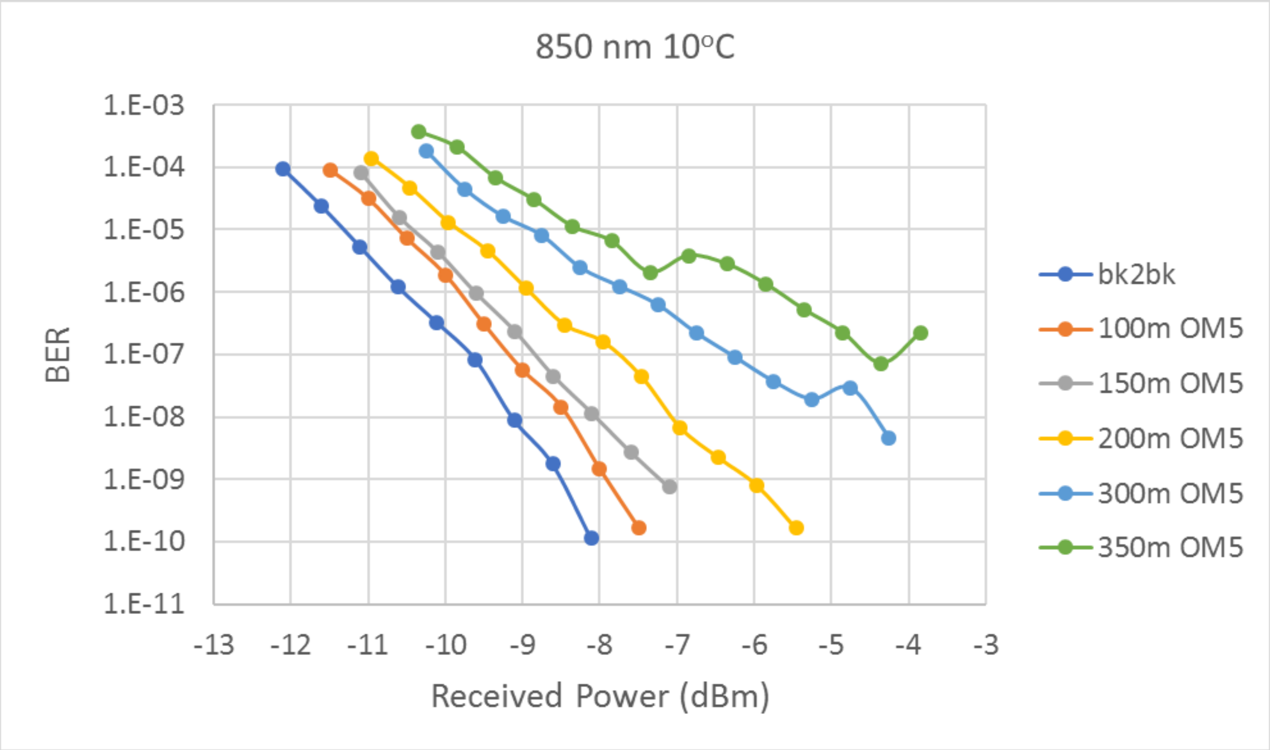
Two different sets of offset patch cords
LG: larger offsets patch cord
DG: smaller offsets patch cord
LDG: larger and smaller offset in serial
fiber shaker

Worst-case 850nm fiber had EMB of 4875 MHz-km , compared to 4700 MHz-km spec limit

Lowest BW 910nm fiber had EMB of ~3900 MHz-km, compared to ~3100 MHz-km for OM5

Penalties vs. length at 850 nm 10°C

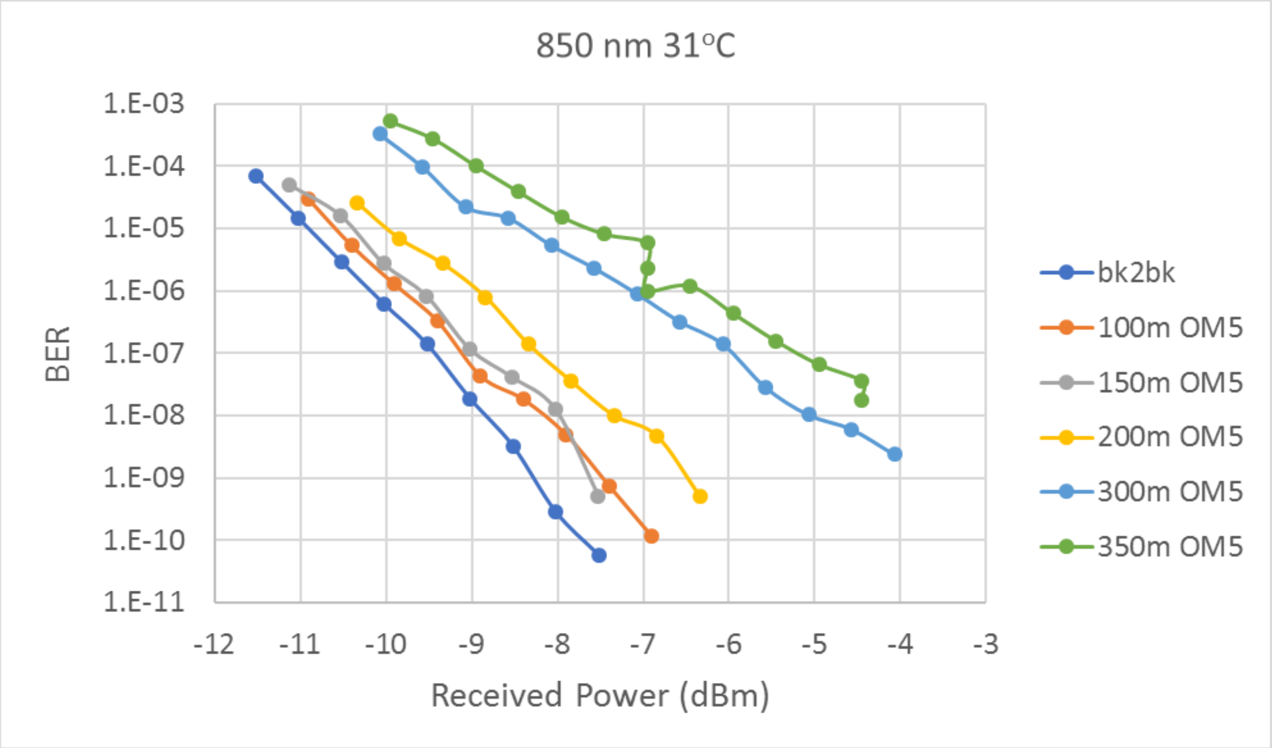
- RMS Spectral Width = 0.331 nm
- Fiber EMB @ 850 nm = 4875 MHz*km
- Center wavelength = 854.6 nm



Length (m)	Transmission Penalty @1e-5 (dB)
100	0.7
150	0.9
200	1.5
300	2.4
350	3

Penalties vs. length at 850 nm 31^{o}C

- RMS Spectral Width = 0.312 nm
- Fiber EMB @ 850 nm = 4875 MHz*km
- Center wavelength = 855.82 nm

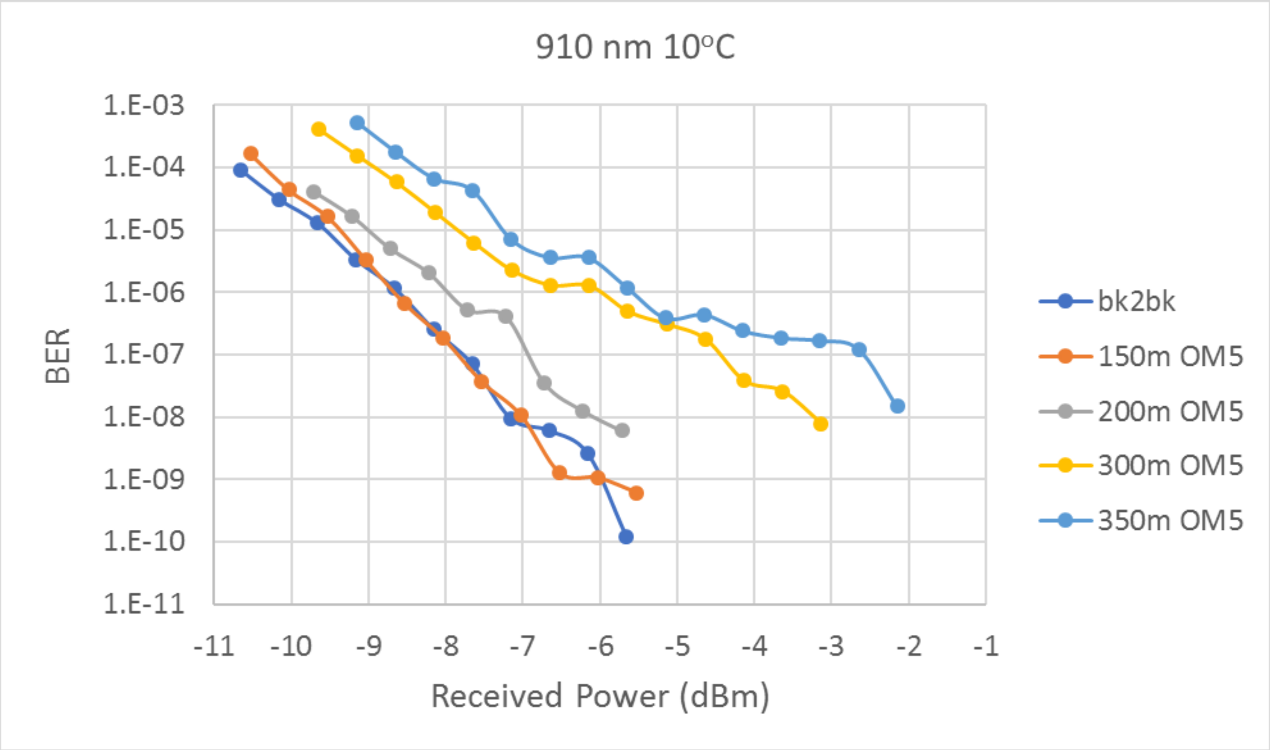


Length (m)	Transmission Penalty @1e-5 (dB)
100	0.3
150	0.5
200	0.9
300	2.5
350	3.3

Penalties vs. length at 910 nm 10°C

- RMS Spectral Width = 0.41 nm
- Fiber EMB @ 910 nm = 3900 MHz*km
- Center wavelength = 903.5 nm

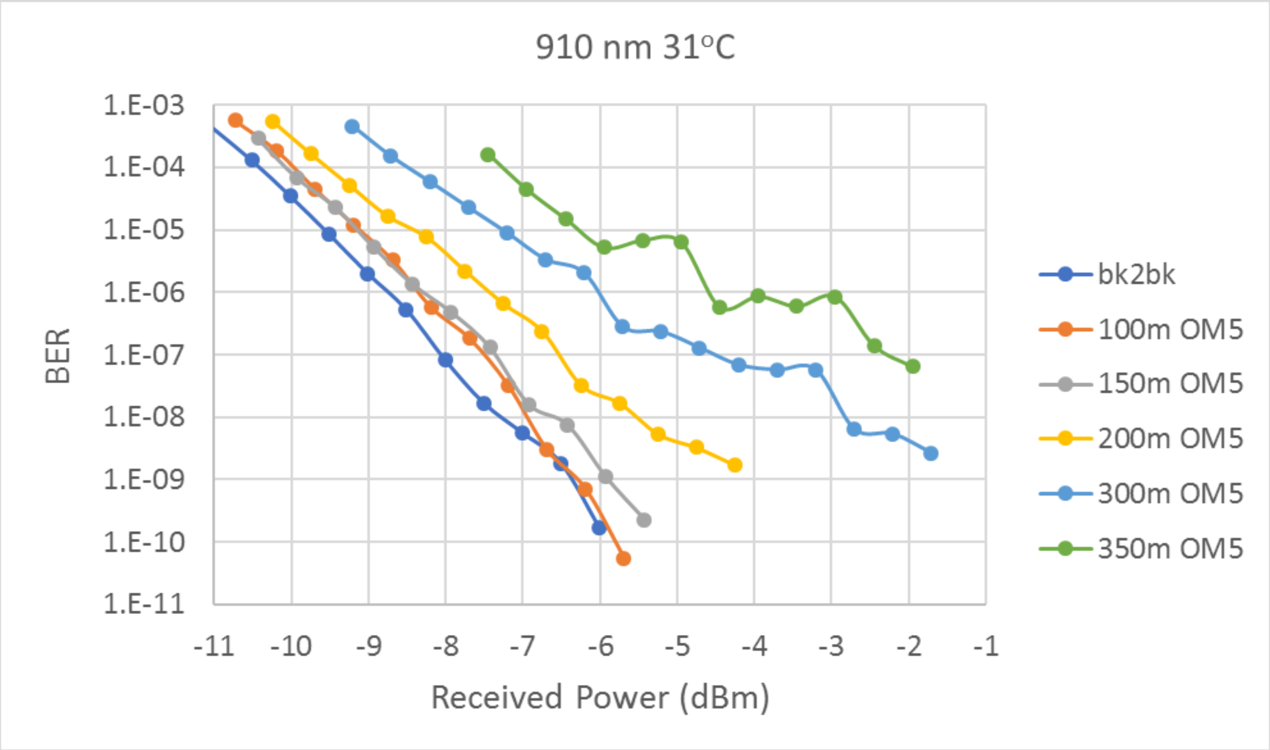
Length (m)	Transmission Penalty @1e-5 (dB)
150	0.2
200	0.6
300	1.7
350	2.3



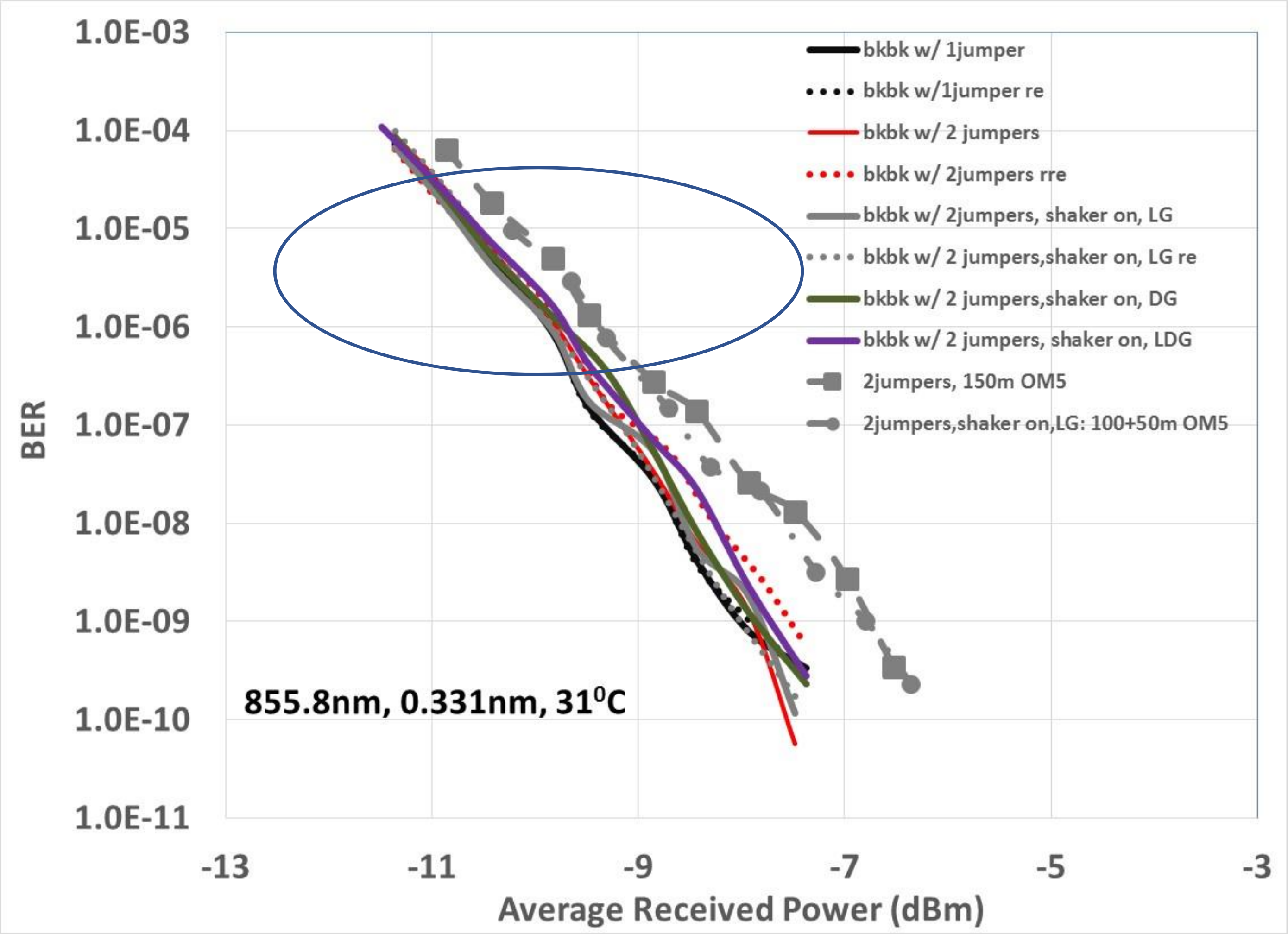
Penalties vs. length at 910 nm 31°C

- RMS Spectral Width = 0.38 nm
- Fiber EMB @ 910 nm = 3900 MHz*km
- Center wavelength = 906.6 nm

Length (m)	Transmission Penalty @1e-5 (dB)
100	0.5
150	0.5
200	1.2
300	2.3
350	3.3



Total penalties with modal noise generator and 150m OM5 fiber at 855 nm at 31^{o}C with worst-case EMB



MPN Penalty for PAM-4 from Ogawa-Agrawal

- MPN standard deviation in the Ogawa-Agrawal model:

$$\sigma_{MPN} = \frac{k_{MPN}}{\sqrt{2}} \cdot [1 - \exp(-\beta^2)] \qquad \beta = \pi \cdot B \cdot D \cdot L \cdot \sigma_\lambda$$

  - where B, D, L, σ_λ are the (effective) baud rate, dispersion, fiber length and RMS spectral width of the VCSEL
  - Used in IEEE spreadsheet

- MPN Penalty for PAM-4:
  - Factor of 9 comes from the fact that the eye closure is 1/3rd that of the NRZ/OOK eye

$$P_{MPN,PAM-4} = -5\log_{10}(1 - 9 \cdot Q^2 \cdot [\sigma_{MPN}^2])$$

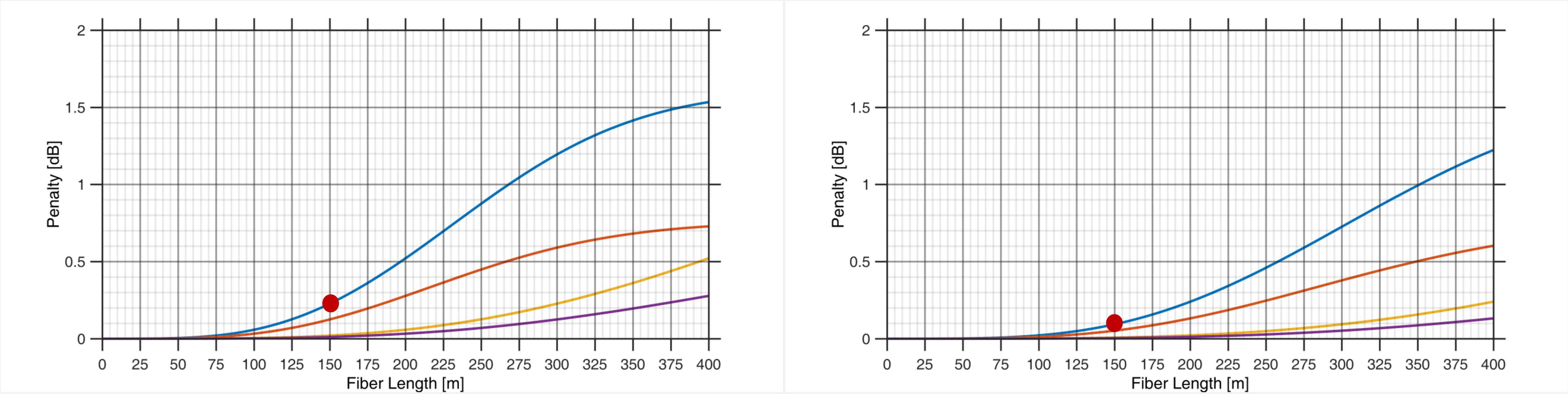
- Balemarthy *et al.* ECOC 2012, paper Th.2.B.4, showed that using a continuum approximation for the spectrum in Ogawa-Agrawal leads to exaggeration of MPN penalty.

MPN Penalty with 150m with σ_λ=0.6nm same as MPN Penalty with 300m with σ_λ=0.3nm

Dependence of calculated Ogawa-Agrawal MPN penalties on several input parameters

- $k_{MPN} = 0.1$, $\sigma_\lambda = 0.6$nm
- $k_{MPN} = 0.075$, $\sigma_\lambda = 0.6$nm
- $k_{MPN} = 0.1$, $\sigma_\lambda = 0.3$nm
- $k_{MPN} = 0.075$, $\sigma_\lambda = 0.3$nm

850nm　　　　910nm



- Dawe has noted values ranging from 0.3 to 0.55 dB relevant to SR4.2

Improvements in RIN that are necessary to implement PAM-4 likely improve k_mpn also

- According to VCSEL experts, it is reasonable that MPN (k factor) decreases when RIN is decreased by design (R. Murty, J. King)
  - Both VCSEL and module optics design may impact practical value of k factor
- 25 GBd PAM4 (with FEC and equalization) does require a lower RIN than a 25G link because of 1/3 OMA.
- Proving the link between MPN k factor and RIN is challenging, requiring a detailed first-principles VCSEL modeling and/or careful experimental determination with sufficient statistics.
- But it seems safe to assume that k_mpn for PAM-4 modules will be lower than k_mpn for NRZ modules at 25 Gbaud

Our interpretation of data and models presented

- It is hard to measure penalties better than ~0.2 dB due to changes when you re-mate connectors, change fibers, clean connectors, move physical layout of jumpers, etc.
- Total penalties are measured vs. fiber length using a commercial 25 Gbaud PAM-4 transceiver at 855 and 904nm, with RMS spectral widths around 0.32 and 0.40nm, respectively, with low bandwidth fibers, at two temperatures:
  - Total penalty at 150m averages ~0.5 dB
  - Total penalty at 300m averages ~2.2 dB
  - One experiment found a 0.5 dB penalty for 150m with worst-case fiber with modal noise injected using a shaker & offsets, with 0.33 nm RMS spectral width VCSEL
- A 300m reach penalty with 0.3 nm RMS spectral width laser is a valid UPPER LIMIT for a 150m reach penalty with a 0.6 nm RMS laser
  - MPN varies as the product of CD, RMS spectral width, and link length.
  - Doubling the length leads to significantly more eye closure due to doubling modal dispersion, mimicking a worst-case transmitter and thus increasing P_cross.
  - 2 to 2.5 dB total penalties for 150m links with worst-case spectral width are high but not extreme for Ethernet transceivers
  - Links with typical spectral width transceivers will be incredibly robust at 150m
- Simple Ogawa-Agrawal theory indicates a pure MPN penalty in the range of 0.3. to 0.4 dB for 150m links with 0.6 nm RMS. However, we believe this is an over-estimate because of the following:
  - Use of continuous spectrum for VCSEL instead of discrete lines has been shown to overestimate MPN (Balemarthy, ECOC 2012).
  - Necessity of reducing RIN for PAM-4 VCSELs naturally reduces k_mpn also, relative to 25 Gbaud NRZ VCSELs.
- It is not clear that there is any reason to increase the MPN penalty allocation for SR4.2 budget