Modal noise update

Re: Comment IDs 1 and 7 against D1.2

P802.3cm, March 2019, Vancouver

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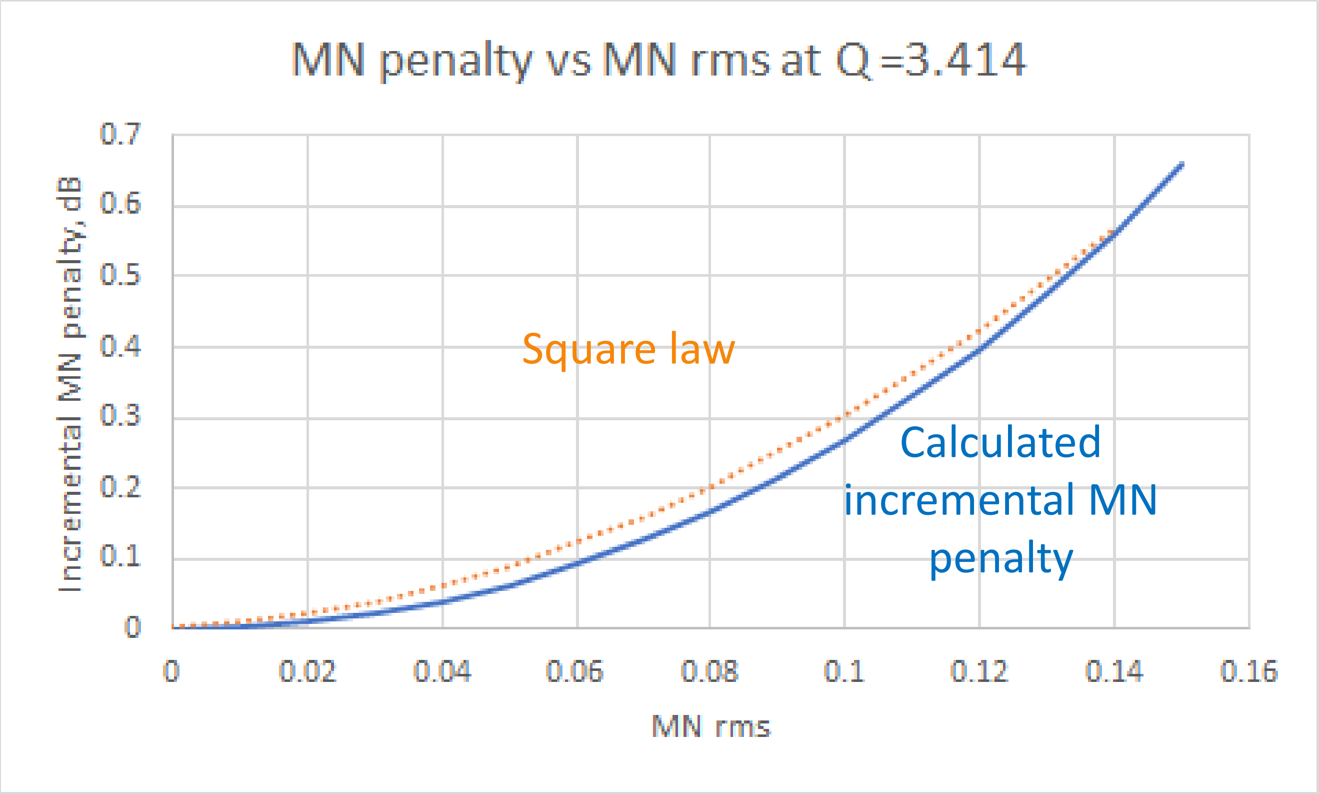
Modal Noise summary

- Modal noise in MMF links plagued early systems with single- or near single-mode sources (ref 1)
- A model for modal noise penalty based on OFL (over-filled launch) links with consequent high fraction of MSL (mode selective loss) became established as an industry reference (ref 2)
  - Experiments with high MSL OFL links showed this to be a reasonable penalty predictor
  - Multimode VCSELs, typical of todays high speed VCSELs, were shown to have greatly reduced MN penalty even with near OFL launches (ref 3)
- Current concern about MN penalty has been based on extrapolating from old and inaccurate models and old MN penalty allocations for NRZ modulation (comments 1 and 7)
  - i.e. OFL launches, high k_{MPN} factor, over-estimation of MSL for current VCSEL launches
- Pepeljugoski_01_0108, added more realistic fibre transforms, Tx launches, and connection losses, and explored the effect of k_{MPN} , for 100m 10Gb/s links using 850nm sources

- Three 'new' things to consider for 50Gb/s PAM4 optics: the effect of FEC and PAM4 modulation, and the higher system bandwidth (13.3 GHz for 50Gb/s PAM4, vs 7.5 GHz for 10Gb/s NRZ)
- Taking these into consideration shows a MN penalty allocation of 0.1 dB is sufficient for 50Gb/s PAM4 links with a total connection loss max ≤ 1.5 dB
  - And connection loss measurement as defined per IEC 61280-4-1 still leaves margin

Scaling incremental penalties for a small noise source in presence of a large noise source

- For this case, modal noise is the small noise penalty and receiver noise is dominant and fixed
  - Modal noise rms assumed to be proportional to signal
  - Receiver noise fixed at 1/3.414 ~ 0.293
    - Signal = 1 for zero modal noise
  - Modal noise rms varied from 0 to 0.15
  - Signal increase (in dB) required to maintain Q = 3.414 is the incremental MN penalty



  - **A square law dependence is a close and conservative approximation**

    as affirmed in dawe_3cd_01b_0918.pd: http://ieee802.org/3/cd/public/Sept18/dawe_3cd_01b_0918.pdf

Effect of FEC: 50Gb/s PAM4 vs NRZ no FEC

FEC

- For sufficiently random errors, Gray coded PAM4 with Clause 91 FEC has a target BER of 2.4×10^{-4}, equivalent to a target Q of 3.414
- For NRZ modulation without FEC, with a target BER of 10^{-12}, the equivalent target Q is 7.034
- The effect of the lower required Q is that the RMS modal noise can increase by a factor of 2.06 for the same penalty
- or, for the same RMS modal noise, the penalty decreases by $(2.06)^2$ ~ 4.2

PAM4 vs NRZ

- For the same OMA_{outer} PAM4 sub eyes are 1/3 the height of NRZ
- the RMS modal noise must decrease by a factor of 3 for the same penalty
- or, for the same RMS modal noise, the penalty increases by $(3)^2 = 9$

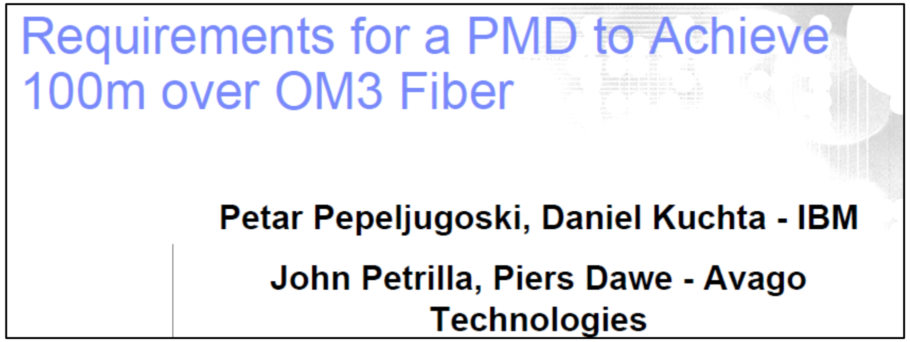
Reference receiver bandwidth

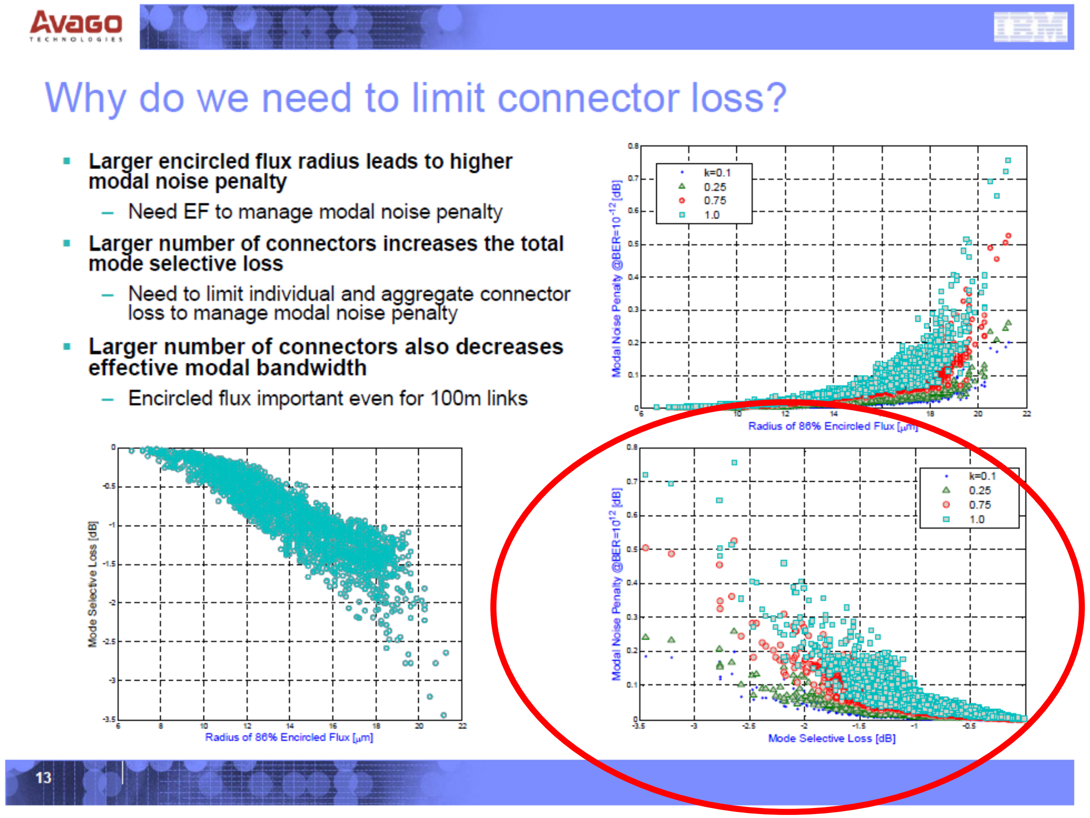
- The MN observation bandwidth increases by 13.3/7.5 ~ 1.77

The combined effect is an increase in the dB MN penalty by a factor of ~3.8

Referencing Pepeljugoski's work from 802.3ba:

- http://www.ieee802.org/3/ba/public/jan08/ pepeljugoski_01_0108.pdf

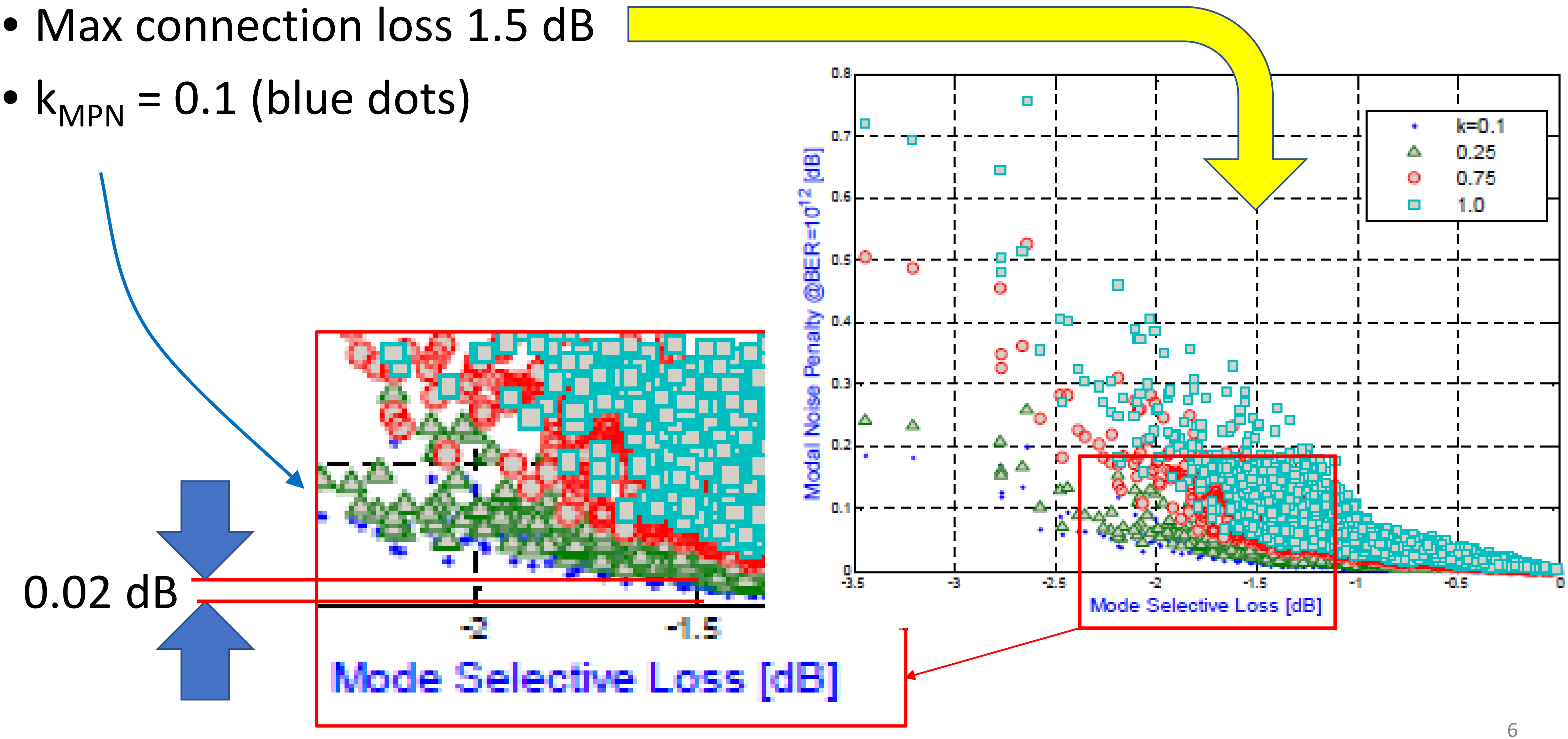




- Results of Monte Carlo modeling of modal noise on 100 m OM3 links
  - MMF transfer functions based on TIA5000 fibre set
  - 10 Gb/s NRZ, target BER = 10^{-12}
  - 850 nm VCSELs
  - Total MSL calculated for up to four connectors
  - MN penalty calculated for k_{MPN} = 0.1, 0.25, 0.75, 1

Estimate of MN Penalty from Pepeljugoski_01_0108

- Max connection loss 1.5 dB
- k_{MPN} = 0.1 (blue dots)



MN penalty allocation for SR8

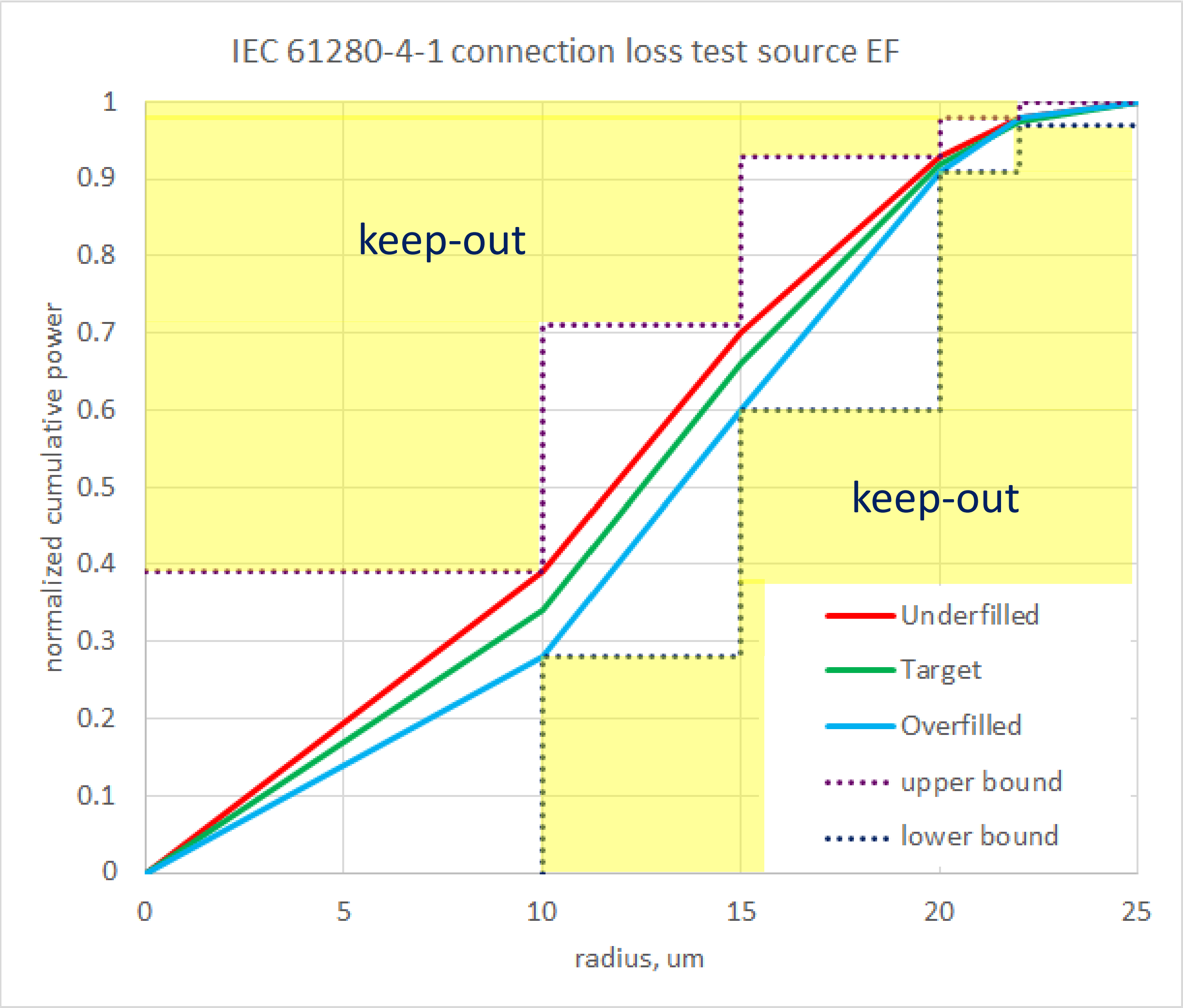
- From slide 6, the predicted MN penalty for a 10 Gb/s 850nm 100m link with total MSL of loss 1.5 dB, and k_{MPN} = 0.1 is **0.02 dB**
- From slide 4, the effect of FEC PAm4 modulation and the higher system bandwidth, the penalty is multiplied up by a factor of **3.8**

- Allocate 0.08 dB for MN penalty for 50Gb/s PAM4 links
  - Consistent with the 0.1 dB total allocation for MN and MPN penalties in the current draft

That’s small - is there still margin in the system ?

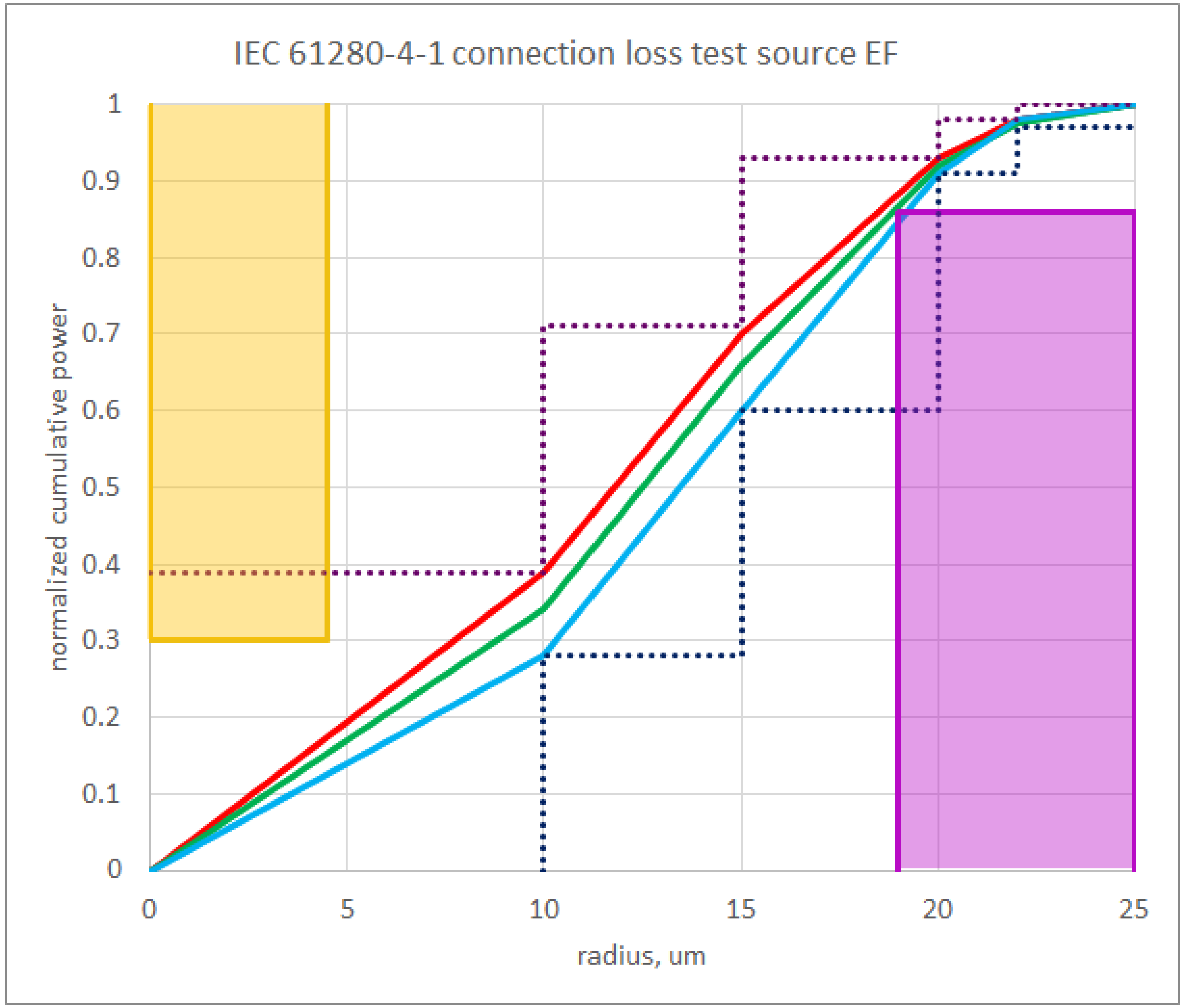
- Yes
- This was obviously so when connection loss was defined for an OFL test source, it’s a bit more subtle for the more recent (2009) encircled flux definition of the connection loss test source
- Let’s look at that….

Connection loss testing IEC 61280-4-1



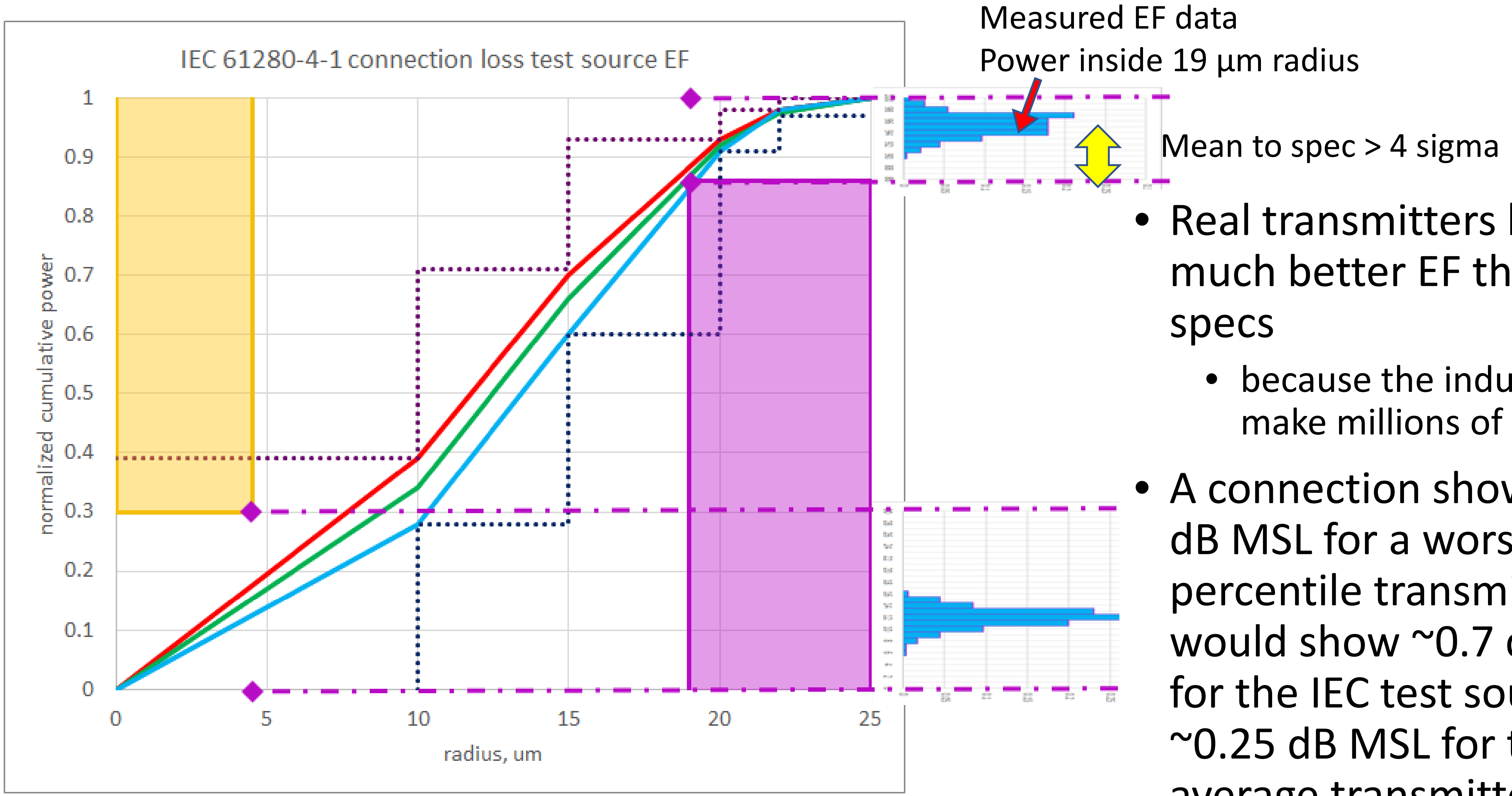
- For insertion loss measurements, IEC 61280-4-1 specifies a test source with tightly controlled encircled flux (EF) vs radius from the centre of the MMF core.
- There's little room for deviation from the target EF, especially at the outer edge of the core, where power distribution most affects measured insertion loss of connections. The tight tolerances on the IEC test source EF leads to more accurate and repeatable insertion loss measurements.

Connection loss testing vs Tx EF specs



- The target EF-compliant launch condition (green) is close to the VCSEL worst-case power distribution profile permitted by the transmitter encircled flux limits (≥86% at 19 um radius) – it's a conservative estimate of mode selective loss (MSL)
  - An overfilled launch (blue) has less power near the centre, more power in the outer core, leading to pessimistic (higher) insertion loss, and overestimates of mode selective loss.
  - An underfilled launch (red) has more power near the center of the core, less power in the outer core. This leads to an optimistic (low) IL reading, and under estimate of MSL.

Connection loss testing vs Tx EF specs and data



- Real transmitters have much better EF than Tx specs
  - because the industry has to make millions of them
- A connection showing 0.5 dB MSL for a worst-case 1 percentile transmitter would show ~0.7 dB MSL for the IEC test source, and ~0.25 dB MSL for the average transmitter

Summary of connection loss definition and MSL

- Connection loss testing
  - IEC 61280-4-1 specifies a test source with an encircled flux (EF) target representative of a worst-case TX that just meets the usual TX EF definition (r=4.5 µm ≤30%, r=19 µm ≥86%)
  - When measured per IEC 61280-4-1, connection loss is always an upper bound on mode selective loss value – MSL measured with real transmitters will be lower
- E.g. from manufacturing distributions of EF
  - The MSL for a 6um offset connection is ~ 0.25 dB for the average transmitter
  - The MSL that would be measured using the IEC defined test source is ~ 0.7 dB
  - The MSL that would be measured for a worst case 1 percentile transmitter is ~ 0.5 dB
- Links with 1.5 dB of MSL as measured with real transmitters are likely to be grossly underestimating the MSL that would be measured per IEC 61280-4-1 – these would be failing links !

Concluding notes

- Referencing Pepeljugoski_01_0108 and taking into consideration the effects of FEC, PAM4 modulation, and the higher MN observation bandwidth for 50Gb/s PAM4, shows a MN penalty allocation of 0.08 dB is sufficient for 50Gb/s PAM4 links with a total connection loss max ≤ 1.5 dB
    - This is consistent with the 0.1 dB total allocation for MN and MPN in the current draft, and consistent with experimental data and measurement uncertainties, for example in sun_3cm_01a_0119.pdf http://www.ieee802.org/3/cm/public/January19/sun_3cm_01a_0119.pdf
- There is still margin in the system: connection loss measurement as defined per IEC 61280-4-1, and by which total connection loss is defined as within or out of spec, is a very pessimistic measure of actual MSL for real transmitters

Back up

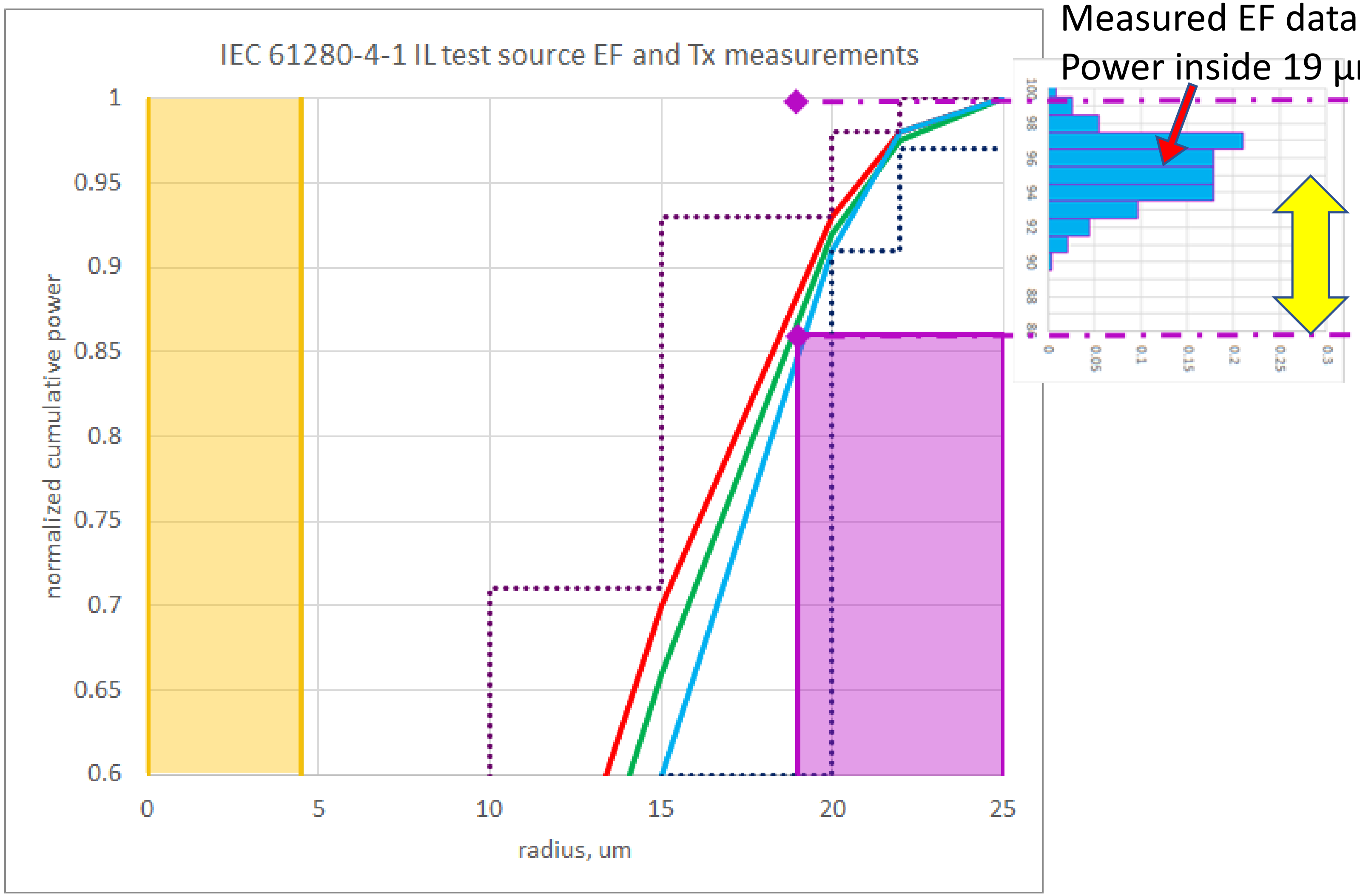
References

1. **Epworth, 1978**: R.E. Epworth, *Proc. of 4th European Conference on Optical Communication*, September 1978
2. **Bates, et. al., 1995:** Richard J. S. Bates, Daniel M. Kuchta, and Kenneth P. Jackson, "Improved Multimode Fiber Link BER Calculations due to Modal Noise and Non Self-Pulsating Laser Diodes," *Optical and Quantum Electronics*, No. 27, 1995, pp. 203-224.
3. **Hahn, et. al., 1993:** K.H. Hahn; M.R. Tan ; Y.M. Houng ; S.Y. Wang, "Large area multi-transverse-mode VCSELs for modal noise reduction in multimode fibre systems", *Electronics Letters*, Vol.29, issue 16.
4. http://www.ieee802.org/3/aq/public/nov04/pepeljugoski_1_1104.pdf
   - Modal noise for 10Gb/s NRZ, 1300 nm wavelength, high coherence source, showed 0.1 dB MN penalty for 1 dB MSL
5. http://www.ieee802.org/3/ba/public/jan08/pepeljugoski_01_0108.pdf
   - Modal noise for 10Gb/s NRZ, 850 nm wavelength, VCSEL source, shows 0.08 dB MN penalty for 1.5 dB MSL

IEC standards relevant to MMF component insertion loss measurement

- IEC 61280-4-1 version 2009 and 2015 define the test source EF criteria
- IEC 61282-11, “Fiber optic communication system design guides - Part 11: Multimode launch conditions,” May 2012.

Expanded high radius EF definitions and data



Measured EF data
Power inside 19 µm radius

Mean to spec > 4 sigma