Dynamic Behavior of Mode Partition Noise in MMF

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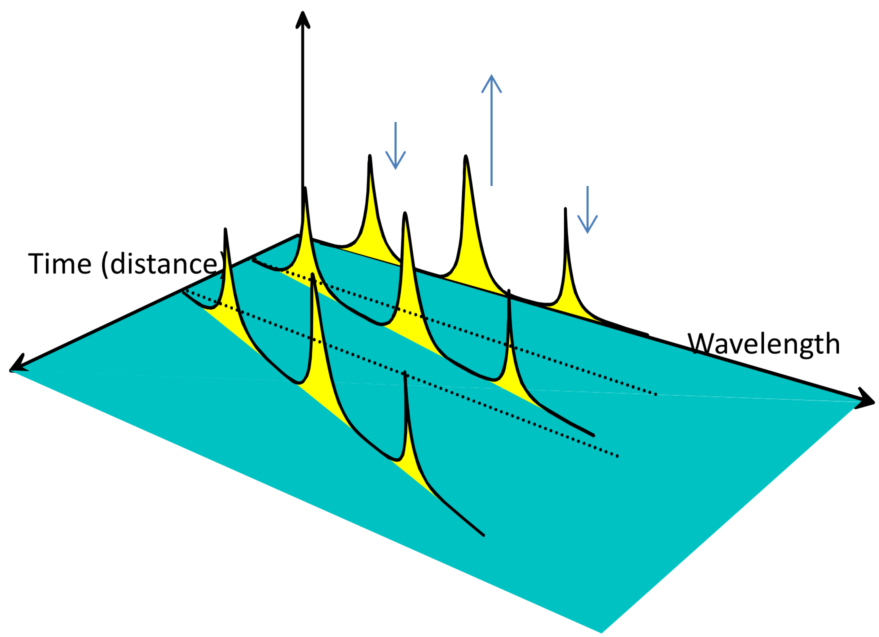
Motivation and Issues

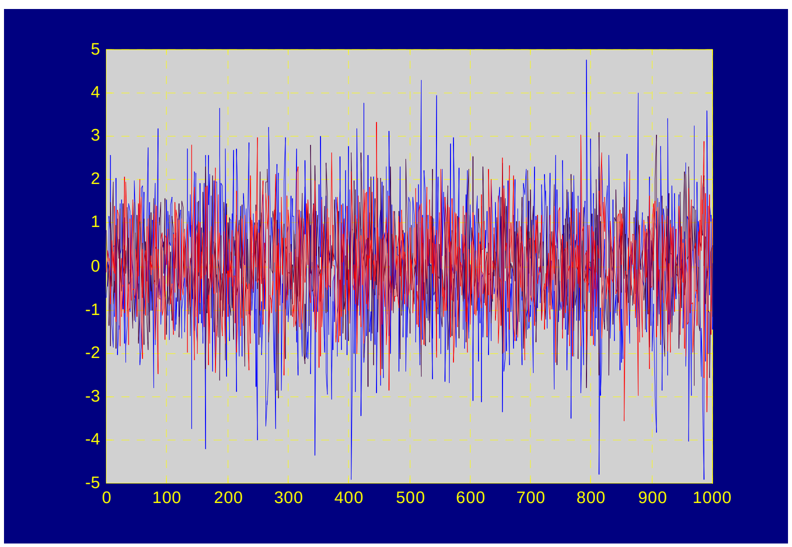
- Inconsistent treatment of mode partition noise (MPN) and relative intensity noise (RIN) in spreadsheet model
  - Need for ISI correction
- Original MPN theory SD formula is:
  - calculated at the center of the bit interval (assumes does not change over the bit interval)
  - applicable to single mode fibers (SMF) only, no bit pattern and launch conditions dependence
- How to apply to multimode fibers (MMF)
- Are current inputs backed by measurements?
  - k-factor currently used may be wrong
  - are all lasers the same (i.e. number of modes, spacing between modes, rms linewidth)

What is MPN

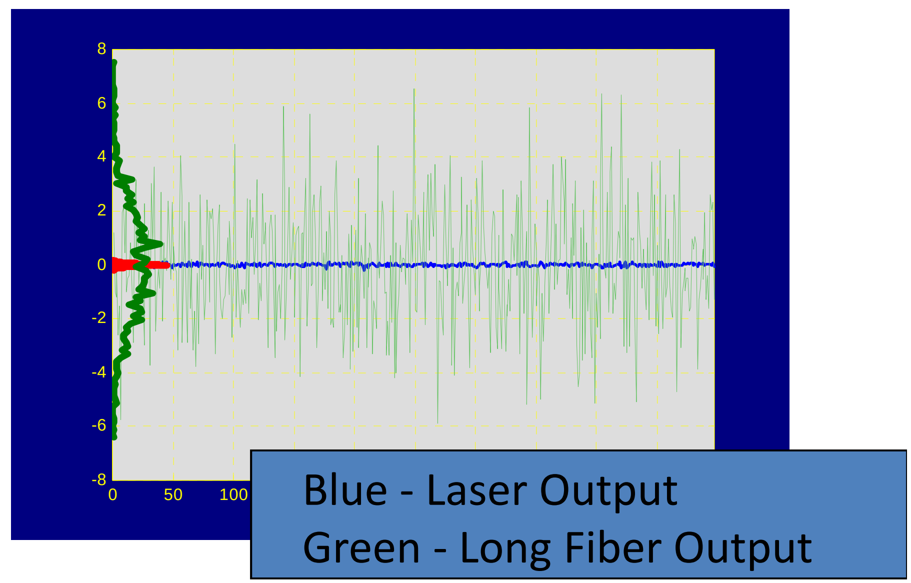
- laser modes fluctuate in synchronism - overall signal noise is small (noise in laser modes anti-correlated)
- It can be a major source of noise in links with MULTIMODE lasers and large chromatic dispersion
- propagation in dispersive media destroys mode "synchronization" - large mode fluctuations can be destructively combined at the receiver - this extra noise is called mode partition noise (MPN)



Noise in individual modes at LD Output



Combined Noise (all modes) at RX output



Approach

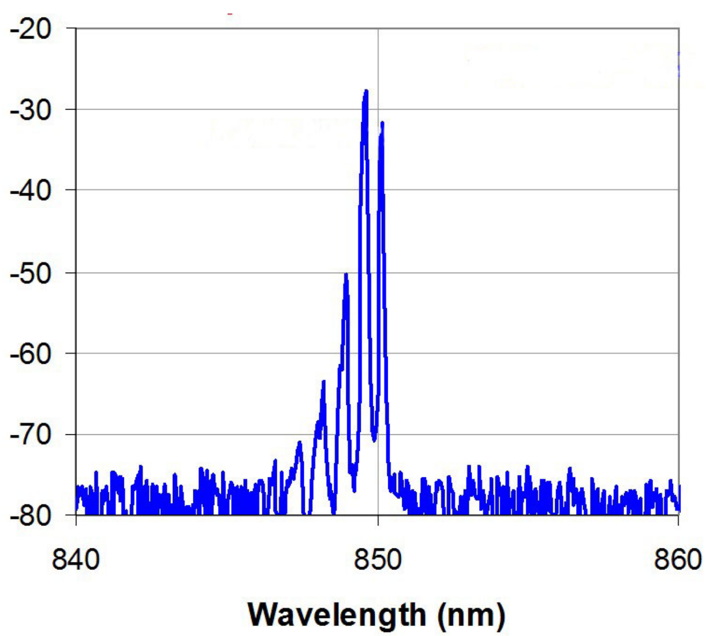
- Start with the theory developed by Ogawa and Agrawal [1,2]
  - Major assumption is that the mode partition noise is calculated in the center of the eye – this is what the spreadsheet model does
- Calculate the MPN SD at each point in the bit interval
  - Use Gaussian approximation for the laser spectrum; also check with measured spectrums
  - Use this result later for MMF
- Compare the SM result with the exact calculation over the entire bit interval
  - Accuracy check point: the results should be the same at the center of the eye (confirmed)
  - Do not normalize the SD
- Extend calculations to multimode fibers and arbitrary bit patterns
  - Use mode power distributions (MPD) and mode group delays (MGD) in the calculation
  - Extend the approach to arbitrary bit pattern

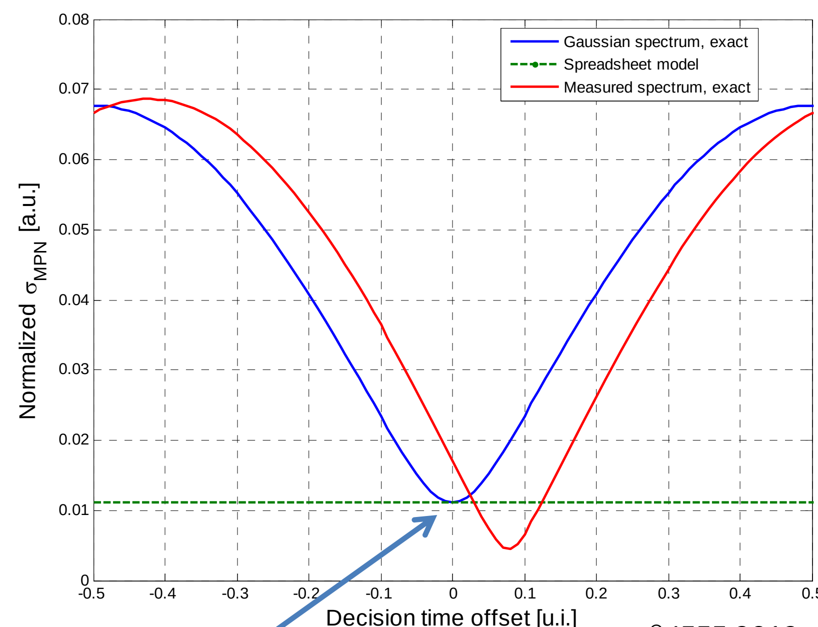
MPN Handling in Spreadsheet and Extended Theory

Shreadsheet	Extended Theory	Comment
$r(t) = \frac{OMA}{2}\sum_{i=1}^{N} A_i f(\lambda_i, t) = \frac{OMA}{2}\sum_{i=1}^{N} A_i f_i$	Same	RX signal
$f_i = f(\lambda_i, t) = \cos\big(\pi B(t_0 + \Delta t_i)\big)$ $= \cos\big(\pi B(t_0 + LD\Delta\lambda_i)\big)$	Same (to illustrate what is missing)	Assumpt. on shape
Ai – Gaussian, continuum of modes to get the closed form formula	Ai - Gaussian or measured	Laser modes
$\sigma(t_0) = \frac{OMA}{2} \cdot k \left[\left(\sum_{i=1}^{N} f_i^2 \overline{A_i}\right) - \left(\sum_{i=1}^{N} f_i \overline{A_i}\right)^2\right]^{0.5}$	Same (but see t_0 below for both)	Std. dev of the MPN
t_0=N/B (center of bit interval)	t_0 variable –T/2 to T/2 (can go beyond bit int.)	Where is it calculated
$\sigma_{mpn} = \frac{k}{\sqrt{2}}\left(1 - e^{-\beta^2}\right)$, where $\beta = \pi BLD\sigma_{rms,laser}$	σ_{mpn} calculated numerically	Results match in bit center
Not possible	arbitrary bit patterns, MMF (MPD, MGD, con.)	full MMF support

MPD SD calculation over the entire bit interval

- Make same assumptions as Ogawa and Agrawal [1,2]
  - only one fiber mode propagates
  - cosine shape for received signal, Gaussian laser spectrum
- Set L = 0.1km, k = 0.3, λ = 850nm, BitRate = 25Gb/s, same rms linewidth as measured spectrum (numbers for illustration purposes)
- Calculation repeated for measured laser spectrum (measurement on 30 Gb/s laser)





Accuracy check: SM and exact calculation agree at eye center

MPN SD calculation (cont'd)

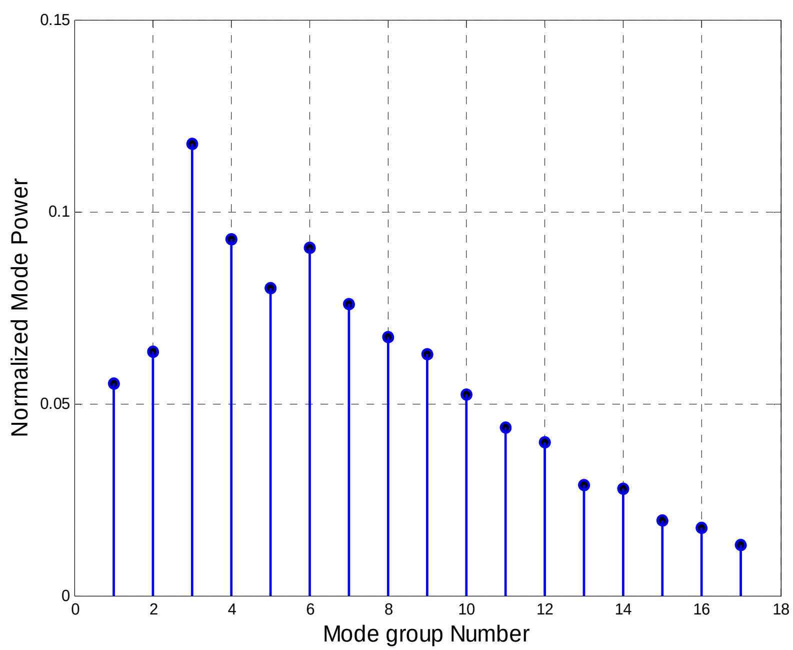
- Calculations of SD using the spreadsheet model and exact calculation agree at the center of the eye for one propagating fiber mode
  - Implication is the calculations are correct
- Figure shows the MPN SD increases away from the center of the eye
  - Both measured spectrum and Gaussian approximation for the spectrum have the same shape, with small difference in SD magnitude and possible time offset
  - Important for MMF, since mode group delays will introduce additional delays

Extension to MMF

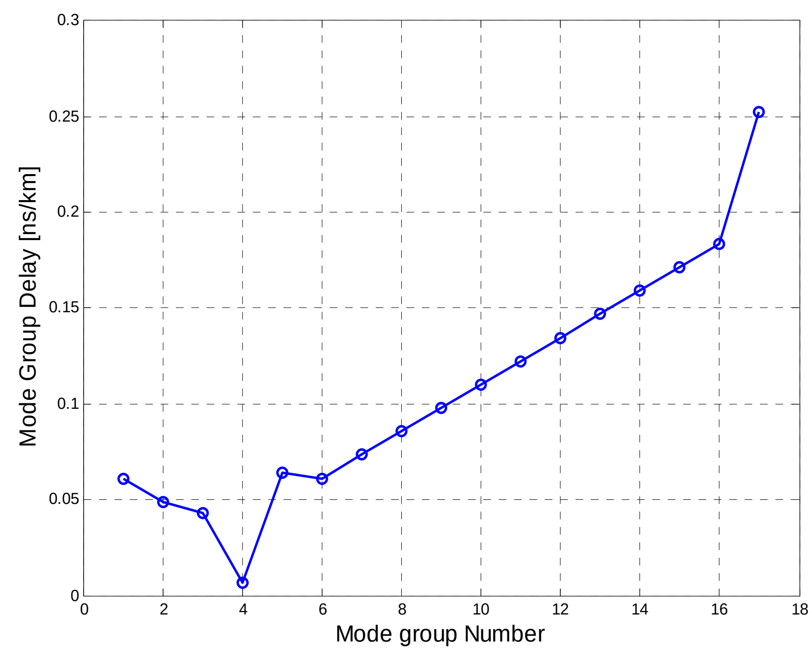
Signal in each mode group	$$r_j(t) = \sum_{i=1}^{N} MPD_{ij} A_i f(\lambda_i, t - t_j)$$
Overall signal at fiber output	$$y(t) = \frac{OMA}{2} \sum_{j=1}^{M} \sum_{i=1}^{N} MPD_{ij} f(\lambda_i, t - t_j) A_i$$
Overall standard deviation at the fiber output	Easily found following Ogawa and Agrawal's formalism [1,2]

Extension to MMF

- Get a fiber MPD and normalized MGD, use measured spectrum
- Calculate the standard deviation for each mode group (use the results for one mode fiber, properly weigh the results using MPDs)



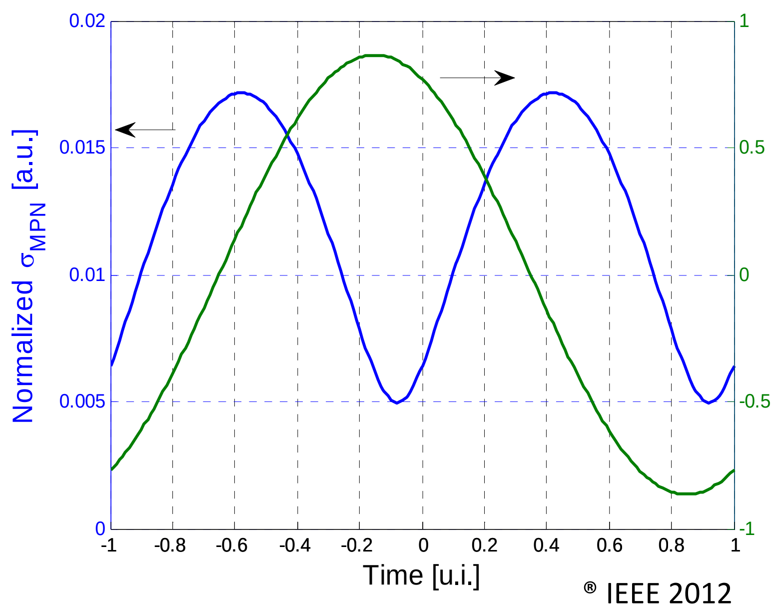
MPD into the fiber



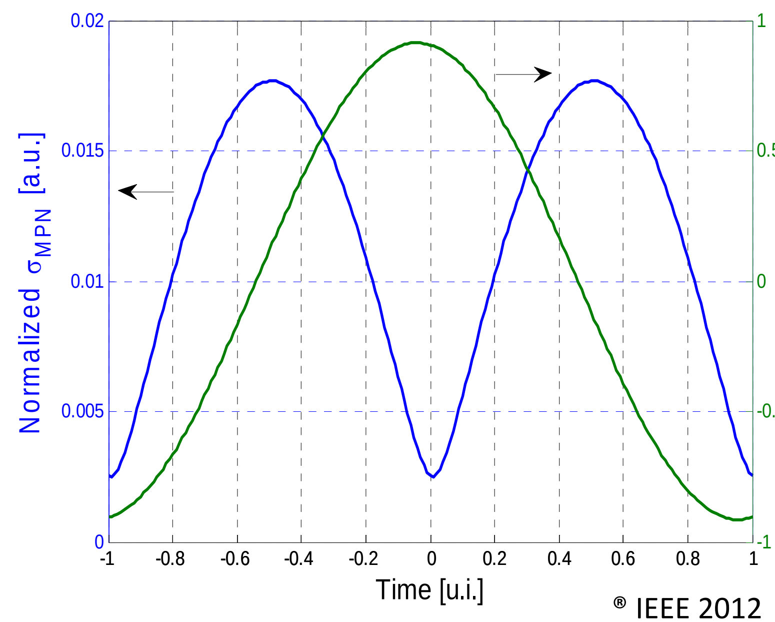
Fiber Mode Group Delays

MMF Results

- Use same delay set for OM3 and OM4, for OM4 scale it to assess OM4 impact
- Figures show MPN SD (left axis) and received signal (right axis)
- Comparison of MMF to single fiber mode propagation shows MPN SD is reduced due to the averaging introduced by mode groups
  - Worst case at bit boundaries – much higher impact on jitter
  - Minimum and maximum MPN SD is reduced, although less for OM4 as expected
- Need to repeat for entire link set used in development of OM3 fiber



Using OM3 MGD

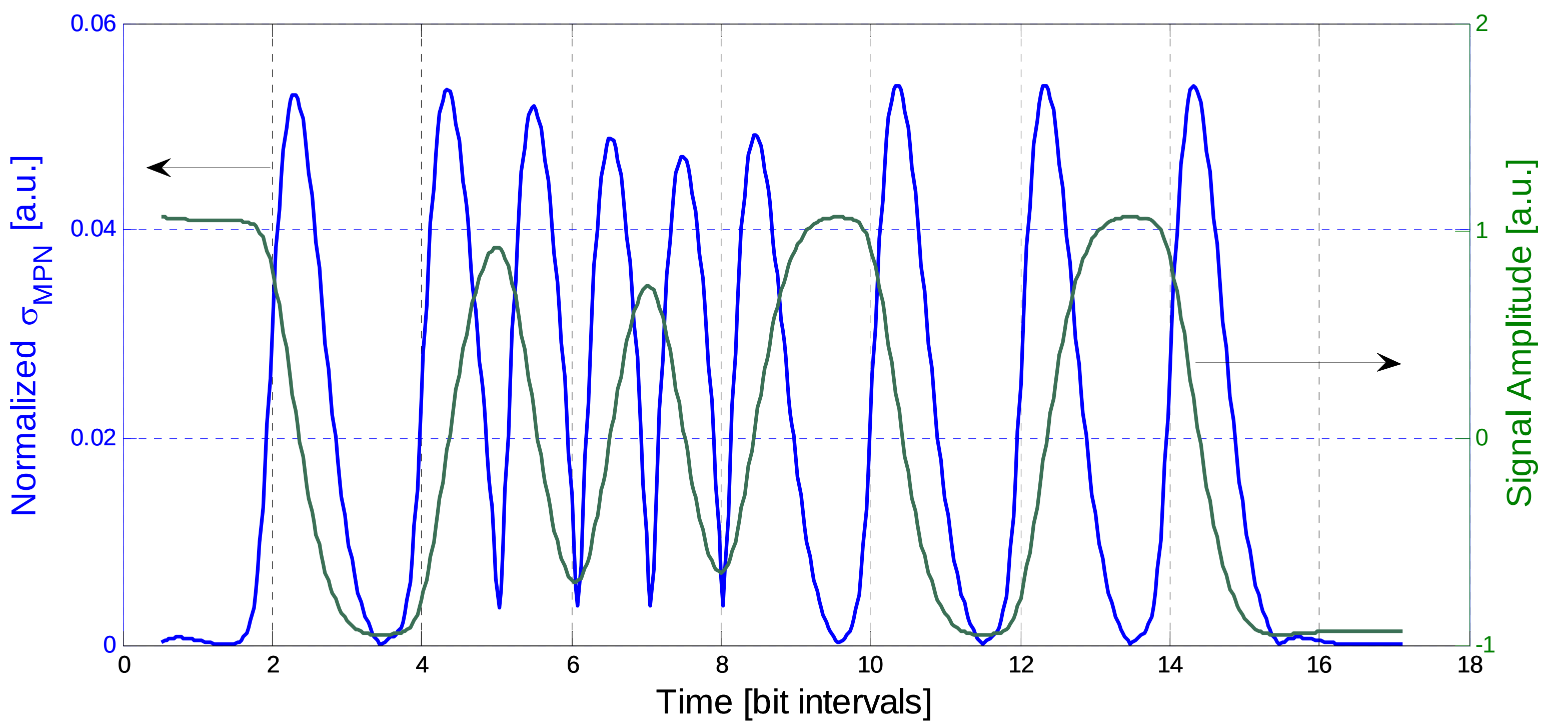


Scaled OM3 delay set to OM4

“Normalized” means OMA/2=1, no normalization done

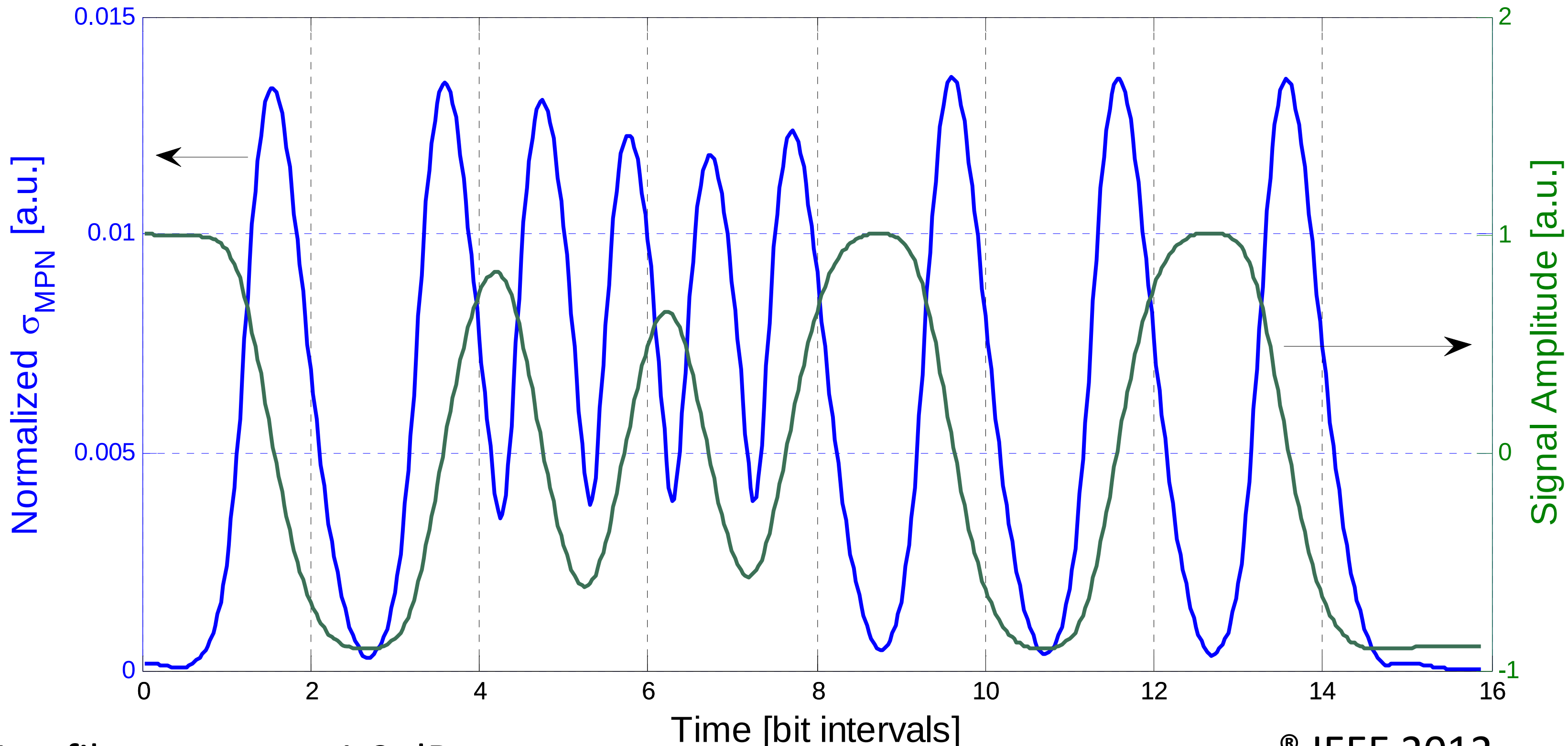
MPD SD for Data Pattern – One Fiber Mode

- ISI does not impact the minimum value of the MPN SD
- MPN SD depends on the slope of the signal



MPN SD for All Mode Groups

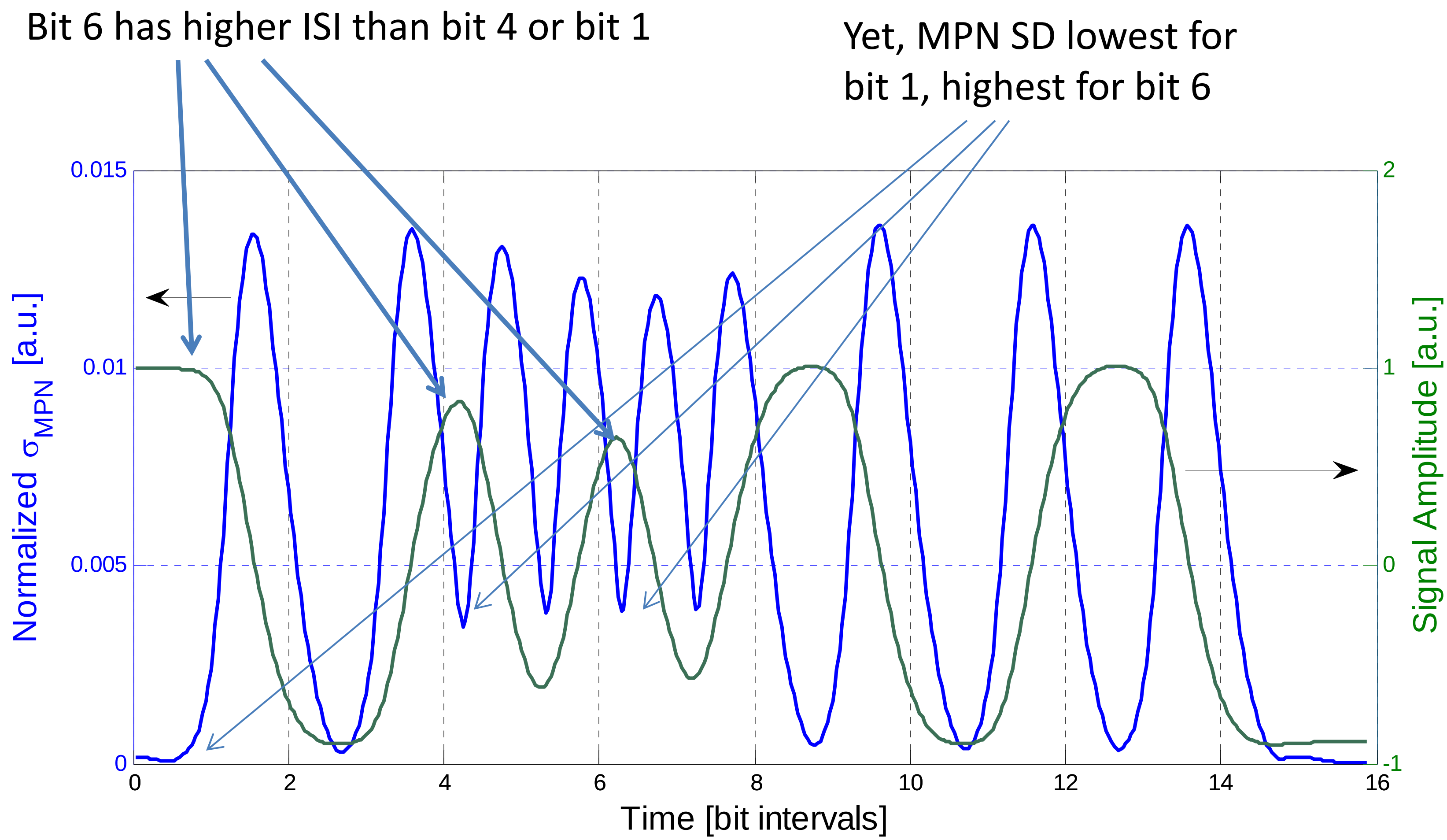
- Calculations repeated for all mode groups
  - MPN SD does not become smaller for higher ISI points
  - Minimum MPN SD value becomes larger
  - MPN SD depends on the slope of the signal – the larger the slope the higher the MPN SD



ISI at fiber output = 1.9 dB

MPN SD for All Mode Groups

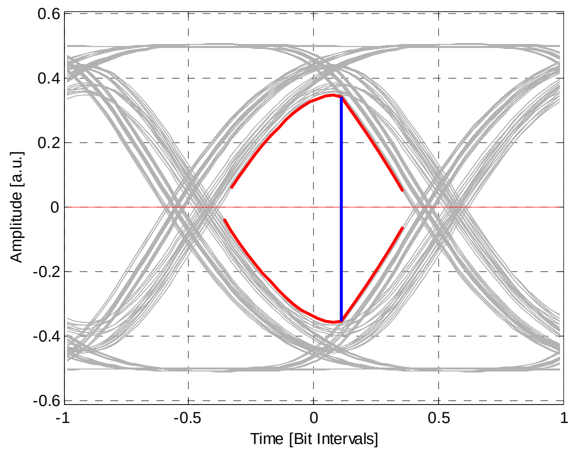
- Bits with higher ISI have higher MPN SD
  - Need correction in Spreadsheet Model



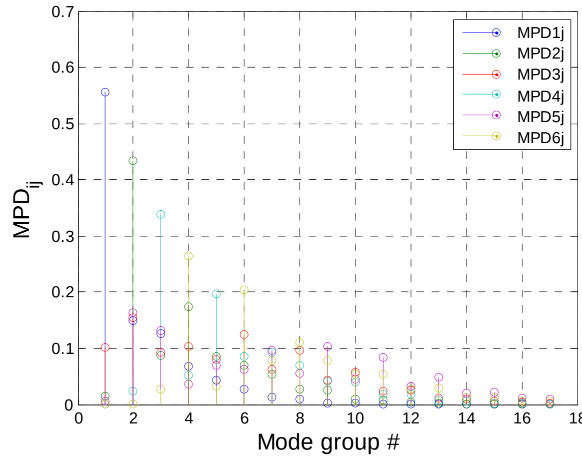
Another example

- OM4 fiber, 4 laser modes

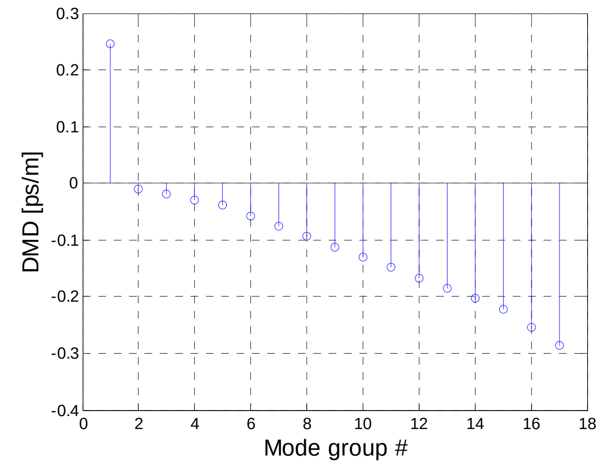
TX eye diagram – 1.6 dB ISI



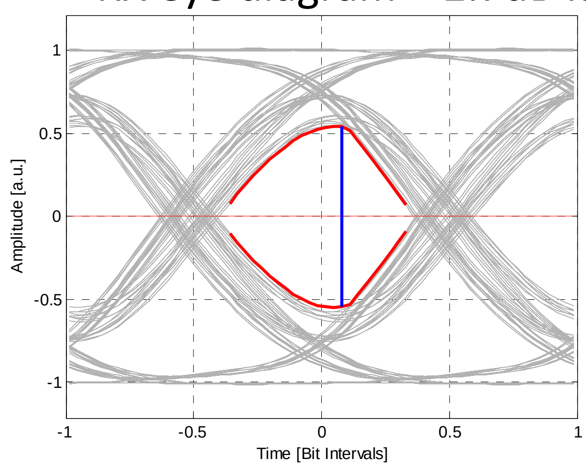
MPDij



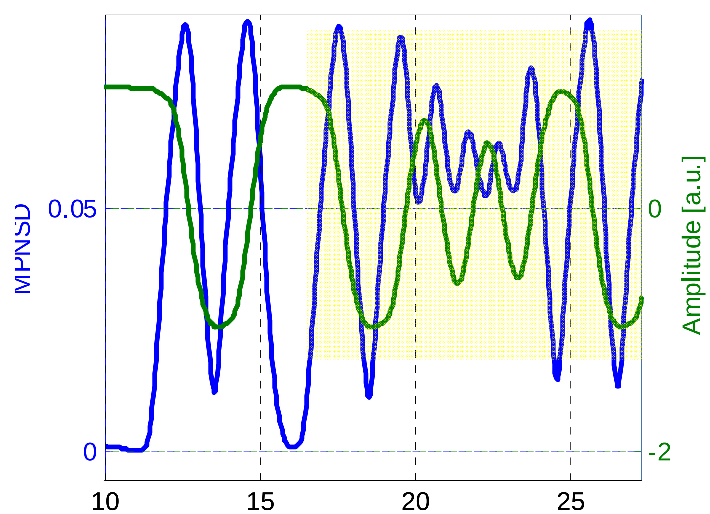
Fiber DMD



RX eye diagram – 2.7dB ISI



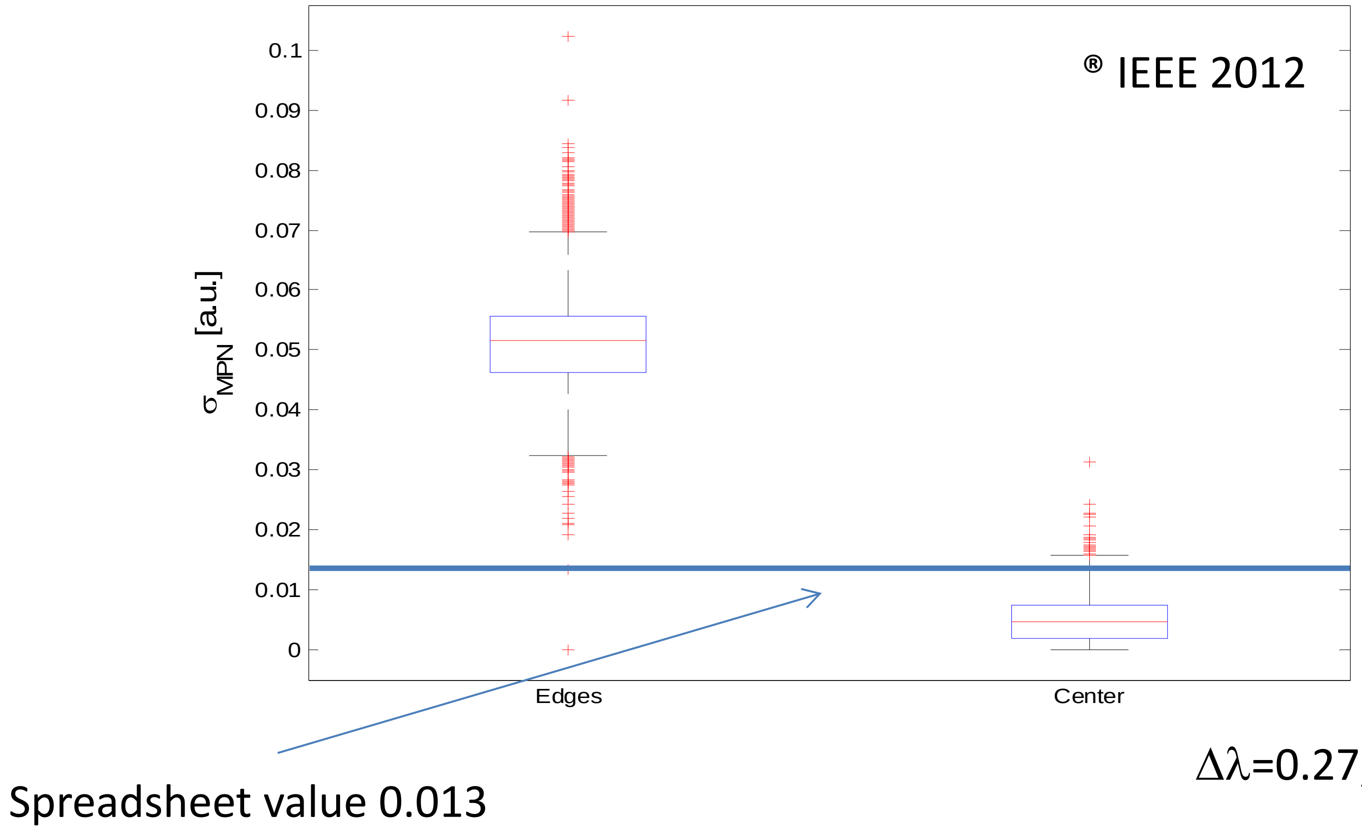
MPN SD



More ISI, larger MPN SD
Compare bits 10,11,25 to 18,19 and 22-25
Bit sequence is (starting bit 10):
1110011100101011100

Statistical Simulation

- 40k link set from OM3 development, various differential mode delays (DMD) and launch conditions
  - MPN SD depends on fiber DMD and launch conditions



Δλ=0.27, L=0.1km, B=25 Gb/s

Conclusion

- Extended MPN theory developed by Ogawa and Agrawal to explore:
  - MPN SD over the entire bit interval
  - dependence of MPN SD on launch conditions and fiber DMD in MMF
  - MPN SD with arbitrary pattern with or without ISI
- Two mechanisms working in opposite direction, need to assess the overall effect
  - MPN SD increases away from the bit center
  - MMF introduces averaging effect, lowering MPN SD
- MPN SD currently calculated by the spreadsheet not suitable to assess the impact on the jitter
  - MPN SD at bit boundaries may be quite high
  - High ISI values will increase the effect of MPN SD

We Need Correction for ISI in The Spreadsheet Model

- Need to divide MPN SD by ISI in the spreadsheet model
  - Lower ISI does not mean higher MPN SD
    - Multiple consecutive 1's or 0's have very little or no MPN SD
- MPN SD statistically lower than what the SM predicts
  - How to include that in the SM
- Further investigate MPN, request more scrutiny in power/jitter budget presentations

References

[1]. Agrawal, Antony and Shen: "Dispersion Penalty for 1.3 um Lightwave Systems with Multimode Semiconductor Lasers", IEEE Journal of Lightwave Technology, Vol. 6 No.5, 1988, pages 620-625

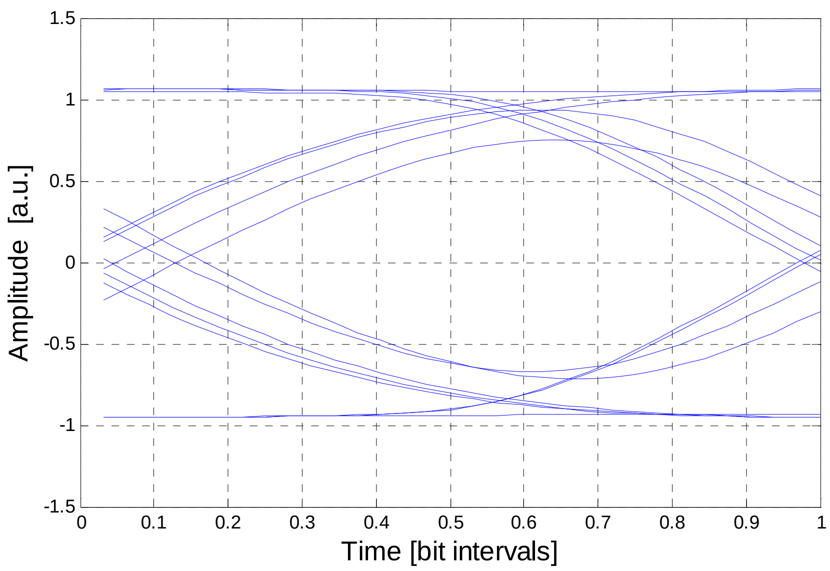
[2] Ogawa: "Analysis of Mode Partition Noise in Laser Transmission Systems", IEEE Journal of Quantum Electronics, Vol. QE-18, No. 5, May 1982, pages 849-855

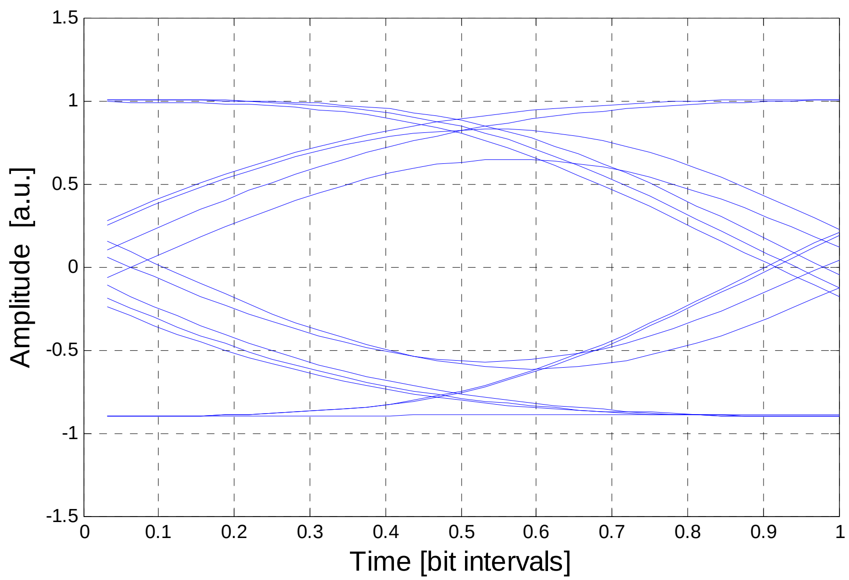
[3] Pepeljugoski, P.: "Dynamic Behavior of Mode Partition Noise in Multimode Fiber Links", IEEE Journal of Lightwave Technology, Vol. 30, No.15, August 2012, pp. 2514-2519.

Backup Slides

Signal Eye diagrams

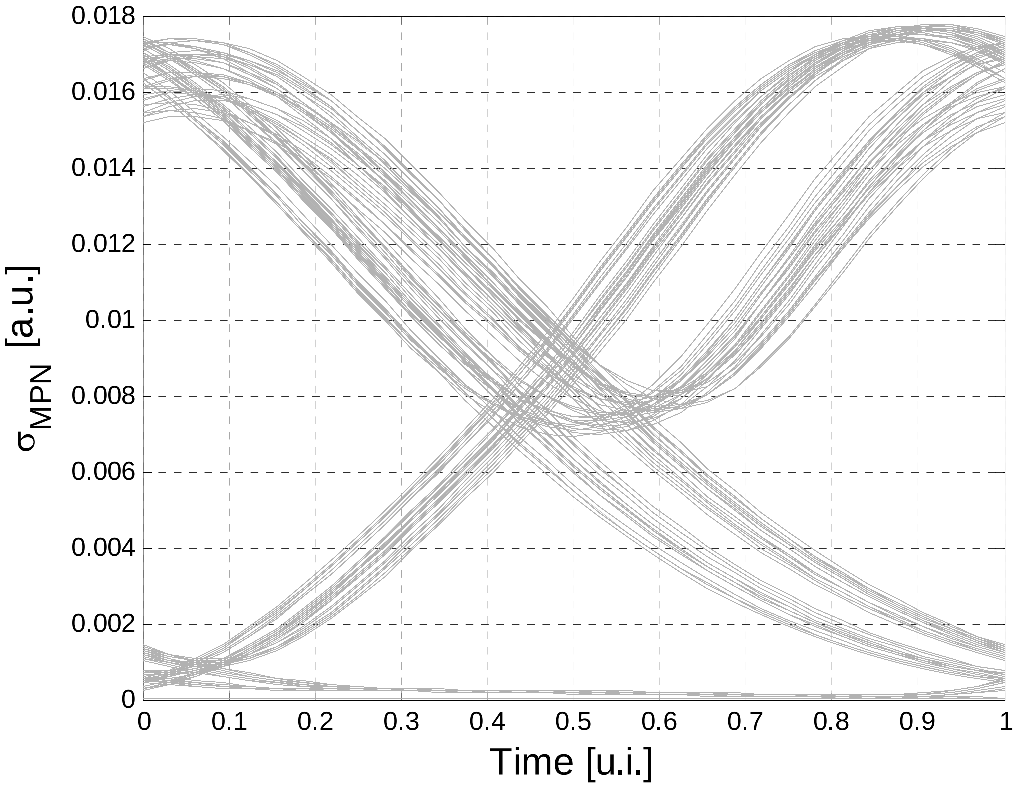
- ISI at laser output is ~1.52 dB
- ISI at the fiber output is ~1.9 dB



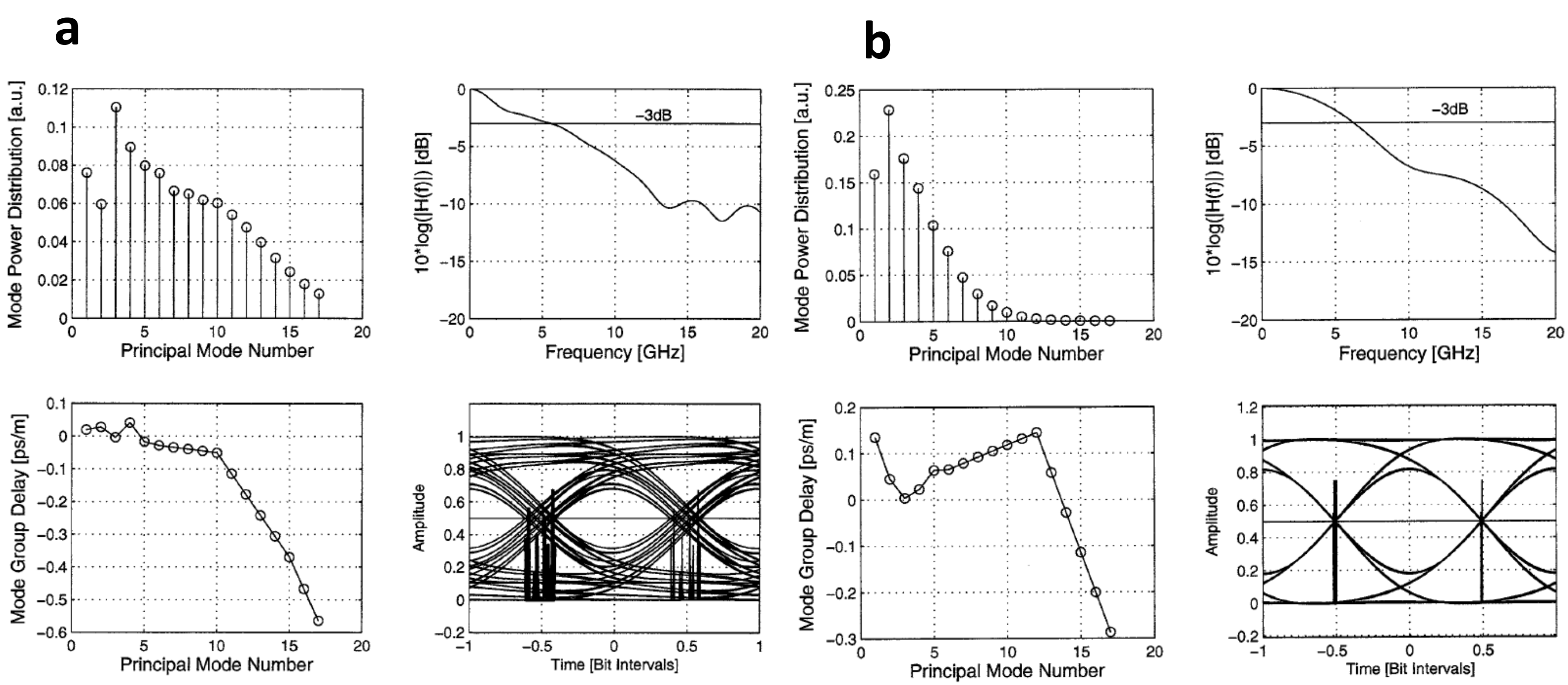


Long Random Bit Sequence

- 2000 bit long sequence, SD data folded into one bit interval
- Gaussian spectrum assumption for the laser spectrum



Two fibers, two launch conditions same bandwidth – very different eyes



Signal shape is important in MPN –> launch conditions, DMD lead to variability