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
- Original MPN theory formula is
  - calculated at the center of the bit interval (assumes stationarity)
  - applicable to single mode fibers (SMF) only, no bit pattern and launch conditions dependence
- Treatment of 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)

Approach

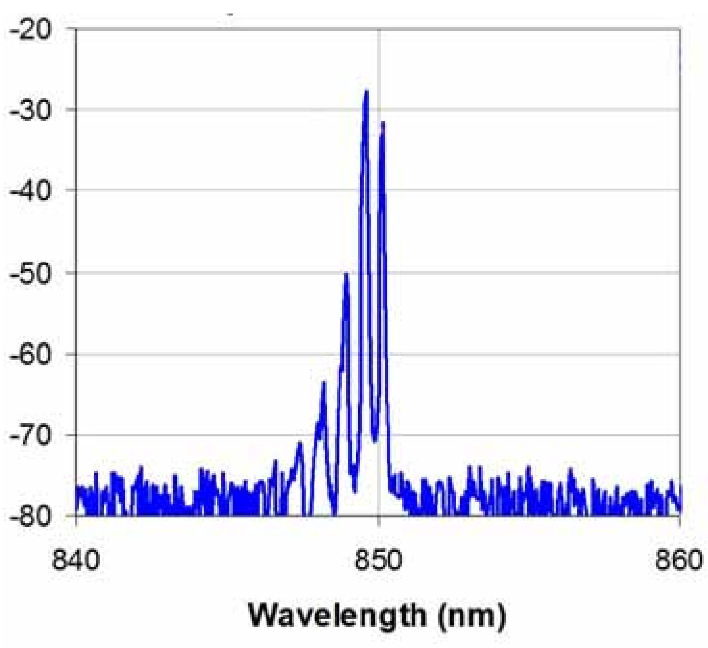
- Start with the theory developed by Ogawa and Agrawal [1,2]
  - Major assumption is that the mode partition noise is calculated in the center of the eye – this is what the spreadsheet model does
- Calculate the MPN SD at each point in the bit interval
  - Use Gaussian approximation for the laser spectrum; 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

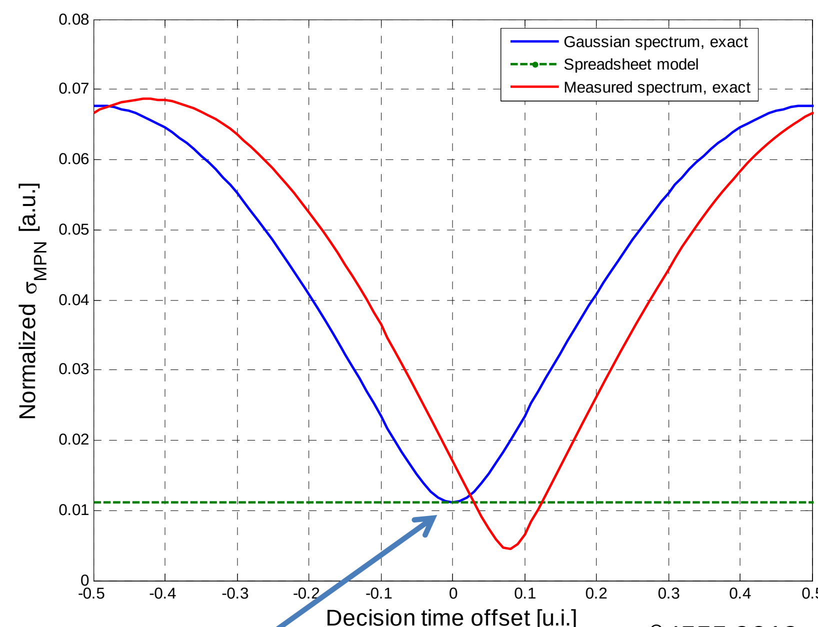
MPN Handling in Spreadsheet and Extended Theory

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
$f_i = f(\lambda_i, t) = \cos\left(\pi B(t_0 + \Delta t_i)\right)$ $= \cos\left(\pi B(t_0 + LD\Delta\lambda_i)\right)$	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, DMD, 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)

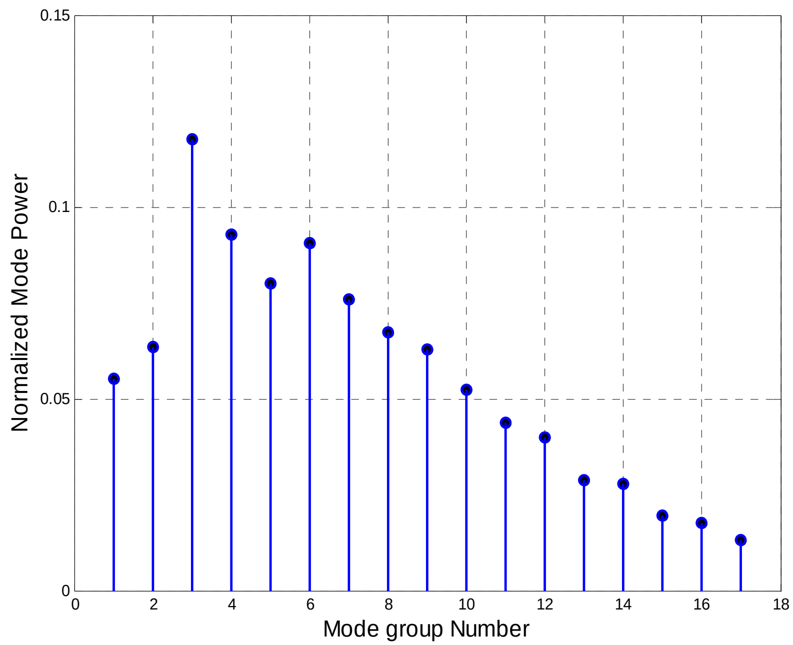
- Calculations of SD using the spreadsheet model and exact calculation agree at the center of the eye for one propagating fiber mode
  - Implication is the calculations are correct
- Figure shows the MPN SD increases away from the center of the eye
  - Both measured spectrum and Gaussian approximation for the spectrum are having 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

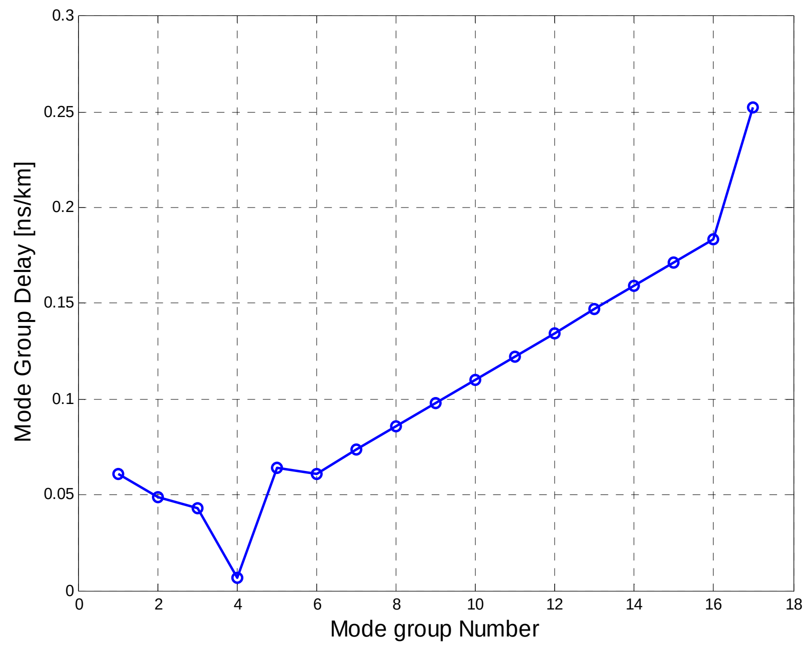
Signal in each mode group	$$r_j(t) = \sum_{i=1}^{N} MPD_{ij} A_i f(\lambda_i, t - t_j)$$
Overall signal at fiber output	$$y(t) = \frac{OMA}{2} \sum_{j=1}^{M} \sum_{i=1}^{N} MPD_{ij} f(\lambda_i, t - t_j) A_i$$
Overall standard deviation at the fiber output	Easily found following Ogawa and Agrawal's formalism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



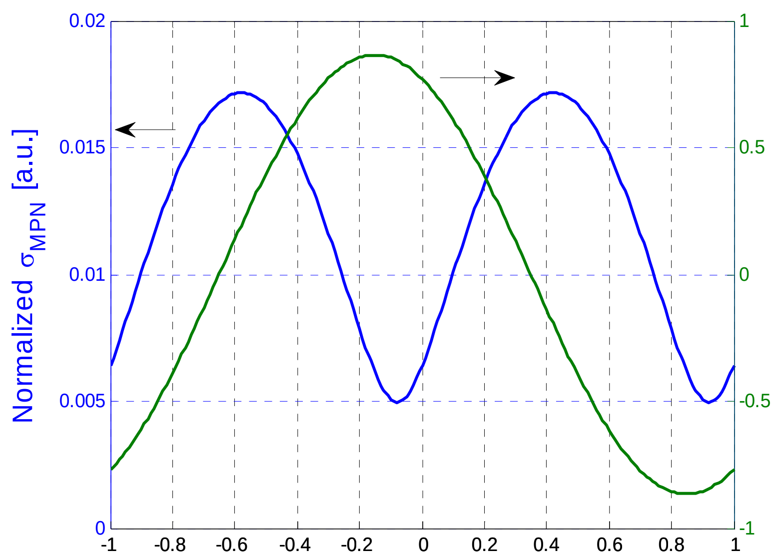
MPD into the fiber



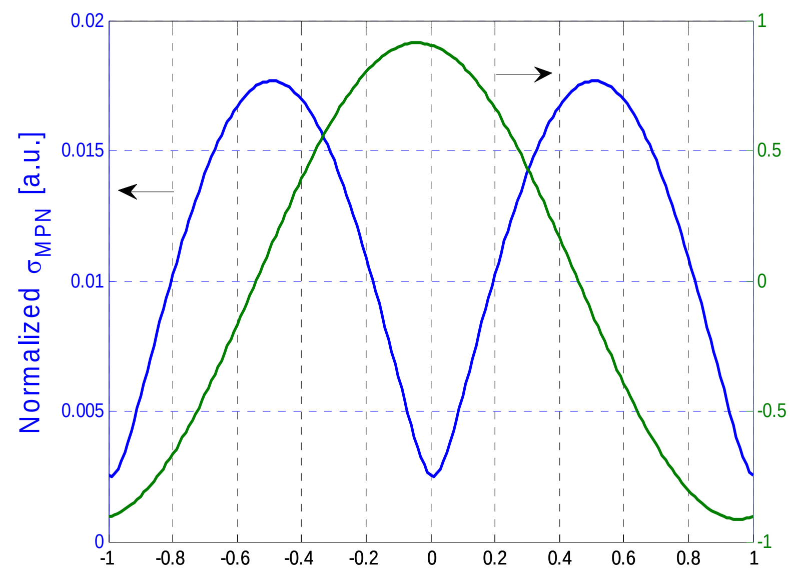
Fiber Mode Group Delays

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

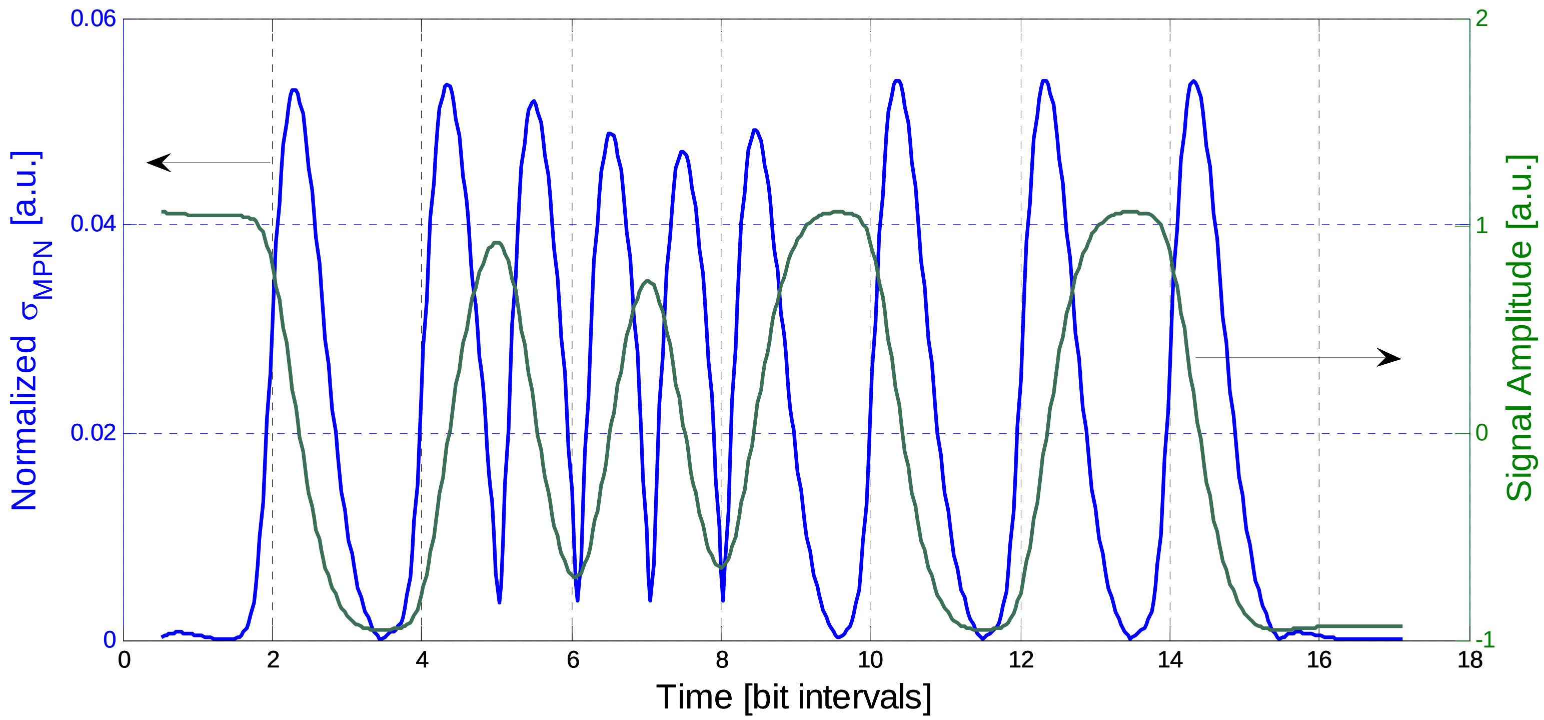


Scaled OM3 delay set to OM4

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

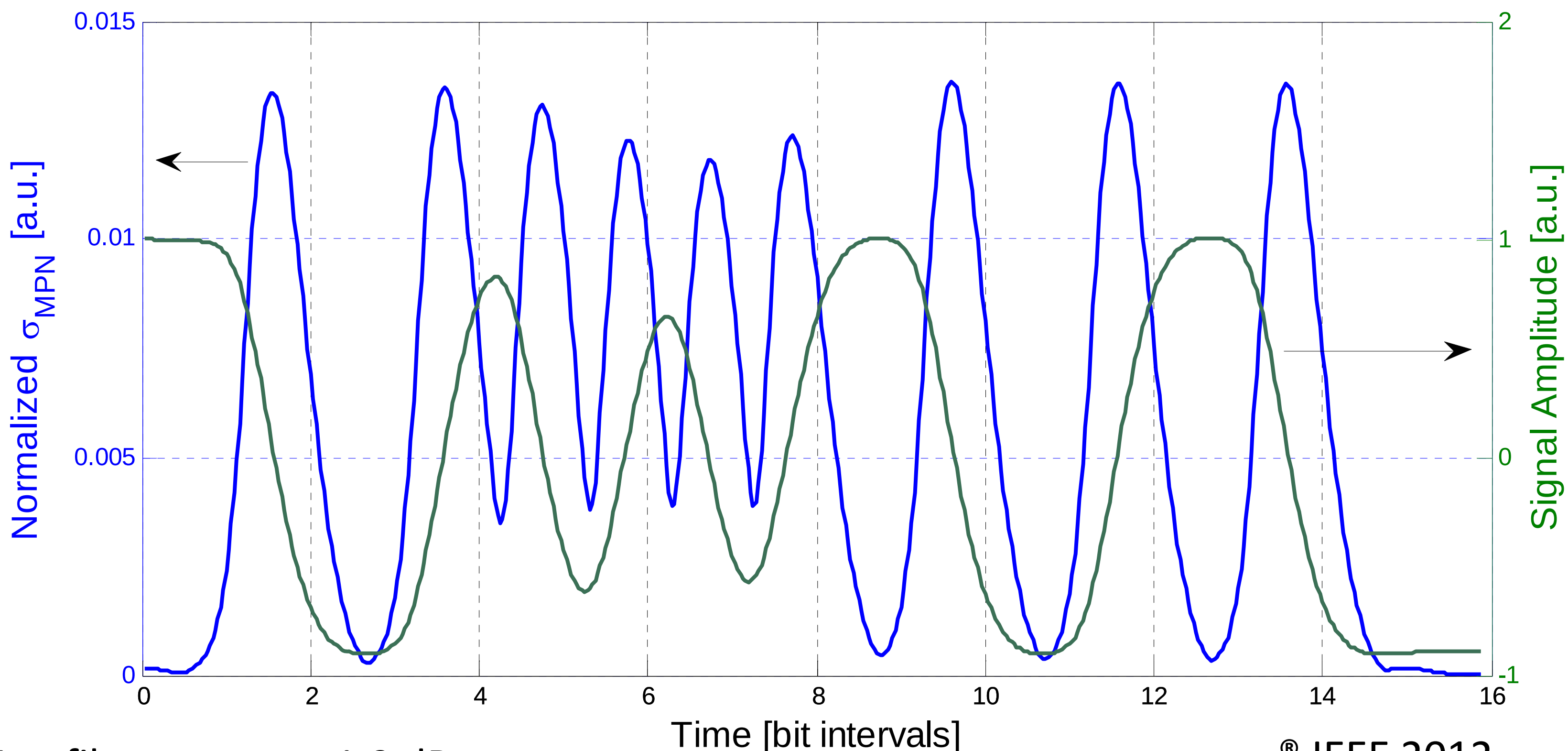
MPD SD for Data Pattern – One Fiber Mode

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



SD MPN for All Mode Groups

- Calculations repeated for all mode groups
  - SD MPN does nor become smaller for higher ISI points
  - Minimum MPN SD value becomes larger
  - SD MPN depends on the slope of the signal – the larger the slope the higher the SD MPN



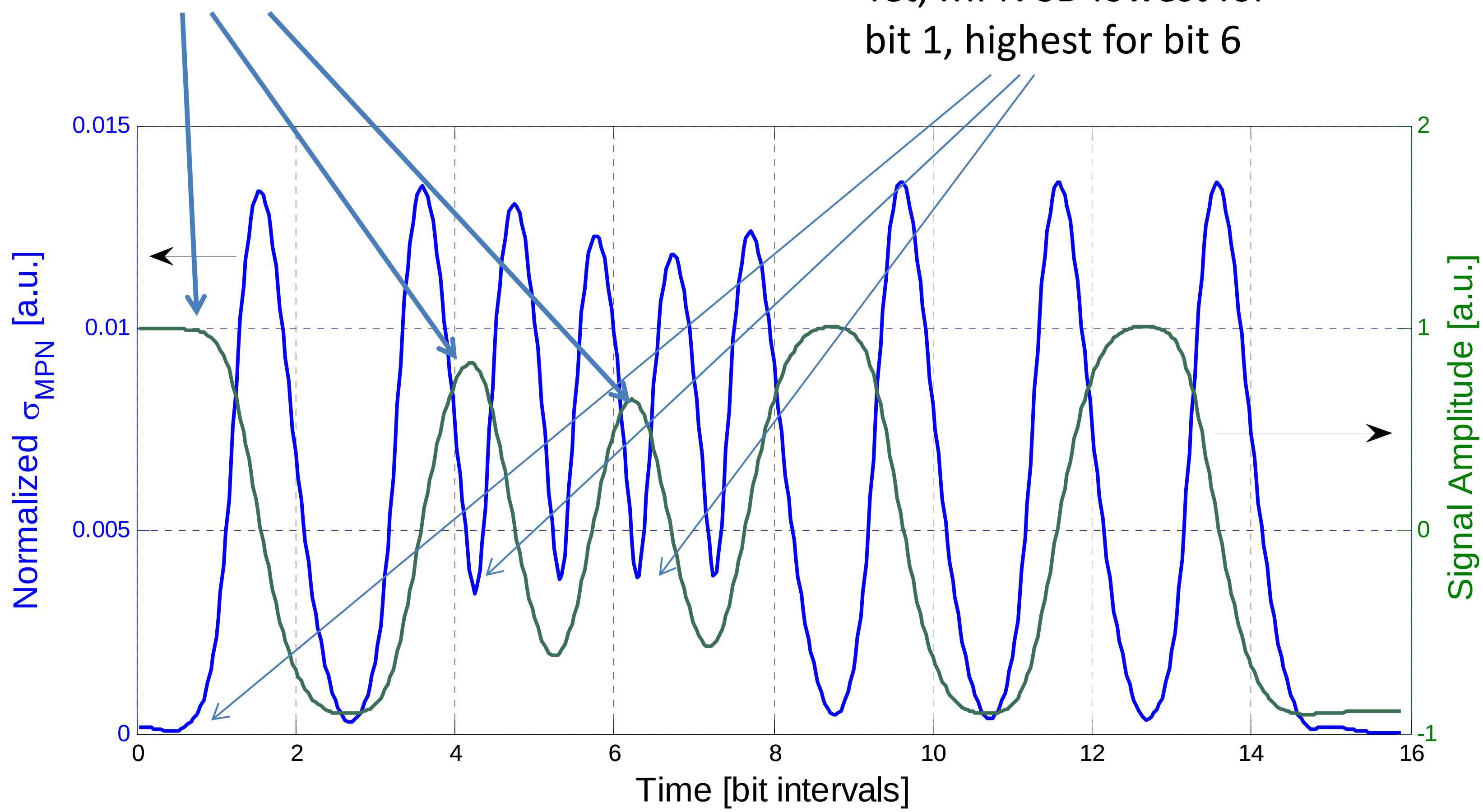
ISI at fiber output = 1.9 dB

SD MPN for All Mode Groups

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

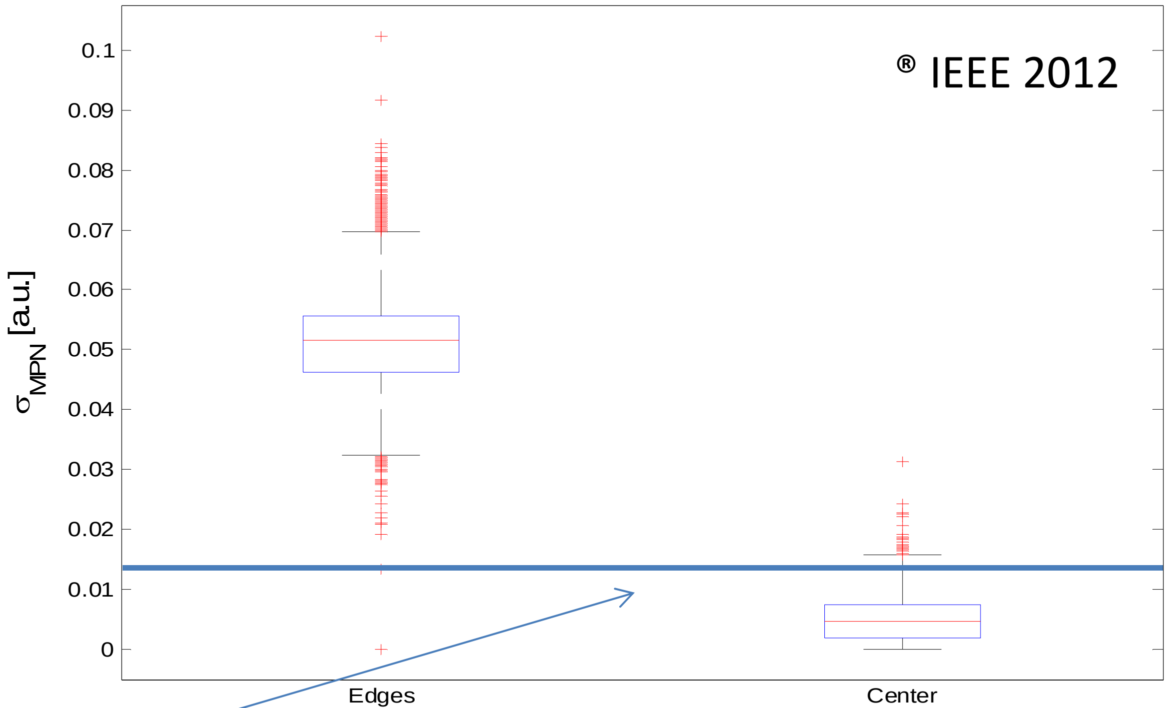
Bit 6 has higher ISI than bit 4 or bit 1

Yet, MPN SD lowest for bit 1, highest for bit 6



Statistical Simulation

- 40k link set from OM3 development, various DMDs and launch conditions
  - MPN SD depends on fiber DMD and launch conditions



Spreadsheet value 0.013

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

References

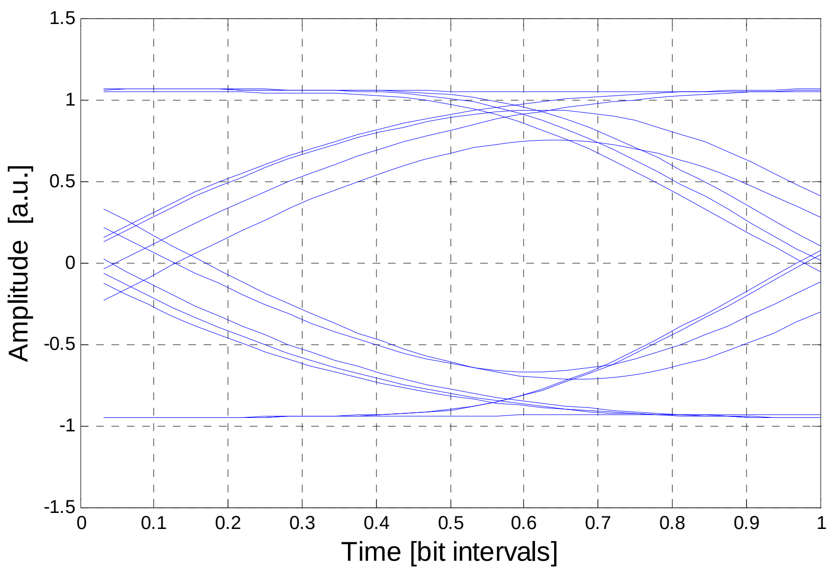
[1]. Agrawal, Antony and Shen: "Dispersion Penalty for 1.3 um Lightwave Systems with Multimode Semiconductor Lasers", IEEE Journal of Lightwave Technology, Vol. 6 No.5, 1988, pages 620-625

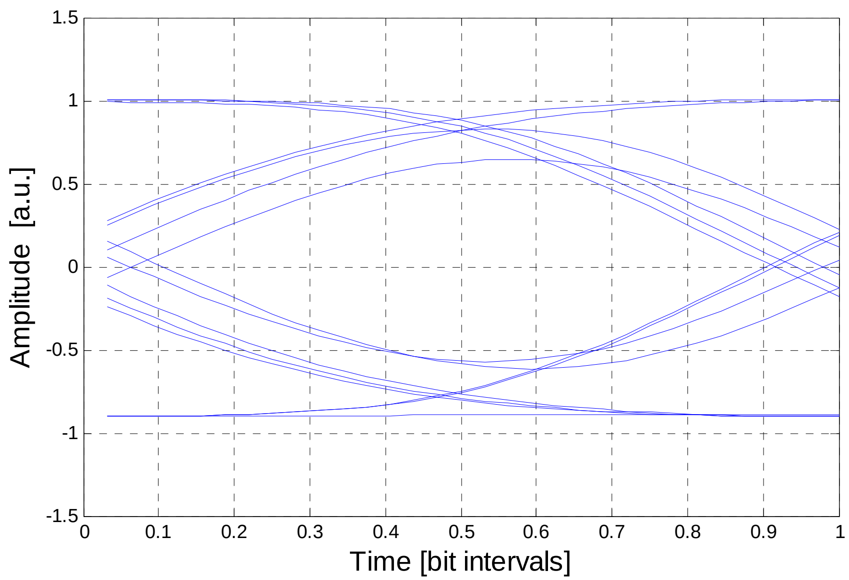
[2] Ogawa: "Analysis of Mode Partition Noise in Laser Transmission Systems", IEEE Journal of Quantum Electronics, Vol. QE-18, No. 5, May 1982, pages 849-855

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