Issues and Progress Toward a Commonly Accepted MMF Link Model

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Outline

- **Working list of important issues**
- **MPN Modeling**
  - Comments on “ISI scaling” of current model
  - A more complete Ogawa-Agrawal model
- **MPN Measurements**
  - Do slow VCSELs exhibit MPN?
  - What is k?
- **Equalization**
  - Noise enhancement of MPN
- **Values of key parameters**
- **Conclusions**

Partial List of Issues

- **FibreChannel spreadsheet**
  - Six months or more ahead of us
  - Can we do it in Excel?
- **Models**
  - Mode partition noise
  - Equalization, noise enhancement
  - γ parameter to account for fiber DMD slope
  - Others
- **Values of key parameters**
  - k-factor
  - R/F time of VCSEL w/w/o equalization
  - RMS spectral width
  - RIN
  - DCD, DJ values
  - Tx power
  - Rx bandwidth
  - FEC limit at which to gauge reach, Others

} coupled parameters?

Mode Partition Noise Penalty

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- **Question has been raised about ISI scaling of the MPN penalty**
- **Questions have been raised about assumptions of the Ogawa-Agrawal (OA) model**

- **Present contribution resolves this issue by revisiting the math behind the Ogawa-Agrawal MPN model**

- **We also propose a truncated Gaussian spectrum to mimic practical VCSELs**

- **We show that:**
  - Greater accuracy can be obtained using an ISI scaling factor
  - MPN penalties with truncated Gaussian spectrum are lower than the current IEEE spread-sheet even after allowing for the proper scaling factor in the MPN penalty formula

Total Penalty with ISI and MPN

- **For the worst-case eye, (heuristically) add the variance of the thermal noise, $\boldsymbol{\sigma_n^2}$, and MPN noise, $\boldsymbol{\sigma_{r_0}^2}$,to get the total noise power**

- **The signal power corresponds to the one with the mean VCSEL mode powers $\boldsymbol{\bar{r}_0}$**
- **Therefore, the system Q can be written as follows:**

$$Q^2 = \frac{\bar{r}_0^2}{\sigma_n^2 + \sigma_{r_0}^2}$$

- **For an ISI-free link without MPN, the Q is given by:**

$$Q^2 = \frac{1}{\sigma_{n,ISI-free}^2}$$

- **Then the total (ISI + MPN) penalty (in dBo) is given by:**

$$Penalty_{ISI+MPN} = 10\log_{10}\left[\frac{\sigma_{n,ISI-free}}{\sigma_n}\right] = -5\log_{10}\left[\bar{r}_0^2 - Q^2\sigma_{r_0}^2\right]$$

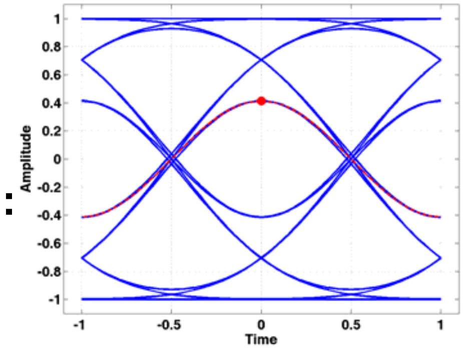
ISI Scaling

- **If mode partition noise is absent, then the ISI penalty is given by:**

$$Penalty_{ISI} = -5\log_{10}[\bar{r}_0^2]$$

- **Subtracting the ISI penalty from the total (ISI + MPN) penalty, we get the MPN penalty:**

$$Penalty_{MPN} = -5\log_{10}\left[1 - \frac{Q^2\sigma_{r_0}^2}{\bar{r}_0^2}\right] \text{ dBo}$$



- **In contrast, the IEEE spread-sheet MPN penalty is based upon:**

$$Penalty_{IEEE} = -5\log_{10}[1 - Q^2\sigma_{r_0}^2] \text{ dBo}$$

- **ISI scaling results from separating the total penalty into ISI and MPN penalties → not a new phenomenon**
- **It appears that when one separates out the MPN penalty, then an ISI scaling factor should be used; however the method of normalizing wrt to the innermost eye amplitude (see insert) in both the OA model and the spreadsheet obviates the need for this. MPN model as it exists in the spreadsheet is as correct as the underlying OA model itself.**

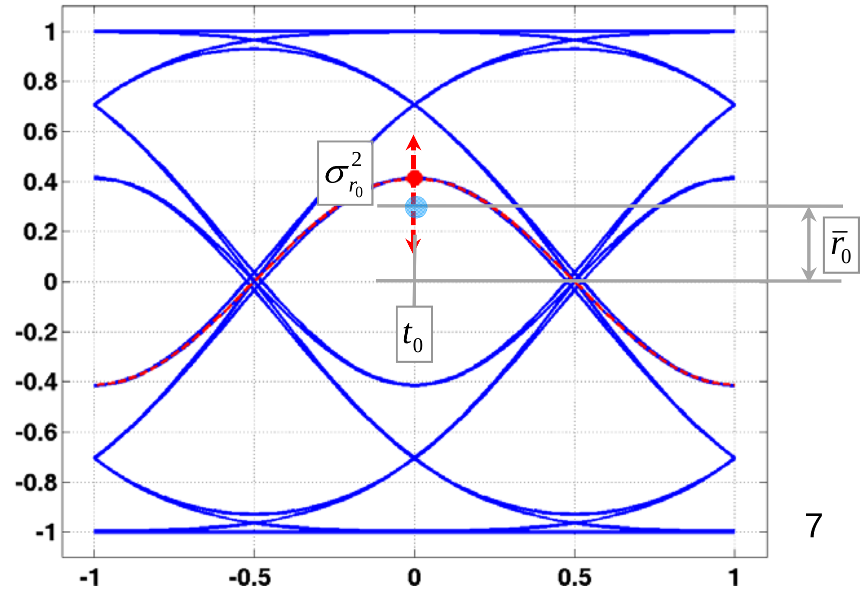
It can be shown that …

- **The OA model is improved by accounting for the additional ISI that a multi-moded VCSEL introduces.**
- **Therefore, the corresponding MPN penalty is given by:**

$$Penalty_{MPN} = -5\log_{10}\left[1 - Q^2\sigma_{MPN}^2\right] \text{ dBo}$$

$$\sigma_{MPN}^2 = \frac{\sigma_{r_0}^2}{\bar{r}_0^2} = \frac{k_{MPN}^2}{2} \cdot \frac{\left[1 - e^{-\beta^2}\right]^2}{e^{-\beta^2}}$$

- **The MPN variance from the OA/IEEE model needs to be scaled w.r.t. $e^{-\beta^2}$ to get the MPN penalty right**
- **The red dot corresponds to inner-most eye**
  - Effectively with a single-moded VCSEL
- **With the mean VCSEL mode powers, we blue dot**
- **The additional drop of the inner-most eye from the red dot to the blue dot is the scaling factor**



VCSEL Spectrum

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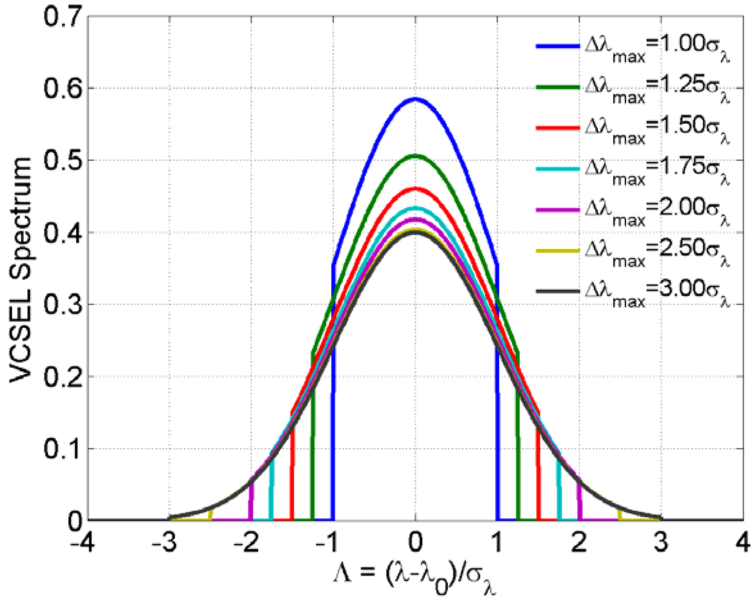
- **Delay corresponding to a VCSEL mode with wavelength λ is given by $BDL(\lambda - \lambda_0)$**

- **The Gaussian spectrum has infinite region of support → VCSEL modes can infinitely large delays (although with smaller and smaller probability)**
  - Not realistic

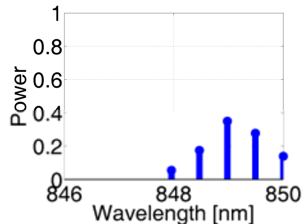
- **Practical VCSELs have limited number of modes and spectrum has a finite region of support → bounded delays**

- **Propose using a truncated Gaussian VCSEL spectrum**
  - Mimics finite region of support of practical VCSELs
  - Results in bounded delays
  - Retaining Gaussian shape to minimize number of changes to OA model
  - Mean and variance of received sample now need to be evaluated numerically

Truncated Gaussian Spectrum

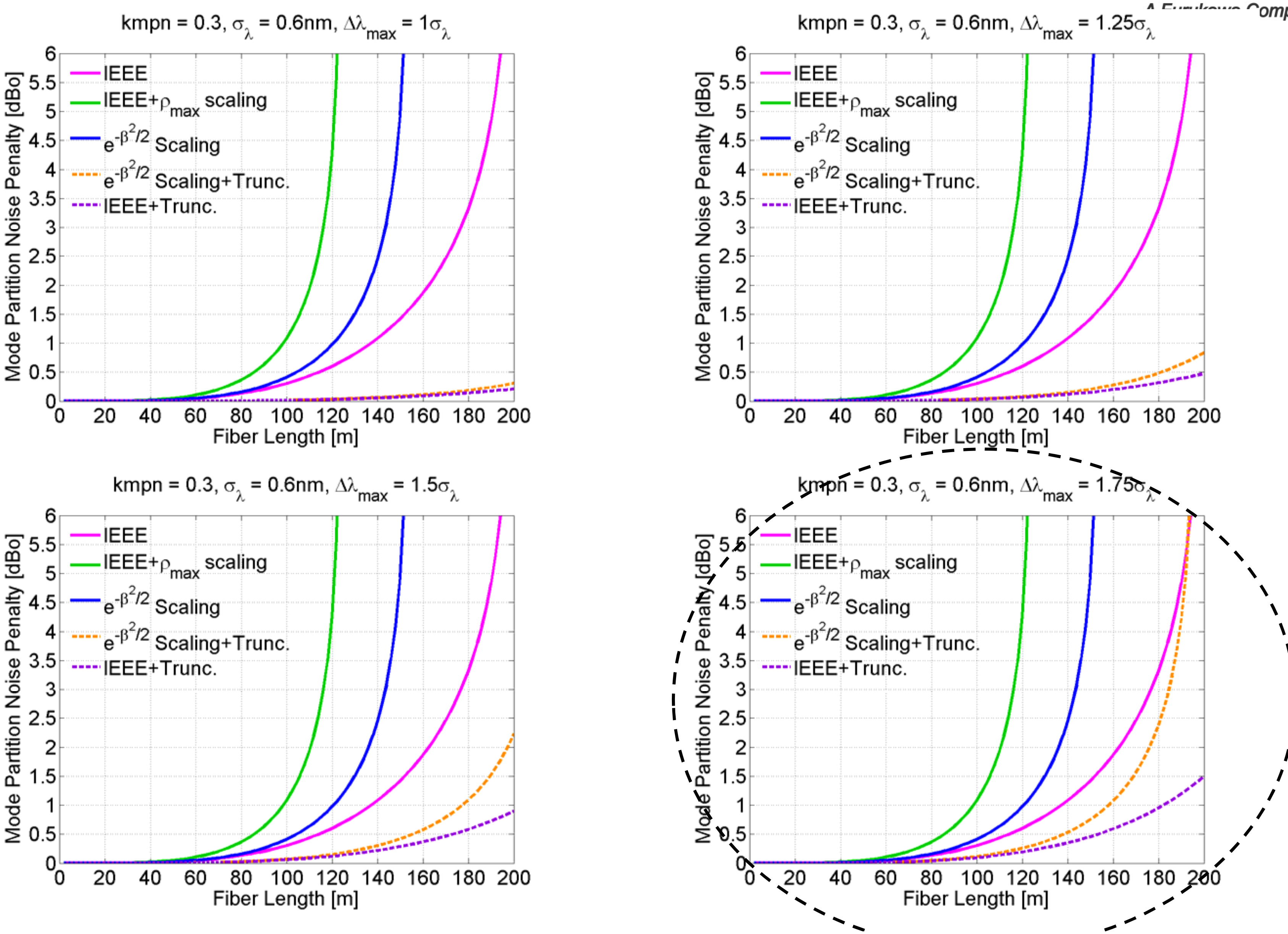


$\Delta\lambda_{max}$	$\Delta\lambda_{max}$ for $\sigma_\lambda = 0.6$nm
$1.00\sigma_\lambda$	1.2nm
$1.25\sigma_\lambda$	1.5nm
$1.50\sigma_\lambda$	1.8nm
$1.75\sigma_\lambda$	2.1nm
$2.00\sigma_\lambda$	2.4nm
$2.50\sigma_\lambda$	3.0nm
$3.00\sigma_\lambda$	3.6nm

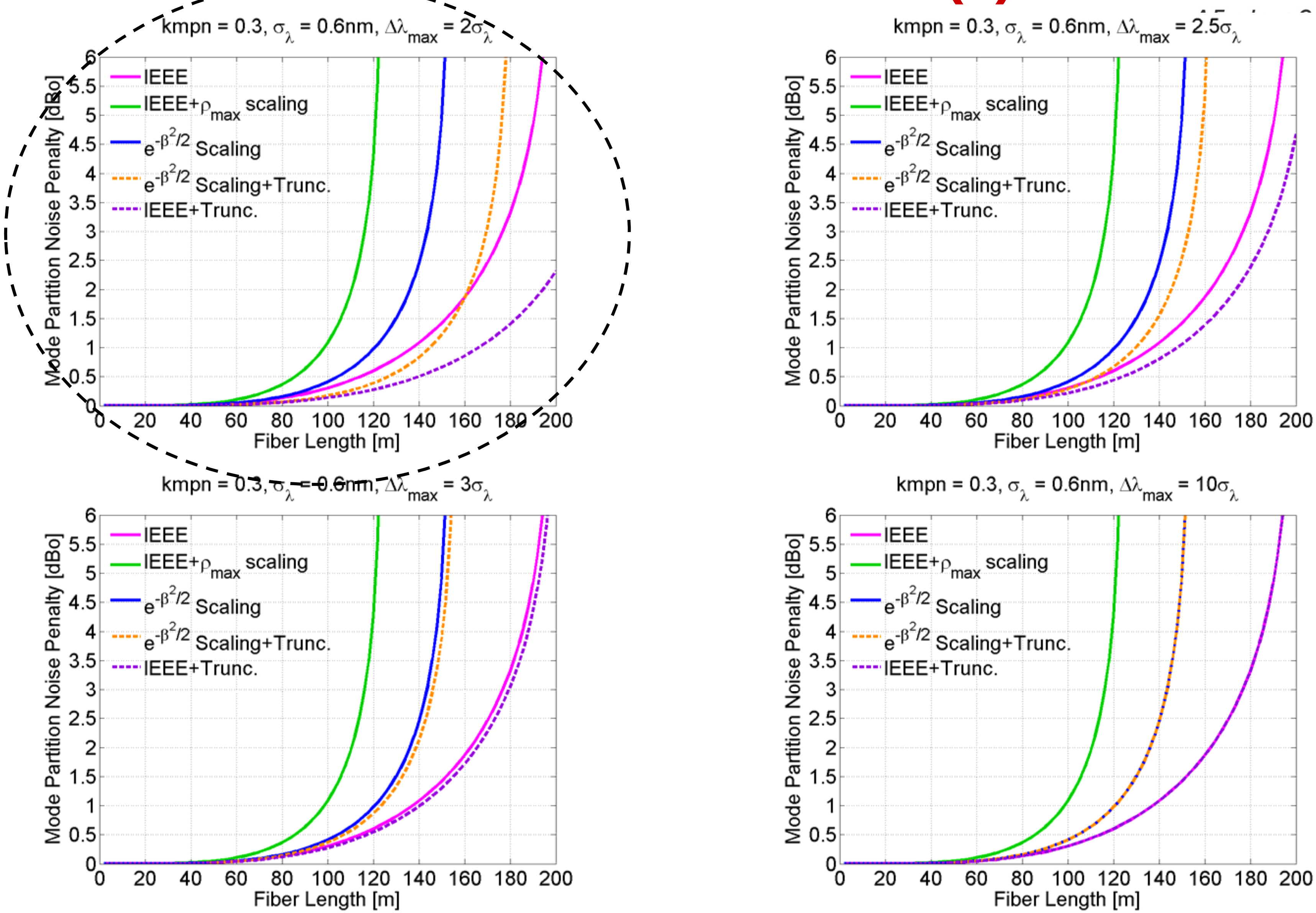


- **Re-normalized to have unity area since there is no net power loss due to the multi-moded nature of the VCSEL**
- **Need to decide the truncation parameter $\delta = \Delta\lambda_{max}/\sigma_\lambda$ for practical VCSELs**
  - For a measured 25G VCSEL spectrum approximated using a discrete line spectrum, $\Delta\lambda_{max} \approx 1nm$ with $\sigma_\lambda \approx 0.55nm \rightarrow \delta \approx 1.8$
  - See lingle_01_0112_NG100GOPTX.pdf
  - On the following two pages, the pink curve labeled "IEEE" shows the standard spreadsheet model, while the orange dashed line shows the improved model predictions
  - Each graph shows a different value of $\Delta\lambda_{max}$, where values of 1.75 to 2.0 correspond to realistic VCSELs with 5 or 6 well-separated peaks in the spectrum

Model Behavior at BER=10^-12 (I)



Model Behavior at BER=10^-12 (II)



MPN Modeling Conclusions

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- **The OA MPN model is coupled to the spreadsheet appropriately, without additional ISI scaling factors.**
- **However, the OA model itself can be improved conceptually by scaling MPN by the additional ISI resulting from the multi-moded nature of the VCSEL**
- **Infinite region of support of the Gaussian spectrum not realistic for practical VCSELs**
- **Propose using a truncated Gaussian spectrum instead**
- **Resulting MPN penalties are a little smaller than the current IEEE spread-sheet even after allowing for the proper scaling factor**

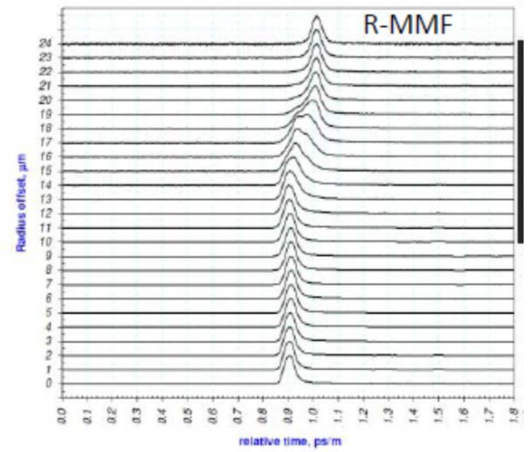
Measurements related to MPN

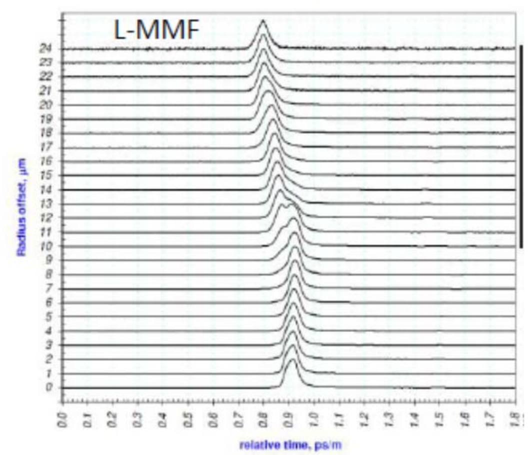
- **What is k parameter?**
  - Notoriously difficult to measure, but important
  - When were the last detailed studies done?
  - To what degree are we extrapolating from distant past?

- **Do slow VCSELs exhibit true mode-partitioning?**
  - There is evidence that driving a slower VCSEL on/off with a faster electrical pulse is a deterministic process. Mode-partitioning may not actually occur.
  - It is possible that MPN is not significant with current 25G VCSELs, but will become more significant as VCSEL speeds increase.
  - Is this true? If so, we should not penalize links with both slow R/F times and MPN simultaneously!
  - Should k be considered a function of R/F time?

Other Useful Models

- **Equalization**
  - In Matlab? FibreChannel has implemented simple equalizers in Excel
  - Noise enhancement is also calculated analytically.
- **γ parameter to account for fiber DMD slope, tilting left or right**
- **Others?**





Essential Parameters

- k-factor
- R/F time of VCSEL w/w/o equalization
- RMS spectral width
- RIN
- DCD, DJ values
- Tx power
- Rx bandwidth
- Will FEC be available? At what uncorrected BER to study reach?
- Others

(k-factor and R/F time of VCSEL w/w/o equalization: coupled parameters?)

- Which will we specify individually?
- Which will we limit in concert?

Conclusions

- FibreChannel has blazed the trail for higher speed VCSELs over MMF.
  - How much of their link model will we adopt?
  - The Task Force should approach this question in an organized and comprehensive way.
  - Don't reinvent the wheel unnecessarily.
  - Will Monte Carlo studies be necessary to supplement?
- An extension of the familiar OA model was presented; details will be supplied for discussion by the group.
  - This also clarifies the "ISI scaling" issue.
  - More experimental data should be produced on MPN and VCSEL performance in general
- Other models used by fiber channel should be explored. OFS is looking at the equalization models next. We preliminarily agree with David Cunningham about MPN noise enhancement.
- Range of critical parameters
- FEC