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Towards Large-Scale Modeling of Equalized MMF-VCSEL Links at 25Gbps

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4x25G Link Modeling

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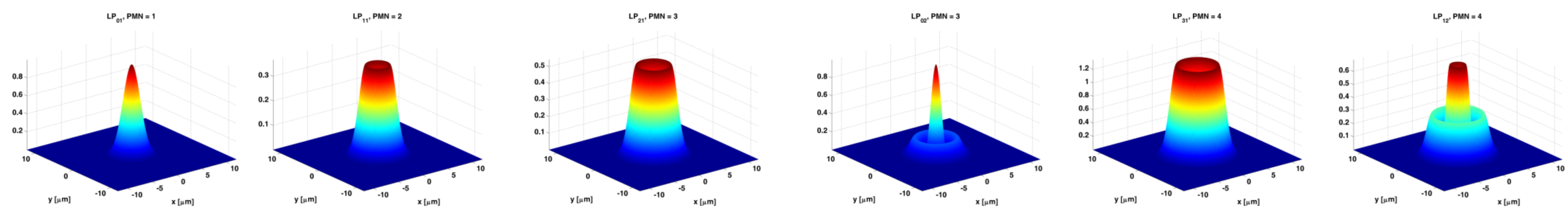
- **Goal: robust 4 x 25G standard that maximizes value to end users**
- **Several variables at play simultaneously**
  - Retiming, FEC
  - VCSEL specifications (rise/fall time, spectral-width, RIN)
  - Impact of fiber profile perturbations
  - Tx and Rx Equalization
- **Link modeling needed to address these and other issues**
- **Modeling effort in this study group thus far:**
  - Spreadsheet model useful within limits
  - Simulating specific cases → cannot make statistical judgments yet

- **IEEE requires high% coverage→ may require large-scale statistical modeling**

Modeling in 10GBASE-SR

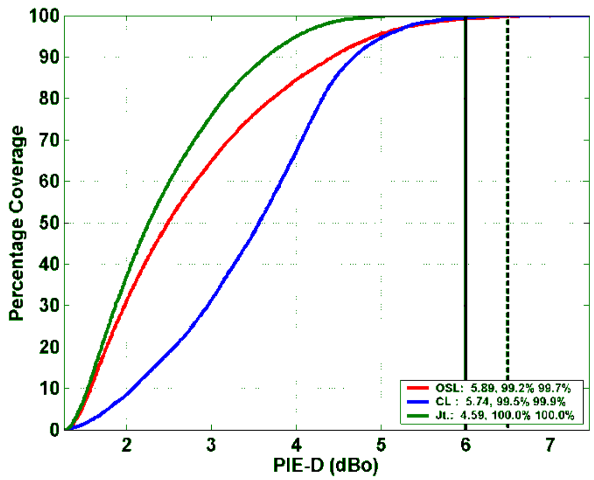
- **10GBASE-SR involved large-scale Monte Carlo simulation**
  - Pepeljugoski *et al*., JLT vol. 21, p 1256, May 2003.
- **Numerous parameters varied:**
  - VCSEL parameters, fiber modal delays, VCSEL-fiber coupling variations
- **Example: analytic VCSEL modes**

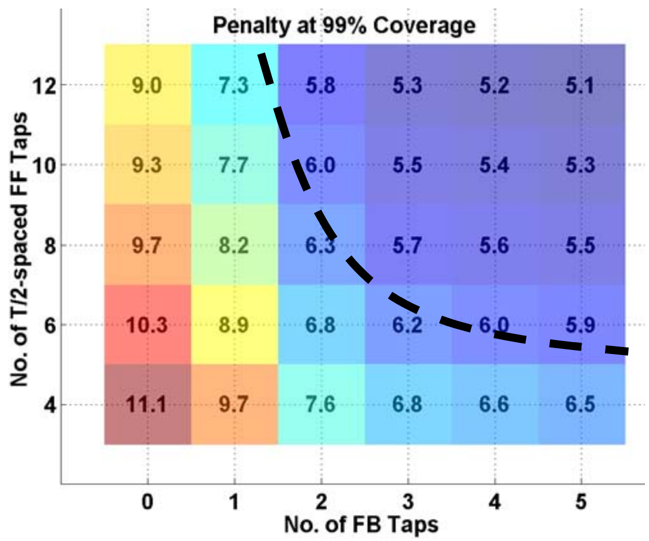


- **May be advantageous to incorporate such large-scale modeling in current effort, to achieve a robust standard, depending on the dominant link impairments**

Equalization: 10GBASE-LRM

- **Equalization was used in 10GBASE-LRM technology**
- **Performance of links evaluated using:**
  - Monte Carlo fiber delay set
  - Cambridge 108 fiber delay set
- **Both infinite and finite-length equalizers considered**





- **Similar effort may be needed if equalization will be used**

Fiber, VCSEL Parameterization

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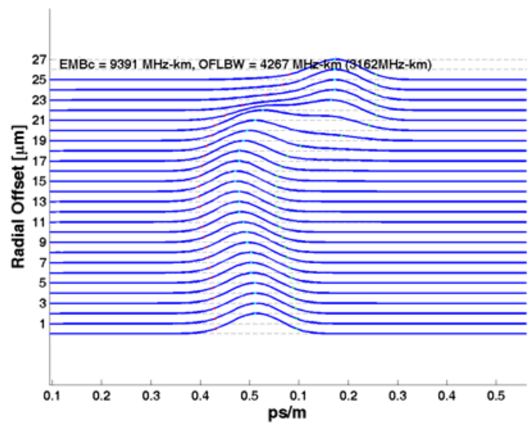
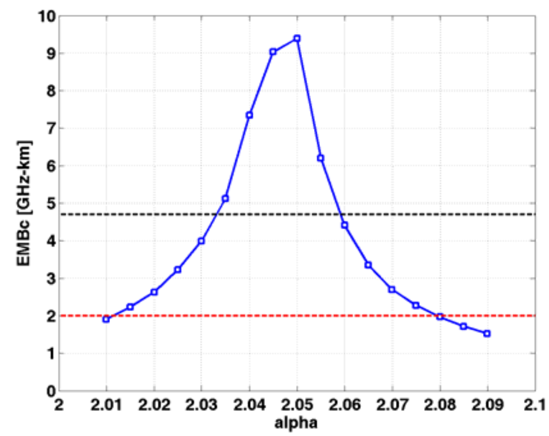
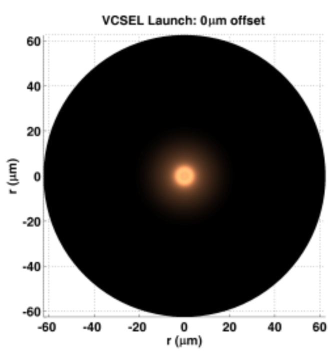
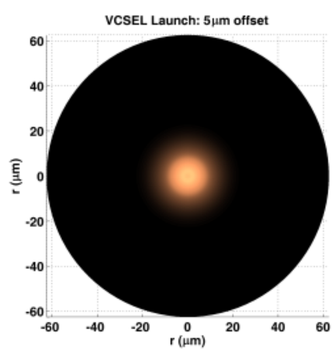
- **Parameterized model fibers yield challenging impulse responses**
  - Some of the Cambridge OM1 fibers can be scaled to be OM3/OM4

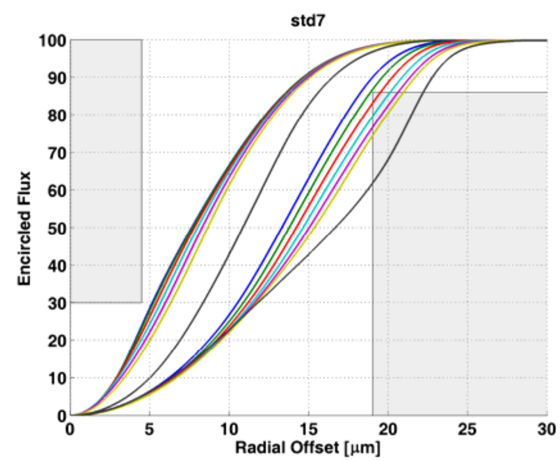




- **VCSEL parameters required**
  - Example: VCSEL models from 10GBASE-SR can be scaled for 25G

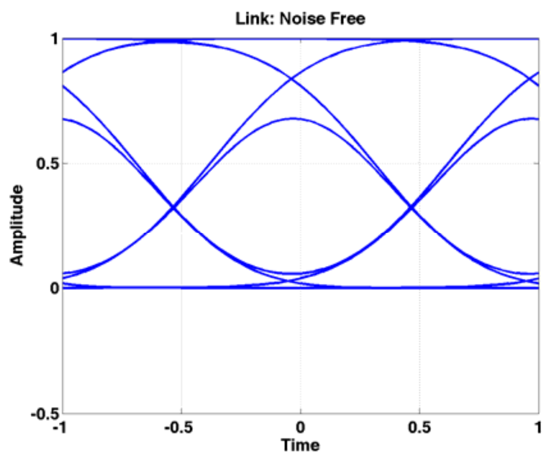


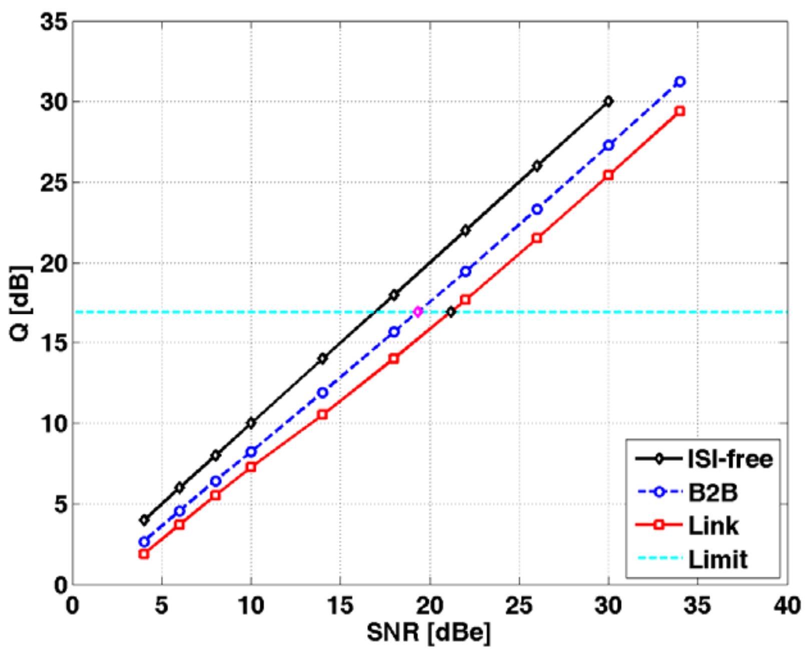




Link Characterization:

Eye Diagrams, Q vs SNR curves, Penalty



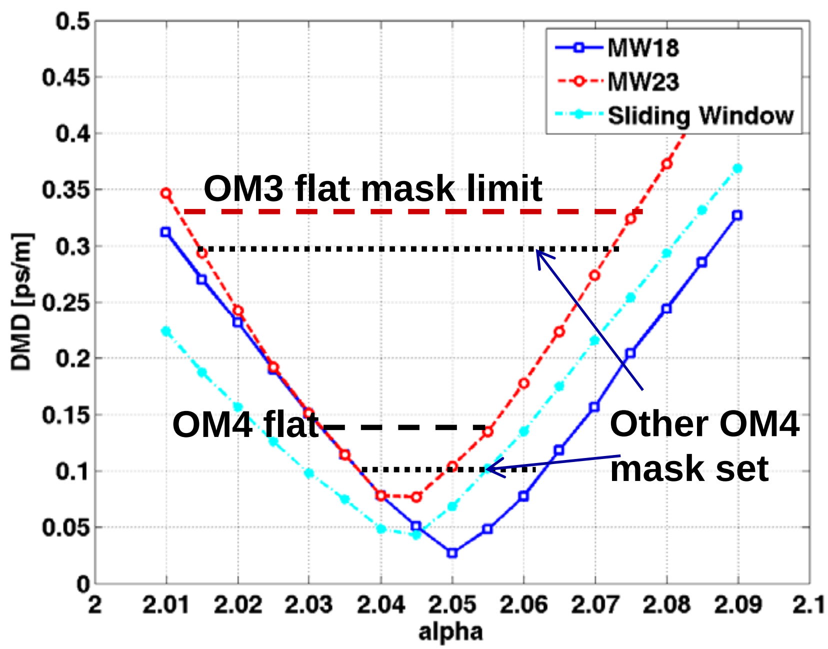


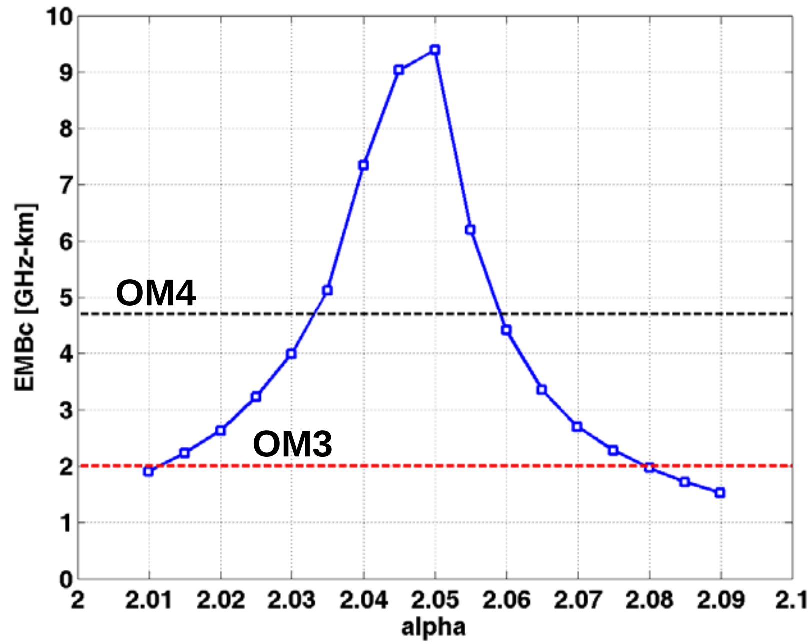
- **Link itself can be characterized in terms of eye-opening penalty or ISI penalty (with or without EDC)**

Baseline case

- **Bit rate = 25.78Gbps**
- **VCSEL 7 from TIA FO-2.2.1 modeling**
  - Pepeljugoski *et al*, JLT vol. 21, p 1256, May 2003
  - Wavelength spacing adjusted to get spectral width, σ_{RMS} = 0.59nm, with the LP01 VCSEL mode assumed to be at 850nm
  - Zero axial offset
  - Radial (launch) offset = 7μm
- **Transmitter rise-time = 22 ps**
- **Receiver bandwidth = 0.6*BitRate**
- **Fiber has power law α profile (unless otherwise mentioned)**
  - α is swept from 2.01 to 2.09 as one of many ways to parametrically vary the profile and thus degrade the delays from optimum values
- **All penalties are with respect to the back-to-back link with these baseline parameters (unless otherwise mentioned)**

OM3/OM4 compliance can be checked by DMD mask widths or EMBc





- **The "flat mask" requires both 5-18μm and 0-23μm DMD to be within same limit. Others trade off tighter MW18 for looser MW 23**
- **OM3 compliance to the "flat mask" above for 2.015 <~ α <~ 2.07**
- **OM4 compliance to the "flat mask" above for 2.035 <~ α <~ 2.055**
  - Other masks increase the upper limit on α in both cases

Example 1: Spectral Width Impact

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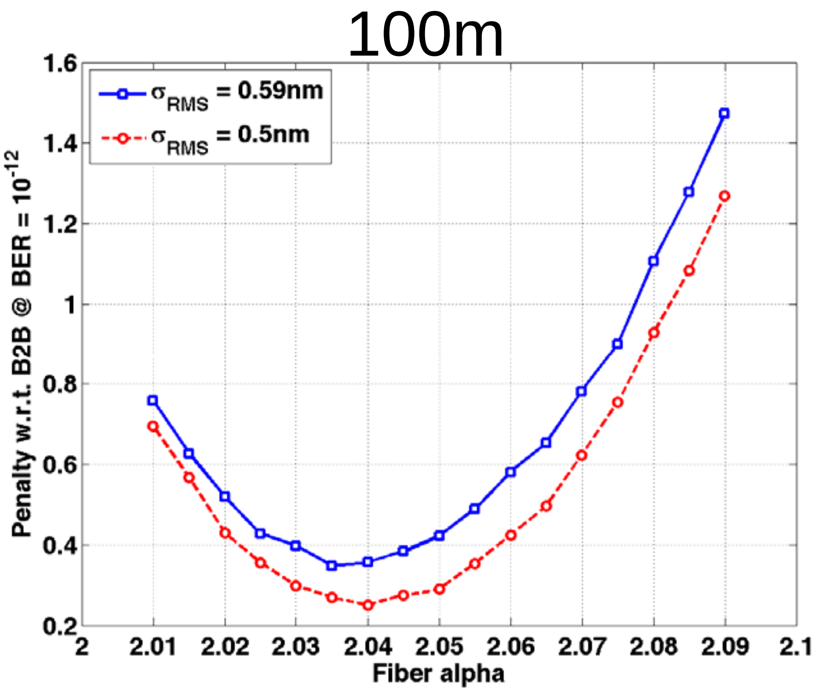
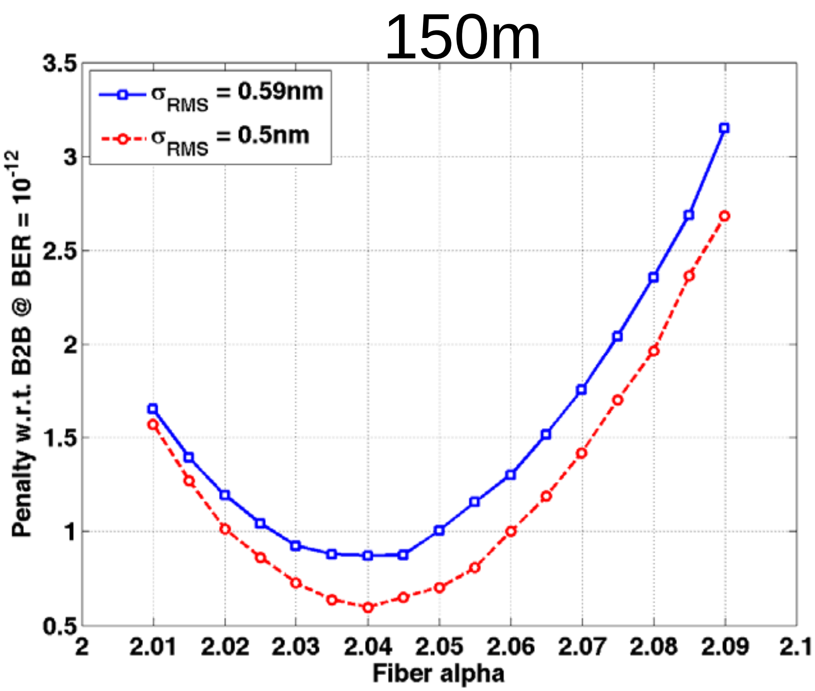
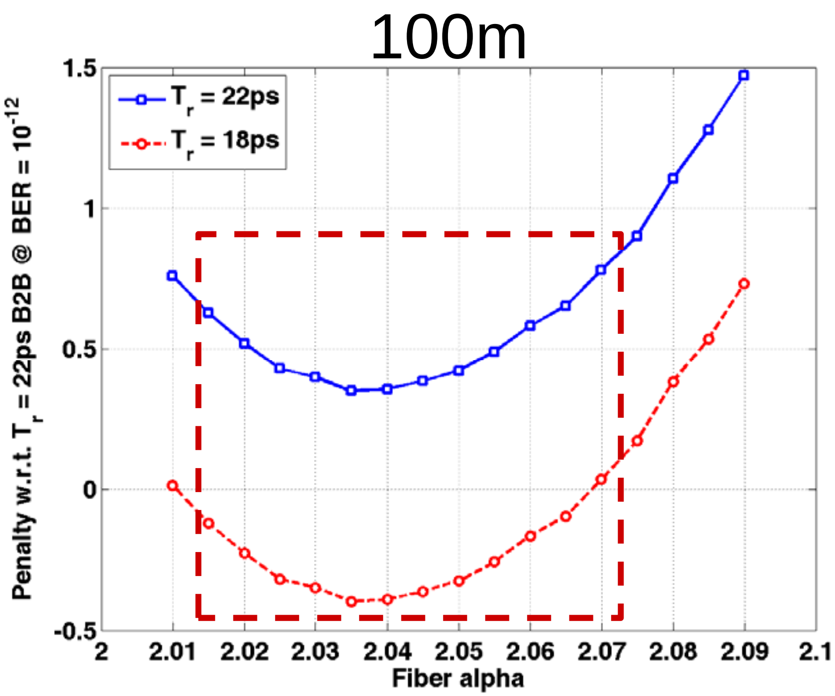
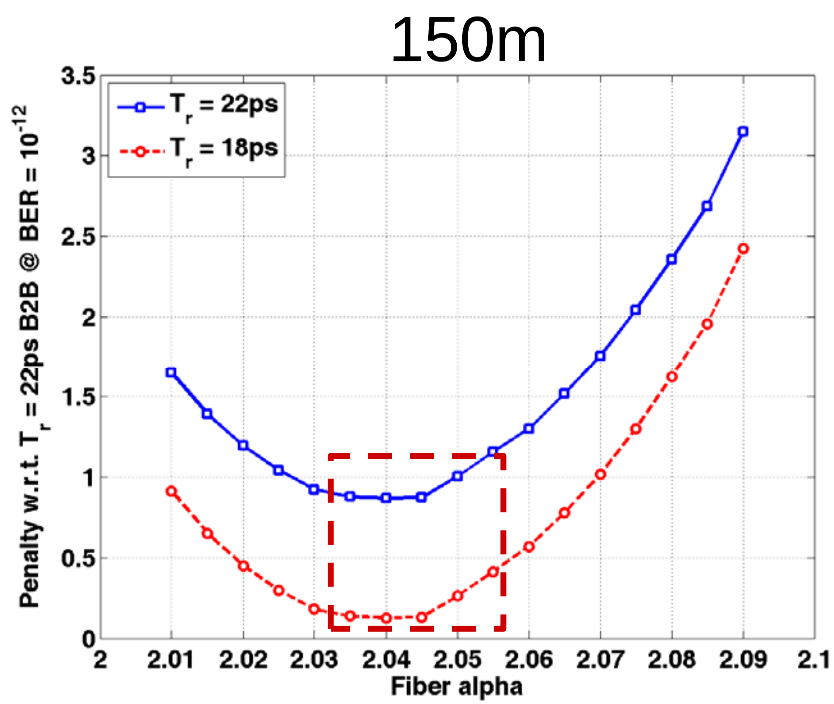




- **ISI (chromatic and modal dispersion) is accounted for; signal-borne noise is not**
- **Penalties vs. B2B**
  - OM3 fibers over 100m in the 0.2-1.2dB range
  - OM4 fibers over 150m in the 0.6-1.5dB range
- **~0.7dB reduction in spectral width results in dispersion penalty reduction of ~0.3dB**

Example 2: Tx Rise-Time Impact



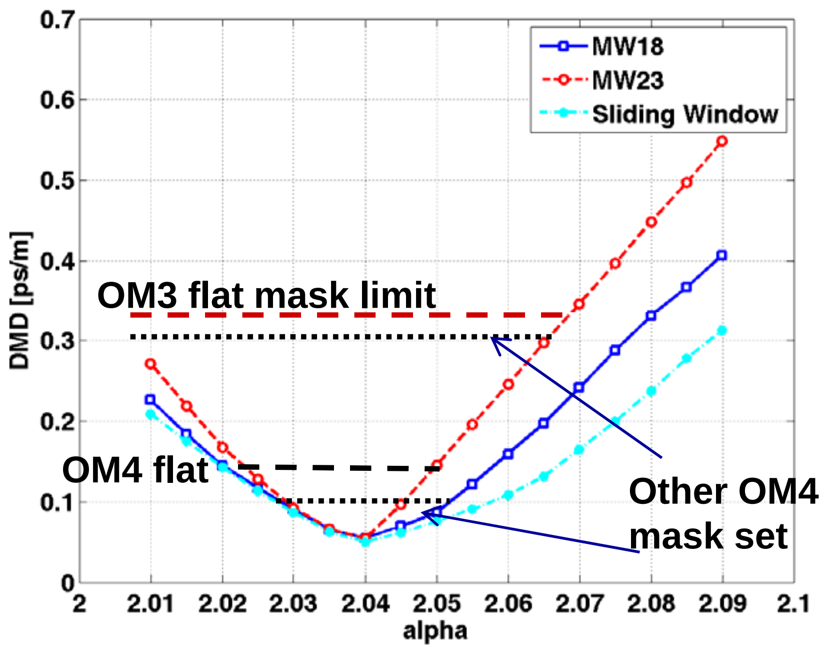


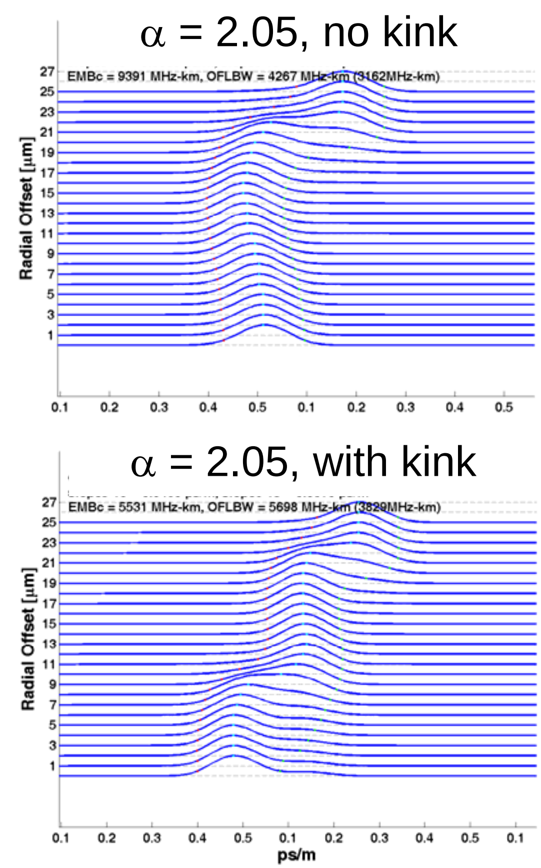
- **All penalties are plotted with respect to 22ps rise-time B2B case**
- **18ps rise-time emulates an equalized transmitter**
- **~0.8dB reduction in rise time reduces penalty by ~0.8dB**
  - Almost entirely due to back-to-back link performance difference between 22ps and18ps cases
- **The transmission penalty for fibers of varying bandwidth is not dependent on the Tx rise time**

Example 3: Profile Perturbation Impact

OM3/OM4 Compliance

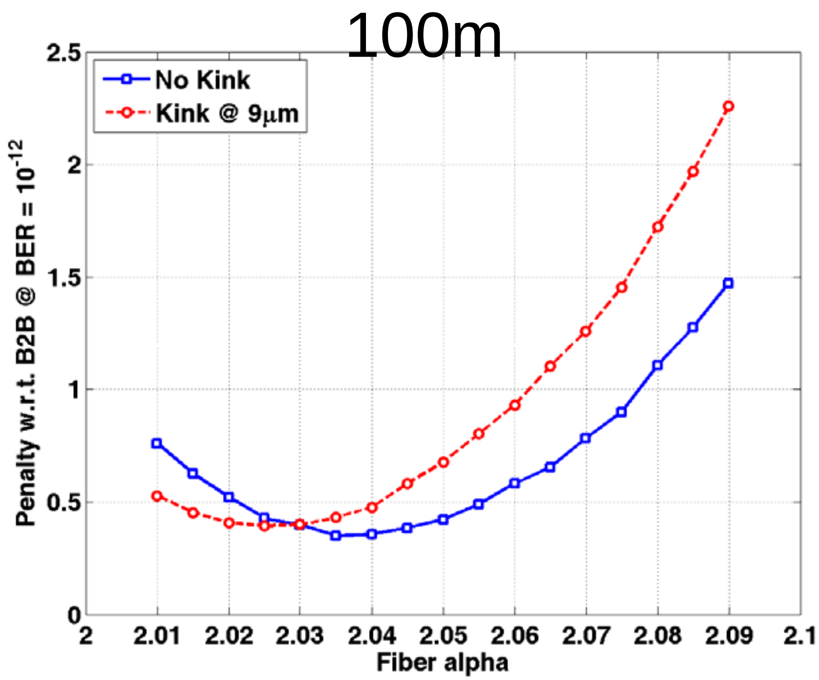
- **Localized profile perturbations decaying exponentially away from $r=r_1$ can impact penalty significantly → introduce a "kink" at 9μm, in addition to alpha variation.**
- **A profile kink shifts the DMD and can introduce a bi-modal temporal response**

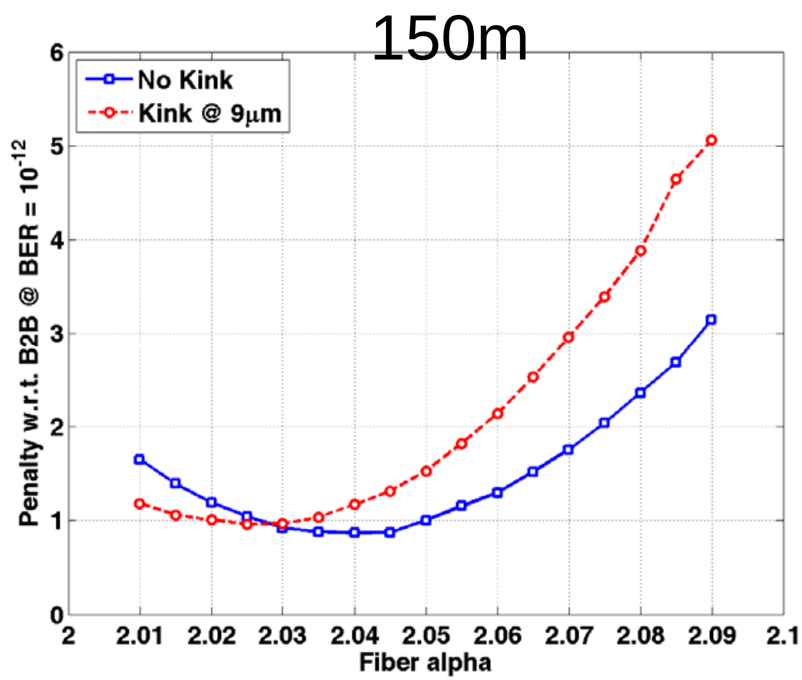




- **OM3 compliance for 2.005 <~ α <~ 2.07 vs. flat mask**
- **OM4 compliance for 2.025 <~ α <~ 2.05 vs. flat mask**
- **Profile deviations from ideal interact to shift the alpha yielding compliant fibers to lower values**

Example 3: Profile Perturbation Impact





- **The presence of a kink can:**
  - **Shift DMD either to the left or to the right, depending on whether the kink is a negative or positive index bump, respectively.**
  - **Increase or decrease link penalty depending on whether the alpha is higher or lower than optimal value (in the absence of the kink)**
  - **Create a split symmetric impulse response important for equalizer studies**

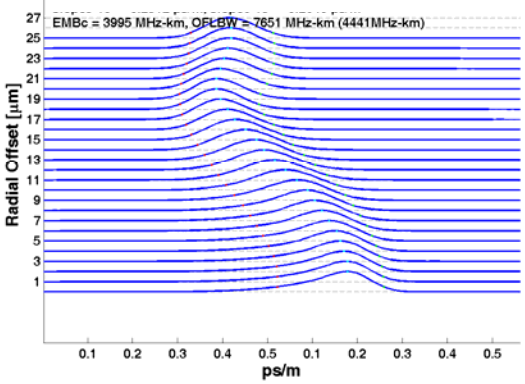
Summary

- **Depending on the dominant link impairments, it may be useful to run large-scale simulations of VCSEL-MMF links to help set a reach objective and then validate performance, in accordance with precedent**
  - Simulations of profile deviations identify likelihood of challenging impulse responses for receiver equalization
- **Simulations can quantify the possible ISI due to specific fiber DMD patterns, which can then be used to interpret experimental data to identify impairments:**
  - In an exemplary case, for a subset of MMF profile perturbations, ISI penalties associated with fiber modal and chromatic dispersion, referenced to B2B, subject to the assumptions of slide 7, are
    - As high as 1.3 dB for 100m over OM3
    - As high as 1.7 dB for 150m over OM4

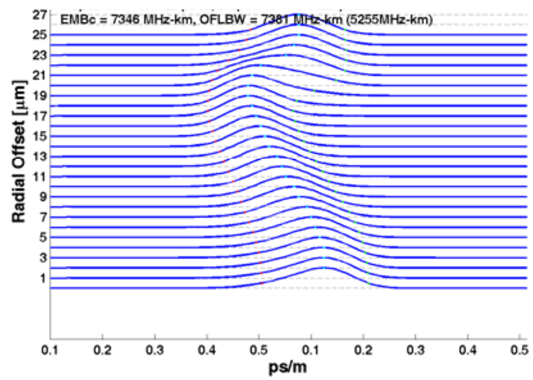
Backup Slide

DMD Plots without and with kink

α = 2.03, no kink



α = 2.04, no kink



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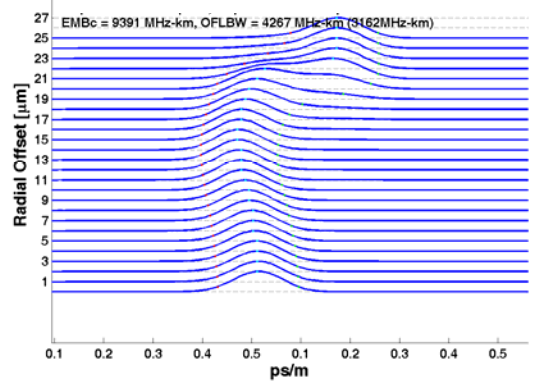
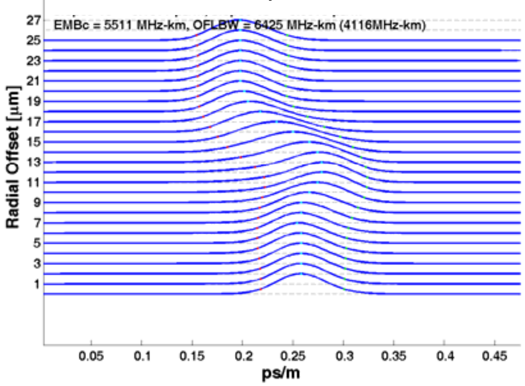


α = 2.03, with kink



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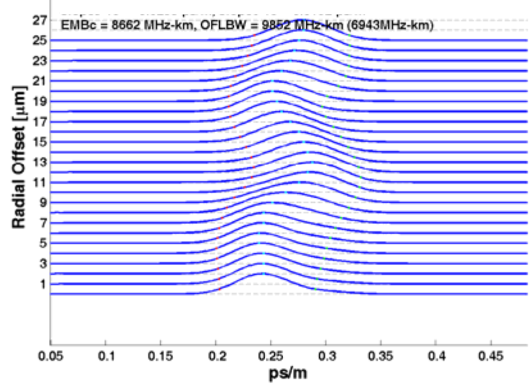

α = 2.05, with kink