Fiber Modeling Resolution and Assumptions: Analysis, Data, and Recommendations

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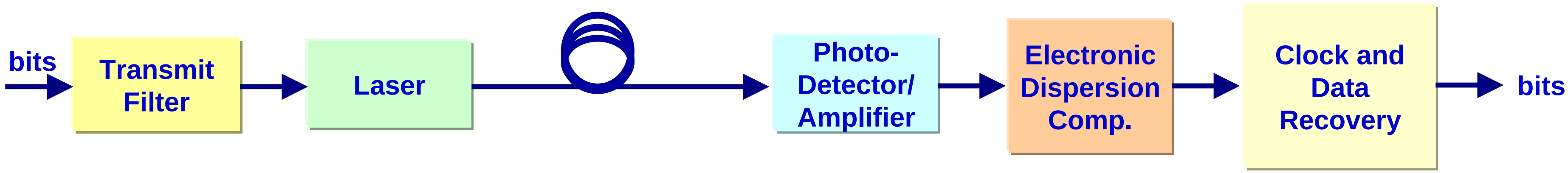
Objectives

- Help establish validation procedures for 802.3aq LRM
    - Analyze use of 108 fiber set to validate EDC performance on installed base
    - Determine PIE metrics of real fibers to assess fiber modeling efforts
    - Furnish examples of worst case impulse responses from this set of real fibers which correspond to various PIE metrics which can be used to establish compliance testing

Model Summary



- Objectives:
  - To evaluate modal delays and mode power distribution of MMF described by index profiles
  - To determine PIE metrics
- Fiber Simulation methodology
  - Scalar wave equation solved by a finite-difference method that results in an eigenvalue equation
  - Perturbation method via Rayleigh quotient to solve for modal delays
  - Use well-known analytic result to validate model for specific cases
  - Evaluate mode power distributions for each fiber uniquely for a Gaussian Beam of FWHM = 7μm
  - Retain only the lower 18 mode groups for 62.5micron fiber
  - Mode power distribution and modal delays used to generate fiber impulse response
- End-to-End response: Convolve transmit filter, fiber impulse response and receiver filter
  - Scale fiber response to reflect the fiber length
  - Transmit Filter + Laser: Gaussian with 47.1ps rise-time (20%-80%)
  - Receiver Filter: 4th order Bessel-Thomson filter with 3dB BW = 7.5GHz
- PIE metric evaluation: Use Sudeep Bhoja's code (see bhoja_1_0704.pdf)

$$|H_a(f)|^2 = \frac{1}{T}\sum_{n=-\infty}^{\infty}\left|H\left(f+\frac{n}{T}\right)\right|^2 \qquad PIE-L = 2T\int_0^{\frac{1}{2T}}\frac{df}{\frac{1}{T}|H_a(f)|^2+\sigma^2} \qquad PIE-D = \exp\left[2T\int_0^{\frac{1}{2T}}\ln\left(\frac{1}{\frac{1}{T}|H_a(f)|^2+\sigma^2}\right)df\right]$$

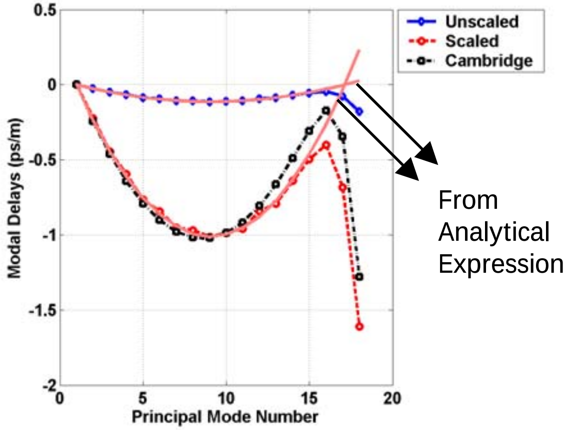
  - where σ^2 is the noise-to-signal-ratio such that we have 6 dBo margin at BER = 10^{-12}

- Details of mode solving (for the 108 fiber set) and scaling yield variation in modal delays sets impacting PIE metrics and coverage

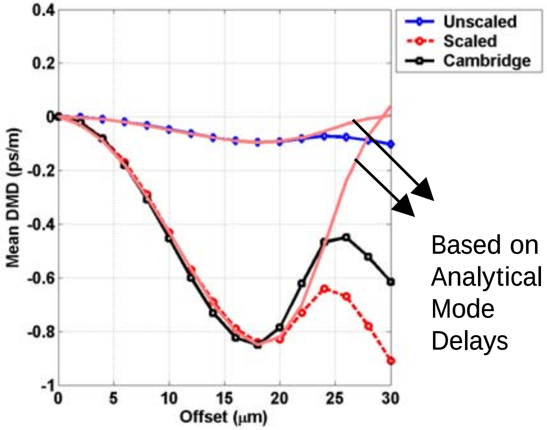
Fiber 51: α = 1.97, no core/clad, no center perturb.

Case I: dispersion parameter y=0

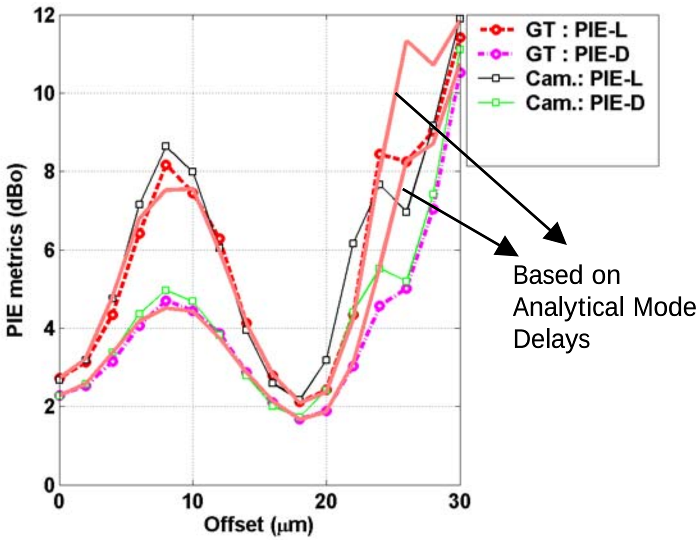
Modal Delays



DMD



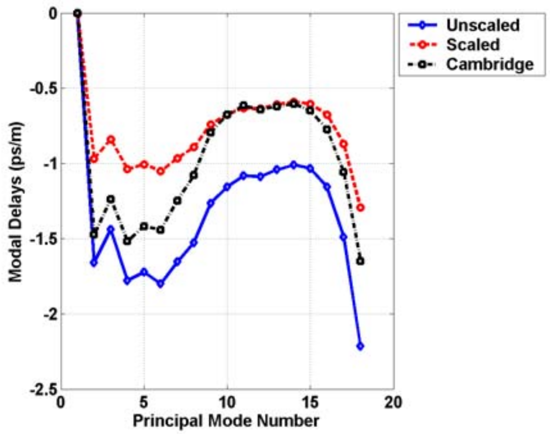
PIE Metrics



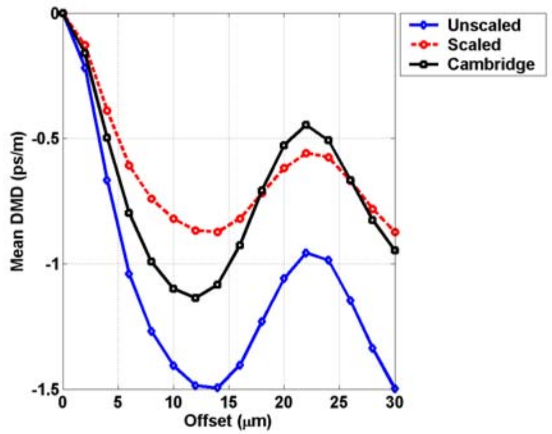
- Modal Delays, DMD and PIE metrics show close but not identical agreement between Cambridge and GaTech models
  - After scaling the deviations are significant
  - PIE metrics show modest deviations
  - GT Modal delay, DMD and PIE metrics are nearly identical to the analytic results
  - GT model uses scaling to match Cambridge not that calculated from OFL-BW or 2ns/km rule
  - Therefore: Deviations here arise from “shape” differences in MD’s vs mode number

Fiber 60: α = 1.97, center peak + exponential core/cladding perturb. + kink at 17μm

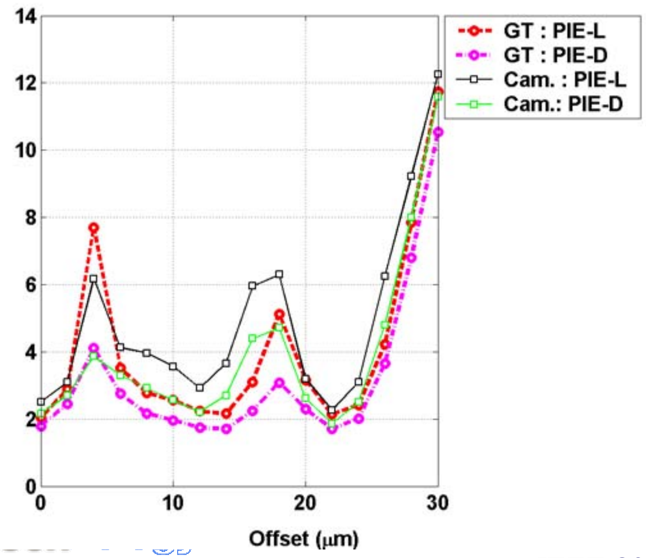
Modal Delays



DMD

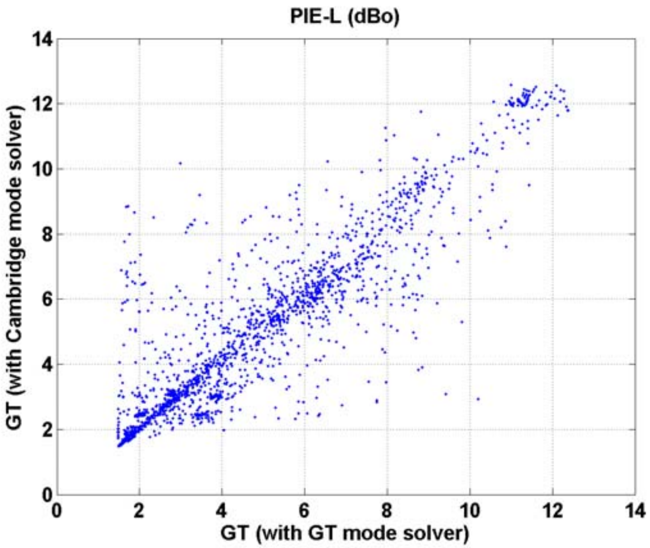


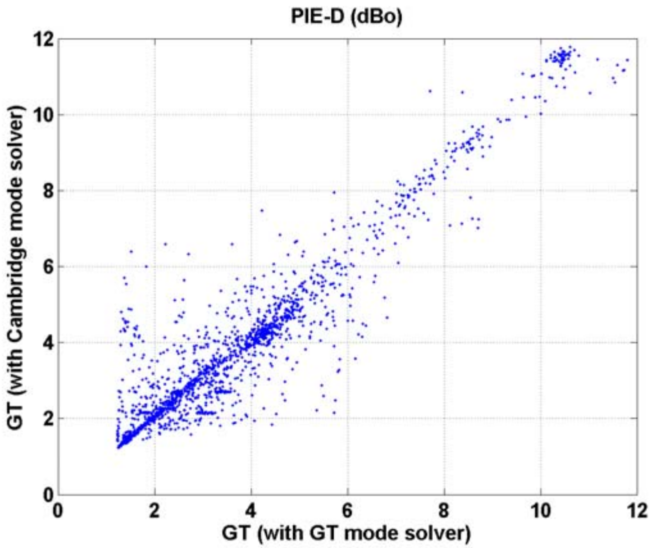
PIE Metrics



- Fibers with kinks show additional variations in modal delay shapes
  - Results in larger PIE metric deviations (as large as 2dB)

PIE Metric Comparison: fiber by fiber



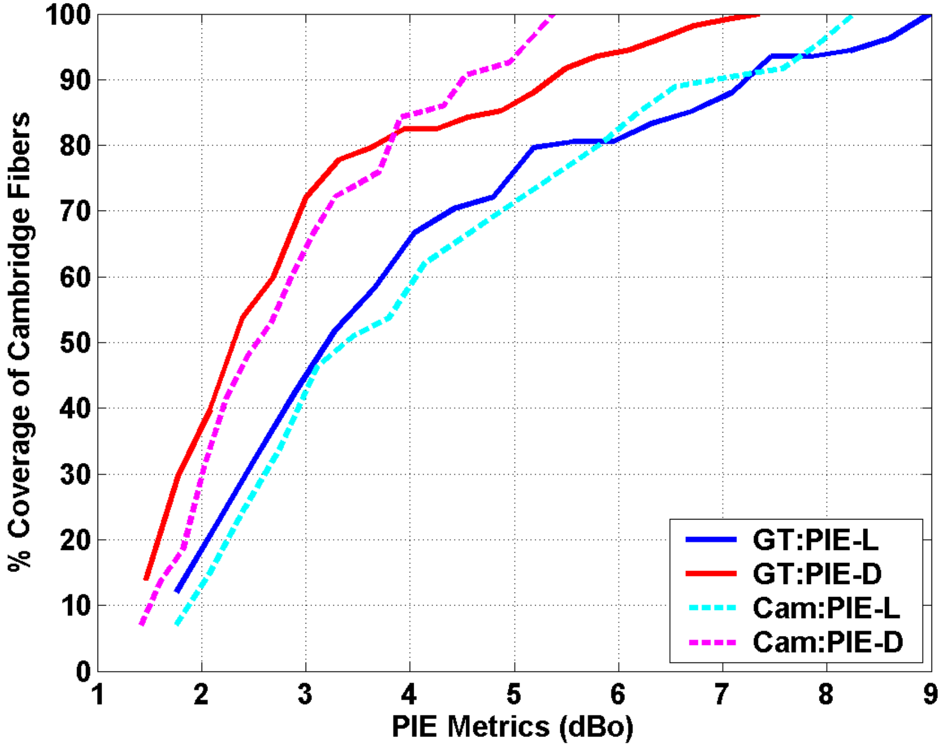


For both plots:

y-axis	x-axis
Cambridge modal delays	GaTech modal delays
Cambridge mode power distribution	GaTech mode power distribution
GaTech channel response	GaTech channel response
GaTech PIE metrics	GaTech PIE metrics

- At least 25% of 1728 configurations have deviations greater than ±1dB
  - 108 fibers x 16 offsets = 1728 configurations
- Therefore the modal delays and resulting scale factors differ significantly

Coverage at 20μm, y = 0



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Observations I

Modal Delays

- Discrepancies suggest uncertainties in evaluating modal delays
- These uncertainties should be considered when evaluating pass/fail wrt PIE metrics

- Dispersion parameter significantly affects modal delays and hence PIE metrics

Profile Dispersion (y) Parameter

- Profile dispersion parameter quantifies the differences in the way the core and cladding indices change with wavelength
- Modal delays are extremely sensitive to the y-parameter

$$y = -\frac{2n_1}{N_1} \cdot \frac{\lambda}{\Delta} \cdot \frac{\partial \lambda}{\partial \Delta}$$

  - where n_1 and N_1 are the core index and group index at the fiber axis, n_2 is the cladding index and $\Delta = \frac{n_1^2 - n_2^2}{2n_1^2}$
- For graded-index fiber, it can be shown that the optimal α is

$$\alpha_{opt} = 2 + y - \Delta(4 + y)(3 + y)/(5 + 2y)$$

- What is the y value?
  - The y-parameter can be computed from published Sellemeier coefficients; y= -0.047, α_{opt}= 1.90
  - Alternatively if α_{opt}= 1.95 then y is implied to be -.01
  - If α_{opt}= 1.97 then y is implied to be 0.0113
  - With n1 = 1.5, n2 = 1.474 and Δ=0.017
- To quantify the sensitivity of the modal delays to y parameter we examine the performance at y=.013 and y=±.03

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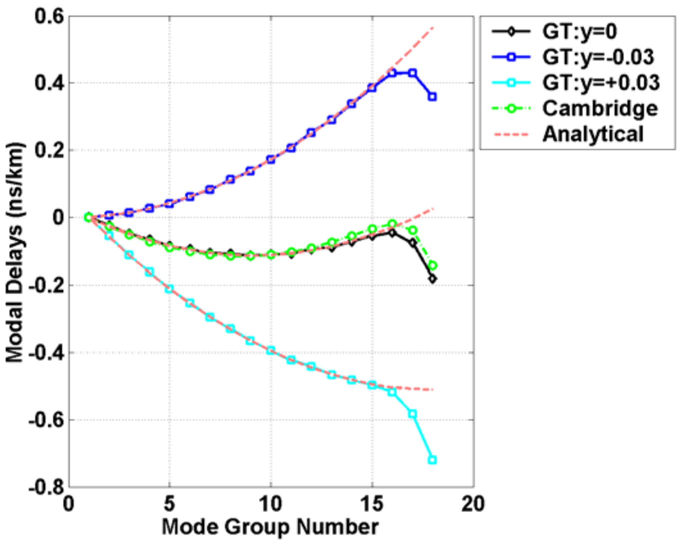
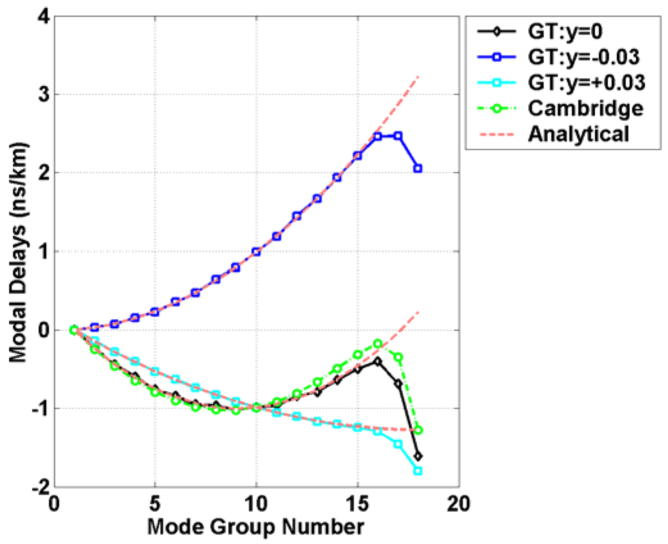
Profile Dispersion and Modal Delays for Fiber 51

Case II: dispersion parameter y=0.03 and y=-0.03



Cambridge Modal Delays are rescaled so that the delay for the 10th mode group matches the corresponding delay from the Georgia Tech model



Georgia Tech (& Analytical) Modal Delays are scaled so that the delay for the 10th mode group matches the corresponding delay from the Cambridge model

- Clearly, the modal delays are sensitive to the value of the y-parameter
  - For y = + 0.03, higher order modes are faster than the lower order modes
  - For y = - 0.03, higher order modes are slower than the lower order modes
  - For y = 0.00, behavior is somewhere in-between the above two cases
- Again the Georgia Tech modal delays are nearly identical to the analytical results in each case

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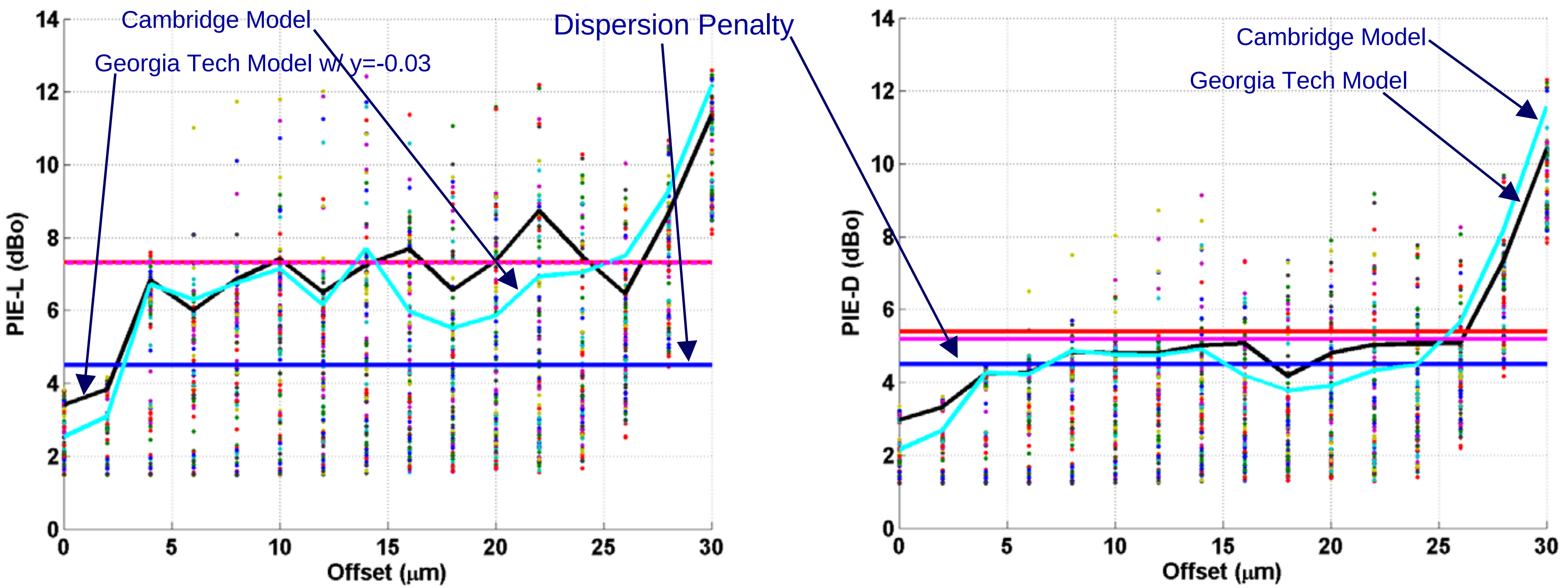
PIE metrics vs. Offset

Case II: dispersion parameter y=-0.03

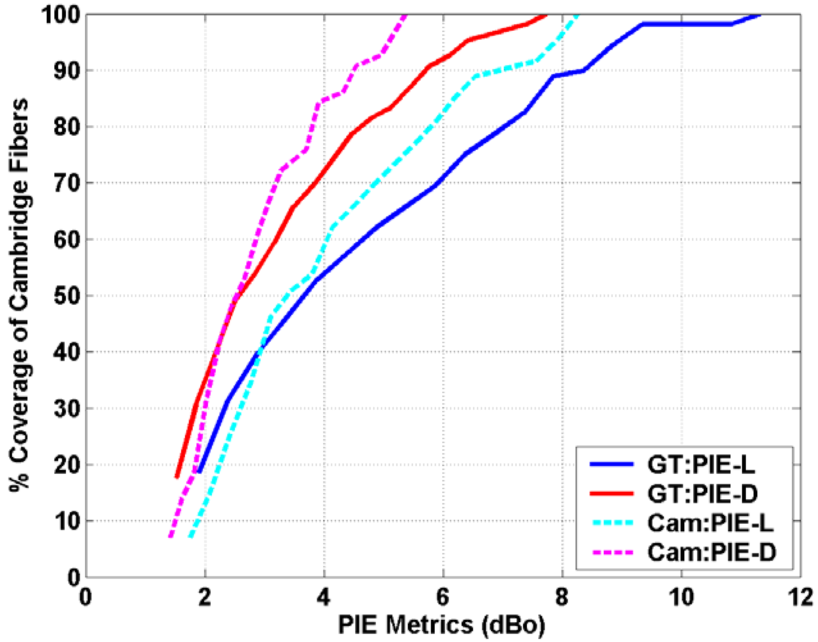


- Large statistical discrepancies between models
  - Linear Equalizer: Worst case ~2dBo deviation (in the 80 percentile curves)
  - Decision Feedback Equalizer: Worst case ~1dBo deviation (in the 80 percentile curves)
  - (The 80th percentile of Cambridge set is sometimes suggested to correspond to the 99th percentile of the installed base. This is an unproven assumption, and the 80th percentile is quoted here only as an illustration.)

(GT models assumes y = -0.03)

Coverage at 20μm Offset

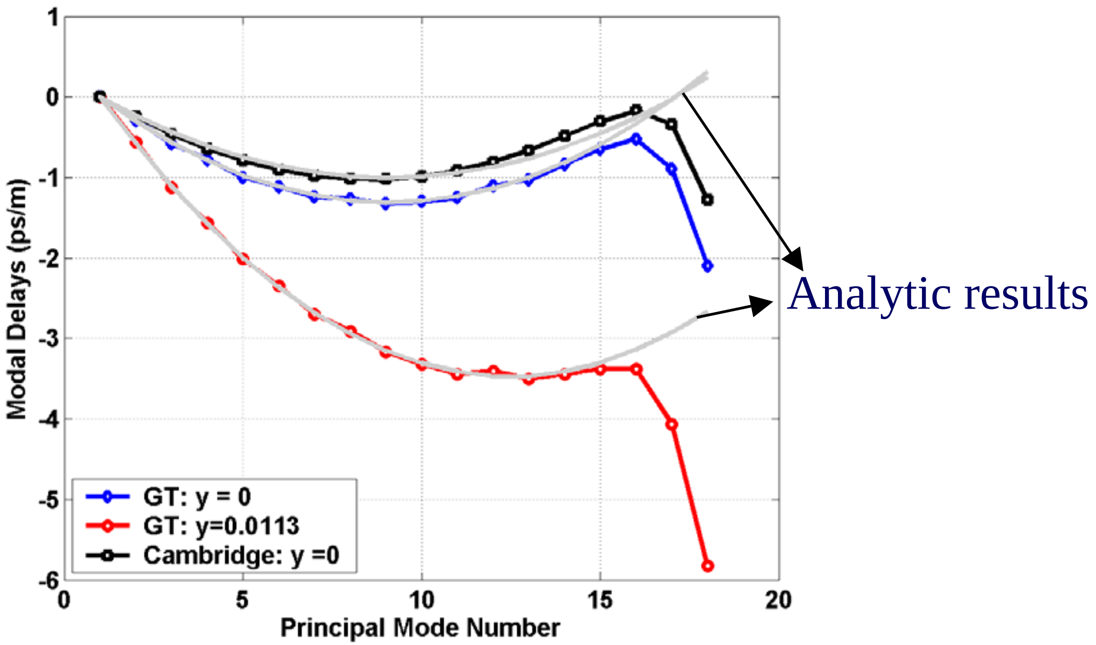
Case II: dispersion parameter y=-0.03



- Coverage at 4.5dBo drops significantly
  - Linear Equalizer: from 66% to 58.5%
  - Decision Feedback Equalizer: from 90% to 79%
- 80% coverage of the Cambridge fiber set is achieved at a higher PIE metric
  - Linear Equalizer: increases by 1.2dBo (from 5.8dBo to 7dBo)
  - Decision Feedback Equalizer: increases by 0.8dBo (from 3.8dBo to 4.6dBo)

Modal Delays for Fiber 51 Y

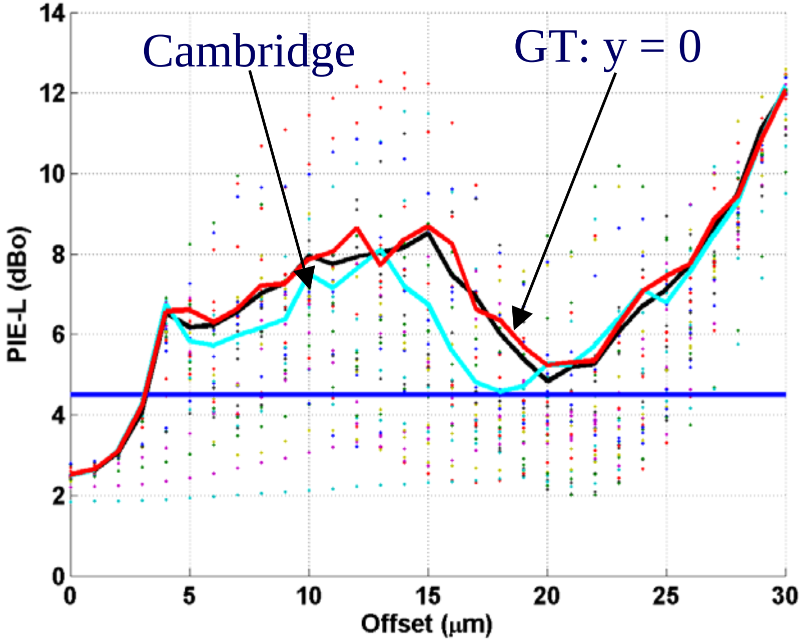
Case III: dispersion parameter y=0.0113

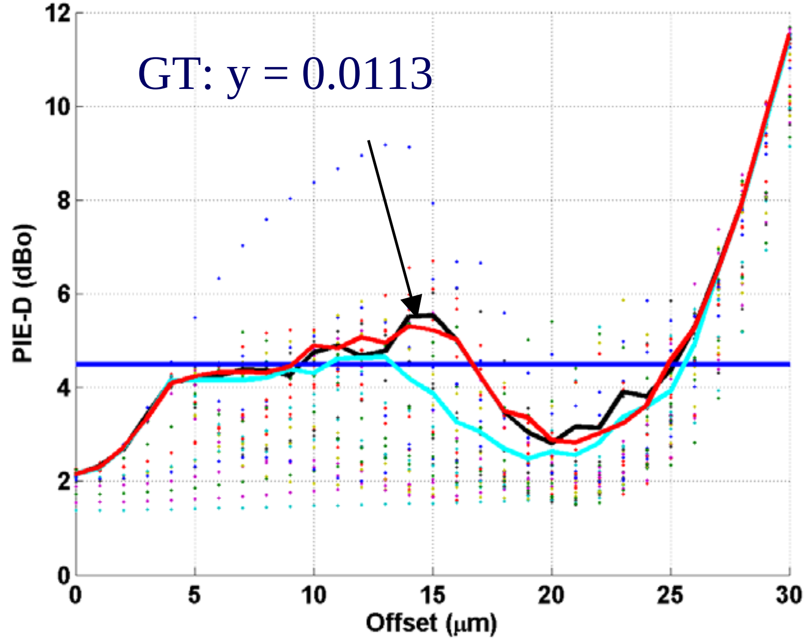


- All modal delays are scaled using the 2ns/km and OFL-BW rules
- Observe significantly different modal delays from y = 0 to y = 0.0113
- Analytic results show GaTech results to be reasonable

PIE vs. Offset

Case III: dispersion parameter y=0.113

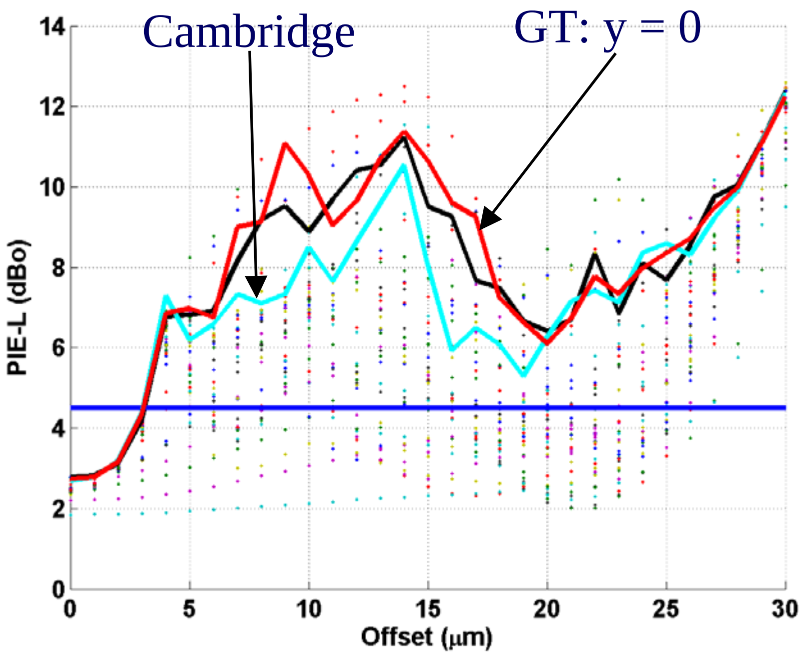


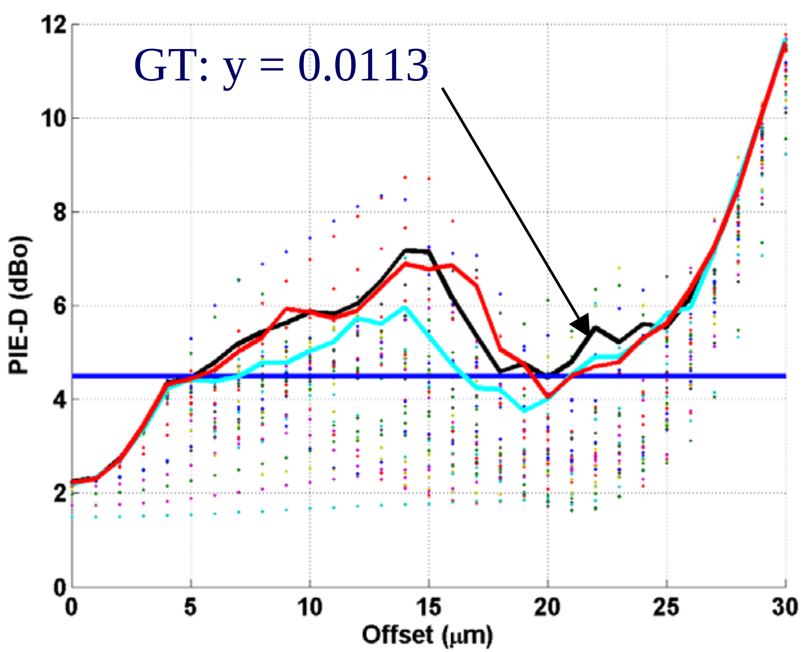


- 80% curves at each offset

PIE vs. Offset

Case III: dispersion parameter y=0.0113





- 90% curves at each offset

Observations II

- Modal delays are
  - sensitive functions of precise numerical method
  - sensitive functions of dispersion parameter y
- Observed modal delay differences produce *statistically* different PIE metric behavior and therefore different coverage
- Georgia Tech modal delays closely agree with analytical results for ideal fibers for all y values examined

Equalization Simulation of Real FDDI grade Fibers

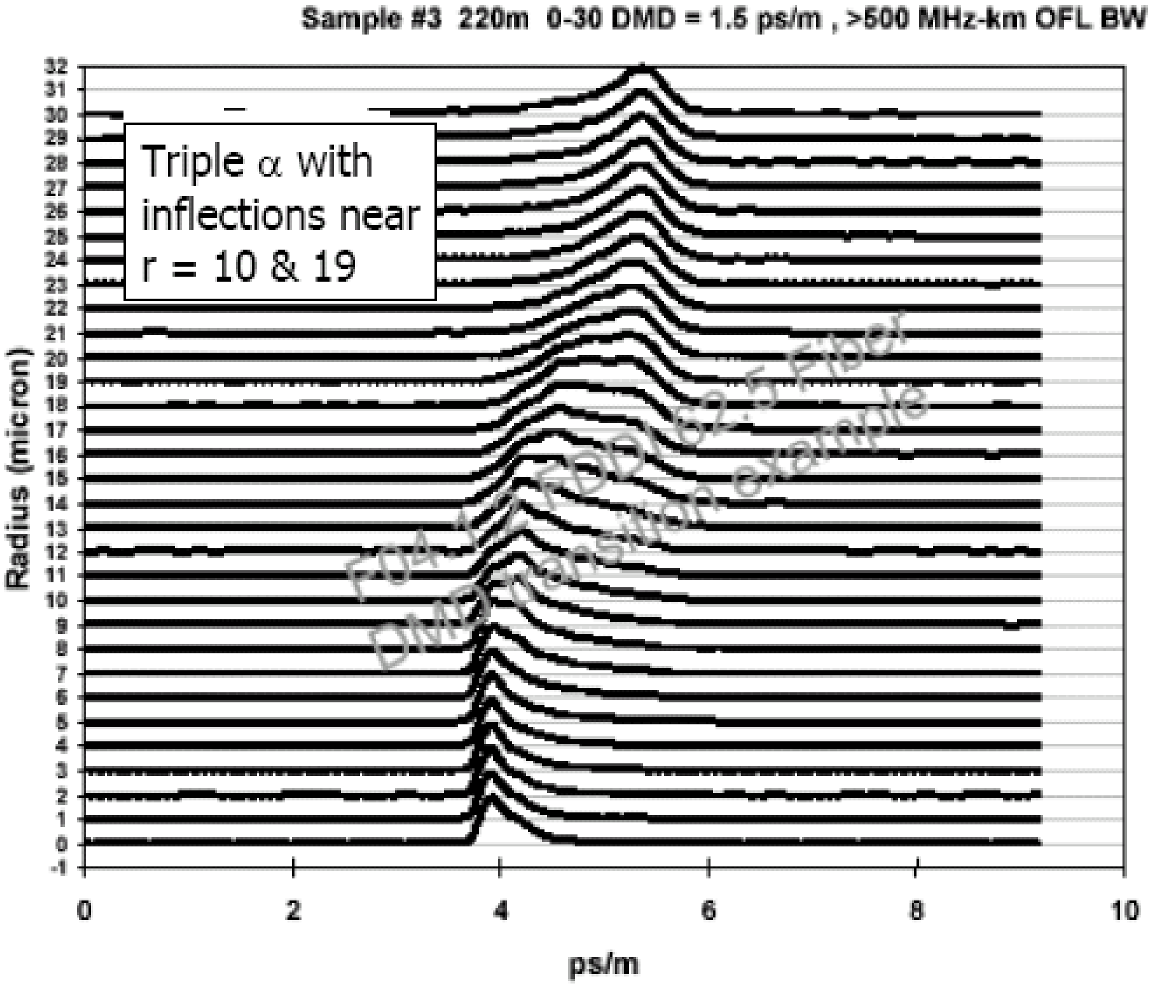
Fiber Characteristics

- Measured data for some FO-4.1.2 fibers plus additional fibers
- Fibers meet 160/500 MHz-km BW criteria, being mostly in lower 5% of installed based distribution between 500 and 550 MHz-km at 1300nm.
- Fibers have DMD clustered between 0.5 ns/km (60th percentile) and 1.7 ns/km (~ 95th percentile).

(DMD is max-min centroid delay)

Fiber	**0-30 um Max-Min CD (ns/km)**	Fiber	**0-30 um Max-Min CD (ns/km)**	Fiber	**0-30 um Max-Min CD (ns/km)**	Fiber	**0-30 um Max-Min CD (ns/km)**	Fiber	**0-30 um Max-Min CD (ns/km)**
1	**1.24**	6	**2.30**	11	**0.99**	16	**1.01**	21	**1.27**
2	**1.15**	7	**1.03**	12	**1.28**	17	**0.58**	22	**0.18**
3	**1.60**	8	**0.94**	13	**0.63**	18	**1.15**		
4	**1.67**	9	**0.83**	14	**0.80**	19	**0.48**		
5	**1.05**	10	**0.81**	15	**1.41**	20	**1.08**		

FO 4.1.2 Sample 3 ---- GaTech F7

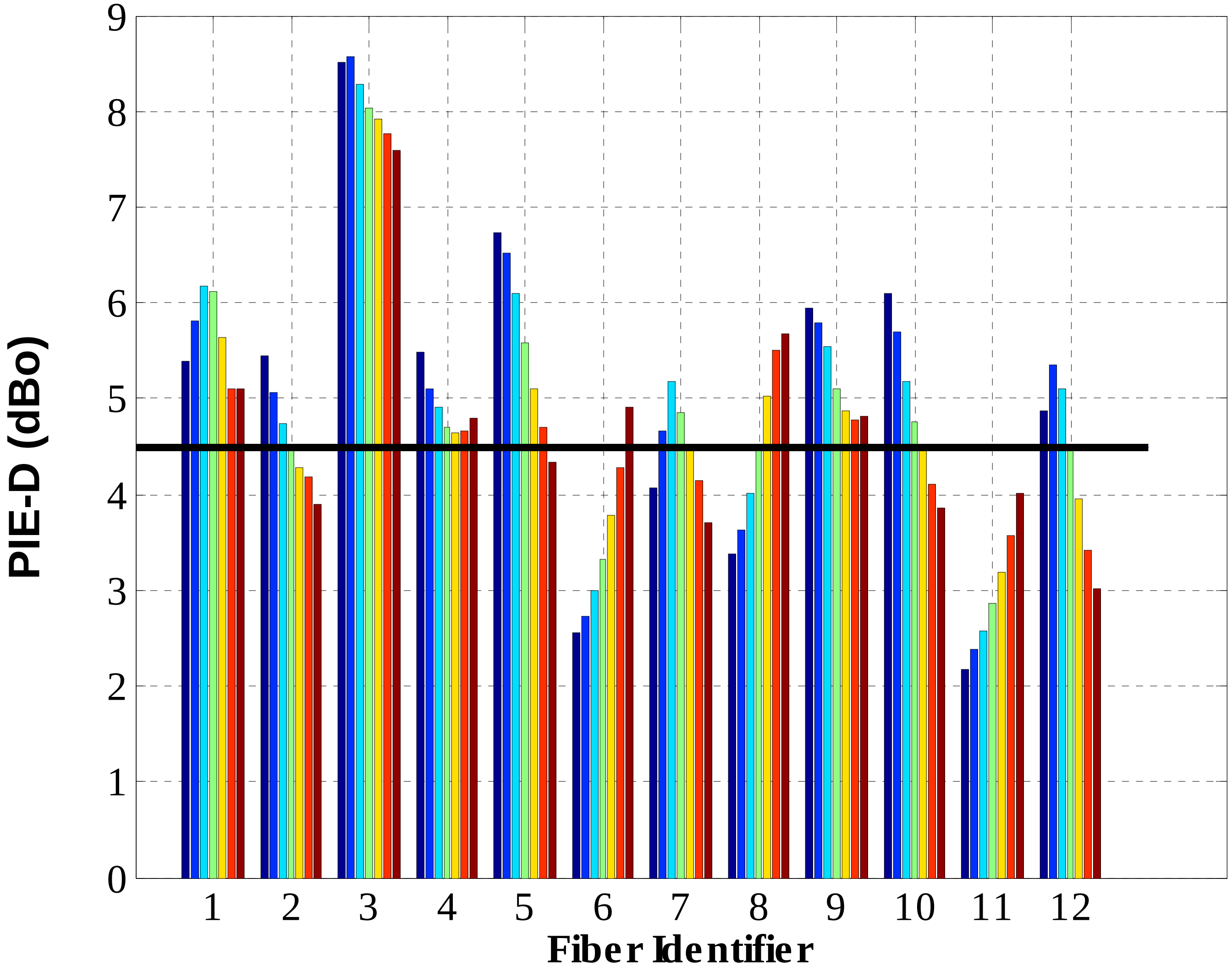


0-18 um MW = 1.52 ps/m
0-23 um MW = 1.50 ps/m
Max-Min CD = 1.03 ps/m

PIE-D for 220m
@17um = 6.89 dB
@20um = 6.11 dB
@22/23um = 5.26 dB

PIE-L for 220m
@17um = 10.56 dB
@20um = 9.04 dB
@22/23um = 7.32 dB

220m PIE-D for FO-4.1.2 and additional fibers



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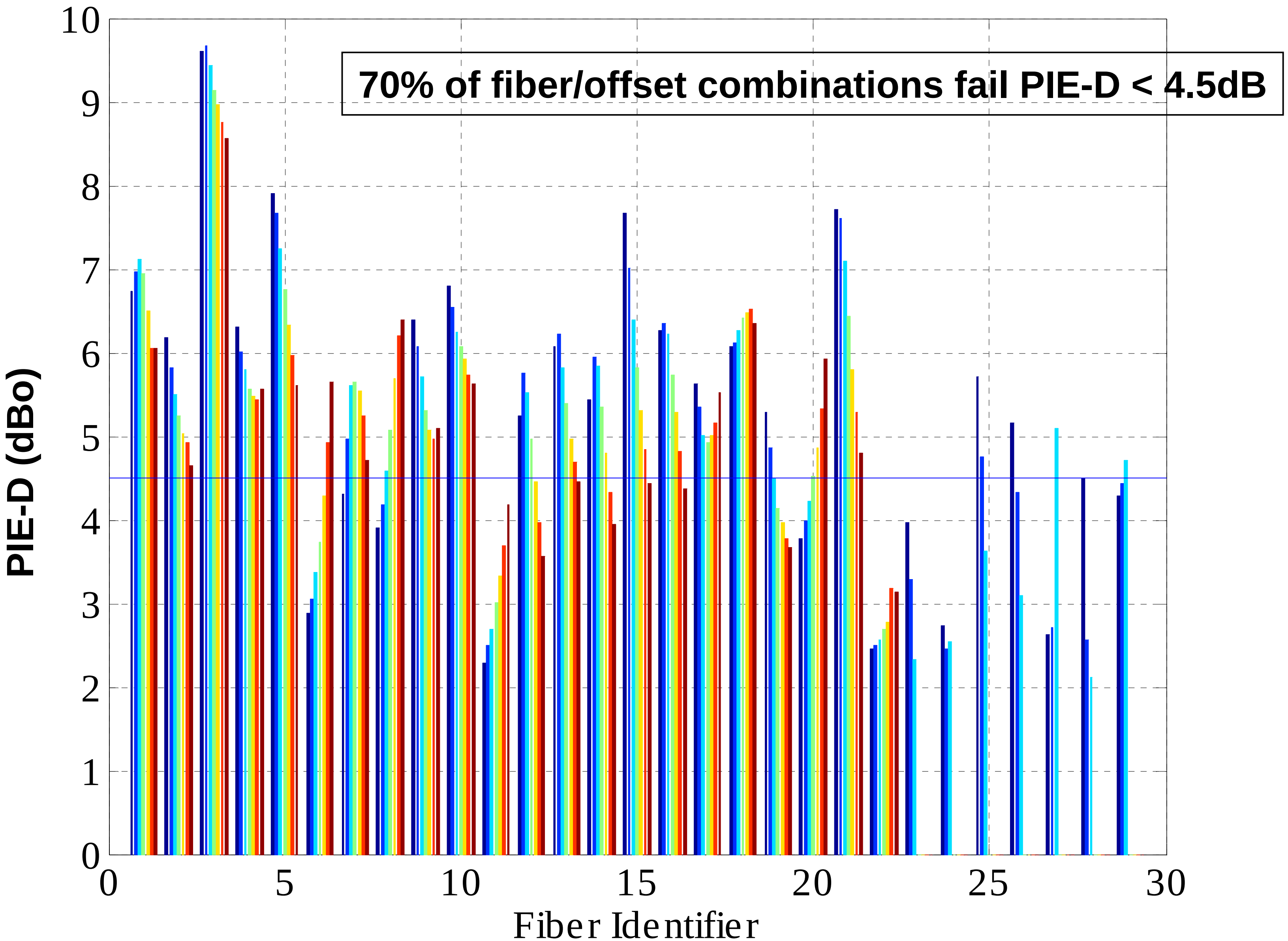
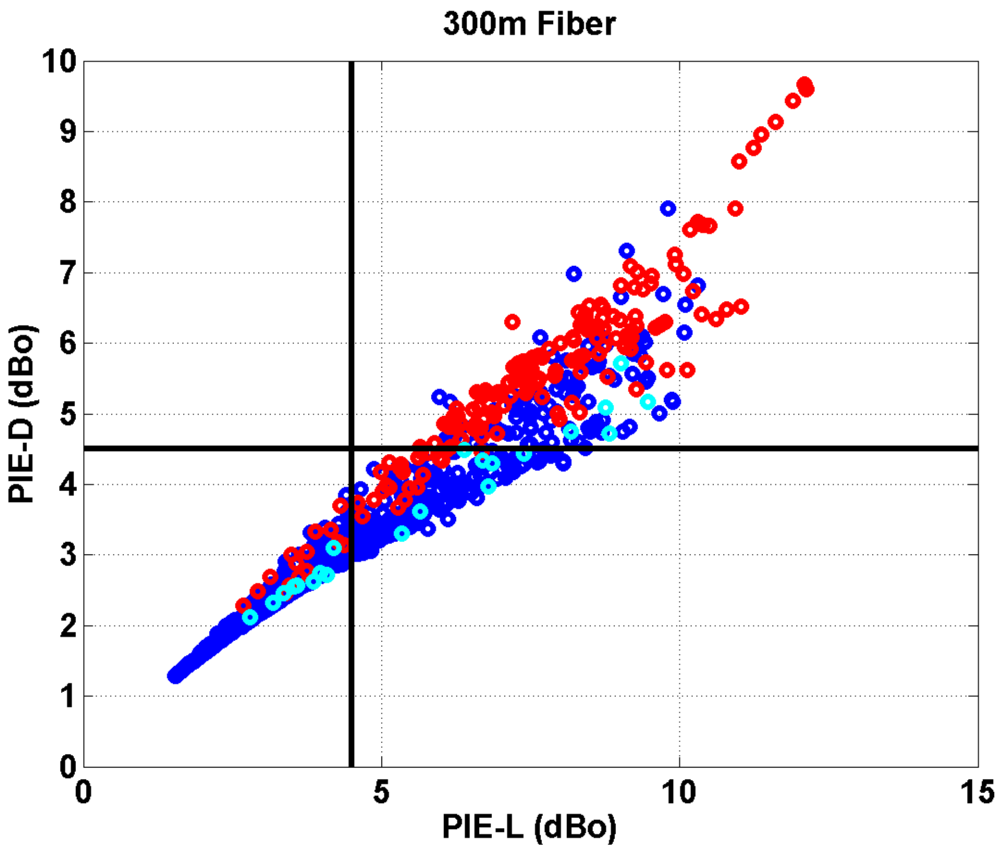
300m PIE-D for FO-4.1.2 and additional fibers



Cambridge and FO-4.1.2 Fibers



- Cambridge DMD ~ 2 ns/km. **FO-4.1.2 real fiber DMD avg is ~1 ns/km**
- FO-4.1.2 fibers exhibit PIE metrics generally larger than the Cambridge set
- FO-4.1.2 fibers are not adequately represented by Cambridge model

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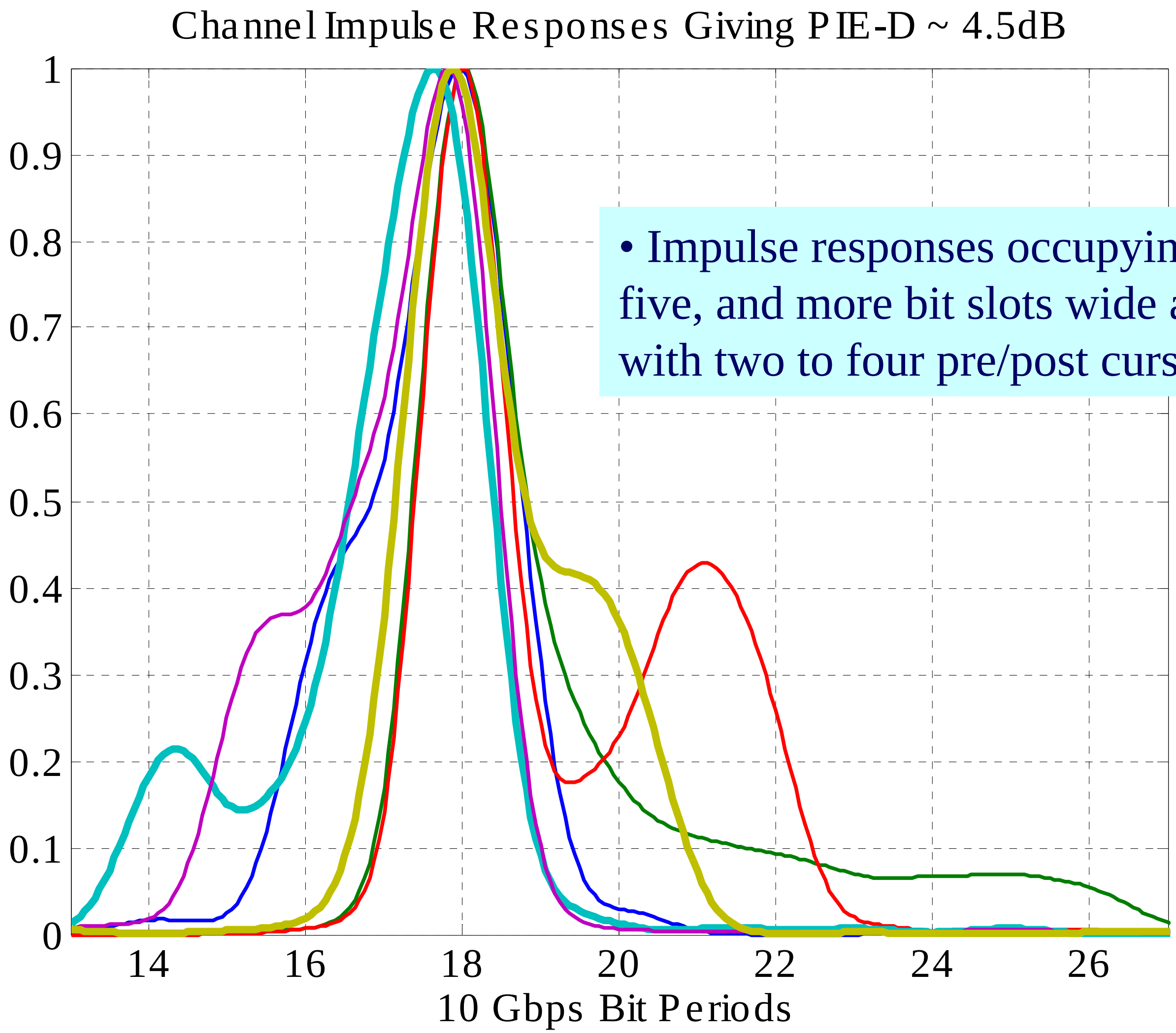
Channel Impulse Responses

Yielding PIE-D ~ 4.5 dB



- Impulse responses occupying three, four, five, and more bit slots wide are evident, with two to four pre/post cursors

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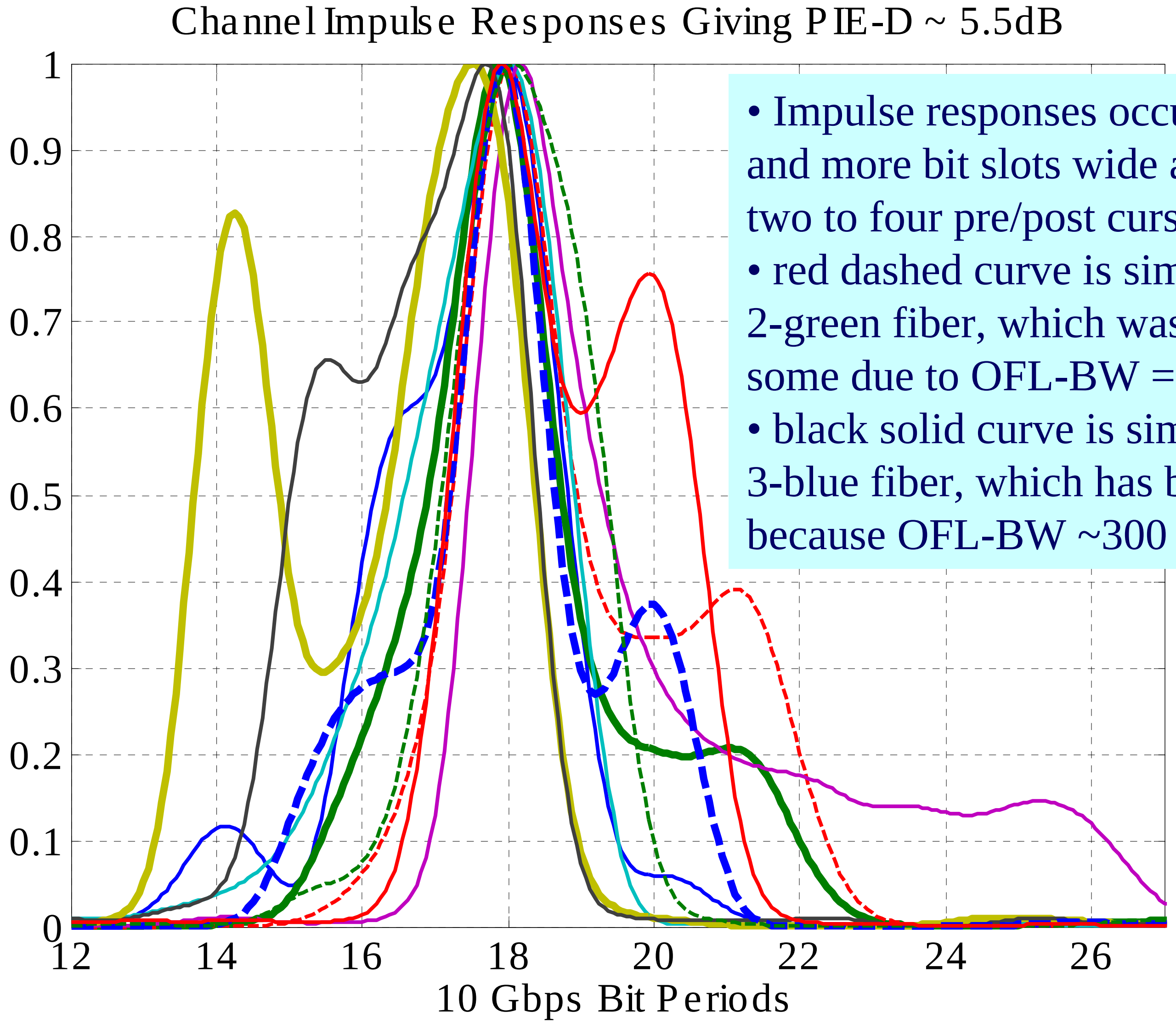
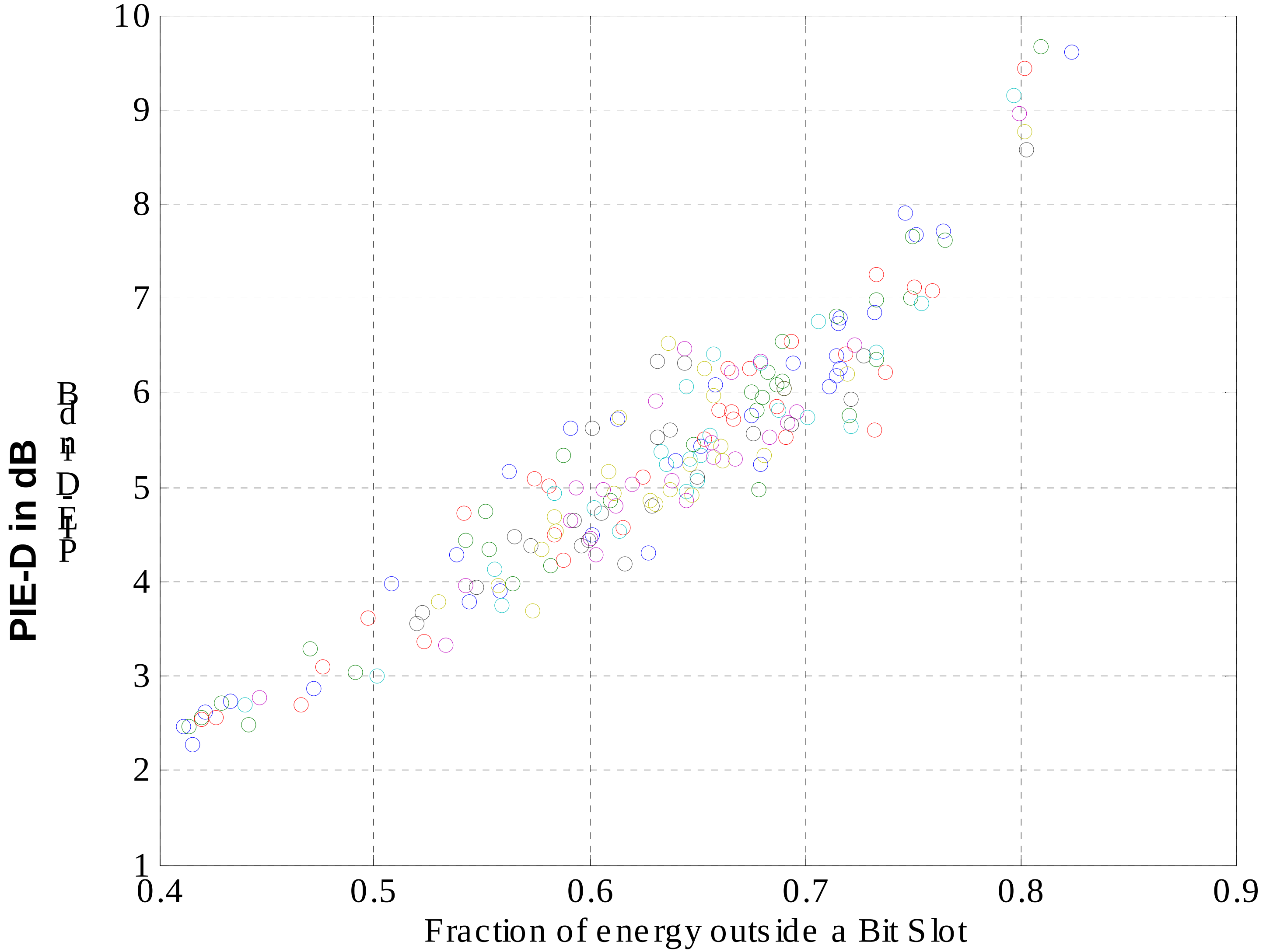
Channel Impulse Responses

Yielding PIE-D = 5.5 dB



- Impulse responses occupying four, five, and more bit slots wide are evident, with two to four pre/post cursors
- red dashed curve is similar to 12-96 cable 2-green fiber, which was dismissed by some due to OFL-BW = 493 MHz-km
- black solid curve is similar to 12-96 cable 3-blue fiber, which has been ignored because OFL-BW ~300 MHz-km

%Energy-Out-of-Bit-Slot is reasonable predictor of PIE-D



Conclusions

- The current use of the 108 fiber model to set pass/fail coverage criteria for EDC is not recommended as it does not account for large PIE sensitivity to small variations in assumptions.
- To counter this variability and use the 108 fibers as pass/fail set, at minimum, a guard band should be added to the power penalty allotted to EDC.
- The 108 fiber model underestimates PIE-D. Using a 2 ns/km basis for fiber models does not translate into 95th (or any) percentile of PIE-D. Real fibers at less than 90th percentile of installed base DMD can readily fail PIE-D.
  - PIE-D 220m: 65/98 > 4.5 dB 16/98>6.0 dB
  - PIE-D 300m: 126/175 > 4.5 dB 56/175>6.0 dB
- The energy outside one bit slot for a given impulse response is a reasonable predictor of PIE-D.
- The energy outside a bit slot at the launch offset can be large, even when fiber DMD is modest.
- The fibers shown give a range of “worst case” impulse responses which can be used to calibrate testing at TP2 and TP3.