Agilent Technologies

UNIVERSITY OF CAMBRIDGE

## Informative Presentation

# More information on statistical modeling of MMF optical fiber links


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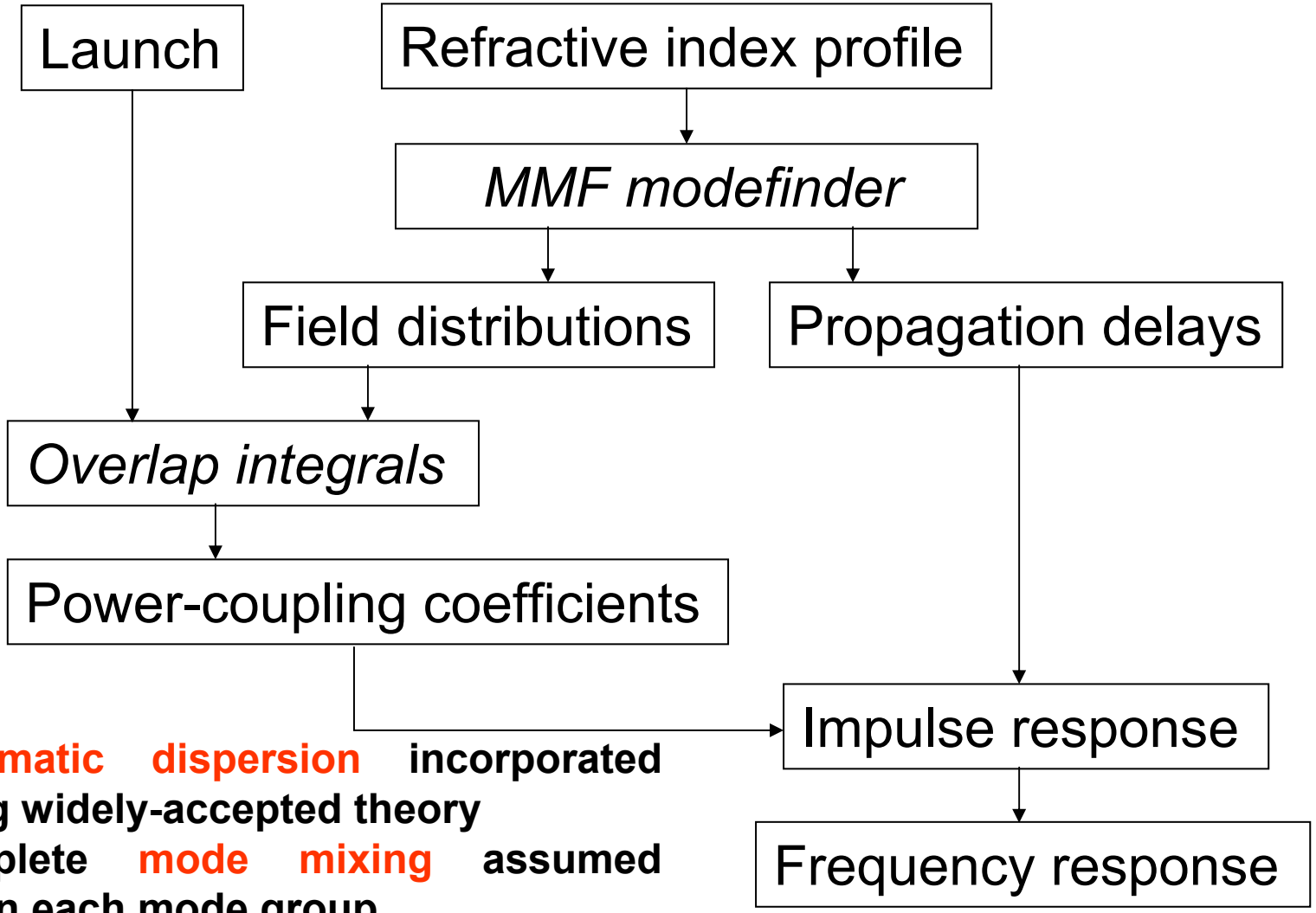
# *Talk outline*

- Overview of the GbE "worst-case" statistical fiber bandwidth model
- Public release of model outputs
- What is the relationship between the scaled DMD and scaled refractive index profiles?
- Is the model accurate?
- How does the statistical approach compare with known measurements?
- Is the use of 2 ns/km mean DMD representative?
- Future actions: what needs still to be done with the model?

# Overview of the GbE “worst-case” MMF statistical model

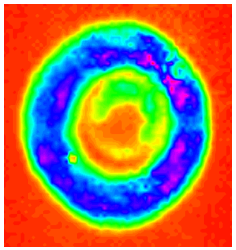
# *MMF model*



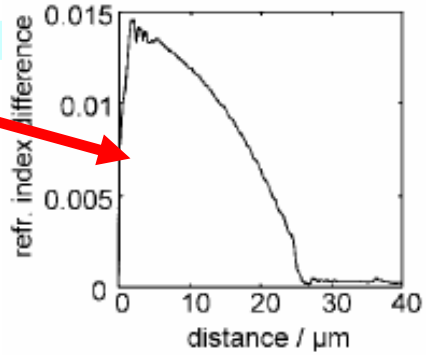

- **Chromatic dispersion incorporated using widely-accepted theory**
- **Complete mode mixing assumed within each mode group**

# *MMF model*

Launch

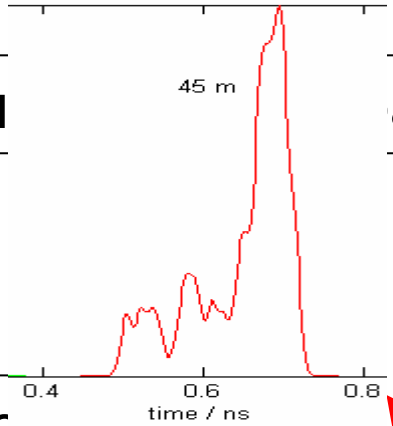


Refractive index profile




*MMF modefinder*

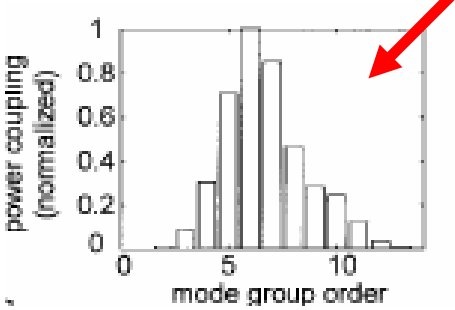
Field distribu




agation delays

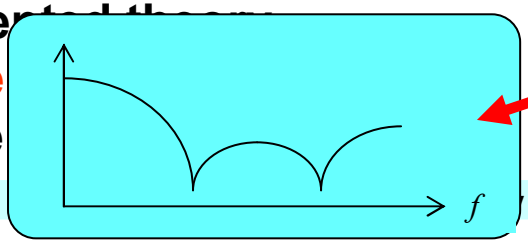
*Overlap integrals*

Power-coupling coefficients




Impulse response

Frequency response




**dispersion incorporated**

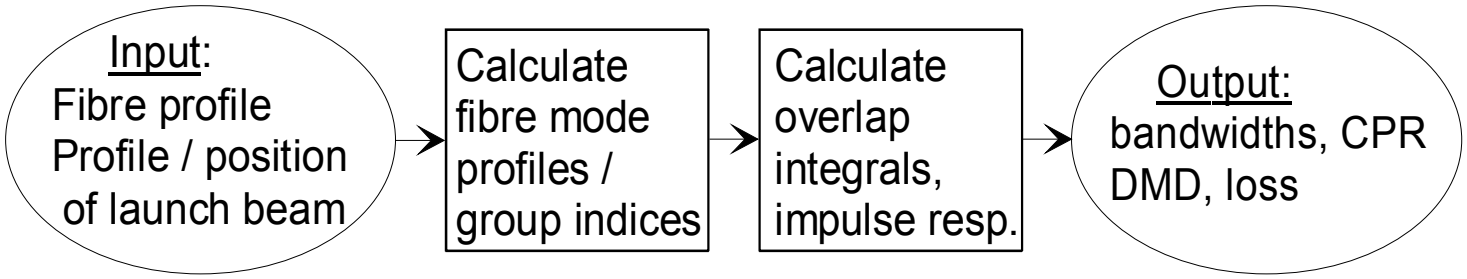
**acce**

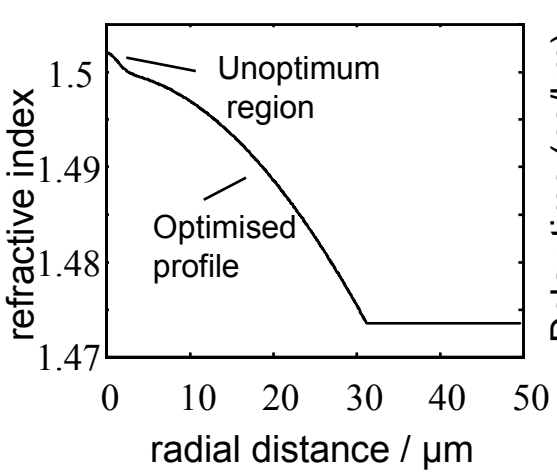
**node**

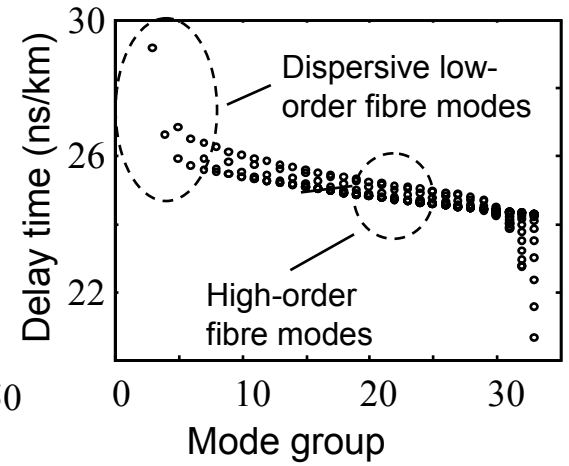
**node**

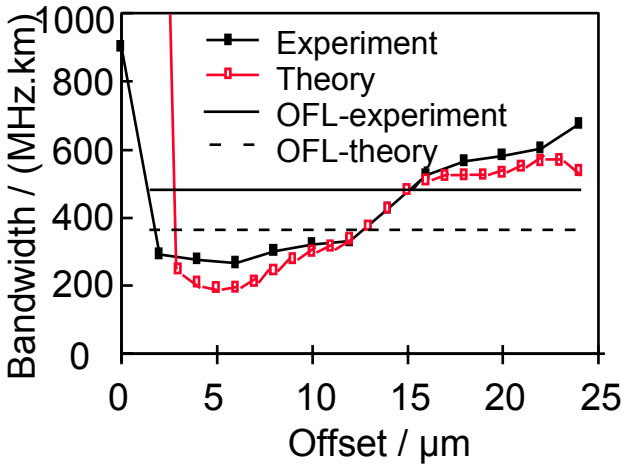
**2004**

# Numerical Modeling of Individual Multimode Fiber



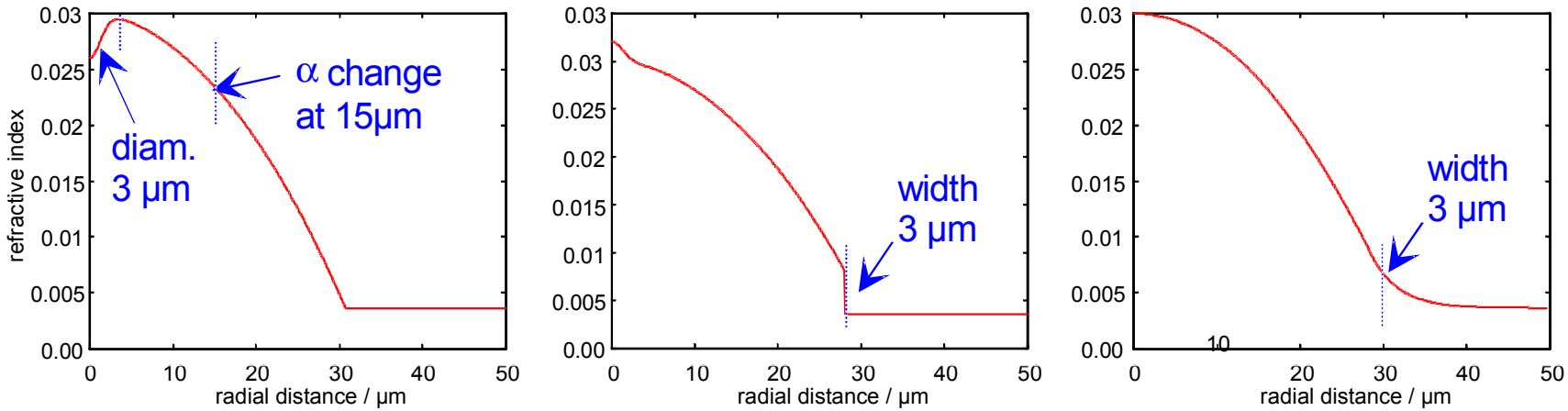




- **Laser Launch conditions determine Mode Power Distribution (MPD) amongst fiber modes**
- **Fibre bandwidth determined by propagation characteristics and the distribution of power amongst fiber modes**

# *Steps in the GbE statistical model*

- Generate a set of representative fiber index profiles
- Calculate OFL frequency response and bandwidth
- Calculate impulse and frequency responses at beam offsets ranging across the entire fiber core radius
- Calculate DMD from assessment of the impulse responses at each offset
- Compare DMD to "worst-case" value, e.g. 5% of installed fibers have DMD > 2 ns/km for 62.5-μm MMF at 1300 nm
- Convert to set of "worst-case" fibers by scaling frequency responses according to ratio of DMD to "worst-case" DMD

# Set of representative fiber index profiles




- **4 different types of perturbation from ideal parabolic index profile**
  - **3 values for the inner profile parameter**
  - **3 values for the outer profile parameter**
  - **3 types of distortions on the fiber axis (peak / dip / none)**
  - **3 types of distortion at the core-cladding interface (sudden / exp decay / none)**

**$3^4$ = 81 representative fibers considered**

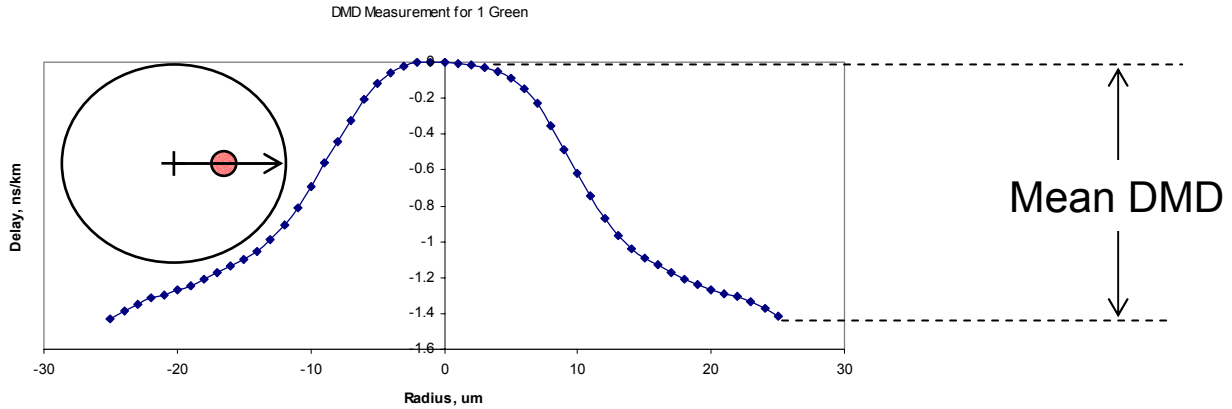
# *Definition of DMD as used in Gigabit Ethernet 81 fiber model*

**DMD**

- Scan a singlemode spot across the core radius.
- Measure the mean delay time as function of the radius.

**Mean DMD**

- In various graphs and for scaling the DMD of the 81 fibres the peak-to-peak value of the DMD curve is used.
- We will call this value the Mean DMD to differentiate it from DMD220 and the peak-to-peak DMD of an ROFL impulse response measurement.




**DMD 220**

- Is defined in TIA FOTP-220

**Peak to Peak DMD**

- Estimated from OFL impulse response (difference between slowest and fastest mode groups as performed in 802.3z field test

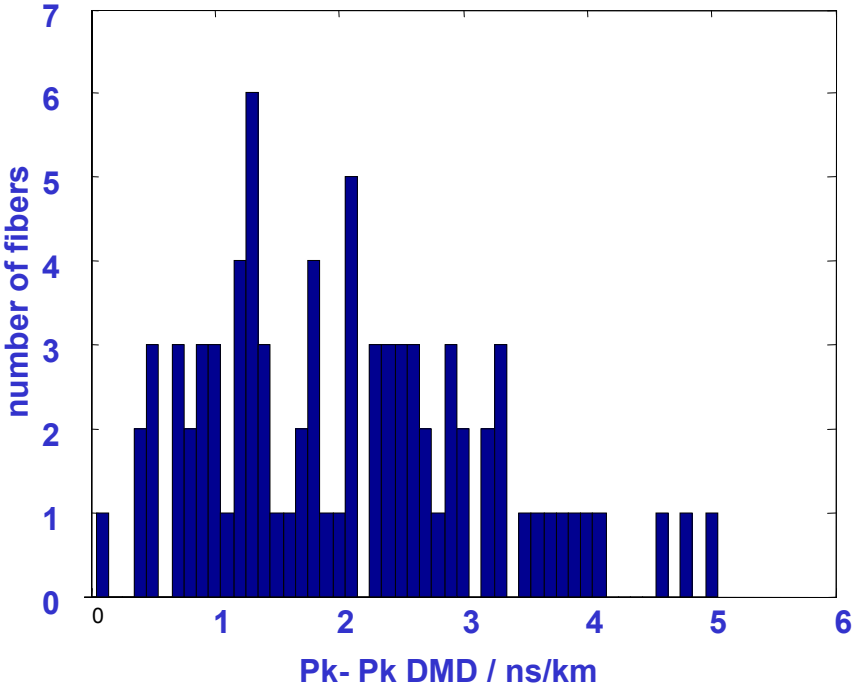
# DMD scaling

- Must ensure that the results are representative of the worst fibers in the field
- DMD is a common parameter to fiber manufacturers

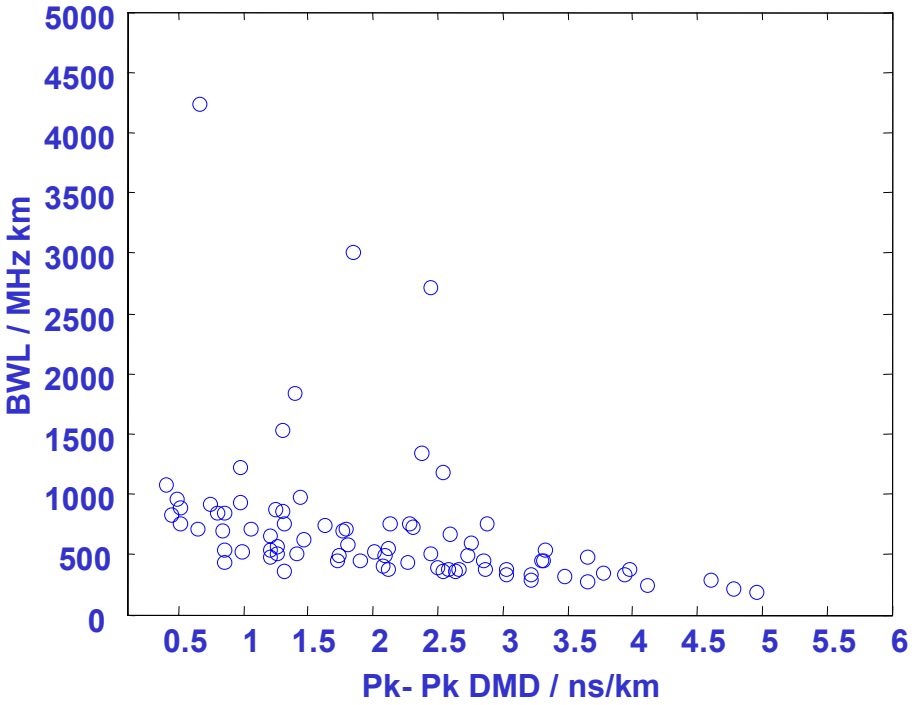
| *2 sigma DMDs* | 50-µm MMF | 62.5-µm MMF |
|---|---|---|
| 1300 nm | 2 ns/km | 2 ns/km |
| 850 nm | 2 ns/km | 4 ns/km |

- DMD numbers provided at time of GbE standardisation – are new numbers available for evolving MMF population?
- Frequency responses, and hence bandwidth, at each offset are scaled by ratio of calculated DMD and worst-case value
- Only those cases with scaled OFL bandwidth conforming to the OFL specification, e.g. 500 MHz.km for 62.5-µm MMF at 1300 nm, are retained in the analysis

# *81 fiber statistical model for LX 62.5 μm :* before the DMD scaling process

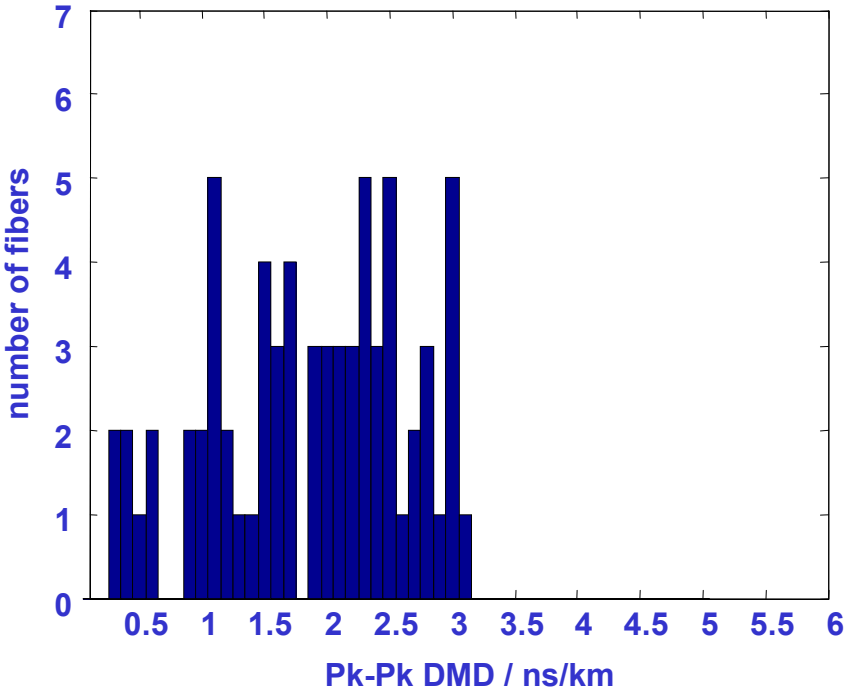



Peak to Peak DMD distribution

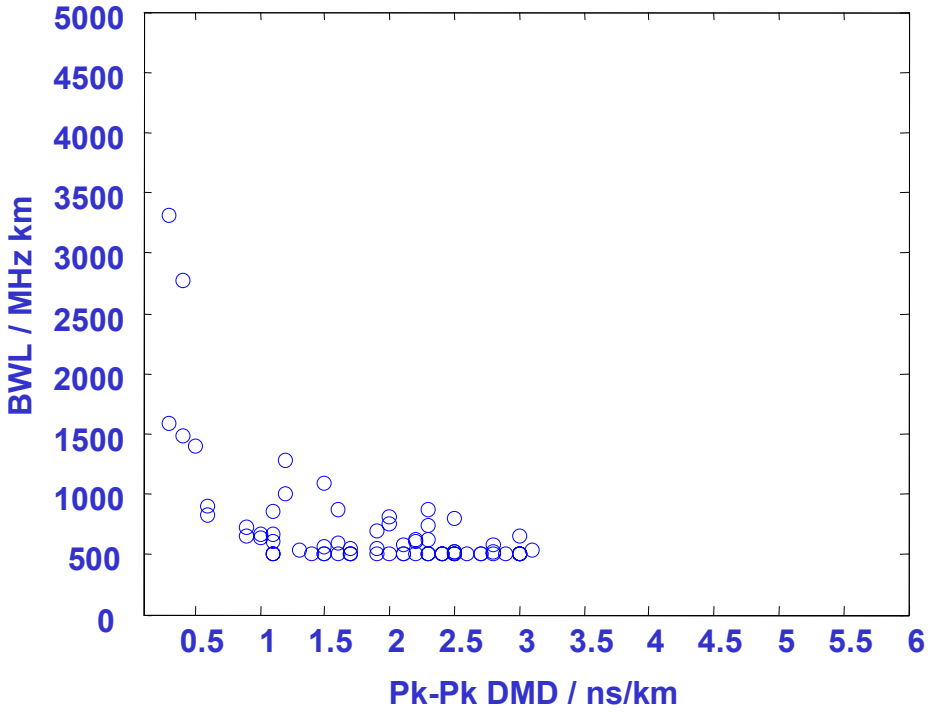



OFL BWL *vs.* Pk-Pk DMD

# *81 fiber statistical model for LX 62.5 μm :* after the DMD scaling process




Scaled Peak to Peak DMD distribution




OFL BWL *vs.* Scaled Pk-Pk DMD

# *How can we justify DMD scaling in the GbE 81 Fiber Model?*

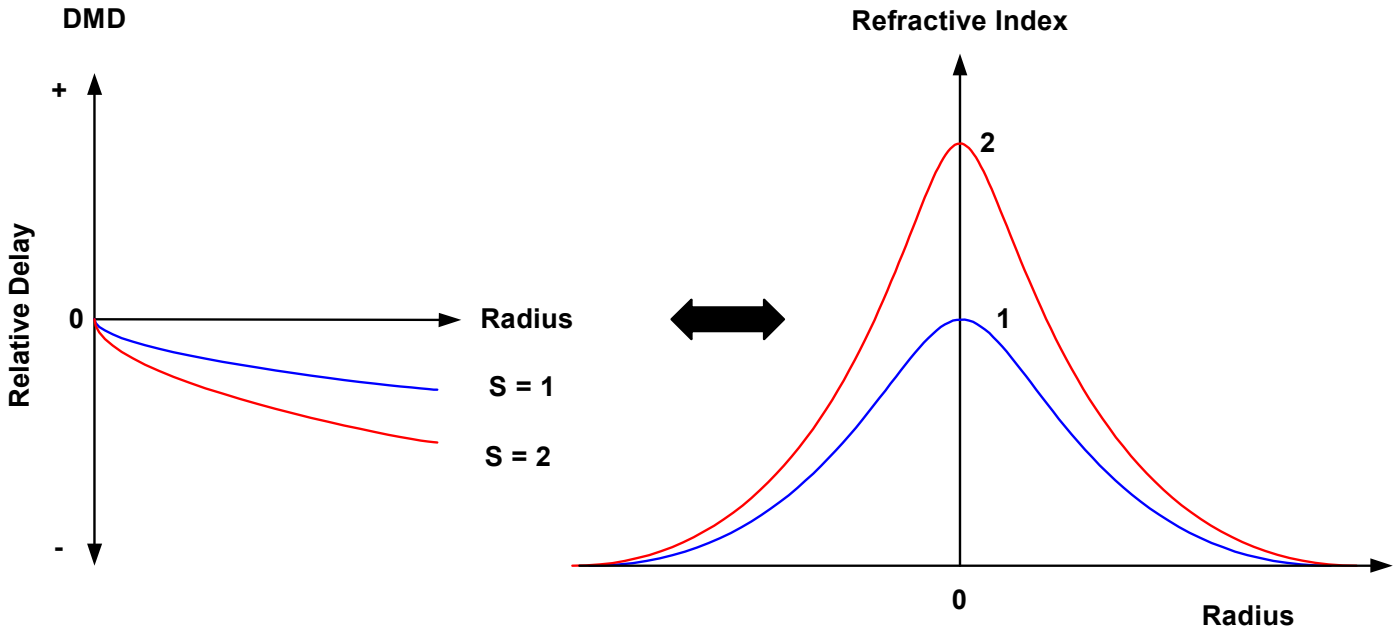
**Let's consider:**

**THE RELATIONSHIP BETWEEN SCALED DMD AND SCALED REFRACTIVE INDEX PROFILES in terms of**

- **Centre and Edge Defects**
- **Power Law Sections**
- **Total Perturbations**

# *Center and edge defects*

**Scaling of the DMD by a factor *S* is equivalent to scaling the center or edge defect by the factor *S*.**



# *Power law sections*

**Scaling of the DMD by a factor of *S* is equivalent to scaling the power law exponent as follows:**

$$g_s \approx S\ (g - g_o) + g_o$$

**where** $g_s$ **is the scaled power law**

$g$ **is the unscaled power law**

$g_o$ **is the optimum power law value**

# *Total Perturbation*

**If the DMD is scaled by, S, then the total perturbation of the refractive index is given by:**

$$\delta n(r) = S\delta n(r)_c + S\delta n(r)_e + \delta n(r)_{gs1} + \delta n(r)_{gs2}$$

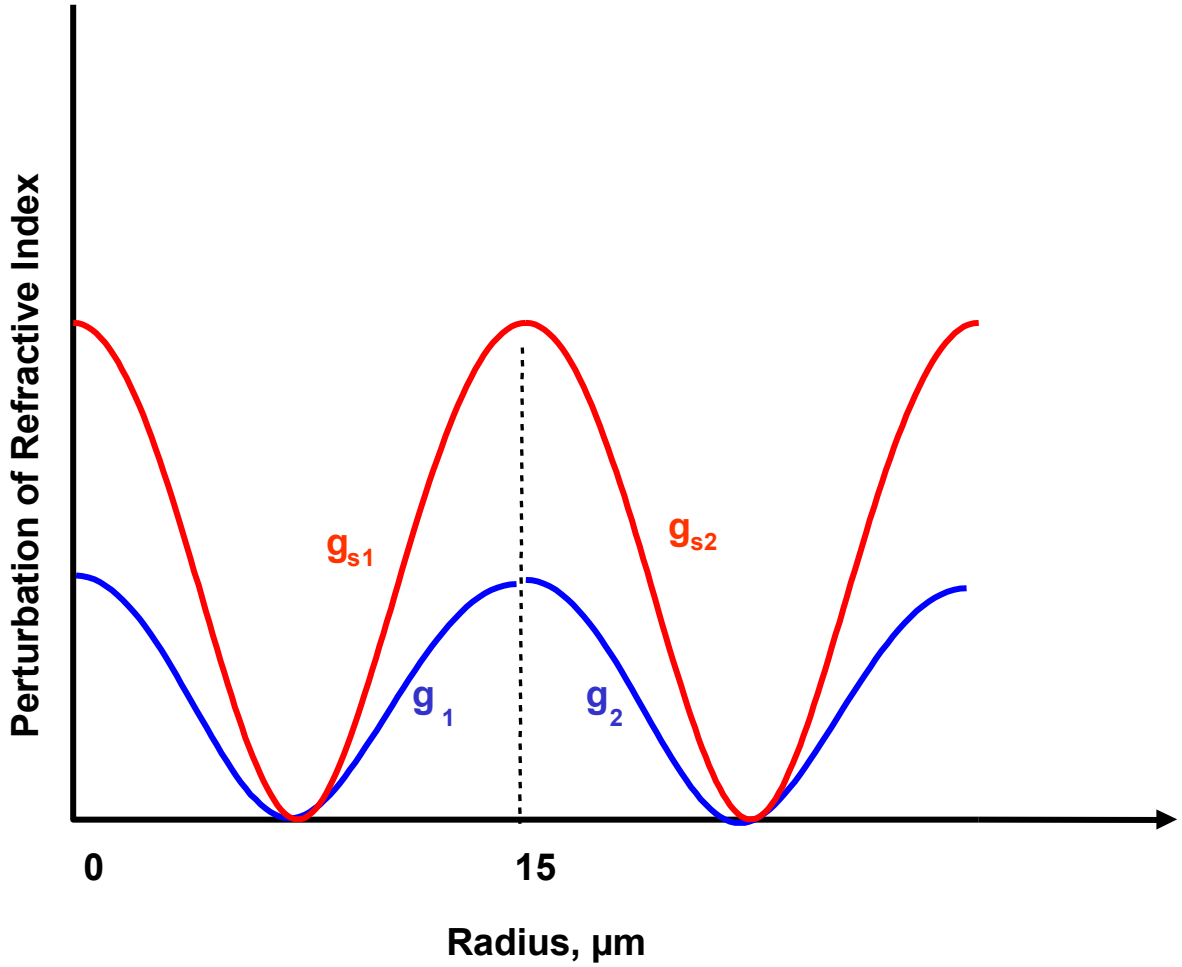
**Where**

$$g_{s1} = S\,(g_1 - g_o) + g_o$$

$$g_{s2} = S\,(g_2 - g_o) + g_o$$

**$g_{si}$ denotes the power law exponent for the scaled profile, $g_i$ denotes the power law exponent for the un-scaled.**

# Sketch of resulting perturbation



# *Public release of model output*

- 1st release made available (from ihw3@cam.ac.uk) modal delays and power coupling coefficients for single mode launch into three offsets
- Later release provides power coupling for 0-30um offsets to enable generation of impulse response for full offset range
- These have been made available to 22 companies involved in IEEE 802.3aq to date

# Construction of impulse response

| LP mode-group order | Relative delay, ns | Relative optical power |
|---|---|---|
| 3 | 0.0000 | 0.00 |
| 4 | 0.0099 | 0.00 |
| 5 | 0.0204 | 0.00 |
| 6 | 0.0318 | 0.00 |
| 7 | 0.0446 | 0.00 |
| 8 | 0.0588 | 0.00 |
| 9 | 0.0744 | 0.00 |
| 10 | 0.0887 | 0.01 |
| 11 | 0.0993 | 0.02 |
| 12 | 0.1077 | 0.04 |
| 13 | 0.1149 | 0.07 |
| 14 | 0.1276 | 0.10 |
| 15 | 0.1483 | 0.14 |
| 16 | 0.1869 | 0.16 |
| 17 | 0.2726 | 0.16 |
| 18 | 0.4048 | 0.13 |
| 19 | 0.6408 | 0.09 |
| 20 | 0.8971 | 0.05 |
| 21 | 1.2199 | 0.02 |
| 22 | 1.3205 | 0.01 |
| 23 | 0.9981 | 0.00 |

Impulse responses are constructed by creating tables of relative delay time and relative optical power for:

- a given fiber and,
- a given offset.

This example is for fibre number 53 and offset 24 µm.

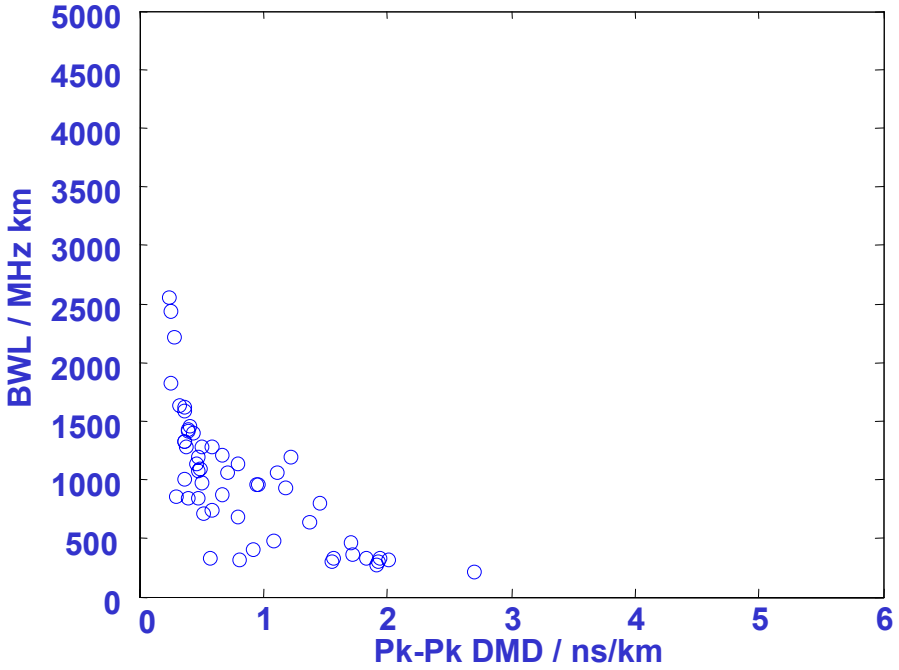
- Used for DMD calculations later

# *Have we any further evidence that the 81 fiber distribution is representative?*

- GbE deployment has reported no problems for offset launch
- Useful to check against measured samples
- To verify 81 fiber profiles are representative we have compared them with the IEEE 802.3z MBI field test data

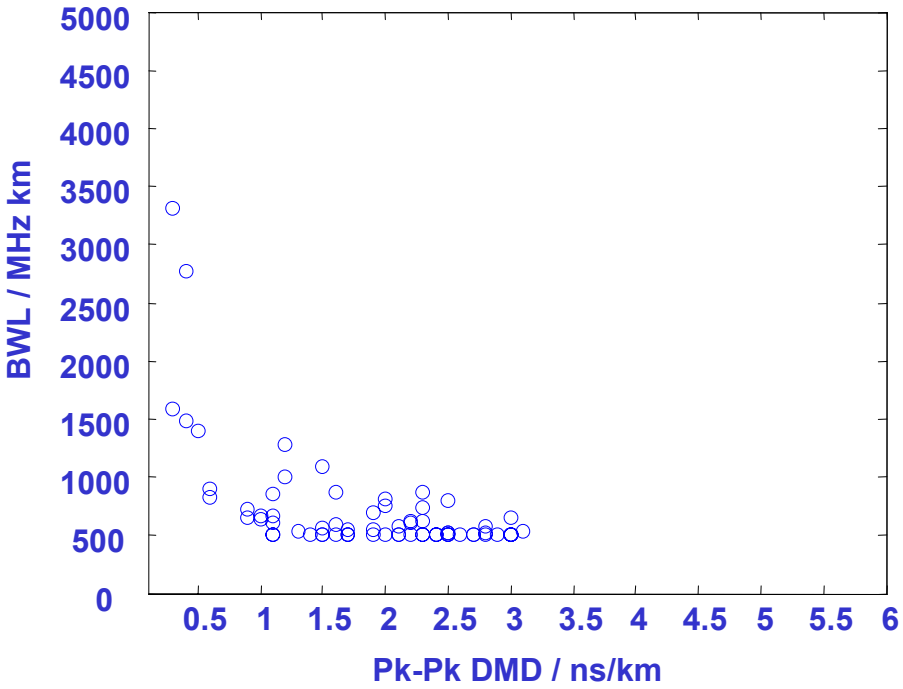
# *IEEE 802.3z MBI field test vs. 81 fiber statistical model*

IEEE 802.3z MBI field test




OFL BWL *vs.* Pk-Pk DMD

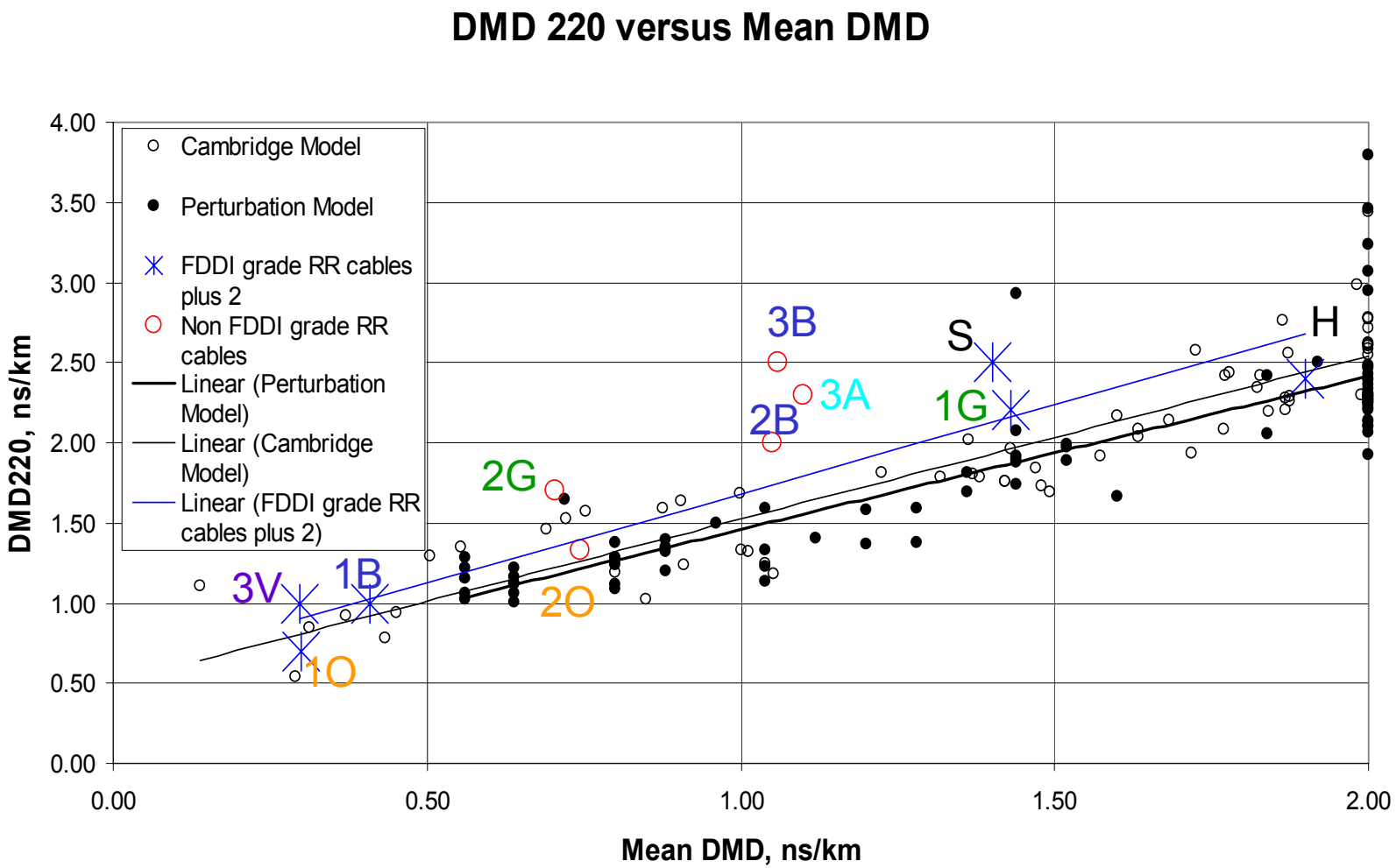
81 fiber statistical model




OFL BWL *vs.* Pk-Pk DMD
*After DMD scaling process*

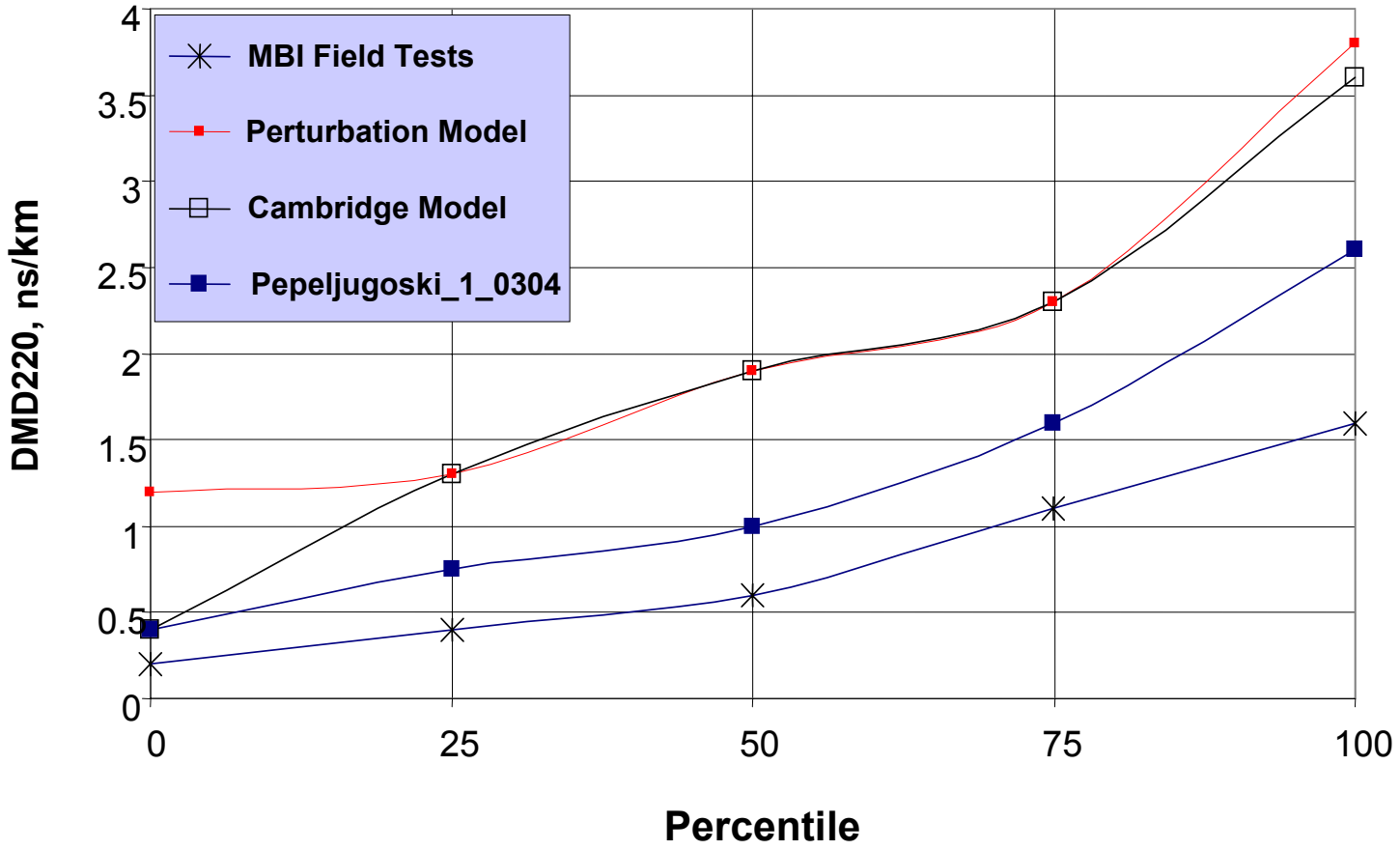
- Consistent statistics for MBI population and 81 fiber model
- Conclusion: 81 fiber model representative of “worst case” installed base fiber population

# *Comparison of Cambridge model, an independently implemented Perturbation model and measured fibers*




**Strong correlation between measurements and theory**

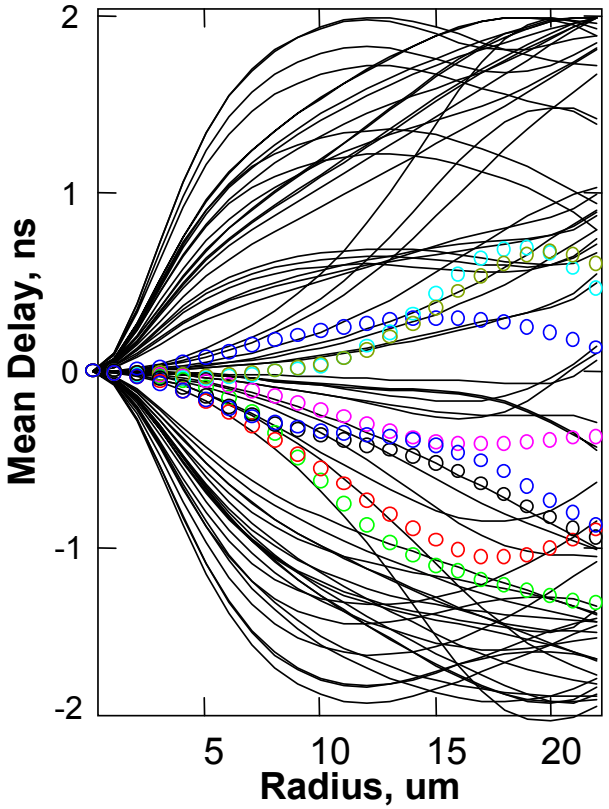
# Comparison of theoretical and experimental DMD distributions for FDDI-grade fibers



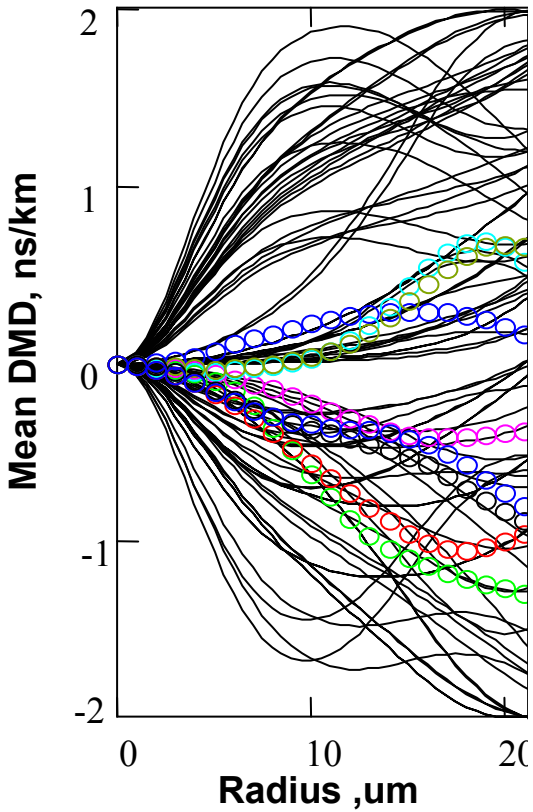

***The Cambridge model appears to include worst-case distributions observed to date elsewhere, and hence seems sufficiently rigorous***

# Comparison of DMD for Cambridge & Perturbation models with experimental fibers

**Cambridge Model, 65 Fibres**




**Perturbation Model**




- In the perturbation model no fibers were removed.
- All 81 fibers were scaled to 500 MHz.km
- Measured DMD's for some RR fibers are also plotted

# Conclusions

- GbE statistical “worst-case” model reviewed
- There is a simple one-to-one mapping between the unscaled and scaled refractive index profiles for the DMD scaling method of the Gigabit Ethernet 81 fiber model
- Cambridge model results and conclusions confirmed to be accurate by comparison with an independently implemented perturbation model
- Statistical 81 fiber model compared with IEEE 802.3z MBI field trial fibers and various round robin fibers:
  - Good agreement in terms of DMD and bandwidth distributions between the two fiber populations
  - 81 fibers are therefore representative of “worst case” field fibers

# *Future work*

- OM3 has not been modeled using this approach – should this be addressed?
- Current public release describes spot launch for wide range of offsets
  - 65 fibers x 31 offsets = 2015 responses
- Long fiber lengths are not necessarily more difficult to equalise than shorter ones
  - Modelling over length should be carried out
- The model can be used to study different launch conditions
  - Should more results be released?
  - *But* trade off between flexibility and complexity
- Currently is static model – doesn't cover time varying channel responses