DEPARTMENT OF ENGINEERING

UNIVERSITY OF CAMBRIDGE

Extension of Statistical Multimode Fiber Channel Model to Electronic Dispersion Compensation

J. D. Ingham, R. V. Penty and I. H. White

University of Cambridge, Department of Engineering
Trumpington Street, Cambridge, CB2 1PZ, United Kingdom
rvp11@eng.cam.ac.uk

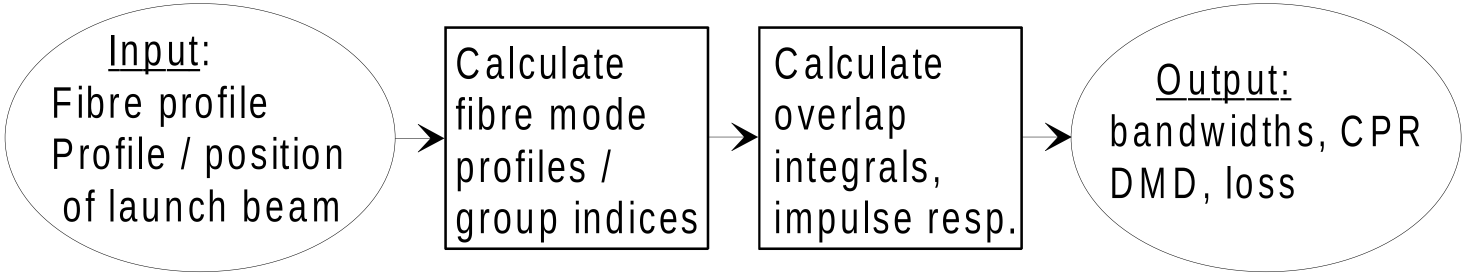
Talk outline

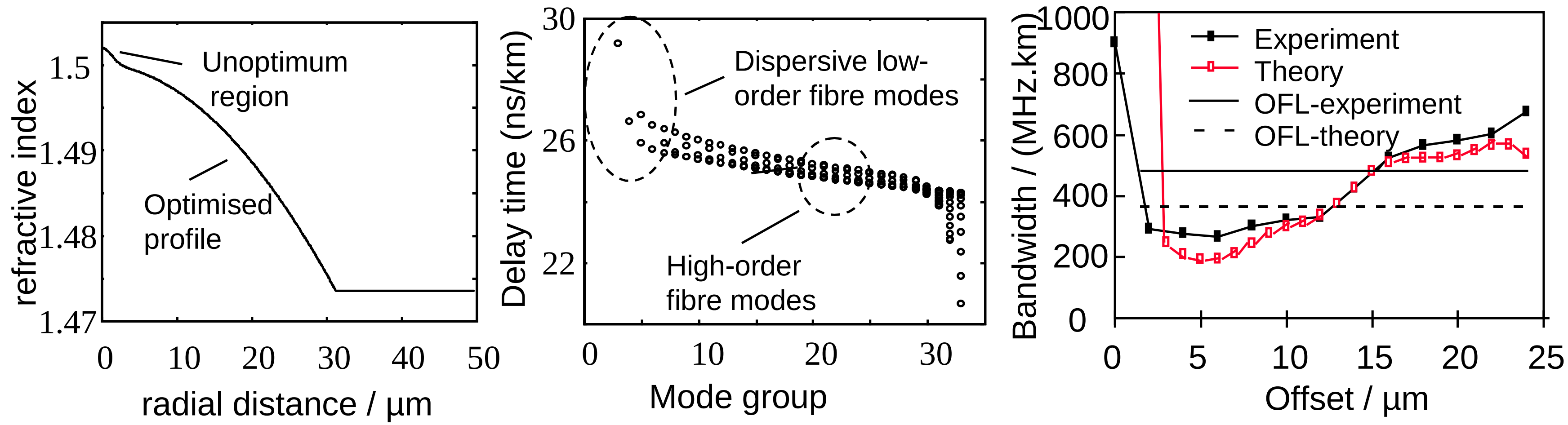
- Brief review of statistical MMF channel model
- Extension of model to EDC
  - Model verification for EDC
- Types of EDC studied
- Link yield as function of
  - EDC type
  - Fiber launch
  - Link length
- Conclusions

Brief Review of Statistical MMF Model

see Cambridge channel modeling talk for detail

Multimode Fiber Numerical Modeling





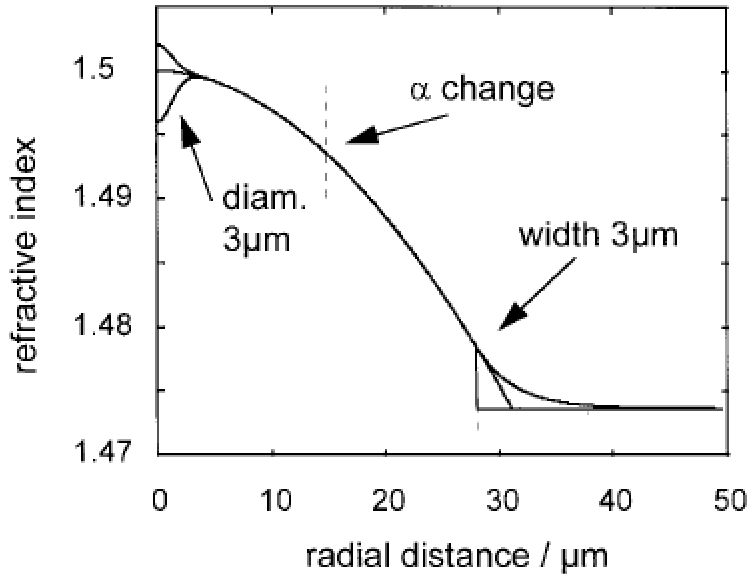
- **Laser Launch conditions determine Mode Power Distribution (MPD) amongst fiber modes**

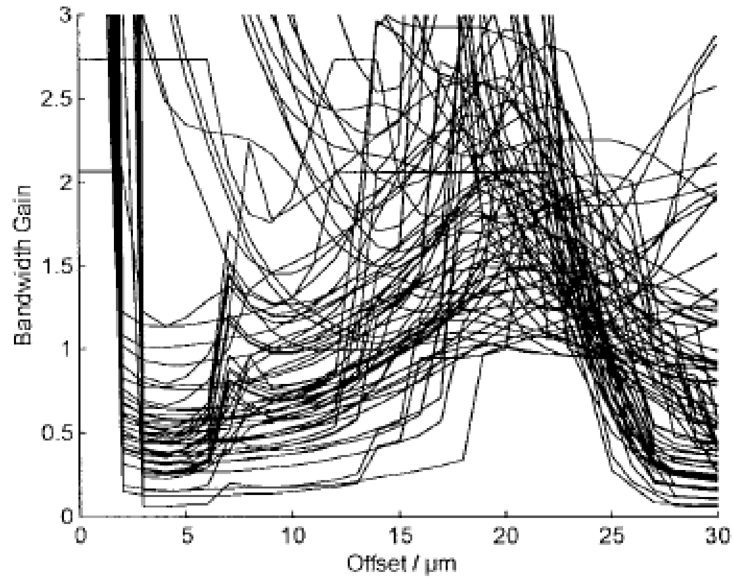
- **Fibre bandwidth determined by propagation characteristics and the distribution of power amongst fiber modes**

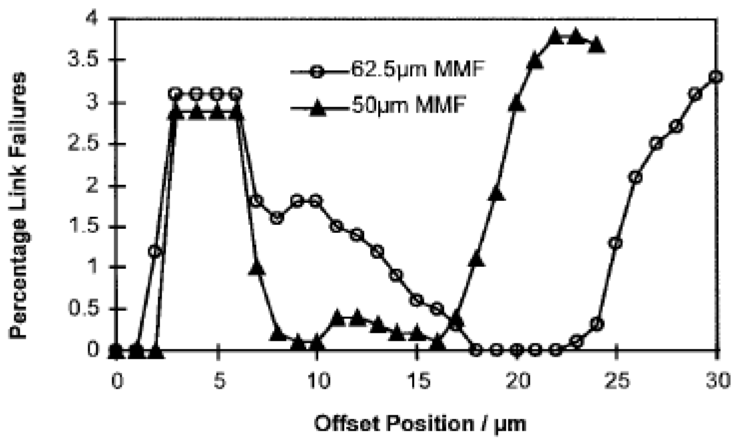
Steps in the GbE statistical model

- **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**

Statistical MMF Bandwidth Simulations





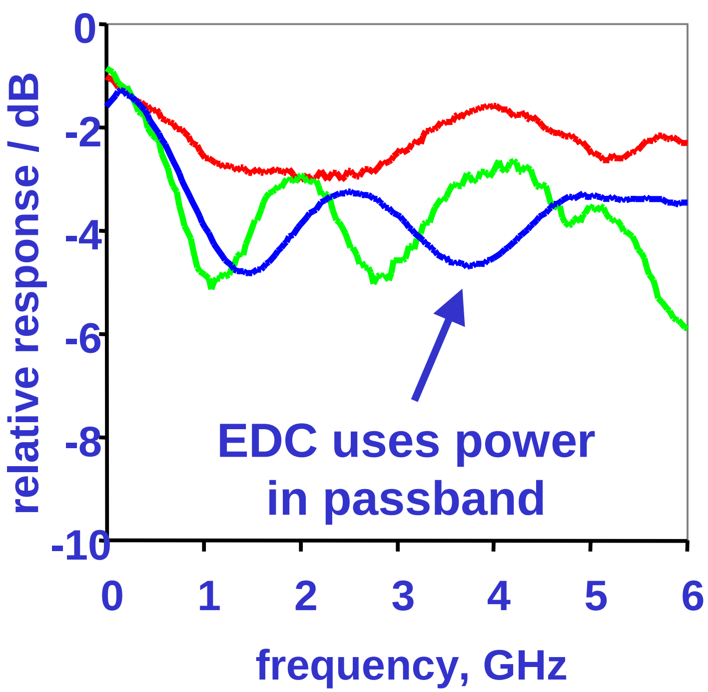


- **81 fiber profiles chosen**
- **DMD scaled to 2ns/km for each profile (worst case 5% population)**
- **Bandwidths calculated using mode profile and group indices**
- **Statistical scaling allows yield calculation**

M. Webster, L. Raddatz, I. H. White, D. G. Cunningham, "A statistical analysis of conditioned launch for Gigabit Ethernet links using multimode fiber," *Journal of Lightwave Technology*, vol. 17, no. 9, pp. 1532-1541, 1999

Initial results for 10GbE EDC

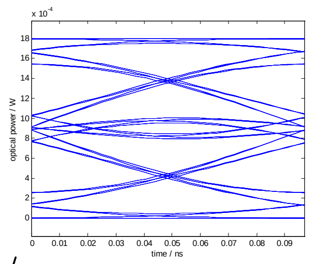
Considerations relating to the extension of model to EDC

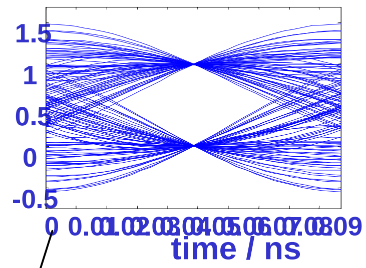


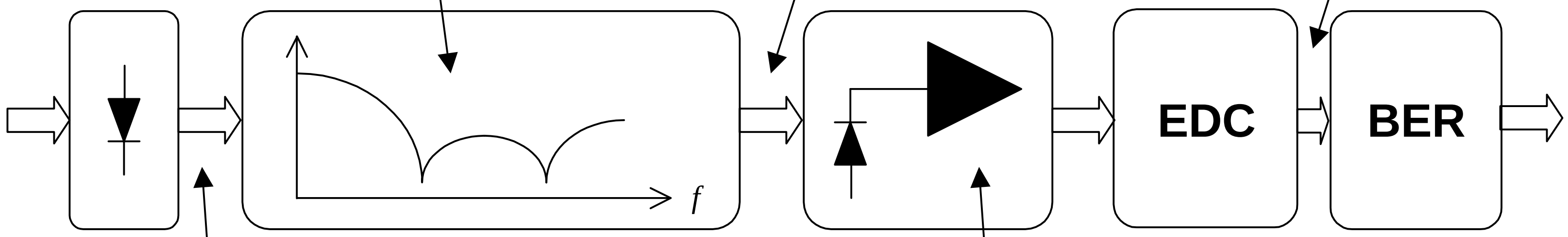
- **At GbE, the statistical model is used to extract MMF bandwidths.**
- **In an unequalized link, there is a strong inverse correlation between ISI penalty and bandwidth**
- **With EDC, knowledge of the bandwidth is not sufficient - the entire MMF link frequency response determines link performance**
- **Use calculated frequency response to determine link response to PRBS**
- **Noise can also be incorporated into the BER calculation determine BERs and penalties**
- **Easy to add different EDCs in the Rx (time or frequency domain)**

Steps in the extended model

MMF frequency response extracted from GbE model and scaled to desired link length – includes chromatic dispersion







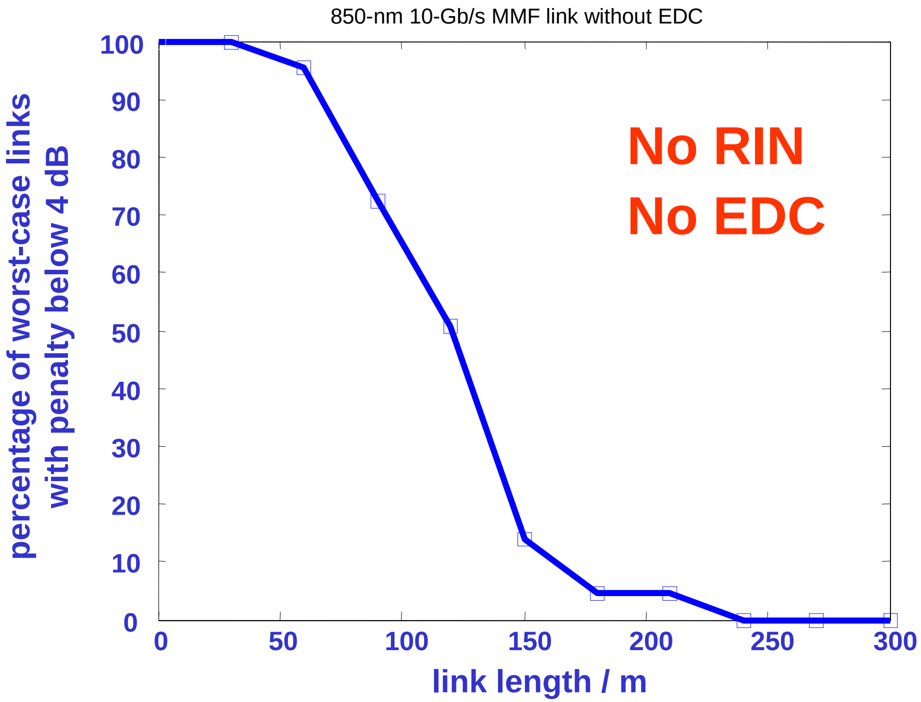
Penalties

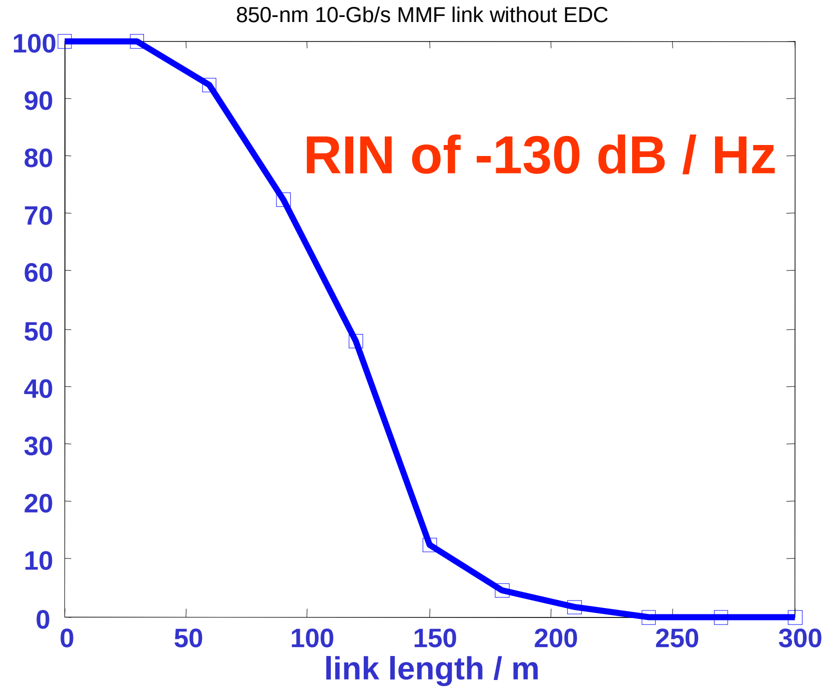
Laser output modeled by PRBS waveform which is low-pass filtered to ensure appropriate rise and fall times

PINTIA thermal noise modeled in conjunction with low-pass filter.
Other noise sources, e.g. RIN, accounted for at this point

Inclusion of Noise into System Model

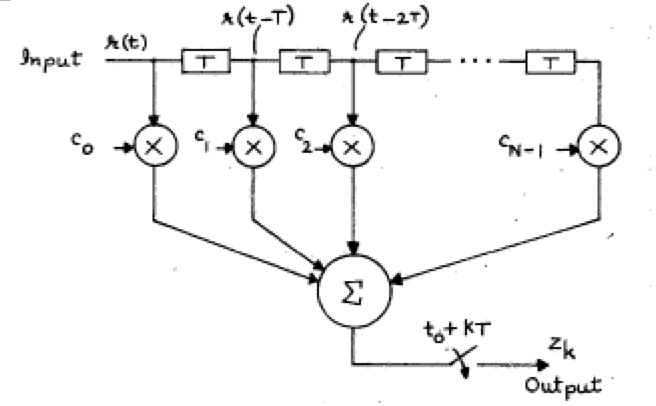
- Important consideration due to the potential for noise enhancement effects in some EDC architectures
- Noise sources considered: receiver thermal noise & RIN



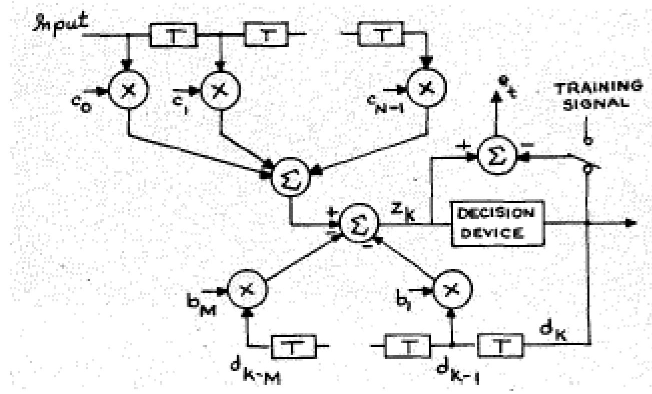


- Additional penalties due to RIN found to be in line with 10 GbE spreadsheet calculations

Types of EDC



Feedforward equalizer (FFE)

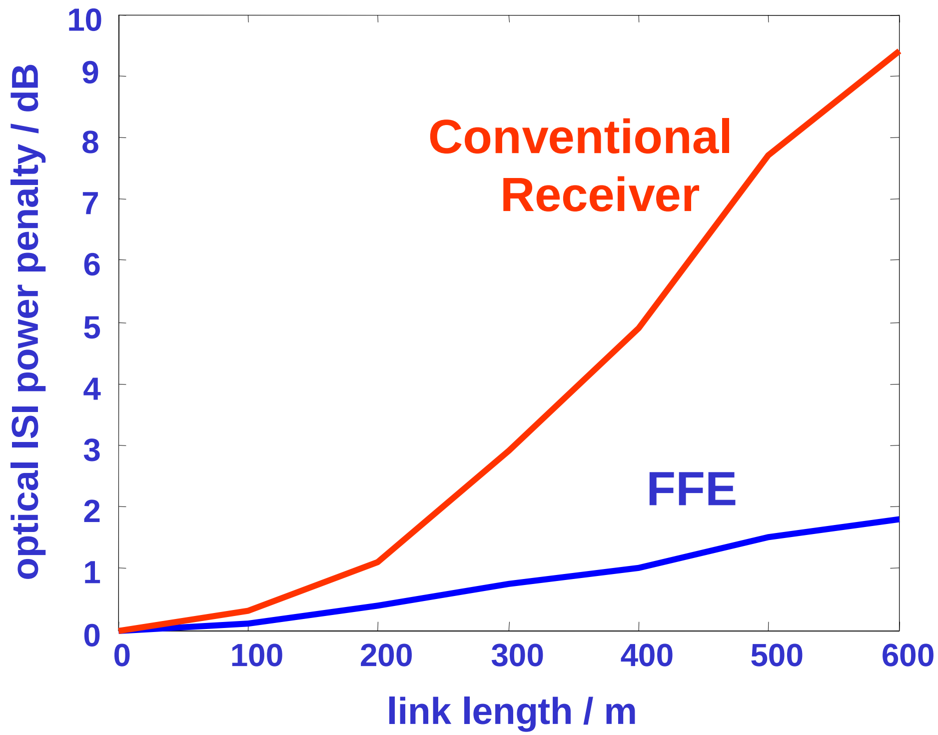


Decision-feedback equalizer (DFE)

For each of the two EDC types, we have considered:

- ***Unconstrained-complexity equalization*** **to determine upper bounds on performance**
- ***Constrained-complexity equalization*** **to determine what may be realistically expected of an implementation.**
    - **FFE is modeled by an N-tap transversal filter which tap coefficients according to the MMSE criterion.**
    - **DFE is modeled by an N-tap MMSE transversal filter followed by M bits of decision feedback**

FFE bound with next-generation MMF



- **10 Gb/s at 850 nm over 50-μm 2000 MHz.km MMF**
- **IBM (OFC 2003): 7-tap transversal filter reduced ISI penalty by 8.8 dB from 11 dB to 2.2 dB over 600 m of next-generation fiber**
- **Simulations agree with IBM results**

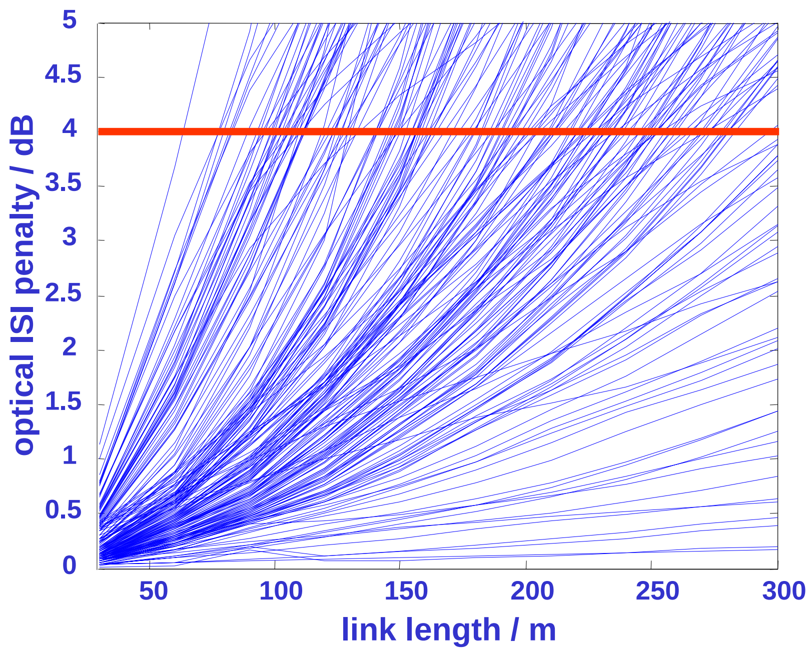
P. Pepeljugoski et al. "Improved performance of 10 Gb/s multimode fiber optic links using equalization," *Proc. OFC 2003*, vol. 2, pp. 472-474

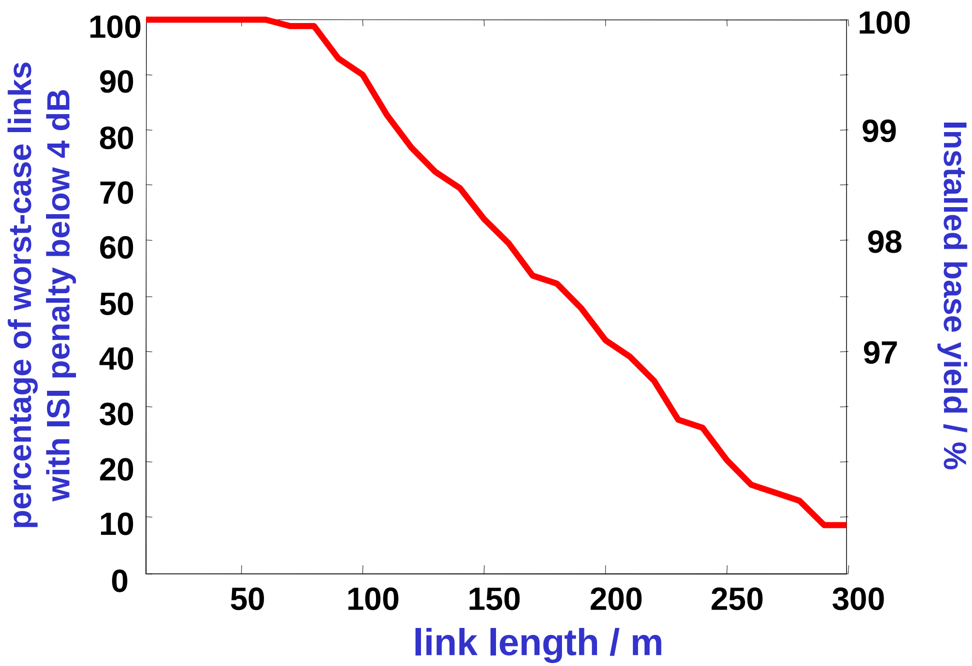
IS

1300-nm 62.5 μm 500-MHz.km MMF – Model Parameter Set

Transmitter	
Transmit pulse rise time	0.2 UI
Laser center wavelength	1300 nm
Laser RMS spectral width	0.1 nm
Laser RIN	-130 dB / Hz
Fiber Launch	
Launch spot	7 μm FWHM Gaussian
Offset launch conditions	20 μm +/- 3 μm
Fiber Properties	
Fiber DMD for scaling process	2 ns/km
Fiber chromatic dispersion	10 ps/(nm.km)
Fiber length	30 m to 300 m
Receiver Properties	
Photodetector responsivity	0.9 A/W
TIA input-referred noise current	1.1 μA
TIA bandwidth	7.5 GHz

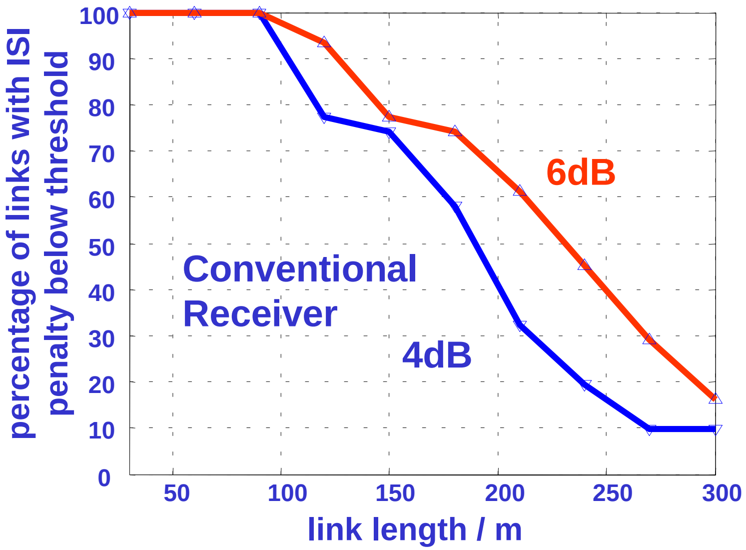
1300nm 10G Transmission Without EDC – Using 81 Fiber Model with 20 μm ± 3 μ m offset launch

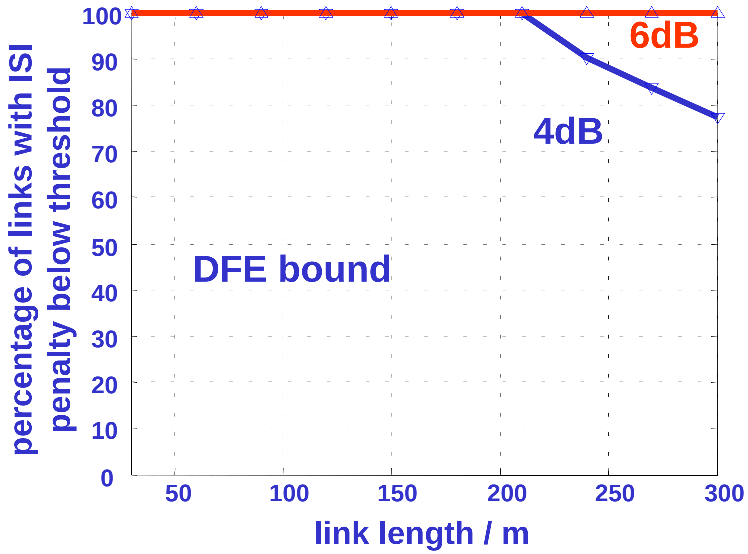


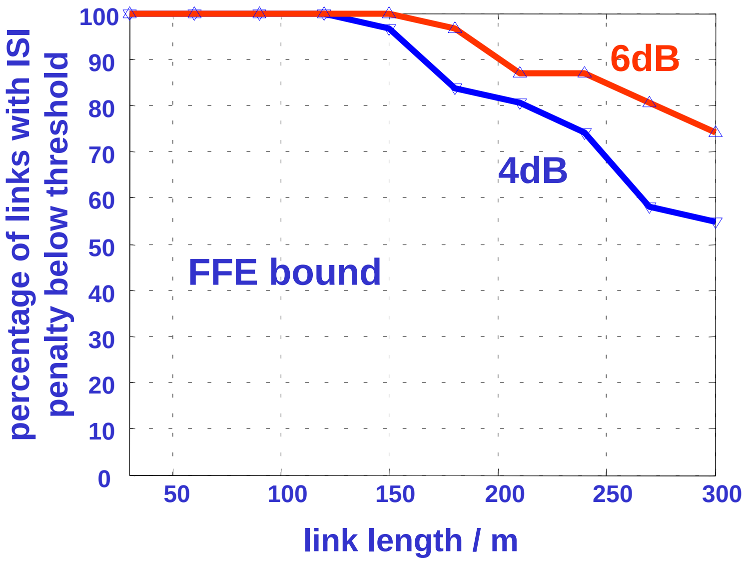


- RH Graph shows pass% of “81 fibre” links with <4dB ISI penalty
- Since these represent worst 5% of installed fibers, it is possible to extrapolate to installed fiber link failure for 4dB penalty
- Installed fiber base yield (%) = (95+100-pass yield/20)
- Valid for pass % > 50% (ie installed base yield >97.5%)

IEEE 802.3z MBI field test: *yields for FFE and DFE bounds*





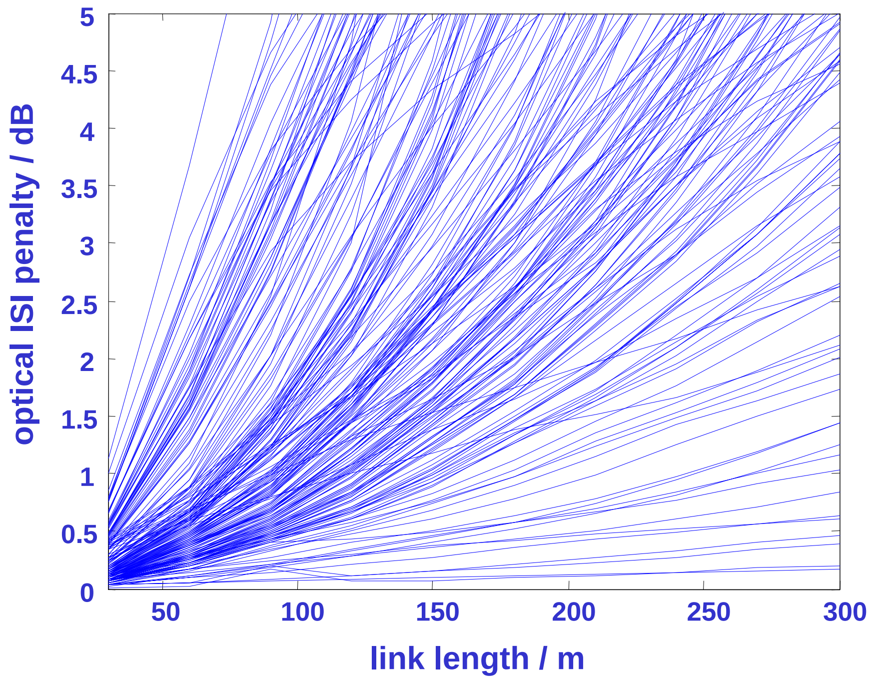


- **ROFL (1.0dB)**
- **Calculated frequency responses scaled to lengths from 0 to 300 m**
- **Links failing the 500 MHz km specification are not included**

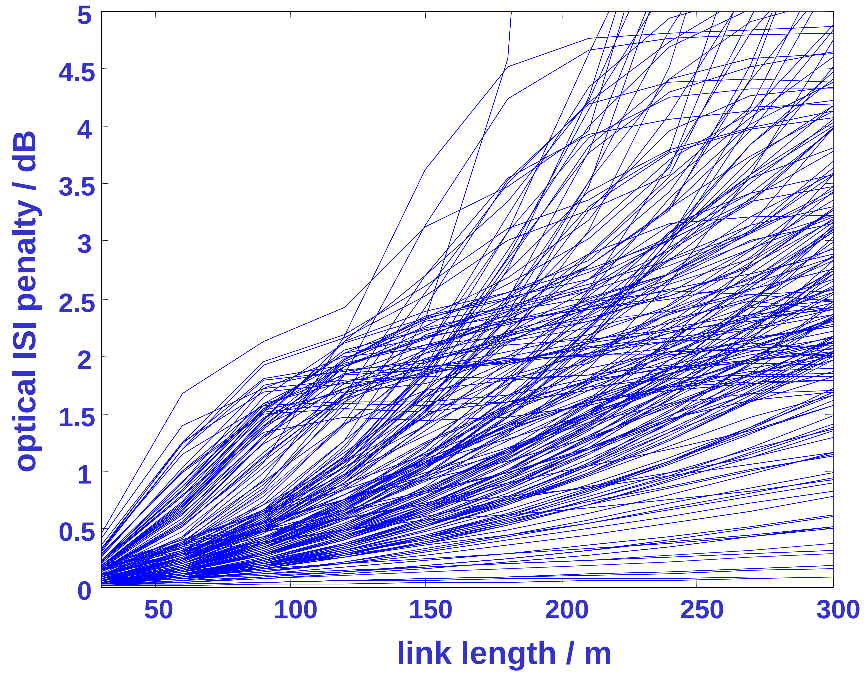
1300-nm 62.5-μm 500-MHz.km MMF - Unequalized & FFE bound

- **Optical ISI power penalty vs. link length**

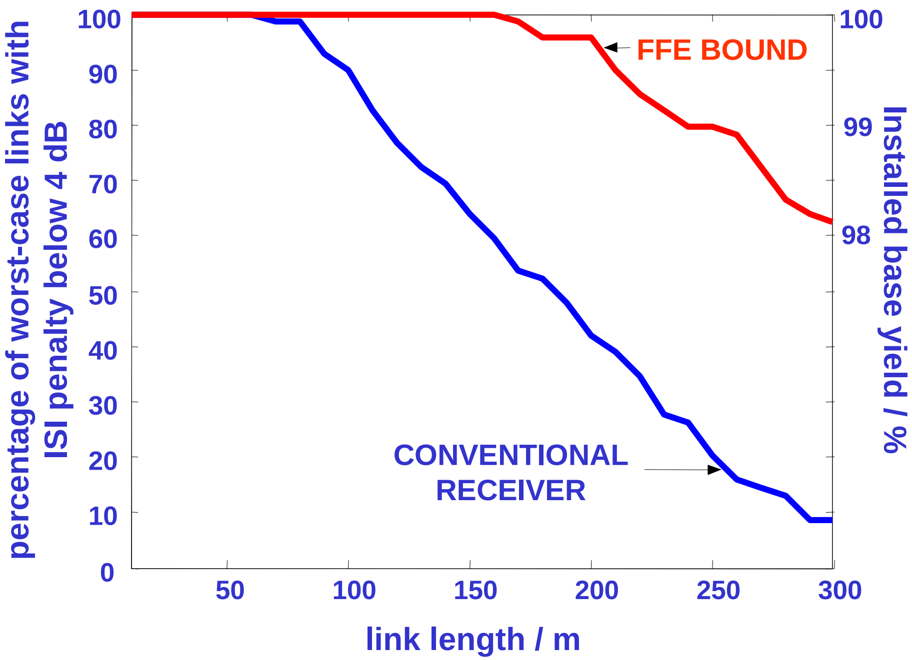
Conventional Receiver

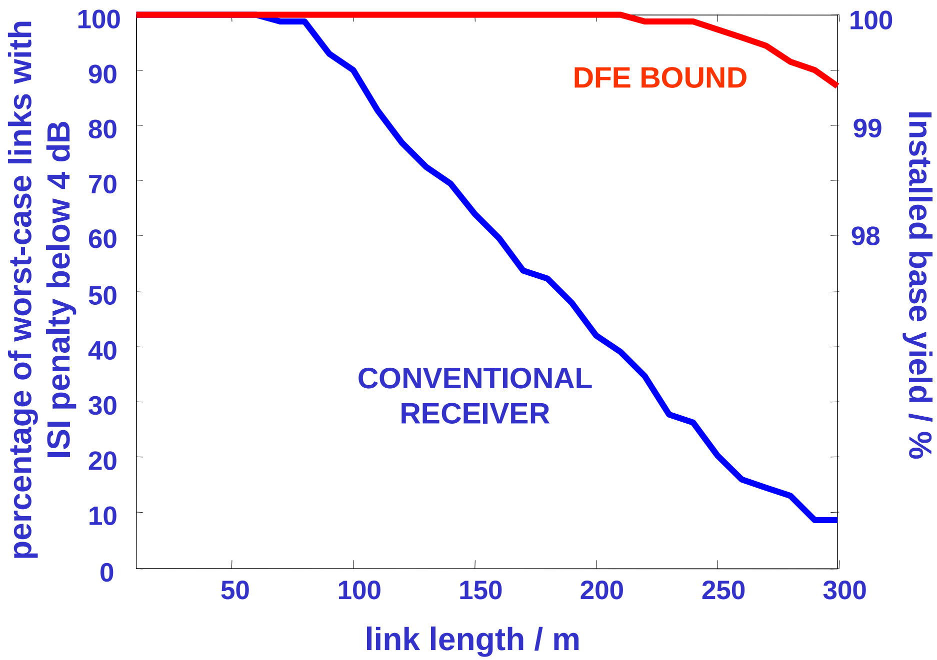


FFE bound



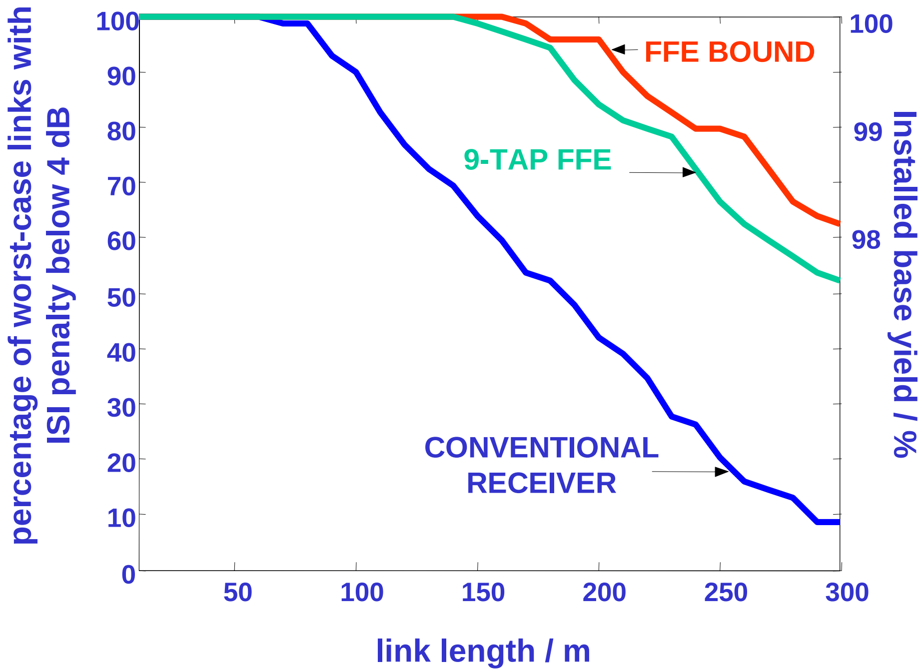
81 fiber statistical model: *yields for FFE and DFE bounds*

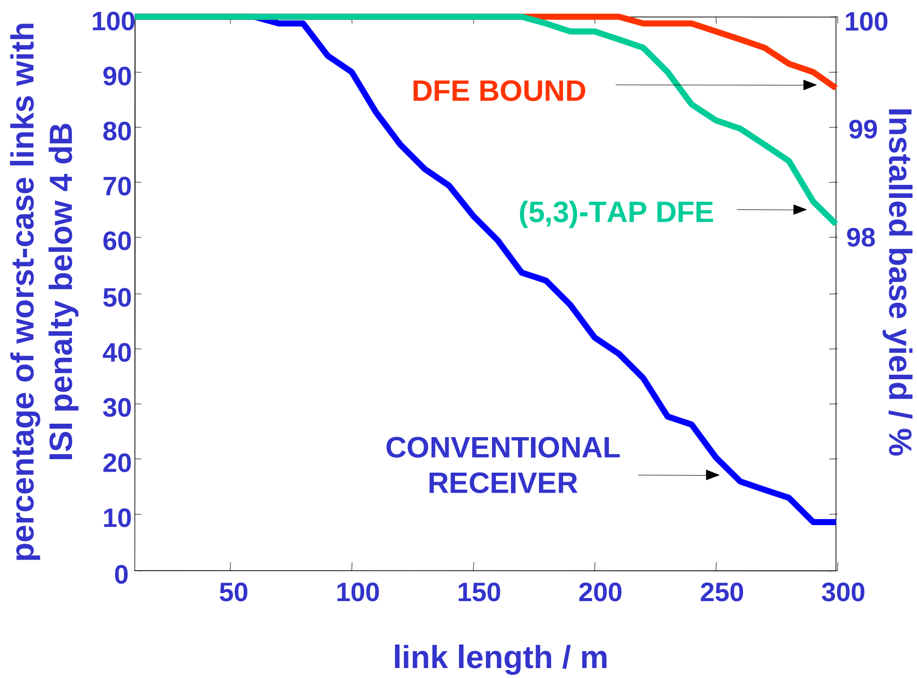




- **All launches offset launch and values quoted for 4dB power penalty**
- **Note simulations do not take error propagation in DFE into account**

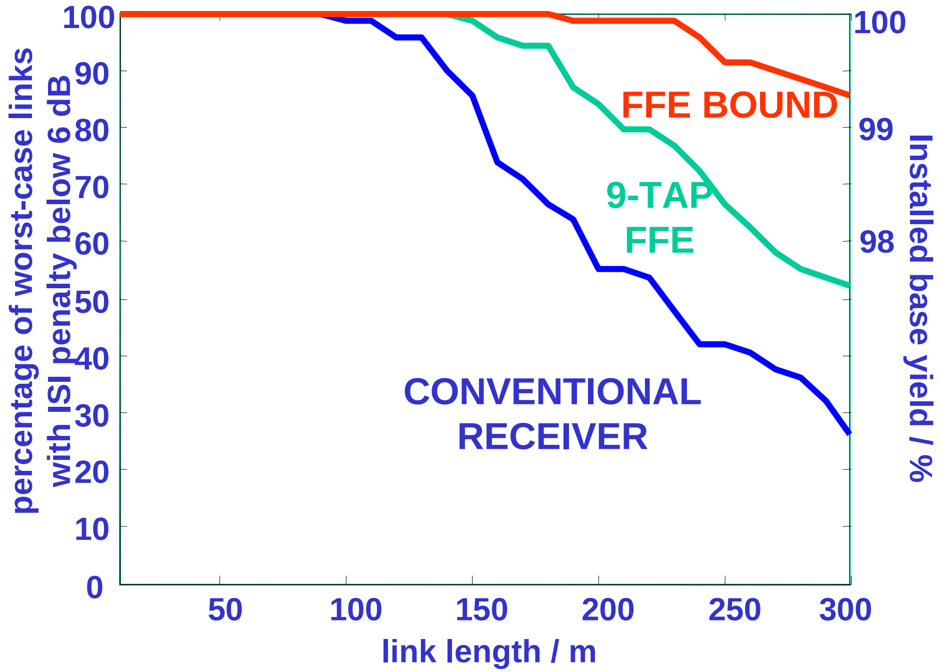
81 fiber statistical model: *yields for constrained FFE and DFE for 4dB penalty*

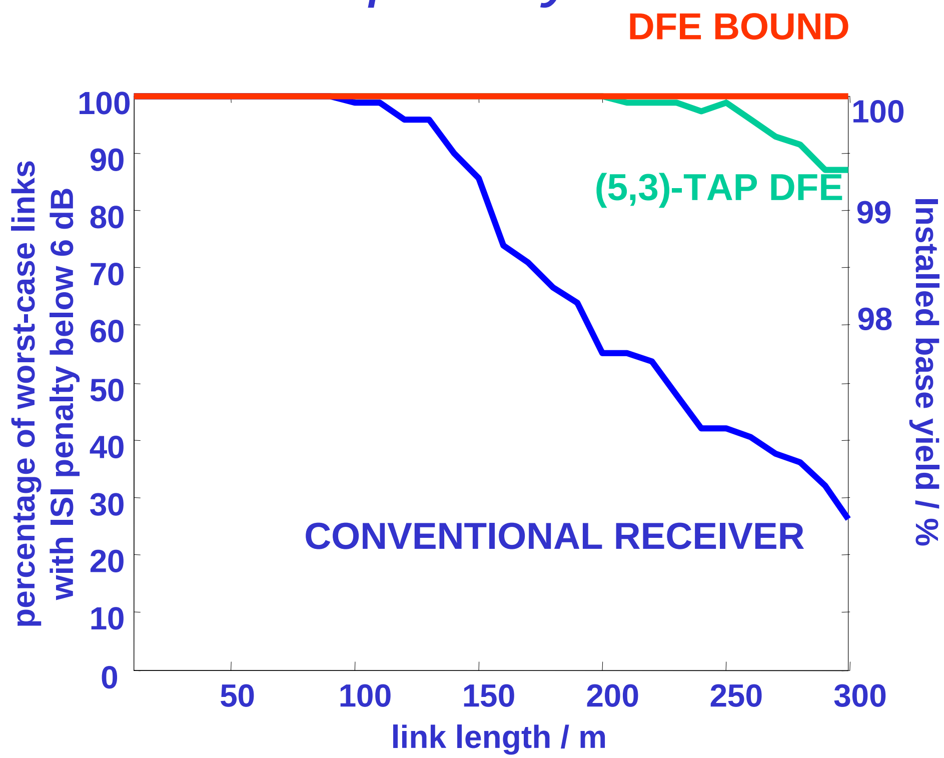




- **Constraining EDC implementation results in reduced achievable link length**

Yields for constrained FFE and DFE for 6dB penalty





- **Allowing ISI penalty to rise to 6dB allows greater link lengths**

EDC Results Summary

	Yield at 300 m for 4dB ISI penalty (installed base yield)	Yield at 300 m for 6dB ISI penalty (installed base yield)
ROFL 1.0 dB MBI fibers		
Unequalized	10 %	16 %
FFE bound	55 %	74 %
DFE bound	77 %	100 %
Offset Launch 81 fiber statistical		
Unequalized	9% (-)	26% (-)
FFE bound	62% (98.1%)	86% (99.3%)
N=9 tap FFE	52% (97.6%)	74% (98.7%)
DFE bound	87% (99.3%)	100% (100%)
(N,M) = (5,3) tap DFE	62% (98.1%)	87% (99.4%)

- **Note: MBI fibre link yield not representative of installed based yield**

Modelling Caveats

- 2 ns/km DMD for 5% worst-case is now dated – should we revisit?
- Model does not include error propagation in EDC
    - Known to be a problem, particularly in DFE
- Model does not take into account any noise statistic modification in the EDC chip
    - May give rise to additional penalties
- Precise implementation of EDC will cause variations in the link yields predicted
- Should look upon the yield figures calculated to date as an upper bound

Conclusions

- GbE statistical "worst-case" model reviewed and extended to 10 G EDC, including noise effects
  - DMD scaling technique appears reasonable
  - General agreement with published experiments
- Extended model allows different EDC approaches to be easily investigated
  - FFE and DFE implementations appear valid
- Preliminary indication of benefit of EDC for 10.51875 Gb/s over 62.5-μm MMF at 1300 nm is achievable link length increase by a factor ~ 2 for 99% link yield
- Precise EDC yield curves will be implementation specific

Future work

- **Work with the Ethernet standards body to develop a statistical fiber model for EDC-enabled 10GbE links**
- **Once the model is agreed, provide a set of corner-case impulse responses for input into simulations to enable estimation of theoretical performance of different classes of EDC**
- **Investigate the development of a “worst-case” spreadsheet based on 10GbE spreadsheet and power-budget model for EDC-enabled links**

Acknowledgment

- **Cambridge would like to acknowledge the involvement of Phyworks Ltd**

References

- **M. Webster, L. Raddatz, I. H. White, D. G. Cunningham, "A statistical analysis of conditioned launch for Gigabit Ethernet links using multimode fiber," *Journal of Lightwave Technology*, vol. 17, no. 9, pp. 1532-1541, 1999.**

- **D. G. Cunningham, W. G. Lane, *Gigabit Ethernet Networking*. Indianapolis, IN: Macmillan Technical Publishing, 1999.**

- **P. Pepeljugoski, J. Schaub, J. Tierno, J. Kash, S. Gowda, B. Wilson, H. Wu, A. Hajimiri, "Improved performance of 10 Gb/s multimode fiber optic links using equalization," *Proc. OFC 2003*, vol. 2, pp. 472-474.**

- **E. A. Lee, D. G. Messerschmitt, *Digital Communication*, second edition. Norwell, MA: Kluwer Academic Publishers, 1994.**

- **S. Quershi, "Adaptive equalization," *IEEE Communications Magazine*, March 1982, pp. 9-16.**