



Extension of Statistical Multimode Fiber Channel Model to Electronic Dispersion Compensation

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Talk outline

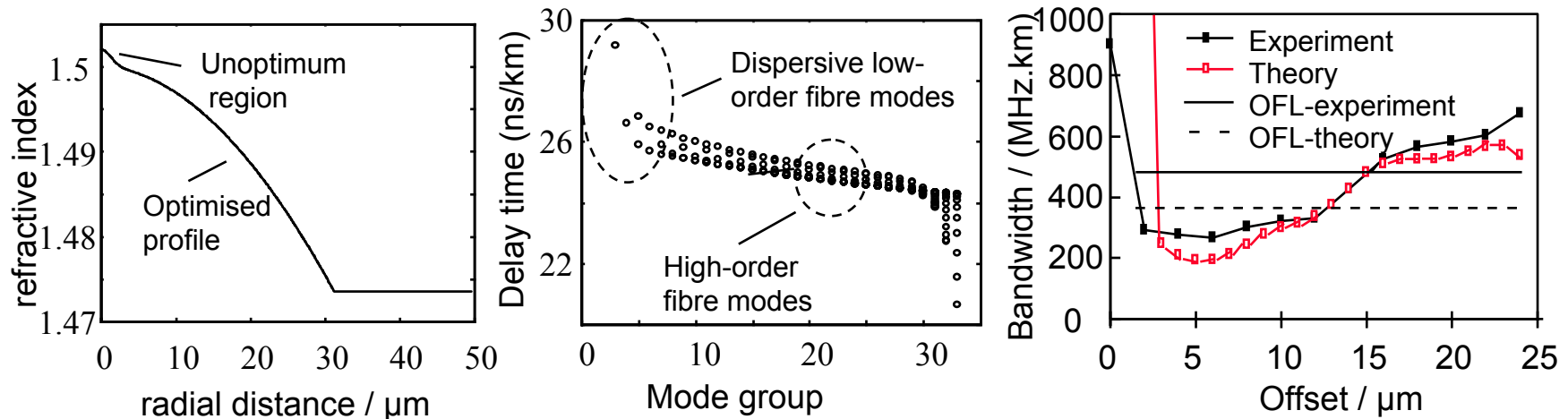
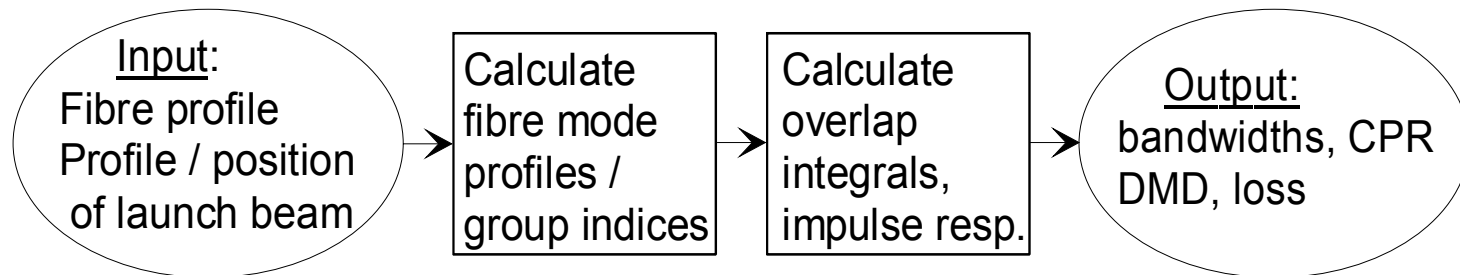
- **Brief review of statistical MMF channel model**
- **Extension of model to EDC**
 - **Model verification for EDC**
- **Types of EDC studied**
- **Link yield as function of**
 - **EDC type**
 - **Fiber launch**
 - **Link length**
- **Conclusions**



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**

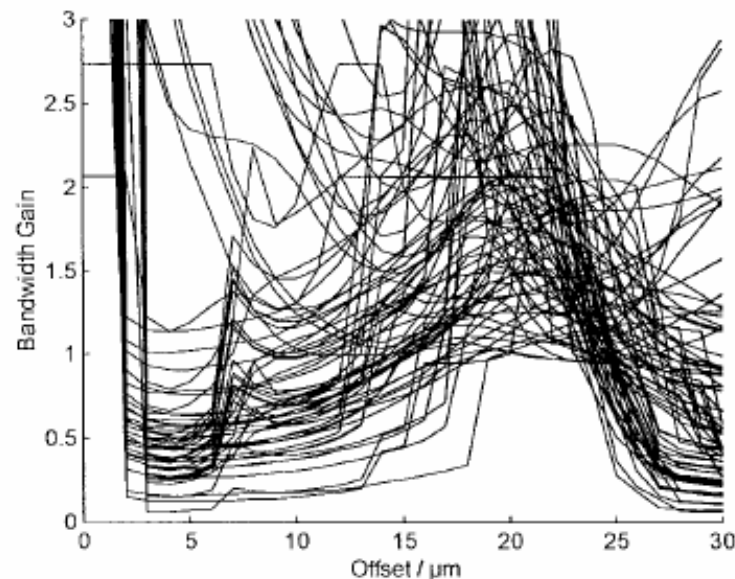
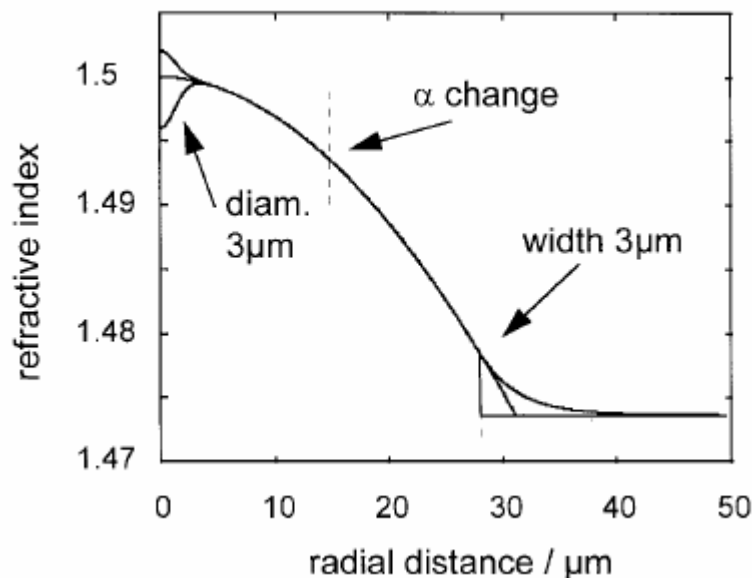


Steps in the GbE statistical model

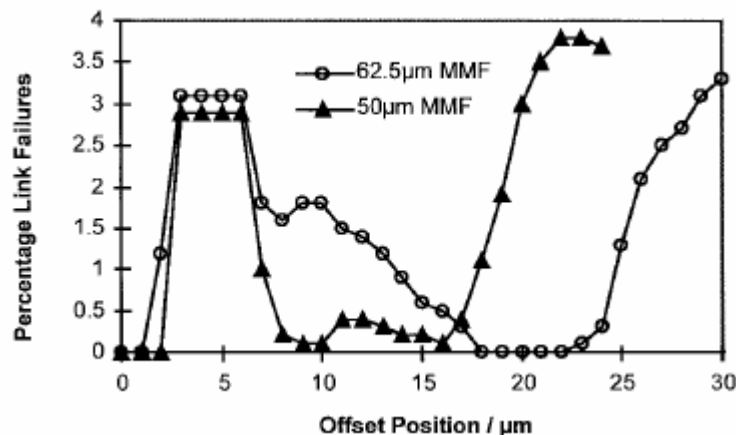
- Generate a set of representative fiber index profiles
- Calculate OFL frequency response and bandwidth
- Calculate impulse and frequency responses at beam offsets ranging across the entire fiber core radius
- Calculate **DMD** from assessment of the impulse responses at each offset
- Compare DMD to “**worst-case**” value, e.g. 5% of installed fibers have $\text{DMD} > 2 \text{ ns/km}$ for $62.5\text{-}\mu\text{m}$ 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

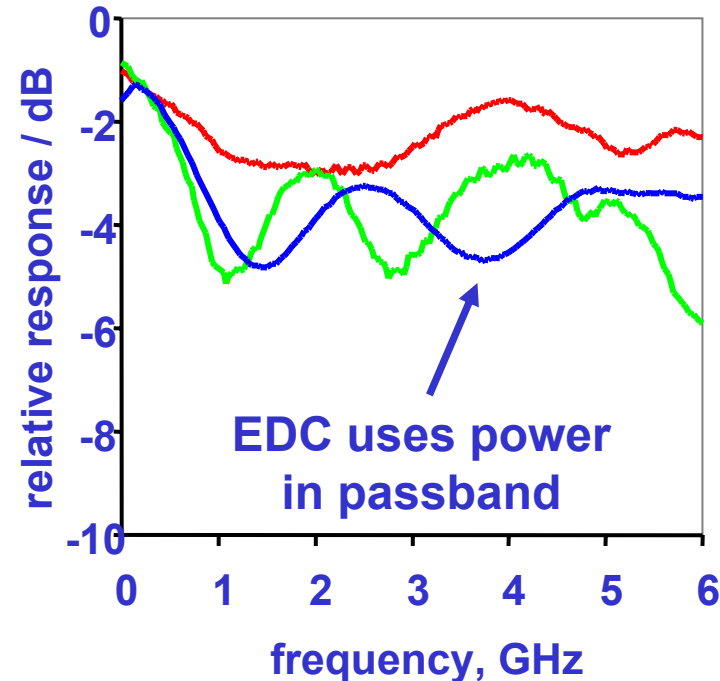


M. Webster, L. Raddatz, I. H. White, D. G. Cunningham, "A statistical analysis of conditioned launch for Gigabit Ethernet links using multimode fiber," *Journal of Lightwave Technology*, vol. 17, no. 9, pp. 1532-1541, 1999



Initial results for 10GbE EDC

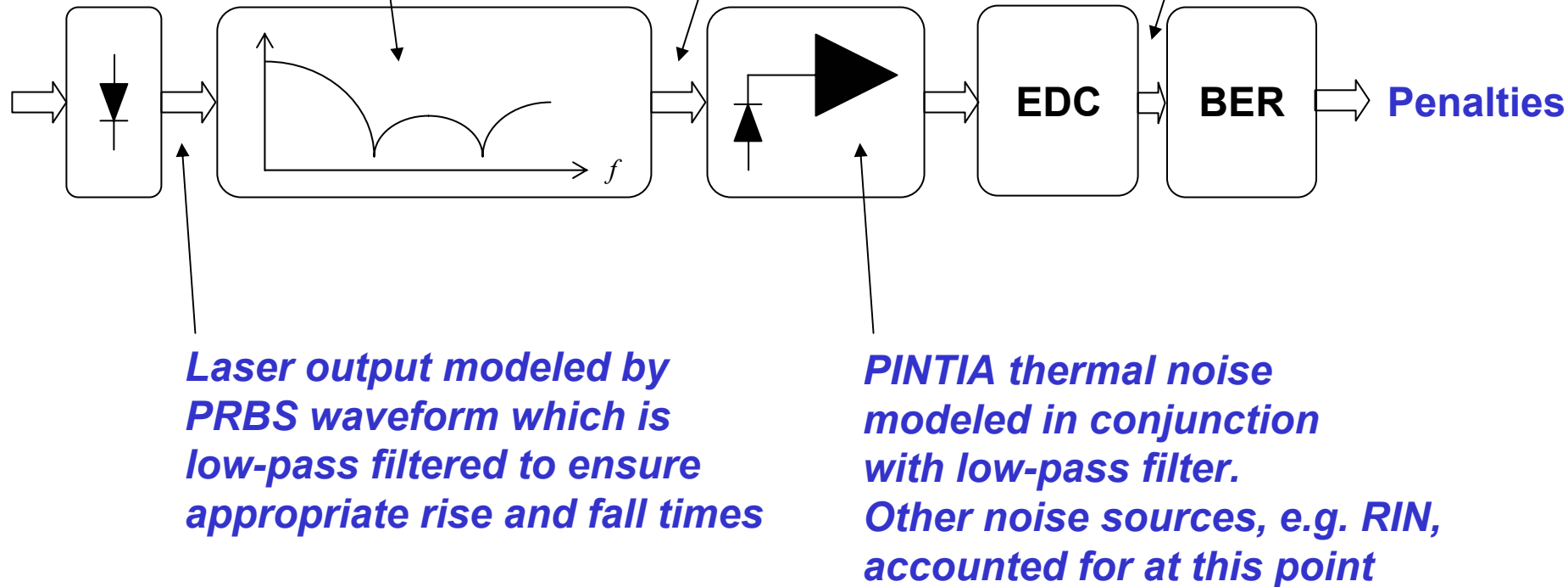
Considerations relating to the extension of model to EDC



- 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)

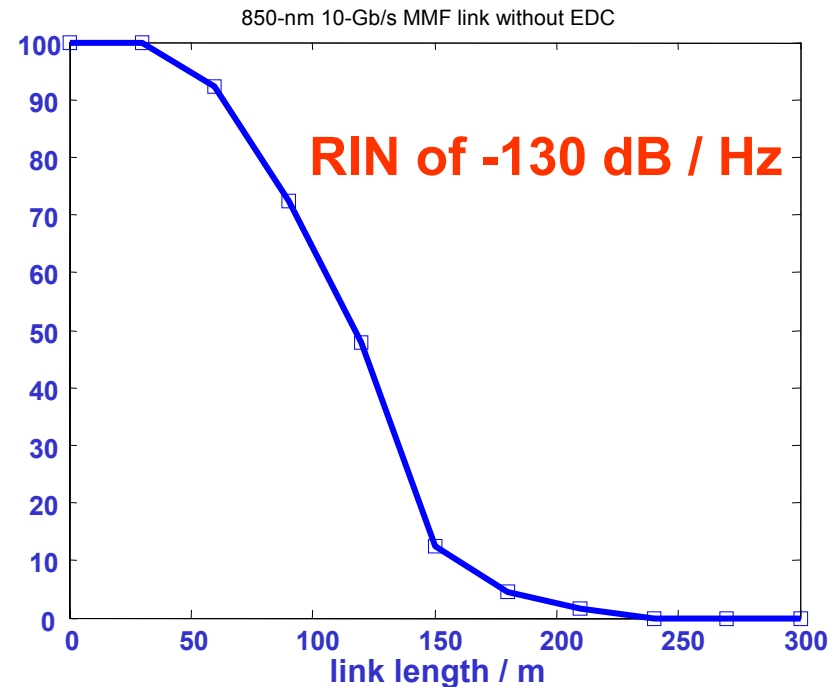
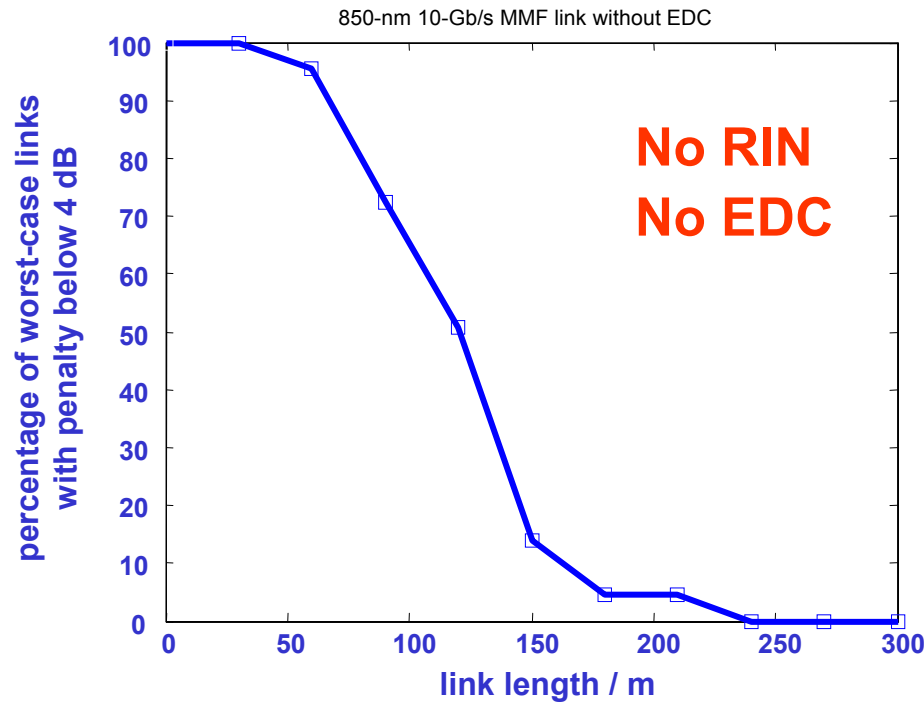
Steps in the extended model

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



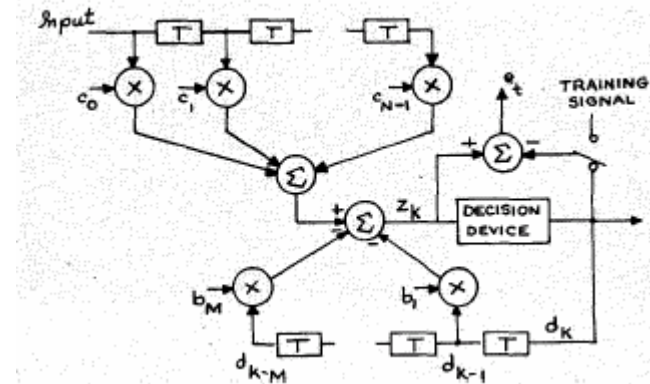
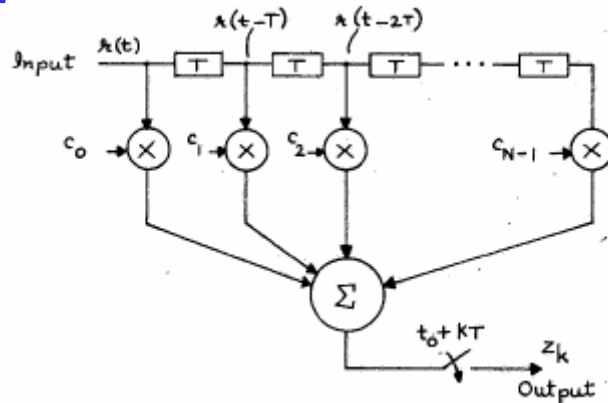
Inclusion of Noise into System Model

- 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)

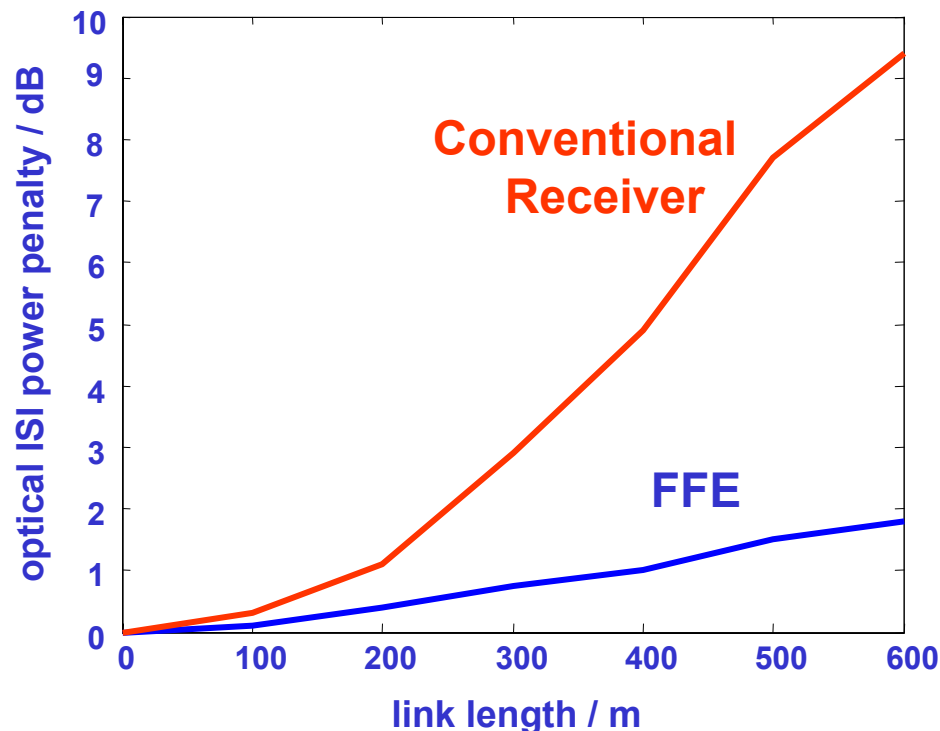
Decision-feedback equalizer (DFE)

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- μ m 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

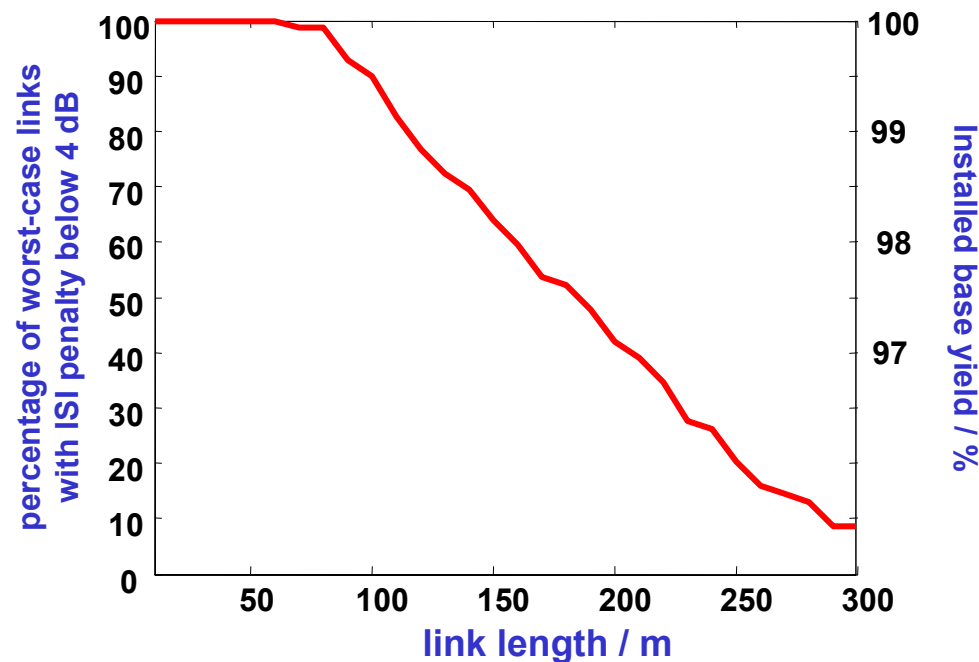
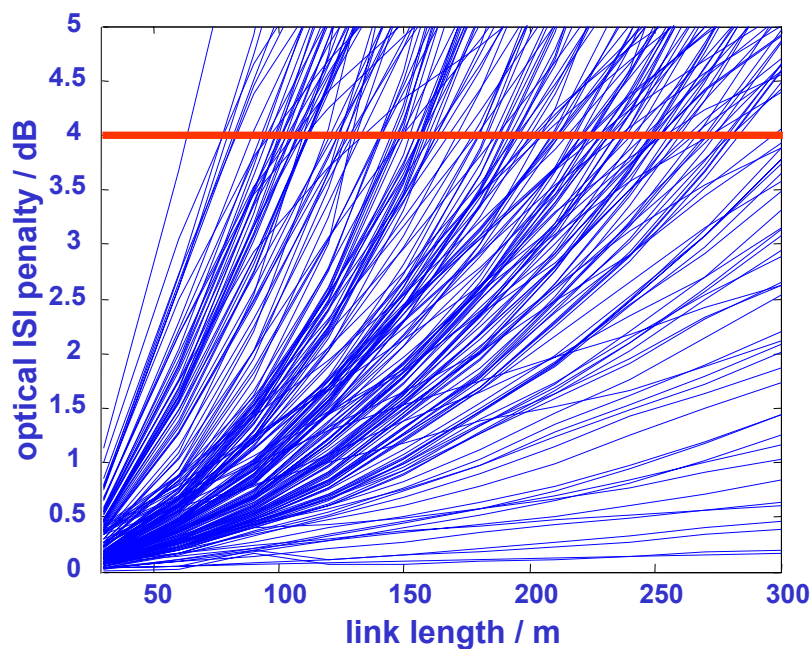
P. Pepeljugoski et al. "Improved performance of 10 Gb/s multimode fiber optic links using equalization," *Proc. OFC 2003*, vol. 2, pp. 472-474



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

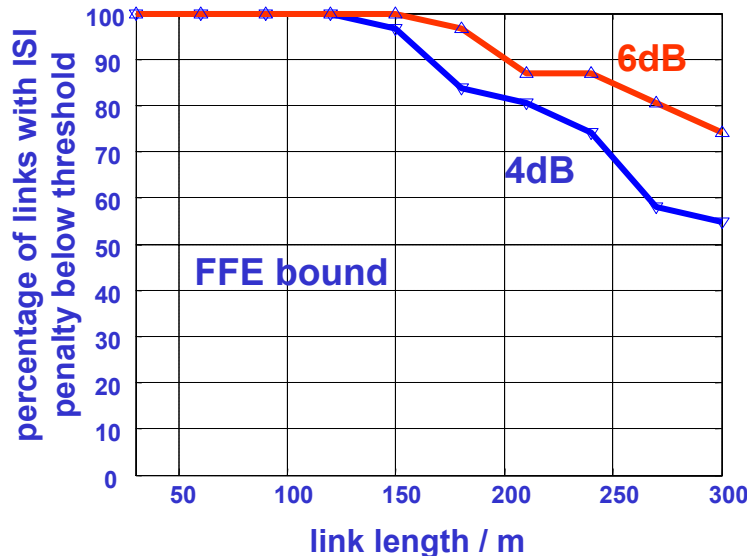
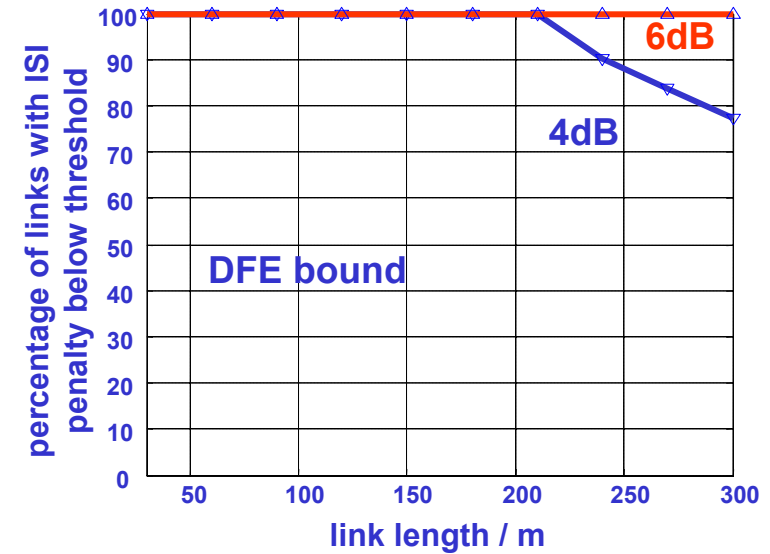
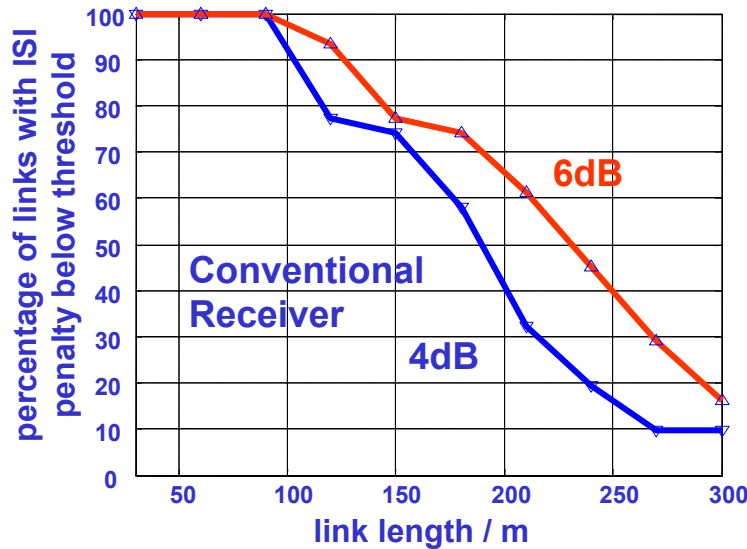
1300nm 10G Transmission Without EDC – Using 81 Fiber Model with $20\ \mu\text{m} \pm 3\ \mu\text{m}$ offset launch (ie 243 links)



- 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 (%) = $(95 + 100 - \text{pass yield}) / 20$
- Valid for pass % > 50% (ie installed base yield > 97.5%)



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

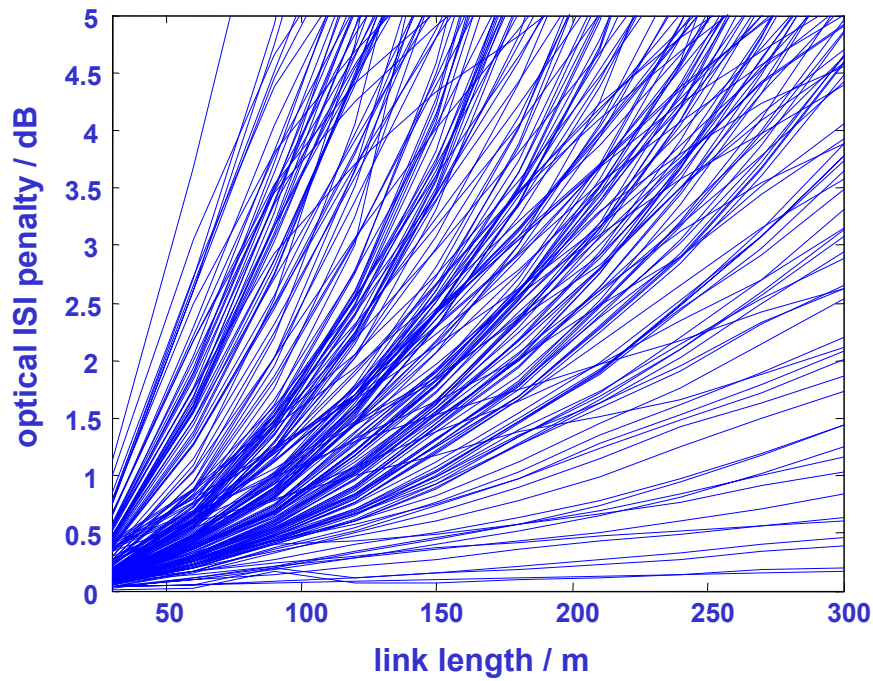


- ROFL (1.0dB)
- Calculated frequency responses scaled to lengths from 0 to 300 m
- Links failing the 500 MHz km specification are not included

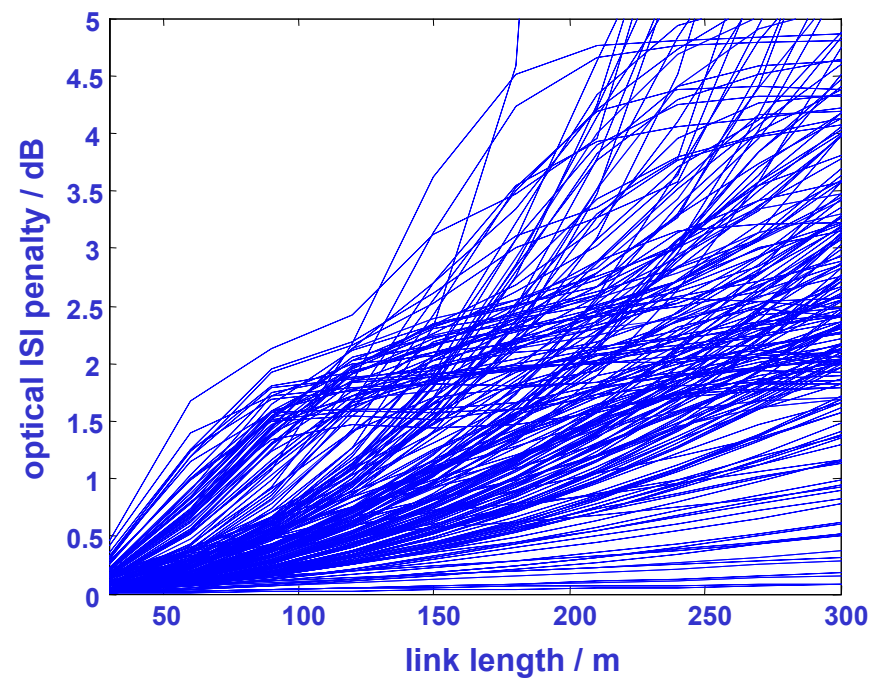
1300-nm 62.5- μm 500-MHz.km MMF - Unequalized & FFE bound

- Optical ISI power penalty vs. link length

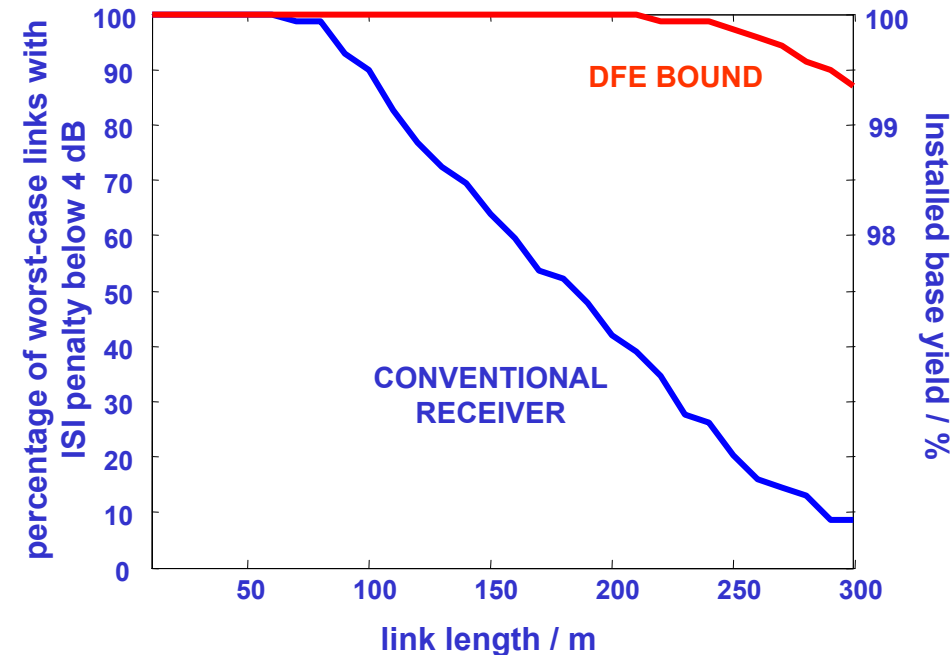
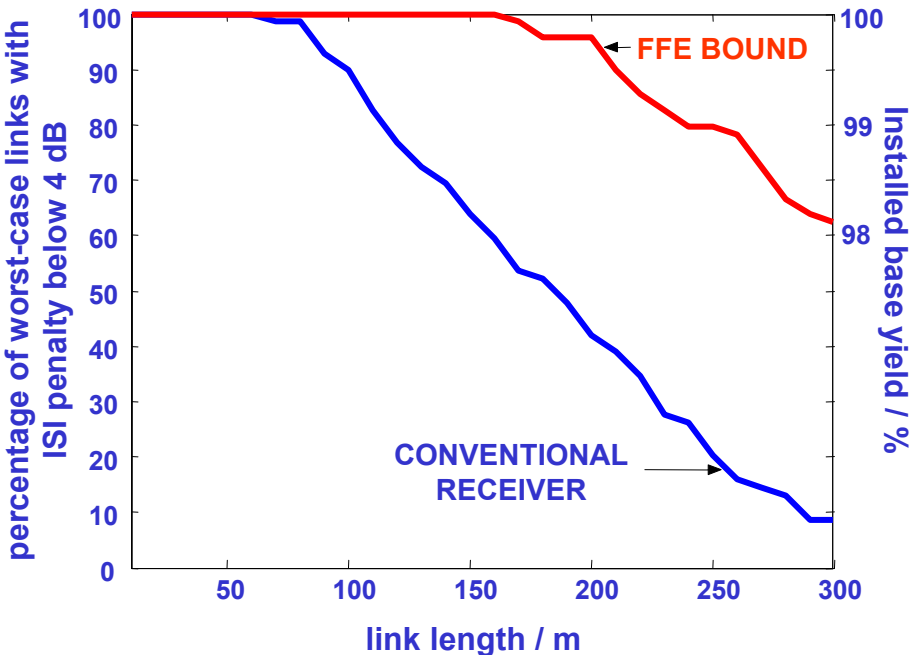
Conventional
Receiver



FFE bound



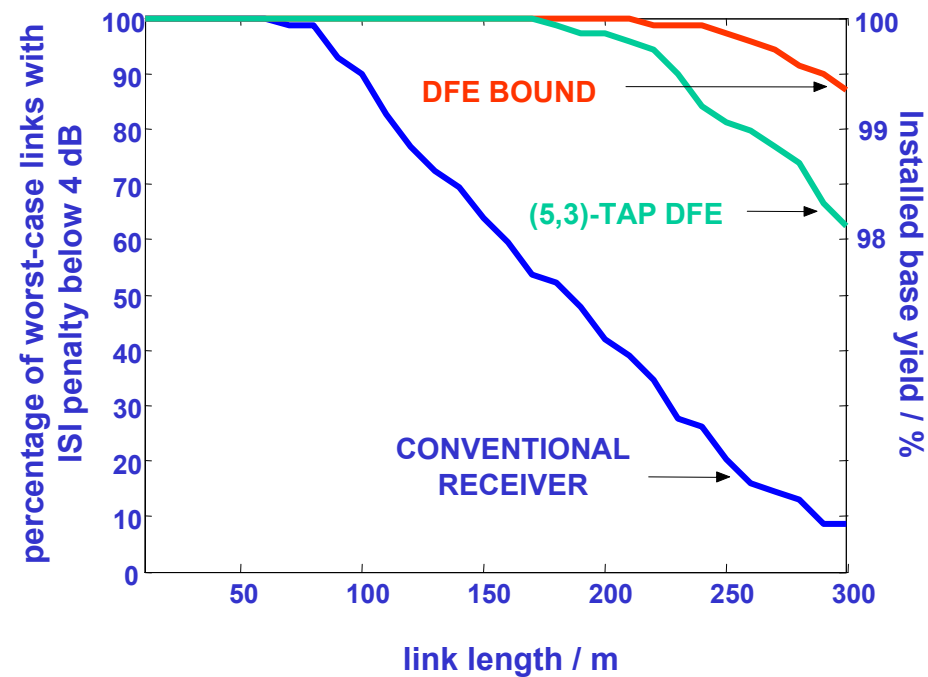
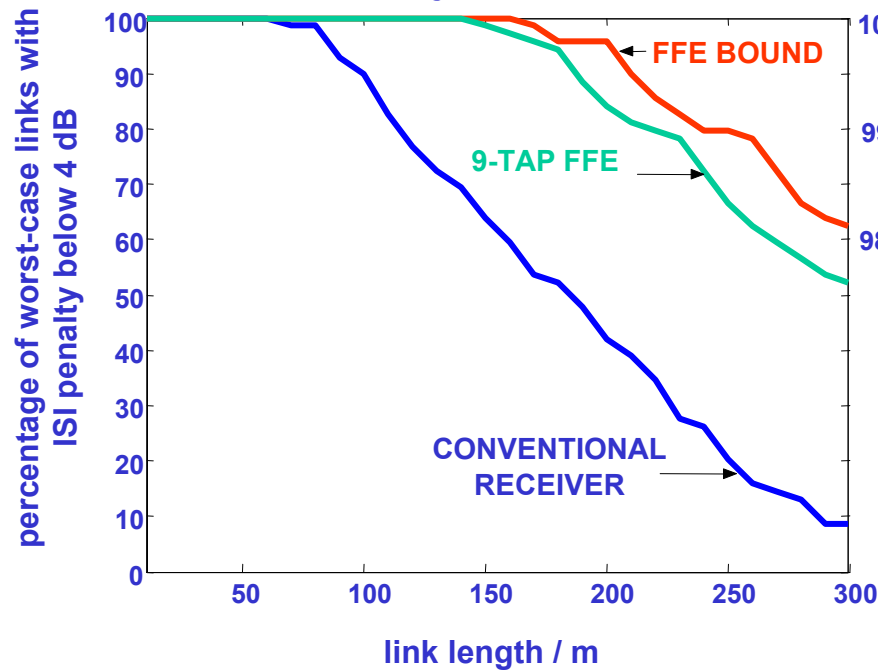
81 fiber statistical model: *yields for FFE and DFE bounds*



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



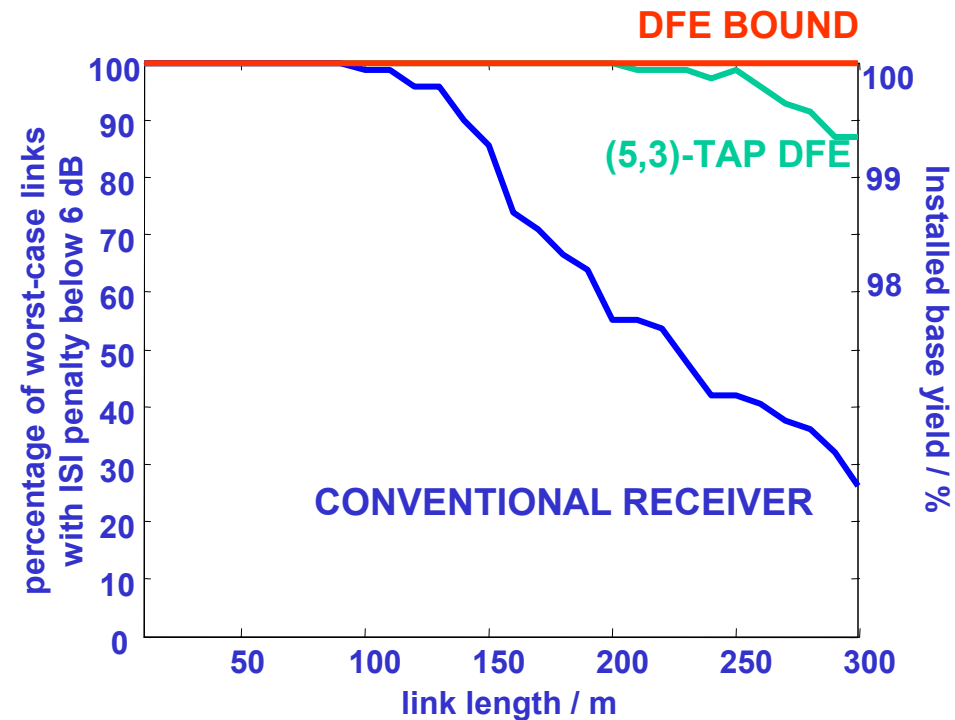
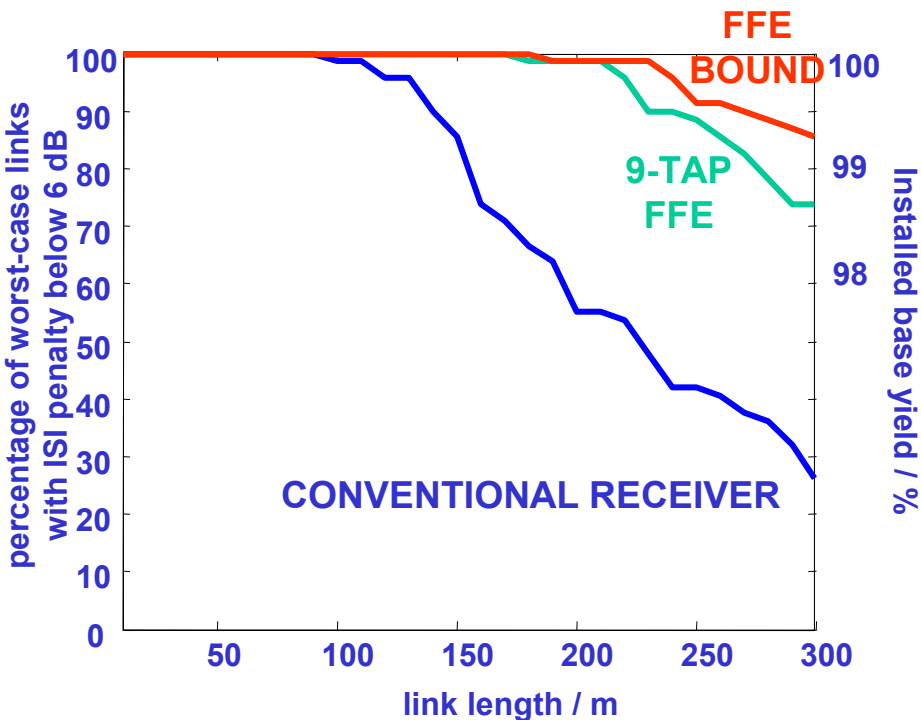
81 fiber statistical model: *yields for constrained FFE and DFE for 4dB penalty*



- **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



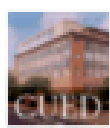
EDC Results Summary

	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		
<i>Unequalized</i>	10 %	16 %
<i>FFE bound</i>	55 %	74 %
<i>DFE bound</i>	77 %	100 %
Offset Launch 81 fiber statistical		
<i>Unequalized</i>	9% (-)	26% (-)
<i>FFE bound</i>	62% (98.1%)	86% (99.3%)
<i>N=9 tap FFE</i>	52% (97.6%)	74% (98.7%)
<i>DFE bound</i>	87% (99.3%)	100% (100%)
<i>(N,M) = (5,3) tap DFE</i>	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 10G 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 over 62.5- μ m 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**
- **Help out in 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 advice / input of Phyworks Ltd**



References

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