Lessons from Gigabit Ethernet

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Outline

- Launch Conditioning:
  Key results from the Gigabit Ethernet EMBI & MBI.
- Power Budgeting for Equalized Links.
- Modal Noise.
- Implications for 10 GbE Project.
- Closing Comments.

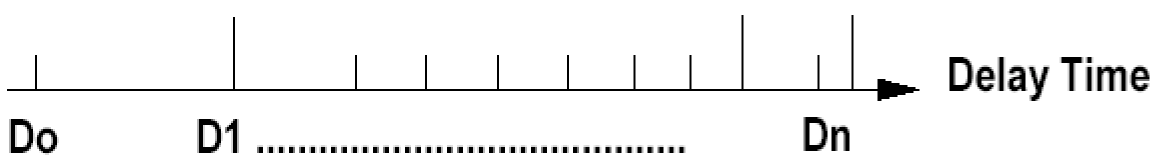
Launch Conditioning

The Gigabit Ethernet EMBI and MBI

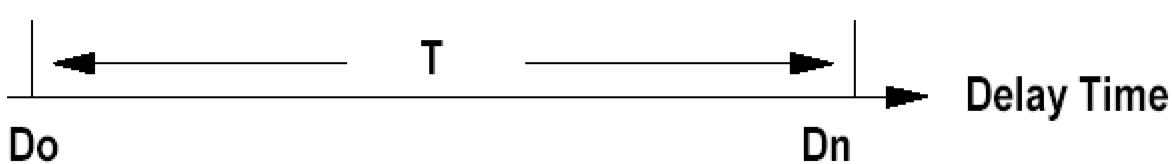
- **Unpredictable bandwidth performance of MMF with unspecified laser launch caused Gigabit Ethernet to conduct two separate investigations as follows:**
  1. The Effective Modal Bandwidth Investigation (EMBI).
  2. The Modal Bandwidth Investigation (MBI).
- **The results of the EMBI produced draft D3.1 that was rejected by IEEE 802.3.**
- **The results of the MBI produced draft D5 that became the IEEE 802.3. Gigabit Ethernet standard.**

EMBI: What determines the impulse and frequency response of a MMF link?

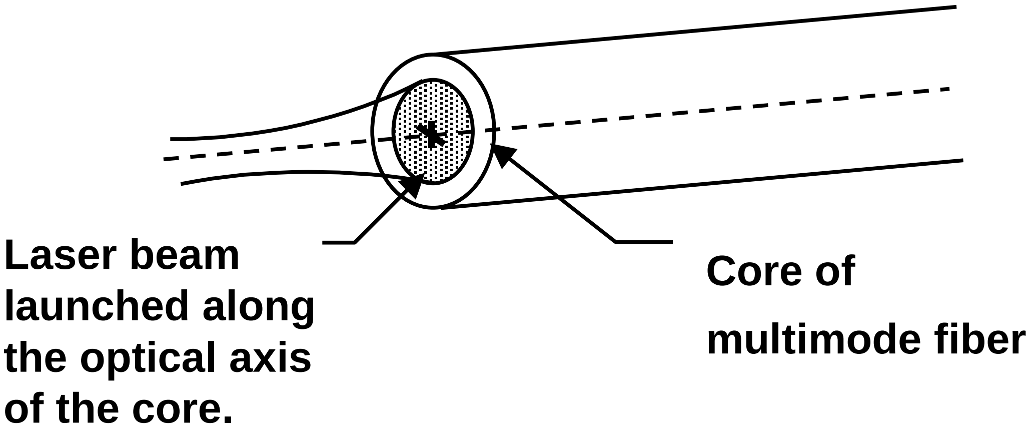
- **Modal delays** (fiber property)
- **Modal weighting** (source launch condition)
- **Filtering** (by reducing optical receiver bandwidth)
- **Mode coupling or mode stripping** (affects weighting independent of launch)



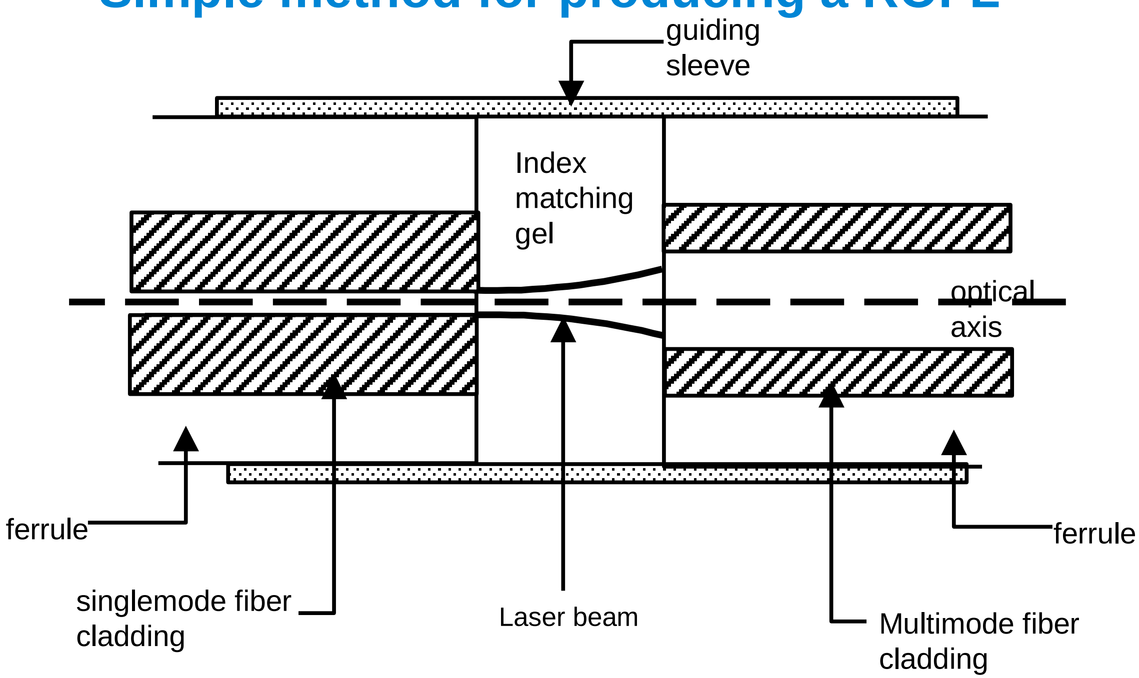
Absolute worst-case Impulse Response (IPR):



EMBI: Radial Overfilled Launch (ROFL)



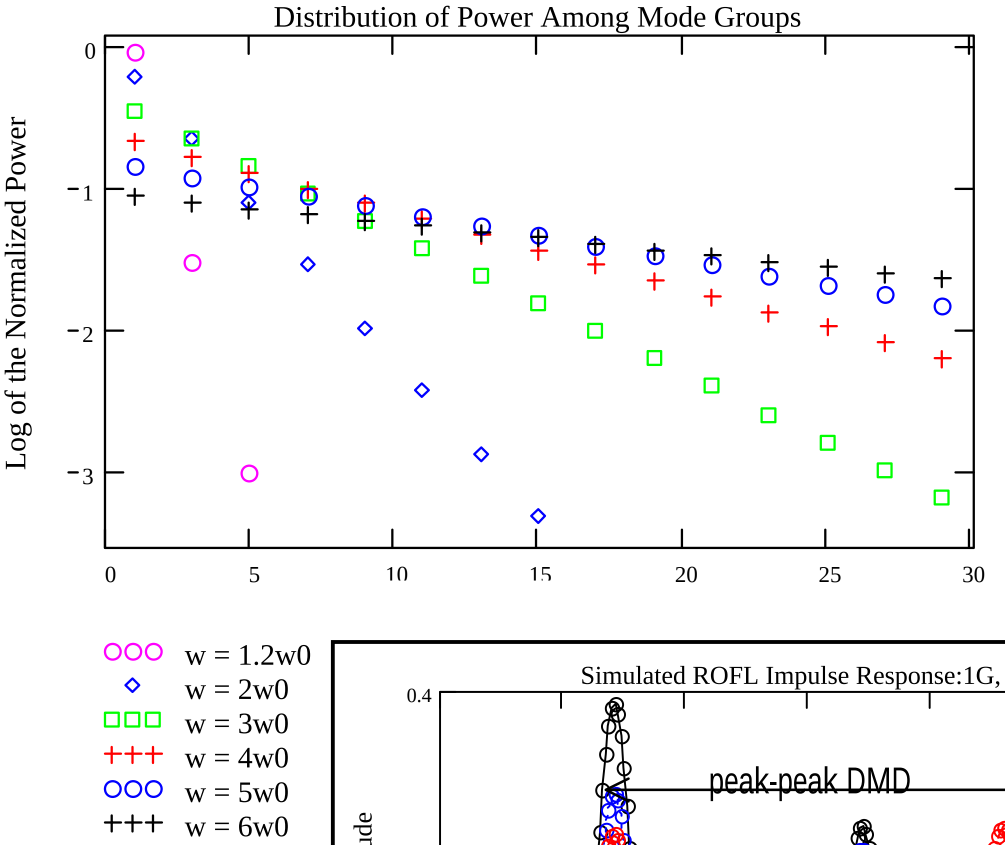
Simple method for producing a ROFL

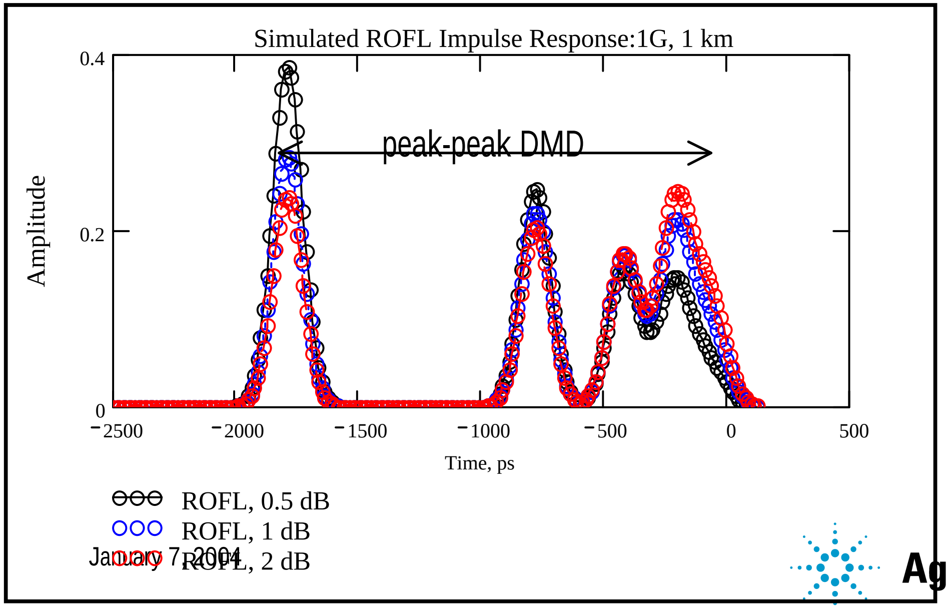


ROFL was invented by the EMBI. It has the following features:

- Reproducibility,
- Simplicity of implementation,
- A near worst case central launch for MMF.

EMBI: Radial Overfilled Launch (ROFL)





- ROFL tends to put equal power into each mode group.
- ROFL tends to produce IPR with the maximum possible peak –peak DMD, this is why it is such a poor launch.
- However, slight offset launches can produce lower bandwidths than ROFL.

Influence of Restricted Mode Excitation on Bandwidth of Multimode Fiber Links

L. Raddatz, I. H. White, *Member, IEEE*, D. G. Cunningham, and M. C. Nowell

IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 10, NO. 4, APRIL 1998

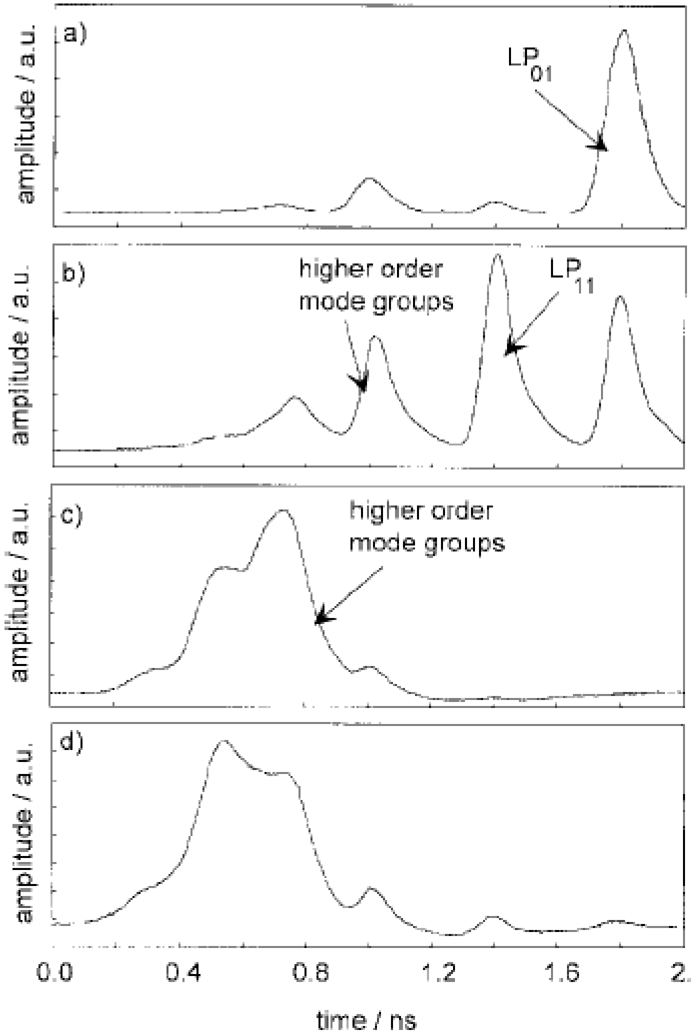


Fig. 1. Fiber impulse response of sample MMF for different launch conditions: (a) launch into center, (b) 6-μm offset, (c) 18-μm offset, (d) OFL.

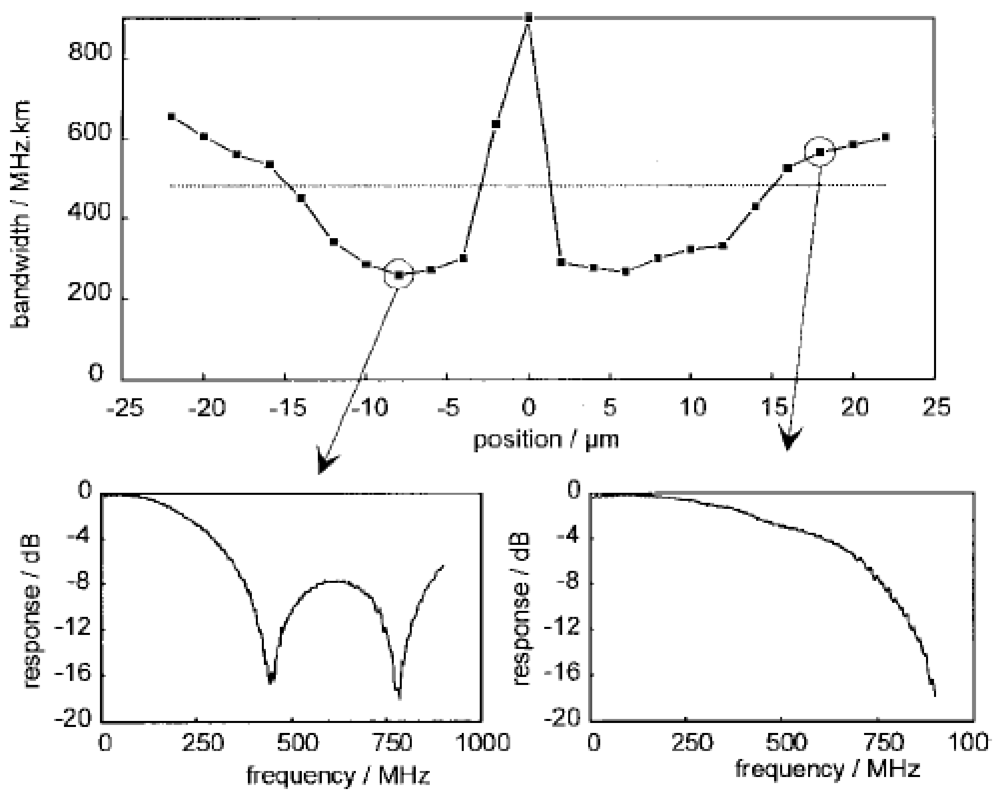


Fig. 2. (top) Dependence of bandwidth on radial offset from core center, the dashed line indicates the OFL bandwidth. (bottom left) Frequency response of fiber for launch offsets of 8 μm and (bottom right) 18 μm.

Summary of key conclusions of the EMBI

- **30 percent of multimode fibers were observed to have bandwidth less than 500 MHz.km for operation at long wavelength with near core center restricted-mode launches.**

LX Observed Bandwidths (MHz.km)

Minimum	Mean	Maximum
250	800	>2400*

* *Limited by measurement capabilities*

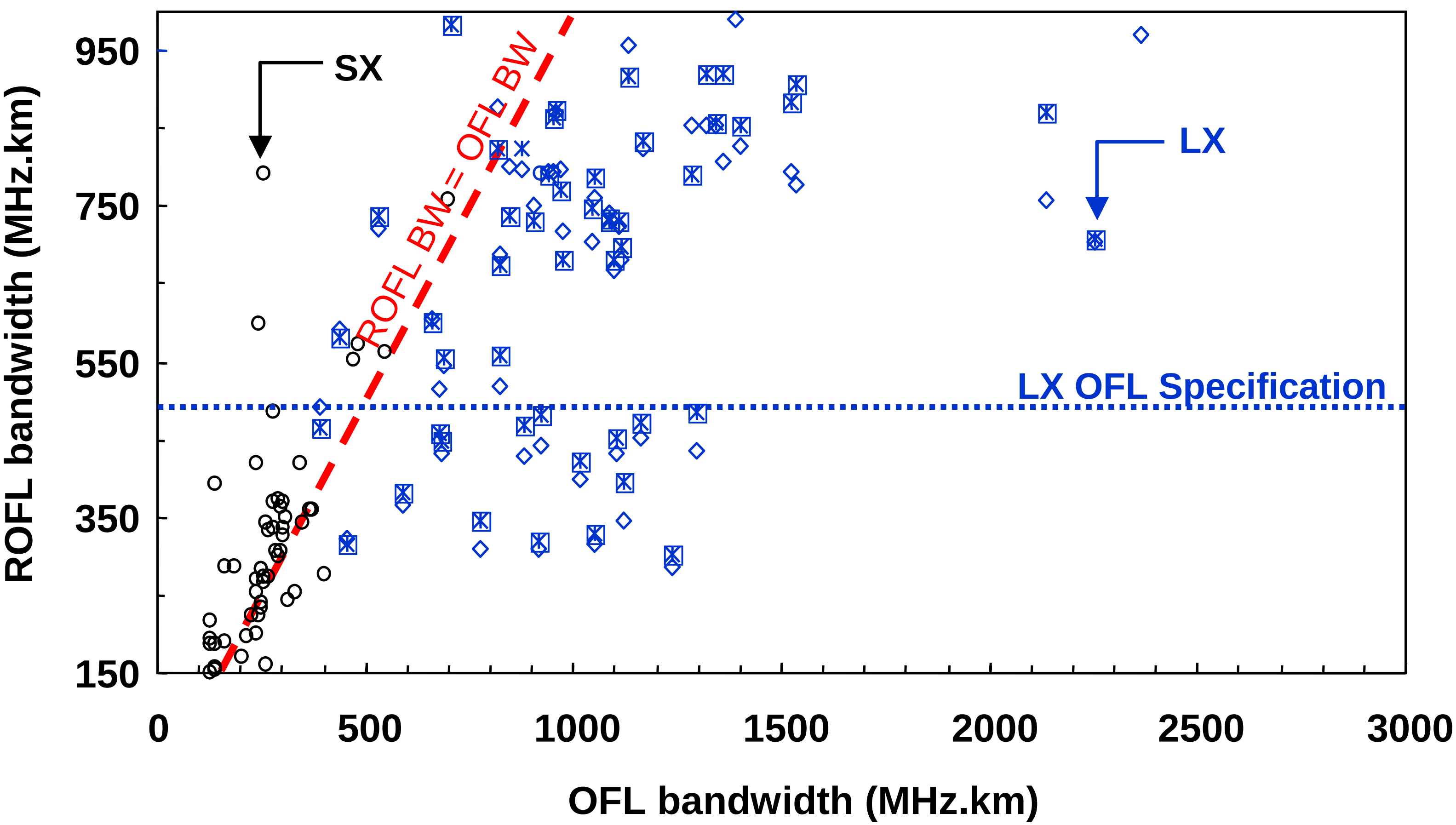
LX Operating Ranges of Draft D3.1

62.5 MMF	**50 MMF**
440 m	550 m

- **IEEE 802.3 viewed these ranges as optimistic because they did not account for the additional jitter associated with low bandwidth launches.**

MBI: Field Tests

ROFL bandwidth versus OFL bandwidth for 62.5 MMF



MBI conclusion: Launch Conditioning for Legacy 62.5 MMF

- In the presence of connectors and patch panels a conditioned laser launch must repeatedly provide:

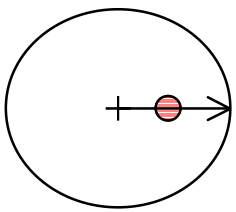
  - stable bandwidth

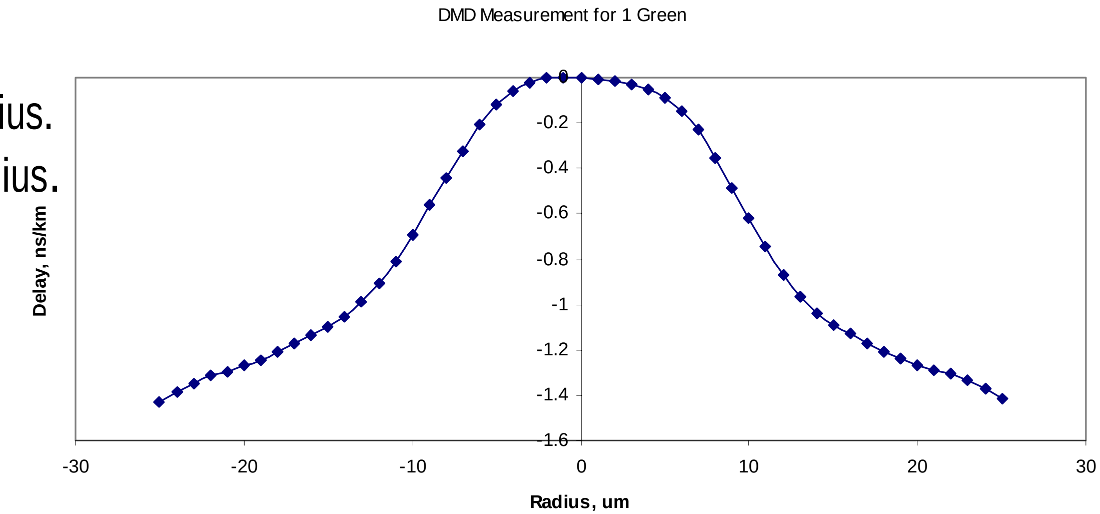
  - low modal noise

MBI: DMD values for installed MMF

DMD Measurement

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





5 % DMD values for 1998 installed base of Gigabit Ethernet MMF.

2 sigma peak-to-peak DMDs	50 mm MMF	62.5 mm MMF
1300 nm	**2 ns / km**	**2 ns / km**
850 nm	2 ns / km	4 ns / km

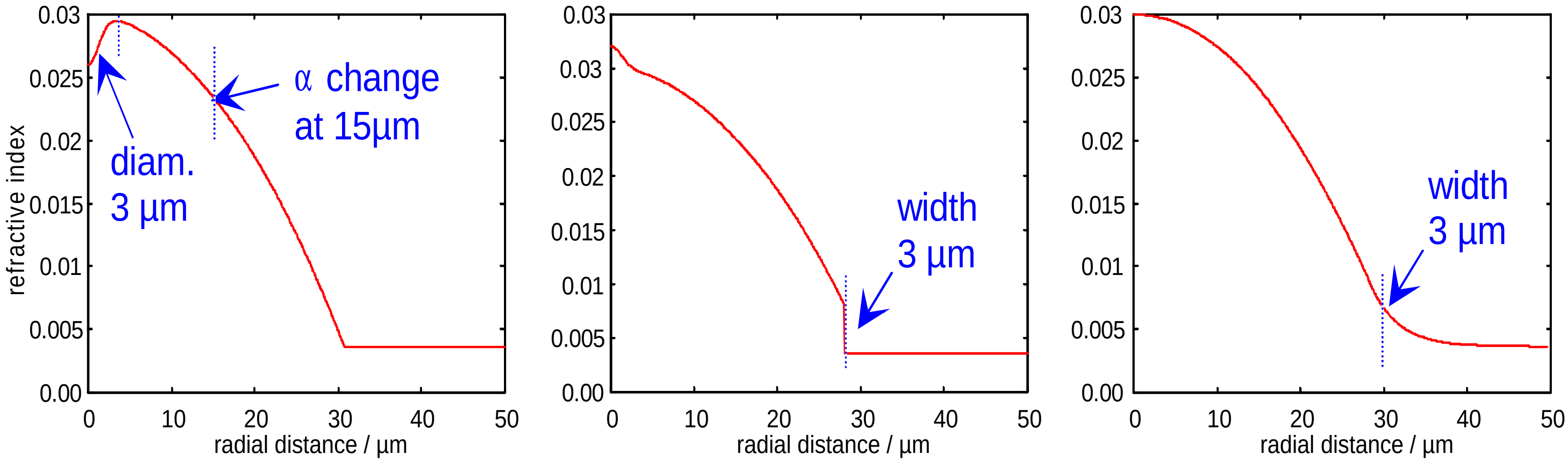
• These values were provided by MMF cable manufacturers as a <u>guide</u> for the development of the Gigabit Ethernet standard.

• Peak-Peak DMD values measured from ROFL or other IPR tend to be larger than the DMD measured by the scanning spot method.

Legacy Fiber Refractive Index Profiles for GbE Simulations

- **Non-ideal features of graded index MMF:**
  Distortion at core center (depression or peak)
  Distortion at core/cladding interface (diameter variation)
  Varying profile parameter (α)

- **Fiber profiles investigated:**
  3 x central distortion (+ve/-ve/none), 3 x edge distortion (+ve/-ve/none),
  3 x inner profile parameter, 3 x outer profile parameter



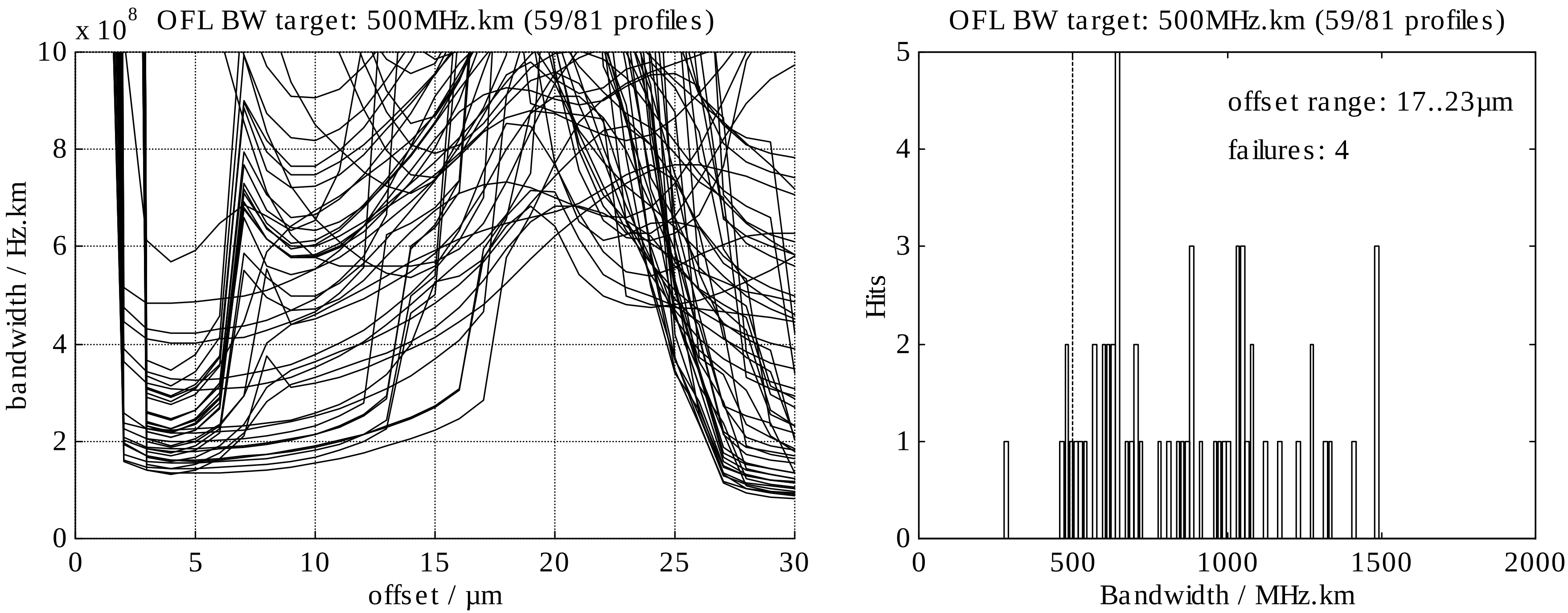
81 basic worst-case (95 percentile) profile types

A Statistical Analysis of Conditioned Launch for Gigabit Ethernet Links Using Multimode Fiber

M. Webster, L. Raddatz, I. H. White, and D. G. Cunningham

JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 17, NO. 9, SEPTEMBER 1999

- Used 5 percentile DMD value of 2ns/km for simulation



⇒ **Out of 59 profiles: 4 have bandwidths<500MHz.km for offsets 17..23µm**

⇒ **Total probability of failure is 7% of 5% , i.e. less than 0.4%**
(probability of severe failure less than 0.1%)

A Statistical Analysis of Conditioned Launch for Gigabit Ethernet Links Using Multimode Fiber

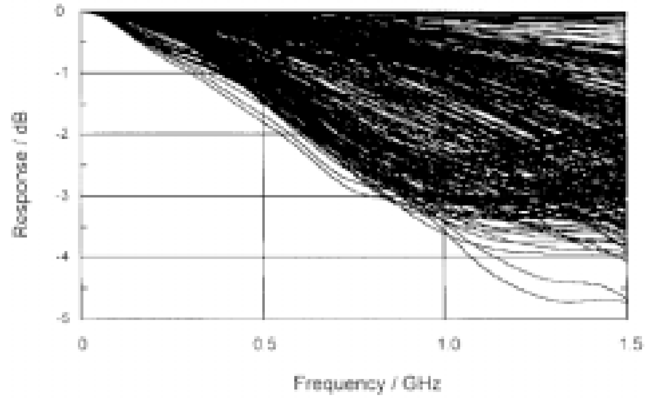


Fig. 10. Frequency response of 81 62.5-μm MMF (length 500 m) at an operating wavelength of 1300 nm for offsets positions from 17 to 23 μm.

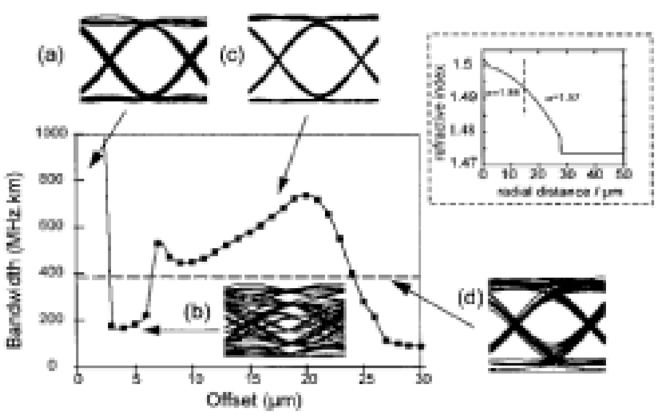


Fig. 11. Transmission performance of a 62.5-μm fiber with a central index peak, an abrupt core/cladding interface, an inner profile parameter of 1.89 and an outer profile parameter of 1.97. The received eye diagrams after 500 m at 1.25 Gb/s are shown for launch positions of (a) 0 μm, (b) 4 μm, (c) 18 μm, and (d) OFL conditions at an operating wavelength of 1300 nm.

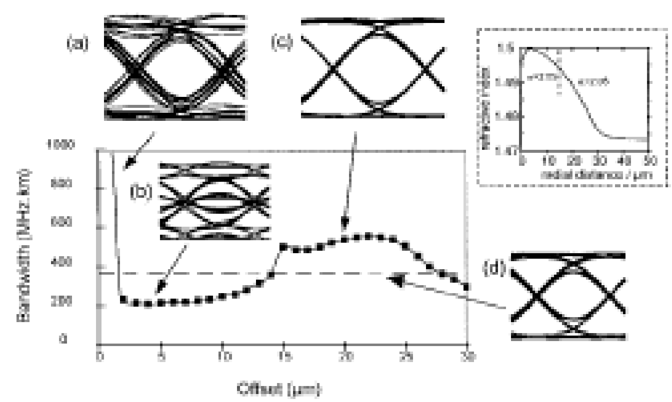


Fig. 12. Transmission performance of a 62.5-μm fiber with a central index dip, a smooth core/cladding interface, an inner profile parameter of 2.05 and an outer profile parameter of 2.05. The received eye diagrams after 500 m at 1.25 Gb/s are shown for launch positions of (a) 0 μm, (b) 4 μm, (c) 20 μm, and (d) OFL conditions at an operating wavelength of 1300 nm.

Effect of MMF Cable Connectors in Legacy 62.5 MMF

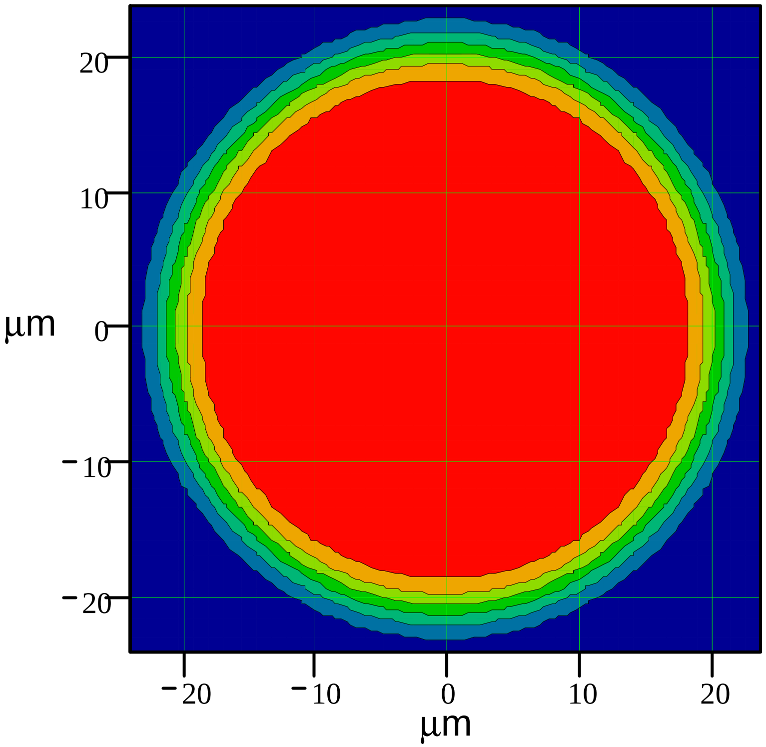
- **Connectors cause mode mixing, loss and under certain circumstances modal noise.**

- **Mode mixing causes:**
  - The power in each fiber mode to tend to be equal
  - The CPR values to tend towards OFL value of about 20 dB

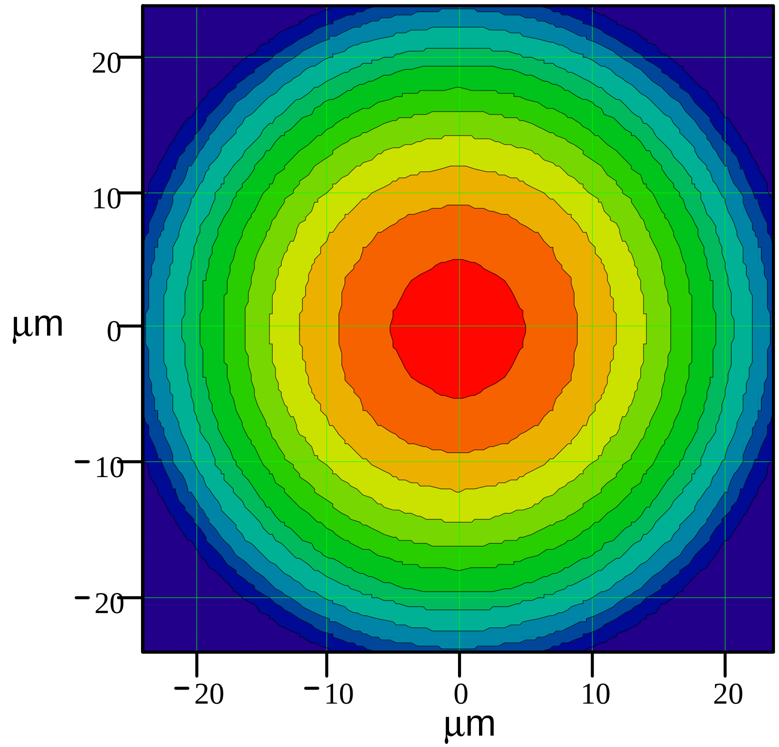
- **Therefore mode mixing:**
  - Initially causes center launch (ROFL) to fall into the low bandwidth region **(very bad!).**
  - Causes the Offset launch bandwidth to tend to the OFL bandwidth **(Good).**
  - Enough mode mixing will cause low bandwidth launches to tend to the OFL bandwidth **(Good).**

- **So long as the total mode selective loss (MSL) is less than 3 dB, modal noise will remain within link allocation for modal noise.**

Near field intensity (speckle averaged per Encircled Flux (EF) measurements) at output of a MMF patch-cord for two launches



Optimum MPD



Restricted OFL
(as for an LED)

- OSL produces a disk of light (speckle averaged) with radius roughly equal the offset value

MMF Cable Connectors: OSL CPR and Bandwidth Performance for DMD challenged Legacy 62.5 MMF

Eye Quality with Offset MMF Connector

CPR versus Offset

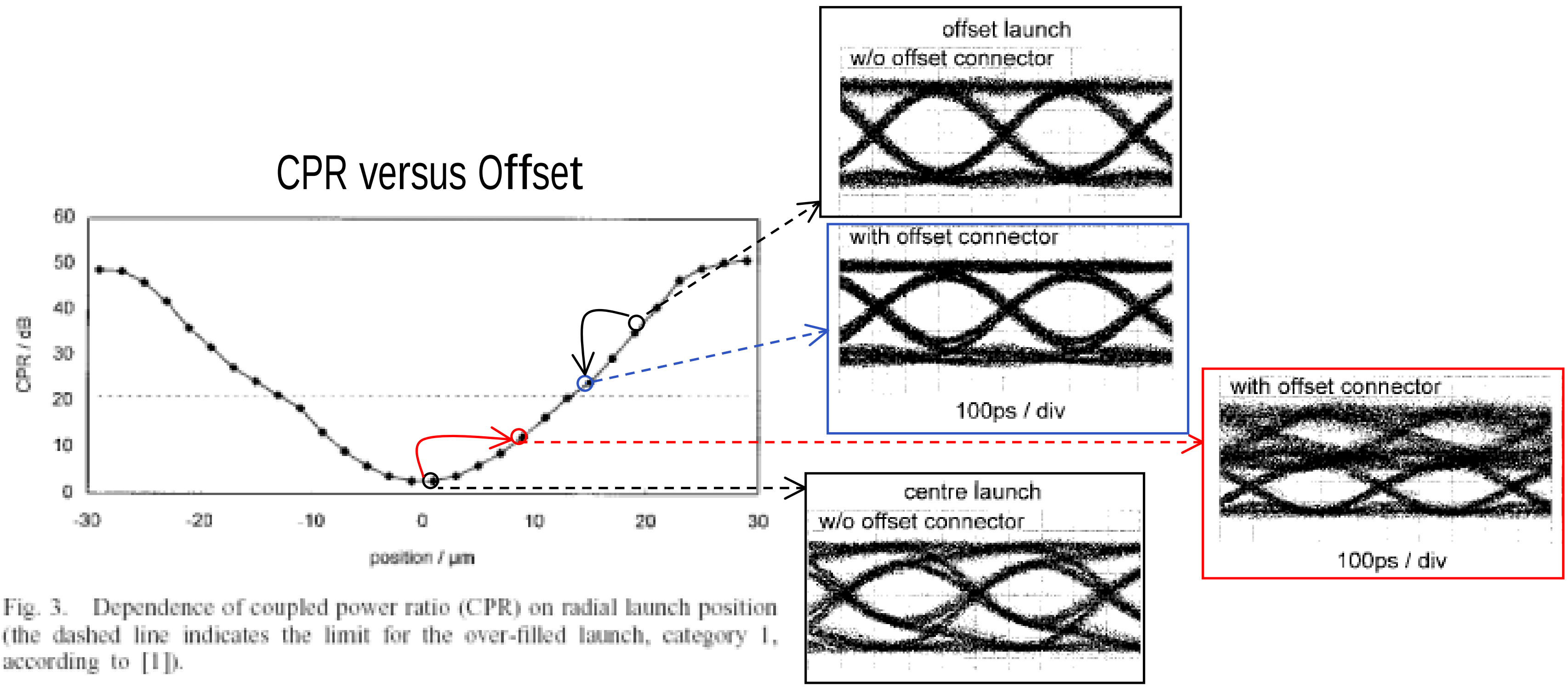


Fig. 3. Dependence of coupled power ratio (CPR) on radial launch position (the dashed line indicates the limit for the over-filled launch, category 1, according to [1]).

Influence of Restricted Mode Excitation on Bandwidth of Multimode Fiber Links
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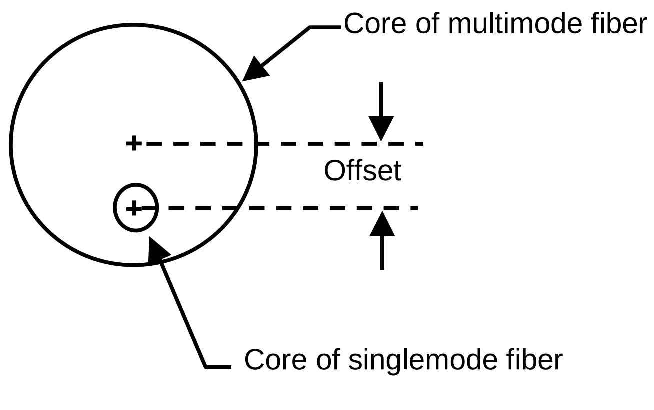
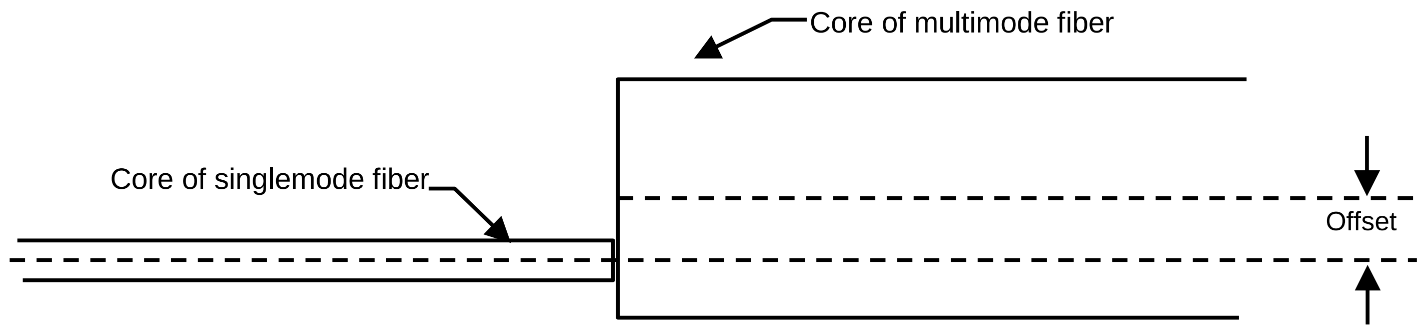
An Experimental and Theoretical Study of the Offset Launch Technique for the Enhancement of the Bandwidth of Multimode Fiber Links
L. Raddatz, I. H. White, D. G. Cunningham, and M. C. Nowell
JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 16, NO. 3, MARCH 1998

Geometry of singlemode offset launch



(a) Top view



(b) Side view

IEEE 802 Specification for Single Mode Offset Launch with 62.5µm MMF for Gigabit and 10Gigabit Ethernet

- The following specifications will guarantee a well behaved link bandwidth of at least 500MHz.km:

⇒ Single Mode Fiber: Standard Single Mode Fiber for operation at wavelengths near 1300nm per ISO/IEC 11801.

⇒ Multi-Mode Fiber: Standard 62.5µm MMF

	62.5 µm MMF
Allowed SMF offset range (µm)	17..23
Allowed CPR range (dB)	28..40

⇒ Field or manufacturing test: CPR specification within the respective range

MBI: Singlemode Center Launch

For LX SM center launch was rejected because:

- The concentricity tolerances of multimode connectors and fiber are such that offsets between 3 um and 5 um are likely:
  - *this would cause the bandwidth to collapse.*
- Mechanical agitation or mechanical stressing of the fiber, especially in the presence of mode selective elements, produces time dependent mode coupling which causes bandwidth variation and collapse.
- The use of center single-mode launch would require the multimode connector tolerances to be tightened (to single-mode tolerances) and even then, the concentricity tolerance of the MMF core and cladding can cause bandwidth collapse.
- Since it was a goal that Gigabit Ethernet should operate on installed ISO 11801 multimode cable plants, connector tolerances could not be changed.

Summary of key conclusions from the MBI

- **As with the EMBI about 30 percent of multimode fibers were observed to have bandwidth less than 500 MHz.km for operation at long wavelength with near core center restricted-mode launches.**
- **Offset Singlemode Launch is required to satisfy the IEEE 802.3 WG requirement that 99% of 62 MMF support an operating range of 550 m (for GbE).**
- **If OSL is not used it was recognized that many links will still operate to ranges of 550 m but the failure rate will be much greater than 1%:** this is beyond the scope of the GbE standard.
- **With OSL D5 of the GbE standard was produced, accepted by IEEE 802.3 and it became the GbE standard.**

LX Operating Ranges of Draft D5

62.5 MMF	**50 MMF**
550 m	550 m

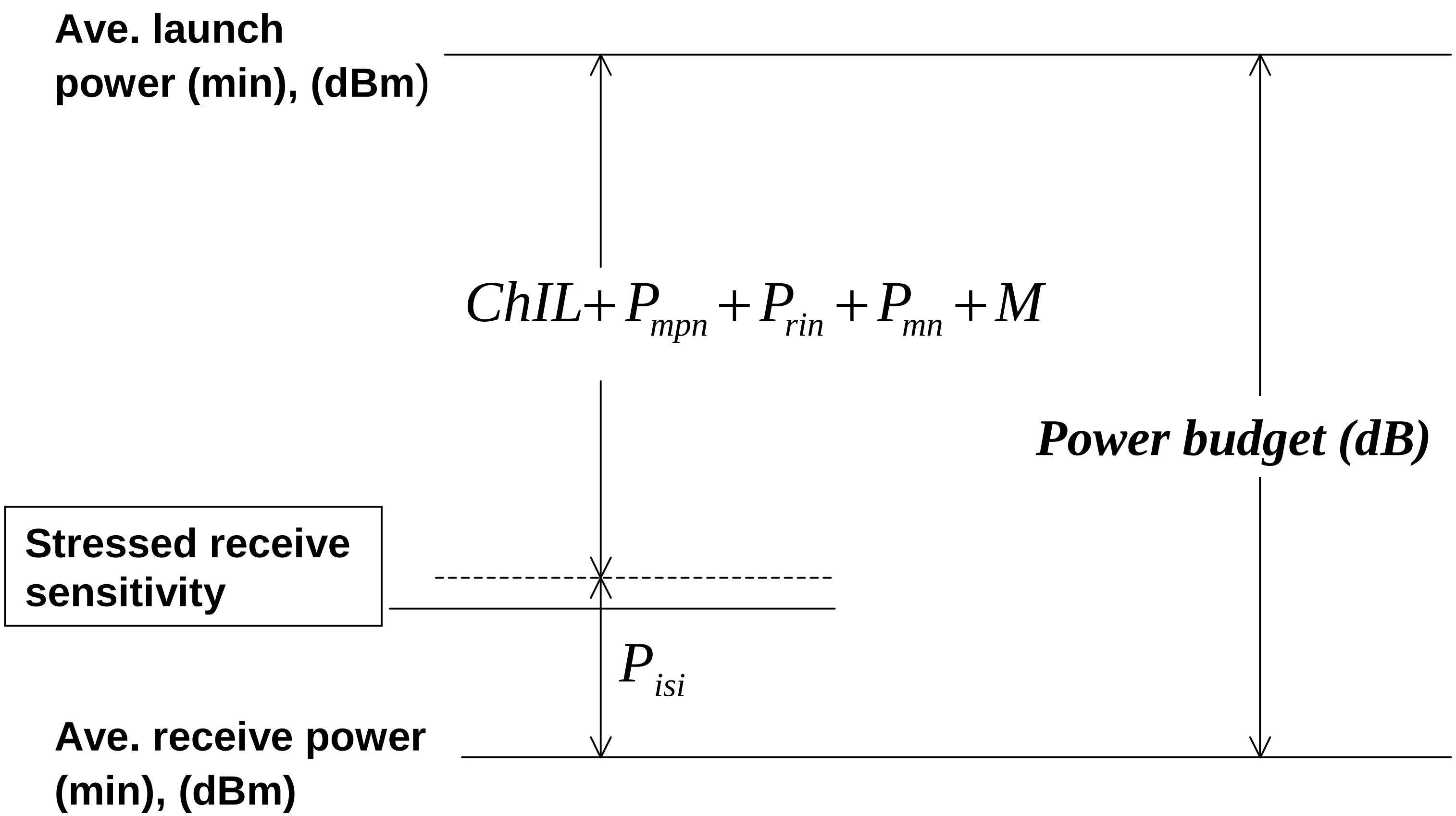
Post GbE: Over Filled Launch (OFL) Modal Bandwidth of MMF for LANs

	Fibre Type				
	62.5 MMF	62.5 MMF	50 MMF	50 MMF	Unit
Modal Bandwidth	200/500	500/500	500/500	2000/500	MHz.km

- Laser grade cable usually requires special TIA/EIA defined launch conditions to achieve OFL or higher bandwidths.
- Encircled flux templates are usually defined for this purpose.
- For operation at 1310 nm on installed base of 62 MMF offset launch ensures at least the OFL bandwidth.

Power Budgeting for Equalized Links

Gigabit Ethernet Power Budget Diagram



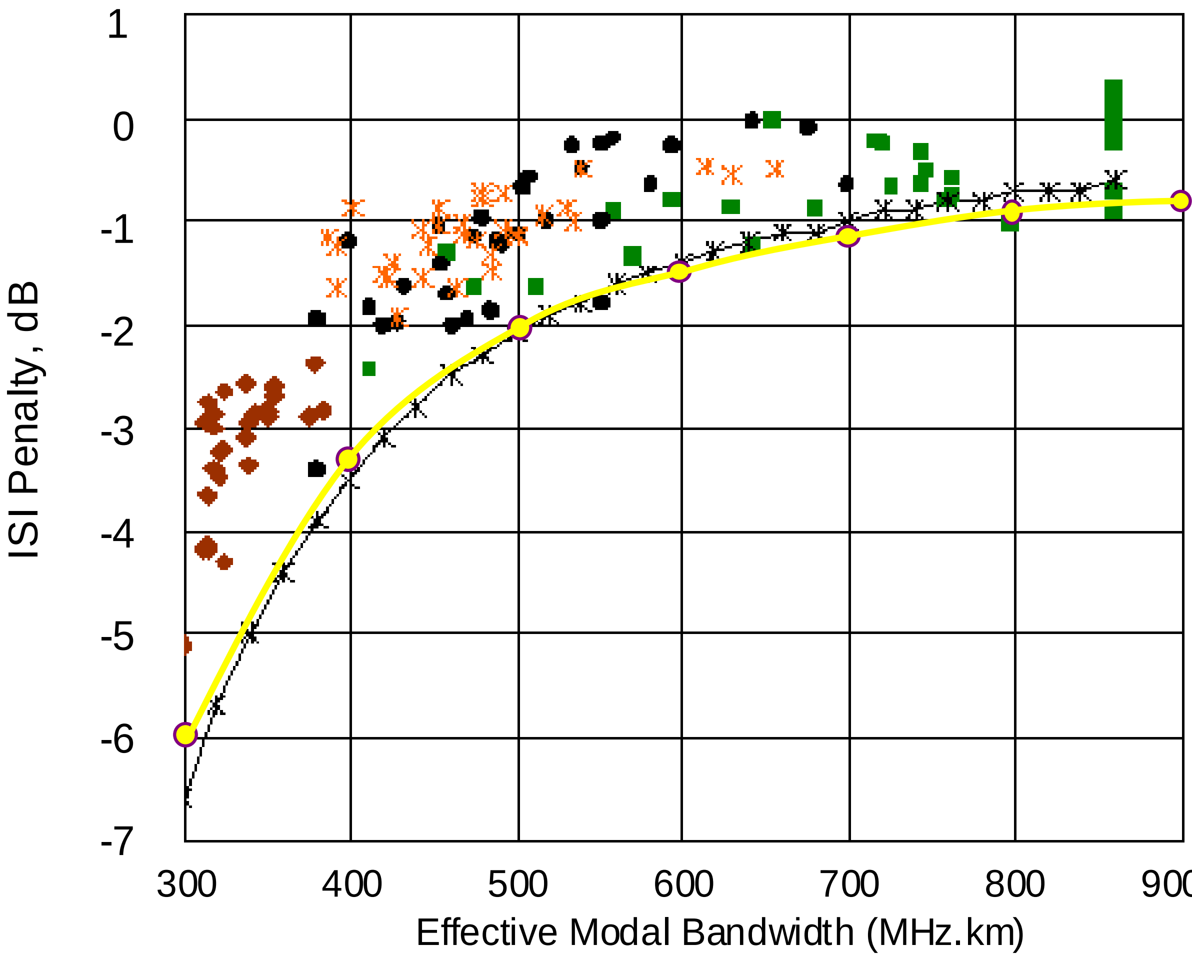
GbE: ISI power penalty equation

The Gigabit Ethernet link model used an approximate solution for the ISI power penatly as follows:

$$P_{isi} = \frac{1}{1 - 1.425 \cdot \exp\left[-1.28 \cdot \left(\frac{T}{T_c}\right)^2\right]}$$

This approximation was used to simplify the spreadsheet implementation of the model.

Comparison of P_{isi} with experimental data



- Pisi gives reasonable worst-case limit.

x GbE approximation.

- Yellow line 10GbE exact solution.

- **3 dB modal bandwidth was sufficient to characterize the ISI power penalty.**

- **This was true for 10GbE too.**

10GbE Equalization: Power penalty (or allocation) equation

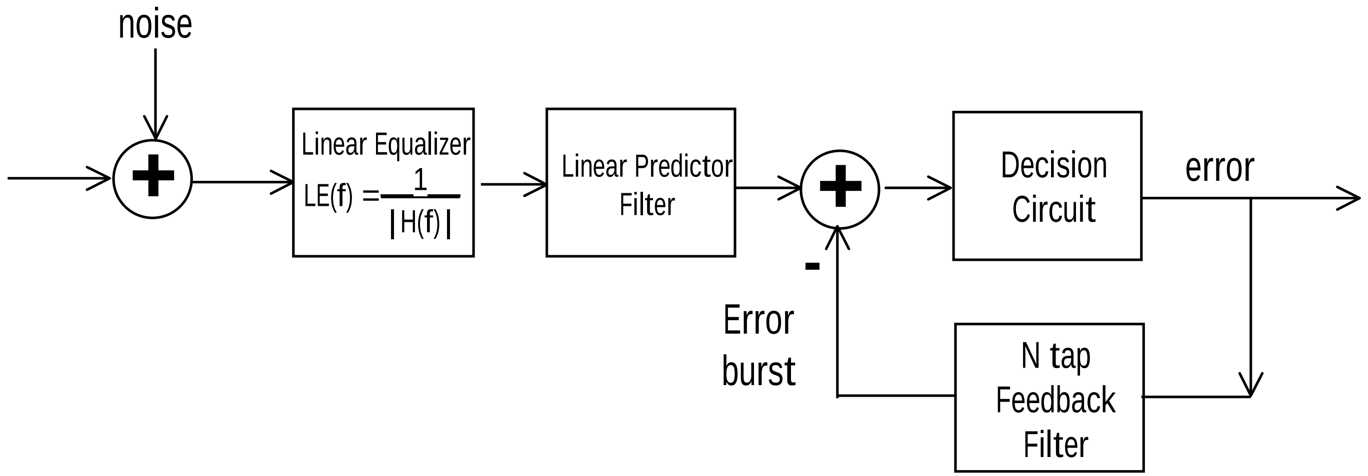
For equalized links the ISI power penalty is replaced by a new power penalty (or allocation) that ensures the equalizer has enough input SNR for correct operation. For perfect equalizers the minimum possible power penalties for LE and DFE are given by the following equations:

$$P_{LE} = \frac{1}{T \cdot \displaystyle\int_{-\frac{1}{2\cdot T}}^{\frac{1}{2\cdot T}} \frac{1}{\left(\left| S(f) \right|\right)^2}\, df}$$

$$P_{DFE} = \exp\left[T \cdot \left[\int_{-\frac{1}{2\cdot T}}^{\frac{1}{2\cdot T}} \ln\left(S(f)^2\right) df\right]\right]$$

Real implementations will require slightly (a dB or so) more power.

Decision Feedback Equalizer (DFE): Error Propagation



Average Length of Error Burst = $2(2^N-1)$

$$P_e = 2^N P_{e,0}$$

- DFE's will increase the undetected error rate for 10GbE. This is because the 64/66 code also propagates errors. CRC 32 was just able to cope with the error propagation of the 64/66 code.

- Also, need to allocate an extra 0.3 dB to compensate for increase in error probability due to error propagation.

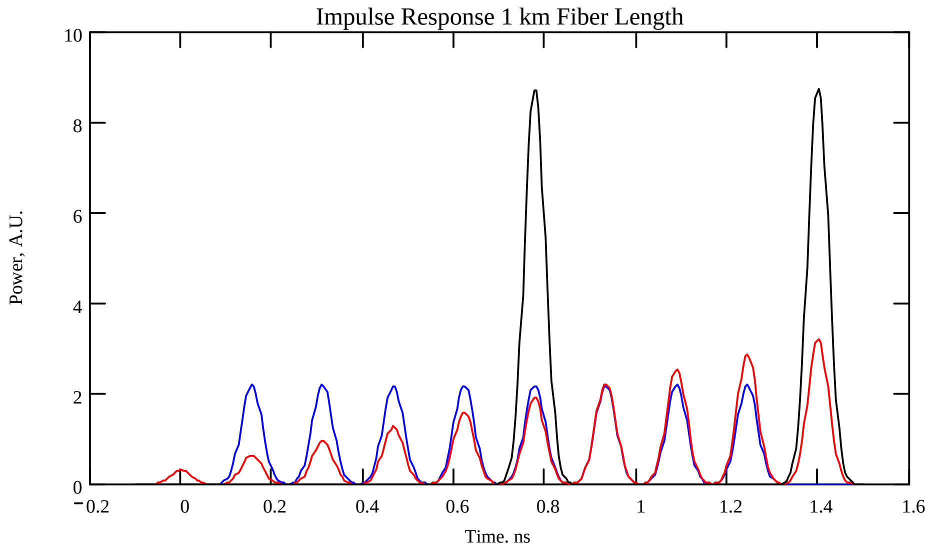
What makes a really bad multimode fibre impulse response?

The following attributes make a MMF impulse response bad:

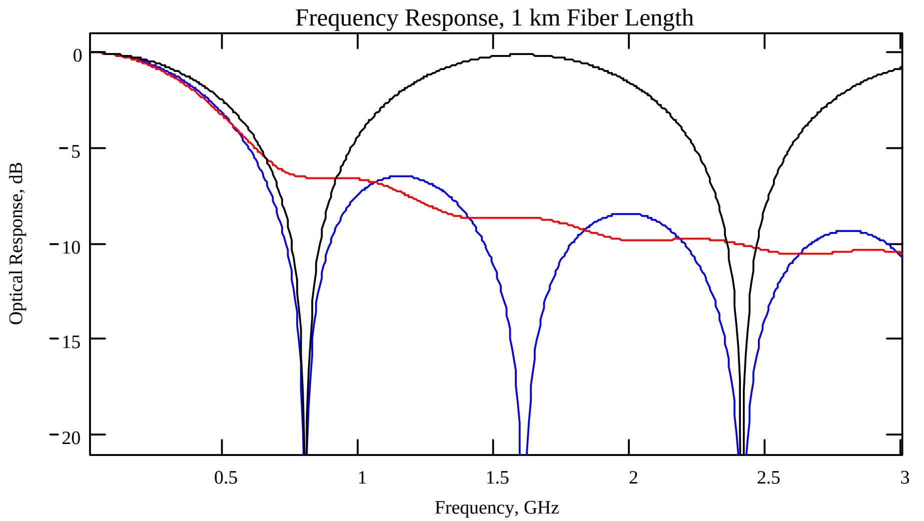
- Modes of equal magnitude.
- Equally space modes.
- Maximum allowed time duration of the impulse

These attributes ensure a low bandwidth response with the deepest possible nulls.

Artificial poor impulse responses



8 equal amplitude qual spaced modes
Ramp of 10 equal spaced modes
Bi-moded response

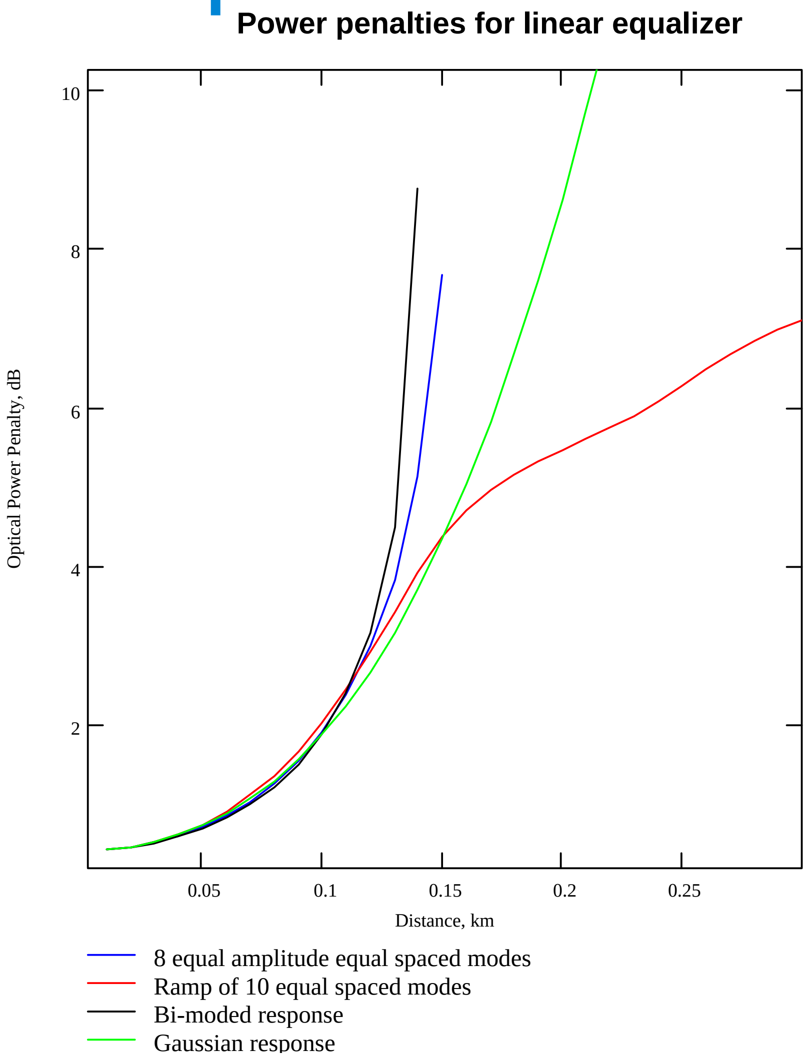


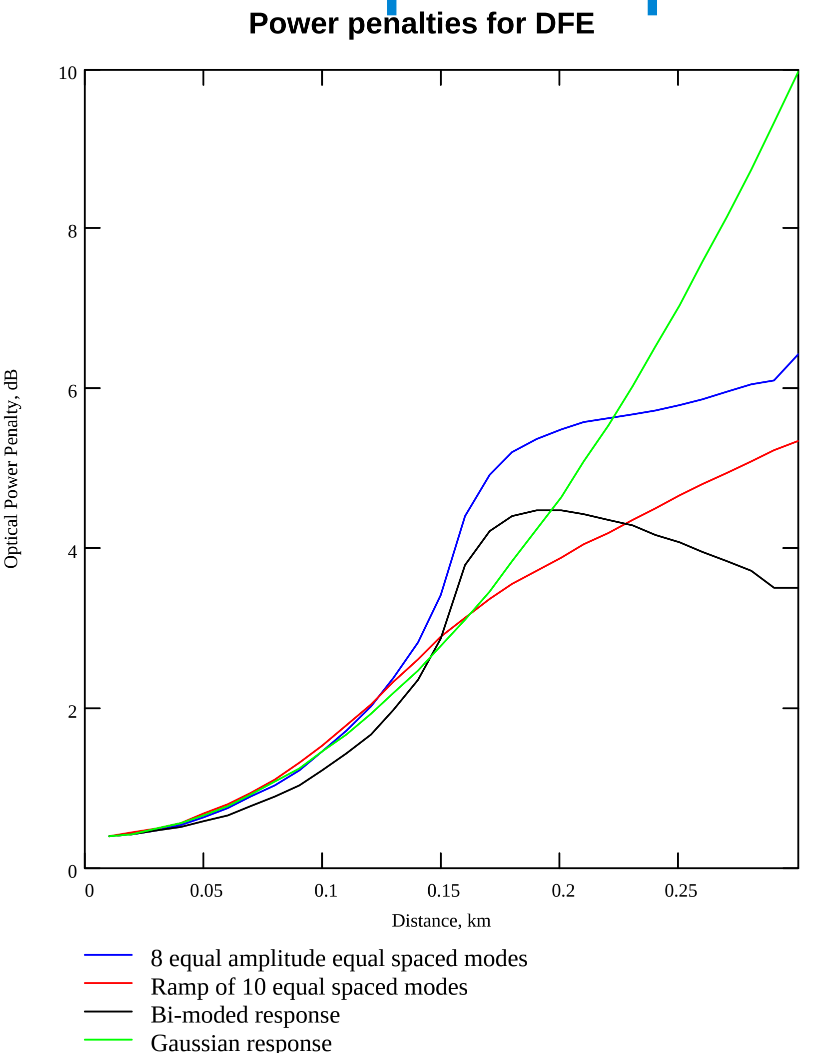
8 equal amplitude equal spaced modes
Ramp of 10 equal spaced modes
Bi-moded response

"Equivalent" comb-like IPRs
(Same 3 dB Optical bandwidth)

Number of modes	IPR duration Normalized
2	0.5
4	0.76
6	0.83
8	0.88
10	0.9
Rect	1.0

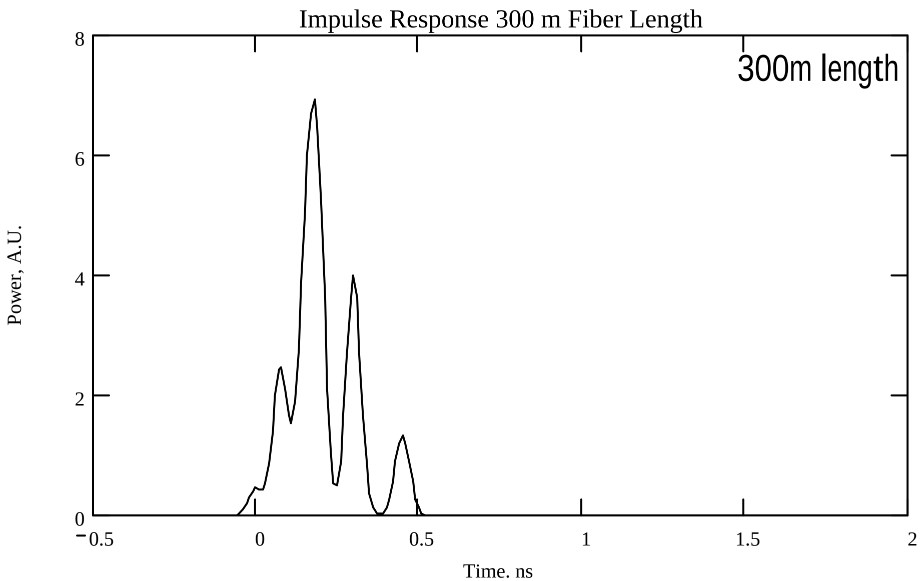
Power penalties at 10 Gb/s for artificial poor responses

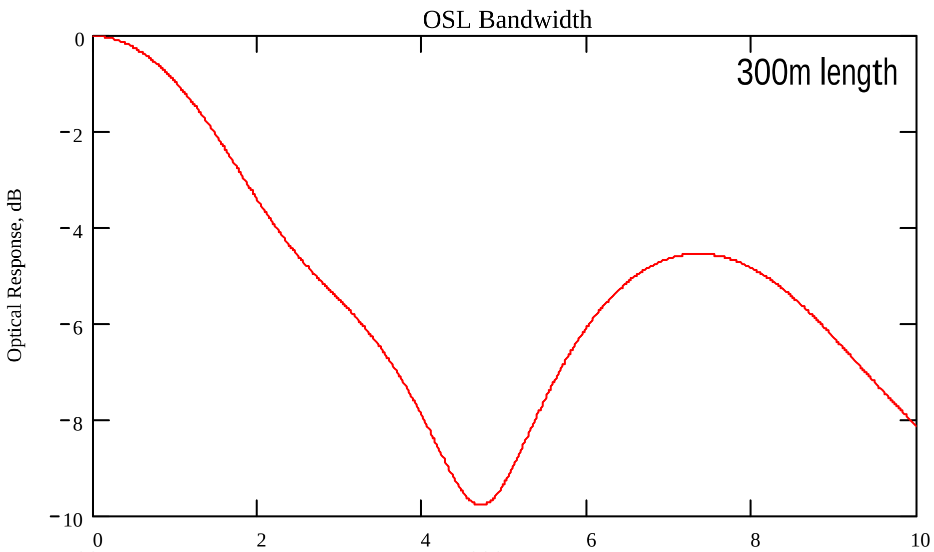


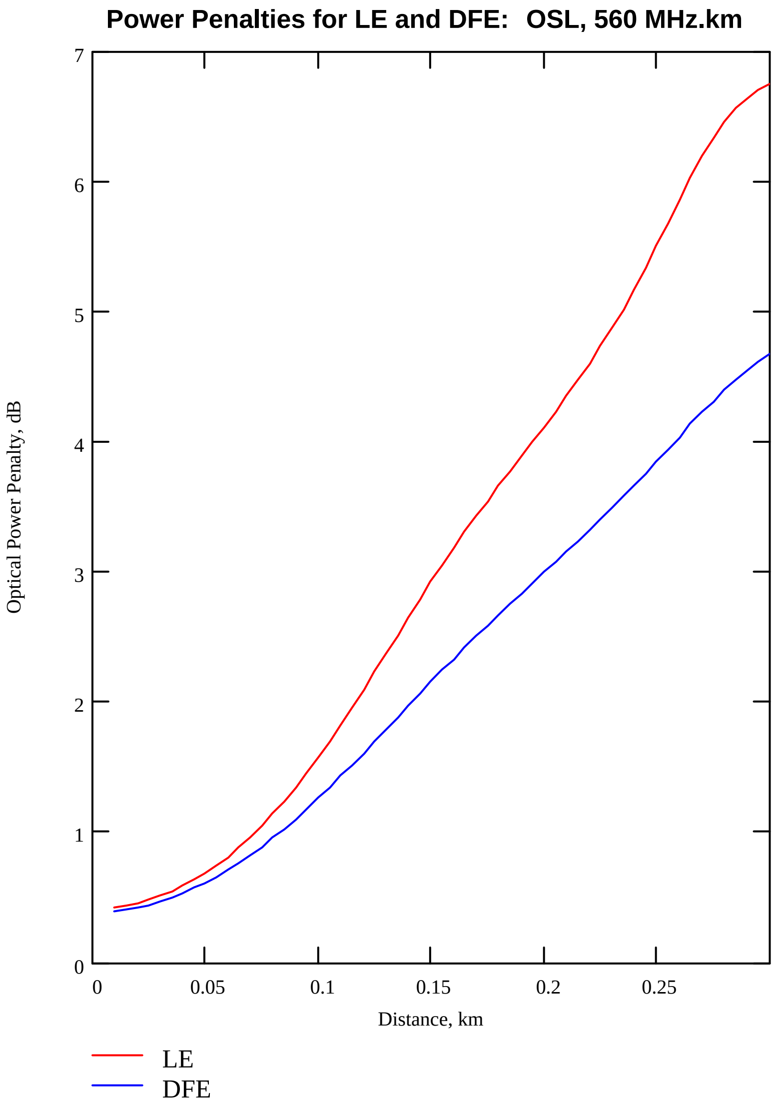


- All responses have a modal bandwidth of 500 MHz.km.
- The power penalty is dependent on the complete impulse response, not the 3 dB modal bandwidth.

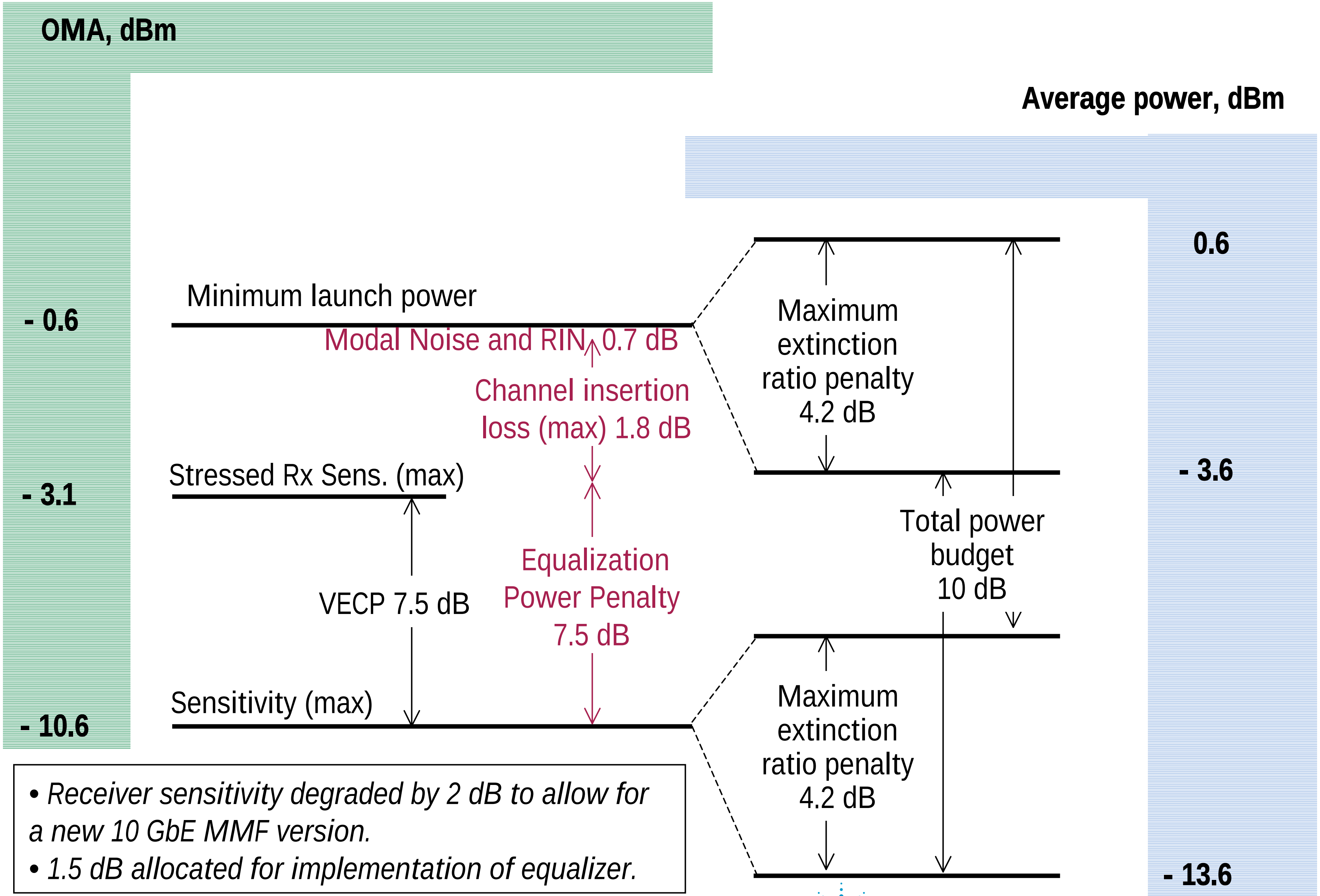
Simulated IPR, FRS and Power Penalties for OSL for a 300 m length of the Fibre as Published in IEEE PTL, V10, No 4, April 1998, p535.







Example Budget: Equalized 10GbE 300 m MMF



- *Receiver sensitivity degraded by 2 dB to allow for a new 10 GbE MMF version.*
- *1.5 dB allocated for implementation of equalizer.*

Modal Noise

Modal Noise (Sometimes called Speckle Noise**)**

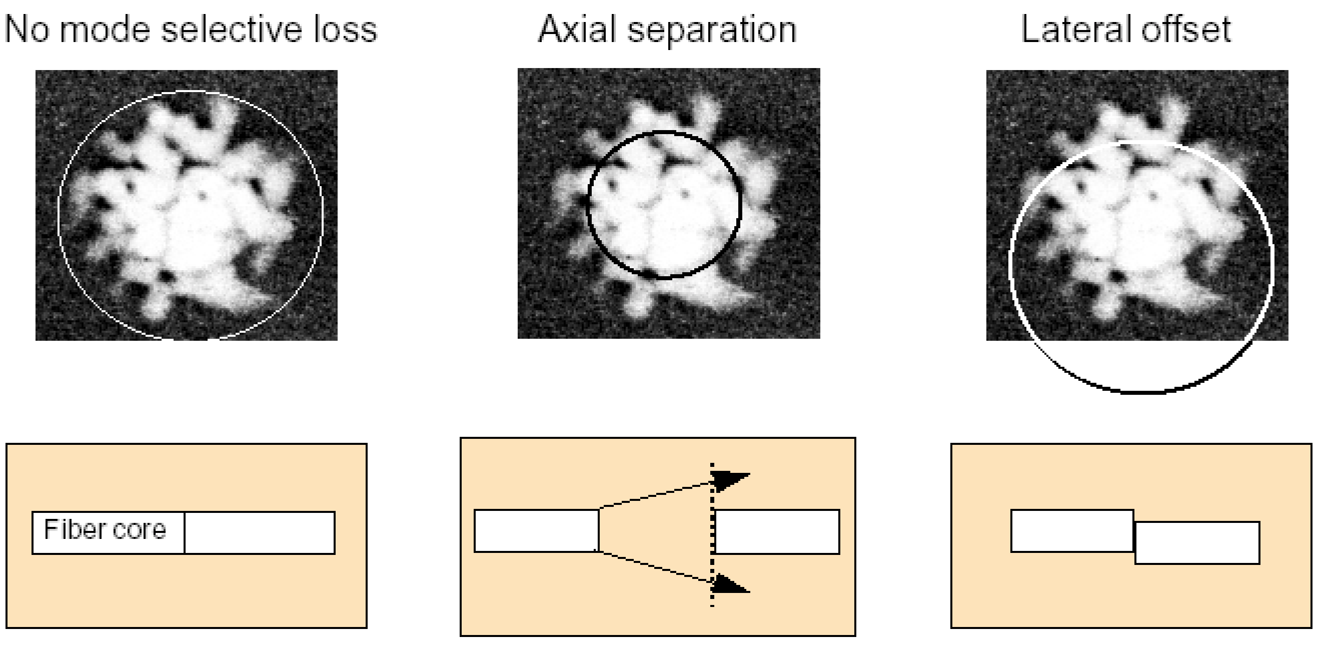
Modal noise (MN) is caused by selective sampling of the speckle pattern of the light within a multimode link.

Modal noise is potentially disastrous because it sets an upper limit to the SNR – bit error rate floors can occur.

Three conditions must be simultaneously present for modal noise to occur:

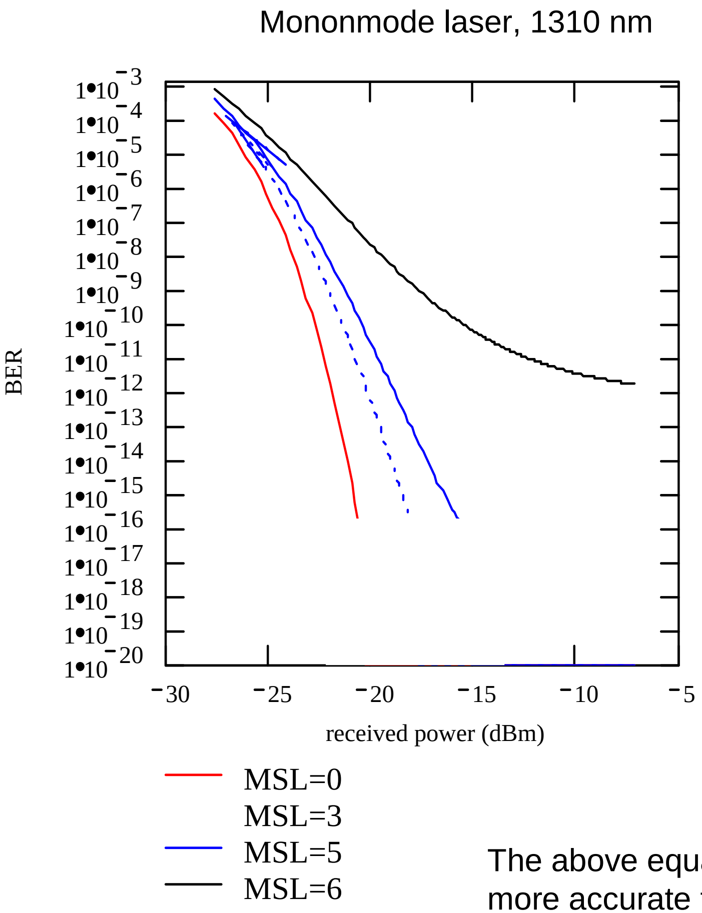
- There must be a speckle pattern.
- There must be points of mode selective loss (MSL).
- The speckle pattern must be time dependent.

Modal noise : Speckle & Mode selective loss



- Lasers produce strong speckle patterns at the output of MMF links.
- Typically mode selective loss (MSL) occurs at connectors.
- If all the light is not detected at the photodiode then MSL is created.

Modal Noise: Variance of the noise and BER example



$$var_{mn} = \frac{\left(V_H\right)^2 \cdot (1 - msl)}{(msl) \cdot N \cdot N1} \cdot k^2 \cdot \left(1 - \frac{1}{N1}\right) + \frac{\left(V_L\right)^2 \cdot (1 - msl)}{(msl) \cdot N \cdot N1}$$

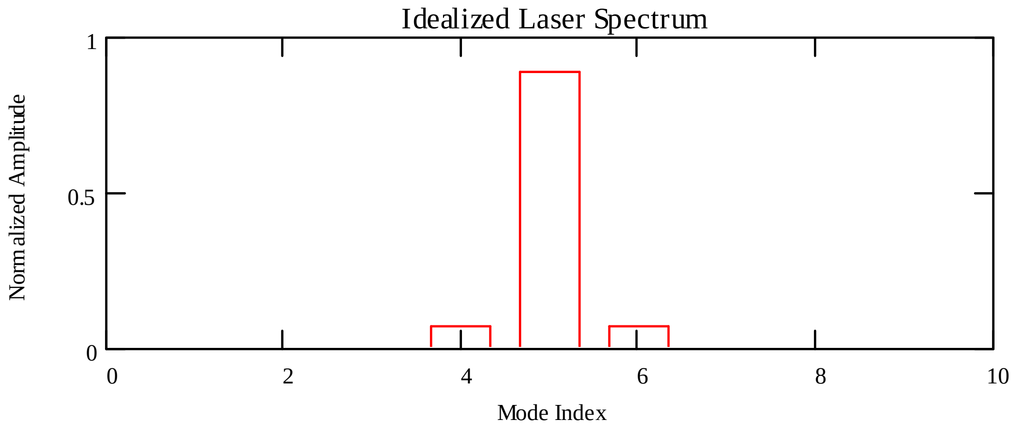
Where:

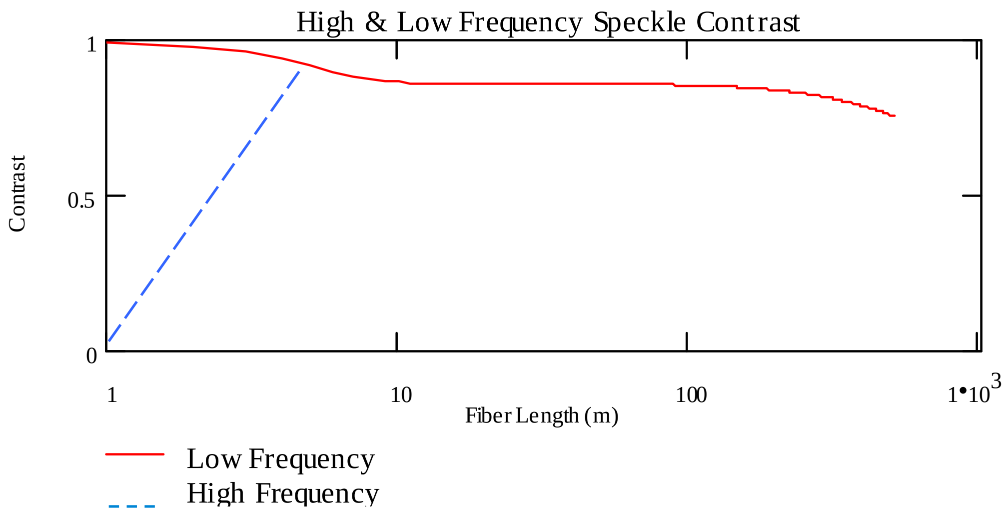
V	=	low frequency visibility
V	=	high frequency visibility
msl	=	mode selective loss (linear units)
k	=	mode partition factor
N	=	effective number of excited fiber modes
N1	=	effective number of laser modes

The above equations are accurate for single points of MSL only. The GbE committee used the more accurate theory of Richard J. S. Bates, Daniel M. Kuchta and Kenneth P. Jackson described in the following publication as the reference model for modal noise:

Richard J. S. Bates, Daniel M. Kuchta, Kenneth P. Jackson, "Improved Multimode Fiber Link BER Calculations due to Modal Noise and Non Self-Pulsating Laser Diodes", Optical and Quantum Electronics, 27 (1995) pp 203-224.

Modal Noise: Speckle Visibility

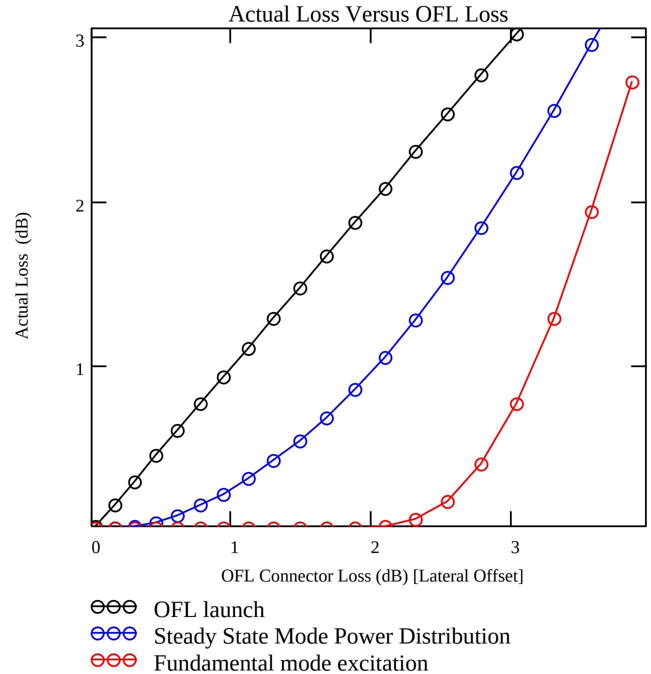


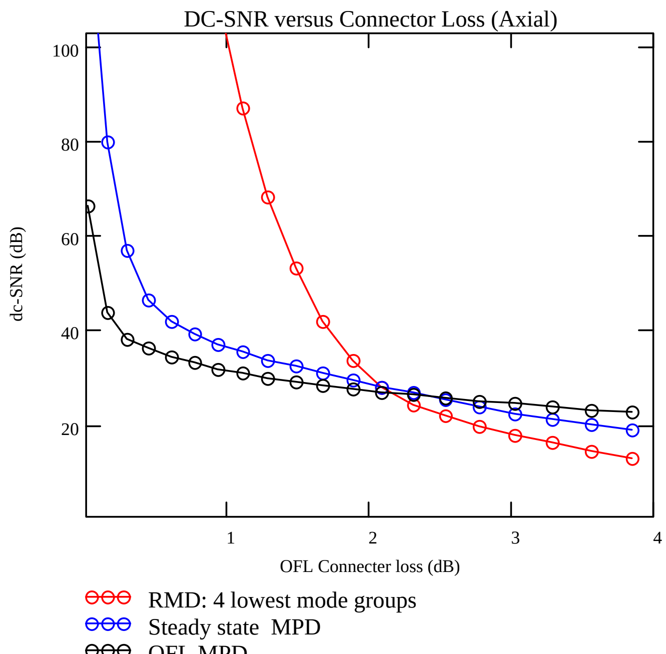


Modal Noise: Low frequency changes in speckle

Changes in the relative phases of the various fibre modes cause low frequency changes in the speckle pattern. Some conditions which can cause these phase changes are:

- Vibrations
- Temperature variations
- Stress on the fibre
- Slight frequency changes of laser output



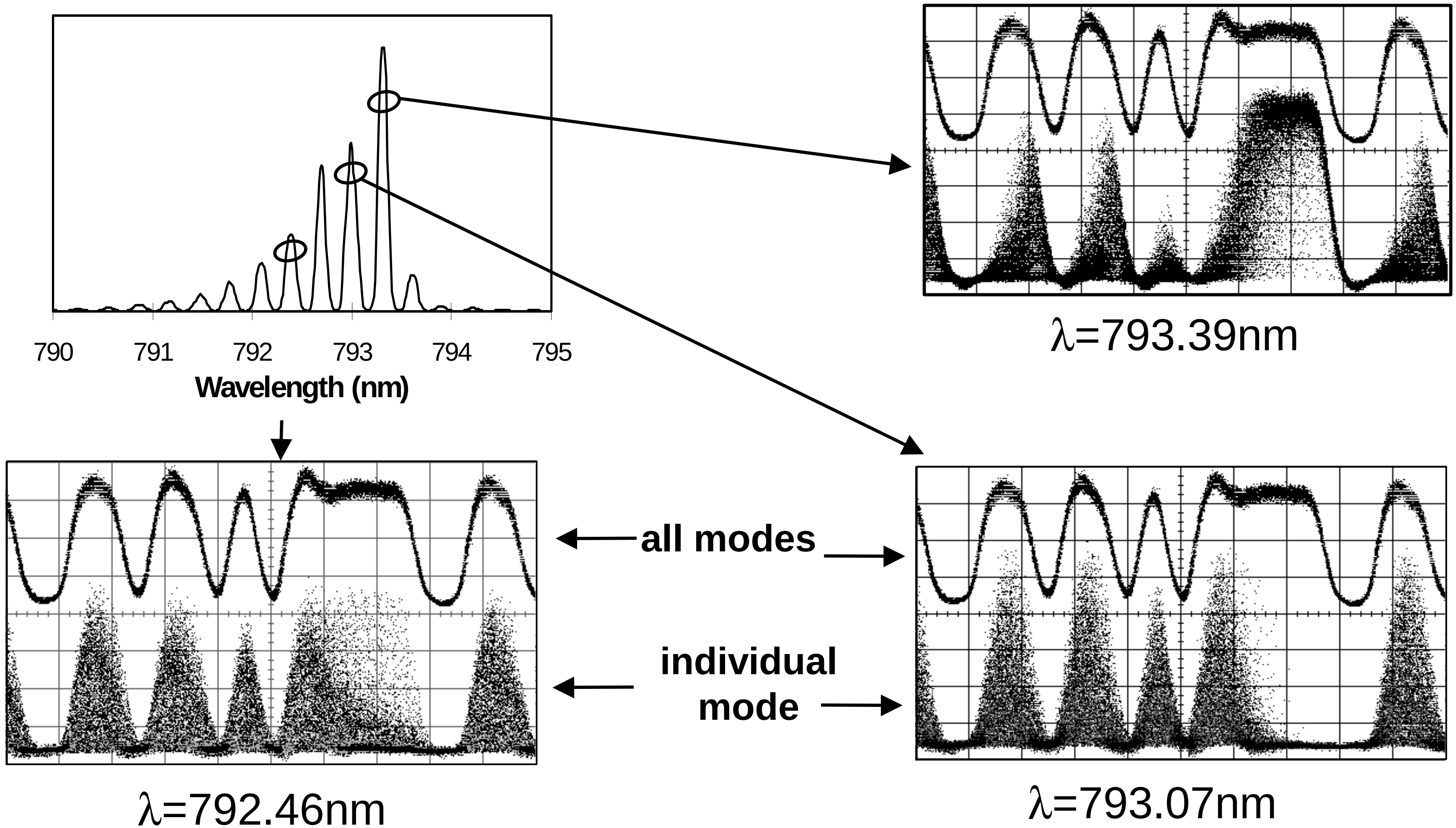


Modal Noise & Restricted launches

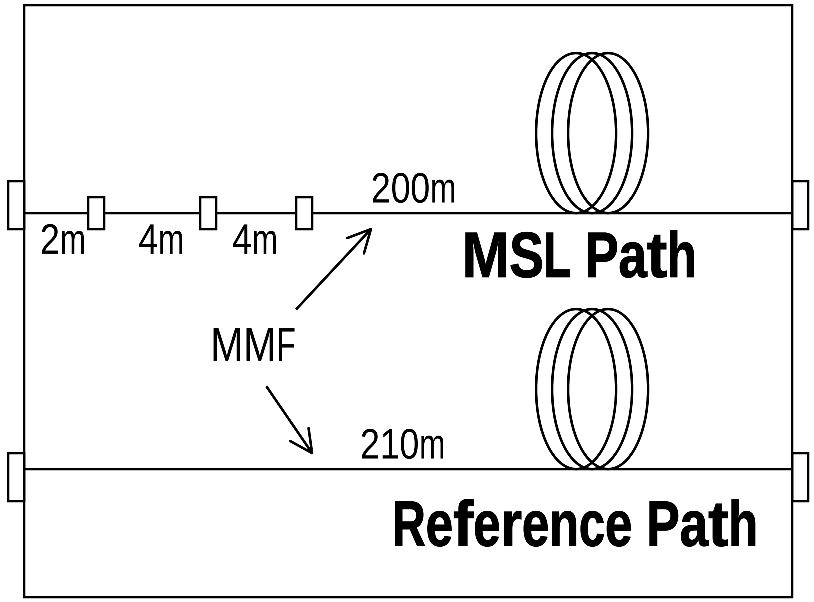
Assuming the optical receiver introduces no MSL:

- Restricted launches tend to suffer less loss and therefore produce less modal noise.
- However, if large amounts of MSL are involved restricted launches eventually produce more modal noise.
- If elements with large MSL values (Mode filters) are used then modal noise will become a major issue that will need to be investigated rigorously.

Modal Noise (FP lasers): Mode Partitioning causes <u>high frequency</u> changes in the speckle pattern



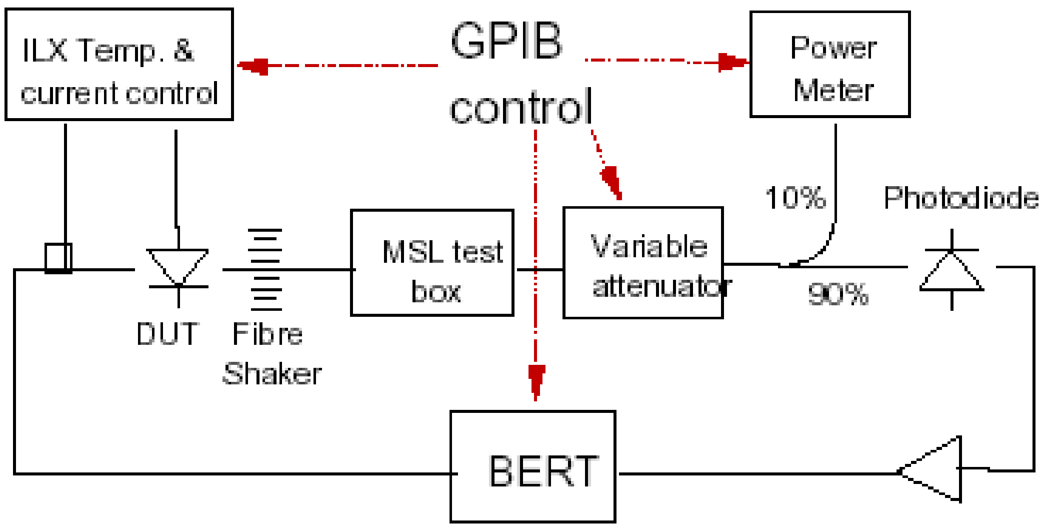
Modal Noise Test Methodology (per GbE 1,2 GFC)



MSL test box

This committee will need to define the equivalent test box for modal noise testing of its 10 Gb/s PMD proposals.

Modal Noise: Test procedure setup



Shake fibre

Ramp laser temperature

Computer controlled modal noise power penalty measurement setup.

- If the MSL value is known then the modal noise power penalty can be theoretically estimated.
- But testing is still required for new situations.

Implications for 10 GbE project

- **Launch conditions are important:**
  - Obviously, I recommend OSL! Acceptance of this or an equivalent TIA EF specification (the TIA has done great work in this area) would significantly speed standardization.
  - But this committee will need to study and define launch conditions.

- **Both static and dynamic tests (shakers with defined points of MSL) are absolutely required for BER, IPR, FRS and modal noise specification.**
  - So far I very few dynamic measurements or simulations have been reported. Static results are necessary but are insufficient!

- **We need a common terminology for simulations and measurements of the power penalty or allocation for equalized links** (and other proposed techniques too).

- **We need a clear technical definition for the installed cables we are to operate over:**
  - The statistical definition of cable parameters (DMD seems to be the most succinct and relevant parameter), the definition of test cables for lab testing.
  - Do we need field testing?

Closing comments

- **The appropriate complexity performance tradeoff enables the economic feasibility sweet spot . SX is a good example of this, it is the most successful Gb / s PMD.**

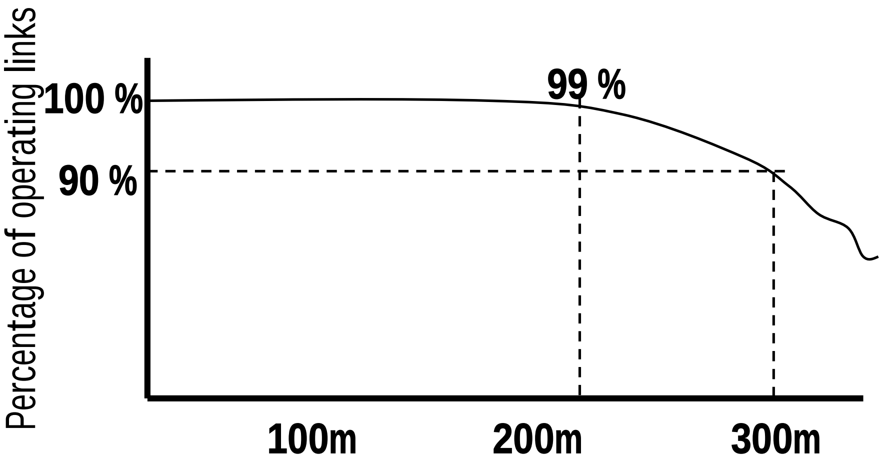
GbE Operating Ranges

	62.5 MMF	50 MMF
SX	220 m	550 m
LX	550 m	550 m

10GbE Operating Ranges

	62.5 MMF	50 MMF
LX4	300 m	300 m
LXEZ	220 m	220 m

- **I believe that pushing for 99% coverage at 300 m will force the wrong tradeoff, increase complexity, increase cost, severely limit implementation scope and push the standard out of Ethernets economic sweet spot.**



Advantages of this approach include:

- Practical equalization power penalties, (3 – 5) dB.
- Wide implementation space (LE, DFE and more).
- Shorter standardization time (this is very important as new cable will obsolete the need for this PMD).

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