1.25 GBAUD, 550 m, BUILDING BACKBONE LINKS ON INSTALLED 62.5 MULTIMODE FIBRE FOR IEEE 802.3: *leveraging existing long wavelength transceiver specifications*.

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Introduction

Near the end of the 5/21-22/96 IEEE 802.3 Gb/s Ethernet Interim Meeting, there was extensive discussion attempting to reconcile the committee's desire for a 550 m multimode fiber (MMF) link length at 1.25 GBd with the achievable limits specified by current worst case 850 nm laser diode (LD) proposals. The proposals were based on over-filled launch (OFL) modal bandwidth specifications. For 50/125 um diameter MMF (50 MMF) operating in the 850 nm range with a modal bandwidth of 500 MHz.km, the projected limits are 450 m with CD LD spectral parameters and 550 m with vertical cavity surface emitting laser (VCSEL) spectral characteristics. For 62/125 um diameter MMF (62 MMF) having a modal bandwidth of 160 MHz.km in the 850 nm range the limits are projected to be 200 m for CD LDs and 250 m for VCSELs.

There was a motion to specify 550 m with 50 MMF and 100 m with 62 MMF (to match the existing in ISO 11801 building wiring system horizontal length). This motion was tabled until the 7/96 IEEE 802.3 Plenary meeting when additional data on link length requirements and technical capabilities were expected to be available. LAN backbone links primarily utilize 62 MMF in the U.S. and Europe. SMF is installed to achieve >= 2 km link lengths.

For 1 Gb/s Ethernet MMF links, recent work reported in this paper demonstrates that 1300 nm SMF transceivers have very high modal bandwidth and sufficiently low modal noise associated with mode selective loss when launched into MMF. This paper proposes leveraging 1300 nm SMF transceivers to support both SMF links and a 550 m link length with existing 62 MMF building wiring. There are many suppliers today of

1300 nm SMF transceivers using Fabry Perot LDs. In the future, 1300 nm VCSEL transceivers will meet this link specification with lower complexity.

We will begin with a review of the current international building wiring standard. Data on the current installed base, which will indicate the necessity for a 550 m 62 MMF PMD, will also be presented.

Long wavelength operation is proposed since it is the only currently available technology which is able to support the 62 MMF installed base. The paper will address the technical issues that might be thought to impede a 62 MMF, 1300 nm LD solution; modal bandwidth and modal noise. Theoretical and experimental results will show that 1.25 GBd, 550 m, 62 MMF, 1300 nm LD links have the same robustness as 1.25 GBd, 550 m, 50 MMF, 850 nm LD links.

Experimental results indicating the future possibility of developing 2 km, 62 MMF, link specifications based on 1300 nm LDs and restricted mode launch will be discussed.

Installed Customer Premises Cabling

Industry standards are being developed for fibre optic components, systems, planning & installation guides and test procedures by IEC SC86, CENELEC in Europe, and IEEE 802 & EIA in the US. Optical cabling specifications are contained in CPC standards produced by ISO/IEC (ISO 11801), CENELEC (EN 50173) and EIA/TIA (EIA/TIA 568). Installation practices are also being developed as supplements to these CPC standards.

Since ISO/IEC 11801 is referenced by most LAN standards and by IEEE 802 LAN standards in particular the ISO/IEC 11801 cable model will be summarized.

ISO/IEC 11801 link lengths

The ISO/IEC 11801 cable model is shown in Figure 1 the maximum link lengths are stated. In addition to the indicated link lengths ISO/IEC 11801 allocates an additional length for connecting cables at each level. In the horizontal and building backbone a maximum of 10 m and 50 m respectively are allocated for connecting hardware.

ISO/IEC 11801 specifies other important parameters such as worst case connector loss, minimum fibre bandwidth etc.,. These specifications will be stated as required later in this document.

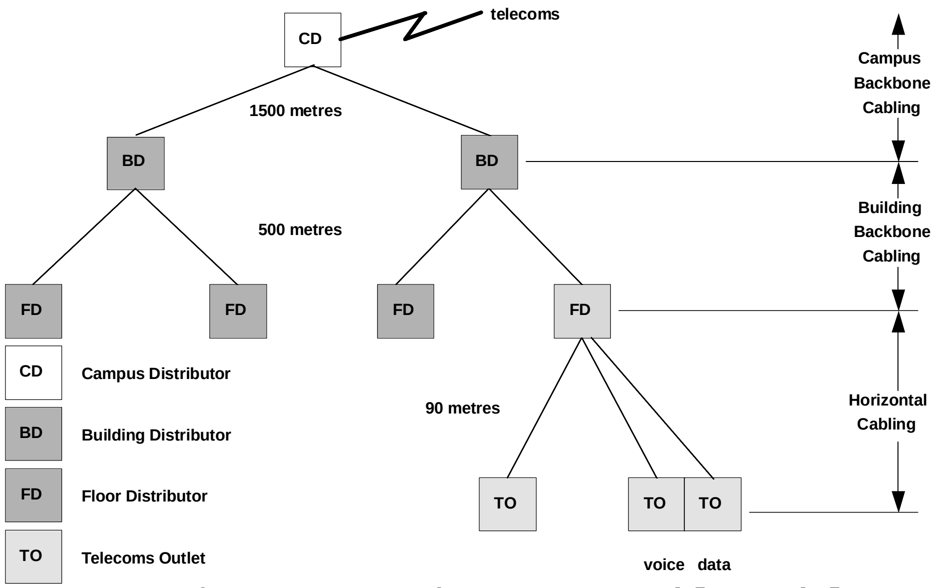


Figure 1: ***ISO/IEC 11801 Cable Model.***

LAN standards *preferred* MMF cable plant

A profile of the primary fibre optic LAN standards is contained in Table 1. The table indicates which fibre type is preferred by the associated standard. Clearly 62 MMF is the preferred cable for LAN applications. Although, there is much less 50 MMF installed world wide it cannot be ignored as it is strongly supported by Fibre Channel and for historical reasons by some particular countries, i.e. Japan and Germany. The listed standards support a maximum distance of 2 km for campus LAN applications. Single mode fibre (SMF) can support much larger distances for WAN applications if required.

LAN Standards	Bit Rate	Distance	Optical Fibre	Connector
IEEE 802.3 FOIRL	10 Mbit/s	2 km	62.5/125 MM	SMA
IEEE 802.3 10Base-F	10 Mbit/s	2 km	62.5/125 MM	ST
IEEE 802.3 100Base-FX	100 Mbit/s	2 km	62.5/125 MM	SC
IEEE 802.5J Token Ring	16 Mbit/s	2 km	62.5/125 MM	SC
IEEE 802.12 Demand Priority	100 Mbit/s	2 km	62.5/125 MM	SC
ANSI X3T12 FDDI	100 Mbit/s	2 km	62.5/125 MM 8/125 SM	FD FD
ANSI X3T11 Fibre Channel	>106 Mbit/s	2 km	50/125 MM 8/125 SM	SC SC
ATM Forum 155Mbit/s	155 Mbit/s	2 km	62.5/125 MM 8/125 SM	SC

Table 1: ***Optical Fibre LAN Standards***

European installations

Market research includes assessments from many cabling vendors regarding the penetration of optical fibre into the building backbone. The key results are summarized in Table 2 for the period 1990 to 1996. The data of [1] indicates that very little SMF has been installed on the campus.

	1990	1991	1992	1993	1994	1995	1996	Dominant Fibre Type
Germany	30%	45%	55%	70%	80%	90%	95%	62.5 MMF*
France	30%	45%	55%	70%	80%	90%	95%	62.5 MMF*
UK	30%	45%	55%	70%	80%	90%	95%	62.5 MMF
Nordic	30%	45%	55%	70%	80%	90%	95%	62.5 MMF
Holland	20%	30%	40%	50%	60%	75%	85%	62.5 MMF
Italy	neg	10%	15%	20%	35%	50%	70%	62.5 MMF
Spain	neg	10%	15%	20%	35%	50%	70%	62.5 MMF
Other	10%	20%	35%	45%	55%	70%	80%	62.5 MMF

Table 2: **European Penetration of Fibre in the Building Backbone** ***(* 50 MMF also installed but of decreasing importance)[1]***

In order to estimate the number of fibre optic backbone links within the building a ratio of 50:1 is assumed between outlet pairs (i.e., voice + data positions) and building backbone nodes. This ratio defines the mean modularity of a Floor Distributor (FD). A ratio of 10:1 is also assumed between Floor and Building Distributors (BD), as shown in Figure 2

Total cable lengths estimated for Horizontal, Building and Campus Backbone application can then be divided by the total number of links in each domain. The average link lengths (rounded) are as follows[1]:

Average Horizontal Link Length: 50 metres

Average Building Backbone Link Length: 250 metres

Average Campus Backbone Link Length: 1000 metres

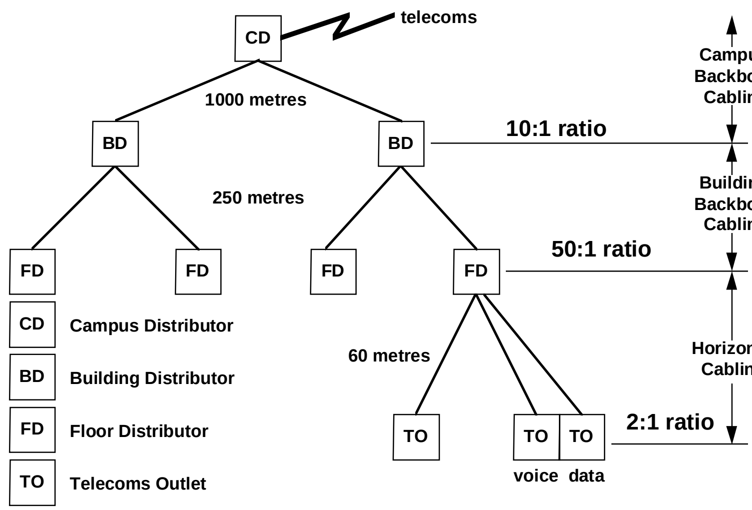


Figure 2: ***Customer Premises Cabling Model with Average Link Length Calculated from [1].***

The dominance of 62 MMF in European installations is not surprising given that it is the preferred cable of ISO/IEC 11801 and for most LAN applications. It is also known that 62 MMF has been installed in the vast majority of LANs within the USA for similar reasons.

The building backbone interconnect(channel and link) model of ISO/IEC 11801 are shown in Figure 3. The maximum allowed link length is 500 m and a worst case philosophy of a connector and splice at each end of the link are assumed. A channel includes patch cords for connecting the equipment to the link, the total length of the patch cords must be less than 50 m.

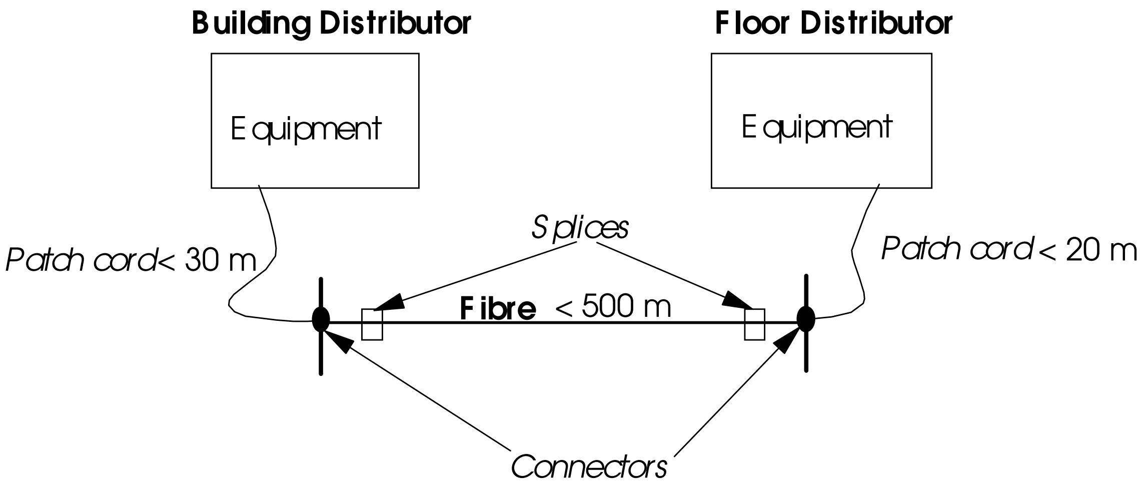


Figure 3: ***Interconnect (Channel and Link) model from ISO/IEC 11801.***

Allocation for Mode Selective Loss (Modal Noise): Theory

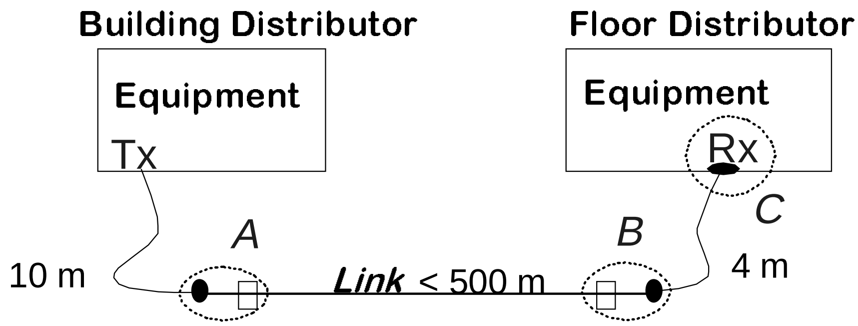
Many standards (ATM Forum, Fibre Channel, Serial HIPPI) contain power penalty allocations to allow for mode selective loss (MSL). A modal niose theory[2] has been developed and used to predict the worst MSL allocation for all these standards.

In addition an ad hoc industry group (Hewlett-Packard, Honeywell, IBM, VIXEL) sometimes called the modal noise test methodology group (MNTMG) has developed an initial MSL power penalty measurement test procedure. A PC based simulation tool which implements the theory of [2] has been agreed and developed by the group for calculating worst case power penalties. An initial draft test procedure has recently been transferred to the TIA FO 6.5 committee for standards development.

Distributed MSL

A very important conclusion from the original theory[2] and the work of the MNTMG was that the MSL is distributed throughout a fibre optic link.

Worst case ISO/IEC 11801 MSL model



- ***Worst case connector loss (0.75 dB) and splice loss (0.3 dB) lumped together:***
  - *MSL of A = 1.05 dB*
  - *MSL of B = 1.05 dB*
  - *MSL of C = 0.75 dB*
  - *Short patch cords produce highest level of modal noise*
- ***MSL** is **distributed** throughout the link*

Figure 4: ***Worst case ISO/IEC 11801 MSL model***

Theory predicts that the MSL nearest the transmitter will generate the most modal noise. However, even for the worst case link model of ISO/IEC 11801 only 1.05 dB of loss can be placed near the transmitter. Figure 5 shows the calculated power penalties as a function of link length for ISO/IEC 11801 links for both short and long wavelength lasers. To maximize modal noise a 10 m patch cord is assumed at the transmit end and a 4 m patch cord at the receive end of the link. For the calculation the worst case loss of the connector and splice at each end of the link are lumped together, the resulting 1.05 dB of loss is assumed to be totally MSL, the minimum separation between the two 1.05 dB MSL points is 4 m. An additional 0.75 dB of MSL is assumed to be present at the connection to the optical receiver. The total amount of MSL is 2.85 dB (see Figure 4).

The laser spectra used for the calculations were those assumed by the MNTMG Mathcad model: three laser modes having relative intensities of 0.1, 1 and 0.1, each mode had a linewidth of 5 GHz and a mode partitioning factor (k) of 1.

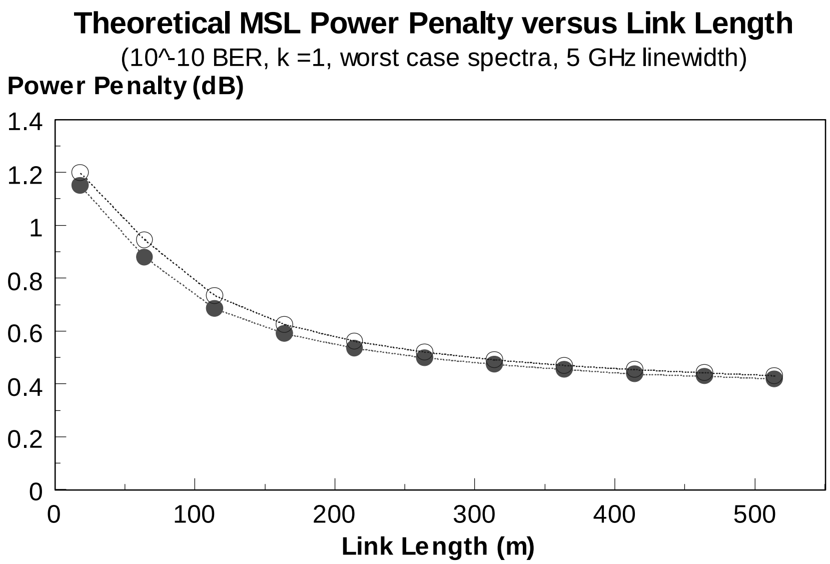


Figure 5: ***Calculated power penalties for 850 nm, 50 MMF (open circles) and for 1300 nm, 62 MMF (filled circles), laser diodes and worst case ISO/IEC 11801 model. Patch cords at transmit and receive end of link assumed to be 10 m and 4 m respectively to maximize modal noise. Total link loss is 2.8 dB.***

MNTMG worst case link model

To ensure that a reasonable worst case link is analyzed and tested the ad hoc modal noise test methodology group assumed that three 1 dB points of MSL separated by 4 m are placed 12 m from the transmitter output connector. The distance of 12 m ensures that the link has enough bandwidth for both high frequency and low frequency modal noise to be present and close to their maximum levels [2]. The laser spectra used for the calculations were those assumed by the MNTMG Mathcad model.

The power penalty of the worst case, long wavelength, 62 MMF link is expected to be equal to that of the worst case, short wavelength, 50 MMF because the number of fibre modes are equal for these two cases(see Figure 6). Figure 7 and Figure 8 plot the predicted worst case power penalties for short and long wavelength lasers according to the MNTMG model. Maximum power penalties of approximately 1 dB are predicted as are specified for ATM Forum, Fibre Channel and Serial HIPPI standards.

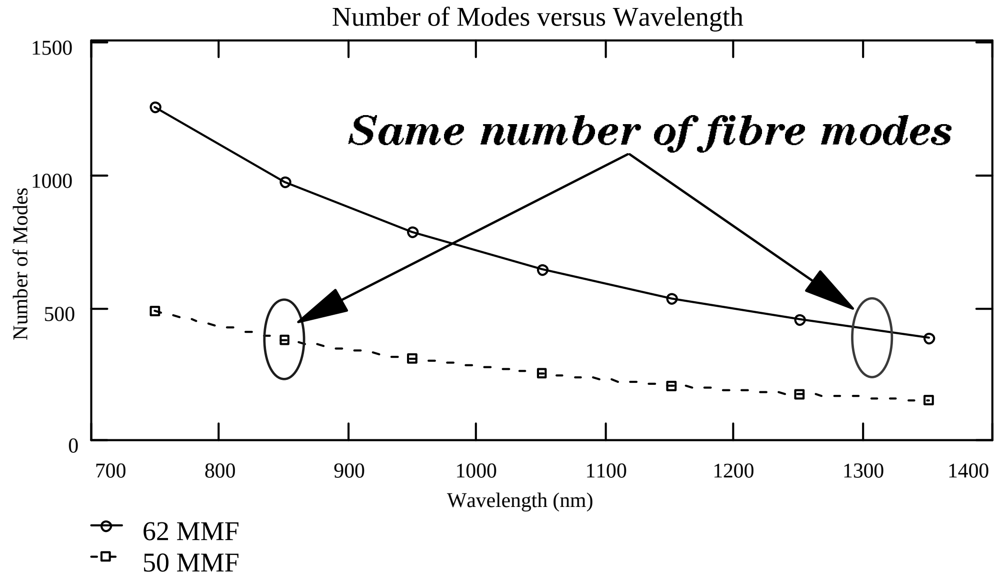


Figure 6: Number fibre modes for 50 MMF and 62 MMf as a function of wavelength.

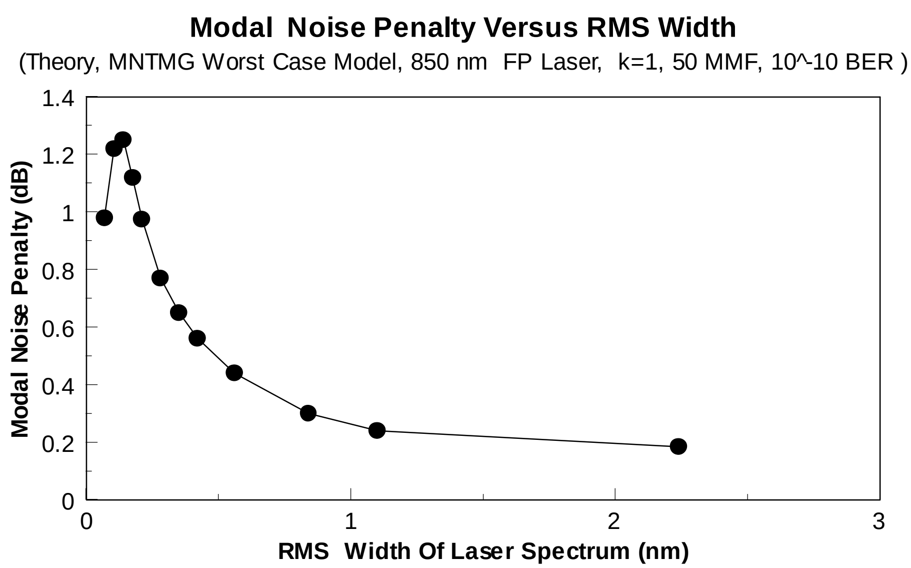


Figure 7: ***Calculated worst case power penalty for 50 MMF, 850 nm laser links as a function of RMS source width using MNTMG model.***

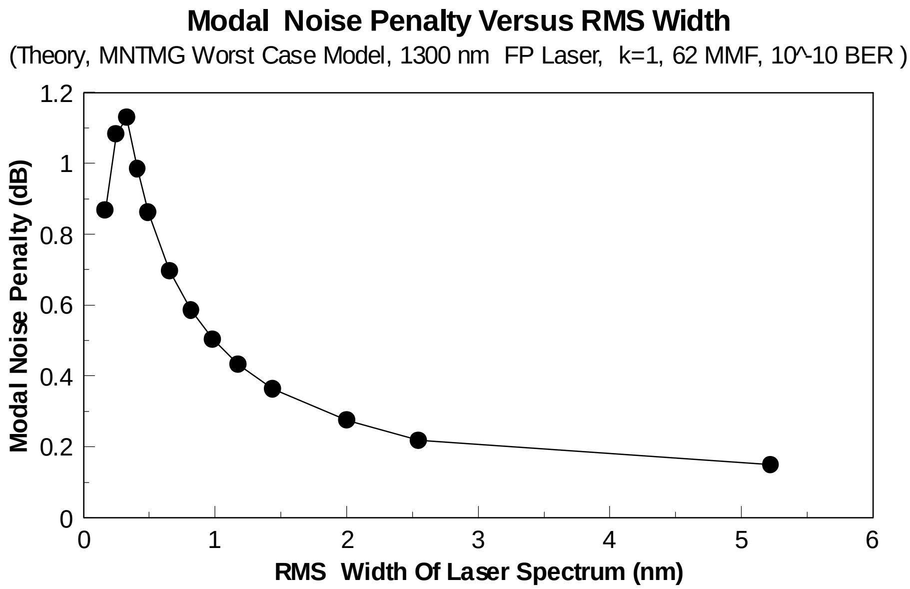


Figure 8: ***Calculated worst case power penalty for 62 MMF, 1300 nm laser links as a function of RMS source width using MNTMG model.***

At least 99% of Hewlett-Packard manufactured low complexity coaxial lasers, suitable for GBd Ethernet, have RMS spectral widths greater than 0.75 nm. From the results plotted in Figure 8 this implies that the worst case modal noise power penalty for these lasers is 0.6 dB with greater than 99% confidence.

Modal Noise: *Experimental Results*

Modal noise testing has been concentrated on a selection of Hewlett-Packard low complexity, 1300 nm, coaxial lasers which are expected to produce worst case modal noise performance. Figure 9 shows the measured visibility of one of these lasers. For comparison, the visibility of a near worst case, 850 nm, CD laser is plotted. It can be seen that the measured visibility is consistent with the measured laser and fibre parameters.

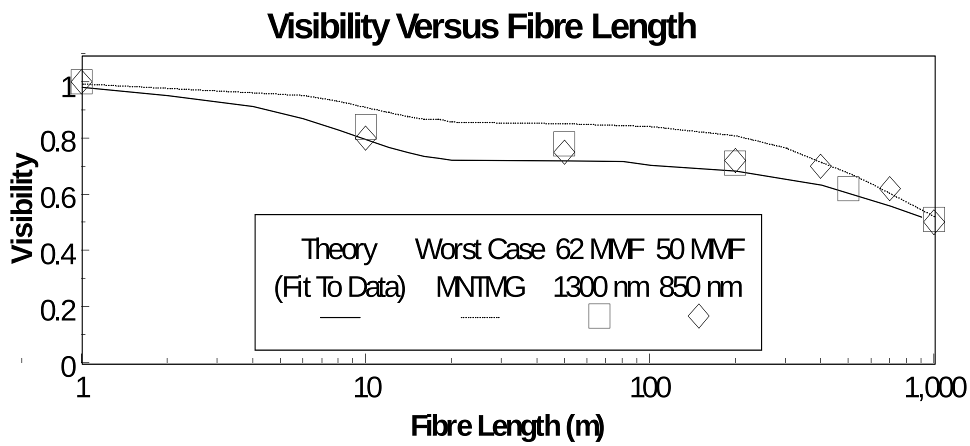


Figure 9: **Visibility versus fibre length for a short and a long wavelength laser. The lasers had approximately equal number of modes and mode linewidths of 1 to 2 GHz.**

The modal noise test box, which is compliant with the current draft test procedure is shown in Figure 10. All tests were computer controlled as depicted in Figure 11. During the testing the fibre was mechanically agitated and the temperature of the laser under test was continuously ramped as required by the draft modal noise test procedure.

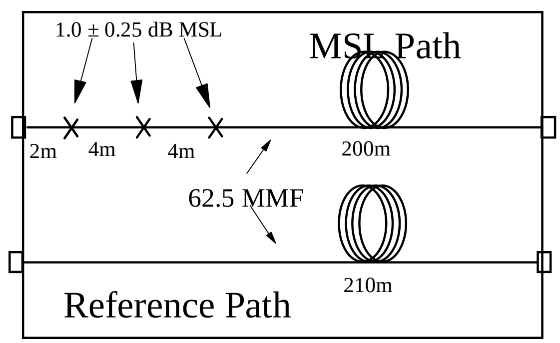


Figure 10: **Diagram of MSL test box as agreed by ad hoc modal noise test methodology group.**

Although near worst case lasers have been tested the maximum power penalty observed to date is 0.3 dB. This is consistent with the predicted maximum power penalty of 0.6 dB for the coaxial lasers. A set of test modal noise results are shown in Figure 12, the same laser for which visibility measurements have been plotted in Figure 9 was used for this test run.

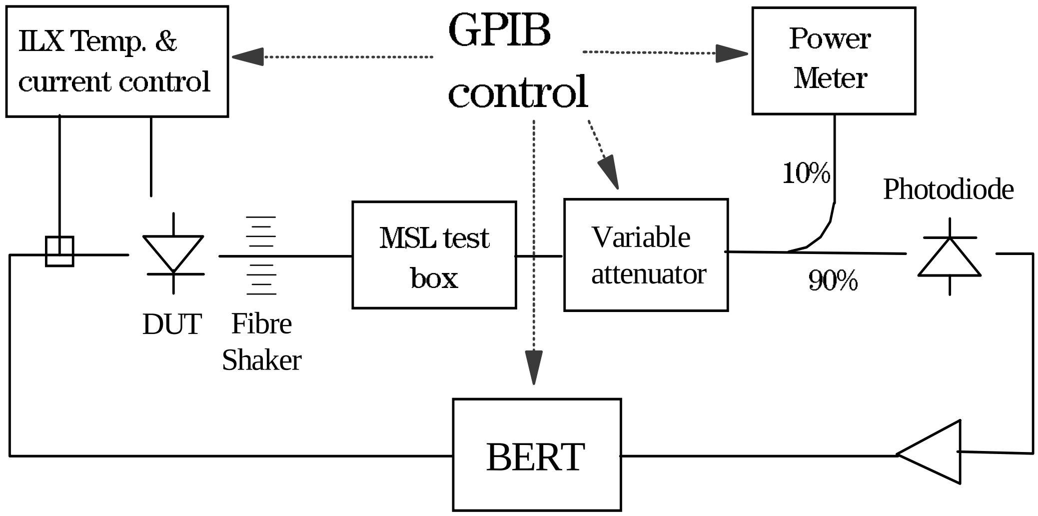


Figure 11: **Computer controlled modal noise power penalty measurement setup used for modal noise testing.**

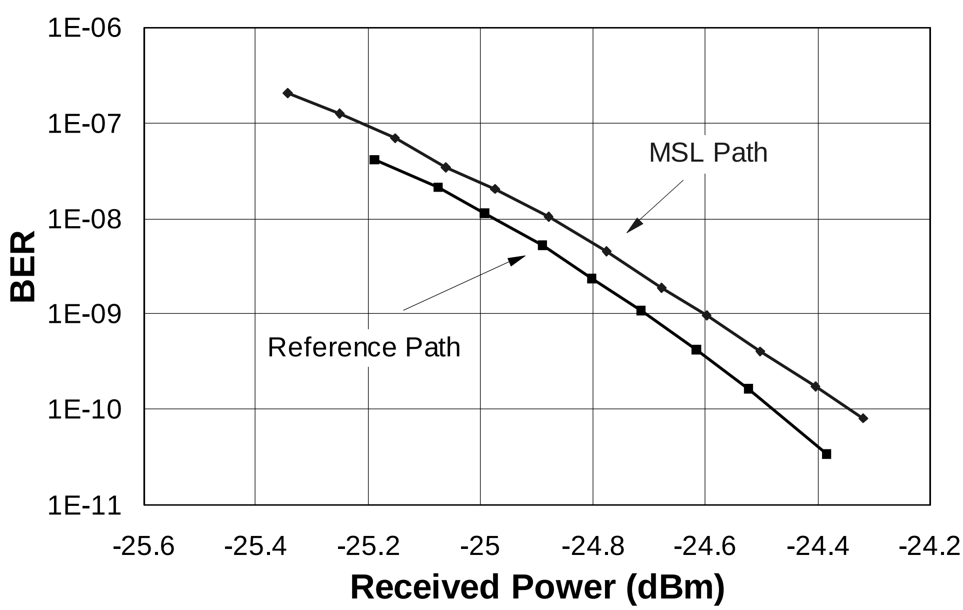


Figure 12: **Measured modal noise power penalty of a low complexity coaxial, 1300 nm laser using the ad hoc modal noise group test methodology. The power penalty is << 1 dB as expected.**

Possibility of 2 km link lengths in the future with restricted mode launch

There is much interest in the possibility of using restricted mode launches to increase the bandwidth distance product of multimode fibre. Such techniques are applicable to both short and long wavelength operation and to both 62 MMF and 50 MMF systems.

We have investigated restricted mode launches of low complexity, 1300 nm, coaxial lasers into 62 MMF. The fibre used for the experiments had an OFL bandwidth distance product of 638 MHz.km.

The output of an SC connectorised, 1300 nm, coaxial laser module was connected directly to various lengths of 62 MMF. Each fibre length was made up by concatenation of 500 m reels of cable. Figure 13 to Figure 16 show the measured eye diagrams of zero, 1 km, 2 km and 3 km length links. Clearly the eye is open to distances in excess of 2 km.

Figure 17 plots the measured power penalties for various link lengths up to 2 km. The power penalty at 2 km is less than 0.2 dB at 10^{-10} BER

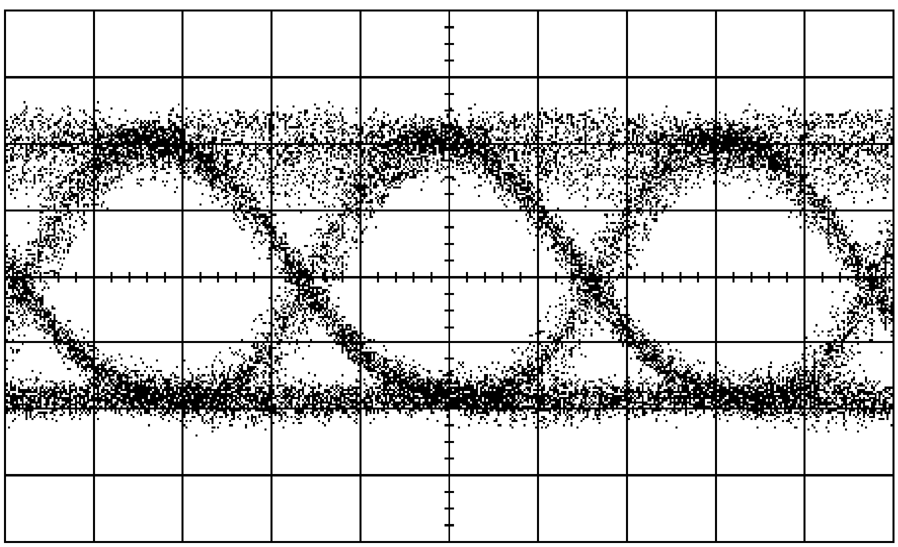


Figure 13: **Measured eye diagram 1.25 GBd, 1300 nm, back to back.**

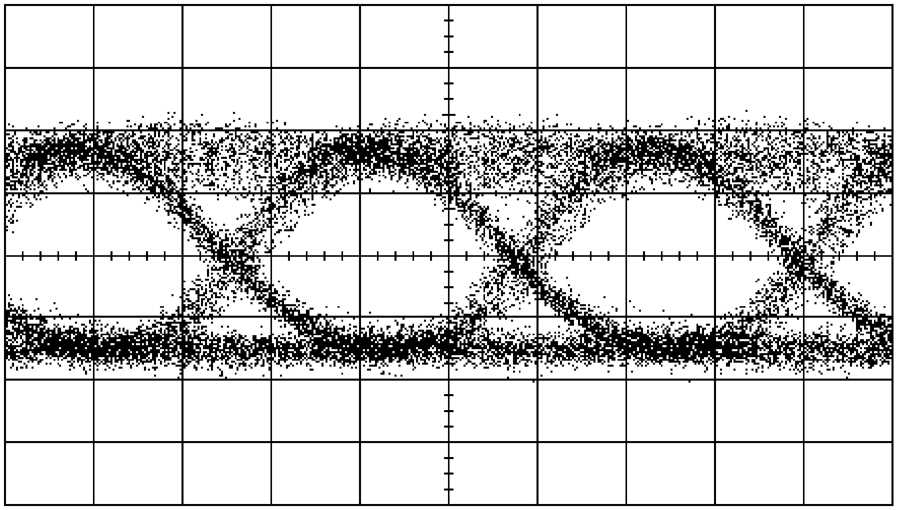


Figure 14: ***Measured eye diagram, 1.25 GBd, 1300 nm, after 1 km 62 MMF.***

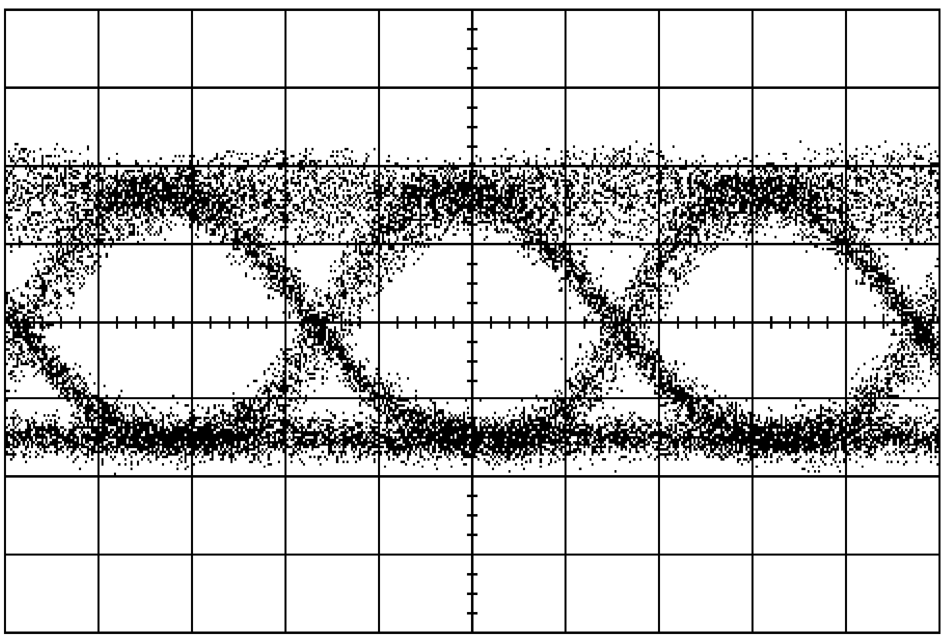


Figure 15: ***Measured eye diagram, 1.25 GBd, 1300 nm, after 2 km 62 MMF.***

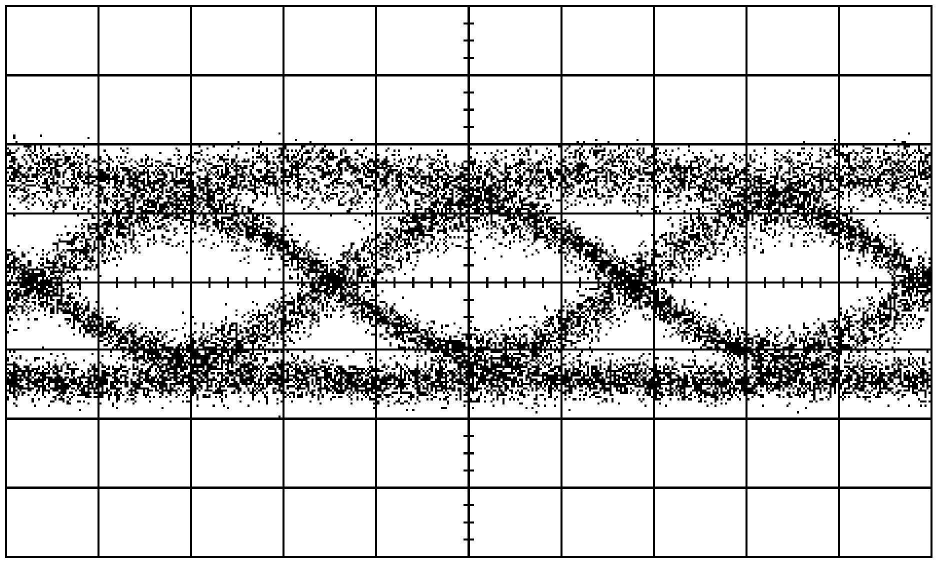


Figure 16: **Measured eye diagram, 1.25** GBd, 1300 nm, after 3 km 62 MMF

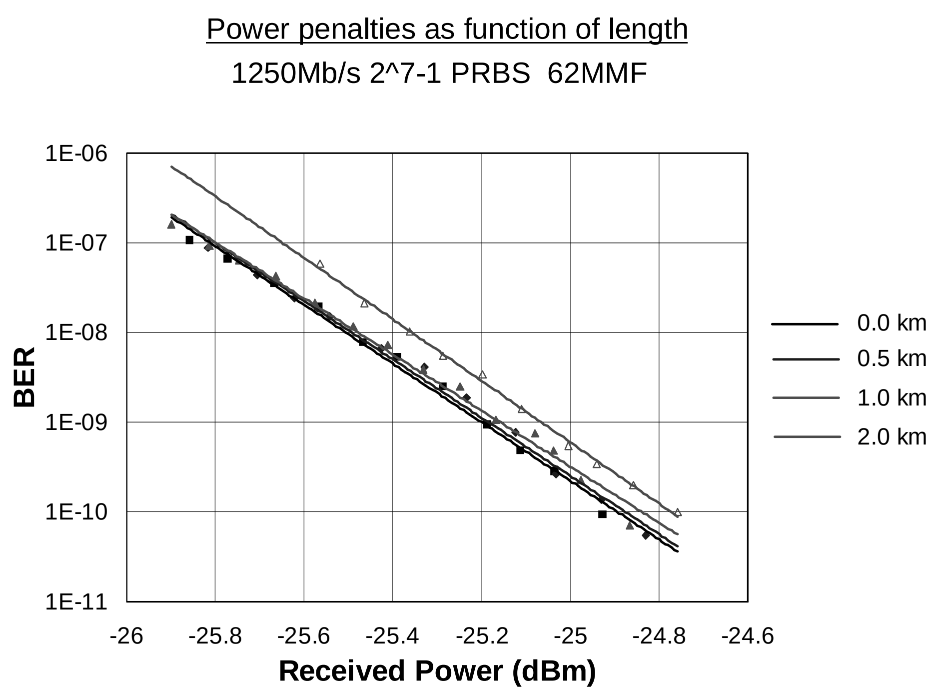


*Figure 17: **BER curves for 0 km, 0,5 km, 1 km and 2 km link lengths.***

1.25 GBd, 550 m proposal for IEEE 802.3

We reviewed the current international building wiring standard and market data on the current installed base, which indicated the necessity for a 550 m, 62 MMF PMD for 1.25 GBd Ethernet. Long wavelength transceivers are the only currently available technology which is able to support the 62 MMF installed base.

This paper addressed the technical issues that might be thought to impede a 62 MMF, 1300 nm LD solution; modal bandwidth and modal noise. Theoretical and experimental results have shown that 1.25 GBd, 550 m, 62 MMF, 1300 nm LD links have the same robustness as 1.25 GBd, 550 m, 50 MMF, 850 nm LD links

This work has shown that low complexity, 1300 nm coaxial lasers have very high modal bandwidth and low modal noise associated with mode selective loss when launched into 62 MMF. We therefore propose leveraging 1300 nm SMF transceivers to support both SMF links and a 550 m link length with existing 62 MMF building wiring for 1.25 GBd Ethernet. There are many suppliers today of 1300 nm SMF transceivers using Fabry Perot LDs. In the future, 1300 nm VCSEL transceivers will meet this link specification with lower complexity.

The possibility of developing 1.25 GBd, 2 km, 62 MMF link length specifications in the future using low complexity, 1300 nm, coaxial lasers or VCSELs has been highlighted.

For higher bandwidth 50 MMF, 850 nm transceiver modules will allow 550 m link lengths at 1.25 GBd. These same short wavelength modules will also support link lengths of up to 250 m on 62 MMF at a somewhat lower complexity when compared to 1300 nm transceivers.

Table 3 summaries the recommended 550 m transceiver specifications for 1.25 GBd, Ethernet. 62 MMF is supported by 1300 nm transceivers whilst 50 MMF is supported by 850 nm transceivers. The table shows worst case response time and jitter specifications. It is generally agreed that in the final specification these parameters will be replaced by a corresponding eye mask specification. Use of short wavelength transceivers for link lengths of up to 250 m on 62 MMF should also be allowed by IEEE 802.3.

Table 3: The proposed short and long wavelength 550m, 50 MMF and 62 MMF links Gb/s Ethernet.

Proposal:	**850 nm Lasers**		**1300nm Lasers**	
	Low	**High**	**Low**	**High**
TRANSMITTER OUTPUT INTERFACE:				
Centre Wavelength, Uc(um)	**0.82**	**0.86**	**1.27**	**1.355**
Spectral Width (FWHM), Uw (nm)		**7**		**14**
Average Power (Over Life), (dBm)	**-10**	**-4**	**-13**	**-3**
Extinction Ratio, (dB)	**9**		**9**	
Rise(Fall) Time Ts, 10-90%, (ns)		**0.35**		**0.35**
Relative Intensity Noise, (dB/Hz)		**-116**		**-116**
Systematic Jitter (Pk-Pk), (ns)		**0.160**		**0.160**
Transmitter Eye Opening, (ns)	**0.46**		**0.46**	
RECEIVER INPUT INTERFACE:				
Average Power (Over Life), (dBm)	**-17**	**-4**	**-20**	**-3**
Rise(Fall) Time To, 10-90%, (ns)		**0.9**		**0.5**
Systematic Jitter (Pk-Pk), (ns)		**0.184**		**0.184**
Random Jitter (Pk-Pk), (ns)		**0.187**		**0.187**
Receiver Eye Opening, (ns)	**0.242**		**0.242**	
FIBER SPECIFICATIONS:				
Core/Cladding Diameter, (um)	**50/125**		**62.5/125**	
Attenuation @ Uref, (dB/km)		**3.5**		**1**
Modal Bandwidth, (MHz.km)	**500**		**500**	
Dispersion Slope, So(ps/nm^2.km)		**0.105**		**0.093**
Dispersion Minimum, Uo(um)		**1.33**		**1.365**
LINK SPECIFICATIONS:				
Signalling Rate, (MBd)		**1250**		**1250**
Link length, (km)	**0.002**	**550**	**0.002**	**550**
Bit Error Rate, BER* 10^-12		**1**		**1**
Reference Wavelength, Uref(um)		**0.85**		**1.3**
Receiver Bandwidth, (MHz)	**1000**		**1000**	
LINK ANALYSIS RESULTS:				
Receiver Input Response, To(ns)	**0.76**	**0.7**	**0.56**	**0.56**
Channel Response Time, Tc(ns)	**0.84**	**0.78**	**0.66**	**0.66**
Fiber Attenuation, (dB)	**2.16**	**1.85**	**0.59**	**0.48**
Mode Selective Loss Allocation, (dB)	**1**	**1**	**1**	**1**
Optical Path Penalty, (dB)	**1**	**1**	**1**	**1**
Allowed Passive Loss, (dB)	**2.84**	**3.15**	**4.41**	**4.52**
Specified Power Budget, (dB)	**7**	**7**	**7**	**7**
Specified Dynamic Range, (dB)	**13**	**12**	**17**	**17**
Eye Centre Penalty, Lo, (dB)	**2.36**	**1.95**	**1.12**	**1.10**
Low Rate, Eye Centre Sensitivity, dBm	**-19.35**	**-18.95**	**-21.12**	**-21.10**

References

[1]"Deployment of Optical Fibre Within European Structured Cabling Systems", Alan Flatman, LAN Technologies, Presented to IEEE 802 Tutorial, Montreal, November 1995

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