RC21195 (log# 94680) 28MAY98 **Engineering and technology** **4 pages**

Research Report

Effect of Launch Conditions on Power Penalties in Gigabit LinksUsing 62.5μm Core Fibers Operating at Short Wavelength

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1. Introduction

An insatiable demand for information bandwidth has led to an explosion of fiber optic networks operating at and above 1Gb/s. There is current development effort by several standards bodies, including the IEEE 802.3z, ATM and Fibre Channel to develop communications standards for gigabit/sec speeds and beyond. For premises distances, the most cost effective optical networks use multimode fiber. The multimode fiber was designed and specified for light emitting diodes (LEDs). However, the LEDs can not achieve gigabit/sec speeds, thereby requiring the use of semiconductor laser diodes. Therefore, there is a need to recharacterize and respecify links for multimode fiber excited by laser diodes. In developing the communications standards, significant differences between the measured fiber bandwidth using historical overfilled launch conditions and those measured using laser launches have been found. In most cases, there was a significant increase in the fiber modal bandwidth using the laser launches; however, there were a few cases in which the bandwidth fell below its rated value. One of the essential requirements of the new communications standards was the ability to address the ubiquitous 62.5μm multi-mode fiber. The rated minimum bandwidth of Fiber Distributed Data Interface (FDDI) grade fiber is 160MHz·km at 850nm, and 500MHz·km at 1300nm. With 1300nm laser excitation, the effective bandwidth of the FDDI 62.5 μm fiber was below specification in nearly ten percent of the fiber population sampled. An offset launch technique has been described to eliminate the problem [1]. This has proven to be costly, and is not practical for the lower cost, higher volume 850nm solutions.

In this paper, we investigate the performance of the 62.5 μm core fiber under various launch conditions. In our study, both CD lasers and VCSELs were used, with variable spot sizes and numerical apertures, generating numerous launched power distributions into the optical fiber. Whereas previous analysis of fiber links have used only the fiber bandwidth as the predictor of link performance [1], we use the entire impulse response of the fiber to calculate both the inter-symbol interference (ISI) and the deterministic jitter (DJ) in the link. Our analysis yields more realistic results than those based on a simple Gaussian response of the fiber transfer function. We find that current IEEE 802.3z (Gigabit Ethernet) link lengths are quite conservative, and typical system performance will greatly exceed the specified 220m link length for FDDI fiber.

2. Method of measurements and analysis

The modal power distribution (MPD) in an optical fiber was measured using a technique similar to that described in reference [2]. In our case, a CCD camera was used to capture the laser's intensity profile with a resolution of 0.2 μm. Additionally, time averaging was employed to reduce the effect of speckle on the near field patterns. The lasers were driven under normal system parameters. The two dimensional data from the CCD camera was analyzed to obtain the intensity distribution, mode transfer function (MTF), MPD, and the 95% cumulative power distribution (CPD). Additionally, the coupled power ratio (CPR) was measured. Circular symmetry was assumed and Figure 1 is a plot of the mode power distribution as a function of mode group number for each laser.

Once the near field intensity profile in the fiber is known, the mode power distribution is estimated following the procedure of Calzavara et al. and Daido et al. [3,4]. This procedure uses the ratio of the derivative of the near field intensity to that of an overfilled launch. Even if the 2D data was azimuthally averaged, we still found it necessary to radially smooth the intensity data to get a workable mode power distribution. Other approaches to obtain the MPD include fitting the beam profile with a sum of Gaussian beams with different offsets and beam diameters (whose individual modal excitations can be calculated exactly) or fitting the beam profile to a sum of modal contributions.

Once the modal power distributions of the individual sources are known, they are used with mode delays to numerically model pulse propagation through the optical fiber. The mode delays for the model were determined from a set of 237 measured index profiles by a perturbation method [5]. Only profiles whose overfilled bandwidth was predicted to meet FDDI requirements (160/500 MHz·km) were used. The mode delays of the individual modes were assumed to be fully coupled and averaged together within each mode group. The transfer function of each optical fiber for each launch condition is then calculated, taking into account differential modal attenuation [6]. The output pulse from the optical fiber can be represented as a weighted sum of Dirac delta impulses. The transfer function of the fiber is given by:. $H(if)=\Sigma C_k \exp(-i2\pi f\tau_k)$. The amount of power, and the propagation delay time of the k^{th} mode is given by c_k and τ_k (ns/km) respectively. The 3dB fiber bandwidth is determined by the minimum frequency that satisfies the condition $|H(f)|/|H(0)|=0.5$. For the fiber lengths under consideration, we can assume without loss of generality, the mode attenuation is uniform, and there is no mode coupling within the fiber.

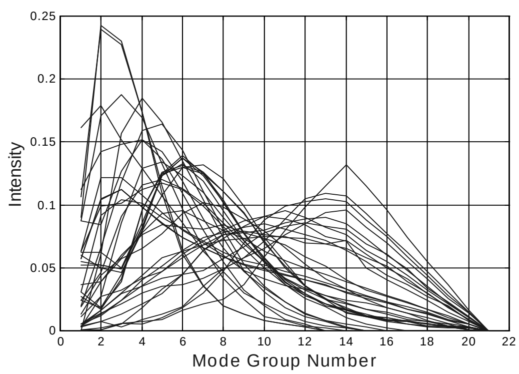

Figure 1. Mode power distribution for all devices used

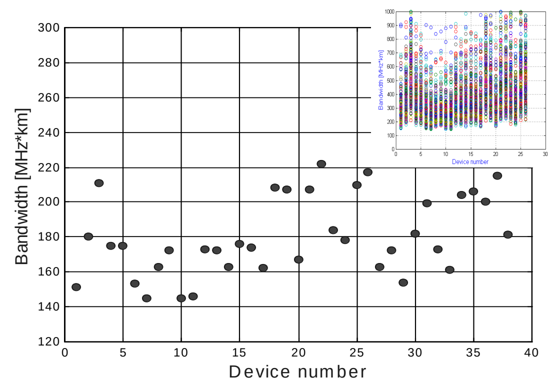

Figure 2. Minimum fiber bandwidth·distance product for each device. The inset shows bandwidths for all fibers and devices

3. Correlation of fiber bandwidth and beam profile parameters

The predicted bandwidths are given in Fig. 2. Of the 9006 simulations performed (237 fiber types and 38 sources) only 0.3% of the results indicate the fiber bandwidth will fall below the 160MHz·km specification of FDDI. For 32 of the 38 sources the predicted bandwidth was above 160MHz·km for all fibers, and for 11 of the 38 sources the predicted bandwidth was above 200MHz·km for all fibers. We are interested in characterizing the robust sources which fall in this upper category.

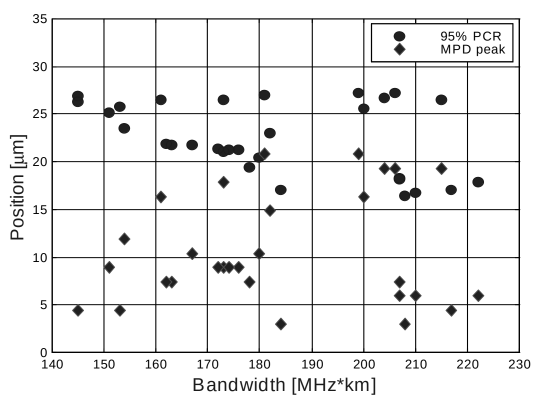

Figure 3. 95% CPD and peak of MPD as a function of minimum fiber bandwidth.

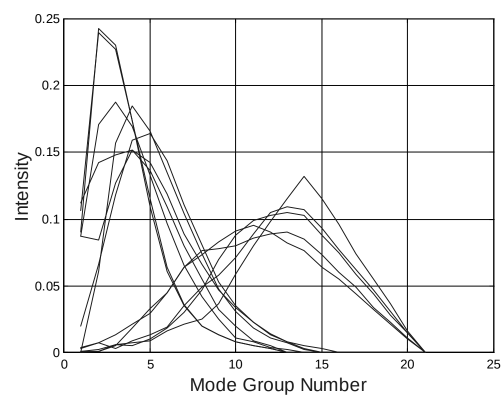

Figure 4. Mode power distribution for devices with bandwidth above 200 MHz km.

In an effort to relate the fiber bandwidth to easily measured parameters, we have examined the bandwidth as a function of 95% CPD, modal power distribution, full width half maximum (FWHM) and coupled power ratio. Figure 3 is a plot of the minimum modal bandwidth for our devices as a function of the 95% CPD and peak of the MPD. While each of the measures of fiber intensity distribution have merit, we find that no method is entirely predictive.

Our data set shows that the following sets of intensity distribution criteria are sufficient to achieve the minimum overfill bandwidth (160 MHz·km): a) 95% CPD less than 25µm and more than 10µm; b) the mode power distribution peaks between 10µm and 25µm; c) coupled power ratio greater than 9dB; d) FWHM between 10µm and 20µm. What we found upon further analysis was that the sources whose minimum predicted bandwidth was significantly above the 160MHz·km fell into two categories: either the modal power distribution was skewed toward the center with little power on the outside, or the power was skewed to the outside with little power in the center. Figure 4 shows the MPD for the sources with a minimum predicted bandwidth of more than 200 MHz·km.

4. Calculations of Deterministic Jitter and ISI Penalty

The link simulations were performed assuming the worst case parameters (as used in IEEE802.3z) for both the transmitter and the receiver. We used the Matlab™ based IBM OBST optical link simulator tool, which has built in models for each component in the link (laser, fiber and the receiver). Our simulations used a modification of a linear laser model which takes into account the duty cycle distortion at the laser output caused by laser turn-on delay. The receiver was modeled as a 800 MHz 4th order low pass Butterworth filter. The simulator was modified to take into account the fiber model described above. The accuracy of the simulator has been previously verified to match experimental results [7]. Our simulations used a transmitter with a rise time of 350ps, and deterministic jitter of 65 ps, sending a repeating k28.5 pattern. The numerical results of the simulator included the bandwidth of the optical fiber, the ISI penalty, and the deterministic jitter (DJ) seen by an analog receiver at the end of the fiber link. The DJ was calculated at the *maximum* horizontal eye closure measured at the zero point in an AC receiver. The simulations were done for link lengths of 220m and 300m.

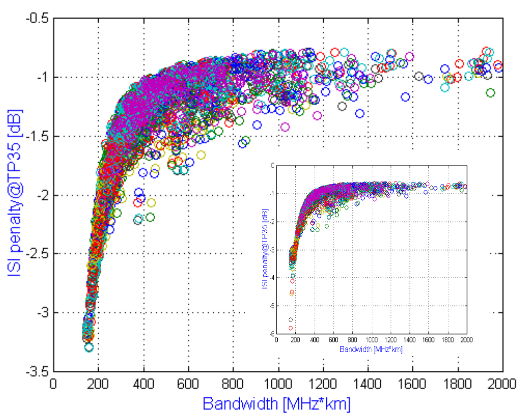

Figure 5. ISI penalty as a function of the bandwidth distance product. The fibers were 220m long. The inset shows the ISI penalty for 300m long fibers.

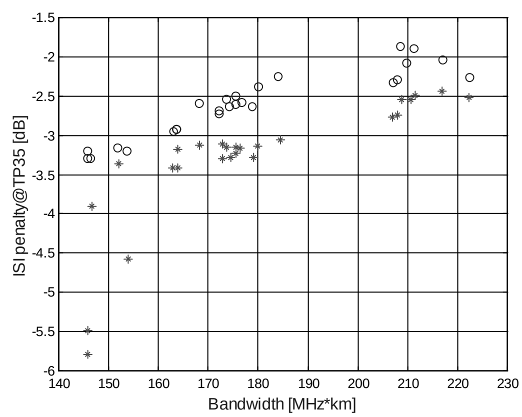

Figure 6. Comparison of the maximum penalties for fibers 220 m (circles) and 300 m long (asterisks). Only for bandwidths less than 160 MHz·km the penalty difference becomes significant.

Figure 5 is a plot of the ISI penalty as a function of the fiber bandwidth-distance product for a 220m optical link. There are three distinct regions of the curve. The first, for fiber bandwidths less than ~300MHz·km, indicates a unique correlation of the system ISI penalty to the fiber bandwidth. In this region, the system ISI penalty is dominated by the bandwidth of the optical fiber. In the second region, between ~300MHz·km and ~1200MHz·km, the system ISI penalty is determined by a complex interaction of the fiber transfer function, the laser transmitter and the receiver. The exact ISI penalty is extremely dependent on the details of the input optical pulse. As can be seen from figure 5, the ISI penalty can range as much as 2dB for a given fiber bandwidth. Clearly the system and fiber response do not have Gaussian shapes. The third region is above ~1200MHz·km where the variance in the ISI penalty decreases, and the ISI penalty begins to be dominated by the finite bandwidth of the laser transmitter and the receiver. Similar comments can be made about the inset to Figure 5, which is the ISI penalty as a function of fiber bandwidth-distance product for a 300m optical link. Figure 6 shows the maximum ISI penalties at 220m and 300m as a function of the bandwidth-distance product. For bandwidths greater than 160 MHz·km the difference between 220m links and 300m links is less than 0.7 dB, below 160 MHz·km the difference between link lengths becomes very significant. Figure 7 is a plot of the deterministic jitter in the link at the output of the analog section of the receiver as a function of the fiber bandwidth-distance product. Again, there appears to be three regions of interest, and similar discussion to that for the ISI applies. The unique relationship between the fiber bandwidth and the deterministic jitter allows for operation of carefully controlled links with fibers having a bandwidth-distance product less than 200MHz·km. As the link length is increased to 300m, the deterministic jitter increases substantially for fiber bandwidths below 200MHz·km.

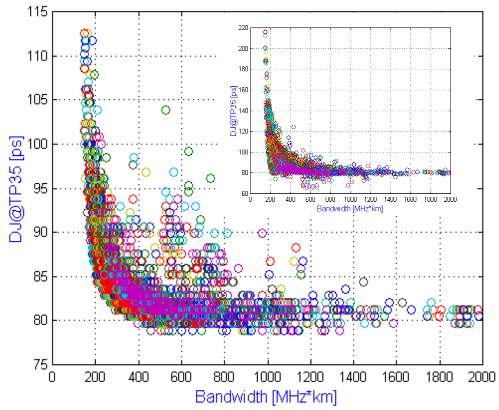

Figure 7. Deterministic jitter at the output of the analog section of the receiver, for 220m long fibers. The inset shows the jitter for 300m long fibers. Note that 40% increase in fiber lengths almost doubled the jitter.

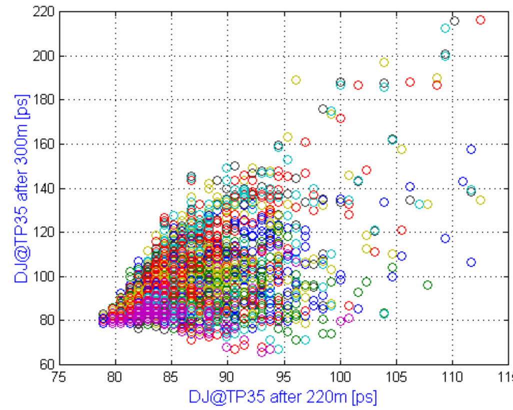

Figure 8. Comparison of deterministic jitter for 220m and 300m long link. This figure illustrates the complex dependence of the jitter in the link on the fiber length, bandwidth and DC unbalance.

Simple link models can often lead to wrong conclusions and conservative estimates. There is quite complex relationship between jitter and link distance, as illustrated in Figure 8. It appears that it is difficult to predict the jitter for longer links, based on measurement at shorter distances. While the DJ introduces a DC imbalance, after the signal travels through the fiber, the DJ effects are initially reduced due to ISI and the resulting trend to DC balance. As fiber lenghts are further increased, the ISI begins to reintroduce DJ. We find the amount of jitter will depend on many factors, including the actual pulse shape of the signal and the impulse response of the fiber, not just the bandwidth.

5. Conclusions

In this paper, we investigated the effects of launch conditions on the fiber bandwidth and the link penalties. Our results show that several parameters may be necessary to fully predict the operation of a fiber optic link. Our results also show that while there is correlation between the bandwidth and the link ISI penalty, this correlation becomes rather weak for bandwidths exceeding 200 MHz·km. Our investigations show not only that the current Gigabit Ethernet lengths can be achieved, but they can be greatly exceeded. Therefore, robust, inexpensive short wavelength solutions, will continue to dominate the gigabit LAN market.

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