RC23156 (W0403-113) March 16, 2004
Electrical Engineering

# IBM Research Report

## DMD Measurements and Equalization Simulations for 62.5 and 50 μm Legacy Multimode Fibers at 1300 nm

**Aleksandar Risteski**
University of Skipje
Department of Electrical Engineering
Skopje, Macedonia

**Eric Corisch, John Ewen**
JDS Uniphase

**Jose Tierno, Petar Pepeljugoski**
IBM Research Division
Thomas J. Watson Research Center
P.O. Box 218

**Research Division**
**Almaden - Austin - Beijing - Haifa - India - T. J. Watson - Tokyo - Zurich**

# DMD Measurements and Equalization Simulations for 62.5 and 50 μm Legacy Multimode Fibers at 1300 nm

Aleksandar Risteski, *Member, IEEE*, Eric Borisch, *Member, IEEE*, John Ewen, *Member, IEEE*, Jose Tierno, *Member, IEEE*, Petar Pepeljugoski, *Senior Member, IEEE*

***Abstract* — In this letter we present the results from Differential Modal Delay (DMD) measurements at 1310 nm performed over a large sample of 62.5 μm and 50 μm FDDI grade multimode fibers (MMF). We have found that the typical DMD values are in the range 0.5-1.5 ps/m, but a significant portion of measured fibers have DMD values exceeding the commonly used value of 2 ps/m. Since the expected yield at moderate (150-300m) distances of 10 Gb/s links employing legacy fibers is very poor, we have simulated equalization techniques in the receiver for the measured fiber impulse responses. We show here that both the yield and the achievable distance are significantly improved when equalization is used.**

***Index Terms*—Optical communications, 10 Gb/s links, Differential Modal Delay, Equalization techniques, Multi-Mode Fiber.**

## I. Introduction

IEEE 802.3ae 10 Gb/s Ethernet standard [1] includes short-wavelength (850 nm) links (10GBASE-SR) for the LAN environment up to 300 m over the next-generation (OM3) multimode fibers [2]. It also defines a WDM solution (10GBASE-LX4) that supports links up to 300m over legacy 62.5 μm and 50 μm fibers. There has been renewed interest in defining serial solutions that support the installed legacy fiber in order to enable smaller form-factor transceivers, lower power dissipation, and higher port densities. To support the required link distances, some form of equalization is required to compensate for the modal dispersion within the fiber. For OM3 multimode fibers, measurement procedures for source encircled flux [3] and fiber differential modal delay (DMD) [4] are also specified to guarantee adequate margin in the link. This letter reports on DMD measurements at 1310 nm on legacy MMF to characterize the fiber impulse response as a function of launch conditions, which can then be used to evaluate different equalization schemes for 10 Gb/s links.

The FDDI-grade fibers (both 62.5 μm and 50 μm) are only characterized by their Overfill Launch Bandwidth (OFL BW). Due to the large number of mode groups in the multimode fibers, possible launch conditions, and mode mixing in the connectors, this is not sufficient to assess the performance of equalized links using these fibers. To achieve better fiber characterization, we performed DMD measurements over a large test sample of legacy fibers previously used in various round-robin measurements by the Telecommunication Industry Association's FO-4.2.1 group over the past several years.

The fibers whose DMD we measured (summarized in Table 1) belong to the following round robin (RR) spools: 1. 1km RR cable (48 fibers, 30+18); 2. RR 12/96, which contained 15 fibers, each 300m long (9 of which were 62.5 and 6 were 50 μm) and whose purpose was to aid the development of the 1 Gb/s Ethernet standard; 3. two worst case spools (DMD RR) for testing compliance of 1Gb/s Ethernet transceivers, which contained 6 fibers, each 300m long. The fibers in the two spools came from different sections of the cable and had different DMD profiles. 4. RR fibers used in the development of the OM3 fiber. This cable has 12 fibers, each 300m long. We used 99 fibers in all spools, for which we measured the DMD profile at both 1300nm and 850nm.

Table 1. Cable Description

| | Cable description | Fiber diameter (μm) | Length (m) | Number of fibers | Spools/ Tubes |
|---|---|---|---|---|---|
| 1a | 1km RR | 62.5 | 1000 | 30 | Blue, Orange, Green |
| 1b | 1km RR | 50 | 1000 | 18 | Brown, Slate |
| 2a | RR 12/96 | 62.5 | 300 | 9 | 1, 2, 3 |
| 2b | RR 12/96 | 50 | 300 | 6 | 4 and 5 |
| 3 | DMD RR | 62.5 | 300 | 12 | 1 and 2 |
| 4 | OM3 RR | 50 | 300 | 12 | Blue, Orange |
| 5 | Other | 50 | 300 | 12 | N/A |

## II. Measurement Setup and Results

Figure 1 shows the DMD measurement setup. Once we aligned the short single-mode fiber (SMF) and MMF and found the optical center of the MMF, we measured the reference pulse waveform. Then we inserted the fiber under test, launched the light from the SMF at different lateral

Manuscript received …

offsets, and took impulse responses. We set $R_{INNER}$ =0 and $R_{OUTER}$ =28 µm for 62.5 µm fibers and $R_{OUTER}$ =24 µm for 50 µm fibers. Using the motion controlled precision stages, we measured signal waveforms at the fiber under test output using a 2 µm step for the lateral offset over the entire fiber core.

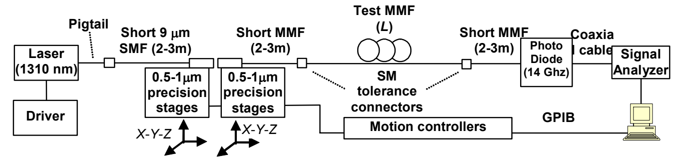


Fig. 1. DMD measurement setup.

Figure 2 shows a measured DMD profile of the 62.5 µm fiber with the highest DMD. The curve at the bottom represents the fiber response when the light is launched in the center of the MMF under test. The impulse responses for lateral offsets 0, ±2, ±4, ..., $\pm R_{OUTER}$ µm are shown with solid and dashed lines for positive and negative offset, each at the corresponding positions of the offset axis. All curves are normalized to the peak amplitude of the pulses. The marker on the left curve shows the minimum of the leading edge times ($T_{fast}$), and the marker on the right shows the maximum of the trailing edge times ($T_{slow}$) from among all the impulse responses. Both the leading and the trailing edge times are defined at 25% of the signal peak value [4]. The DMD is defined as [4]: $DMD=T_{slow}-T_{\text{fast}}-\Delta T_{ref}$ [ps or ns], where $\Delta T_{ref}$ takes into account the width of the laser reference pulse and the pulse broadening due to chromatic dispersion in the fiber [4]. The DMD value is normalized by fiber length $L$: $DMD_{norm} = DMD/L$ [ps/m].

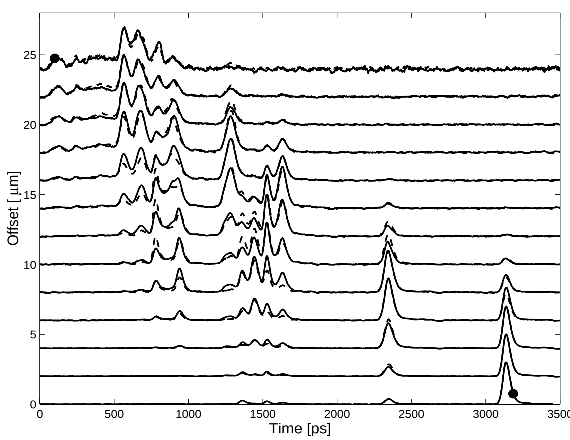


Fig. 2. Measured DMD profile of one 62.5 µm MMF from 1km RR cable. The normalized DMD is very high (3 ps/m) and low order modes can be easily resolved. The impulse responses measured at the same lateral offset but at opposite sides of the optical center of the MMF (e.g. ± 10 µm), shown with solid and dashed lines, are almost the same and indistinguishable.

In Figure 3 we show a histogram (0.5 nm bin width) of the distribution of peak-to-peak DMD values of measured fibers. We see from Figure 3 that there is a significant portion of fibers whose peak DMD exceeds 2 ns/km and in several cases between 2.5 and 3 ns/km. This conclusion is valid for both the 62.5 µm and 50 µm legacy fibers. OM3 fibers have DMDs between 0.5 and 1.5 ps/m. One fiber within the round robin cables that has OFL bandwidth significantly less than 500 MHz·km is not FDDI grade compliant and is excluded. The rest of the fibers described above are FDDI compliant.

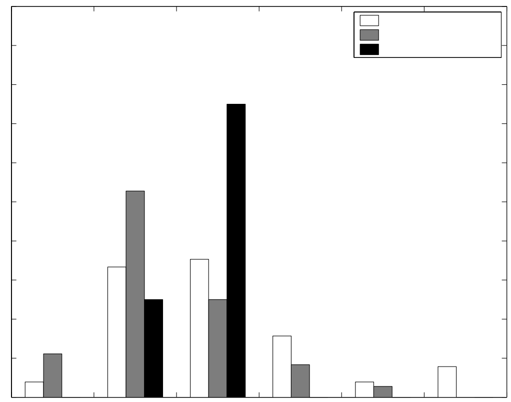

Fig. 3 Distribution of measured DMD values for 62.5 and 50 µm MMFs.

This suggests that the prevalence of fibers with DMD higher than 2 ns/km is larger than originally thought and should be reflected in any performance specification for equalized links using legacy fibers.

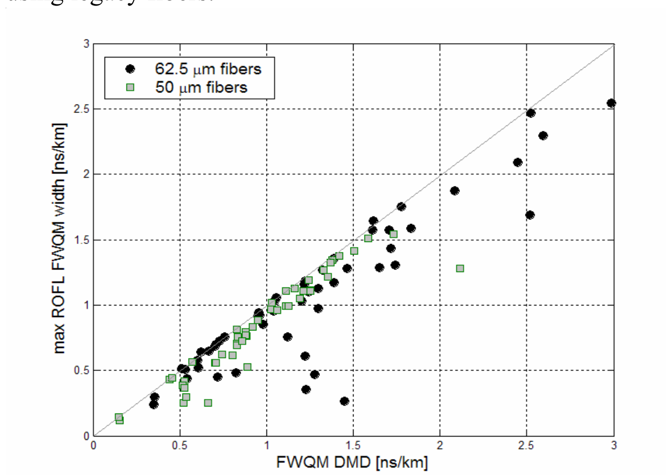


Figure 4. Comparison of the maximum ROFL FWQM width (from 0.5dB, 1dB and 2dB ROFL launches) width with the corresponding DMD width.

We also compared the measured DMD magnitude with the maximum measured full width quarter maximum (FWQM) width of three radial overfill (ROFL) launches (0.5dB, 1 dB and 2 dB). In many cases, the FWQM ROFL width is underestimating the DMD in the fiber, as shown in Figure 4.

## III. Link Yield nalysis

In the following preliminary analysis of the effectiveness of various equalization schemes we considered the measured responses of the various fibers at each offset as a unique channel. Indeed, the possible launch condition is a single mode launch, either with or without offset to provide compatibility with the existing 10 Gb/s Ethernet and Fibre

Channel single mode physical media dependent layers. We can think of the fiber responses at various offsets as a single mode launch, with uncertainty of the relative position of the laser and the receiving fiber, or the alignment tolerances for the offset launch. For completeness, we consider the entire range of offsets. For a 300 m long fiber and worst case DMD between 2.5 and 3 ps/m, the resulting impulse response width is approximately 750-900 ps (around 7-9 bit intervals). The Inter-Symbol Interference (ISI) in such a link would completely close the eye diagram and lead to infinite power penalty in a symbol by symbol detection system. One method of improving performance is through receive-side equalization. In this context, it is necessary to find the optimal number of taps and the delay of each cell of the transversal filters. For each of these channels, the optimal coefficients in the equalizers should be determined and residual ISI penalty calculated. In the preliminary investigation, we chose 2 equalizer structures, a 7 tap Feed-Forward Equalizer (FFE) structure with 50 ps tap delay, and a Decision-Feedback Equalizer (DFE) in which a 5-tap section is added to the 7-tap forward equalizer [5]. Simulations were performed at 10 Gbd.

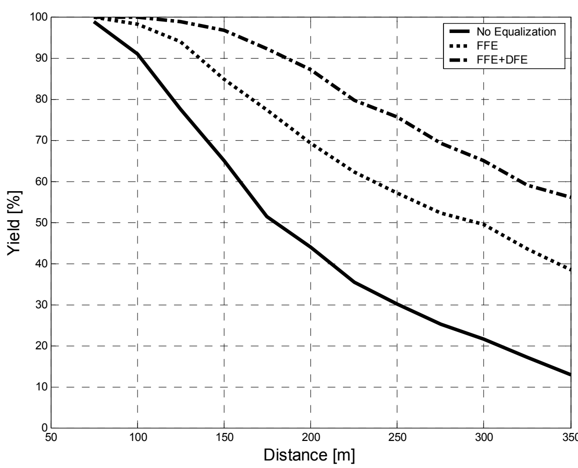


Figure 5. Yield vs. distance for 62.5 μm fibers (Maximum allowed ISI penalty = 2.5 dB). The solid line is when no equalization is used, the dashed when forward equalizer (FFE) is used and the dot-dashed when DFE+FE is used. Marked improvement is observed with the DFE+FFE scheme.

We calculated the yield curves and achievable distances when no equalization is used, as well as when FFE or a DFE are employed. We define the yield as the fraction of all links that at a given distance have residual ISI penalty less than the allocation in the power budget. We considered several values for the allowed residual ISI penalty, ranging from 2.5-5 dB, leading to different yield curve families. In Figure 5, we show the yield curves as a function of length, when the ISI penalty allocation is 2.5 dB. As expected, the yield drops with length, and the DFE+FFE offers best performance, at the price of higher complexity. Note that the 300m target has low yield.

We also calculated the achievable distance after equalization as a function of the achievable distance before equalization, for both equalization schemes and present the results for 62.5 μm MMFs as a scatter plot on Fig. 6. To visualize the improvement factor, we drew lines at 1x, 1.5x, 2x, 3x and 4x improvement factors when equalization is used. We observe that with FE the improvement is mostly below 2x, and for FFE+DFE between 1.5x and 3x. Again, these curves were calculated using the 2.5 dB allocation for the residual ISI penalty. Figure 5 and 6 show the results only for 62.5 μm MMFs. Although we do not present them here, we have found almost the same results for 50 μm MMFs.

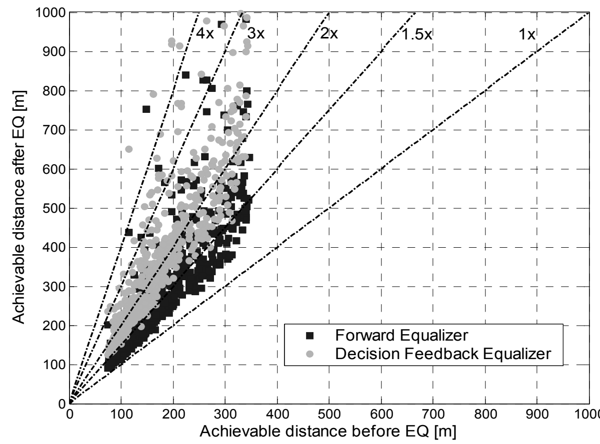


Figure 6. Achievable distance improvement with equalization for 62.5 μm fibers (Maximum allowed ISI penalty = 2.5 dB). The improvement factor with FFE scheme (black squares) is 1.5x-2x and 2x-3x with DFE+FE scheme (gray circles). We drew dot-dashed lines at 1x, 1.5x, 2x, 3x and 4x improvement factor.

In this letter we report our DMD and ROFL measurements on FDDI-grade fibers at 1300nm. Unexpectedly, the magnitude of the peak-to-peak DMD in these fibers is larger than the commonly used number of 2ns/km, and in some cases approaches 3 ns/km. We use these measurements to simulate the performance of equalized links using two equalizer structures. We found that the FFE offers up to 1.5x improvement in achievable distances compared with links without equalization, while the FFE combined with DFE offered up to 2x improvement, when the allowed ISI penalty is 2.5 dB. In both cases the yield is well below 90% at 300m, suggesting that a more meaningful target is between 180 and 220 m. These distances are improved if we allow a larger ISI penalty. The single mode type launch gives better results after equalization than the ROFL type launch.

## REFERENCES

[1] IEEE 802.3ae 10 GbE standard, June 2002

[2] "Detail specification for laser optimized, 50μm core diameter/125μm cladding diameter class Ia graded index multimode optical fibers," TIA-492AAAC, 2002

[3] "Launched Power Distribution Measurement Procedure for Graded-Index Multimode Fiber Transmitters", TIA/EIA-455-203, June 2001

[4] "Differential Mode Delay Measurement of Multimode Fiber in the Time Domain", TIA/EIA-455-220, December, 2001

[5] S. U. Qureshi, "Adaptive equalization", Proceedings of the IEEE, vol. 7, no. 9, September 1985.