Statistical Analysis of Electrical Equalization of Differential Mode Delay in MMF Links for 10-Gigabit Ethernet

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Abstract: Through statistical analysis of a large number of worst-case multimode fiber channels, we demonstrate that using electrical equalization, the 300m-transmission reach at 10Gb/s can be guaranteed for installed multimode fiber under any launch condition.

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1. Introduction

The characteristics of multimode fiber (MMF) links vary greatly from one link to another. Since the data rate for MMF links is extended to 10Gb/s and beyond, the overfilled launch (OFL) based on LED light sources has been replaced with restricted mode launch (RML) by using lasers, like FP or VCSELs. The bandwidth of MMF not only depends on the channel itself but also greatly on the launch condition, which includes different launch offset positions and different incident beam sizes.

Therefore, the electronic dispersion compensation (EDC) of differential mode delay (DMD) needs to be evaluated effectively for various MMFs under different launch conditions. In this work, through the examination of a very large number of different MMF channel impulse responses, we demonstrate that by using EDC with feedforward FIR filter and decision feedback equalizer filter (DFE), the required 300m-transmission distance [1] at 10Gb/s can be guaranteed for installed MMF with bandwidth-distance product 500MHz-km.

2. Influence of different launch conditions on the MMF bandwidth

The MMF channel is modeled as the superposition of the power P_m carried by each mode m (from 1 to M, where M the maximum mode number), which has different delay τ_m. The impulse response is $h(t)=\sum_{m=1}^{m=M} P_m \delta(t-\tau_m)$. The mode delay and the electrical field distribution for each LP mode are examined by a numerical mode solver [2]. We assume that the mode dependent attenuation satisfies modified Bessel function of the first kind [3]. Mode coupling within the same mode group is assumed to be complete. Mode noise is not considered in this paper. We take 62.5µm-MMF at 1300nm wavelength with bandwidth-distance product 500MHz-km as a typical example. The following conclusions are also tenable for 50µm-MMF at 1300nm as well as at 850nm.

For our statistical analysis we investigate in total 1674 different samples, derived from various MMF types, various incident beam spot sizes, and various offset launch positions. Simulations and experimentations [4,5] have shown that the deformation of index profiles can cause large bandwidth degradations when RML technique is introduced. To address this issue, the simulations are carried out on six typically installed MMF #1 to #6 with various deformations (dip or peak) located at the core center as well as different index exponents (g_1, g_2) as listed in Table.1. The six MMFs represent the worst 5% of installed MMF [4,5]. The DMD of each MMF is scaled accordingly in order to achieve the 3dB bandwidth-distance product of 500Mhz-km. Additionally we considered nine different Gaussian incident beam spot sizes with full-width-half-maximum (FWHM) from 4µm to 20µm with step of 2µm, and 31 offset launch positions from 0 to 30µm with step of 1µm.

Eye opening analysis of the received signal after 130m-transmission at 10Gb/s is illustrated in Fig.1 (a), which exhibits that with near center launch (from 3µm to 14µm offset), the RML bandwidth has larger degradation compared to OFL (dash-dot line shown in Fig.1 (a)) case. The reason is that the dip or peak located at the center has larger influence on the velocity of lower order modes, especially on LP_{0n} modes. As two examples, the relative mode group delay for fiber #1 and #4 are shown in Fig.1 (b) (c). Fig.1 (a) also reveals that with appropriate offset launch (from 15µm to 25µm offset), larger RML bandwidth over OFL bandwidth can be achieved and thus avoid the serious influence of the lower modes. This explains why offset RML scheme is recommended.

Table 1. Six MMF with different refractive index profiles considered for analysis (g: power-law exponent)

MMF	#1	#2	#3	#4	#5	#6
Index profile	g=2.03 with dip	g=2.03 with peak	g=1.88 with dip	g=1.88 with peak	g_1=1.96, g_2=2 with dip	g_1=1.96, g_2=2

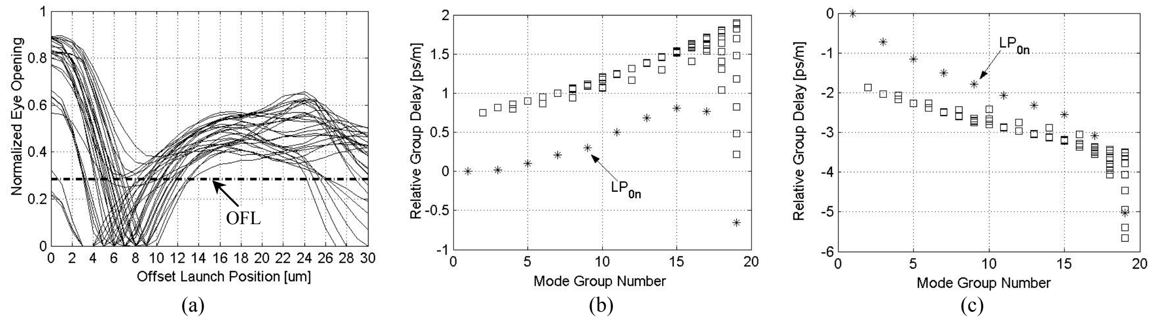


Fig.1. (a) The normalized eye opening with different launch positions for fiber #1 to #5 after 130m-transmission distance at 10Gb/s, FWHM of incident beam spot is 4μm~14μm with step size 2μm . (b) Relative group delay versus mode group number for fiber #1. (c) Relative group delay versus mode group number for fiber #4.

To illustrate the various characteristics of the MMF channel, the eight typical impulse responses and frequency responses for fiber #4 and #5 for different launch positions under the assumption of incident beam spot size of FWHM=10μm are plotted in Fig.2. The eight impulses are chosen as representative samples among the 1674 cases. As shown in Fig.2, different launch positions result in different impulse responses and thus frequency responses, which correspond to the different mode groups and different mode power distribution (MPD) among these modes.

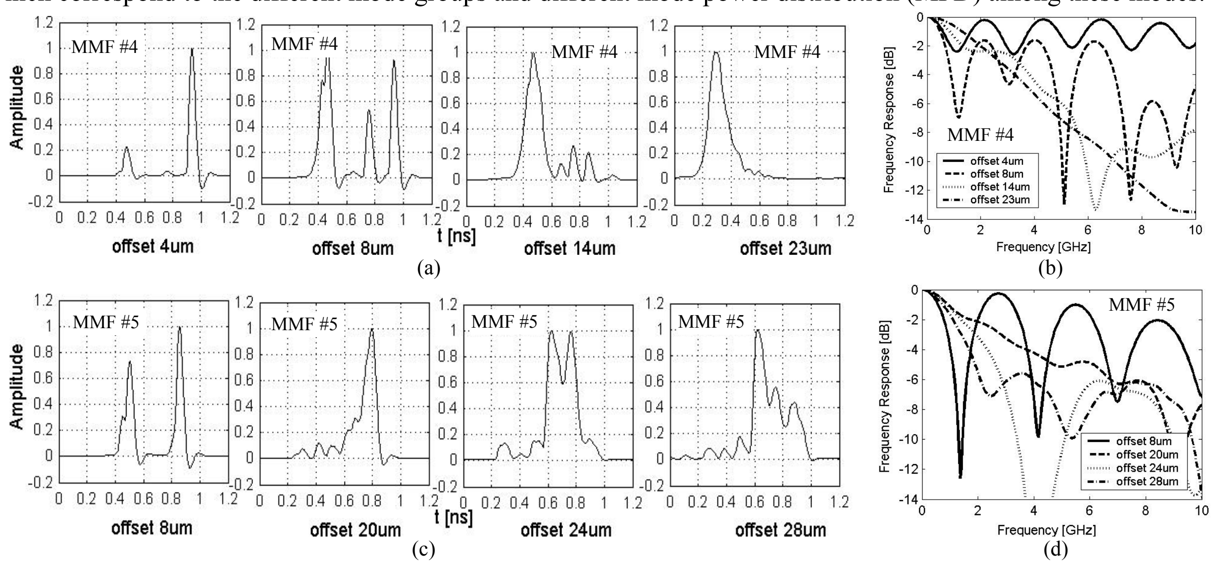
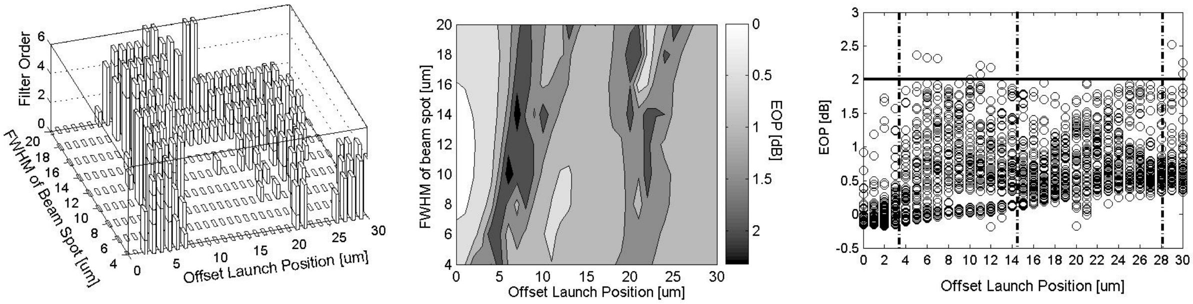


Fig.2. The impulse responses and frequency responses of MMF with different launch positions after 300m-transmission distance at 10Gb/s, FWHM of beam spot is 10μm. (a) Impulse responses for fiber #4. (b) Frequency responses for fiber #4. (c) Impulse responses for fiber #5. (d) Frequency responses for fiber #5.

3. Statistical analysis of electrical equalization of DMD in MMF

To study the EDC performance on DMD of MMF links, we presume the following rules and parameters: The coefficients of the FIR and DFE filter taps [6] are calculated based on minimum mean square error (MMSE) rules. The order (number of delay elements) of the feedforward FIR filter is fixed to 12 and the feedback DFE filter has variable order from 0 to 6. We assume a 2dB eye-opening penalty (EOP, compared to back-to-back) target to be acceptable. I.e. DFE order of zero (linear equalizer) is tried first to observe whether the EOP of the signal after equalization is less than 2dB, otherwise the DFE order is increased by one until the EOP target is achieved. The maximum DFE order is limited to six. The EOP values as well as the order of feedback filter are recorded for all the 1674 sample channels for a MMF length of 300m at 10Gb/s. In terms of the above rules, the order required for the feedback filter is given in Fig.3 (a) and plotted versus beam spot size and launch position.

Fig.3 (a) reveals that near center launch (about from 3μm to 14μm) needs more taps or causes larger ISI, which is consistent with the conclusions drawn from Fig.1 (a). Within this offset range, most impulse responses with multiple echos (peaks) are observed. See Fig.2 (a) and (c) for offset launch 4μm and 8μm. The multiple echo impulse response is related with strong ripples in the frequency response. Linear (feedforward) FIR equalizer has the basic limitation that it performs poorly on channels having strong spectrum ripples or spectrum nulls. Center launch with very small offset shows good performance, but should be avoided due to the required low offset tolerances. In addition, Fig.3 (a) shows that with offset launch of about 16μm~28μm, DFE order of one or two is sufficient to mitigate the ISI and achieve an EOP of less than 2dB. By examining the impulse responses in fig. 2 (a) and (c) for offset 23μm, 24μm and 28μm we see that the echos tend to merge and the spectral dips extend to higher frequencies, so we need a lower degree DFE to mitigate the postcursor ISI. From above analysis, we conclude that launch offset from 16μm to 28μm is preferable offset launch range within which a feedback DFE of order one or two is sufficient to eliminate the postcursor ISI.



(a) (b) (c)

Fig.3. (a) Feedback filter order required by DFE at 2dB EOP target for the six MMF (300m) versus incident beam spot size and offset launch position.(b) The EOP versus incident beam spot size and offset launch position for fiber #2.(c) The EOP values for 1674 channels versus offset launch position with optimized equalization.

By using the DFE with feedforward filter of order 12 and feedback filter with order as derived from Fig.3 (a), the EOP distribution versus beam spot size and offset launch position for fiber #2 as an example is illustrated in Fig.3 (b). Fig.3 (b) shows that larger EOPs are observed for offset launch from 5μm to 10μm and from 20μm to 25μm, which is consistent with the analysis of Fig.3 (a).

The EOPs for the total 1674 channel samples are plotted in Fig.3 (c) versus offset launch position. Fig.3 (c) displays that only nine cases are out of the criterion of 2dB EOP. I.e, the fail ratio is about 0.5%. Moreover, among these nine worst cases, the largest EOP value is still less than 2.5dB. The nine cases failing the 2dB EOP target can be considered as the worst cases of the equalization performance, analysis of which is important for the EDC design. Through the examination of the nine cases, we found that most of them exhibit simultaneously the spectrum with zeros and the impulse response with high-energy precursors, the former limits the performance of linear equalizer and the latter limits the performance of DFE. For these worst cases, the performance of equalization can be improved either by increasing the filter order or using other equalizer like fractionally spaced equalizer or Viterbi equalizer, however, both of which increase the complexity of EDC design. From the density of the EOP values in fig. 3 (c) we conclude again that the range from 3μm to 14μm offset results in the worst EOP and six of the nine worst cases locate in this range. This further demonstrates that the near center launch causes severe ISI.

4. Conclusions

Through the statistical analysis of electronic equalization of DMD on large number of installed MMFs with bandwidth distance-product 500MHz-km after 300m-transmission at 10Gb/s, we conclude as follows: (1) Linear equalizer alone can not guarantee the performance for all considered cases. (2) DFE with order 12 feedforward filter and order 6 feedback filter can achieve less than 2dB EOP for almost any launch condition. Statistical study shows the fail ratio is only 0.5% for 5% worst cases. (3) The off center launch with offset from 16μm to 28μm is optimum offset launch range within which a feedback DFE of order one or two is sufficient to eliminate the postcursor ISI. (4) The worst case for equalization on MMF is the channel having the impulse response with high-energy precursors and the frequency response with null points simultaneously.

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