Electronic Compensation Techniques for Multi-Mode Transmission Systems

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Abstract *Based on statistical analysis of representative worst-case MMF samples, we present comprehensive comparisons and analysis of different electrical dispersion compensation on differential mode delay in MMF links for 10-Gigabit Ethernet.*

Introduction

For high-speed data rate multimode fiber (MMF) short links such as 10GE, the transmission capacity is mainly limited by the intermodal dispersion resulting from the differential mode delay (DMD). The overfilled launch (OFL) bandwidth for installed MMF is only about 500MHz-km, which is far from the requirement of 300m-transmission distance for 10GE. IEEE 802.3aq 10GBASE-LRM Task Force focuses on the study of the electrical equalization to mitigate the ISI caused by DMD to extend the MMF links to 300m [1]. In this work, based on statistical analysis of typical worst-case installed MMF samples, we investigate comprehensively various electrical dispersion compensation (EDC) on DMD mitigation. Different electrical equalization techniques including feedforward equalizer (FFE), decision feedback equalizer (DFE), Viterbi equalizer (VE) and reduced state VE are compared.

MMF links consideration

We use the MMF model described in [2,3]. The characteristics of MMF links vary greatly from one link to another. First, MMF bandwidth is directly determined by DMD distributions or the refractive index profiles. Therefore, worst case MMF should be considered to evaluate effectively the EDC performance. In total 11 MMF with different index profile exponents g and various deformations listed in Table 1 are examined. Typical index profile deformations such as dip or peak at core center, two index exponents and sinusoidal index ripples are taken into account. All of these deformations of index profiles are introduced by manufacturing process and can result in severe bandwidth degradation, especially under restricted mode launch (RML) by using laser. The DMD calculated from the 11 MMF is scaled to approach the 3dB-OFL bandwidth of 500MHz-km.

Since the data rate for MMF links is extended to 10Gb/s and beyond, the overfilled launch (OFL) based on LED has been replaced with RML by using lasers such as VCSELs. The MMF bandwidth also greatly depends on the launch conditions such as different launch offset positions. To demonstrate this, statistical analysis has been carried out on the 11 MMF. In fig.1, we show the eye opening versus launch positions with Gaussian beam spot size variable from 4μm to 14μm and MMF length of 130m. Fig.1 demonstrates that with offset launch from 17μm to 23μm, larger bandwidth compared to OFL case for most cases can be achieved.

Table.1.

MMF	Distortion	Description
#1	g=2.03,with dip	With depth or height of 10% of maximum index difference and width 4% of core diameter
#2	g=2.03,with peak	
#3	g=1.88,with dip	
#4	g=1.88,with peak	
#5	g=2.03,with dip	With depth or height of 5% of maximum index difference and width 8% of core diameter
#6	g=2.03,with peak	
#7	g=1.88,with dip	
#8	g=1.88,with peak	
#9	g=1.96, 2,with dip	Same to MMF #1~#4
#10	g=1.88,sinusoidal	Amplitude of 0.5% of maximum index difference and period of 5. [4]
#11	g=2.03,sinusoidal	

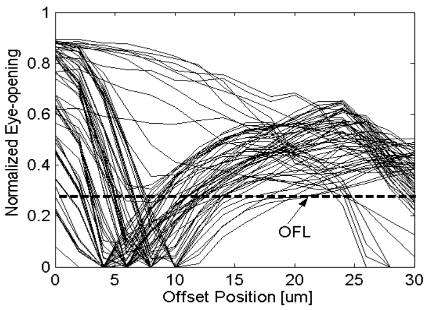

Fig.1. Normalized eye opening versus offset launch positions for 11 MMF with length of 130m.

Statistical analysis of FFE and DFE

FFE and DFE are considered as cost-effective solution in MMF short links. To examine the EDC performance on DMD mitigation, the parameters are assumed as follows: 6 MMF selected from Table.1, 9 beam spot sizes variable from 4μm to 20μm with a step size of 2μm, 30 launch positions variable from 0μm to 30μm with a step size of 1μm. We have in total different 1674 impulse responses. For equalization setups, we assume a DFE with a feedforward filter of order 12 and a feedback filter of order variable from 0 to 6 at a target of eye-opening penalty (EOP) of 2dB. The orders or tap numbers for both filters are high enough to eliminate the pre-cursor and post-cursor ISI in consideration of 300m-transmission. The required order of feedback filter versus launch positions and beam spot sizes for the worst case of the 6 MMF is shown in Fig.3. Fig.3 shows that larger order is required to reach 2dB EOP target with near center launch but order 2 is enough to eliminate the post-cursor ISI with appropriate offset launch from 17μm to 28μm. Obviously, FFE alone (with feedforward filter of order 0) can not guarantee the EDC performance for all the cases.

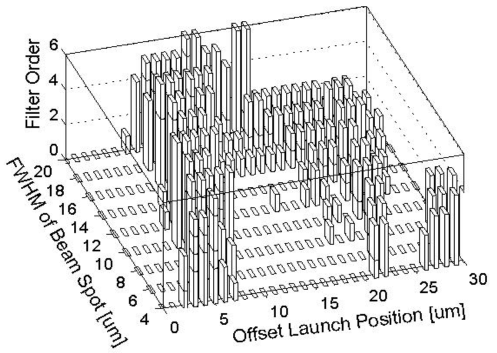

Fig.3. Feedback filter order required by DFE at 2dB EOP target for the six MMF (300m) versus incident beam spot size and offset launch position.

Comparison of various EDC performances

FFE and DFE have been examined above. In this part, we introduce the maximum-likelihood sequence estimation (MLSE) based on Viterbi algorithm or Viterbi equalizer (VE) as well as reduced state VE. VE can achieve the optimum performance with most complexity. One of the reduced complexity VE is the channel memory truncation by means of sequence feedback. It can be regarded as an extension of DFE and called delayed-decision-feedback-sequence-estimation (DDFSE) equalizer, which is widely discussed in wireless communications [5]. However, DDFSE can achieve better performance for the channel with much energy concentrated near the beginning of the channel impulse response. As motioned previously, impulse responses in MMF links vary greatly from one link to another. Therefore, most of the observed impulse responses do not satisfy this condition. In this work, one FIR prefilter is used to reshape the MMF channel into impulse response with minimum phase properties and then the reshaped impulse response is processed further by DDFSE.

To compare the EDC performance for different schemes, Monto carlo simulations are carried out on the 11 MMF. We assume the Gaussian input beam spot with FWHM=12μm and offset launch 20μm. Channel estimations for VE and equalizer coefficients for FFE and DFE are optimized based on the minimum mean square error rules. The transmission distance is presumed to be 300m. The equalizer setups are considered as follows. To be compared to VE, both FFE and DFE are assumed to be with high enough delay tap. We assume a FFE of 12-tap (FFE[12]) and a DFE with 12-tap feedforward filter and 6-tap feedback filter (FFE[12]-DFE[6]). Observation of the impulse responses of the 11 MMF shows that ISI span varies from 4 to 6 bits. Channel memory of 4 or trellis state of 16 is assumed for VE. For DDFSE, first of all, a prefilter of 12-tap FIR is used to reshape the channel impulse response to have minimum phase characteristics. Channel memory of VE is truncated to 2 and an additional 4-tap DFE is used to cancel the pulse tail. The noise in MMF links is predominantly from the receiver electronics and assumed as additive white Gaussian noise. BER in the simulations is achieved using time-consuming Monto-carlo method. Therefore, We compare the performance for a BER of 10^{-5} instead of 10^{-12}.

The electrical power penalty compared to b2b case before the equalizer by using different EDC with two-fold oversampling is shown in Fig.4. We can see that FFE exhibits great variability from one MMF sample to another. FFE performance depends directly on characteristics of frequency responses. FFE shows poor performance on the channel having null points. Other three EDC can achieve much more stable performance. DFE can achieve sub-optimum performance without the noise enhancement. VE can achieve the optimum performance. Reduced state VE with memory of 2 can approach or even outperform VE with memory of 4. VE performance is related to the ISI span not the frequency responses provided the exact channel estimation can be obtained.

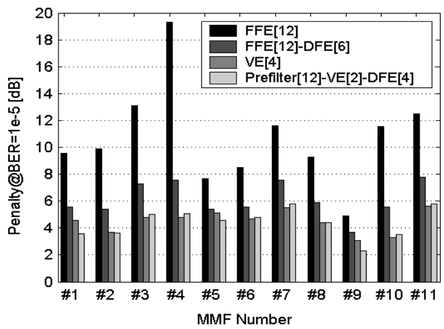

Fig.4: Penalty (compare to b2b@BER=10-5) for the 11 MMFs with oversampling of 2 by using the four different EDC techniques.

Conclusions

Based on statistical analysis of representative worst-case MMF samples, various EDC techniques on DMD mitigation in MMF links are examined and compared. FFE alone cannot achieve 300m-transmission distance for 10GE. DFE and reduced state VE are proposed to guarantee the EDC performance with a trade off between performance and complexity.

References

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