Nonlinear Electrical Equalization in MMF Links for 10-Gigabit Ethernet

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Abstract *We demonstrate the transmission distance for conventional multimode fiber can be extended to 300m or beyond @10Gb/s by utilizing different electrical equalization techniques including nonlinear equalization.*

Introduction

The goal of 10-Gigabit Ethernet for the conventional Multimode Fiber (MMF) is to obtain 300m-transmission distance. However, the intermodal dispersion induced by the Differential Mode Delay (DMD) in MMF channel dramatically limits the bandwidth-distance product to 500MHz-km for 62.5µm-MMF at 1300nm or 50µm-MMF at 850nm as well as 1300nm.

The Intersymbol Interference (ISI) resulting from DMD can be compensated by utilizing electrical equalization technique. In this work, through comparison and analysis of different electrical equalizers we prove that the transmission distance for installed MMF can reach or extend the 300m-goal. We present three kinds of equalizers: linear equalizers including bit synchronous equalizer or Finite Impulse Response (FIR) filter and Fractionally Spaced Equalizer (FSE), Decision Feedback Equalizer (FIR-DFE and FSE-DFE) and the nonlinear equalizer named as NL-FIR-DFE based on Volterra theory, which can eliminate the nonlinear ISI caused by the nonlinear operation due to the modulation and direct detection in optical fiber systems. This kind of nonlinear equalizer has been introduced and proven to have better performance in single mode fiber long haul links [1].

Model of MMF links

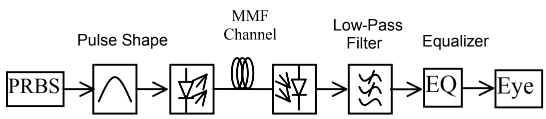

Fig.1: MMF links with direct modulation and electrical equalization

As shown in Fig.1, PRBS with length 2^9-1 and NRZ line coding are assumed. Considering the cost-effective MMF links, the directly modulated laser like Fabry-Perot laser or VCSEL is employed and modeled as the linear laser without considering chirp. Signal extinction ratio is assumed to be 10.4dB.

The MMF channel is modeled by the sum of the power P_m carried by each mode m (from 1 to M, where M the maximum mode number), which has different group delay τ_m. The impulse response is

$$h(t)=\sum_{m=1}^{M} P_m \delta(t-\tau_m)$$

The different mode group delay as well as the electric field distribution for each LP mode in MMF channel is examined by solving a numerical mode solver [2,3]. The mode group delay distribution, which mostly depends on the refractive index profile, is different from one MMF channel to another. It is impossible and also unnecessary for us to analyse all kinds of those refractive index profiles. To approach the practical refractive index profile of conventional MMF, the maximum DMD as well as the imperfection of refractive index at center of core should be considered together. To approach the maximum DMD of 2ps/m of 95% installed MMF at 1300nm [4], the typical index profile with index power-law exponent 2.03 for standard 62.5µm-MMF with a small local dip at the centre of the core is chosen. Under these assumptions and operated at 1300nm, the relative group delay is shown in Fig.2, in which the highest mode group has been cut off by considering the mode dependent loss.

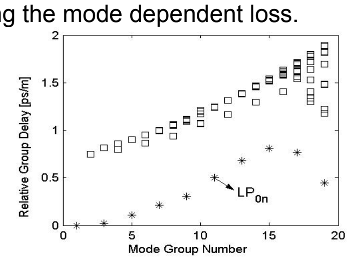

Fig.2: Relative group delay versus mode group number

We assume the mode dependent attenuation satisfies modified Bessel function of first kind [5]. In addition, only mode coupling within the same mode group is sufficient in our model. A low-pass Butterworth filter of 3rd order with cut-off frequency 7GHz is used after photo-detector. The low-pass filter is followed by electrical equalizer and then the eye analyzer. We scale the group delay shown in Fig.2 to reach 3dB bandwidth-distance product of 500MHz-km for Overfilled Launch (OFL) condition including the mode dependent loss.

Since the standardization of Gigabit Ethernet, Restricted Mode Launch (RML) scheme based on the partial mode excitation by using directly modulated laser has been recommended. However, RML bandwidth is not always larger and even worse than that of OFL case owing to the imperfection of refractive index profile. Subsequently offset RML technique is developed to overcome this problem.

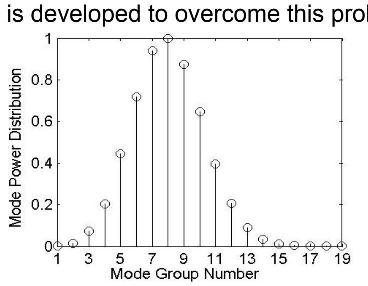

Fig.3: Mode power distribution versus mode group number, Gaussian beam spot with FWHM=7µm, offset 18µm.

Gaussian beam with spot FWHM of 7µm is assumed, which is a typical value for most multimode lasers [3,6]. By solving the overlap integral between the source and LP modes excited in MMF channel, mode power distribution is calculated. The mode power distribution by offset 18µm is drawn in Fig.3. The normalized eye opening versus offset position is shown in Fig.4.

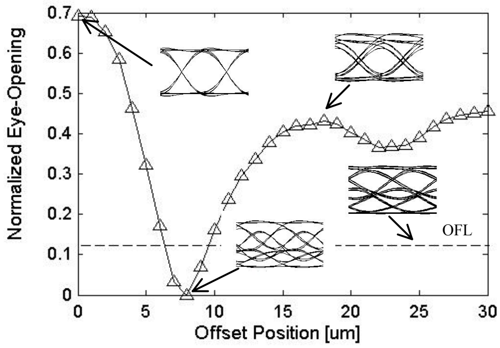

Fig.4: Normalized eye opening versus offset position. The received signal diagrams are obtained after 150m for offset 0µm, 8µm, 18µm and OFL condition, respectively.

Equalization used for MMF channel

The coefficients of equalizers are calculated based on minimum mean square error rule without considering noise and Eye-Opening Penalty (EOP, compared to b2b) is the criteria of assessment of equalization. EOP of received signal with and without utilizing equalization is shown in Fig.5. For comparison, EOP for OFL condition is also given. Fig.5 shows that for OFL condition, the transmission distance is limited to only about 88m with 2dB EOP. Under the assumptions of above parameters, the transmission distance for RML condition is extended to about 125m@2dB EOP. However, by using equalization, the transmission distance for all the five kinds of equalizers or combination can reach 300m with 2dB EOP. In particular, as mentioned earlier, by employing NL-FIR-DFE, which is capable of eliminating the nonlinear ISI caused by modulation and direct detection, much more improvement can be achieved in comparison to using normal FIR-DFE. With the criteria of 2dB EOP, 700m-distance can be obtained by utilizing NL[3,2]-FIR(6)-DFE(2). The meaning of the numbers is: nonlinear order 3 and 6 delay taps for feedforward filter, and nonlinear order 2 and 2 delay taps for feedback filter. As an example, the setup of NL-FIR-DFE with NL[2,2]-FIR(1)-DFE(2), i.e. with nonlinear order 2 and 1 delay tap for feedforward filter and nonlinear order 2 and 2 delay taps for feedback filter, is shown in Fig.6.

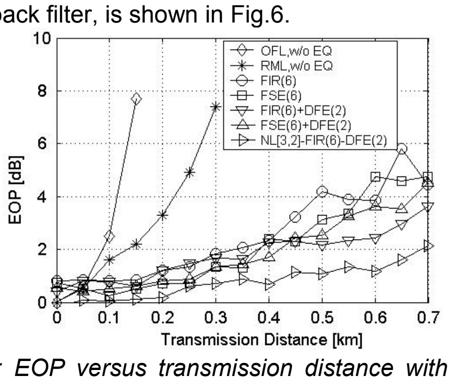

Fig.5: EOP versus transmission distance with and without using electrical equalizers. Gaussian beam spot FWHM=7µm and offset 18µm.

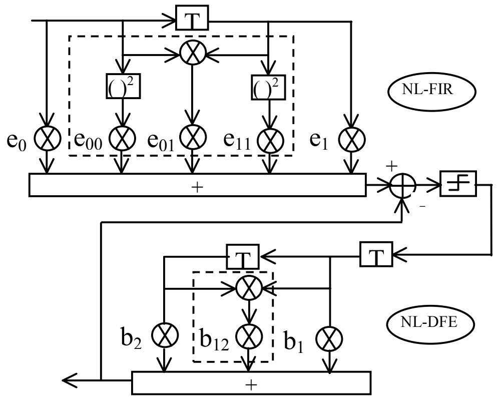

Fig.6: Setup of NL[2,2]-FIR(1)-DFE(2): nonlinear part of setup marked with dash-line.

Influence of laser spot on equalization

It is evident that the maximum transmission distance which can be reached by utilizing equalization is dependent on the mode power distribution as well as the number of modes excited, namely, on the spot size of laser. Furthermore, the commercial lasers are different from one to another; therefore, it is worth studying the influence of the spot size on the equalization. Equalization by using three kinds of DFE with different spot size containing most multimode lasers [3,5] is shown in Fig.7, from which we can see that for the worst case at 300m transmission distance, EOP is about 3dB with FIR(6)-DFE(2) and 1.5 dB with NL[3,2]-FIR(6)-DFE(2).

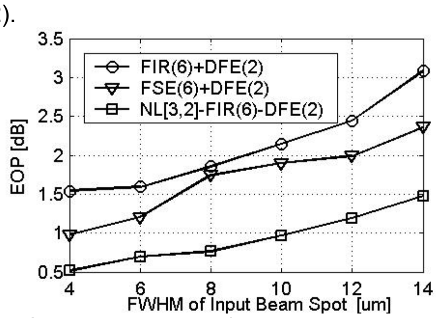

Fig.7: EOP versus size of input beam spot after 300m-transmission distance and offset 18µm.

Conclusions

We show that transmission distance for installed MMF with bandwidth-distance product 500MHz-km can be extended to 300m or beyond @10Gb/s by utilizing normal DFE. In particular, we present the nonlinear equalizer named as NL-FIR-DFE, which exhibits superior performance in comparison to normal FIR-DFE. Moreover, we examine the influence of beam spot size of lasers on the equalization.

References

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