Mitigation of Laser Nonlinearity and Channel ISI Simultaneously by Using Nonlinear Equalization for 4-ASK Signalling in MMF Links

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ABSTRACT

Multilevel intensity modulation such as 4-ASK signalling can reduce the bandwidth requirement in multimode fiber (MMF) links. However, 4-ASK signalling is susceptible to the laser nonlinearity. In addition, even with 4-ASK signalling, the maximum transmission distance over installed MMF is still limited by differential mode delay (DMD) to less than 300m for 10GE. We propose and demonstrate that directly modulated laser nonlinearity and modal dispersion resulting from DMD can be eliminated simultaneously by using a nonlinear electrical equalizer for 4-ASK signalling in high-speed MMF short links.

Keywords: 10-Gigabit Ethernet, Differential Mode Delay (DMD), Multimode Fiber (MMF), nonlinear electrical equalization, multilevel modulation.

1. INTRODUCTION

An important goal of 10-Gigabit Ethernet over installed Multimode Fiber (MMF) is to obtain 300m-transmission distance. However, the intermodal dispersion induced by the Differential Mode Delay (DMD) in MMF limits the transmission distance to only about 80m. Recent research has shown that MMF with bandwidth of 500HMz-km can be extended to 300m for most cases through Electrical Dispersion Compensation (EDC) for conventional Non-Return-to-Zero (NRZ) signal [1-3,9-12]. However, due to the limited equalization performance in severe ISI environment, 300m-goal cannot be guaranteed for 10GE with Feed Forward Equalizer (FFE) or Decision Feedback Equalizer (DFE) by using conventional NRZ or 2-Amplitude Shit Keying (2-ASK) signaling [1,10,13]. Multilevel modulation such as 4-ASK has been considered as the effective solution to reduce the bandwidth requirement [4,5]. However, 4-ASK signalling is susceptible to the Laser Diode (LD) nonlinearity, especially when large output power is required. In addition, 4-ASK scheme alone cannot achieve 300m-distance for 10GE application and therefore it should be combined with other techniques such as electrical equalization. The LD nonlinearity and channel ISI can be compensated by digital pre-distortion at the transmitter side [6] and by post-equalization at the receiver side, respectively. However, this is not cost effective solution for 10GE application. Instead, in this work, we propose a nonlinear FFE based on Volterra theory [3,7] to mitigate the LD nonlinearity and DMD, simultaneously.

This paper is organized as follows. First of all, the directly modulated laser nonlinearity is analyzed. Second, MMF channel characteristics including modal dispersion and launch conditions will be addressed based on representative worst-case MMF samples. Then the nonlinear equalizer will be introduced. After that, the mitigation of laser nonlinearity and MMF channel ISI by using the nonlinear equalizer will be investigated in detail based on the analysis of eye-diagrams as well as Bit Error Ratio (BER).

2. LASER DIODE NONLINEARITY

LD nonlinearity can result from numerous factors such as temperature variations, internal parameters, improper modulation, leakage current and axial hole burning. Typical transfer characteristics of directly modulated laser such as Fabry-Perot laser or VCSEL exhibit two kinds of basic nonlinearities, one is due to the spontaneous emission, which is related to the bias, and the other is due to the saturation. Generally, the former can be avoided by adjusting the bias to larger than the threshold. Therefore, we only consider the second nonlinearity effect. The LD nonlinearity can be categorized into static and dynamic [6]. The dynamic nonlinearity is studied through the laser rate equations. We focus on the mitigation of LD nonlinearity, therefore, we assume the static method, which may be given as

$$P(t) = P_0[1 + ms(t) + A_2 m^2 s^2(t) + A_3 m^3 s^3(t)]$$

Where, $s(t)$ is the input electrical signal, P_0 is the average optical power, m is the optical modulation index and A_2, A_3 are device dependent nonlinearity coefficients. High order nonlinearity terms have been omitted. We assume the transfer characteristic of LD satisfies

$$P(t) = s(t)[1 - 0.15s(t) - 0.15s^2(t)]$$

Here, the DC part has been assumed to be zero and the normalized relative nonlinear coefficients (compared to linear part) have been assumed to be –0.15 for both order second and third nonlinearity terms. The nonlinear characteristics under these assumptions can approach the general practical case. The normalized P-I curves are shown in Fig.1. From Fig.1, we can see that the nonlinearity is directly determined by the extinction ratio. The lower the extinction ratio, the less the nonlinearity is. However, we assume the infinitive extinction ratio to examine the nonlinear equalizer performance on the laser nonlinearity mitigation.

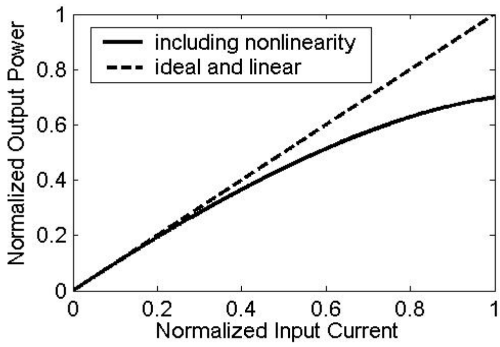


Fig.1. P-I characteristics of linear and nonlinear LD.

3. MMF CHANNEL CHARACTERISTICS

We use the MMF model described in [1,2]. The characteristics of MMF links vary greatly. First, MMF bandwidth directly depends on DMD distributions, which is determined mainly by refractive index profiles. As shown in [1,2,8,10,13], due to the manufacture process, most of installed MMFs exhibit the deformation of index profiles, especially at the core center. Both simulations and experimentations have demonstrated that the deformations usually cause very large bandwidth degradation based on laser center launch condition for high-speed data rate links [1-3,8]. Therefore, worst case MMF should be considered to evaluate effectively the MMF links performance as well as the EDC performance. In total, five MMF with different index exponent g and various profile deformations with small dip or peak as listed in Table 1 are examined. DMD is scaled to approach 3dB bandwidth of 500MHz-km based on overfilled launch (OFL). It is important to mention that five MMF samples are far not enough to examine the performance of installed MMF links for 10GE application because the deformations of index profiles are various from one MMF to another. However, we focus on the demonstration of EDC performance on DMD mitigation, therefore, we only focus on the five most representative worst case MMF samples. Later on will we demonstrate that it is unnecessary to examine a large number of MMF samples to compare the linear and nonlinear equalization performance in our case.

Table.1

MMF	Distortion	Description
#1	g=2.03,with dip	Dip or peak is located at core center, with depth or height of 10% of maximum relative 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=1.96, 2,with dip	

Since the data rate for MMF links is extended to 10Gb/s and beyond, the OFL based on LED has been replaced with Restricted Mode Launch (RML) by using lasers. Generally, only subset mode groups is excited by using laser. Therefore, the total effective MMF system bandwidth is dependent on which mode groups excited as well as the mode power distribution among these mode groups. That is to say, the MMF link bandwidth greatly depends on the launch conditions including launch beam spot sizes and offset launch positions. Usually, launch beam spot of FWHM=7μm is assumed based on single mode fiber launch. However, for practical consideration, the excited modes by the laser will excite more modes or mode groups during propagation due to the unavoidable mode coupling from connectors and bending. Therefore, larger beam spot is assumed in this paper to examine the EDC performance. In addition, statistical analysis has shown that RML with offset launch in the range from 17μm to 23μm can achieve at least OFL bandwidth for 62.5μm MMF [1-3, 8]. Based on these analysis, we assume offset launch position is 20μm and the laser beam spot size of FWHM=12μm.

4. INTRODUCTION OF NONLINEAR EQUALIZER

The nonlinear FFE setup is based on Volterra theory and has been demonstrated to mitigate the nonlinear ISI in optical communication system [3,7]. For illustration, the structure of this kind of equalizer under assumption of the order 1 and nonlinear order 2 (FFE[1]-NL[2]) is shown in Fig.2. This kind of nonlinear FFE can be considered as the extension of conventional linear FFE including the nonlinear coefficients part. Obviously, without the nonlinear part, it turns into conventional FFE of 1-delay tap.

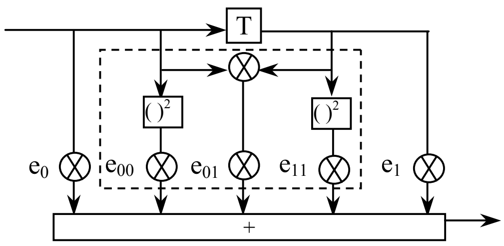


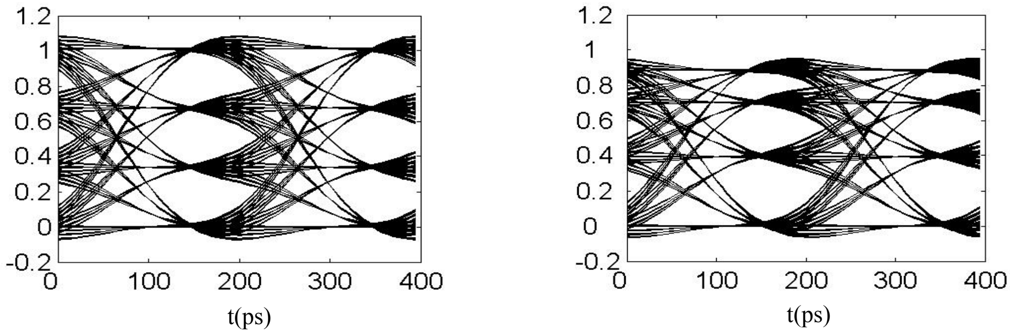
Fig.2. Nonlinear FFE[1]-NL[2]. nonlinear part of setup marked with dash-box.

This nonlinear FFE can mitigate both linear and nonlinear ISI. However, the additional required nonlinear coefficients increase the design complexity especially for higher order case. Therefore, As a trade off between performance and complexity, we assume a nonlinear FFE of order 4 and nonlinear order 2 (FFE[4]-NL[2]). Under this assumption, the total coefficients is 20 including both linear and nonlinear parts.

5. MITIGATION OF LD NONLINEARITY AND CHANNEL ISI

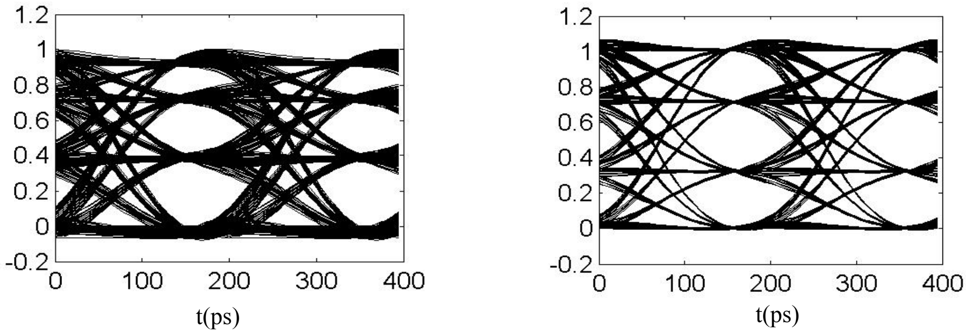
The b2b received eye-diagrams filtered by a Butterworth low-pass filter with 3dB-bandwidth of 3.5GHz with bit rate 10Gb/s 4-ASK signalling for linear and nonlinear LD (nonlinearity coefficients as given in pervious part 2) are shown in Fig.3. From Fig.3 we can see that the nonlinearity of P-I characteristic results in the asymmetrical eyes as shown in Fig.3 (b). The top eye will be most sensitive to the noise and thus causes larger BER.

First of all, we examine the performance on laser nonlinearity mitigation by using conventional FFE and nonlinear FFE for b2b case. For fair comparison, order 19 is chosen for the conventional FFE (FFE[19]) to be compared with FFE[4]-NL[2] having the same number of total coefficients. The equalized eye-diagrams are shown in Fig.4. Compared to the b2b case without equalization as shown in Fig.3, we see that conventional FFE even of high order cannot mitigate the LD nonlinearity. However, nonlinear FFE can inverse the LD nonlinearity characteristics with nonlinear coefficients and exhibits superior performance to eliminate the nonlinearity impairment.



(a) (b)

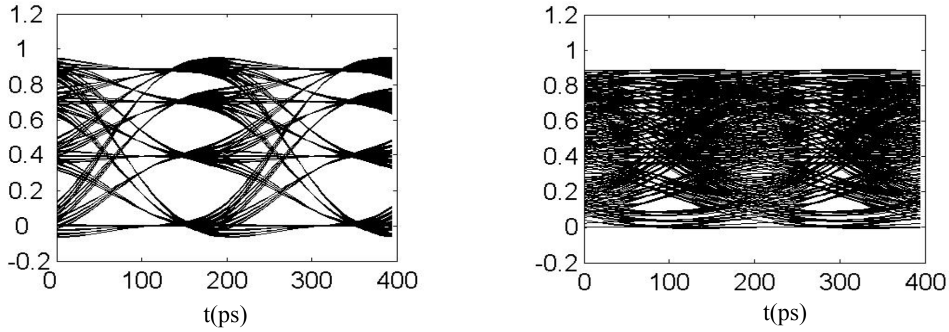
Fig.3. B2b received normalized 4-ASK eye-diagrams with linear (a) and nonlinear LD (b).



(a) (b)

Fig.4. B2b equalized 4-ASK eye-diagrams with FFE[19] (a) and FFE[4]-NL[2] (b).

Second, we show that nonlinear FFE can also mitigate the channel ISI effectively caused by the DMD. Under the assumption of the launch conditions presented in previous part, the received eye-diagrams for b2b and 300m-transmission distance without equalization for MMF #1 are shown in Fig.5. The severe DMD has caused completely closed eye as shown in Fig.5 (b). This has confirmed that 300m-transmission distance cannot be achieved even with 4-ASK modulation. The equalized eye-diagrams are shown in Fig.6, which reveals that nonlinear FFE can mitigate both LD nonlinearity and DMD effectively, compared to conventional FFE. Conventional FFE can only compensate the modal dispersion without affecting the laser nonlinearity.



(a) (b)

Fig.5. Received 4-ASK eye-diagrams over MMF #1.(a): b2b. (b): 300m-transmission distance.

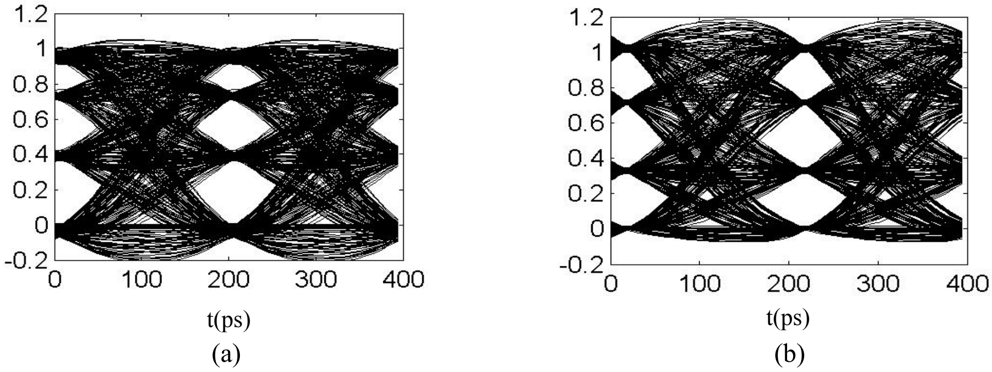


Fig.6. Equalized 4-ASK eye-diagrams over MMF #1 after 300m-transmission distance by using FFE[19] (a) and nonlinear FFE[4]-NL[2] (b).

The coefficients of linear and nonlinear equalizer are plotted in Fig.7. Let $[e_0, e_1, ..., e_{19}]$ represent the coefficients of FFE[19]. Let $[e_0^1, e_1^1, ..., e_4^1, e_{00}^2, e_{01}^2, ..., e_{11}^2, ..., e_{44}^2]$ represent the coefficients of nonlinear FFE[4]-NL[2] and the superscript represents the nonlinear order of 1 or 2 (nonlinear order of 1 corresponds to the linear part). The linear coefficients $[e_0^1, e_1^1, ..., e_4^1]$ and nonlinear coefficients $[e_{00}^2, e_{01}^2, ..., e_{11}^2, ..., e_{44}^2]$ of FFE[4]-NL[2] are illustrated with unfilled and filled circles, respectively, as shown in Fig.7(b). First of all, from the coefficients weighting of linear FFE[19] as shown in Fig.7 (a), we can see that the coefficients $[e_5, e_6, ..., e_{19}]$ approach zero and hence a FFE of 4 order is enough to eliminate the channel ISI. This demonstrates that the nonlinear equalizer of order of 4 is enough to compensate the modal dispersion. Second, the similarity of the coefficients $[e_0, e_1, ..., e_4]$ of FFE[19] and linear part $[e_0^1, e_1^1, ..., e_4^1]$ of FFE[4]-NL[2] demonstrates that nonlinear equalizer compensates the impairments of modal dispersion and laser nonlinearity with linear and nonlinear coefficients separately. Therefore, the interaction of modal dispersion and laser nonlinearity can be omitted.

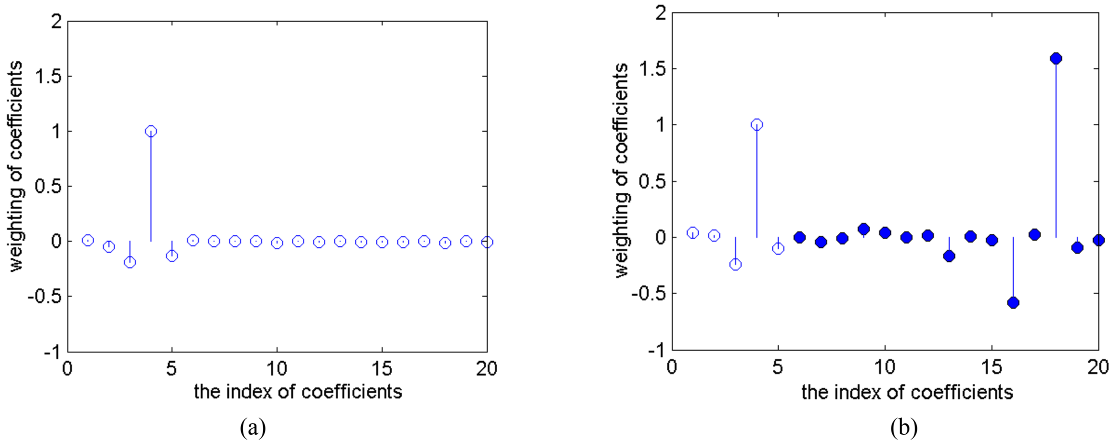


Fig.7. The weighting coefficients of linear FFE[19] (a) and nonlinear FFE[4]-NL[2] (b).

Above discussions are assumed to be without noise. Monto-Carlo simulations are carried out to examine the noise influence. In contrast to the dominance of Amplified Spontaneous Emission (ASE) noise from EDFA in single mode long haul links, the noise in MMF short links is mainly from receiver electronics. Therefore, Additive White Gaussian Noise (AWGN) is assumed. We compare EDC performance to achieve a BER of 10^{-6} due to the time-consuming Monto-Carlo simulations. A BER of 10^{-6} is far from 10^{-12} which is required by 10GE standard. However, the required power penalty (compared to without equalization) by using different equalizers is not so much between BER of 10^{-6} and BER of 10^{-12} if only no error floor appears. The electrical power penalty before the equalizer to achieve a BER of 10^{-6} referred to b2b is shown in Fig.8. Nonlinear FFE outperforms normal FFE with a gain of from about 2dB to 3dB for different

MMF samples. We notice that the performance difference between linear and nonlinear FFE is not very large for different MMF samples. This can be explained as follows. Both linear and nonlinear FFE can compensate the ISI from modal dispersion and only nonlinear FFE can compensate the impairment from laser nonlinearity. This has been demonstrated by above analysis of equalizer coefficients as shown in Fig.8. Therefore, the performance difference between linear and nonlinear equalizer is mainly due to the laser nonlinearity. From this viewpoint, it is not necessary to examine further large number of MMF samples to compare the equalizer performance provided that the linear order is high enough to compensate the modal dispersion.

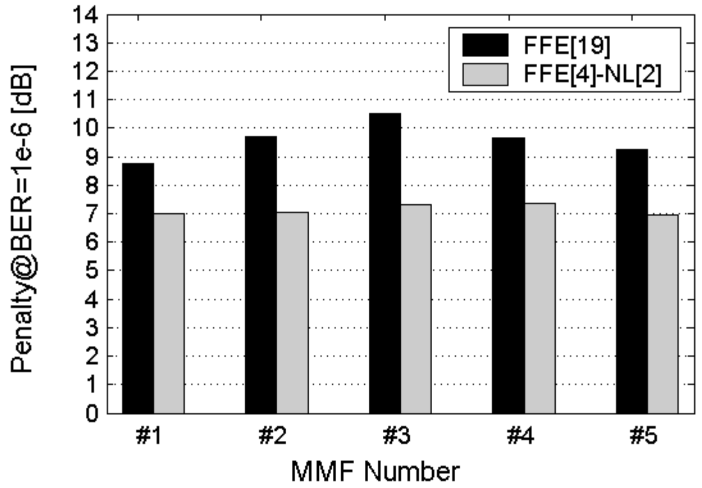


Fig.8. Electrical power penalty compared to b2b for the two kinds of equalizer setups over 300m-MMF for 10Gb/s data rate.

6. CONCLUSIONS

Multilevel signaling 4-ASK is susceptible to both laser nonlinearity and modal dispersion in high-speed multimode fiber short links. Based on typical worst-case MMF samples and offset selective launch, we have proposed and demonstrated that both above impairments can be mitigated simultaneously at the receiver side by using a nonlinear feedforward equalizer (FFE) in contrast to conventional FFE, which can only compensate distortion from modal dispersion.

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