Mitigation of Optical Intrachannel Nonlinearity Using Nonlinear Electrical Equalization

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Abstract *A nonlinear electrical equalization technique is proposed to mitigate the intra-channel nonlinearities in 40Gb/s optical fiber communications. High efficiency of this nonlinear equalizer for mitigation of nonlinearities is demonstrated.*

Introduction

The system performance for high-speed 40Gb/s optical fiber communications is severely limited by intrachannel nonlinearities including intrachannel four wave mixing (IFWM) and intrachannel cross phase modulation (IXPM) [1]. The techniques proposed to mitigate fiber nonlinearity include advanced modulation formats, electrical pre-distortion [2] and phase conjugation [3]. In this work, we investigate the mitigation of intrachannel nonlinearities by using nonlinear electrical equalization based on Volterra theory [4,5]. We have demonstrated that this kind of equalizer can mitigate efficiently the distortion due to chromatic dispersion (CD) in optical duobinary systems [4]. Here, we will show that it can also mitigate the fiber intrachannel nonlinearity efficiently.

Introduction of nonlinear FFE-DFE

This kind of nonlinear equalizer has been introduced in [4,5] and it can be considered as the extension from a normal feed forward equalizer (FFE) and decision feedback equalizer (DFE). We call it NL[x,y]-FFE[m]-DFE[n]. This designation means FFE of order m, DFE of order n and nonlinear order x for FFE and y for DFE. The case for x=1 and y=1 is equivalent to normal FFE[m]-DFE[n]. As an example, the signal outputs from FFE and DFE part for a equalizer NL[3,2]-FFE[4]-DFE[2] can be expressed as equation (1) and (2), respectively. Where, $y_r(t)$: the signal input into the FFE, d : the signal output from decision device or input into the DFE, T : bit period, e and b are the coefficients for FFE and DFE, respectively.

$$y_e(t)=\sum_{k=0}^{4}e_k y_r(t-kT)+\sum_{k=0}^{4}\sum_{l=k}^{4}e_{k,l}y_r(t-kT)y_r(t-lT)+\sum_{k=0}^{4}\sum_{l=k}^{4}\sum_{m=l}^{4}e_{k,l,m}y_r(t-kT)y_r(t-lT)y_r(t-mT) \quad (1)$$

$$y_b(q)=\sum_{k=1}^{2}b_k d_{q-k}+\sum_{k=1}^{2}\sum_{l=k+1}^{2}b_{k,l}d_{q-k}d_{q-l} \quad (2)$$

System setup

The system setup is illustrated as shown in Fig.1. A 8-span single channel OOK transmission with data rate of 43Gb/s including FEC overhead is used to investigate the nonlinear equalizer performance. Two Mach-Zehnder modulators (MZM) are cascaded to generate 50% duty cycle return-to-zero (RZ) OOK signal. Both optical band-pass filters (OBF) at transmitter and receiver side are Gaussian and with 3dB bandwidth of 120GHz. A 5th order Bessel electrical low-pass filter (ELF) with 3dB cut-off frequency of 30GHz is applied before the equalizer. In order to examine the performance of nonlinear equalizer for mitigating intrachannel nonlinearities, the dispersion in the standard single mode fiber (SSMF) with length of 80km is fully compensated with dispersion compensating fiber (DCF) (dispersion coefficient *D*=-60ps/nm/km and nonlinear coefficient γ =5/W/km) for each span. The span loss is fully compensated with inline erbium doped fiber amplifier (EDFA). The power launched into DCF is 6dB less than that into SSMF. Both nonlinearities of SSMF and DCF are taken into account. Pre- and post-compensation are not used here.

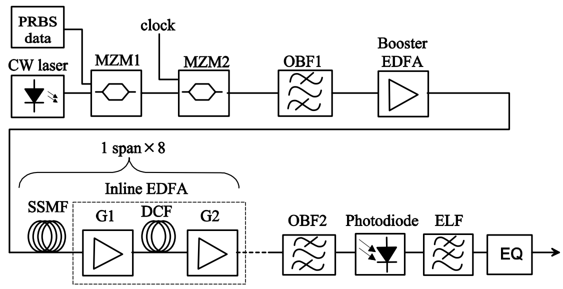

Fig.1: System setup for 43Gb/s RZ transmission.

Results and discussions

First of all, we examine the nonlinear equalizer performance for nonlinearity mitigation based on RZ-OOK system shown in Fig.1 without considering noise. The eye-opening penalty (EOP) of received signal compared to b2b ideal case with and without using equalization versus average input power is shown in Fig.2. We assume 1dB EOP as the system margin. Without equalization, the average input power is limited by strong intrachannel nonlinearities to less than 2dBm. With conventional FFE/DFE (e.g, FFE[4] or FFE[20]-DFE[1] shown in Fig.2), negligible improvement can be observed. More simulations have shown that even with very high order, conventional FFE/DFE shows negligible performance improvement. This demonstrates that intrachannel nonlinearity cannot be well mitigated by using conventional FFE/DFE. However, remarkable improvement can be achieved by using nonlinear FFE-DFE. For example, with 1dB EOP, average input power can be as high as 4dBm with NL[2]-DFE[4]. Moreover, Better performance can be achieved when the nonlinear order is increased. As shown in Fig.2, the average input power can be increased to 5dBm and 6dBm by using NL[3]-FFE[4] and NL[4]-FFE[4], respectively. These results demonstrate that intralchannel nonlinearities can be mitigated efficiently by using nonlinear FFE. In addition, through the comparison of EOP between NL[2]-FFE[4] and NL[2,1]-FFE[4]-DFE[1], we can conclude that NL-FFE-DFE exhibit negligible performance improvement compared to NL-FFE. Additional simulations have demonstrated that NL[x,y]-FFE[m]-DFE[n] shows very similar performance in comparison to NL[x]-FFE[m] for the intralchannel nonlinearity mitigation. This is mainly due to the nonlinear distortion characteristics caused by IFWM and IXPM.

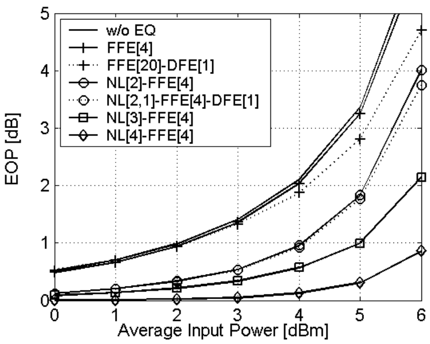

Fig.2: Eye opening penalty versus average input power with and without equalization for 43Gb/s 8-span RZ-OOK single channel transmission.

Similarly, we investigate the nonlinear equalizaiton for the non-return-to-zero (NRZ) pulse shape. Based on the setup as shown in Fig.1 with the second MZM omitted, we show the simulation results for NRZ-OOK in Fig.3. We draw similar conclusions as above. NRZ signal exhibits less tolerance to fiber nonlineaities compared to RZ signal. However, average input power tolerance can be dramatically improved through nonlinear equalization. For example, the average input power can be increased from about –1dBm without using equalization to 3.5dBm using NL[4]-FFE[4] at 1dB EOP.

Secondly, the influence of ASE noise on equalization performance is investigated by Monte-Carlo simulations. The noise figure of each EDFA

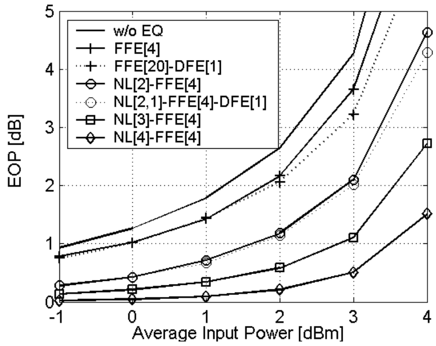

Fig.3: Eye opening penalty versus average input power with and without equalization for 43Gb/s 8-span NRZ-OOK single channel transmission.

shown in Fig.1 is assumed to be 5dB. The bit error ratio (BER) versus optical signal-noise ratio (OSNR) in 0.1nm bandwidth with and without equalization for average input power of 5dBm and RZ signal is shown in Fig.4. About 2.8dB improvement can be achieved with NL[4]-FFE[4] .

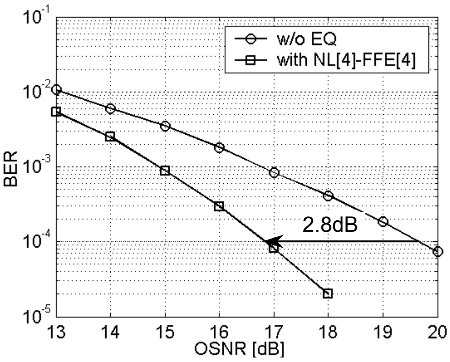

Fig.4: BER versus OSNR with and without using equalization for 43Gb/s 8-span RZ-OOK single channel transmission.

Conclusions

We propose and investigate the mitigation of intrachannel nonlinearities for 40Gb/s optical fiber communications by using nonlinear electrical equalization. Simulations based on both EOP and BER demonstrate the good performance of this nonlinear equalizer for mitigating fiber nonlinearities.

References

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