Transmitter-side Volterra Filtering for Increased Dispersion Tolerance in 56 Gbaud PAM-4 Systems

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Abstract: We experimentally demonstrate that a transmitter-side Volterra-based pre-distortion for 56 GBaud, PAM4 signal with receiver FFE outperforms receiver-side Volterra filtering and allows for 70% higher tolerance to chromatic-dispersion. Transmitter coefficients are computed without receiver feedback.

OCIS codes: (060.2330) Fiber optics communications; (060.4510) Optical communications.

1. Introduction

PAM-4 systems have been widely explored for data-center interconnects (DCI) and short reach links owing to their transmitter and receiver simplicity that essentially cuts down the cost in system deployment. 56 Gbaud, PAM-4 signal with 4-channel wavelength division multiplexing (WDM) is a potential candidate for the upcoming 400G systems. At this high baud rate, the chromatic dispersion (CD) is a major limiting factor in terms of achievable transmission distance. The square-law detection (SLD) in combination with CD induces nonlinear distortions in the system. Nonlinear equalizers are required to tackle these distortions, for which, receiver based Volterra equalizers have been explored as an option [1-3]. Due to the nonlinearity, it is not clear if receiver or transmitter side equalization provides the best performance. Further, in intensity modulation direct-detection systems, the transmitter side has access to the real part of the optical field, while the receiver sees the power of the optical field. Transmitter side pre-processing has been explored using duo-binary pre-coding with a fractionally spaced neural network trained to negate the effect of inter-symbol interference (ISI) [4]. Further, Tomlinson Harashima Precoding (THP) [5] which uses a linear feedback filter and a nonlinear modulo operator at the transmitter has been investigated for 30 Gbaud PAM-4 signals [6].

In this paper, we propose a transmitter side 3rd order Volterra filter based pre-processing with pre-calculated filter coefficients provided in a look-up table (LUT) and compare the results to Volterra filter post-processing. The Volterra filter coefficient are calculated offline without knowledge of the true channel, thus avoiding any active feedback from the receiver to the transmitter. We show that using Volterra pre-filtering alone, without any additional receiver DSP, gives a 20% increase in CD-tolerance compared to doing no DSP at the transmitter and only Volterra based equalization at the receiver. When combining transmitter side Volterra pre-filter with a receiver side linear feed-forward equalizer (FFE) of 8 taps, a CD-tolerance gain of 70% was experimentally demonstrated assuming KP4 FEC threshold of 2.2E-4 [7].

2. Concept

The schematic of our proposed system is shown in Fig. 1(a). The 3rd order Volterra (l,m,n) filter is applied in the digital signal processing of the transmitter before optical intensity modulation with a Mach-Zehnder modulator. The

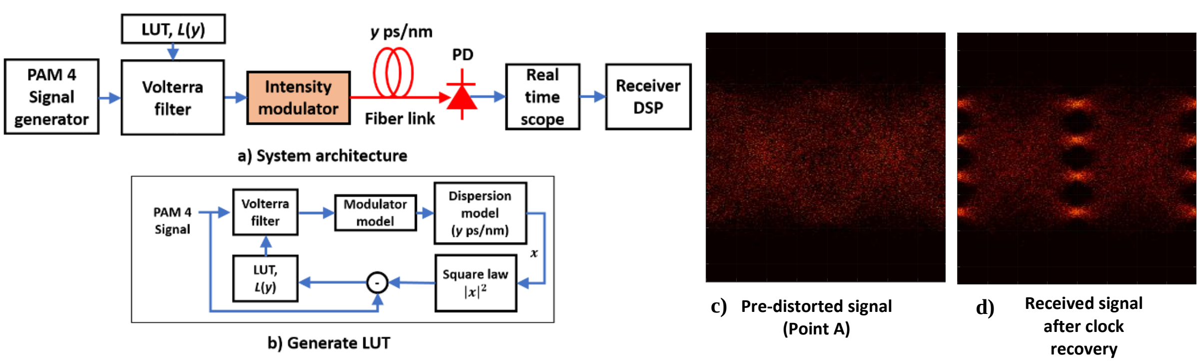

Fig. 1. a) System with pre-processing Volterra filter, b) Look-up table (LUT) generation, Eye digs. of c) pre-distorted and d) received signal.

values (l,m,n) denote the first, second and third order tap lengths of the Volterra filter respectively. For a Volterra (l,m,n) filter, there are total $l+m(m+1)/2+n(n+1)(n+2)/6$ filter coefficients. The filter coefficients for the Volterra filter were pre-computed in simulations for different chromatic dispersion (CD) (y ps/nm) using the predefined models of system components as shown in Fig. 1(b) and stored in the LUT, L(y). We assume the Kerr-nonlinearity of the fiber to be negligible and thus, the CD model [4] can accurately describe the fiber characteristics for a fixed transmission length. Using LMS algorithm, the coefficients are obtained by minimizing the mean square error between desired PAM4 symbols and those obtained with the model. Once taps have converged and the LUT is generated, the system simply needs to load the Volterra kernels and pass the PAM-4 signal through the Volterra filter bank and use this predistorted signal to drive the optical intensity modulator. This predistorted signal is generated by the DAC and applied to the optical intensity modulator. After passing through the fiber link, the signal is detected with a photodiode. Received-side equalization, if any, is performed in the DSP. Fig. 1c and Fig. 1d show the eye diagram of electrical signal preprocessed for 70 ps/nm to be given to the MZM and the eye diagram of the recovered PAM-4 signal at the receiver in simulations.

3. Experimental setup and results

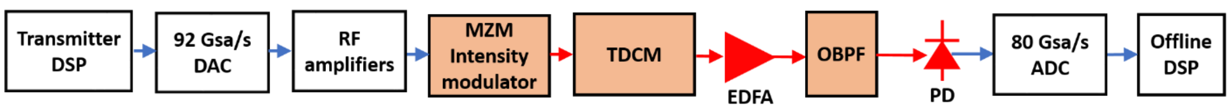

Fig. 2. Experimental setup. DAC: digital-analog converter, MZM: Mach-Zehnder modulator, TDCM: Teraxion© tunable dispersion compensation module, EDFA: Erbium-doped fiber amplifier, OBPF: Optical bandpass filter, ADC: analog-digital converter.

The experimental set-up is shown in Fig. 2. The data to be transmitted (with or without pre-filtering) is generated offline in MATLAB, uploaded into a 92 GSa/s digital-analog converter (DAC) and repetitively launched into a driving amplifier controlling a MZM intensity modulator whose bias is set at quadrature for linear driving characteristics. A Teraxion© tunable dispersion compensating module (TDCM) is used to emulate a variable fiber CD. The CD can be varied in steps of 10 ps/nm. After pre-amplification by an EDFA, the dispersed optical signal is passed through an optical band pass filter to remove the out-of-band noise, detected using a photodiode and sampled by a 33 GHz, 80 GSa/s real-time scope. The clock recovery and post-processing (if applied) are performed offline.

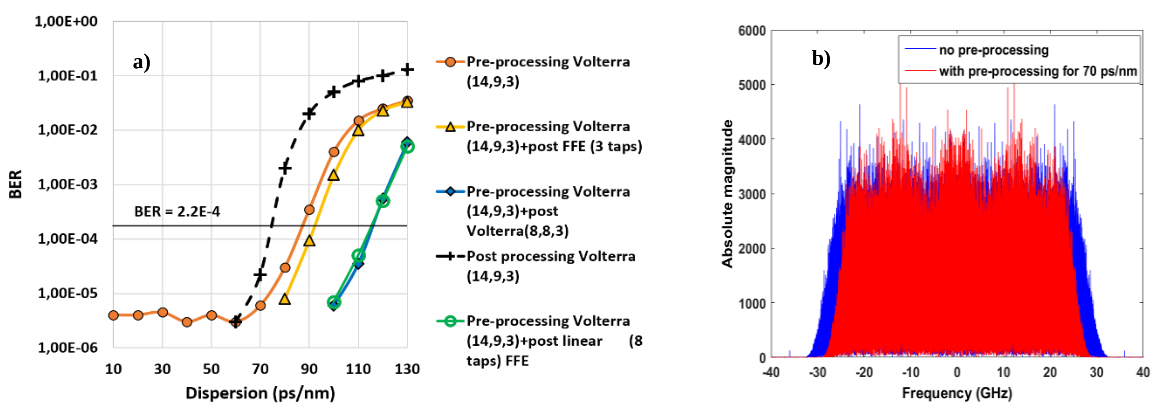

Fig. 3. a) BER *vs*. CD (ps/nm) for pre-processed and post-processed signals. b) Spectrums of signal at the transmitter w/ and w/o pre-processing.

In Fig. 3a, the BER is plotted as a function of dispersion for the various cases investigated in the experiments. As a reference, the bit error-rate (BER) of PAM-4 signal without pre-processing and post-processing only by a 3rd order Volterra (14,9,3) filter is measured and shown as black dashed line in Fig. 3a. The tap count is chosen as the maximum number needed before the performance saturates. All the comparisons in this work are made at the KP4 FEC threshold, i.e. at BER = 2.2×10^{-4}. The maximum tolerable CD for the reference case of receiver-side Volterra processing was found to be 72 ps/nm. Next, we perform the Volterra filter (14,9,3) based pre-distortion at the transmitter side using the LUT, L(y) for different CD (y) and transmit. Thus, the Volterra filter is optimized for each dispersion value and BER is measured for different tests. The BER curve of the signal pre-processed with a Volterra (14,9,3) equalizer and without any post-processing (except clock recovery) gave a 20% increase in CD-tolerance (orange solid circles) compared to only post-processing with Volterra (14,9,3) filter (dashed black line). This benefit can be understood from the spectrums shown in Fig. 3(b) where the pre-processed signal's spectrum is more compact compared to the original signal spectrum. This essentially reduces the effects of CD which grows exponentially with signal bandwidth. However, Volterra pre-distortion increases the BER floor to 6×10^{-5} (orange solid circles) in experiment. This can be resolved by using a 3-tap FFE filter at the receiver that drops the BER floor to a value below what we are able to measure with good statistics (yellow triangles). The maximum tolerable CD can be extended by 70% to 115 ps/nm by increasing the length of the receiver-side equalization FFE from 3 taps to 8 taps (green open circles). However, replacing the receiver side FFE by a Volterra (8,8,3) equalizer gives no further benefits (blue diamond), showing that with Volterra pre-filtering, a simple linear FFE suffices on the receiver side.

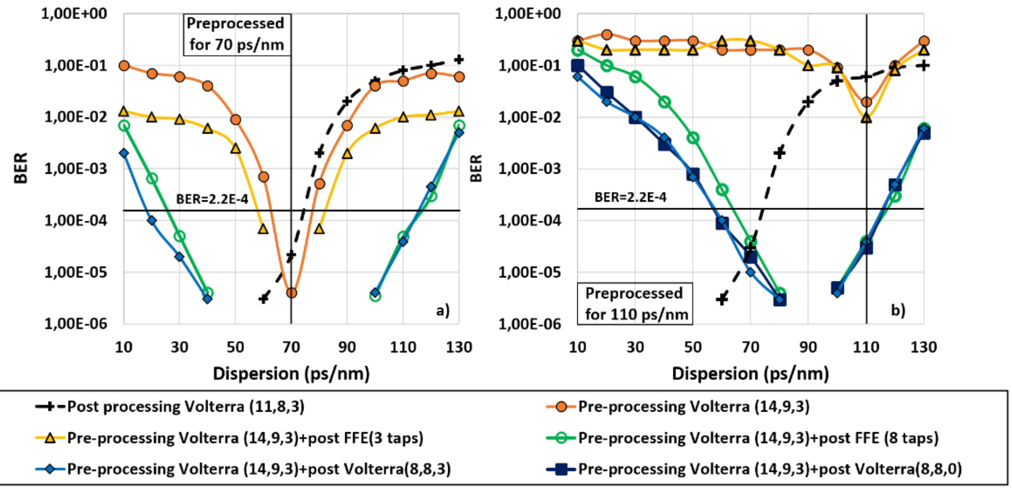

Fig. 4. BER *vs.* CD (ps/nm) of signal preprocessed for a) CD = 70 ps/nm and b) 80 ps/nm for FFE and Volterra post-processing equalizers.

The 20% tolerance gain for pre-processing system over post-processing is achieved when the pre-processing is performed for the exact CD induced over the link. Since the pre-processing is done offline and stored in a look-up table, two problems arise: We will have a limited granularity of dispersion values and we might not have exact knowledge of the induced CD over the link. If we apply Volterra pre-processing without any receiver side equalization, the performance is heavily penalized by a CD mismatch, as can be seen in Fig. 4a and 4b. In this second experiment, we pre-process the PAM-4 signal for a fixed CD of 70 ps/nm (Fig. 4a) or 110 ps/nm (Fig. 4b) and then sweep the CD. As seen, the minimum BER is achieved at the optimization point, but the BER increases drastically when the mismatch is as small as ± 10 ps/nm. If we apply a receiver side FFE with 3 taps, the BER at the point of optimization can be decreased. However, the system still needs a very precise knowledge of the dispersion. If we increase the FFE length to 8 taps, the mismatch tolerance range can be increased to ±45 ps/ nm, translating to ±2.6 km of fiber in a deployed system. On extending the receiver filter to a Volterra (8,8,3) filter, the range of mismatch tolerance at lower dispersion values can be slightly increased (green open circles *vs*. blue diamonds) but the gain is small. Moreover, the maximum tolerable CD reached by either of these is the same (115 ps/nm at BER = 2.2×10^{-4}) for both systems optimized at 70 and 110 ps/nm. Thus, we can conclude that on pre-filtering with Volterra equalizer, a linear FFE (8 taps) is sufficient at the receiver to achieve the 70% CD-tolerance gain.

4. Conclusions

We have experimentally investigated 3rd order Volterra filters for pre- and post-compensation for 56 Gbaud PAM-4 signals in dispersion limited intensity-modulation direct-detection systems. We have shown that receiver side Volterra (14,9,3) pre-processing can bring 20% larger gains compared to receiver-side Volterra processing of the same size. By combining the transmitter-side Volterra filter with a receiver-side 8-tap linear FFE, the CD-tolerance can be increased to 115 ps/nm, which corresponds to a 70% increase over receiver-side Volterra filtering, permitting transmission with KP4 FEC. Applying the receiver side FFE also increases the mismatch tolerance to ±45 ps/nm. The transmitter-side Volterra coefficients are calculated offline without active feedback and stored in a LUT.

5. References

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