Volterra-based Nonlinear Compensation in 400 Gb/s WDM Multiband Coherent Optical OFDM Systems

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Abstract: We apply a 3rd-order inverse Volterra series nonlinear equalizer to a 400 Gb/s WDM multiband PM-16QAM OFDM signal. IVSTF-NLE provides a 0.6 dB Q-factor improvement and 1 dB nonlinear threshold increase compared to linear equalization.

OCIS codes: (060.2330) Fiber optics communications; (060.1660) Coherent communications.

1. Introduction

Multicarrier coherent optical communication systems with high spectral efficiency modulation formats, e.g., 16- and 64- quadrature amplitude modulation (QAM) can be used to achieve 400 Gb/s and 1 Tb/s per channel in the near future [1]. Digital equalization techniques might be employed on the receiver's side for the joint compensation of chromatic dispersion (CD) and Kerr nonlinearities [2]. Nonlinear compensation techniques have been employed in both the optical and the electronic domain, such as spectral inversion [3], digital back-propagation (DBP) [4, 5], and Volterra series equalizer [6–10]. Using DBP yields a significant Q-factor improvement but at the expense of the computational complexity, which is a key problem for real-time implementation even in the case of single-wavelength, single-carrier transmission systems.

This paper examines the merits of nonlinear compensation using a 3rd-order inverse Volterra series transfer function nonlinear equalizer (IVSTF-NLE) based on a variant of the algorithm proposed in [10]. In particular, we examine whether the IVSTF-NLE performs better in a WDM, multiband, multicarrier coherent optical communication system than its most prominent counterpart, i.e., a digital back-propagation, split-step Fourier (DBP-SSF) equalizer. We show that the IVSTF-NLE provides a ~0.6 dB Q-factor improvement with respect to the purely linear equalization after 1000 km of propagation over both standard single-mode fiber (SSMF) and large effective area fiber (LEAF), while pushing the nonlinear threshold of ~1 dB. This improvement appears rather modest, due to the detection and compensation of each OFDM sub-band separately, leaving interband nonlinearities uncompensated. Nevertheless, it is superior to the one provided by the single-step-per-span DBP-SSF, which appears to be inadequate to reach the maximum efficiency of the IVSTF-NLE in the multicarrier systems under study. In addition, we show that the IVSTF-NLE can be preferable to multistep-per-span DBP-SSF in terms of computational complexity. Consequently, the IVSTF-NLE can be a reasonable choice as a first-generation nonlinear equalizer in multicarrier 400 Gb/s and 1 Tb/s systems.

2. Simulation setup

The investigated equalizer is based on the IVSTF of an optical fiber and solves the Manakov equation, in the absence of polarization-mode dispersion and polarization-dependent loss, by using the 3rd-order kernels [9, 10]. The simulation setup of the investigated system is depicted in Fig. 1. The signal propagates in an optical link comprised of 10×100 km of SSMF (Table 1) with no inline dispersion compensation. The block-diagram of the IVSTF-NLE is presented in Fig. 2. The CD is compensated in the frequency domain and the nonlinear distortions are compensated in the time domain. The net bit rate is 400 Gb/s. We assumed 16.67% overhead for forward error correction (FEC) and 3% overhead for protocol services, leading to a total bit rate of 480 Gb/s. We use 13 dB clipping ratio to reduce the peak-to-average power ratio (PAPR). The cyclic prefix is set to 11.1%. The noise figure of the inline erbium-doped fiber amplifier (EDFA) is set to 5.5 dB, whereas the gain is equal to the fiber loss. The system under study is a 3-channel, 4 sub-band configuration (see Fig. 3). The channel spacing is set to 100 GHz. Each channel carries a 4 sub-band, polarization-multiplexed (PM)-16QAM OFDM signal. Each sub-band accommodates 500 data subcarriers carrying 100 Gb/s in 20 GHz bandwidth. In order to avoid crosstalk between the 4 sub-bands constituting the OFDM signal, a guard band of 2 GHz is created by switching off 4 neighboring subcarriers. In addition, 8 subcarriers have been used for carrier phase estimation [11]. The laser phase noise is neglected. Unless otherwise stated, only the third sub-band is detected and compensated, as the two middle sub-bands are more affected by the interband nonlinear impairments. The effective number of bits (ENoB) is set to 5. A total number of 420,000 bits per band is

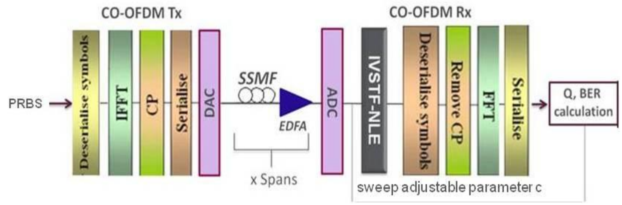

Fig. 1. Simulation setup

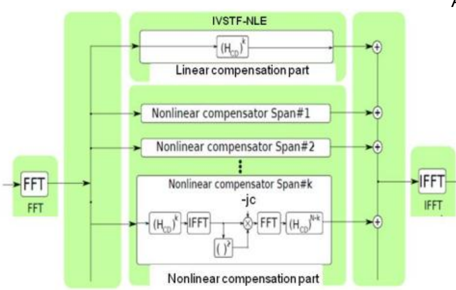

Fig. 2. Block diagram of IVSTF-NLE equalizer.

Table 1. Fiber parameters

Parameters	SSMF	LEAF
Attenuation (α)	0.2 dB/km	0.19 dB/km
GVD (β_2)	-21.75 ps^2/km	-5.12 ps^2/km
Kerr coefficient (γ)	1.3 $km^{-1}W^{-1}$	1.5 $km^{-1}W^{-1}$
Effective area	80 μm^2	72 μm^2
Dispersion	17 ps/nm/km	4 ps/nm/km

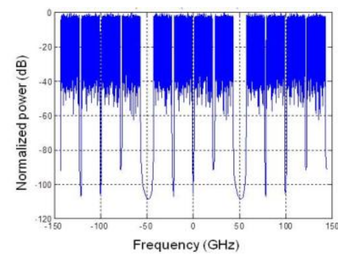

Fig. 3. Spectrum of 3-λ, 4 sub-bands 400 Gb/s OFDM signal

used. As a figure of merit for the performance of the equalization methods is used the Q-factor related to BER by $Q=20\log_{10}[\sqrt{2}\mathrm{erfc}^{-1}(2BER)]$. The optimum Q-factor is evaluated by sweeping the nonlinear adjustable parameter c in the vicinity of its nominal value $c_0=\gamma(1-e^{-\alpha L span})/\alpha$.

3. Results and discussion

We compare the performance of the IVSTF-NLE and various DBP-SSF equalizers in a three-wavelength, 4 sub-band, PM-16QAM OFDM system after using 1000 km of SSMF and LEAF links. For brevity, we employ the notation DBP-SSF_{Nsteps}, where N_{steps} is the number of steps per fiber span. In Fig. 4(a) we show the Q-factor improvement at various numbers of samples per symbol (SpS) in the SSMF link obtained by the IVSTF-NLE. The net Q-factor improvement is obtained by subtracting the maximum Q-factor values at the optimum launch power with and without IVSTF-NLE (-3 dBm and -4 dBm, respectively) and it is equal to 0.6 dB. We observe that almost all Q-factor improvement is obtained at 8 SpS [12]. In Fig. 4(b), we show the variation of the Q-factor as a function of the input power when the IVSTF-NLE and the DBP-SSF_{Nsteps} are used with 8 SpS. We observe that the DBP-SSF reaches the maximum efficiency at 8 steps-per-span, whereas the IVSTF demonstrates equal performance with the DBP-SSF_{64}, offering a 0.6 dB Q-factor improvement. With respect to DBP-SSF_1, only 0.3 dB of Q-factor improvement is provided. Then, we increase the nonlinearities by replacing the SSMF link with a LEAF link (Table 1). The IVSTF-NLE offers 0.6 dB Q-factor improvement compared to linear compensation whereas the performance of the DBP-SSF_{64} is inferior by 0.2 dB compared to the performance of the DBP-SSF_{64} in the SSMF link (see Fig. 4(c) and Fig. 4(b)).

Computational complexity is currently one of the most important considerations when designing the digital post-compensation techniques. We estimate the computational effort required for the IVSTF-NLE and the DBP-SSF_{Nsteps} algorithms in terms of real multiplications following the analysis of [10]. The FFT and IFFT at both ends of the IVSTF-NLE require $4\log_2 N_{FFT}$ real multiplications per polarization per sample, where N_{FFT} represents the number of samples fed to each FFT block. The linear compensation part of IVSTF-NLE requires 4 real multiplications per polarization per sample (Fig. 2). The nonlinear compensation part is comprised of K parallel

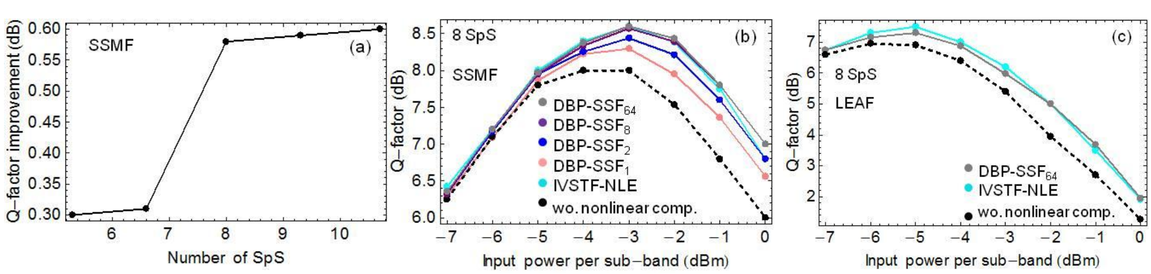

Fig. 4. Performance improvement obtained for 400 Gb/s 3-λ, 4 sub-band, PM-16QAM OFDM signal transmitted over 10×100 km. a) Q-factor improvement vs. number of SpS with IVSTF-NLE in SSMF; b) Q-factor vs. input power without/with IVSTF-NLE and DBP-$SSF_{1,2,8,64}$ in SSMF; c) Q-factor vs. input power with IVSTF-NLE and DBP-SSF_{64} equalizer in LEAF.

branches which are equal to the number of fiber spans, N_{spans}. The necessary number of real multiplications per pola- -rization per sample per branch is $6.5+4\log_2 N_{FFT}$. More specifically, 4 real multiplications are needed for the CD, $4\log_2 N_{FFT}$ multiplications for the FFT/IFFT, and 2.5 multiplications for the nonlinear phase computation per polarization [10]. Thus, the total number of real multiplications per polarization per sample, required for the IVSTF-NLE, is $4N_{spans}\log_2 N_{FFT}+6.5N_{spans}+4\log_2 N_{FFT}+4$ in order to reach the maximum performance. The required number of real multiplications, per polarization per sample, for the DBP-SSF$_{Nsteps}$ is, $N_{steps}\times(4N_{spans}\log_2 N_{FFT}+10.5N_{spans})$ [6, 10]. As the number of steps of the DBP-SSF increases, the computational load increases prohibitively for real-time implementation. Both the IVSTF-NLE and the DBP-SSF$_1$ require the same number of real multiplications over 10×100 km. On the contrary, the gain in real multiplications as a function of the FFT size is lower for IVSTF-NLE compared to DBP-SSF$_{2,8}$ reaching almost the same performance as the computationally intense DBP-SSF$_{64}$ (see Fig. 5 and Fig. 4(b)).

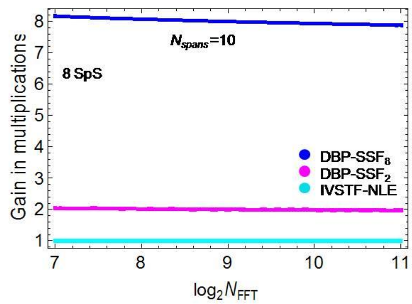

Fig. 5. Gain in real multiplications when using IVSTF-NLE and DBP-SSF$_{2,8}$ with 8 SpS over (10×100) km.

5. Conclusion

In this paper, we compared, for the first time, the performance of the 3rd-order IVSTF-NLE vs. several DBP-SSF$_{Nsteps}$ equalizers in a three-wavelength, 4 sub-band PM-16QAM coherent optical OFDM system. The simulation results for a 400 Gb/s signal transmitted over a 10×100 km of SSMF and LEAF revealed a 0.6 dB Q-factor improvement using the IVSTF-NLE compared to linear compensation only. The IVSTF-NLE demonstrates very similar performance to the DBP-SSF$_{64}$ with a significantly lower computational complexity. Thus, the low computational complexity is a key attribute, rendering the IVSTF-NLE the method of choice for compensating nonlinear distortion and CD in WDM multicarrier long haul terrestrial systems.

Acknowledgement

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