Comparison of Multi-Channel Nonlinear Equalization using Inverse Volterra Series versus Digital Backpropagation in 400 Gb/s Coherent Superchannel

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Abstract *We investigate the performance of a Volterra-based nonlinear equalizer and the digital backpropagation (DBP) method in multi-channel nonlinear equalization after 20×80 km transmission distance. The Volterra equalizer, which operates with single-step-per-span, performs similarly compared to DBP with 40 steps-per-span.*

Introduction

Fiber bandwidth exhaustion and exponentially increasing traffic render the upgrade of legacy optical networks based on wavelength division multiplexing (WDM) absolutely necessary. In order to meet the requirements of high speed transmission, superchannel transceivers have been proposed[1]. A superchannel comprises a number of channels (e.g., five to nine), each carrying e.g., 40 Gb/s to 100 Gb/s, which are either optically orthogonal frequency division multiplexed (OFDM) or quasi-Nyquist multiplexed, in order to form a single entity which is transmitted/routed in the network as a whole[1]. A major concern though is that the maximum system reach of these superchannels is severely limited by fiber nonlinearities[2]. The techniques dealing with the linear and nonlinear impairments can be grouped into two broad categories[3]: a) mitigation strategies that render the signal propagation more robust to fiber nonlinearities and b) compensation techniques that apply signal processing to the distorted signal to compensate for the nonlinearities. The latter category includes the well-known digital backpropagation (DBP)[4] and Volterra series nonlinear equalizers[5]. The nonlinear equalizers have been applied to superchannels either on a channel-by-channel or on a multi-channel basis. It is shown that the latter enables better compensation of the inter-channel nonlinearities[6]. Recently published experimental results have shown the poor performance of the channel-by-channel equalization scheme providing only 0.3 dB Q-factor improvement in 400 Gb/s superchannel after 1000 km transmission distance[7]. On the other hand, the multi-channel equalization scheme, using 80-steps-per-span (SpS) DBP, has revealed Q-factor improvements of up to 3.8 dB after ~3200 km transmission reach[8]. Nonetheless, this impressive performance is achieved at the expense of vast computational complexity due to the many SpS that are required.

In this paper, we reveal that although the inverse Volterra series transfer function nonlinear equalizer (IVSTF-NLE), which is essentially implemented with a single-SpS, is inferior compared to the single-SpS DBP in single-channel equalization. On the contrary IVSTF-NLE performs similarly compared to the highly complex iterative DBP split-step Fourier (SSF) equalizer even with 40 SpS in the case of multi-channel equalization. We demonstrate this in simulations of a 400 Gb/s dual-polarization (DP) 16-QAM quasi-Nyquist multiplexed OFDM superchannel after 1600 km transmission distance.

The IVSTF-NLE considered in this study is a variant of a previously published work[9]. In our IVSTF-NLE version, the same FFT block size (N_{FFT}) is used for both the linear and nonlinear branches while in Ref. 9 each of the nonlinear branches operates with $N_{FFT}/2$. The total number of real multiplications per polarization per sample required for the IVSTF- NLE and DBP-SSF are $N_{spans} \times (4log_2 N_{FFT} + 10.5) + 4log_2 N_{FFT} + 4$ and $N_{steps} \times N_{spans} \times (4log_2 N_{FFT} + 10.5)$ respectively[10].

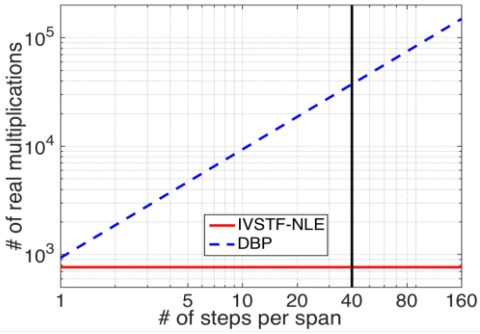

Fig. 1 Complexity of IVSTF-NLE and DBP in terms of the number of real multipliers used for $\boldsymbol{N_{FFT} = 512}$.

The complexity per FFT block is a function of the N_{FFT} without, however, affecting the performance of the equalizer. Fig. 1 shows how the complexity of the DBP increases with the number of SpS (N_{steps}), compared with that of the IVSTF-NLE.

Simulation setup

The simulation setup is depicted in Fig. 2.

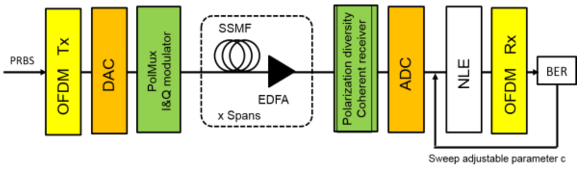

Fig. 2 Simulation setup

The system consists of 3 superchannels, with a bandwidth of 88 GHz each including the guard band spacing of 12 GHz. Each superchannel comprised 9 channels with an 8 GHz signal bandwidth and 2 GHz guard band (see inset of Fig. 3). Each OFDM channel accommodated 500 data subcarriers using a FFT size of 512, modulated with DP-16 QAM OFDM signal yielding a net bit rate of 44.44 Gb/s per channel. Note that 4 subcarriers, referred to as "null subcarriers", were dropped to insert 2 GHz guard band between the channels to avoid linear crosstalk between the channels and 8 symbols were utilized for channel estimation. Clipping was applied to reduce the signal peak-to-average power ratio (PAPR) to 13 dB. The cyclic prefix was set to 2.6%. Note that the laser phase noise was neglected. An overhead of 7 % for forward error correction (FEC) and 3% overhead for protocol services were assumed.

The transmission link comprised 20×80 km of standard single mode fiber (SSMF) with no inline dispersion compensation. The link parameters, attenuation, dispersion and Kerr coefficient, were 0.2 dB/km, 17 ps/nm/km, and 1.3 km^{-1}W^{-1}, respectively. The chromatic dispersion (CD) was compensated in the frequency domain, whereas the nonlinear distortions were compensated in the time domain. The noise figure of the inline erbium-doped fiber amplifier (EDFA) was 5.5 dB, and the gain was equal to the fiber loss of each span.

To emulate the receiver bandwidth to select the channel(s) used in the compensation stage, an ideal ("brick-wall" shaped) band-pass filter was utilized. The effective number of bits (ENoB) of the ADC was set to 6 bits. The bit-error-rate (BER) was calculated by error counting. As a figure of merit, the Q-factor related to BER (i.e. $Q = 20log_{10}\left[\sqrt{2}erfc^{-1}(2BER)\right]$), was used to evaluate the performance of the equalization methods. The optimum Q-factor is evaluated by sweeping the nonlinear adjustable parameter c in the vicinity of its nominal value $c_0 = \gamma(1 - e^{-\alpha L_{span}})/\alpha$, where α is the fiber attenuation and L_{span} is the span length.

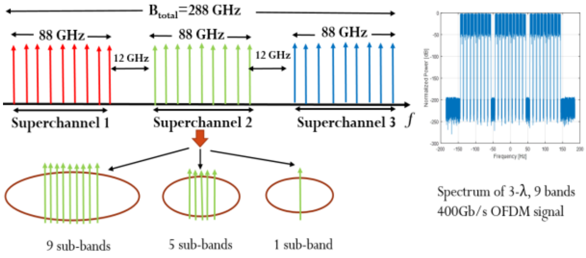

Fig. 3: Simulation concept

Results and discussion

We consider two scenarios in order to explore the limits of the IVSTF-NLE, the single- and the multi-SpS DBP-SSF: a) equalizing only the central channel, and b) equalizing 5 and 9 channels (full superchannel equalization). In all study cases, 2 samples per symbol were used since it has been observed that further increase of the number of samples per symbol provides a marginal performance improvement whilst adding extra computational load. The Q-factor with respect to the input power per superchannel is shown in Fig. 4 in which IVSTF-NLE is applied by changing the number of channels from 1 to 9. For the single-channel case, IVSTF-NLE provides only ~0.4 dB Q-factor improvement. This modest performance, compared to linear case, is mainly due to the detection and compensation of only one channel leaving inter- channel nonlinearities uncompensated. On the other hand, ~0.6 dB and ~0.8 dB Q-factor gains are obtained when the number of equalized channels increases to 5 and 9, respectively.

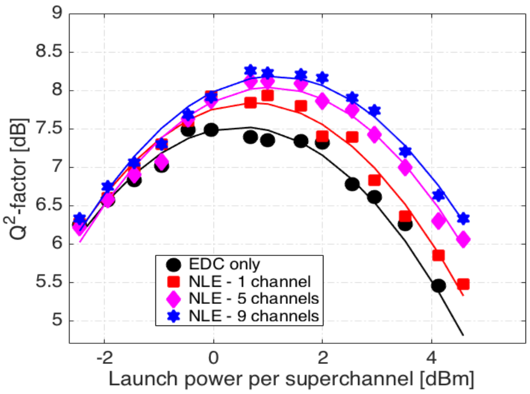

Fig. 4 Q-factor vs. launch power per superchannel when applying IVSTF-NLE in single channel, 5 and 9 channels of the central superchannel after 20×80 km distance.

Fig. 5 shows the impact of the number of SpS on the performance of the DBP-SSF for the single and 9 channel equalization cases. The performance of the DBP-SSF is almost unaffected by the number of SpS in the single channel equalization case. Therefore, the DBP-

SSF$_1$ (the subscript indicates the number SpS used) performs sufficiently with any number of SpS. On the contrary, the DBP-SSF$_1$ performs poorly in the case of full superchannel equalization case. Only values of 20 SpS or more provides a significant Q-factor improvement. This is due to the inaccurate inversion of the forward propagation of the high bandwidth signal with an insufficiently short step size (or insufficiently number of SpS). Therefore, it introduces extra distortion and degrades the performance.

Finally, Fig 6 shows the results comparing the IVSTF-NLE, DBP-SSF$_1$ and DBP-SSF$_{40}$ for the single and 9 channel equalization schemes. For the single channel equalization case, the DBP-SSF$_1$ clearly outperforms IVSTF-NLE. Nonetheless, when the full superchannel equalization is performed, the IVSTF-NLE offers similar performance compared to the DBP-SSF$_{40}$ which provides slightly better performance, however, at the expense of vastly increased computational complexity as indicated in Fig 1.

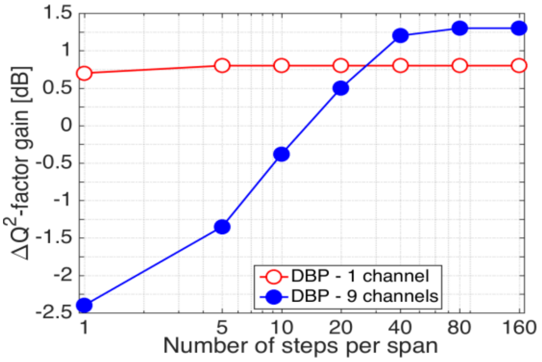

Fig. 5 Gain in Q-factor vs. number of SpS after 20×80 km transmission.

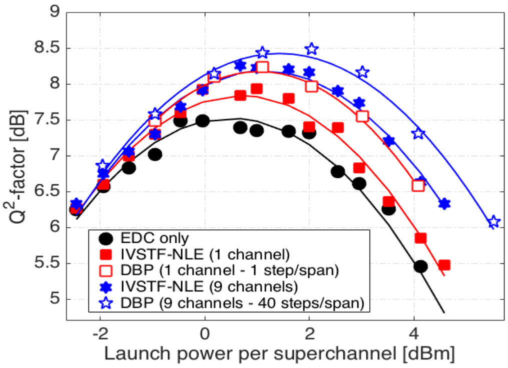

Fig. 6 launch power when applying IVSTF-NLE, DBP-SSF$_1$ and DBP-SSF$_{40}$ to the single channel and 9 channels of the central superchannel after 20×80 km distance.

Conclusions

The performance of multi channel equalization schemes, namely 3rd-order IVSTF-NLE and DBP-SSF, over a 400 Gb/s DP-16QAM superchannel, formed by 9 quasi-Nyquist multiplexed channels, were compared. For a low number of channels being compensated, the IVSTF-NLE provides quite low Q-factor improvement compared to the linear compensation, while the DBP-SSF$_1$ seems to be the method of choice. However, in the equalization of multiple channels, the DBP-SSF method performs well only with a high number of steps (at least 40), introducing prohibitively high computational effort. On the contrary, the IVSTF-NLE performs similarly to the heavily iterative DBP-SSF$_{40}$ with only one SpS. Therefore, the IVSTF-NLE could be a promising candidate for the next generation high capacity long-haul terrestrial systems, offering relatively low implementation complexity, and consequently, lower power consumption.

Acknowledgements

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References

[1] A. Klekamp et al., “Transmission reach of optical-OFDM superchannels with 10-600 Gb/s for transparent bit-rate adaptive networks,” Proc. ECOC’11, paper Tu.3K.2, (2011).

[2] R.-J. Essiambre et al., “Capacity limits of optical fiber networks,” J. Lightwave Technol., Vol. **28**, no. 5, p. 662 (2010).

[3] J. Cartledge et al., “Signal processing techniques for reducing the impact of fiber nonlinearities on system performance,” Proc. OFC, paper Th4F.5, (2016).

[4] Ip and Kahn, “Compensation of dispersion and nonlinear impairments using digital backpropagation,” J. Lightwave Technol., Vol. **26**, no. 20, p. 3416 (2008).

[5] F. P. Guiomar et al., “Simplified Volterra series nonlinear equalizer for polarization-multiplexed coherent optical systems,” J. Lightwave Technol., Vol. **31**, no. 23, p. 3879 (2013).

[6] R. Maher et al., “Reach enhancement of 100% for a DP-64QAM superchannel using MC-DBP,” Proc. Conf. Opt. Fiber Commun., Th4D.5, Los Angeles (2015).

[7] M. Song et al., “Transmission performance of 400 Gbps coherent 16-QAM multi-band OFDM adopting nonlinear mitigation techniques,” Digital Communications (TIWDC), 2015 Tyrrhenian International Workshop on, Florence (2015).

[8] G. Liga et al., “On the performance of multichannel digital backpropagation in high-capacity long-haul optical transmission,” Opt. Express, Vol. **22**, no. 24, p. 30053 (2014).

[9] L. Liu et al., “Intrachannel nonlinearity compensation by inverse Volterra series transfer function,” J. Lightwave Technol., Vol. **21**, no. 3, pp. 310 (2012).

[10] V. Vgenopoulou, et al. “Volterra-based nonlinear compensation in 400 Gb/s multiband coherent OFDM systems” Proc. ACP’14., paper AF1E.4 (2014).