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Experimental Demonstration of a Frequency-Domain Volterra Series Nonlinear Equalizer in Polarization-Multiplexed Transmission

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Abstract *Experimental demonstration of a dual-polarization Volterra series nonlinear equalizer applied in frequency-domain is carried out for 100G polarization-multiplexed QPSK test signals. We were able to reduce the BER by a factor of ~2.5× relatively to the single-polarization approach, with a 1 dB increase in the optimum power.*

Introduction

Thanks to coherent detection, digital equalization of linear fibre impairments can nowadays be performed with negligible penalty. The ultimate limits of fibre capacity are then set by nonlinearities and their interaction with noise. The development of efficient nonlinear compensation algorithms is therefore of utmost importance. The issue of nonlinear compensation has been most commonly approached through digital backward propagation (DBP) employing split-step Fourier (SSF) methods[1]. Recently, new algorithms based on Volterra series theory have been reported either in time[2] or frequency-domain[3]. In[3], an intra-channel Volterra series nonlinear equalizer (VSNE) applied in frequency-domain has been proposed and assessed through numerical simulations. The VSNE algorithm can be beneficial for real-time implementation due to its parallel structure, while maintaining very high equalization performance even at 2 samples per symbol[3].

Digital compensation of single-polarization inter-channel[4] and dual-polarization (dual-pol) intra-channel[5] effects has been already experimentally demonstrated using SSF approaches. Time-domain Volterra series filtering has been demonstrated in single-polarization QPSK transmission[6] at 10 Gbaud, using 5 samples per symbol. A recent experimental demonstration of the single-polarization VSNE algorithm has been reported for a 28 Gbaud polarization-multiplexed (PM)-16QAM transmission over 250 km of ultra-large area fibre[7]. However, these performance assessments of Volterra series equalization are limited by their underlying scalar model. Although a dual-pol VSNE based on the regular perturbation method has been recently proposed[8], its performance is only assessed through simulations.

In this paper we experimentally demonstrate the validity of the dual-pol VSNE in different PM-QPSK transmission links and data rates, providing direct comparisons with the well-known SSF method. Significative gains in terms of BER and optimal input power are shown, relatively to the single-polarization version.

Volterra Series Nonlinear Equalizer

The propagation of polarization-multiplexed optical signals can be analytically modeled by the nonlinear Schrödinger (NLS) equation in its vectorial form. However, being a complex and computationally expensive model, the vector NLS equation is not adequate for DBP. To overcome this complexity issue, the vectorial model can be replaced by the Manakov equation. This simplified approach is based on the observation that, since the polarization scattering length is much shorter than the typical nonlinear interaction length, the resulting nonlinearities can be determined with small penalty by averaging the fast polarization changes along the fibre. Then, using the Manakov equation we may analytically describe DBP as[1]

$$\frac{\partial A_{x/y}}{\partial(-z)} = \frac{\alpha}{2}A_{x/y} + i\frac{\beta_2}{2}\frac{\partial^2 A_{x/y}}{\partial t^2} - i\frac{8\gamma}{9}\left(|A_x|^2 + |A_y|^2\right)A_{x/y}, \quad (1)$$

where $A_{x/y}$ is the slowly varying complex field envelope in x/y states of polarization, z and t are the spatial and temporal coordinates respectively, β_2 accounts for chromatic dispersion and γ is the nonlinearity parameter.

Starting from equation (1) we may redefine the frequency-domain Volterra series nonlinear equalizer derived in[3] in order to account for polarization-dependent nonlinear crosstalk:

$$\tilde{A}_{eq_{x/y}}(\omega_n) = \\ = \frac{8}{9}\sum_{n_2=1}^{N_{FFT}}\sum_{n_1=1}^{N_{FFT}} H_3^{'}(\omega_{n_1}, \omega_{n_2}, \omega_n - \omega_{n_1} + \omega_{n_2}) \\ \times P(\omega_{n_1}, \omega_{n_2})\tilde{A}_{rx_{x/y}}(\omega_n - \omega_{n_1} + \omega_{n_2}), \quad (2)$$

where $\tilde{A}_{rx_{x/y}}$ and $\tilde{A}_{eq_{x/y}}$ are the Fourier transforms of the received and nonlinearly equalized electrical fields after each fibre span, in both states of polarization. The inverse third-order Volterra kernel, $H_3^{'}(\omega_{n_1}, \omega_{n_2}, \omega_n - \omega_{n_1} + \omega_{n_2})$ is defined in[3]. The $P(\omega_{n_1}, \omega_{n_2})$ term refers to the coherent cross-polarization power transfer, and it is given by

$$P(\omega_{n_1}, \omega_{n_2}) = \tilde{A}_{rx_x}(\omega_{n_1})\tilde{A}^*_{rx_x}(\omega_{n_2}) \\ + \tilde{A}_{rx_y}(\omega_{n_1})\tilde{A}^*_{rx_y}(\omega_{n_2}). \quad (3)$$

Expression (2) is applied span-by-span for each angular frequency, ω_n, composing the signal spectrum. By scanning the spectrum of interest with the auxiliary angular frequencies, ω_{n_1} and ω_{n_2}, the nonlinear equalizer is evaluated over a memory range of N_{FFT} samples, corresponding to the length of each fast-Fourier transform (FFT) block. Regarding numerical complexity, only an extra N^2_{FFT} complex additions per sample are required, relatively to the single-polarization VSNE.

Experimental Setup

In terms of experimental setup we will consider two single-channel PM-QPSK scenarios: i) transmission at 30 Gbaud over non-zero dispersion shifted fibre (NZDSF) and ii) transmission at 25 Gbaud over standard single-mode fibre (SSMF). In both cases, multi-span propagation is achieved using a recirculating loop composed of a single fibre span. Analog-to-digital conversion is performed at 50 GSa/s using a Tektronix DPO71604 oscilloscope, whose measured -3 dB analog bandwidth is ~13 GHz. The most relevant experimental parameters for both experimental scenarios are shown in Tab. 1, where R_s is the symbol rate, L_{span} is the fibre span length and SpS denotes the number of samples per symbol at the receiver. Further details about the experimental setup i) employing NZDSF fibre can be found in[9], but we use a different transmission rate (30 Gbaud) and single-channel propagation. In turn, scenario ii) is a single-channel trial of the experiment detailed in[10], which uses a recirculating loop composed of an SSMF installed span in the city of Torino.

Tab. 1: Experimental setup parameters.

	i)	ii)
Tx	R_s =30 Gbaud	R_s =25 Gbaud
Fibre	NZDSF $\alpha = 0.22$ dB/km β_2 =-3.29 ps^2/km γ =2.01 W^{-1}km^{-1} $L_{span} = 100$ km	SSMF $\alpha = 0.20$ dB/km β_2 =-21.37 ps^2/km γ =1.35 W^{-1}km^{-1} $L_{span} = 63.6$ km
Rx	SpS =1.6	SpS =2

Experimental Results

Off-line processing for BER evaluation has been carried out on 2^{17} bits. We employ the overlap-save method to process the signal in frequency-domain, using an FFT block length, N_{FFT}, of 128 samples. Linear equalization is performed by a frequency-domain chromatic dispersion equalizer (CDE). Digital nonlinear equalization is performed using both the SSF and VSNE methods. The SSF method with N steps per span is denoted as SSF$_N$. Single- and dual-pol approaches have also been compared. Polarization demultiplexing and residual dispersion compensation are performed by a 25 taps adaptive filter driven by the constant modulus algorithm (CMA). Phase estimation is implemented by the Viterbi-Viterbi algorithm. Finally, BER evaluation is carried out after symbol decoding.

In Fig. 1 we show the evolution of BER as a function of input power in scenario i), propagated over 16 (Fig. 1(a)) and 31 spans (Fig. 1(b)). For both models, we have observed that the maximum SSF performance is attained with only 1 step per span. This stems from the low temporal resolution (1.6 samples per symbol) associated with narrow electrical filtering at the oscilloscope, imposing severe limitations on the performance of nonlinear equalization. The same limitation is setting the performance of VSNE. On the other hand, for both transmission distances we observe that the dual-pol versions of SSF and VSNE enable to increase the optimum input power by about 0.7 dB, simultaneously reducing the BER by a factor of 2.5× and 2.2× for the 16 and 31 spans cases, respectively.

In Fig. 2 we provide a similar analysis for scenario ii) composed of 50 spans with a 25 Gbaud PM-QPSK input signal. Advantages of scenario ii) are twofold: temporal resolution is increased to 2 samples per symbol and the oscilloscope bandwidth limitation is less stringent at 25 Gbaud. In this scenario, the best SSF

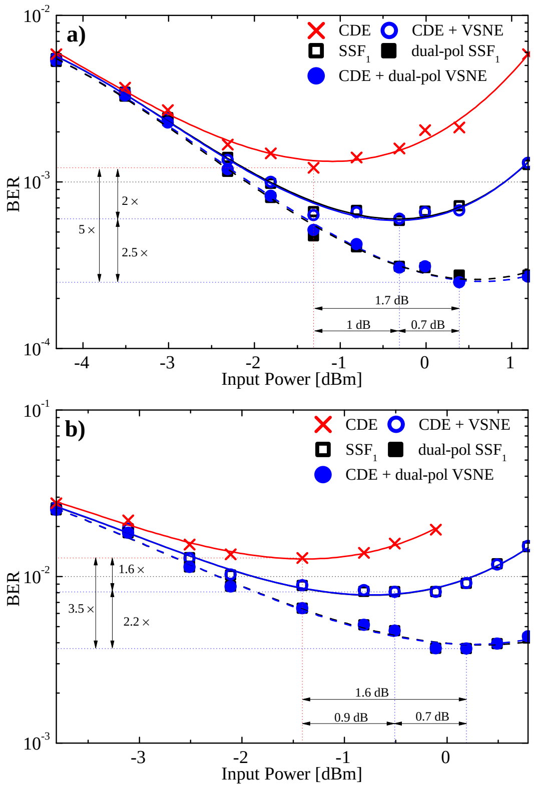

Fig. 1: BER results obtained for scenario i) composed of: a) 16 spans; b) 31 spans. Solid/dashed lines are obtained by third-order polynomial fittings of data.

performance is now attained at 4 steps per span (for clarity reasons, SSF_1 is not show in the graph). The dual-pol equalizers provide around 1 dB improvement in terms of optimal input power and a BER reduction of $\sim$2.7$\times$. However, the negligible improvement of VSNE over SSF_4 denotes that the equalization accuracy is still being limited by the available electrical bandwidth. In fact, besides limiting the accuracy of nonlinear equalization in general, a low receiver bandwidth also works as an anti-aliasing filter, reducing the VSNE performance gain over SSF, as reported in[3]. In this sense, the use of lower symbol rates can be beneficial for nonlinear equalization.

Conclusions

Recurring to experimental data, we have demonstrated the high performance of a dual-pol VSNE in different propagation scenarios. The dual-pol VSNE has shown to attain the maximum accuracy of its SSF counterpart. Being intrinsically single-step, the VSNE is most beneficial in scenarios with less stringent temporal resolution and electrical bandwidth limitations, where the maximum SSF performance is attained at several steps per span. In comparison with the previous single-polarization approach, we have shown an improvement of up to 2.7$\times$ in BER and 1 dB in

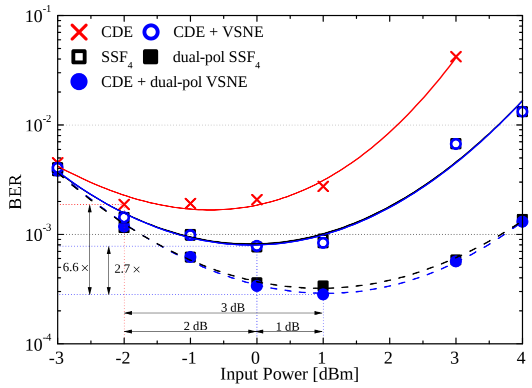

Fig. 2: BER results obtained for scenario ii) composed of 50 spans. Solid/dashed lines are obtained by third-order polynomial fittings of data.

optimum power, with negligible added numerical complexity. Although the reported simulation-based nonlinear tolerance improvement[3] over SSF could not be achieved in realistic PM-QPSK 100 Gb/s links due to limited electrical bandwidth and sampling rate, the dual-pol VSNE has proved its robustness in polarization-multiplexed transmission, enabling linear and nonlinear compensation to be performed in parallel independent stages.

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