Fast Adaptive Digital Back-Propagation Algorithm for Unrepeatered Optical Systems

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Abstract: We propose a gradient descent method with momentum for the estimation of γ in DBP for unrepeatered links. Fast convergence is achieved in the experimental transmission of 17×200-Gb/s DP-16QAM over a 350-km heterogeneous link.

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1. Introduction

The recent evolution of coherent detection and digital signal processing (DSP) algorithms allowed the compensation of nonlinear distortions induced by the Kerr effect in optical fibers, and digital back-propagation (DBP) became the reference method [1]. Techniques for nonlinearity compensation are particularly attractive in single-link and short-reach systems [2], and their implementation in unrepeatered optical systems has the potential to extend the link reach while avoiding unwanted amplification in remote or hostile areas. To achieve the best performance, DBP requires a precise estimation of the fiber nonlinear parameter γ. However, unrepeatered optical systems with remote and Raman amplification may be built by heterogeneous fiber types, and the optimal γ parameter may not be available at the receiver or might suffer fluctuations as a consequence of the system deployment [3]. Furthermore, low computational effort is a key aspect to enable cost-effective hardware implementation [4,5]. Therefore, an adaptive DBP (ADBP) is desirable for tracking optimal fiber parameters with high convergence speed, reducing the computational load towards an application-specific integrated circuit (ASIC) implementation.

Several works on ADBP have been reported recently. In the schemes presented in [3, 6, 7], noise variance, phase variance and Godard's error are employed as cost function (CF) to estimate the optimal fiber parameters. These works use the gradient descent algorithm (GDA) as the search algorithm and consider a repeatered optical transmission scenario. Alternatively, we propose in this paper an ADBP to determine the nonlinear parameter γ based on the gradient descent algorithm with momentum (GDAM), employing the mean square error (MSE) derived from dynamic equalizer (DE) as CF. The proposed method is experimentally evaluated by the unrepeatered WDM transmission of 17×200 Gb/s channels (32-GBd DP-16QAM) over 350-km of large effective area and low loss single-mode fibers (LL-SMF). Results indicate that the proposed technique achieves performance similar to the ideal DBP, with full knowledge of fiber parameters, even for a heterogeneous optical link. Moreover, tangible gains in convergence speed and mutual information are achieved compared to conventional GDA.

2. Adaptive digital back-propagation algorithm

The DSP subsystem block diagram considering the proposed ADBP is shown in Fig. 1. First, the received electrical signals are sampled by a high-speed analog-to-digital converter (ADC) and resampled to 2 samples per symbol in the pre-processing stage. Next, they are orthonormalized to compensate the optical front-end distortions and in-phase and quadrature imbalances. ADBP is employed for joint compensation of linear and nonlinear impairments. The nonlinear mitigation loop begins with an initial γ value, and the constant modulus algorithm (CMA) is applied. Then, the CF is calculated based on the MSE estimated blindly from the CMA output. Subsequently, the method verifies if the CF is lower than the MSE limit, previously defined as the minimum MSE, and, consequently, the maximum mutual information (MI). If the condition is false, the γ value is updated according to either GDA or GDAM, and a new loop is performed. GDA is defined as:

$$\gamma(i+1) = \gamma(i) \pm \mu \nabla \mathrm{CF}(i) \tag{1}$$

where i is the iteration index, μ is the convergence speed factor, $\nabla\mathrm{CF}(i)$ is the gradient of the CF at the step i, and $\gamma(i)$ and $\gamma(i+1)$ are the nonlinear parameters at iterations i and i+1, respectively. Alternatively, the GDAM is defined as:

$$\gamma(i+1) = \gamma(i) \pm \mu \nabla \mathrm{CF}(i) + p\Delta\gamma(i-1) \tag{2}$$

where p is the momentum parameter. When the γ estimation stop condition is achieved, the DE is performed by a radius-directed equalizer (RDE), where CMA is employed for pre-convergence. After this, carrier recovery (CR) performs the compensation of frequency offset and phase noise. Lastly, the MI is calculated.

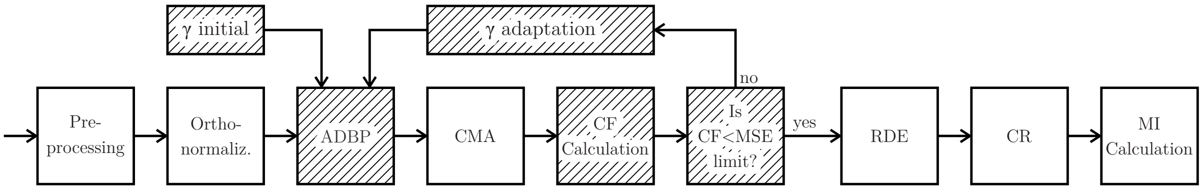

Fig. 1. Block diagram of DSP subsystems considering the proposed ADBP.

3. Experimental setup and results

The experimental setup is shown in Fig. 2. At the transmitter side, seventeen 50-GHz-spaced external cavity lasers (ECLs) (100-kHz linewidth) with wavelengths ranging from 1552.93 nm to 1559.39 nm are modulated by a pair of $LiNbO_3$ dual-polarization in-phase quadrature modulators (DP-IQM). Each DP-IQM is driven by four independent 32-GBd 16QAM electrical signals for X and Y polarizations, generated by a digital-to-analog converter (DAC). The unrepeatered optical link comprises four amplification stages: two hybrid amplifier (Tx and Rx HYB) consisting of an EDFA booster/pre-amplifier and a first-order distributed Raman amplifier (DRA), and two remote optically pumped amplifiers (Tx and Rx ROPA).

Between the amplification stages, the unrepeatered optical link is composed by three fiber sections for the signal transmission and two dedicated fibers to pump the ROPAs. We use EX2000 large effective area ultra-low loss fibers (112-μm^2 effective area and 0.157-dB/km attenuation) at the first two fiber spans to allow higher pumping power at the transmitter side. In the rest of the optical link, LL-SMF (82-μm^2 effective area and 0.18-dB/km attenuation) fibers are employed. After the optical fiber transmission, the central channel is optically filtered and detected by a polarization-diversity coherent optical receiver. Then, the electrical signals are sampled by a real-time oscilloscope for offline processing using a standard DSP, as presented in Fig. 1. For the ADBP, all the blocks depicted in Fig. 1 are considered, while for linear compensation (LC) or conventional DBP only the white blocks are performed. For the DBP and ADBP, 12 steps were uniformly distributed along the first three fiber spans. In the last fiber spans only LC is applied because of the low optical power, as depicted by the simulated power profile in Fig. 3(a). Lastly, the DE, CR, and MI calculation are performed as described in Section 2.

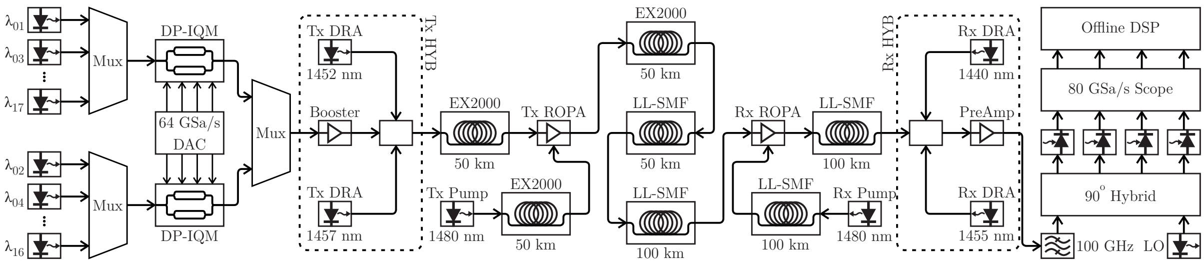

Fig. 2. Experimental setup.

The MSE and MI versus applied γ are shown in Fig. 3(b), for 1-dBm launch channel power. Considering the initial γ equal to 3 km^{-1}W^{-1}, the algorithm adapts γ, minimizing the MSE and, consequently, maximizing the MI. In this case, the optimal value is $\gamma_{OPT} \approx 0.9$ km^{-1}W^{-1}. Figure 3(b) also depicts the γ for the EX2000 (γ_{EX2000}=0.75 km^{-1}W^{-1}) and LL-SMF (γ_{LL-SMF}=1.31 km^{-1}W^{-1}) fibers. Both γ_{EX2000} and γ_{LL-SMF} are shifted away from the γ_{OPT}, increasing the MSE and, consequently, decreasing the MI. However, the difference compared to the γ_{OPT} is slightly lower for the EX2000 fiber, resulting in a reduced MI penalty.

Figure 3(c) shows the convergence analysis for the ADBP using both GDA and GDAM in terms of MSE per number of iterations. The MSE limit corresponds to the minimum MSE at Fig. 3(b). Different convergence speed factors μ were evaluated for both schemes. For the GDAM, the momentum parameter p was optimized to achieve the MSE limit at the minimum number of iterations. For all the convergence speed factors μ considered, the GDAM-based ADBP converges to the MSE limit with lower number of iterations compared to the conventional GDA. Figure 3(d) compares the system performance in terms of MI per launch channel power, for LC, DBP, and ADBP. In the case of ADBP using the GDA and GDAM with the number of iterations equal to 17 and

5, respectively, the results demonstrate comparable performance with the ideal DBP, i.e. γ_{ideal}=1.31 and 0.75 km^{-1}W^{-1}, which are the correct γ values for the employed optical fibers. Two other cases for the DBP are considered using γ_{EX2000} and γ_{LL-SMF}, applying the same nonlinear parameter in all fibers. For the γ_{LL-SMF} is clear that the application of the wrong value results in a significant performance degradation. However, for γ_{EX2000}, which is slightly shifted from the γ_{OPT}, the performance degradation is reduced, being similar to the ideal DBP. Also, as indicated in Fig. 3(d), the GDAM-based ADBP with 5 iterations presents mutual information and launch power improvements of 0.1 bit/symbol and 1 dB, compared with the linear compensation, and 0.4 bit/symbol and 2 dB, in relation to the conventional GDA with the same number of iterations.

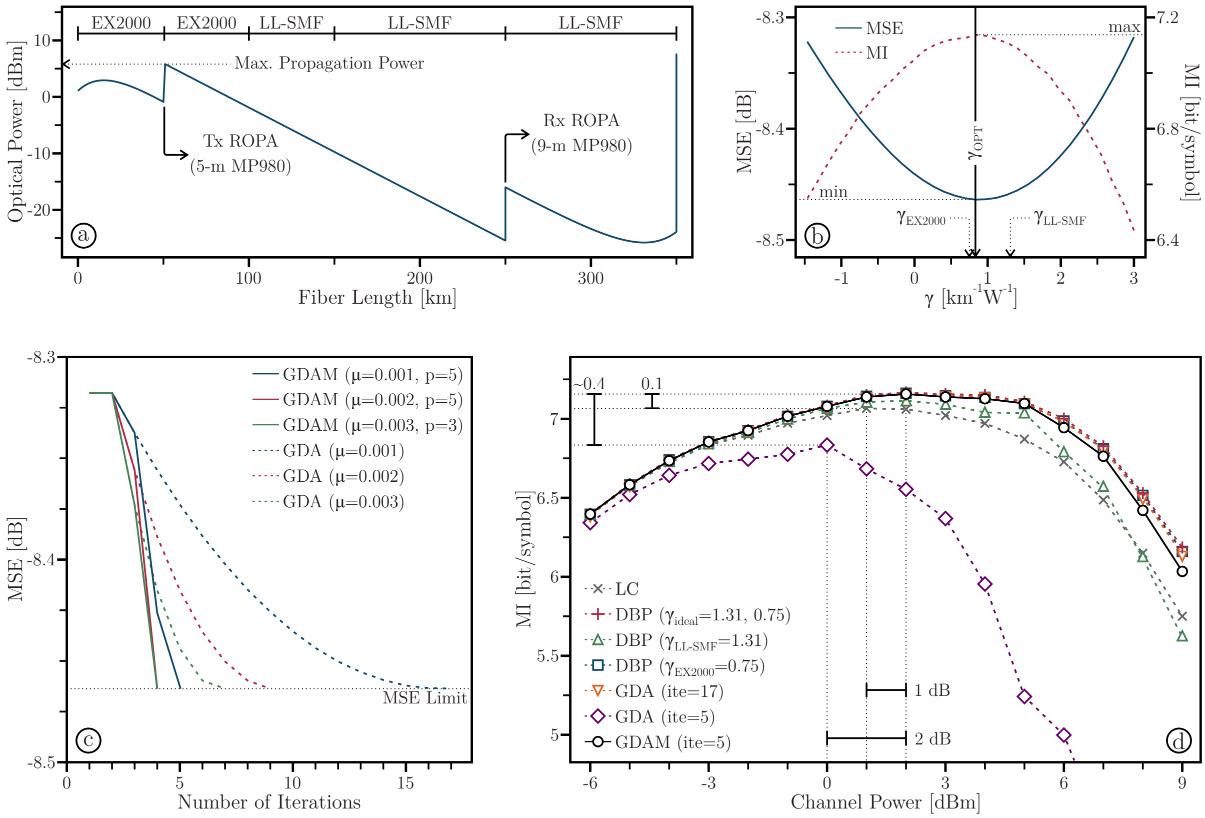

Fig. 3. Experimental results for the adaptive DBP with GDAM-based γ estimation: (a) channel power profile, (b) MSE and MI vs. γ parameter, (c) MSE vs. iterations, and (d) MI vs. launch channel power considering μ=0.001 and p=5.

4. Conclusion

We proposed a GDAM-based approach to reduce convergence time and improve performance of adaptive digital back-propagation algorithms, employing MSE as cost function to estimate the optimal nonlinear parameter γ. An experimental validation of the proposed technique in an unrepeatered optical link allowed higher launch channel power and mutual information improvements, enabling increase in reach and/or capacity.

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