Evaluation of Digital Back-propagation Performance Dependent on Stepsize and ADC Sampling Rate for Coherent NRZ- and RZ-DQPSK Experimental Data

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Abstract: We experimentally transmit coherent NRZ-DQPSK and RZ-DQPSK over four spans of SSMF and compare the performance gain due to digital back-propagation and its dependency on back-propagation split-step size and ADC sampling rate.
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1. Introduction

In order to satisfy the growing demand for high data rates, spectral efficiency and high receiver sensitivity for long-haul optical transmission, coherent detection with digital signal processing (DSP) is the most promising solution [1]. In contrast to direct detection, where the absolute phase information of the signal is lost, coherent detection allows a linear transformation of the optical signal into electrical domain and therefore simple equalization of linear impairments such as chromatic dispersion and polarization mode dispersion by DSP. Several attempts on mitigating non-linear impairments such as self-phase modulation (SPM), cross-phase modulation (XPM), four wave mixing (FWM) and non-linear phase noise (NLPN) by non-linear phase rotation, Volterra equalizers and digital back-propagation (DBP) have been undertaken [2-6]. DBP uses the model of the split-step Fourier method which numerically solves the non-linear Schrödinger equation. The equation is divided into linear and non-linear part, which are computed consecutively, either by dividing the linear part into two sections and locating the non-linearity in the middle (symmetric split-step) or by computing first the nonlinear part followed by the linear (asymmetric split-step). In contrast to the modeling of the non-linear fiber, where the numerical evaluation should converge to a solution of the Schrödinger equation, DBP tries to simplify the model as much as possible, mainly by increasing the length of the split-steps, i.e. reducing the number of steps per span (SpS) in a multi-span transmission link.

Non-linearity mitigation by DBP has already been shown for experimental data at several data rates up to 112 Gb/s and for various modulation formats, such as (differential) quadrature phase shift keying ((D)QPSK) and orthogonal frequency division multiplexing (OFDM), as well as in combination with polarization multiplexing (PolMux) [5,6]. However, the impact of sampling ratio for the received signal and number of steps per span, which is exhaustively investigated in [4] is not evaluated systematically in most of the experiments. In this paper, we choose 25 Gb/s DQPSK in order to evaluate the performance of DBP in dependency of sampling ratio and SpS by using the symmetrical split-step model. The data rate of 25 Gb/s was chosen to enable four samples per symbol with a 50 GS/s real-time sampling oscilloscope. Moreover, we compare DBP performance for non-return-to-zero (NRZ) and return-to-zero (RZ) pulse shapes.

2. Experimental Setup

The experimental setup is shown in Fig. 1. At the transmitter side, 25 Gb/s QPSK is generated by driving an IQ-Mach-Zehnder modulator (IQ-MZM), which consists of two integrated parallel MZMs, with the data and inverted data signals of a 12.5 Gb/s pulse pattern generator (PPG). For 50%-RZ pulse shape generation, an additional MZM driven by the clock frequency of 12.5 GHz is used as a pulse carver. Afterwards, the QPSK signal is transmitted over four spans of 75 km standard single mode fiber (SSMF, OFS All Wave) each. The launch power P_{launch} into the spans is varied from -2 to 10 dBm, adjusting the output power of the erbium doped fiber amplifiers (EDFAs) at the beginning of each fiber section. At the receiver side, a variable optical attenuator (VOA) and an additional EDFA are used to vary the optical signal-to-noise ratio (OSNR) measured by the optical spectrum analyzer (OSA). The signal then is noise limited by a 50 GHz optical flat-top filter. The same external cavity (ECL) laser as for the transmitter is used at the receiver as local oscillator (LO). The received signal is coherently detected using a 90° hybrid two balanced receivers. The outputs of the balanced receivers are A/D converted using a real-time oscilloscope with 50 GS/s and an electrical bandwidth of 16 GHz.

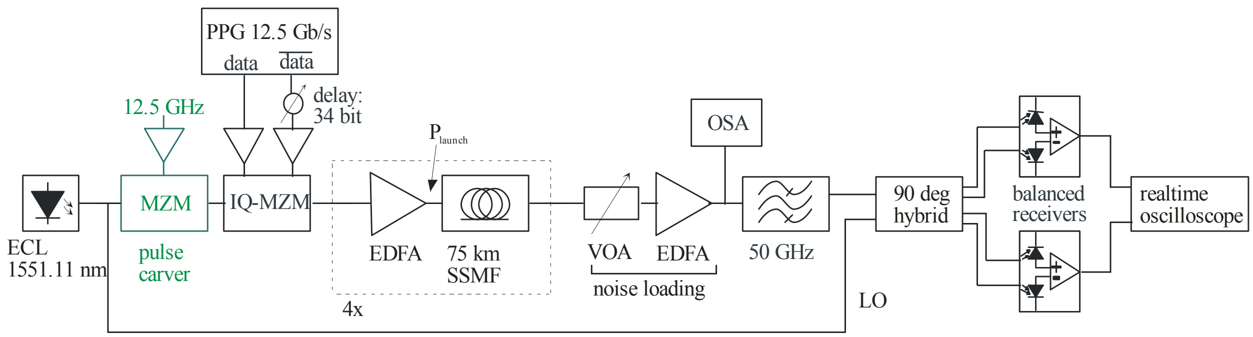

Fig. 1: Experimental setup. NRZ- and RZ-QPSK are transmitted over four spans of SSMF with varying fiber input power P_{launch}.

3. DSP Configuration

Figure 2 shows the configuration of the DSP unit implemented in Matlab™. A recorded signal of length of 2^{17} symbols is used for evaluation. Originally, four samples per symbol are captured by the scope. In order to investigate two samples per symbol, the received signal is down-sampled. This is equivalent to directly setting the oscilloscope to 25 GS/s. DBP is performed using N = 100, 10 and 1 SpS. The high number of 100 is chosen to determine the optimum results that can be achieved by DBP. The non-linear part of the split-step calculation is weighted by a factor of η ($0 < \eta < 1$), which accounts for the non-optimum non-linearity approximation in case of small N [4]. This factor is optimized for each N and P_{launch}. For comparison purposes, the case of purely linear equalization ($\eta = 0$), i.e. only dispersion compensation, is considered. The next block is a clock recovery using a square timing recovery (squarer) [7]. If the incoming signal offers only two samples per symbol, the squarer internally up-samples the incoming signal to four samples per symbol. If the whole DSP should run at a clock rate of two samples per symbol, another type of clock recovery like a phase-locked loop with Gardner phase detector [8] could be used with only minor degradation. The clock recovery is followed by a constant modulus algorithm equalizer (CMA) [9], which is often used to separate the two polarizations in PolMux transmission. However, it could also equalize a certain amount of chromatic dispersion. Since the exact chromatic dispersion for our transmission link was not measured, the CMA is used to eliminate any residual dispersion. Omitting it will have not much influence on the results. In the next step, a Viterbi and Viterbi carrier recovery is used to mitigate the effects of laser phase noise [10]. Finally, the bit error ratio (BER) is determined. For the signal recovery in the DSP we assume the transmitted data to be differentially precoded, so that we detect DQPSK instead of QPSK.

Fig. 2: DSP configuration for offline processing. Down sampling is optionally used if two samples per symbol are investigated.

4. Results and Discussion

From the BER vs. OSNR curves we evaluate the required OSNR for a bit error ratio of 10^{-3}. Figure 3 shows the required OSNR vs. P_{launch} for linear equalization and DBP with four samples per symbol for NRZ- and RZ-DQPSK. The number of SpS is varied. For NRZ-DQPSK the optimum input power turns out to be 4 dBm. This is a balance between noise limitation at low powers and non-linearity at high powers. For linear equalization, 8 dBm is the maximum launch power at which a BER of 10^{-3} can be reached. The results for DBP with carefully optimized η are similar for 1, 10 and 100 SpS, thus showing that the equalization with one SpS is sufficient for our transmission length. DBP improves the OSNR requirement for 10 dBm from unreachable to 20.9 dB, which is similar to the required OSNR for 8 dBm and linear equalization. For 8 dBm, a 3.8 dB OSNR improvement is observed, whereas for 6 dBm a gain of 0.3 to 0.5 dB is possible.

In case of RZ-DQPSK the optimum launch power is 0 dBm. Since RZ pulse shape offers the same vertical eye opening at half of the mean power compared to NRZ, the noise tolerance is improved by 3 dB. The results for linear equalization show in addition that RZ is more tolerant towards non-linearity – even 10 dBm launch power is tolerable with a required OSNR of 19 dB. However, DBP can improve this tolerance by 2.3 dB. For a launch power of 8 dBm a minor improvement of 0.2 to 0.5 dB is achievable.

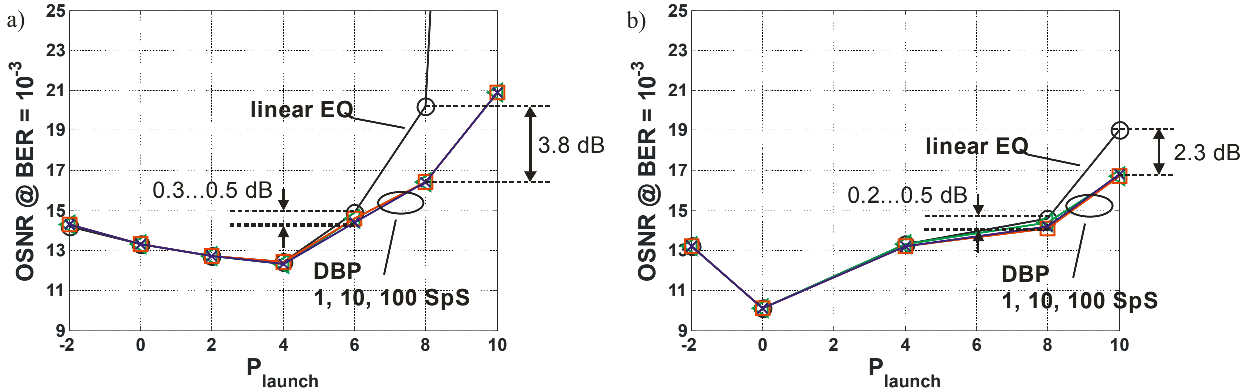

Fig. 3: Required OSNR vs. P_{launch} for linear equalization and DBP with 1, 10 and 100 steps per span, using four samples per symbol. (a) NRZ-DQPSK, (b) RZ-DQPSK.

Figure 4 shows the results for two samples per symbol. Again, one SpS is sufficient for all scenarios. In comparison with Fig. 3, it can be seen that lowering the sampling ratio reduces the gain of DBP. However, in case of NRZ-DQPSK DBP still enables the use of 10 dBm launch power with 21.6 dB OSNR and reduces the required OSNR for 8 dBm by 2.5 dB. For RZ-DQPSK DBP with two samples per symbol the differences to four samples per symbol are less: For P_{launch}=10 dBm 2 to 2.2 dB OSNR improvement can be achieved.

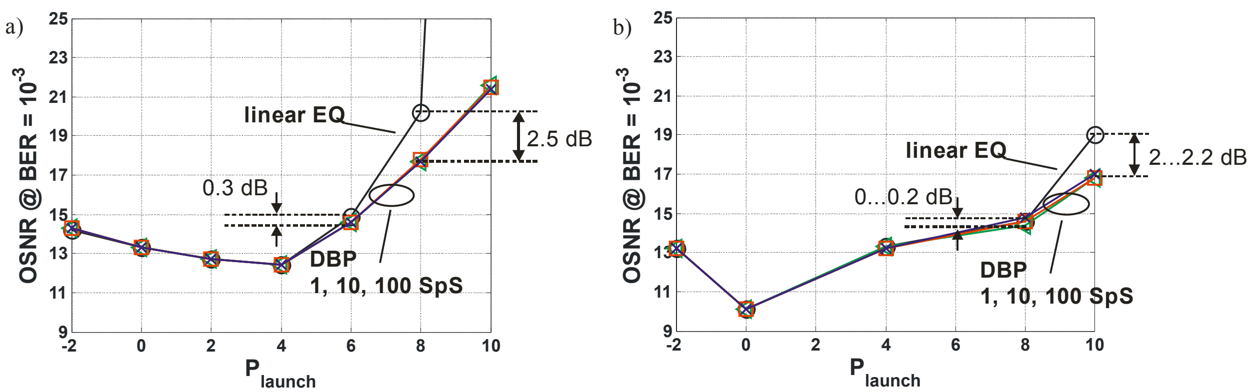

Fig. 4: Required OSNR vs. P_{launch} for linear equalization and DBP with 1, 10 and 100 step per span, using two samples per symbol. (a) NRZ-DQPSK, (b) RZ-DQPSK.

5. Conclusions

In this paper we experimentally investigated digital back-propagation for the equalization of non-linear impairments for NRZ- and RZ-DQPSK at 25 Gb/s. We evaluated the impact of number of steps per span used for DBP and the influence of number of samples per symbol provided for the equalization. For four spans of SSMF, a single step per span is sufficient in all cases. DBP performs better for NRZ-DQPSK, whereas RZ-DQPSK is inherently more tolerant towards non-linearities. Reducing the number of samples per symbol from four to two reduces the performance of DBP slightly, especially in case of NRZ-DQPSK, but still a significant gain can be achieved.

6. References

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