MLSE-Based Nonlinearity Mitigation for WDM 112 Gbit/s PDM-QPSK Transmissions with Digital Coherent Receiver

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Abstract: We investigate the performance of linear equalization combined with MLSE in long-haul transmission. In the nonlinear regime with high launch powers Q-factor improvement up to 1.4 dB is demonstrated with a quaternary state model.

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1. Introduction

Long-haul transmission of 112 Gbit/s polarization-division multiplexed (PDM) quaternary phase shift keying (QPSK) is widely considered due to its spectral efficiency and its compatibility with existing 10G and 40G architectures. Coherent demodulation followed by digital signal processing for synchronization and equalization allows compensating large amounts of optical and electrical distortions. Typically, linear filters are employed to compensate for deterministic linear channel distortions like chromatic dispersion (CD) and polarization-mode dispersion (PMD) [1] (and references therein). Fiber nonlinearity remains as one of the major limitations for long-haul transmission.

Equalization based on maximum likelihood sequence estimation (MLSE) is widely employed in 10 Gbit/s on/off-keying (OOK) systems with direct detection in order to increase the tolerance with respect to CD and PMD [2]. Recently, MLSE has gained new attention in digital coherent receivers mitigating penalties induced by narrow-band anti-aliasing filters, which enable low complexity equalization with one sample per symbol [3] and spectrally efficient transmission [4]. For the latter case, a maximum a posteriori probability (MAP) decoder has been investigated [5], also with respect to mitigating fiber nonlinearity [6]. However, the implementation complexity of the equalizers based on MLSE or MAP has not been addressed and performance trade-offs due to limitations of practical realizations have not been discussed.

In the following, we present experimental results from long-haul 112 Gbit/s PDM-QPSK transmission with digital equalization by MLSE subsequent to linear impairment compensation. A quaternary state model with Euclidian distance and histogram-based metrics is analyzed. In particular, the minimum MLSE requirements necessary for the mitigation of nonlinear effects are investigated.

2. Experiment and Simulation Setup

The evaluations are based on data captured from a digital storage oscilloscope (DSO) and offline processing in a PC. Eight C-band lasers on a 50 GHz grid (4 even and 4 odd channels on 100 GHz spacing) modulate a PDM-QPSK signal. Twenty identical spans build a link of 1500km consisting of sections with 75 km SSMF, a variable optical attenuator (VOA) and an erbium-doped fiber amplifier (see Fig. 1, left). The fifth channel was extracted for offline processing.

The digital representation of the electrical baseband signal is obtained after intradyne polarization-diverse demodulation, balanced detection and analogue-to-digital conversion (ADC). The DSO with a sampling rate of 50 Gsample/s captured 2x10^6 samples. After resampling to 56 Gsample/s (2 samples/symbol), digital equalization by

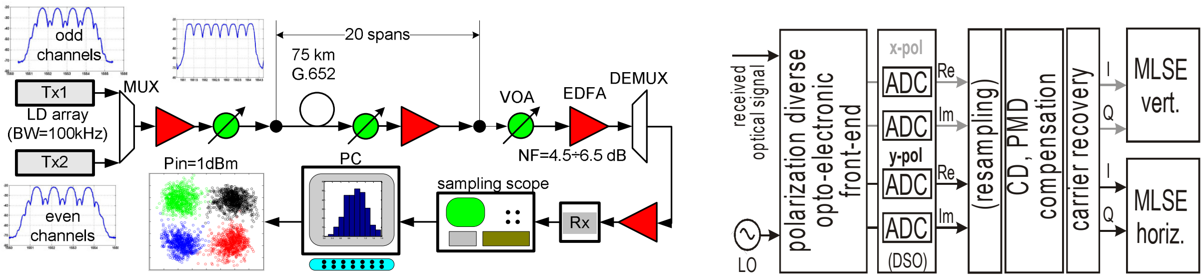

Fig. 1: Experimental measurement setup (left) and digital coherent receiver with opto-electronic front-end, ADC stage and DSP (right).

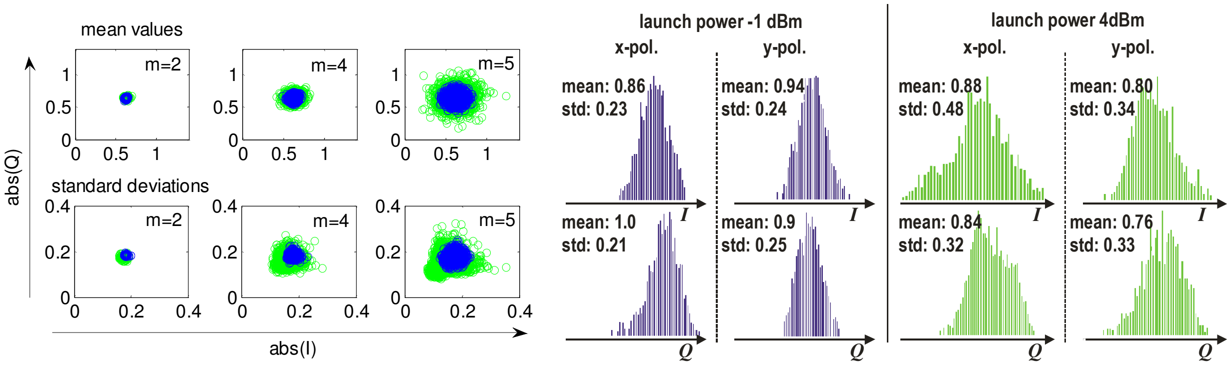

Fig. 2: Distribution of mean values and standard deviations (std) for launch power -1 dBm (blue) and 4 dBm (green) in case of a memory length m=2, 4, and 5 (left) and exemplary signal distributions for state {00 01 10 01 11} (right)

means of linear and nonlinear filters as well as synchronization of timing phase and carrier phase is performed. After the carrier phase recovery, the inphase (I) and quadrature (Q) components of vertical and horizontal data are fed into a dual input MLSE (Fig. 1, right). Note that a sophisticated carrier phase estimation which prevents error bursts due to phase slips and which provides soft-decision samples at the output is vital for the MLSE. Half of the data is applied for metric acquisition, the second half for BER evaluation.

2. MLSE Implementation

In contrast to FIR filters where the implementation complexity scales linearly with the channel memory, the number of required states for MLSE implemented by the Viterbi algorithm grows exponentially by M^m, where M defines the magnitude of the state model and m refers to the memory length. Ideally, M refers to the number of signal constellation points of the modulation format and m is larger than the channel memory. Based on our investigations and known from differential detection systems with QPSK modulation, binary state models perform poorly in a nonlinear system [7]. However, a state model with basis M=16, which would be required to account for PDM-QPSK, seems out of scope for implementation. Therefore, we chose a quaternary state model with M=4 for the QPSK signal in each polarization. We are aware that this architecture cannot effectively mitigate cross-polarization interference. However, it is a good compromise between effectiveness and implementation complexity. For each state transition, the metric is composed by the joint probability density function (PDF) of I and Q. For simplicity, we treat both tributaries independently and sum up the contributions in each branch metric. Metrics based on Euclidean distances assuming Gaussian PDFs with identical standard deviation in every state as well as metrics based on histograms are investigated. Metric acquisition, shaping and update is described in [7, 8] and the references therein.

Since linear and nonlinear effects interact during propagation and only the linear impairments are compensated by digital filters, we analyzed the state-dependent PDFs for several channel scenarios. The mean values and the standard deviations for each state are given in Fig. 2, left, for three different memory lengths m=2,4 and 5. Blue and green points refer to -1dBm and 4 dBm launch power respectively. It can be clearly seen that in the linear regime at low launch power the mean values and the standard deviations do not largely differ among each state, which indicates Gaussian PDFs symmetrical with respect to I and Q. Increasing the memory length from m=2, to m=5 increases the diversity among mean values and standard deviations, which refers to the enhanced resolution of different inter-symbol interference (ISI) patterns. This effect is aggravated in the nonlinear regime with large launch powers. Not only the mean values may divert between I and Q and among different states but also the standard deviation of each tributary can be different. This indicates that those PDFs start to differ from the Gaussian shape due to the influence of fiber nonlinearities. Exemplary distributions for state {00 01 10 01 11} at both launch powers are given in Fig. 2, right. In case of low launch power, regular Gaussian distributions can be observed with only slight deviation at the tails. For high launch powers the distributions may become highly asymmetric with non-Gaussian shapes. Also the standard deviations between I and Q can differ largely, which limits the application of Euclidean metrics. We could not observe any regular pattern, which can be attributed to the manifold superposition of linear and nonlinear distortions, of intra- and inter-channel interference and the influence of digital equalization and synchronization. The excellent performance of histogram-based metrics (H-MLSE) under those conditions is sacrificed by the requirement for large amounts of data for metric acquisition with sophisticated tail-extrapolation methods caring for bins with weak statistics [8]. In contrast, MSLE based on Euclidean metrics (E-MLSE) only requires estimating one mean value per state which allows for a faster update rate and requires less counters and less memory than the H-MLSE.

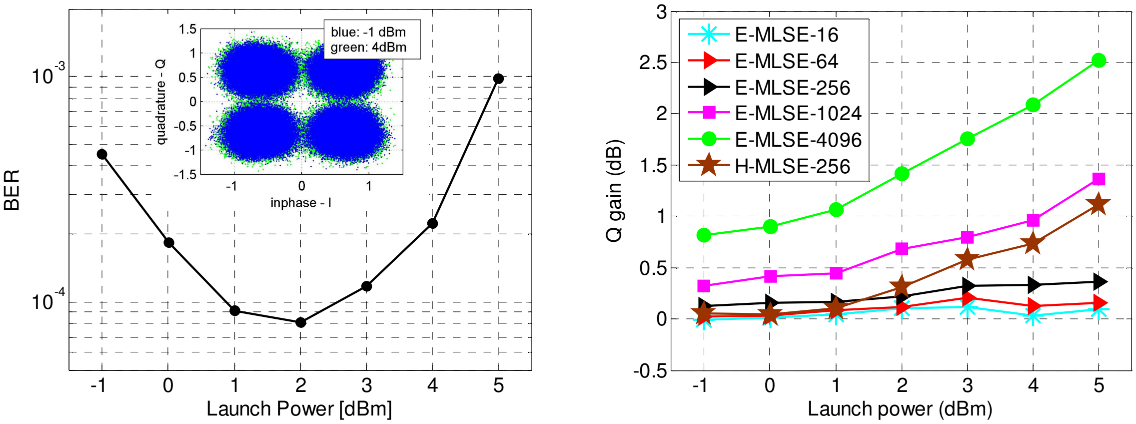

Fig. 3: Performance for 1500 km transmission. Left: BER vs. launch power after carrier recovery with signal constellation at -1 dBm (blue) and 4 dBm (green). Right: BER improvement by E-MLSE in terms of Q gain vs. launch power for various numbers of states including one example of H-MLSE.

3. Long-haul Transmission Performance

The BER performance after carrier recovery is shown in Fig. 3, left. The BER is well below the FEC limit for a wide range of launch powers between -1 and 5 dBm. Due to the enhanced carrier recovery no cycle slip can be observed even in the nonlinear region of 5 dBm launch power. Still soft-decision variables are available for MLSE. The Q improvement by using MLSE relative to the BER performance after carrier recovery is shown in Fig. 3, right. Unquantized samples were used for the E-MLSE while a 5-bit resolution was used for building histograms in the H-MLSE. The E-MLSE proves a steady increase of Q gain towards large launch powers demonstrating its ability to compensate for nonlinear channel impairments. In contrast to the relatively short channel memories induced by amplitude filtering [3-5], the interaction of linear and nonlinear impairments requires a larger number of states to obtain significant performance improvements. For a memory length of m=5 (1024 states) a Q gain of up to 1.4 dB can be obtained, while below m=5 there are only minor improvements below 0.5 dB. Note, that intra- and inter-channel nonlinearities are present in this WDM transmission experiment. The H-MLSE with only 256 states (m=4) outperforms the E-MLSE and nearly reaches the performance of the E-MLSE with 1024 states (m=5). In particular, in the nonlinear region above 2 dBm launch power where the channel memory clearly starts to exceed the equalizer memory, the histogram approach handles the resulting non-Gaussian PDFs more efficiently. Likely, using more sophisticated tail extrapolation [8] and more ADC bits the H-MLSE performance can be further improved in the weakly nonlinear region. However, it should be taken into account that updating and storing the histograms requires a large implementation complexity. It should be mentioned that in the experiment the PRBS 2^{13} did not provide sufficient statistics to satisfy reliable operation above 1024 states. Although this problem was addressed by the use of default metrics providing a suboptimum performance, the Q improvement for 4096 states should be handled with care.

4. Conclusion

To the first time, we have reported MLSE-based mitigation of nonlinear impairments in coherent optical systems. We demonstrated that for a typical 100Gbit/s PDM-QPSK transmission scenario a Q gain up to 1.4 dB can be achieved using m=5 symbols of memory with quaternary state model and Euclidean metrics. Applying enhanced methods for state reduction the implementation complexity can be significantly reduced, which enables realistic implementation in future high-performance transponders.

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