On the Optimization of Link Design Using Nonlinear Equalization for 100Gb/s 16QAM Transmission

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Abstract *The reduction of the number of EDFAs in a transmission link using nonlinear equalization was investigated for a 25GBaud RZ50-16QAM transmission. Nonlinear equalization was found to reduce the amount of EDFAs by up to 50% in comparison with linear equalization, depending on the type of fiber and the sampling rate of receiver ADC.*

Introduction

The rationale behind the inevitable evolution of fiber-optic systems in general and long-haul fiber-optic systems in particular is the simplification of the transmission link by minimizing implementation efforts and costs. In the first step, it is desired to eliminate the in-line dispersion compensation fibers, which are bulky and expensive components. This step is feasible by replacing them with a lumped linear equalizer, which is responsible for dispersion compensation of the entire link, at the receiver side. The second step would be the reduction of the number of erbium-doped fiber amplifiers (EDFAs) per transmission link, again in order to simplify the system and reduce costs. Since reduction of the number of EDFAs is equivalent to the extension of the span length, it is necessary to transmit with a higher input power in order to withstand the additional fiber loss. Since in high intensity levels the nonlinear behavior of the optical fiber is no longer negligible, equalization of nonlinear impairments has to be taken into account together with the system's evolution. This could be done with the digital back-propagation (DBP) method[1-2] (in conjunction with coherent detection).

Reducing the Number of EFDAs per Link

In order to examine the potential for span extension using nonlinear equalization, the span length of a 1000 km long transmission link was varied between 50 and 200 km. According to the rationale mentioned in the introduction, each span is composed of a single-mode fiber (SMF) followed by an EDFA for complete power compensation. For the nonlinear compensation the DBP method was chosen, where its parameters were set in order to offer the same computational complexity for all link compositions for a fair comparison (see next section for more details). All link compositions under investigation are specified in Tab. 1.

Tab. 1: Investigated link compositions

Max Length of Span (km)	Link Composition for 1000km total link length	Number of EDFAs
50	20×50km	20
60	16×60km + 1×40km	17
80	12×80km + 1×40km	13
90	11×90km + 1×10km	12
100	10×100km	10
120	8×120km + 1×40km	9
150	6×150km + 1×100km	7
160	6×160km + 1×40km	7
180	5×180km + 1×100km	6
200	5×200km	5

System Set-up

A schematic of the system used for the investigation is given in Fig. 1. A single channel transmission was considered, where RZ50-16QAM modulation with a net symbol rate (R_s) of 25GBaud plus 7% overhead was chosen, in order to achieve a net data rate of 100Gbits/sec. The 2^{12} symbols long complex data signal was generated as a pseudo-random M-ary sequence (PRMS) with the *deBruijn* rule[7], where M=16, and was convolved with a raised-cosine shaped (in time domain) shaping filter to generate an analog signal. An IQ modulator composed of two parallel Mach-Zehnder modulators (MZMs) was used to modulate the laser's optical signal with a wavelength of 1550 nm. The launch power was set to vary from -12 to +12 dBm. The optical signal was then transmitted through a link of 1000 km, composed of spans of different lengths, as described in Tab. 1, where each span is composed of a standard SMF (SSMF) or a non-zero dispersion shifted fiber (NZDSF) followed by an EDFA with a noise figure of 5 dB for complete power compensation. The parameters of the transmission links are specified in Tab. 2.

At the receiver side, the optical signal was detected with a homodyne coherent receiver composed of a 2×4 90˚ hybrid, followed by two

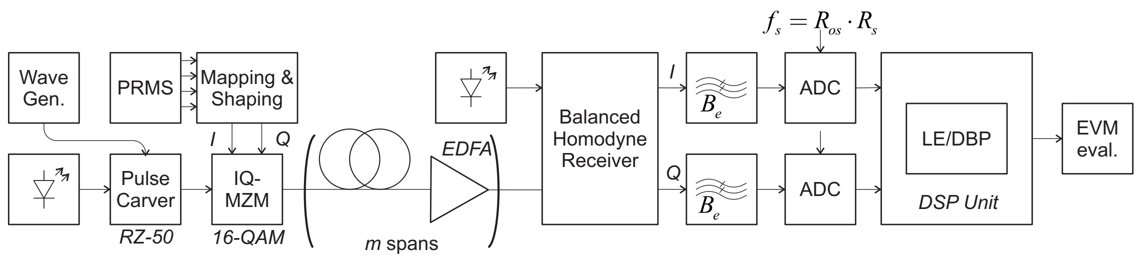

Fig. 1: A block diagram of the investigated system. Here, B_e is the electrical bandwidth, f_s is the sampling rate, R_{os} is the number of samples per symbol, and R_s is the symbol rate. In the DSP unit, LE and DBP stand for linear equalization and digital back propagation, respectively.

balanced-detectors. The recovered complex envelope was then filtered with a fifth-order *Butterworth* filter with a one-sided bandwidth B_e,

Tab. 2: Fiber Parameters

Fiber	α (dB/km)	D (ps/nm/km)	γ (1/W/km)
SSMF	0.2	17	1.46
NZDSF	0.2	4	1.46

which was optimized to achieve the best performance, and sampled with four, three or two samples per symbol, which yielded the digital signal to be processed with either the DBP method or plain linear equalization. In this paper, The DBP's split step size[1,2] was kept constant as 10 km, regardless of the span size, in order to offer the same computational complexity for all link compositions. The equalized signal was then compared with the transmitted signal in order to derive the root mean square (RMS) of error vector magnitude (EVM), which was used for the assessment of performance[4]. For 16QAM transmission, an EVM value of 0.149 (given in this paper in percentage as 14.9%) is equivalent to a BER of 10^{-3}, and was used as a reference. For all simulations, the effects of laser phase noise and polarization-mode dispersion were neglected[1].

Results

Fig. 2 shows the performance of the SSMF system for three link compositions: 50, 100 and 150 km, where the results are given for linear equalization (left subfigure) and DBP (right subfigure) with a sampling rate and number of split steps per span equal to the simulated transmitted analog signal. This can be referred to as analog back-propagation (ABP), and given here in order to understand the highest improvement potential using nonlinear equalization. The point of interest in these plots is the so-called *optimal launch power* (OLP), where the EVM receives the minimal value along the curve. In order to clarify the results in case of 10 different system compositions, all OLP points are mapped to a third curve (middle subfigure, given for both linear equalization and DBP), where all EVM values at OLP points are plotted as a function of the span length. Clearly, since the curve is a monotonically increasing function, a trade-off exists between the amount of EDFAs per link and the performance of the system. In all figures the EVM reference value equivalent to a BER of 10^{-3} is marked with a dashed curve. Making this constraint, the maximal span length with optimal back propagation cannot exceed 183 km, since the nonlinear impairments are too strong to be

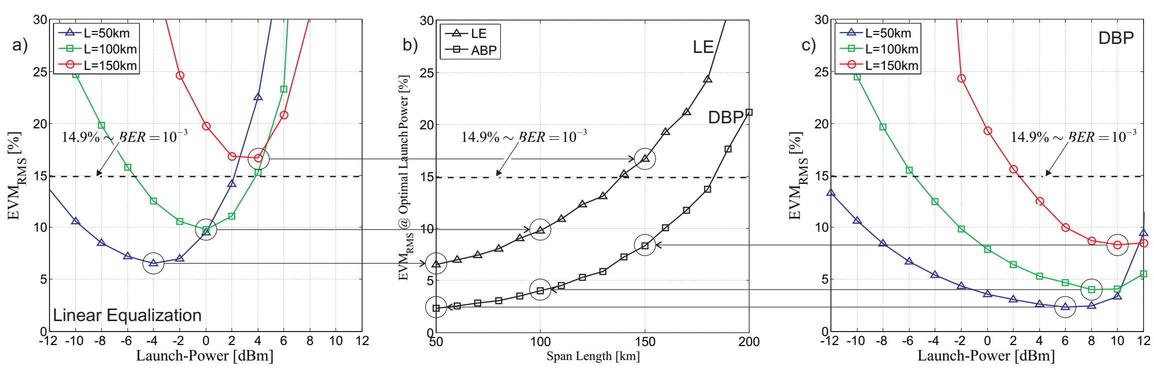

Fig. 2: Mapping of EVM values at optimal launch power points (side figures) to a plot with a variable span length in case of (a) linear equalization (LE) and (c) digital back propagation (DBP).

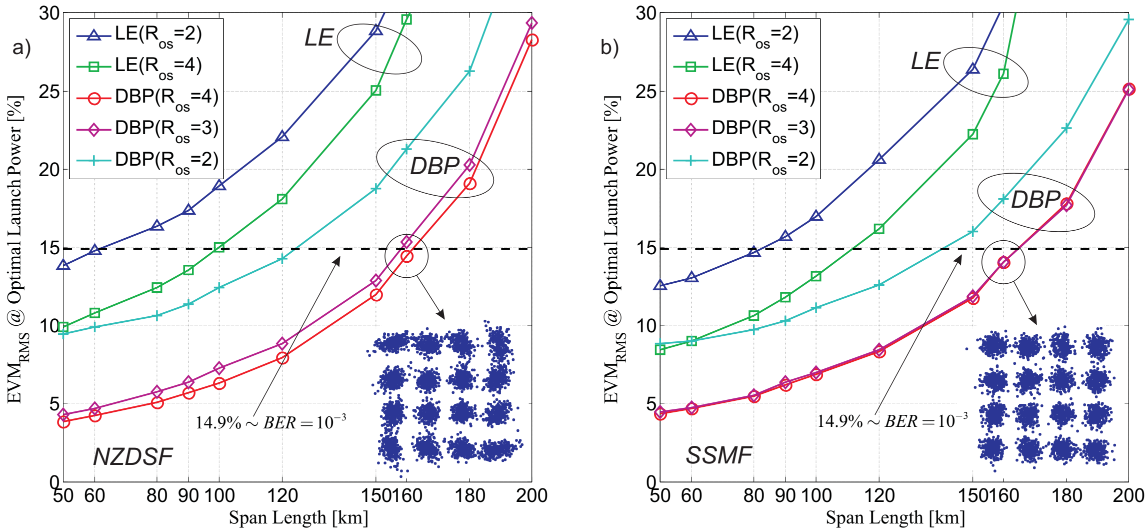

Fig. 3: EVM at optimal launch power vs. span length for linear equalization (LE) and digital back propagation in case of a system with (a) NZDSF and (b) SSMF. R_{os} stands for the number of samples per symbol.

equalized.

The performance of DBP for more realistic sampling rates (given in Fig. 3.) was investigated for systems with SSMF and NZDSF, where the over-sampling ratio (R_{os}) between the sampling rate and the symbol rate was set to 2, 3 and 4, as mentioned before. At the time of publication an over-sampling ratio R_{os}=2 was possible with state-of-the-art ADCs[3], whereas R_{os}=3 and 4 was assumed to be feasible in the near future.

First, as can be seen from both subfigures, the results for equalizers with R_{os}=3 and R_{os}=4 are comparable for the system with NZDSF and indistinguishable for the system with SSMF.

Assuming BER of 10^{-3} as the performance limit for the communication system, the maximal span length for each subsystem is given in Tab. 3. In Addition, given in the table is the number of EDFAs, which could be omitted, when using DBP instead of linear equalization. As can be seen, the amount of EDFAs can be reduced by at least 30%, where the most distinguishable results are in case of NZDSF and R_{os}=2, where the span length is doubled, i.e. almost half of the EDFAs in that link can be omitted.

Following the increment of the span length, DBP with comparison to linear equalization manages to delay the performance degradation

Tab. 3: Maximal span length (km) for a BER of 10^{-3}.

	SSMF			NZDSF		
R_{os}	LE	DBP	EDFAs Omitted	LE	DBP	EDFAs Omitted
2	82	140	5 (38%)	61	124	8 (47%)
3	111	165	3 (30%)	98	158	4 (36%)
4	111	165	3 (30%)	99	162	4 (36%)

and the difference in the EVM values is becoming larger as the span length increases.

Comparing the results of the SSMF and NZDSF systems shows better performance for the first, which is due to the fact that dispersion makes the optical noise to "walk off" from the signal, hence reducing the effect of the nonlinear phase noise[1]. This can be seen by examining the constellations *after* equalization: for SSMF the constellation points at high amplitudes seemed to be evenly distributed, while for NZDSF a distortion due to nonlinearities is evident.

Conclusions

In this paper the reduction of the number of EDFAs in a transmission link using DBP, was investigated. Simulation results have shown that for span lengths greater than 50 km a trade-off exists between the span length and the system's performance. In addition, it was shown that for a 1000 km link the maximal span length, even with an optimal back propagation, cannot exceed 183 km. DBP was found, in the system under investigation, to reduce the amount of EDFAs needed in case of a system with linear equalization by up to 50% and at least 30%, depending on the type of fiber and the sampling rate of the receiver ADC.

References

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