Investigation of Phase Noise Compensation Methods for 43 Gbit/s RZ-DQPSK Multi-Span Transmission with Direct Detection

C. Hebebrand[1], H. Grießer[2], J. Leibrich[1], C. Fürst[2], W. Rosenkranz[1]

1: Chair for Communications, University of Kiel, Kaiserstr. 2, D-24143 Kiel, Germany, ch@tf.uni-kiel.de

2: Ericsson GmbH, Gerberstraße 33, D-71522 Backnang, Germany

Abstract

This paper investigates the performance of different phase noise compensation options for a 43 Gbit/s RZ-DQPSK multi-span transmission system with distributed inline under-compensation and direct detection. The efficiency of different phase noise compensation methods, namely (i) the compensation of the mean nonlinear phase shift (MEAN), (ii) the multi-symbol phase estimation (MSPE) and (iii) the combination of both methods is examined by Monte-Carlo simulations for varying pre- and post-compensation. Furthermore, the performance of these three strategies for different average fibre input powers is investigated. Not only the optimum phase noise compensation strategy is identified, also the impact of the dispersion map is considered and compared to the conventional receiver. For the best noise tolerant receiver option a maximum Q-gain of up to 2.7 dB can be achieved for a wide range of values for the fibre input power.

1 Introduction

Phase noise is an important limiting effect in high-speed optical communication systems that make use of phase-shift keying modulation formats [1]. One method to mitigate nonlinear phase noise distortions is the compensation of the mean nonlinear phase shift (MEAN) [2]. In addition, multi-symbol phase estimation (MSPE) [3, 4] can be used to reduce the loss in sensitivity due to direct detection compared to a coherent receiver by estimating a reference phase over several consecutive received symbols. Both phase noise compensation methods, MEAN (in a post detection version for DQPSK) and MSPE are applied at the receiver side after optical to electrical conversion.

In the following the performance of different phase noise compensation options is investigated for a directly detected RZ-DQPSK transmission system at 43 Gbit/s with eight spans and distributed inline under-compensation of 10%. The effectivity of MEAN, MSPE and the combination of both is examined by Monte-Carlo simulations for varying pre- and post-compensation. Moreover the performance of these three strategies for different average fibre input powers is evaluated.

2 Simulation Setup

The simulation setup for the 43 Gbit/s RZ-DQPSK multi-span transmission system is shown in Fig. 1. At the transmitter side an optical I/Q-modulator based on a parallel Mach-Zehnder-Modulator (MZM) structure is used to generate the DQPSK signal. After RZ-pulse carving the optical signal is filtered (Gaussian filter 1st order, f_{FWHM} = 50 GHz), taking into account an optical multiplexer, and then amplified to achieve the desired average input power. The optical channel is characterized by a variable chromatic dispersion (CD) pre-compensation, eight spans and a variable CD post-compensation. The pre- and post-compensation values are varied in steps of 50 ps/nm. Each span consists of 80 km SMF (D = 17 ps/nm/km, γ = 1.37 W^{-1} km^{-1}), a DCF and an EDFA, which fully compensates for the attenuation of the whole span. The OSNR of the system is adjusted to 14 dB. In each span the DCF compensates for 90% of the CD of the SMF (10% inline under-compensation). In the simulation the transmission fibres are assumed to be nonlinear. At the receiver side the signal is filtered (Gaussian filter 1.5th order, f_{FWHM} = 50 GHz) and then received by two Mach-Zehnder delay interferometers (MZDI) followed by a balanced detector. The inphase- and quadrature components are then filtered by an electrical lowpass filter (Bessel 5th order, f_{3dB} = 15.05GHz). Both phase noise compensation methods MEAN and MSPE are implemented. Either one of them or both can be used for these investigations.

The MEAN method [2], which exploits the fact, that the mean nonlinear phase shift is proportional to the received power, is implemented in the electrical domain using an additional intensity detection branch. The intensity difference of two consecutive symbols has to be determined to get a value that is proportional to the received nonlinear phase noise. This is the difference of the nonlinear phase noise of two consecutive symbols due to the reception with MZDIs. The intensity difference is multiplied by a scaling factor α and then used to rotate the phase of the inphase and quadrature component of the received signal.

The MSPE method as described in [3, 4] calculates recursively a new decision variable $x(n)$ using the received signal $u(n)$ and the previous variable $x(n\text{-}1)$. A forgetting factor *w* slowly fades out the contribution of the previous symbols. This method averages out the phase noise of the received symbols, leading to a better phase reference and thus eliminating the loss of direct detection compared to coherent reception.

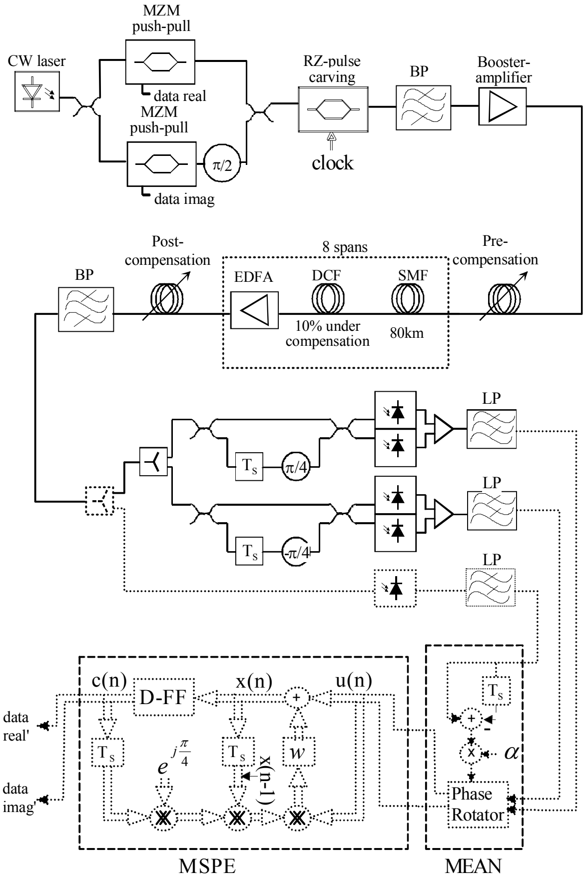

Fig. 1 Simulation setup; MZM: Mach-Zehnder Modulator; BP: Bandpass; LP: Lowpass; D-FF: D-flip-flop; MEAN: Compensation of the mean nonlinear phase shift; MSPE: Multi-symbol phase estimation

3 Simulation Results

Fig. 2 shows the Q-factor for various values of the pre-compensation and residual dispersion of the transmission link for an OSNR of 14 dB and the conventional receiver (without MEAN and MSPE) (Fig. 2a), the MEAN (Fig. 2b), the MSPE (Fig. 2c) as well as the combination of both methods (Fig. 2d), assuming an average fibre input power of 4 dBm. The Q for each combination of pre- and post-compensation is calculated from the bit error rate (BER) of Monte-Carlo simulations. The forgetting factor *w* of the MSPE and the scaling factor α of the MEAN are optimized for each dispersion map individually.

Fig. 2 demonstrates that all investigated methods are sensitive to the used dispersion map. The system performance is mainly influenced by the entire residual dispersion, but is quite robust with respect to the pre-compensation. A maximum Q for all four investigated receiver variants can be achieved for dispersion maps with approximately 38 ps/nm residual dispersion of the link.

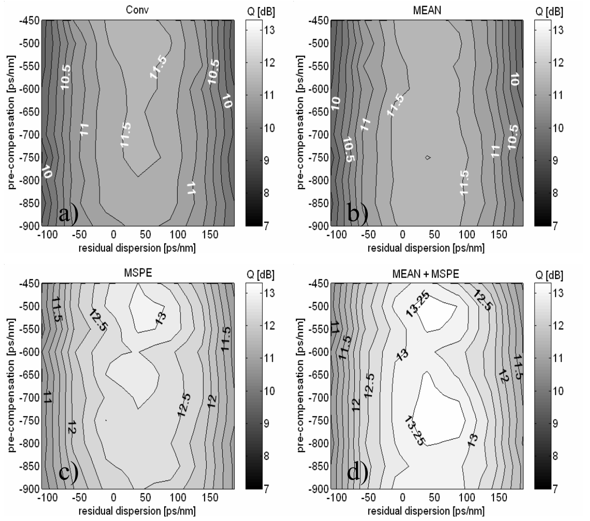

Fig. 2 Q [dB] vs. pre-compensation and residual dispersion [ps/nm] for a) the conventional receiver, b) MEAN, c) MSPE and d) for MEAN and MSPE for an OSNR of 14 dB, given an inline under-compensation of 10% and 4 dBm average fibre input power

Another observation is that for all examined pre- and post-compensations the efficiency of the MEAN method is the poorest. The MSPE method performs much better compared to the MEAN, whereas the best performance exhibits the combination of both methods.

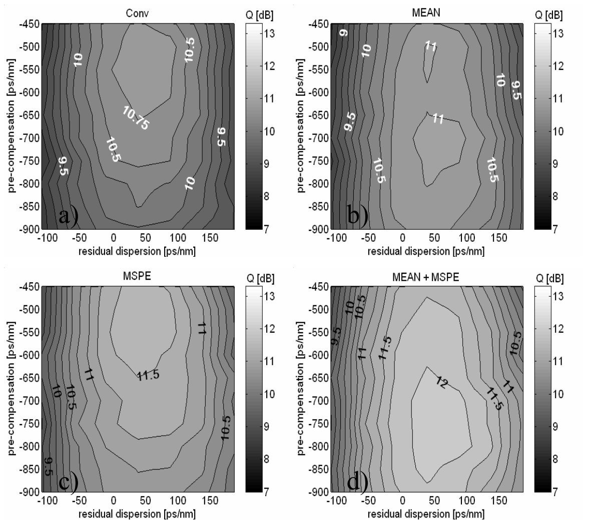

Fig. 3 Q [dB] vs. pre-compensation and residual dispersion [ps/nm] for a) the conventional receiver, b) MEAN, c) MSPE and d) for MEAN and MSPE for an OSNR of 14 dB, given an inline under-compensation of 10% and 6 dBm average fibre input power

For 6 dBm average fibre input power (Fig. 3), the maximum Q for all four variants is also achieved for a residual dispersion of approximately 38 ps/nm. In general the maximum Q for 6 dBm input power is smaller compared to 4 dBm due to the higher degradation of the signal due to nonlinearities. The system performance for 6 dBm is mainly influenced by the residual dispersion as well, but the impact of the pre-compensation used is higher than for 4 dBm, especially for larger values of pre-compensation.

The influence of pre-compensation on the system performance increases again for an average fibre input power of 8 dBm especially for the conventional receiver and the MSPE method (Figs. 4a) and c)). Apart from this the system performance is again mainly influenced by the residual dispersion of the link, and the maximum Q can be also achieved with dispersion maps of approximately 38 ps/nm residual dispersion.

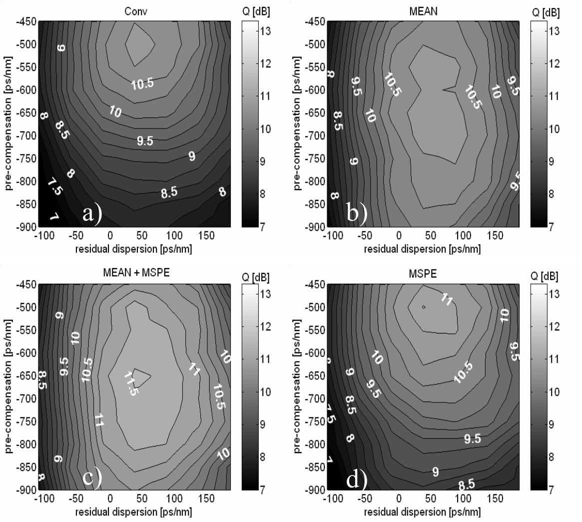

Fig. 4 Q [dB] vs. pre-compensation and residual dispersion [ps/nm] for a) the conventional receiver, b) MEAN, c) MSPE and d) for MEAN and MSPE for an OSNR of 14 dB, given an inline under-compensation of 10% and 8 dBm average fibre input power

To investigate the efficiency of the examined methods with respect to the conventional receiver, Fig. 5 depicts the Q gain versus the residual dispersion of the MEAN and the MSPE for three different pre-compensation values and the three fibre input powers. It can bee seen that for 4 dBm the Q gain is almost the same for the three pre-compensations as well for MEAN as for MSPE. For MEAN there is almost no improvement, whereas the MSPE achieves a Q gain of 1-1.5 dB. For 6 dBm and 8 dBm the efficiency of MEAN increases for those values of pre-compensation where the performance of the conventional receiver is worse. Moreover, it can be seen that the performance of MEAN increases with increasing average fibre input power. For 6 dBm a maximum Q gain of 0.9 dB and for 8 dBm of 2.3 dB can be achieved. This leads to the conclusion that MEAN is most efficient for systems with performance loss due to the influence of nonlinearities, as in the case of non-optimised dispersion maps.

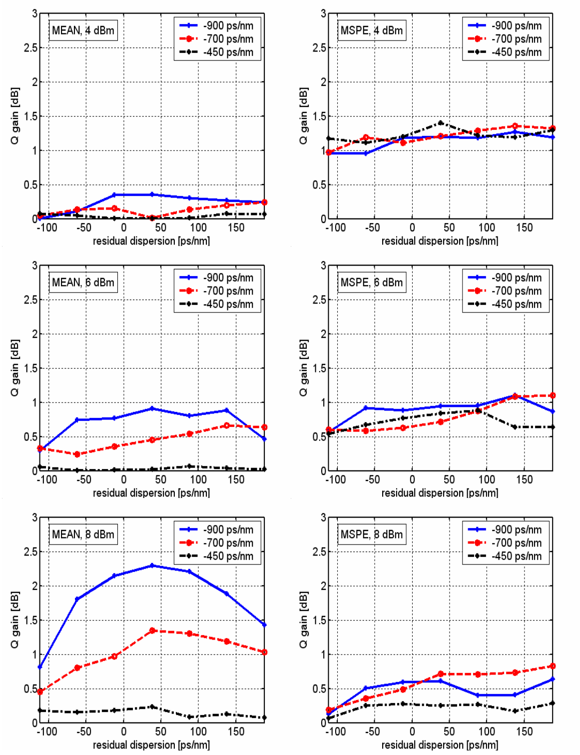

Fig. 5 Q gain [dB] with respect to the conventional receiver vs. residual dispersion [ps/nm] for MEAN (left column) and MSPE (right column) for different pre-compensations and 4 dBm (upper row), 6 dBm (middle row) and 8 dBm (lower row) average fibre input power

The improvement of MSPE, however, is almost the same for all investigated pre-compensation values for each of the input powers. Furthermore, the efficiency of MSPE decreases for increasing input power due to the higher influence of the nonlinearities.

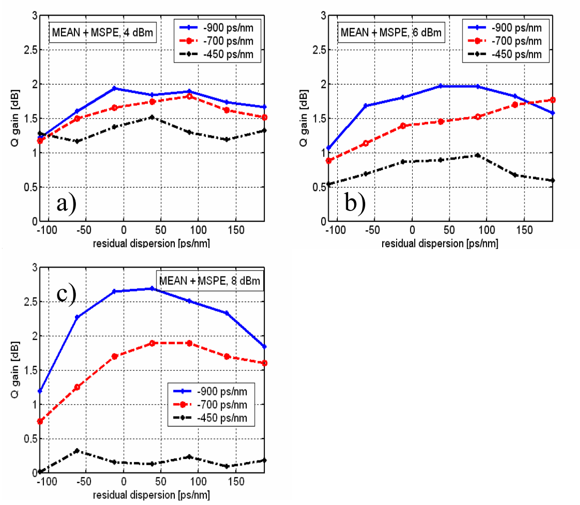

Fig. 6 Q gain [dB] with respect to the conventional receiver vs. residual dispersion [ps/nm] for the combined method MEAN + MSPE with different pre-compensations and a) 4 dBm, b) 6 dBm and c) 8 dBm average fibre input power

The efficiency with respect to the conventional receiver of the combination of MEAN and MSPE is shown in Fig. 6 for different pre-compensations and the three fibre input powers. The Q gain of the combined method is approximately equal to the sum of the Q gain of each method alone. The combined method is hence most efficient if the improvement of MEAN and MSPE is relative high, e.g. as for 6 dBm input power and -900 ps/nm pre-compensation, or if the improvement of one method is very high.

4 Conclusion

We have investigated three strategies for compensation of phase noise effects: the compensation of the mean nonlinear phase shift, the multi-symbol phase estimation and the combination of both methods for 43 Gbit/s RZ-DQPSK multi-span transmission. The performance of these methods was obtained by Monte-Carlo simulations for various dispersion maps and different fibre input powers. In general, all three methods exhibit the same optimum dispersion map with respect to the residual dispersion as is given for the conventional receiver. Thus, it is not required to change the dispersion map if receivers are upgraded with one of these phase noise compensation methods. Furthermore, it was shown that the MEAN is most efficient for systems with high performance loss due to the influence of nonlinearities and therefore also for non-optimised dispersion maps (0.9 dB Q gain for 6 dBm input power and 2.3 dB for 8 dBm with 38 ps/nm residual dispersion). The improvement of this method for systems with low influence of nonlinearities however is very poor (0.35 dB Q gain for 4 dBm with 38 ps/nm residual dispersion).

The Q gain of MSPE is almost independent of the dispersion map that is used. The maximum Q gain decreases with increasing fibre input power (1.4 dB Q gain for 4 dBm input power, 0.9 dB for 6 dBm and 0.7 dB for 8 dBm with 38 ps/nm residual dispersion).

The improvement of the combination of MEAN and MSPE is approximately equal to the sum of the improvement from each individual method (1.8 dB Q gain for 4 dBm input power, 1.9 dB for 6 dBm and 2.7 dB for 8 dBm with 38 ps/nm residual dispersion). Therefore, depending on the system setup, it has to be decided if the additional gain of implementing both methods, MEAN and MSPE, is reasonable.

5 References

[1] J. P. Gordon and L. F. Mollenauer, "Phase noise in photonic communications systems using linear amplifiers", Opt. Lett., Vol. 15, No. 23, pp. 1351-1353, 1990

[2] K.-P. Ho and J. M. Kahn, "Electronic compensation technique to mitigate nonlinear phase noise", JLT, Vol. 22, No. 3, pp. 779-783, 2004

[3] X. Liu, "Receiver sensitivity improvement in optical DQPSK and DQPSK/ASK through data-aided multi-symbol phase estimation, ECOC 2006, paper We2.5.6

[4] D. van den Borne, et. al., "Differential quadrature phase shift keying with close to homodyne performance based on multi-symbol phase estimation," IEE Seminar on Optical Fiber Comm. and Electronic Signal Processing 2005