Nonlinear mitigation using carrier phase estimation and digital backward propagation in coherent QAM transmission

Chien-Yu Lin,^{*} Rameez Asif, Michael Holtmannspoetter and
Bernhard Schmauss

*Institute of Microwave and Photonics (LHFT), University of Erlangen (FAU), Erlangen
(91058), Germany
Erlangen Graduate School in Advanced Optical Technologies (SAOT), Erlangen (91052),
Germany*

*[*sichilin@lhf.eei.uni-erlangen.de](mailto:sichilin@lhf.eei.uni-erlangen.de)*

Abstract: We investigate the performance of carrier phase estimation (CPE) and digital backward propagation (DBP) in compensating fiber nonlinearity for 224Gbps polarization-multiplexed quadrature-amplitude-modulation coherent systems with level of 4 and 16 (PM-4-QAM and PM-16-QAM) over standard single-mode fiber (SSMF) uncompensated link. The results from numerical simulation show the individual performance of CPE and DBP as well as their mutual influence. With DBP compensation, required CPE tap number for optimal performance can be reduced by 50% for 4-QAM signal and 67% for 16-QAM signal compared to linear compensation. On the other hand, employing CPE compensation after DBP also allows to reduce DBP steps. In the mentioned PM-16-QAM system, 60% reduction in the required number of DBP steps to achieve $\text{BER}=10^{-3}$ is possible, with a step-size of 200km, which reveals great potential to reduce the complexity for future real time implementation.

© 2012 Optical Society of America

OCIS codes: (060.2330) Fiber optics communications; (060.1660) Coherent communications; (190.4370) Nonlinear optics, fibers.

References and links

1. E. Ip and J. M. Kahn, "Fiber impairment compensation using coherent detection and digital signal processing," *J. Lightwave Technol.* **28**(4), 502–519 (2010).
2. P. J. Winzer and A. H. Gnauck, "112-Gb/s polarization-multiplexed 16-QAM on a 25-GHz WDM grid," in *Proc. European Conference on Optical Communications*(2008), Th.3.E.5.
3. S. J. Savory, "Digital filters for coherent optical receivers," *Opt. Express* **16**, 804–817 (2008).
4. P. J. Winzer, A. H. Gnauck, C. R. Doerr, M. Magarini, and L. L. Buhl, "Spectrally efficient long-haul optical networking using 112-Gbps polarization-multiplexed 16-QAM," *J. Lightwave Technol.* **28**(4), 547–556 (2010).
5. X. Zhou and J. Yu, "Multi-level, multi-dimensional coding for high-speed and high-spectral-efficiency optical transmission," *J. Lightwave Technol.* **27**(16), 3641–3653 (2010).
6. C. Behrens, R. Killey, S. J. Savory, M. Chen, and P. Bayvel, "Nonlinear distortion in transmission of higher order modulation formats," *IEEE Photon. Technol. Lett.* **22**(15), 1111–1113 (2010).
7. T. Pfau, S. Hoffmann and R. Noe, "Hardware-efficient coherent digital receiver concept with feedforward carrier recovery for M-QAM constellations," *J. Lightwave Technol.* **27**(8), 989–999 (2009).
8. I. Fatadin, D. Ives, and S. J. Savory, "Blind equalization and carrier phase recovery 16-QAM optical coherent system," *J. Lightwave Technol.* **27**(15), 3042–3049 (2009).

9. C. R. S. Fludger, T. Duthel, T. Wuth, E. D. Schmidt, C. Schulien, E. Gottwald, G. D. Khoe, and H. de Waardt, "Carrier phase estimation for coherent equalization of 43-Gb/s POLMUXNRZ- DQPSK transmission with 10.7-Gb/s NRZ neighbours," in *Proc. European Conference on Optical Communications*(2007), We.7.2.3.
10. K. Piyawanno, M. Kuschnerov, B. Spinnler, and B. Lankl, "Nonlinearity mitigation with carrier phase estimation for coherent receivers with higher-order modulation formats," *Topic Meeting in Lasers and Electro-Optics Society*(2009), We.3.
11. L. Li, Z. Tao, L. Liu, W. Yan, S. Oda, T. Hoshida and J. C. Rasmussen, "XPM tolerant adaptive carrier phase recovery for coherent receiver based on phase noise statistics monitoring," in *Proc. European Conference on Optical Communications*(2009), P3.16.
12. E. Ip and J. M. Kahn, "Compensation of dispersion and non-linear impairments using digital backpropagation," *J. Lightwave Technol.* **26**(20), 3416–3425 (2008).
13. D. Rafique, J. Zhao, and A. Ellis, "Digital back-propagation for spectrally efficient WDM 112 Gbit/s PM m-ary QAM transmission," *Opt. Express* **19**, 5219–5224 (2011).
14. D. S. Millar, S. Makovejs, C. Behrens, S. Hellerbrand, R. Killey, P. Bayvel, and S. Savory, "Mitigation of fiber non-linearity using a digital coherent receiver", *IEEE J. Sel. Top. Quantum Electron.* **16**(5), 1217–1226 (2010).
15. C. Lin, M. Holtmannspoeetter, R. Asif, and B. Schmauss, "Compensation of transmission impairments by digital backward propagation for different link designs," in *Proc. European Conference on Optical Communications*(2010), P3.16.
16. R. Asif, C. Lin, M. Holtmannspoeetter, and B. Schmauss, "Multi-span digital non-linear compensation for dual-polarization quadrature phase shift keying long-haul communication systems," *Opt. Communications* **285**(7), 1814–1818 (2012).
17. L. Du and A. Lowery, "Improved single channel back-propagation for intra-channel fiber non-linearity compensation in long-haul optical communication systems," *Opt. Express* **18**, 17075–17088 (2010).
18. D. Rafique, M. Mussolin, M. Forzati, J. Martensson, M. N. Chugtai, and A. Ellis, "Compensation of intra-channel nonlinear fibre impairments using simplified digital back-propagation algorithm," *Opt. Express* **19**, 9453–9460 (2011).
19. S. Oda, T. Tanimura, T. Hoshida, Y. Akiyama, H. Nakashima, K. Sone, Y. Aoki, W. Yan, Z. Tao, L. Dou, L. Li, J. C. Rasmussen, Y. Yamamoto, and T. Sasaki, "Experimental investigation on nonlinear distortions with perturbation back-propagation algorithm in 224 Gb/s DP-16QAM Transmission," in *Optical Fiber Communication Conference*(2012), OM3A.2.
20. G. Goldfarb and G. Li, "BER estimation of QPSK homodyne detection with carrier phase estimation using digital signal processing," *Opt. Express* **14**, 8043–8053 (2006).
21. E. Ip and J. M. Kahn, "Feedforward carrier recovery for coherent optical communications," *J. Lightwave Technol.* **25**(9), 2675–2692 (2007).

1. Introduction

Compensation of fiber transmission impairments by using digital signal processing (DSP) in combination with coherent receivers has become the most advantageous technique for high-speed long-haul optical transmission [1], especially for systems with high-order modulation formats such as polarization-multiplexed m-ary quadrature amplitude modulation (PM-m-QAM, where m=4 and 16 have been widely used), which attract more and more attention due to their capability of increasing the spectral efficiency [2]. Standard DSP setups include compensation of fiber linear effects such as chromatic dispersion (CD) and polarization mode dispersion (PMD). Normally CD can be compensated by either frequency or time domain filters [1, 3] and PMD mitigation can be carried out by constant modulus algorithm (CMA) [4, 5]. However, this cannot avoid performance degradation due to the phase shift caused by fiber nonlinearity [6] or the frequency mismatch of local oscillation (LO) laser [7].

As such, effective carrier phase estimation (CPE) equalization is also an essential part in coherent receivers to suppress the laser phase noise [8]. Well-known Viterbi-and-Viterbi algorithm has been mostly used for m-ary phase shift keying (m-PSK) signals but the decision-directed (DD) algorithm performs better for higher-order QAM signals. Prior works have also successfully demonstrated the mitigation of average phase variation from cross-phase modulation (XPM) by optimizing the averaging window length in CPE according to experienced XPM strength [9–11]. In case of low nonlinearity accumulation during transmission, the system performance can be clearly improved by CPE. However, this benefit of CPE degrades for strong

nonlinear signal distortion as an average phase de-rotation becomes insufficient to compensate the nonlinear phase shift caused by self-phase modulation (SPM). On the other hand, algorithms based on digital backward propagation (DBP) have shown to effectively enable nonlinear compensation [12, 13]. Nevertheless, as the DBP technique uses split-step Fourier method (SSFM), actual DBP implementation is currently extremely challenging due to its complexity in terms of fast Fourier transform (FFT) operations. In order to enhance the computational efficiency of DBP, recent research has dedicated to reducing the number of DBP steps by either shifting the nonlinear calculation point [14, 15], employing filtered-DBP [16–18] or perturbation-DBP [19], which reduces the number of DBP steps up to 80%.

In this paper, we numerically investigate the ability of nonlinear mitigation with both DBP and CPE compensation. Our CPE is implemented by the DD algorithm but can be also implemented by other methods. The performance of various DBP step sizes and CPE tap length as well as their mutual influence is evaluated in 224Gbps PM-4-QAM and PM-16-QAM systems over an uncompensated standard single-mode fiber (SSMF) link. Considerable reduction in required DBP steps has been shown in the presence of CPE compensation.

2. Simulation setup and equalizer algorithms

In our simulation configuration, both PM-4-QAM and PM-16-QAM signals operating at 224Gbps are analyzed for uncompensated standard single mode fiber (SSMF) links, as shown in Fig. 1. The transmission distance is adapted to the different systems in order to ensure sufficient OSNR for signal quality evaluation: 15x80km for PM-4-QAM and 10x80km for PM-16-QAM signals. The transmission parameters of SSMF are: $\alpha=0.2\text{dB/km}$, $D=16\text{ps}/(\text{nm}\cdot\text{km})$ and $\gamma=1.2(\text{km}^{-1}\cdot\text{W}^{-1})$. Each transmission span also includes an Erbium doped fiber amplifier (EDFA) which is modeled with 16dB of gain and 4dB of noise figure. For simplicity, we neglected all the polarization and laser linewidth effects in our simulations. Excluding fast varying laser phase noise will allow the use of longer averaging window length of CPE [20] so that the influence of CPE length on SPM compensation can be observed more clearly. At the receiver side a standard coherent homodyne optical receiver for dual-polarization systems is used as depicted in Fig. 1. A DSP module is included to apply linear and nonlinear equalization to the received digitized signals sampled at twice of symbol rate. To analyze the DBP performance, the results are compared with linear dispersion compensation as a reference. In the DBP algorithm, the complete link is uniformly divided into steps and asymmetric SSFM computing the nonlinear part in the end of the DBP step is implemented. As we neglect the polarization effects in transmission, no CMA-based polarization de-multiplexing is used. The carrier phase estimation (CPE) is implemented to cancel out residual averaged phase rotations. For a 16-QAM signal which has multiple-level amplitudes, instead of conventional Viterbi-Viterbi algorithm, we employ a decision-directed algorithm [10, 21] illustrated by the a block diagram in Fig. 2. The process includes two stages: a decision-directed carrier phase estimator (DD CPE) with tap length N is used to estimate the symbol-wise phase shift, and the phase interaction between x- and y- polarizations is taken into account by a coupling coefficient C that is set to optimize the performance. As shown in Fig. 2, the first stage includes a decision device to compare the received $(x(k)$ and $y(k))$ and ideal $(\bar{x}(k)$ and $\bar{y}(k))$ symbols. The averaged phase shift of the incoming received symbol is calculated over N consecutive symbols to serve as the phase derotation for the following symbol φ_x and φ_y in Eq. (1). In the second stage, the phase derotation of each polarization multiplies by the coupling coefficient C as additional phase shift for the other polarization. Finally the joint phase derotation of each polarization is applied to the following symbol $x(k-1)$ and $y(k-1)$, as shown in Eq. (2) representing the formula for the employed CPE algorithm where the coupling coefficient C is chosen as 1 for optimum performance according to [10]. In our investigation, we use the same DBP and CPE algorithms for both 4-QAM and

16-QAM signals. Two types of comparison are demonstrated: 1. influence of varying CPE tap number on the performance with and without DBP, and 2. influence of DBP step number on the performance with and without CPE compensation.

Fig. 1. Dual-polarization coherent transmission with digital signal processing module for 4-QAM and 16-QAM signals.

Fig. 2. Block diagram of employed CPE algorithm according to [10] and [21].

$$\varphi_x(k-1) = \frac{1}{N} \sum_{i=0}^{N-1} (\angle x(k+i) - \angle \bar{x}(k+i))$$

$$\varphi_y(k-1) = \frac{1}{N} \sum_{i=0}^{N-1} (\angle y(k+i) - \angle \bar{y}(k+i)) \quad (1)$$

$$x(k-1) = x'(k-1) \cdot \exp \left[-j \left(\frac{1}{C+1} (\varphi_x(k-1) + C \cdot \varphi_y(k-1)) \right) \right]$$

$$y(k-1) = y'(k-1) \cdot \exp \left[-j \left(\frac{1}{C+1} (\varphi_y(k-1) + C \cdot \varphi_x(k-1)) \right) \right] \quad (2)$$

3. Results and discussions

Figure 3 shows the impact of CPE tap length on the performance with and without DBP compensation for 4-QAM and 16-QAM systems, respectively. The required OSNR for a bit error rate of 10^{-3} is evaluated. Obviously less OSNR is required as the tap length increases and a minimum required OSNR level is reached after a threshold tap length. The penalty at low CPE tap numbers rise from the fiber nonlinearity and the reduction in required OSNR becomes saturated due to the presence of ASE noise. The threshold tap length depends on launch power and the employment of DBP helps to reduce the threshold tap length. At high launch power of 3dBm

without DBP compensation, 11 CPE taps are needed for 4-QAM signals while 21 CPE taps are necessary for 16-QAM signals in order to achieve minimum required OSNR for $\text{BER}=10^{-3}$. The general behavior also shows that 4-QAM signals require less taps than 16-QAM signals due to the higher tolerance towards nonlinearity. Furthermore, DBP compensation significantly brings down the required tap length (from 11 taps to 5 taps for 4-QAM and 21 taps down to 7 taps for 16-QAM respectively) as the great amount of phase variation due to nonlinearity has been diminished by DBP. At lower launch powers, DBP does not contribute significant benefit and also a very short tap length is sufficient to reach the optimum performance. For 16-QAM signals at 3dBm, using DBP reduces the minimum required OSNR by $\approx 2.5\text{dB}$ with respect to using linear compensation only. For 4-QAM signals the minimum required OSNR is the same for both cases, which shows more robustness against fiber nonlinear effects.

Fig. 3. Required OSNR dependent on CPE tap length with and without DBP compensation for (a) 4-QAM and (b) 16-QAM signals.

Figure 4(a) shows the variation of BER against the number of DBP steps per fiber span to compensate the entire link with and without using CPE for 16-QAM signals at a launch power of 3dBm and 0dBm. In the presence of CPE, performance is improved allowing for a reduced number of DBP steps in order to get a certain BER. Also the improvement depends on the tap length of CPE. For the 3dBm case, more than one DBP step per fiber span (i.e. more than 10 steps for the complete 10-span link) is required to achieve $\text{BER}=10^{-3}$ without using CPE, whereas only 0.4 DBP steps per fiber span (i.e. 4 steps for the complete 10-span link) are required if CPE with 7 taps is used. Both increasing the tap length and number of DBP steps enhances the system performance, however, if a large number of CPE taps is used, changes in the number of DBP steps give less influence on BER. We also compare the results with 4-QAM signals as shown in Fig. 4(b). 16-QAM and 4-QAM signals have similar behavior but the 16-QAM signal requires more DBP steps for the same applied CPE tap length. Figure 5 is a contour plot showing the variation of $\log_{10}(\text{BER})$ as a function of CPE tap length and number of DBP steps in 224Gbps PM 16-QAM transmission at launch power=3dBm. From the result, we found that BER decreases along with rising number in both CPE taps and DBP steps but the decreasing rate is faster with increasing CPE tap number while small number of DBP steps is used, implying that CPE compensation gives significant improvement for insufficient DBP compensation.

Figure 6 illustrates the impact of different compensating configurations on the constellation diagrams of the received symbols: compensation with only DBP, linear compensation (LC)

Fig. 4. (a) BER vs. number of DBP steps per fiber span without and with CPE (3 and 7 taps) for 16-QAM signal comparing different launch powers of 0dBm and 3dBm.(b) BER vs. number of DBP steps per fiber span without and with CPE (3 and 7 taps) for 4-QAM and 16-QAM signals at launch power=3dBm.

Fig. 5. Contour plot of $\log_{10}(BER)$ as function of CPE tap length and DBP step number in 224Gbps PM 16-QAM system.

combined with CPE and DBP combined with CPE. In this comparison signal launch power is 3dBm and 10 DBP steps as well as 7 CPE taps are used. Without DBP compensation, the symbol points get more spread and the constellation has the remaining counterclockwise rotation induced by fiber nonlinearity despite longer tap length of CPE. The averaged phase de-rotation provided by CPE is not sufficient for recovering the individual nonlinear phase shift. On the other hand, with only DBP compensation, we see clockwise rotation of symbols located on the outer circle of the constellation but less remaining rotation happens to the symbols on the inner circle. This is because DBP overcompensates the phase of the symbols of high amplitude levels due to their higher instant power. Such phase variations can be suppressed by combining with CPE as shown in Fig. 6 (right).

Figure 7 depicts performance for nonlinear compensation for the scenario investigation em-

Fig. 6. Constellation diagrams for different compensating configurations at 3dBm. left: only DBP; middle: LC combined with CPE and right: DBP combined with CPE.

playing different number of steps (represented in the parentheses) and CPE with varying tap numbers (represented in the square bracket). The results show improvement in both Q-factor and nonlinear threshold (NLT) point (the optimum launch power) can be achieved by DBP compensation. Here the Q-factor is calculated by BER under the assumption of Gaussian noise distribution and BER is based on Monte-Carlo simulations. The NLT point of only linear compensation with CPE=3 taps locates at 1.5dBm with the maximum Q-factor =11.2dB for 4-QAM signal and 7.7dB for 16-QAM signal. Only DBP compensation of 1 step per span (single-span DBP) without CPE compensation, the maximum Q-factor improved by 0.6dB for 4-QAM and 1.2dB for 16-QAM signals whereas the optimum launch power remains at 1.5dBm. With CPE compensation using tap length of 3, the NLT point can be shifted to 4dBm with improved Q-factor of 13.1dB and 10.4dB for 4-QAM and 16-QAM signal respectively. Increasing the tap number of CPE allows to reduce the number of DBP steps without losing significant Q improvement. With CPE tap number of 7, the DBP step number can be reduced down to 9 steps for compensating 15 fiber spans (0.6 step per fiber span) for 4-QAM signal, and 7 steps for compensating 10 fiber spans (0.7 step per fiber span) for 16-QAM signal to compensate the whole link. Longer CPE tap length even improves the system performance for multi-span DBP compensation. Figure 7(a) shows that by using CPE of 11 taps, 5 steps of DBP compensation outperforms single-span DBP with only 3 taps of CPE by 1dB at launch power=6dBm and the step size can be enlarged upto 240km for 4-QAM signal. Similarly for 16-QAM signal, 3 DBP steps give comparable performance as with 10 DBP steps by using 11 CPE taps, which turns the possible step size to 266km. This is because residual phase rotation of received signal has been effectively eliminated by CPE compensation.

4. Conclusion

We have numerically investigated the mitigation of signal distortion due to fiber nonlinearity by using both digital backward propagation and carrier phase estimation for 224Gbps polarization-multiplexed 4-QAM and 16-QAM transmission for an uncompensated fiber link. Both DBP and CPE mutually improve their individual performance. Reduced tap number is tolerable for CPE in the presence of DBP compensation. We found that for 16-QAM signals with DBP compensation, only 1/3 number of taps is sufficient to achieve optimal performance with respect to linear compensation (CPE tap number has been reduced from 21 taps down to 7 taps), and the required OSNR is 2.5dB less than LC. On the other hand, combined with CPE, 60% reduction in the required number of DBP steps for BER= 10^{-3} can be achieved for 16-QAM signals at 3dBm, which shows great potential to reduce the real time implementation complexity. The performance analysis of nonlinear compensation proved that longer CPE tap length

Fig. 7. Performance analysis of 224Gbit/s (a) PM-4-QAM signal over 1200km SSMF transmission and (b) PM-16-QAM signal over 800km SSMF transmission with DBP and CPE compensation.

makes multi-span DBP possible with large step sizes upto 240km for the mentioned 4-QAM signal and 266km for the mentioned 16-QAM signal.

Acknowledgment

The authors gratefully acknowledge funding of the Erlangen Graduate School in Advanced Optical Technologies (SAOT) by the German National Science Foundation (DFG) in the framework of the excellence initiative.