Abstract

We numerically investigate the performance of Viterbi-Viterbi (VV) carrier phase estimation (CPE) and feed-forward decision directed (DD) CPE along with digital backward propagation (DBP) to mitigate laser phase noise, linear and nonlinear fiber impairments for polarization multiplexed (PM) 4 and 16-ary quadrature amplitude modulation (QAM) coherent systems. For 16-QAM, DD-CPE is compared with quadrature phase shift keying (QPSK) partitioning method that is based on the modification of VV-CPE. When the laser phase noise is negligible, both CPE methods exhibit a similar performance when employed after DBP. However, in the presence of phase noise, non-decision directed VV-CPE (for 4-QAM) and QPSK partitioning (for 16-QAM) methods outperform DD-CPE with greater phase noise tolerance and reduced complexity.

Keywords: Digital backward propagation; carrier phase estimation; coherent systems; QAM; nonlinearity; phase noise

1. Introduction

Fiber linear and nonlinear transmission impairments like chromatic dispersion (CD), polarization mode dispersion (PMD), self phase modulation (SPM), and laser phase noise, impose a challenging constraint on the transmission distance and channel capacity, especially, in long haul optical transmission. Consequently, coherent detection and digital signal processing (DSP) techniques became the most prominent solution to mitigate the fiber transmission impairments Ip (2010). In addition, they enable to increase the spectral efficiency with the use of higher order modulation formats and multiplexing techniques, among which, polarization multiplexed (PM) m-ary quadrature amplitude modulation (QAM) schemes with m equal to 4 and 16 have attracted high attention. In a typical coherent receiver, CD and PMD are compensated by adaptive linear digital filters Savory (2008), Ip (2010). In the recent years, digital back
propagation (DBP) has been proposed which can mitigate both linear and nonlinear impairments simultaneously Ip (2008). Nevertheless, DBP can only compensate deterministic impairments and the performance of DBP deteriorates in the presence of phase noise. In order to suppress the phase noise, DSP based carrier phase estimation (CPE), also became an essential component in the coherent receivers. Recently, CPE techniques have also been under investigation to mitigate the phase shift due to nonlinearity Li (2009), Piyawanno (2009) and the mutual influence of DBP and CPE, to mitigate nonlinearity and reducing complexity of DBP has been investigated in Lin (2012).

CPE methods can be broadly classified into two main categories, feedforward methods Ip (2007), Pfau (2009) and feedback methods Khalil (2012). Owing to their efficient hardware implementation avoiding feedback loops Ip (2007), feedforward methods have gained more interest. Depending on how the data phase is wiped off, the CPE methods can be further classified into non-decision directed (NDD) and decision directed (DD) algorithms. The NDD methods like Viterbi-Viterbi (VV) CPE algorithm Viterbi (1983) employ the m-th power scheme to remove the phase modulation, which are well suited for quadrature phase shift keying (QPSK) systems and QPSK partitioning Fatadin (2010) has been proposed for 16-QAM systems. In order to achieve a better performance over m-th power methods, DD-CPE methods have been proposed Zhang (2010), Ip (2007). However, the DD-CPE methods, when employed without any measure like differential encoding to prevent decision errors, suffer from the main drawback of error propagation due to erroneous decisions which may lead to cycle slips and eventually leading to a catastrophic failure Ip (2007), Zhang (2010).

In this paper, we numerically investigate and compare two feedforward CPE methods, namely the VV-CPE as proposed in Viterbi (1983) (for 4-QAM systems) and DD-CPE as proposed in Piyawanno (2009), to mitigate phase noise and fiber nonlinearity when employed after DBP. For 16-QAM systems, a modified version of VV-CPE based on QPSK partitioning as proposed in Fatadin (2010) is compared with DD-CPE. From the simulation results, it will be shown that both the CPE methods exhibit a similar performance to mitigate fiber nonlinearity, when employed after DBP. However, in the presence of laser phase noise, the DD-CPE algorithm, in spite of its high complexity due to the decision modules, makes more and more erroneous decisions leading to noisy phase estimates most of the time, whereas, the NDD methods, VV-CPE and QPSK Partitioning outperform DD-CPE with reduced complexity and better tolerance towards phase noise.

2. Simulation Setup and Parameters

The performance of the aforementioned CPE algorithms is analyzied through numerical simulations that were performed on both PM-4-QAM and PM-16-QAM signals operating at 224 Gbps. The PM-4-QAM / PM-16-QAM signals are transmitted over N spans of an uncompensated standard single mode fiber (SSMF), where each span also includes an erbium doped fiber amplifier (EDFA) modeled with a gain of 16 dB and noise figure of 4 dB. The transmission distance has been adapted to 15 x 80 km and 10 x 80 km for 4-QAM and 16-QAM signals, respectively, in order to ensure sufficient optical to signal noise ratio (OSNR) for the evaluation of signal quality measures like bit error ratio (BER). The transmission parameters of SSMF are given by an attenuation coefficient of 0.2 dB/km, dispersion coefficient of 16 ps/nm-km and nonlinear coefficient of 1.2/km-W. At the receiver side, a standard homodyne optical coherent receiver for dual polarization systems has been employed. Assuming ideal detection, the digitized signals are resampled to twice the symbol rate and are further processed in the DSP module which is included to compensate the transmission impairments. The linear and nonlinear impairments are compensated by DBP which employs a standard asymmetric split step fourier method (SSFM) without any parameter optimization. The total number of DBP steps is equal to the number of spans, i.e., a step size of 1 step/span is utilized. The signals after being compensated by DBP are further processed by the CPE methods under investigation followed by data decision and BER evaluation. For simplicity, we neglect all polarization effects. First, we investigate the performance of VV-CPE / QPSK Partitioning and DD-CPE in mitigating the fiber nonlinearity after DBP compensation, neglecting the laser phase noise. Later on, we investigate their performance by considering both nonlinearity and phase noise.

3. Results and Discussions

Fig. 1 depicts the BER vs OSNR curves for 4-QAM signals at launch power of 3 dBm, with and without linewidth effects. Both VV-CPE as well as DD-CPE methods exhibit the same performance when employed after DBP to
mitigate the residual phase shift due to SPM, which can be clearly seen in Fig. 1(a). By introducing a laser linewidth of 100 kHz, in addition to the fiber nonlinearity, the performance of DBP starts degrading owing to its low tolerance to phase noise which can be observed in Fig. 1(b). However, the VV-CPE and DD-CPE are still capable of mitigating both nonlinearity as well as phase noise, but, the DD-CPE algorithm shows a slightly degraded performance because of the increased number of decision errors and consequent error propagation. When the laser linewidth effects are further increased to 500 kHz, the performance of both the DBP and DD-CPE are severely degraded which can be seen in Fig. 1(c). This is to be expected because DBP cannot mitigate non-deterministic effects like phase noise. For the DD-CPE algorithm, almost 80 percent of the pre-decisions are wrong and therefore, the data phase is not removed properly from the symbol leading to noisy phase estimates most of the time and furthermore, the unwrap function will lead to cycle slips. Although, the performance of VV-CPE is also degraded compared to the previous discussed cases, it still shows a better tolerance towards phase noise and nonlinear mitigation.

The BER vs launch power for 4-QAM signals with and without linewidth effects are depicted in Fig. 2. The OSNR is 20 dB. As explained earlier, when there is no influence of phase noise, both the CPE algorithms perform in a similar manner, but, it can be observed in Fig. 2(a), that the performance of DBP starts degrading with the increasing launch power owing to high nonlinear accumulation which cannot be compensated by an asymmetric DBP without any parameter optimization.

Fig. 1. BER vs OSNR (dB/0.1 nm) for 4-QAM signals, (a) without linewidth; (b) with linewidth of 100 kHz; (c) with linewidth of 500 kHz.

Fig. 2. BER vs Launch power for 4-QAM signals, (a) without linewidth; (b) with linewidth of 100 kHz; (c) with linewidth of 500 kHz.

In Fig. 2(b), with the inclusion of laser linewidth of 100 kHz, the DD-CPE performs similar to the VV-CPE at low launch powers, however, as the launch power increases, once again, the pre-decision errors start increasing resulting in a high BER. Fig. 2(c) can also be interpreted in a similar way as the case in Fig. 1(c).

Fig. 3(a) depicts the BER vs OSNR, and Fig. 3(b) depicts the BER vs launch power, for 16QAM signals, with and without linewidth effects, where the QPSK partitioning method and DD-CPE are compared against their performance. The OSNR is 25 dB. In the absence of phase noise, both QPSK partitioning and DD-CPE methods exhibit a similar performance. With the inclusion of linewidth effect of 100 kHz, both DBP and DD-CPE, once again, exhibit degraded
performance. Because of denser constellation, the symbols are closely spaced in 16-QAM, and the DD-CPE becomes more sensitive to pre-decision errors and therefore, its tolerance towards phase noise is severely degraded. Also, the performance of QPSK partitioning method deteriorates owing to the complex partitioning scheme, some of the symbols are wrongly classified leading to noisy estimates. Nevertheless, it shows a better tolerance towards phase noise compared to DD-CPE at low signal launch powers.

4. Conclusions

We numerically investigated and performed a comparative analysis on two feedforward CPE algorithms, VV-CPE and DD-CPE in mitigating the residual phase shift due to fiber nonlinearity and laser phase noise. The algorithms are studied for their performance after compensating the linear and nonlinear fiber impairments by DBP using asymmetric SSFM. Numerical results show that the DD-CPE algorithm exhibits a similar performance to that of VV-CPE (for 4-QAM) and QPSK partitioning (for 16-QAM). In the presence of laser phase noise and nonlinearity, besides its increased complexity due to decision modules, the DD-CPE algorithm makes more and more erroneous pre-decisions which result in noisy phase estimates most of the time. The VV-CPE and QPSK partitioning algorithms, although NDD, shows a better tolerance in mitigating phase noise and nonlinearity with reduced complexity.

Acknowledgements

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

References

Ip, E.M., Kahn, J.M., 2010. Fiber Impairment Compensation Using Coherent Detection and Digital Signal Processing, Journal of Lightwave Technology, vol. 28, no.4, 502-519.
Savory, S.J., 2008. Digital Filters for Optical Coherent Receivers, Optics Express 16, 804-817.
Ip, E.M., Kahn, J.M., 2008. Compensation of Dispersion and Nonlinear Impairments Using Digital Back Propagation, Journal of Lightwave Technology, vol. 26, no. 20, pp. 3416-3425.
Li, L., 2009. XPM Tolerant Adaptive Carrier Phase Recovery for Coherent Receiver Based on Phase Noise Monitoring, in Proceedings European Conference on Optical Communications, p3.16.
Piyawanno, K., 2009. Nonlinearity Mitigation With Carrier Phase Estimation for Coherent Receivers with Higher-order Modulation Formats, Topic Meeting in Lasers and Electro-Optics Society, We.3.
Lin, C., 2012. Nonlinear Mitigation Using Carrier Phase Estimation and Digital Backward Propagation in Coherent QAM Transmission, Optics Express, vol. 20, no. 26.
Ip, E.M., Kahn, J.M., 2007. Feedforward Carrier Recovery for Coherent Optical Communications, Journal of Lightwave Technology, vol. 25, no. 9, pp. 2675-2692.
Pfau, T., Hoffmann, S., Noe, R., 2009. Hardware-Efficient Coherent Digital Receiver Concept With Feedforward Carrier Recovery for M-QAM Constellations, Journal of Lightwave Technology, vol. 27, no. 8, pp 989-999.

Khalil, M. I., 2012. Low Complexity Non Decision Directed Blind Carrier Phase Recovery Algorithm for 16-QAM Optical Coherent Receiver, 3rd International Conference on Photonics 2012, Penang.

Viterbi, A. J., Viterbi, A. M., 1983. Nonlinear Estimation of PSK-Modulated Carrier Phase With Application to Burst Digital Transmission, IEEE transactions on Information Theory, vol. 29, no. 4, pp 543-551.

Fatadin, I., Ives, D., Savory, S., 2010. Laser Linewidth Tolerance for 16-QAM Coherent Optical Systems Using QPSK Partitioning, IEEE Photonics Technology Letters, vol. 22, no. 9, pp 631-633.

Zhang, S., 2010. Decision-Aided Carrier Phase Estimation for Coherent Optical Communications, Journal of Lightwave Technology, vol. 28, no. 11, pp 1597-1607.