Flexible Modulation and Nonlinear Tolerance for Coherent Transceivers

Qunbi Zhuge1,2,*, Michael Reimer1, Andrew D. Shiner1, Andrzej Borowiec1, Douglas Charlton1, Fangyuan Zhang2, Meng Qiu1, Wei Wang2, David V. Plant2 and Maurice O’Sullivan1

1Ciena Corporation, Ottawa, Ontario, Canada, K2H 8E9
2McGill University, Montreal, QC, Canada, H3A 2A7

*qzhuge@ciena.com

Abstract—We present advanced flexible modulation formats and reduced-complexity digital nonlinear compensation schemes to increase the capacity of next generation optical networks.

I. INTRODUCTION

Optical coherent transceivers are being deployed on nearly all network applications worldwide. In order to keep pace with capacity demand, novel digital signal processing (DSP) techniques based on coherent detection have been exploited to achieve higher spectral efficiencies and longer transmission distances. Amongst these, advanced flexible modulation formats and digital fiber nonlinearity compensation have been shown to hold promise [1-4]. Present commercial transceivers deliver discrete data rates on two polarizations usually using standard two-dimensional formats such as polarization multiplexed (PM) binary phase-shift keying (BPSK), quaternary phase-shift keying (QPSK), and 16 quadrature amplitude modulation (QAM). In a geographically diverse network, different links offer different capacities according to link conditions such as the fiber length, fiber type, dispersion map, etc. A transceiver that allows for a flexible data rate can adapt to maximize the overall network capacity in this scenario [5, 6]. Moreover, advanced formats with increased linear and nonlinear tolerance are desired [7, 8]. On the other hand, digital nonlinear compensation increases the nonlinear Shannon capacity limit of optical fibers. Digital back-propagation (DBP) [3] and perturbation based pre-distortion (PPD) [4] algorithms in particular have been shown effective in reducing intra-channel nonlinear distortion. However, it remains to design a low complexity digital nonlinear compensation scheme that can be implemented with the current CMOS technology.

In this paper, we present and discuss recent progress in advanced flexible formats including time-domain hybrid QAM (TDHQ) [5, 6] and optimized multi-dimensional formats [7, 8]. In particular, we highlight the improved linear and nonlinear tolerance of polarization balanced (PB) 8-dimensional (8D) formats for submarine applications [7]. Moreover, reduced-complexity implementations of DBP [9] and PPD [10] are reviewed. Measurements of improved nonlinear tolerance using Ciena WaveLogic 3 (WL3) transceivers are reported.

II. FLEXIBLE MODULATION

TDHQ is a reconfigurable modulation scheme for fine-tuning the average bits per symbol by interleaving two formats with different ratios in the time domain [5, 6]. Fig. 1 illustrates an example of TDHQ with one QPSK symbol and one 8QAM symbol interleaved. The average number of bits per symbol is calculated from the ratio of the formats in the TDHQ frame. At the receiver, the two formats are decoded independently based on the minimum Euclidean distance criterion. The relative powers of the two formats are adjusted to achieve a minimum bit error rate (BER) when averaged across the two formats. In Ref. [6], the impact of fiber nonlinearity on TDHQ signals was investigated. In dispersion-unmanaged links the TDHQ pulses are significantly broadened by chromatic dispersion (CD) and overlap with each other in the time domain, leading to a negligible instantaneous power difference between the two formats. A very limited nonlinearity penalty was observed compared to standard QAM formats in high dispersion scenarios.

Fig. 1 Illustration of the TDHQ frames with QPSK and 8QAM symbols.

Modulation of the optical field provides 4 dimensions (4D) including the in-phase $I$ and quadrature $Q$ fields on two polarizations at each instant of time. Recently, 8D formats have been proposed by further modulating the optical signal across the temporal correlations introduced by encoding symbols [3] and perturbation based pre-distortion (PPD) [4] algorithms in particular have been shown effective in reducing intra-channel nonlinear distortion. However, it remains to design a low complexity digital nonlinear compensation scheme that can be implemented with the current CMOS technology.

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proposed to improve the performance in Ref. [8]. The optimization was achieved by trading off the constellation minimum Euclidean distance and Hamming distance. As shown in Fig. 2, ~0.7 dB improvement is observed compared to TDHQ signals at 5 and 6 bits/interval. The nonlinear-tolerant PB-8D increases the ROSNR for signals with spectral efficiencies >3 bits/interval. For spectral efficiencies within 2 to 3 bits/interval, PB-8D formats improve the ROSNR by 0.3 to 0.6 dB relative to standard 4D modulation.

The PB-8D format at the same spectral efficiency as PM-BPSK, referred to here as the X-constellation, was demonstrated to significantly improve nonlinear tolerance in dispersion-managed WDM systems [7]. The constant symbol energy of X-constellation acts to reduce cross-phase modulation (XPM) and self-phase modulation (SPM). The two time slots that define an 8D symbol have equal and opposite polarization Stokes vectors. This strongly suppresses nonlinear polarization effects in dispersion-managed links.

The performance of the proposed ADBP is evaluated in Fig. 5, which plots the transmission distance of various linear and nonlinear DBP schemes versus launch power at the BER threshold of 3.8×10⁻³ for PM-QPSK.

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III. DIGITAL NONLINEAR COMPENSATION

Conventional DBP requires a large number of stages, each containing a pair of fast Fourier transform (FFT) and inverse FFT (IFFT) operations, to compensate nonlinearity in high dispersion links. Low-pass filtered DBP (LDBP) was proposed to significantly reduce the number of stages [11]. Recently, an advanced XPM model based DBP (denoted as ADBP) was proposed for subcarrier-multiplexing (SCM) systems to further reduce implementation complexity [9]. Fig. 4 depicts the block diagram of one ADBP stage with 2 subcarriers as an example. The compensation consists of two operations, namely self-subcarrier nonlinearity (SSN) compensation and cross-subcarrier nonlinearity (CSN) compensation, wherein the former is the same as the conventional DBP and the latter is implemented based on the XPM model. Because of the reduced symbol rate, the waveform of each subcarrier evolves much more slowly with respect to distance compared to the single carrier (SC) signal. Therefore, the step size for each DBP stage can be increased.
compensation (LC) and nonlinear compensation schemes versus the launch power at an uncoded BER of 3.8×10^{-4} for PM-QPSK. In the single channel transmission setup, 35 Gbaud root raised cosine (RRC) pulse shaped (roll-off factor α = 0.1) signals were generated offline and uploaded to Ciena WL3 transmitter. The numbers of subcarriers of the SCM signals tested were 2, 4, 8, and 16. Fig. 5 shows the best performance of these for each case. Other configurations are found in Ref [9]. In Fig. 5, the ADBP with 4 spans/step achieves the longest distance. However, when we increase the step size to 40 spans/step, the ADBP still provides a sizable performance improvement. In particular, combining the nonlinear benefit from both SCM and ADBP, the transmission distance is increased by 49.7% (40 spans/step QPSK) compared to the SC system with LC only, which is even better than the SCM system with 4 spans/step LDBP.

Perturbation based nonlinear compensation has been widely exploited in recent years mainly because in this method the nonlinear field can be evaluated in a single step [4]. More interestingly, a multiplier-free implementation was proposed for QPSK signals [4]. However, this low complexity scheme does not extend to higher order QAM without a significant decrease in performance. Based on perturbation theory, the nonlinear field can be evaluated in a single step [4]. More recently, nonlinearity pre-compensation using symmetric EDC and pulse shaping, [8] has been proposed to reduce the number of triplets by a factor of ~7, and reduce the number of quantized coefficients to 3, respectively.

Fig. 4 shows an experimental demonstration of system performance achievable with the reduced-complexity PPD with 50% CDPC [10]. Single channel 35 Gbaud 16QAM RRC signals (α = 0.14) generated by Ciena WL3 transmitter were transmitted over 10 spans of 80 km TrueWave Classic (TWC) fiber. The BER was measured online using the WL3 receiver and the ROSNR at the soft-decision forward error correction (SD-FEC) threshold was collected. The system margin relative to the maximum system margin of the case without PPD and CDPC was evaluated versus signal launch power. The “Full PPD” here refers to a full complexity implementation of PPD in which all terms in the evaluation of Δux are retained, while “3C PPD” refers to a quantization of the perturbation coefficients to only 3 unique values. It can be seen that with 50% CDPC, the system margin of “3C PPD” is reduced by only ~0.6 dB relative to the full complexity PPD, and achieves a 2.4 dB improvement in maximum system margin at a much lower implementation complexity. This result demonstrates the practicability of aggressive quantization of the perturbation coefficients with 50% CDPC.

IV. CONCLUSION

We have compared the linear performance of time domain hybrid QAM and multi-dimensional formats in consideration of advanced flexible modulation formats supported by coherent transceivers, and highlighted the improved linear and nonlinear tolerance of polarization-balanced 8D formats for submarine applications. We have also reviewed two reduced-complexity nonlinear compensation schemes based on digital back-propagation and perturbation based pre-distortion, respectively. The increased nonlinear tolerance from them was demonstrated using a commercially available Ciena WaveLogic 3 transceiver.

REFERENCES