Efficient Digital Backpropagation for PDM-CO-OFDM Optical Transmission Systems

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Abstract: We demonstrated experimentally that computationally-efficient digital nonlinearity compensation using backpropagation can increase the nonlinear tolerance of 61.7 Gb/s PDM-CO-OFDM by 2.2 dB in a 500 km link using only 3 backpropagation steps.

OCIS Codes: (060.2330) Fiber optics communications; (060.4080) Modulation.

1. Introduction

Polarization-division multiplexed coherent optical OFDM (PDM-CO-OFDM) has been experimentally demonstrated to be capable of 100+ Gb/s in long haul optical communications [1, 2]. PDM-CO-OFDM has the advantages of being able to compensate for linear effects such as chromatic dispersion (CD) and polarization mode dispersion (PMD) with relatively low computational complexity. It also has a well confined optical spectrum which allows multiple channels to be tightly packed without requiring optical filtering, thus making very high spectral efficiencies possible [3]. The digital-to-analog converter (DAC) at the transmitter increases the flexibility of the transmitted signals, making it possible to upgrade the bit-rate with only modifications to the electronics.

Digital nonlinearity compensation has also been proposed with varying degrees of computational complexity for both CO-OFDM [4, 5] and CO-QPSK [6]. Computationally efficient methods have been shown to be beneficial in periodically dispersion compensated or low dispersive links [4, 7]. However, in standard single mode fiber (SMF) link without periodic dispersion compensation, only digital backpropagation (BP) using many computationally intensive steps has been shown to be beneficial [8, 9]. This has been demonstrated experimentally for a 85.5 Gb/s PDM-CO-QPSK system [10].

In this paper, we experimentally demonstrated that BP can be used to significantly improve the nonlinear tolerance of polarization multiplexed Pol-Mux CO-OFDM systems. We demonstrate an improvement of 2.3 dB for a 61.7 Gb/s Pol-Mux CO-OFDM system operating above 5 dBm after 500 km. We show that the system is robust to inaccuracies in the estimation of the dispersion map. Additionally, we find that the number of calculations can be halved (to less than one BP iteration step per span) whilst still providing 2.2-dB improvement.

2. Experimental setup

The system diagram is shown in Fig.1. The OFDM signal was generated in MATLAB using a 1024-point FFT/IFFT with 658 subcarriers modulated with 8-QAM. A 256-sample cyclic prefix was used. Two arbitrary waveform generators (AWG) operating at 20 Gsamples/s were synchronized and used to drive the I and Q inputs of a complex MZM modulating an external cavity laser (ECL), which generated an optical signal 13.3-GHz wide. This give a bit-rate of 61.7 Gb/s.

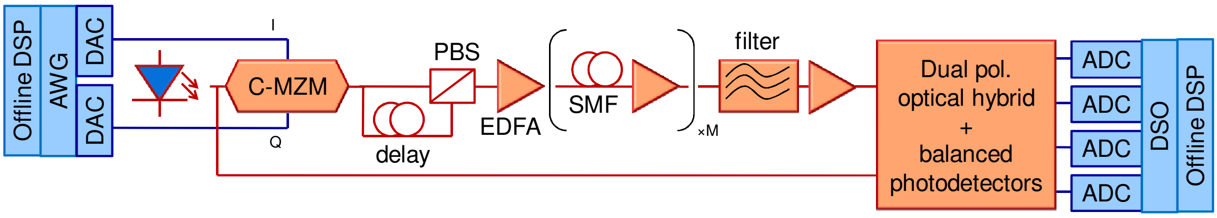

Fig. 1. System diagram of experimental setup.

The 500-km optical link consisted of one 50-km span, followed by five 80-km spans and finally a 50-km span of SMF. An EDFA was used at the end of each span to compensate for the span loss. The signal was then passed through an optical filter before being fed into the signal input of a dual-polarization optical hybrid. A 3-dB coupler was used to split the output of the ECL, and passed it into the local oscillator input of the optical hybrid. Because the delay from 500 km of SMF is much greater than the coherence time of the laser (around 80 times longer), the two received inputs functions as independent sources with the same optical frequency. Balanced photodiodes were used to detect the I and Q outputs from both polarizations. A 50-Gsample real-time digital sampling oscilloscope (DSO) was used to capture the signal and offline processing was done in MATLAB. Three instances, separated by around one minute, were captured with the DSO for each power. Each capture consisted of 149 OFDM data symbols which contain 552,700 bits. Fig. 2 shows the equalization processes used in the receiver. After BP, a typical MIMO-OFDM equalizer was used to remove remaining linear impairments such as I-Q imbalance, residual CD and PMD. The compensation of CD was performed in the frequency-domain. FFT/IFFT using overlap-add was used to convert from to the time-domain to the frequency-domain and vice-versa. The phase shifts proportional to instantaneous power were calculated and applied in the time-domain and were given by,

$$\phi_{x(y)} = K \times P_{x+y}^{av} \times \gamma \times L_{eff}(P_{x(y)}(t) + C \times P_{y(x)}(t))$$

where: γ is the nonlinearity factor, P^{av} is the average signal power in both polarizations, L_{eff} is the effective length of the span being compensated for, *P(t)* are the instantaneous powers in each polarization, *C* is the cross-polarization XPM coupling factor and *K* is a scaling factor which can be optimized.

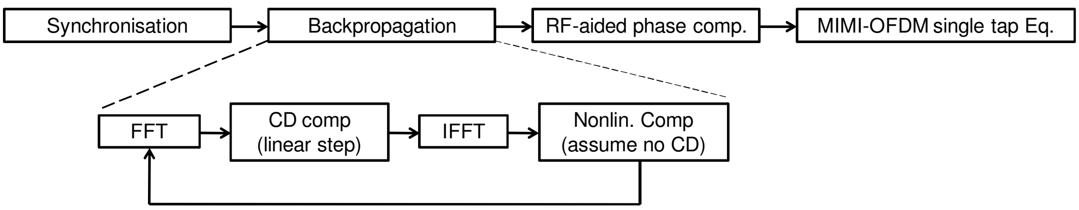

Fig. 2. Block diagram of the offline equalization process.

3. Experimental Results

An optical spectrum analyzer (OSA) was used to measure the signal power in a 0.2-nm bandwidth after the link allowing an accurate estimate of P^{av}. This can also be calculated from the received signal if the receiver's response is known. Each step of the BP compensated for a span of SMF. The L_{eff} of each step was set to the effective length of a span of SMF, which is 21 km [5]. Fig. 3 (left) shows *Q* against the scaling factor *K* for different coupling factors, *C*. The *Q* is calculated from the measured BER from both polarizations. This shows that the optimal coupling factor was around unity which is consistent with that presented in [7, 10]. Sweeps of *K* and *C* for different powers were conducted, and the optimum values were found to be reasonably constant for each power. These values of *K* and *C* where used in the remainder of this paper for BP using one step for every span. Fig. 3 (middle) and Fig. 3 (right) show the constellation without and with optimal BP at an EDFA target power of 6 dBm respectively.

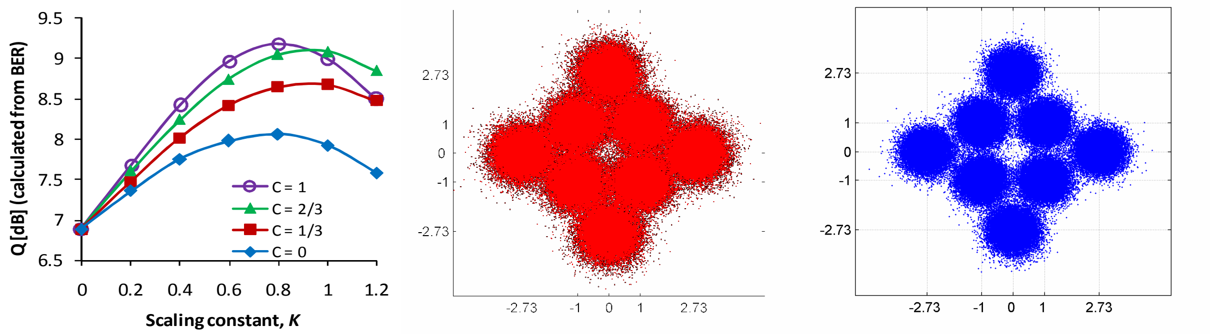

Fig. 3. (left) Q against *K* for different *C*; (mid) received constellation without BP; (right) received constellation optimum BP.

Fig. 4 (left) plots the *Q* versus launch power into each fiber span, set by the amplifiers' automatic power control. The signal power, measured with an OSA, was around 1-dB lower than the set power of the amplifiers due to the large amount of ASE. Using backpropagation, the *Q* could be improved by over 2 dB when the link is strongly nonlinear (for powers greater than 5 dBm).

The precise details of an installed fiber link are usually unknown; however, the amount of net dispersion can be calculated from the phase of the OFDM channel response, which can then be used to estimate the length of the link. The exact location of the amplifiers will be much harder to determine. It is therefore of interest to know how robust BP is to inaccuracies in the estimation of amplifier locations. Fig. 4 (right) shows the *Q* after BP against the mismatch in the length of the first step of the BP (which should compensate the last span in the physical link) and the length of the last span of the link, at a target amplifier power of 6 dBm.. This shows the Q to be almost constant over a 60-km variation, which suggests that the exact dispersion map is not required for BP to significantly improve the performance of PDM-CO-OFDM systems.

In order to reduce the computational complexity, the 500 km link was compensated for in just three iterations. This is less than one step for every two spans. The optimal K value was found to be 1.4 and the Q against the length of the first step for this K is plotted on Fig. 4 (right). We find that at the optimal length for the first linear BP span (compensating the last span in the link), almost the same benefit is possible with only 3 steps, unlike for single carrier systems, where it has been suggested that the high symbol rate greatly reduces the benefit from BP when less than one step per span is used [9]

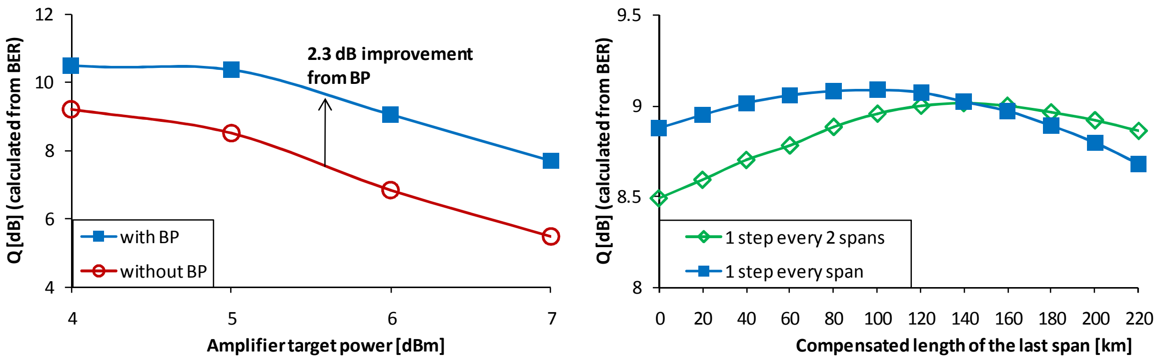

Fig. 4. (left) Q against target amplifier power; (right) Q against compensated length of last span.

4. Conclusion

We have experimentally demonstrated that back-propagation (BP) using one step for every two spans is sufficient to improve the nonlinear performance of Pol-Mux CO-OFDM systems. Q was improved by 2.2 dB for a given nonlinearity limited power was demonstrated for a 61.7 Gb/s PDM-CO-OFDM system. This amounted to an increase of 3-dB in the maximum operational power. We also show that inaccuracies in the prediction of the dispersion map will not significantly degrade nonlinearity compensation with BP in PDM-CO-OFDM systems.

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