Phase-conjugated Pilots for Fibre Nonlinearity Compensation in CO-OFDM Transmission

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Abstract *We experimentally demonstrate a novel fibre nonlinearity compensation technique for CO-OFDM based on phase-conjugated pilots (PCPs), showing that, by varying the PCP overhead a performance improvement up to 4 dB can be achieved allowing highly flexible adaptation to link characteristics.*

Introduction

The fibre Kerr nonlinearity imposes an upper bound on the maximum achievable data rate in optical fibre communications[1]. There have been extensive efforts in attempting to surpass the Kerr nonlinearity limit through nonlinearity compensation. Digital-back-propagation (DBP) is one such digital nonlinearity compensation technique[2]. However, beside the high complexity, the effectiveness of DBP is reduced in wavelength-division multiplexed (WDM) systems as the neighbouring WDM channels are unknown to the compensator. Mid link or transmitter side digital and optical phase conjugations are other well-known nonlinear compensation techniques that conjugate the signal phase after transmission in one segment of the link in order to achieve a net cancellation of both inter and intra channel nonlinear phase shifts[3]. However, they reduce the flexibility of optical networks.

Recently a novel nonlinear compensation technique called phase-conjugated twin waves (PCTW) has been proposed[4]. PCTW is a transponder-based technique that can be implemented with minimal additional optical hardware or digital signal processing (DSP) which tracks some of the inter channel nonlinearity. However, the one serious shortcoming is that it sacrifices half the capacity.

In this paper, we propose and experimentally demonstrate a novel nonlinearity compensation technique for CO-OFDM systems based on the transmission of phase-conjugated pilots (PCPs). In this scheme, a portion of the OFDM subcarriers are transmitted as PCPs of other subcarriers. The PCPs are used at the receiver to estimate the nonlinear distortion of their respective original subcarriers. The estimated distortions are then also used to compensate the nonlinear impairments in other subcarriers close to the PCPs. By transmitting PCPs, the optical fibre nonlinearity due to the Kerr effect in OFDM systems can be effectively compensated without the complexity of DBP or 50 % loss in capacity of PCTW. The technique proposed here can be effectively implemented in both single polarization and polarization division multiplexed (PDM) systems, in both single channel and WDM systems. Nonlinearity compensation using PCPs offers a simple and easy implementation applicable to any optical links where the level of nonlinear compensation may be readily tuned by selecting an appropriate number of PCPs.

Phase conjugated pilots for fibre nonlinearity compensation

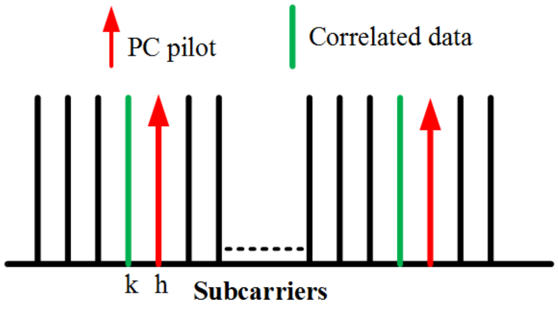

Fig. 1: Inserting phase-conjugated pilots for fibre nonlinearity compensation

Since the frequency spacing in an OFDM system is often small (tens of MHz), at the end of the optical link, the nonlinear phase shifts on adjacent subcarriers will be strongly correlated. This implies that nonlinear phase noise experienced in one spectral region may be used to estimate the distortion in other closely space regions, as observed in pilot tone compensation schemes[5]. Thus nonlinear compensation can be achieved by sparsely inserting PCPs across the OFDM band.

The concept of inserting PCPs for fibre nonlinearity compensation is illustrated in the Fig. 1. Suppose the information symbol carried by the k^{th} subcarrier is $S_k = A_k \cdot exp(j \cdot \varphi_k)$ where A_k and φ_k are the amplitude and the phase of this information symbol, then the phase conjugated symbol can be transmitted in the h^{th} subcarrier, $S_h = S_k^* = A_k \cdot exp(-j \cdot \varphi_k)$, where $(.)^*$ represents complex conjugation. To simplify the exposition, we assume that during propagation nonlinear

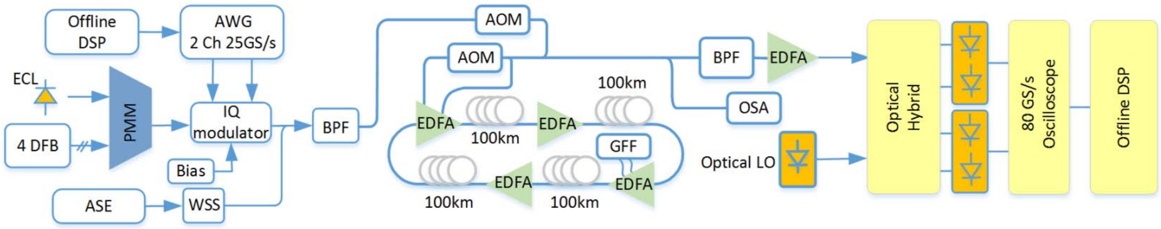

Fig. 2: Schematic of experimental setup of WDM CO-OFDM transmission with PCPs for fibre nonlinearity compensation. ECL: external cavity laser, PMM: polarization maintaining multiplexer, WSS: Wavelength Selective Switch, DFB: distributed feedback laser, BPF: band-pass filter (optical), AOM: acousto-optic modulator, GFF: gain flatten filter, OSA: optical spectrum analyser, LO: local oscillator.

phase shifts, represented by θ_k and θ_h, are added to these subcarriers. The received information symbols on the k^{th} and h^{th} subcarriers are $R_k = A_{r,k}\cdot exp(j\cdot\varphi_k+j\cdot\theta_k)$ and $R_h = A_{r,h}\cdot exp(- j\cdot\varphi_k+j\cdot\theta_h)$, respectively. If the frequency spacing between k^{th} and h^{th} subcarriers is small enough, the nonlinear phase shifts will be highly correlated, $\theta_k \approx \theta_h$, providing the opportunity of cancelling the nonlinear phase shift on the k^{th} subcarrier by averaging the received information symbol on this subcarrier and the subcarrier which carries its phase conjugate (after a second conjugation):

$$\overline{R_k} = (R_k + R_h^*)/2 \approx A_{r,k}\cdot\cos(\theta_k)\cdot\exp(j\varphi_k) \qquad (1)$$

Note that the nonlinear phase shift on the original subcarrier k can be estimated as[6]:

$$\theta_k = \arg(R_k\cdot R_h)/2 \qquad (2)$$

Ideally, a data carrying subcarrier and its PCP should be closely spaced in frequency (adjacent) to maximize the level of correlation of the nonlinear phase shifts between these subcarriers. For those data carrying subcarriers which do not have PCPs, the nonlinear phase noise of the j^{th} subcarrier can be estimated and compensated as:

$$\theta_j = \arg\Big(\sum_{k,h}\eta_{jkh}\cdot R_k\cdot R_h\Big)/2$$

$$\overline{R_j} = R_j\cdot e^{-j\cdot\theta_j} \qquad (3)$$

where η_{jkh} is the conventional FWM efficiency coefficient and in this paper η_{jkh} is approximated as 1 if the j is closest to k or h and 0 otherwise.

By applying this technique, the nonlinear phase noises on data subcarriers in an OFDM system can be compensated without conjugating all pairs of subcarriers. In this system configuration, several data carrying subcarriers are placed between conjugate pairs. The nonlinear phase noises for all of these subcarriers are similar assuming the frequency spacing is small. These nonlinear noises can be compensated using the estimated nonlinear phase noise on the closest pair of subcarrier data and PCP. In this scheme one PCP can be used to compensate the phase noises on several subcarriers and the overhead due to PCPs is relaxed and can be optimized according to the link characteristics.

Experimental setup and results:

The experimental set-up is shown in Fig. 2. It comprised a laser grid of five standard DFBs on 100 GHz grid which are substituted in turn by a 100 kHz linewidth laser. The DFBs are located between 193.5 to 193.9 THz. Additional loading channels (10 GHz of bandwidth) were generated using an ASE source which is spectrally shaped using a WaveShaper wavelength selective switch (WSS). The twenty loading channels were spread symmetrically around the test wavelengths so that the total bandwidth of the transmission signal was 2.5 THz. A wideband filter was used to filter out of band ASE noise at the transmitter. The transmission path is an acousto-optic modulator (AOM) based re-circulating loop consisting of 4 x 100 km spans of Sterlite OH-LITE (E) fibre, having 18.9 to 19.5 dB insertion loss. The loop switch was located in the mid-stage of the first EDFA and a gain flattening filter (GFF) was placed in the mid stage of the third EDFA. After propagation the signal was filtered using a 4.2 nm flat topped filter and coherently detected. The received electrical signals were then sampled by a real-time oscilloscope at 80 GS/s and processed offline in MATLAB.

The OFDM signal (400 symbols each of 20.48 ns length, 2% cyclic prefix) encoded with QPSK modulation format was generated offline in MATLAB using an IFFT size of 512, where 210 subcarriers were filled with data and the remainder zeros giving a line rate of 20 Gb/s (18.2 Gb/s after cyclic prefix and FEC overhead removed). When 25 %, 33.3 % and 50 % of OFDM subcarriers are transmitted with its PCPs the net data rate are 13.65 Gb/s, 12.12 Gb/s and 9.1 Gb/s respectively. In this work, in order to maximize the similarity between nonlinear phase noises on data subcarrier and PCP, data subcarrier and its PCP are placed next to each other. The DSP at the receiver includes chromatic dispersion compensation using an overlapped frequency domain equalizer with overlap-and-save method, channel estimation and equalization with the assistance of initial training sequence (2 training symbols every 100 symbols), common phase error (CPE) compensation with the help of PCPs[6] or 16 pilot

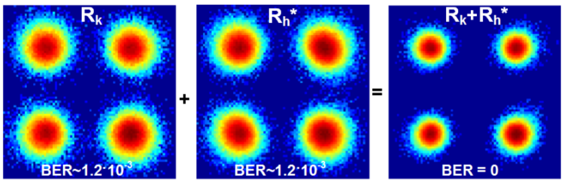

Fig. 3. Cancelllation of the nonlinear distortions by coherently combined subcarriers with its couterpart PCPs, 800 km of distance, the launch power (per/ch) was 0 dBm

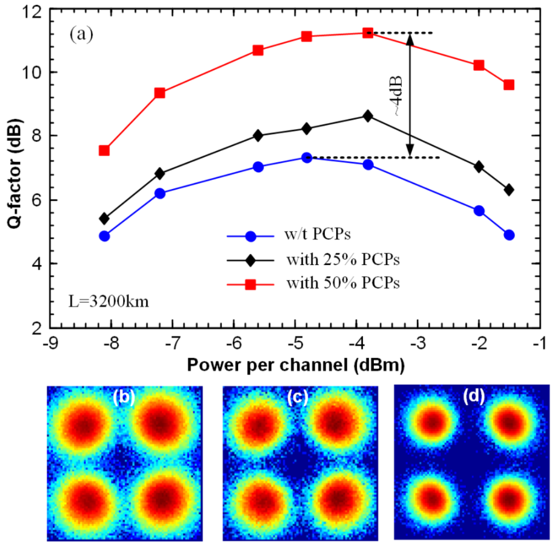

Fig. 4. Q-factor of the center channel as a function of the launch power in system with and without PCPs for fibre nonlinearity compensation (a) and constellation diagrams at Pin=-1.5 dBm for the cases of wihout PCPs (b) and with 25%, 50% of PCPs (c and d) respectively.

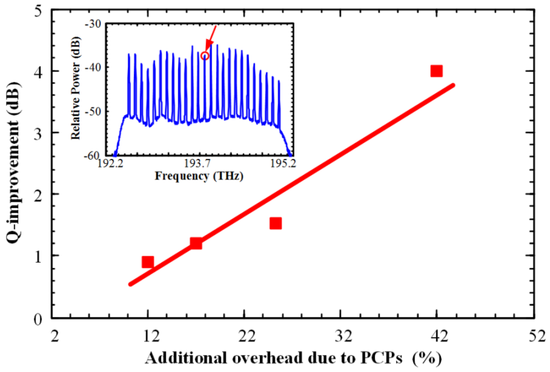

Fig. 5. Performance gain as a function of the additional overhead due to PCPs for the center channel, after 3200 km of distance. Without PCPs, an overhead of ~8% was required for CPE compensation.

subcarriers if PCPs are not transmitted, fibre nonlinearity compensation and symbol detection. The system performance is evaluated using the Q-factor derived directly from the BER by processing 10 recorded traces (~10^6 bits).

The effectiveness of transmitting PCPs for fibre nonlinearity compensation in CO-OFDM is shown in the Fig. 3, indicating clearly that a substantial fraction of the nonlinear phase noise can be mitigated by coherently averaging the PCPs and its correlated data subcarriers. This leads to a dramatic performance gain of around 4 dB after 3200 km of transmission distance when 50 % of OFDM subcarriers are transmitted with its PCPs (Fig. 4), which is consistent with results obtained for PCTW[4]. The overhead can be reduced by using fewer PCP and Eq. 3. Specifically, one PCP can be used for 2, 3, 4 or more data subcarriers at the cost of 33 %, 25 %, 20 % or smaller overhead respectively. The trade-off between the additional overhead due to PCPs and performance gain (for the optimum Q-factor) is shown in the Fig. 5, , showing that 0.9, 1.2, 1.5 and 4 dB performance improvements can be achieved with additional overhead of 12 %, 17 %, 21 % and 42 % respectively. This result clearly shows the flexibility of the proposed technique for fibre nonlinearity compensation.

Conclusion

An effective and flexible fibre nonlinearity compensation technique for CO-OFDM based on the transmission of PCPs has been proposed. This technique can be applied adaptively according to the optical link requirements to achieve a performance improvement up to 4 dB.

Acknowledgements

This work was partially supported by the UK EPRSC programme Grant UNLOC (EP/J017582/1) and the European Communities 7th Framework Programme FP/2007-2013 grants 258033 (MODE-GAP) and 318415 (FOX-C), and the support of Sterlite Technologies and Finisar is gratefully acknowledged.

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