Hybrid Analogue/Digital Nonlinear Interference Compensation

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Abstract *We demonstrate hybrid analogue optical and digital nonlinear interference compensation, combining optical injection locking with digital back-propagation. We show that DBP complements the analogue OIL compensation, giving substantial measured peak* Q *improvements of 1.9 dB in long-haul WDM systems.*

Introduction

Interference arising from optical fiber nonlinearity, form a barrier to continued growth in capacity per mode in optical fibers[1,2]. Recent studies have shown that the effectiveness of nonlinear interference compensationin the digital domain is limited due to stochastic nonlinear effects, including distortions from unknown neighboring wavelength multiplexed (WDM) channels[3,4]. Moreover, optical compensation techniques have shown limited efficacy in practical systems[5]. Significant performance gains can be made by by carrying conjugate signals[6,7], at the cost of bandwidth, limiting achievable capacity. Reach improvements of up to 3$\times$ have been shown using correlated optical carriers in full-band digital compensation techniques[8], suppressing inter-channel distortions where the waveforms of the neighboring channels are accurately known.

An alternative to full-band digital techniques for inter-channel distortion compensation is to infer the distortion from an alternate measurement[9,10], such as through carrier recovery via optical injection locking (OIL)[11]. These techniques do not require full knowledge of fields of neighboring WDM channels, and are so suited to systems where inter-chanel interfernce can be considered stochastic, such as optically routed networks.

Here, we complement the inter-channel nonlinear distortion compensation afforded by the *analogue* OIL-based technique, with a modified *digital* back-propagation (DBP) algorithm to compensate for intra-channel nonlinear distortions. Proof-of-concept WDM transmission experiments show that the combined effect of DBP and OIL gives a peak Q improvement of 1.9 dB, outperforming either technique operating alone. This demonstration shows the potential for single-channel receivers to effectively compensating for both inter- and intra-channel nonlinear distortion.

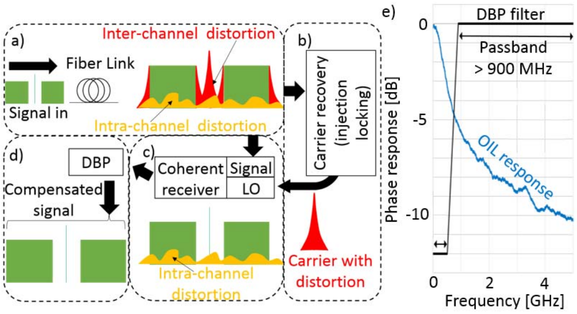

Fig. 1: a-d) Schematic of hybrid nonlinearity compensation. e) The measured optical injection locking phase transfer response at the injection ratio used in experiment, and the high-pass filter in the nonlinear DBP step.

Concept and Experimental Set-Up

Fig.1 shows the concept of our hybrid analogue/digital nonlinear compensation scheme. Propagation of WDM channels in long and dispersive fiber systems cause wide-band intra-channel nonlinear distortion, while inter-channel distortions from other WDM channels spaced apart by tens of GHz to several THz produce only narrow-band (single-GHz-scale) distortion products due to walk-off[9] (Fig.1a). The inter-channel distortions can be monitored using a residual carrier in a central guard band within the channel, as has been done in residual carrier based compensation techniques[10,11], and can then be recovered through polarization independent optical injection locking (Fig.1b)[12]. Mixing the recovered carrier with the received signal in a coherent receiver can help compensate inter-channel nonlinear distortions[11] (Fig.1c), and here we extend this approach by using a modified single-channel DBP algorithm to cancel out intra-channel nonlinear distortions (Fig.1d). We back-propagate only a single received channel, but modify the phase rotation step to accommodate for the low bandwidth phase noise removal by optical injection locking. We include a simple high pass filter (Fig.1e) in the estimation of the per-step nonlinear phase pertur-

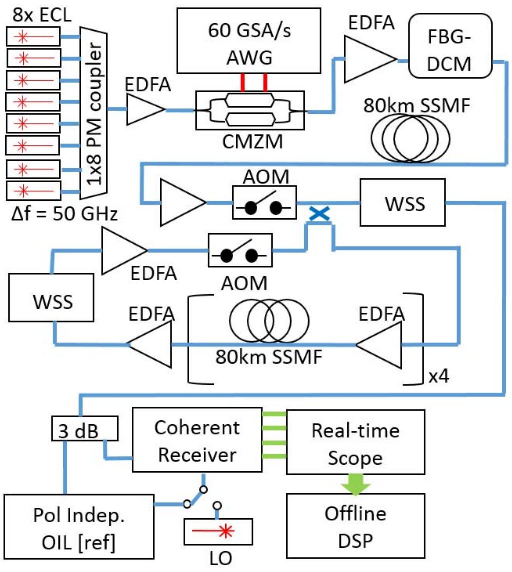

Fig. 2: Experimental set-up. AOM: Acousto-Optic Modulator

bation, to account for the cancellation of low ($<$ 900 MHz) frequency phase distortions by the optical injection locking based technique. The phase modulation transfer function for our injection locking set-up with a -44 dB injection ratio is also shown in Fig.1e.

As a proof-of-concept demonstration of this scheme, we transmitted eight 50-GHz spaced WDM channels in a recirculating loop experiment (Fig. 2). We modulate light from eight external cavity lasers (ECLs, $<$ 100 kHz linewidth) with a 20-GHz bandwidth dual-parallel 'complex' Mach-Zehnder modulator (CMZM) driven by the output of an arbitrary waveform generator with 25 GHz bandwidth running at 60 GSa/s. For the ease of providing a central guard-band in the channel, we modulated a coherent OFDM signal, with 100 occupied sub-carriers, with a 10-sub-carrier wide central guard band for the residual carrier, using a 156-point FFT. This translates to a 25 Gbaud effective symbol rate with a 2.5 GHz central guard band on a single polarization.

The eight WDM channels were delay decorrelated using 80 km of standard single mode fibre (SSMF), then per channel dispersion compensated with a channelized fibre Bragg grating module (FBG-DCM), leaving the channels with approximately 550 ps delay between neighbors. This WDM band was then passed into a recirculating loop, consisting of four 80 km spans of SSMF with lumped amplification (EDFAs, 6 dB NF specified) and an in-loop wavelength selective switch (WSS) to suppress out-of-band noise. The output of the loop was amplified, a single channel extracted with a WSS, then passed into the optical injection locking assisted coherent receiver.

At the receiver, the signal was split by a 3-dB coupler, with one arm heading to the signal port of the receiver, while the other extracted the residual optical carrier using a polarization independent injection locking stage[12]. The phase transfer function for the OIL stage with the -44 dB injection ratio used in experiment is shown in Fig.1e. The optical injection locking stage boosts the recovered carrier up to 20 dBm, suitable for use as a local oscillator in the coherent receiver. When not using OIL in the receiver, the local oscillator is a $<$100-kHz-linewidth ECL, similar to the transmit lasers.

The DSP flow begins with the modified DBP algorithm. The nonlinear step in the DBP can be written as $\hat{N} = \exp[i \times \gamma \times \mathcal{F}^{-1}[H(f) \times \mathcal{F}[P(t)]] \times h]$, where $\mathcal{F}$ denotes a Fourier transform, γ is the fiber nonlinear coefficient, h is the step size and $P(t)$ is the signals instantaneous power. $H(f)$ is a high-pass filter (as shown in Fig. 1), with a passband from 900 MHz upward. We use a 20 logarithmically spaced steps (h) per span to maximize the effect of DBP. As injection locking removes frequncy offset, and DBP compensates chromatic dispersion, we then synchronize the OFDM frame, demultiplexed using an FFT, passed through a training-based single-tap equalizer and residual phase compensated using a training-based maximum-likelihood estimator, before demodulation and error analysis. When DBP and/or OIL is not used, frequency offset compensation is achieved via spectral peak search, and dispersion compensation using an overlap-add technique.

Results and Discussion

Fig.3 plots the performance of the received signal against launch power for transmission distances of 2440 & 3520 km using QPSK and 640 and 1600 km using 16-QAM. Comparing first the results without OIL or DBP with those with OIL in the receiver, we observe between 0.7-0.9 dB peak Q improvement. When the modified DBP algorithm is included, there is an extra 1 dB of peak Q improvement on top of the benefits afforded by OIL. Comparing the curves presented in Fig.3 for different transmission distances, we observe that although there is still significant benefit in using our technique for both modulation formats, the peak Q gains change.The 1600 km, 16-QAM results, no-OIL case may show worse performance than expected, resulting in an inflated peak Q improvement. We do not expect that our system should

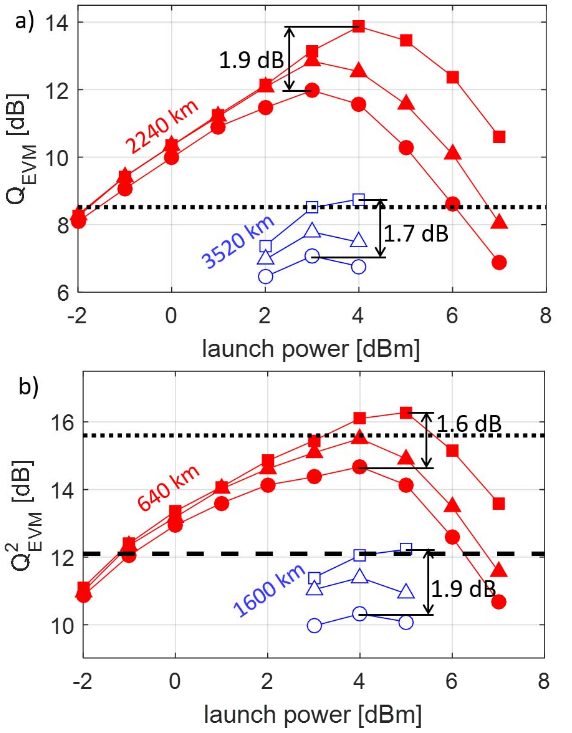

Fig. 3: Transmission performance curves for a) QPSK and b) 16QAM encoded sub-carriers (Key - ○ : no DBP, no OIL; △: no DBP, with OIL; □: with DBP & OIL). FEC limits correspond to BER = 3.8×10^{-3} (···) for the 7% HD-FEC threshold and BER = 2.6×10^{-2} (- - -) for a concatenated LDPC SD-FEC.

work any better for propagation distances longer than a few spans.

The improvement in peak performance afforded by our compensation technique compares favorably with other compensation techniques. The peak Q improvement exceeds systems based on the nonlinear Fourier transform[13], and begins to close the gap toward the 2.7 dB improvement observed in[8]. Moreover, compared with recently explored limits of digital back propagation in fully loaded WDM systems[3], our hybrid OIL and DBP approach outperforms predictions for single-channel back propagation.

We note that our proof-of-concept experiment uses only single-polarization channels. We may expect some further degradation from polarization rotation noise. In a dual polarization system we expect the Manakov model to ensure that nonlinear distortions carried on the residual carrier will be similar on the polarization multiplexed signals. We also note that the optical injection locking stage only compensated for phase distortions, and not amplitude noise that can also arise from nonlinear distortions. A carrier recovery system that could account for distortions in phase amplitude and polarization may improve performance.

Conclusions

We have shown that analogue optical injection locking nonlinear distortion compensation can be aided by a modified digital back propagation algorithm, to give 1.9-dB peak Q improvement, exceeding expectations for single-channel digital nonlinearity compensation in WDM systems. This indicates that joint intra- and inter-channel nonlinear distortion can be achieved without knowledge of the signals carried in neighboring WDM channels, and shows a new path to nonlinear distortion compensation in optically routed systems.

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