Fiber Nonlinearity Compensation for CO-OFDM Systems with Periodic Dispersion Maps

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Abstract: We show that the nonlinear limit of CO-OFDM systems at 100+ Gbps in periodic dispersion maps can be increased by 4 dB using nonlinear precompensation. We also show compensation is beneficial in WDM systems.
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1. Introduction

Recently, optical OFDM has been shown to be suitable for 100+ Gbps DWDM systems [1, 2]. The ability to insert training symbols to equalize for chromatic dispersion and PMD in coherent optical OFDM (CO-OFDM) means the computational complexity of the equalization algorithm at the receiver is significantly lower than in single-carrier coherent systems [3].

Currently, most installed long-haul optical systems use a periodic dispersion map in order to compensate for chromatic dispersion. The nonlinear performance of optical OFDM systems has been shown to be poorer in such dispersion maps due to the Self-Phase-Modulation (SPM) adding coherently span-on-span [4, 5]. It is thus preferable to remove the DCF from systems when upgrading to OFDM.

In this paper, we show that fiber nonlinearity precompensation [6] is very effective for OFDM systems with periodic dispersion compensation. Thus OFDM can be used to upgrade fiber links without removing the optical dispersion compensation. We also present the first simulations of precompensation in a 50-GHz-spacing WDM system. We find that nonlinear precompensation offers up to 2-dB signal-quality benefit, even in the presence of Cross-Phase-Modulation (XPM) from neighboring WDM channels.

2. Simulation setup

The complete system is similar to that in [6]. An optical equivalent of the precompensator is shown in Fig. 1 (left); this phase modulates the optical OFDM signal in proportion to its instantaneous power. In this paper we introduce an electrical low-pass filter to limit the bandwidth of the precompensation input signal, to match the frequency-dependence of the Four-Wave-Mixing (FWM) efficiency. In a real system, the precompensator could be implemented in the digital domain, with only a small increase in computational complexity. In the simulations, a 30-GHz OFDM signal is transmitted, which could support 60 Gbps per polarization using 4-QAM. 512 subcarriers are used at a spacing of 59 MHz. The fiber link comprises 10×80km spans of S-SMF (16 ps/nm/km) and DCF (-90 ps/nm/km). Two different dispersion maps were considered, as shown in Fig. 1 (right):

- Fully periodic: DCF is used to fully compensate for dispersion, after each span.
- 100 ps/nm residual: Each span is under-compensated by 100 ps/nm. An additional span of -1000 ps/nm DCF pre-compensates for dispersion. This is similar to the near optimal link proposed in [7].

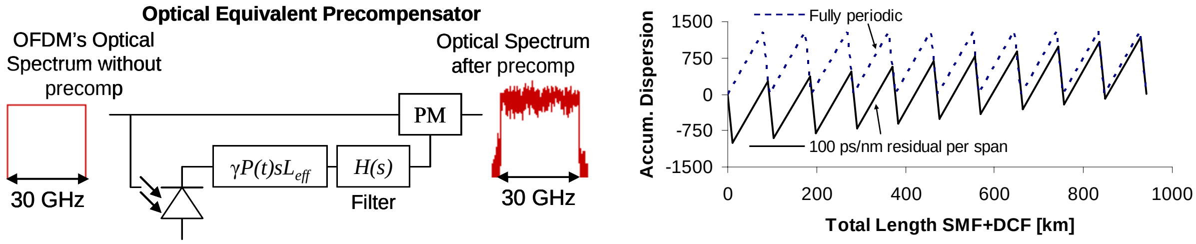

Fig. 1. Simulation setup: (left) Optical equivalent of the precompensator; (right) Dispersion maps of the two systems.

An EDFA (6 dB noise figure) is used before each fiber. The launch power into SMF was swept from -16 dBm to 6 dBm, to show the benefit to the performance when operating at the optimal power and the nonlinear limit. The

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launch power into DCF is 8-dB less than for SMF. For each case, 20 OFDM symbols were simulated, giving a total of 20,480 bits. VPItransmissionMaker was used for simulations.

3. Single-carrier results

The precompensation signal was band-limited as shown in Fig. 2 (left), as this improves the signal quality, as shown in Fig. 2 (right). The optimum filter bandwidth is a small fraction of the signal bandwidth, because only close (near neighbor) OFDM subcarriers interact through FWM, because of walk-off within each span. The optimum precompensation factor, L_{eff}, ('effective length' [6]) is longer when filtering is used; suggesting that the FWM from near neighbors is compensated for more fully. The filtering also works by reducing the compensation of FWM from far-apart subcarriers; this is beneficial because this compensation actually causes signal degradation. This degradation is because the compensation is no longer antiphase to the SPM, due to the dispersion within each span.

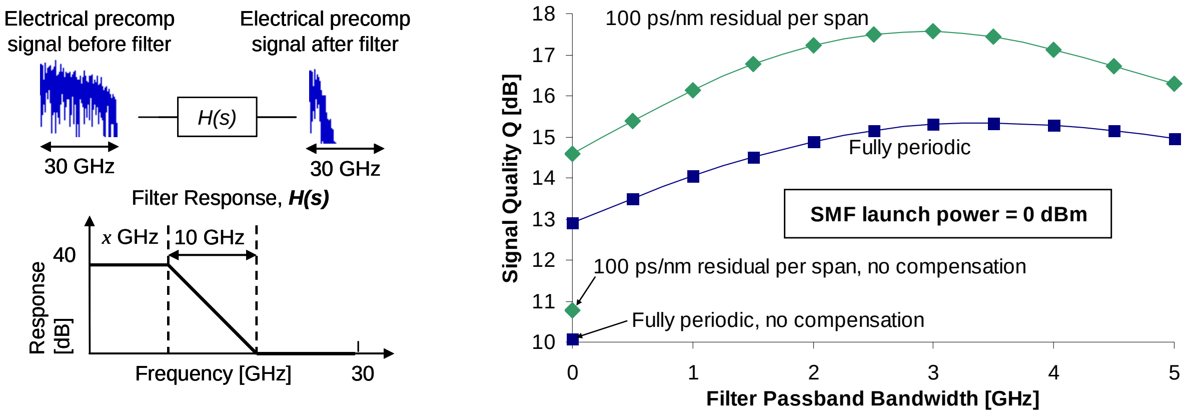

Fig. 2. Filtered precompensation: (left) filter characteristic; (right) Signal quality Q *vs.* filter bandwidth. Note that some precompensation is applied even when the pass-band has zero bandwidth, because some signal will still pass through the transition-band.

Fig. 3 shows the signal quality for the uncompensated and optimally-compensated cases of both dispersion maps for a single-channel system. Electronic precompensation offers significant benefits to CO-OFDM in both dispersion maps. For the fully periodic case, the optimal Q can be increased by 2 dB and the nonlinear limit increased by over 3 dB: in the nonlinear limit, precompensation results in a 6-dB improvement in Q. For 100 ps/nm residual dispersion, even greater benefits are obtained: the optimal Q can be increased by 3 dB; the nonlinear limit is increased by 4 dB; the Q in the nonlinear limit is increased by 8-dB for a given power.

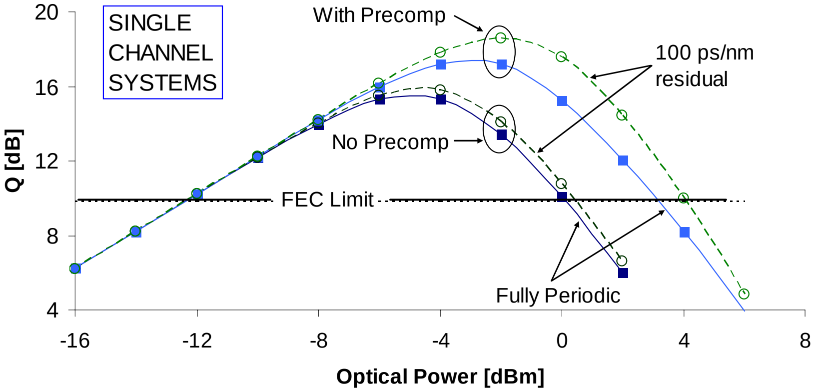

Fig. 3. Signal Quality (Q) *vs.* optical power for single channel systems in the two dispersion maps.

4. WDM system results

In WDM systems, XPM from neighboring channels plays a significant role in nonlinear degradation [4, 7]. An eight-channel WDM system with 50-GHz channel spacing was simulated to investigate the performance of precompensation in WDM situations. Only the dispersion map with residual dispersion was used. Fig. 4 shows results for channel five of the WDM system. The 3-dB drop in the Q of the uncompensated system at higher powers suggests that XPM is more significant than SPM. Thus XPM limits the effectiveness of precompensation (which can only mitigate SPM); however, a benefit of over 1-dB is still possible in the nonlinear limit, equating to a 2-dB increase in *Q* for a given power.

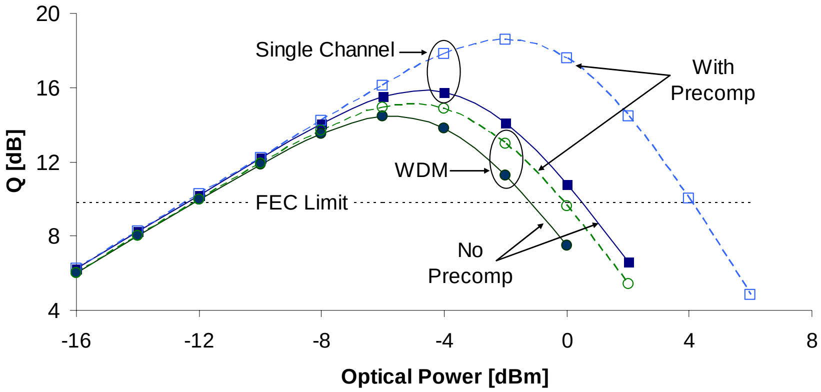

Fig. 4. *Q* vs. optical power for single carrier and WDM in the link with 100 ps/nm residual dispersion per span.

5. Discussion

Bringing the accumulated dispersion back to zero at the end of every span causes both the SPM and the XPM from every span to add constructively. This has a significant adverse effect on OFDM systems [4]. However, simulations of OFDM systems with low-dispersion fibers [8] have shown that reducing walk-off makes nonlinear precompensation more effective. In the dispersion managed systems in this paper, walk-off is also reduced, which greatly increases the effectiveness of precompensation, even for standard SMF.

The small amount walk-off between the spans in the 100 ps/nm residual dispersion systems slightly improves their uncompensated performance due to the phase shift between the SPM products of subsequent spans. The nonlinear precompensation is also more effective, possibly because the link is more symmetrical about the zero dispersion point, making it similar to a combination of pre/post compensation, which has been shown to work better than precompensation alone [6].

6. Conclusion

This paper shows that nonlinear precompensation is capable of increasing the nonlinear limit of CO-OFDM dispersion-managed systems by 4 dB, thus allowing launch powers of over 4-dBm in a single carrier system. In WDM systems, this limit is reduced to 0 dBm, due to XPM. These results show precompensation can mitigate the majority of SPM effects in both single-carrier and WDM systems.

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