# Distributed Nonlinear Compensation using Optoelectronic Circuits

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(Invited)

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**Abstract** We review our progress in using few-gigahertz-bandwidth optoelectronic circuits to compensate for cross-phase modulation between widely spaced WDM channels. This technique is suitable for distributed nonlinearity compensation, so suits networks with ROADMs.

## Introduction

The mitigation of the effects of the Kerr nonlinearity in optical fibres has occupied the minds of researchers for many years. Early methods included optimizing dispersion maps[1], and developing pre-compensation[2,3] and post-compensation[4,5] for single channels. The re-introduction of coherent receivers brought the possibility of digital nonlinearity compensation, with its progression towards sophisticated digital back propagation (DBP—essentially using fibre simulation algorithms with inverted parameters to undo the nonlinearity in the real fibre)[6,7]. Mid-span spectral inversion (MSSI)[8], and end-span spectral inversion promoted all-optical methods of nonlinearity mitigation. Recent work on Nonlinear Fourier Transforms (NFT) has proposed signals that remain orthogonal through a nonlinear system [9]. Unfortunately, DBP and NFT are computationally expensive, and MSSI adds complexity within the network.

Fundamentally, all of these techniques fail in optically switched networks[7], where the neighbouring channels are added and dropped along the link—therefore the receiver has no knowledge of what has affected a channel along its path from transmitter to receiver, and in the case of MSSI, the "middle" of a network path is unknown, though MSS could be used in each path between ROADMs.

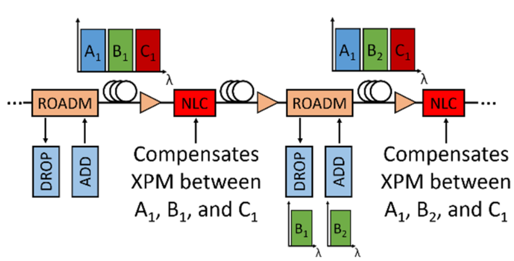


**Fig. 1:** Nonlinear interactions in a network with ROADMs.

It has been known for many years (since the use of optical amplifiers to create multi-span links) that cross-phase modulation (XPM) between widely spaced optical channels is a low-frequency effect[10]. That is, only the low-frequency component of the intensity fluctuations of one channel will induce significant phase modulation of another channel *across the entire link.* Within each km of fibre, however, XPM is a broad-band effect. The reduction of XPM efficiency is caused by walk-off of the channels, such that within an amplified span, the phases of the phase modulation products precess, so do not add constructively. In a green-field system (with no dispersion compensation), the phases across multiple spans also precess. Du and Lowery provided some graphical representations of these effects[11]. This observation raises the question: "*Why are high-bandwidth optics or high-sample rate DBP required to compensate XPM?"* Indeed, Du and Lowery showed that low-pass filtering the intensity signal within a DBP algorithm considerable reduces the computational complexity, so that less than one step for span becomes as effective as having multiple steps per span[12].

Optical techniques have been proposed for compensating single-channels. For example, Xu and Liu used a phase modulator driven by the intensity of a single channel at the receiver to undo the phase-modulation caused by the fibre's Kerr effect[4]. This idea translates to DSP systems, where it could be implemented digitally at the receiver[5], at the transmitter[2], or both[3].

Du and Lowery showed that the phase modulation could be driven by the combined intensity of several channels, to mitigate XPM in dispersion-compensated (brownfield systems) [13,14]. The idea was simply to move the intensity detector (a photodiode) to *before* the receiver's wavelength demultiplexer, so that it detects the combined intensity of several channels. This was demonstrated by feeding the output of this photodiode into a spare channel of a real-time oscilloscope, and using this signal to derive a compensating phase waveform, implemented in DSP. A 1.3-dB gain in *Q* was achieved[13].

Of course, the mitigation could be applied with a phase modulators in Xu's systems, and so combining Xu's ideas with those of Du and

Lowery led to proposals of using an 'electro-photonic' (or optoelectronic) circuit to compensate XPM. This idea has been vigorously pursued by Ben Foo as part of his PhD at Monash University. This paper draws on his work[15-17].

**In-line Optoelectronic NL Compensator**

If we assume that a polarization-independent phase modulator is available, the schematic of Fig. 2 applies to both single-wavelength and WDM systems. A photodiode detects the sum of the intensities of all channels, in both polarizations. A low-pass filter restricts the bandwidth of the photodiode's output, to account for walk-off of the channels. The output of the filter is used to drive the phase modulator, such that the Kerr nonlinearity in the fibre is compensated —A *Total Intensity Directed Phase Modulation* (TID-PM). Wavelength-dependent delays can be added to the input and output of this subsystem, to account for group delays between the wavelength channels.

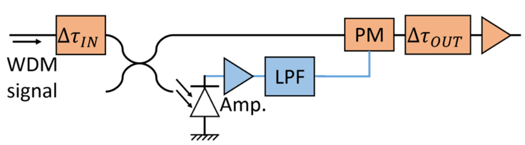

**Fig. 2:** TID-PM block diagram.

The bandwidth of the electronics needs only be a few GHz (due to the walk-off of the channels), which is surprising given that hundreds of GHz of optical bandwidth is being processed.

We have simulated in-line TID-PMs in various dispersion maps[15], and modulation formats[16]. These studies found that our technique is effective for all dispersion maps, and is modulation-format agnostic. Simulation results for a 15×100-km dispersion unmanaged link are presented in Fig. 3[16]. The transmitted signal comprised 8 WDM channels on a 50-GHz grid. Each channel was modulated with DP-16QAM at 28-Gbaud. We compared the performance on in-line TID-PMs with DBP using one step per span. The in-line TID-PMs improved $Q$ at the optimum launch power by 1 dB, while DBP gives a 0.6-dB increase in peak $Q$. The additional improvement is because in-line TID-PMs can suppress both SPM and XPM.

Further simulations showed that one TID-PM per span can mitigate the distortion on several WDM channels simultaneously[16]. Fig. 3 plots the average $Q$'s of all eight channels against launch power and Fig. 4 is their individual $Q$'s. All channels are improved by between 0.7 and 1 dB.

Recently we demonstrated in-line TID-PMs experimentally in a long-haul WDM system[17]. The TID-PM was constructed using off-the-shelf components, and a re-circulating loop emulates an 800-km dispersion unmanaged link with in-line NLC. Five channels of 28-Gbaud DP-16QAM were transmitted on a 50-GHz grid. To omit the OSNR penalty caused by the insertion loss of the TID-PMs, the performance after NLC is compared to a link with an equal optical loss. This result is shown in Fig. 5, which plots $Q$ against launch power for the centre channel. There is a 0.4-dB improvement in $Q$ at the optimum launch power. This is less than the simulated increase, possibly because of the different responses of the ideal LPF and the off-the-shelf filter.

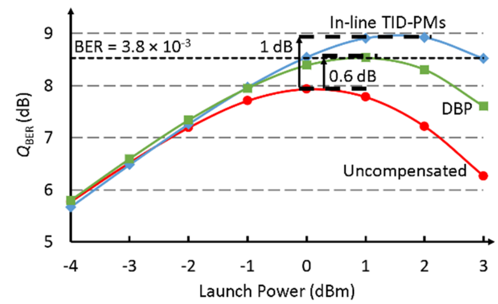

**Fig. 3:** Simulation of signal performance in a 15×100-km dispersion unmanaged link for in-line TID-PMs and DBP.

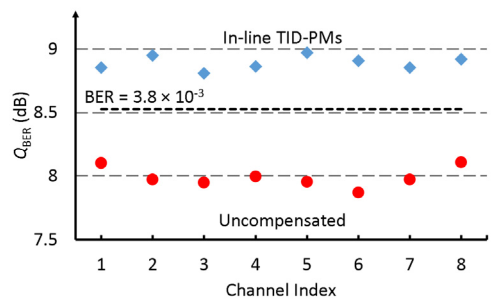

**Fig. 4:** Simulation result showing NLC of 8 WDM channels using one in-line TID-PM per span.

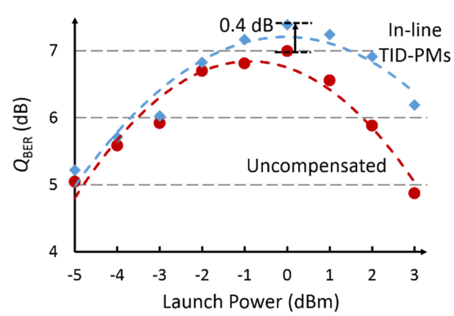

**Fig. 5:** Experimental demonstration of NLC using in-line TID-PMs in a 10×80-km dispersion unmanaged link.

**Fundamental Limitations**

Within a span the signal shape is considered to be constant, so that the intensity waveform detected by the photodiode represents the intensity waveform along the length of the span. A mitigating factor is to use more TIDs, just as DBP works better with more steps. As Du and Lowery showed for DBP, the LPF vastly improved the performance of systems using only one nonlinear step per few spans, and this advantage carries over to this optoelectronic system.

Secondly, polarization rotation within a span is problematic, because of the 'factor of two' difference in the XPM between co-polarized and orthogonally polarized signals. Therefore there is a compromise between under-compensating co-polarized channels or overcompensating the orthogonally-polarized channels. Under-compensation (50% of co-pol.) is preferable because the over-compensation of orth.-pol. would be 200%, which gives a greater overall error. A more-complex TID (Fig. 6), applied sufficiently frequently along the link, would be able to apply ideal compensation factors.

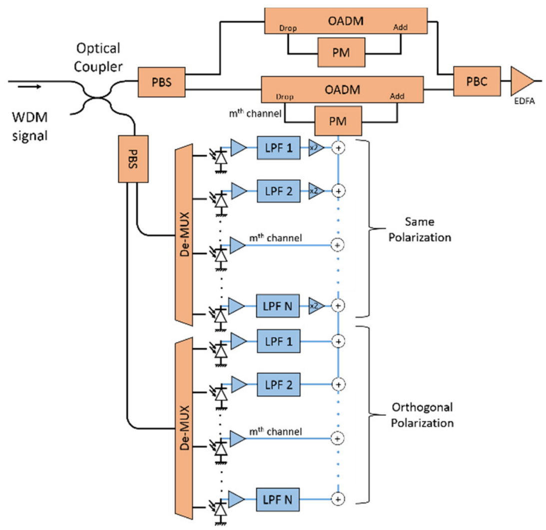


**Fig. 6:** Method accounting for polarization scattering and channel-dependent walk offs.

Thirdly, the walk-off of widely spaced channels is greater than closely spaced channels. Thus the LPF's bandwidth should be different for each frequency spacing. To account for this effect, a photodiode would be required for each channel (Fig. 6), and a bank of LPFs provided, together with independent phase modulators for each wavelength. Complexity-wise this is similar to separate SPM compensators per channel, but requires a cross-connection of the compensation signals. Some of these signals will have high bandwidths, as they are compensating SPM.

## Practical Issues

Obviously adding components in-line will incur a noise penalty, due to the amplification that is required to overcome their losses. This can be reduced by surrounding the compensator with two amplifiers: if the loss of the TID is the same as a span of fibre, the overall SNR due to noise will drop by 3 dB; however, for a TID loss of 5 dB gives only a 0.1 dB penalty for 20-dB span losses. At present, the main loss is the phase modulators, and so low-loss polarization-independent modulators would be beneficial. Pre-and post-TID group delay matching also requires space, but may use fibre Bragg gratings.

## Conclusions

Optoelectronic compensators can be placed in-line, so are suitable for optical networks, surprisingly use only low-bandwidth electrical components. Integration of the design Fig. 6 may offer better performance in a reasonably-compact format.


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