Fiber Nonlinearity Compensation (NLC)

Research Vignette – a brief history and selection of papers and figures

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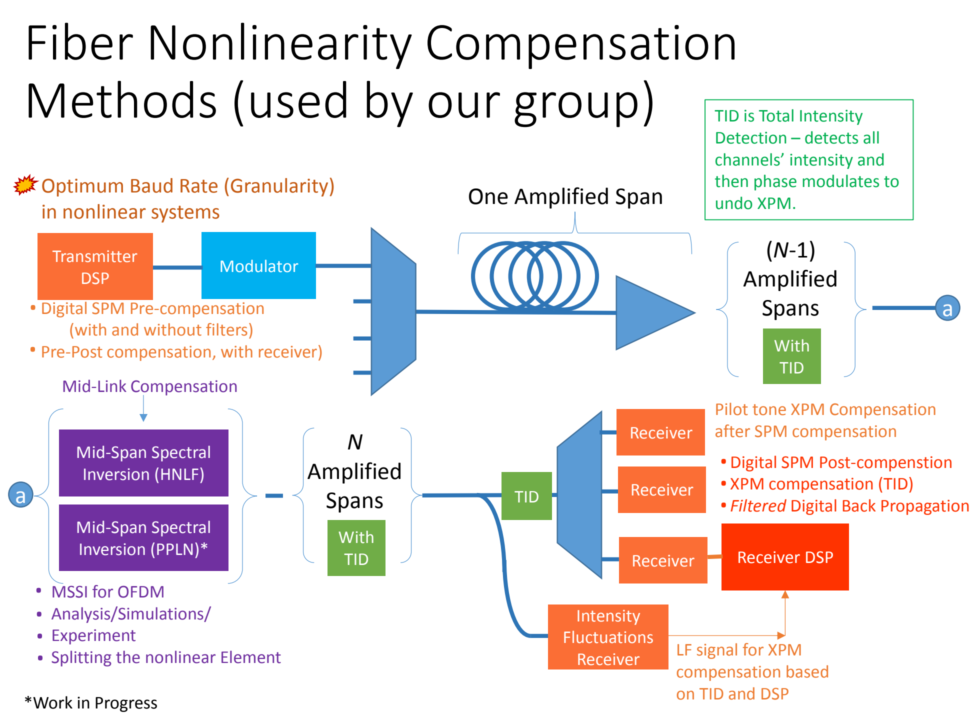
Our interest in compensating for the effects of fiber nonlinearity (FWM, XPM, SPM – all from the Kerr effect) started when we were researching the performance of Optical-OFDM for Long Haul optical systems. Of course, we had a great background with our experience in VPIphotonics, as the time-domain and split-step nonlinear fiber models we had developed could be "reversed" to form digital backpropagation algorithms!

Along the way we showed that there is an optimum baud rates in nonlinear systems (2011), which has recently become a hot topic.

A summary of some of the techniques that we have developed, and where they fit along a fiber system, is presented in the figure below. The techniques are:

- **Digital** {Precompenstion, Postcompensation, Symmetric Compensation, Filtered Digital Back-Propagation}, (2007-)
- **Nonlinear** optical Mid-span/link spectral inversion (2012-)
- **Electro-optical** {XPM using Total Intensity Detection and phase modulation} (2009-)
- **Electronic** {XPM using pilot tones, in our case after SPM compensation) (2011)

A recurrent theme is **low-pass filtering** the correction signal before applying the corrective phase modulation.



Motivation

We wished to make optical OFDM systems more resistant to fiber nonlinearity. The NLC techniques (for XPM, SPM, FWM) that we developed are, however, applicable to many other modulation formats, such as coherent OFDM, N-WDM and WDM. For example,

- The filtered backpropagation idea is fundamental to making digital back-propagation practical for almost all modulation formats.
- The Total-Intensity Detection (TID) work makes in-line compensation practical; in-line compensation is necessary for long-haul switched optical networks.
- Mid-span spectral inversion can be applied to any modulation format.
- The optimum baud rate (dependent on transmission distance) seems to hold for most modulation formats.

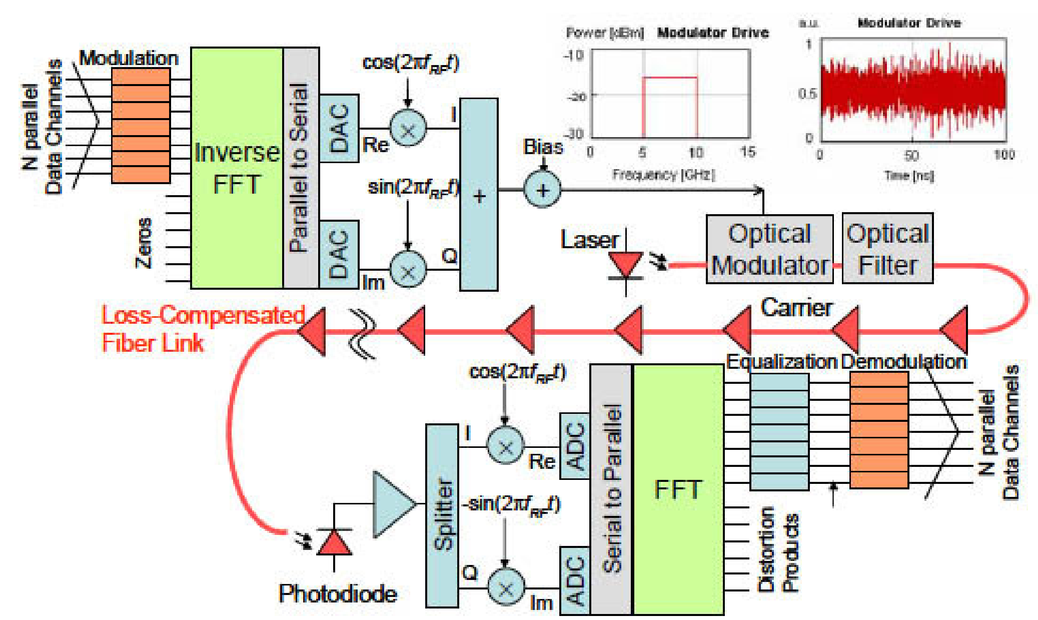
Many of these ideas are published in our patents.

Direct-Detection Optical OFDM (See US Patent: 8,111,993)

The original journal paper for long-haul direct-detection optical OFDM (DDO-OFDM) used a combination of:

1. single-sideband, bandwidth, *B*
2. a supressed carrier
3. a frequency gap between (1) and (2) with a bandwidth of at least *B*, is:

A. J. Lowery and J. Armstrong, "Orthogonal frequency division multiplexing for dispersion compensation of long-haul optical systems," Opt. Express, vol. 14, pp. 2079-2084, Mar. 20 2006. https://www.osapublishing.org/oe/fulltext.cfm?uri=oe-14-6-2079



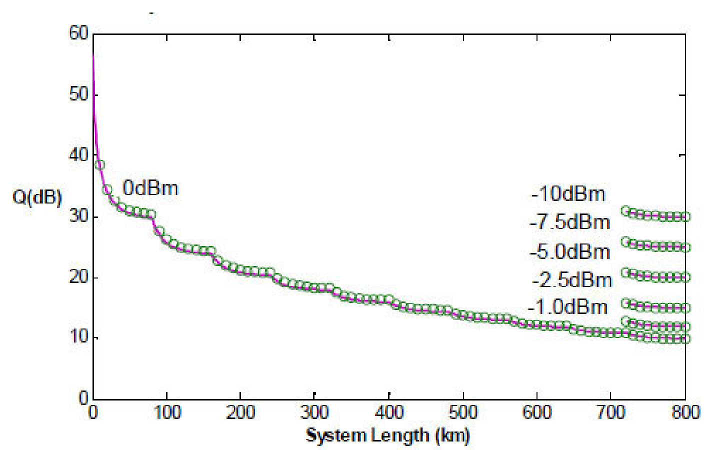
Assessing the impact of Fiber Nonlinearity on Optical OFDM (Coherent Optical OFDM)

Our most cited work showed that fiber nonlinearity is not as bad as thought for OFDM – many people thought OFDM would have huge impairments due to the FWM (Four-Wave Mixing) between the hundreds of subcarriers. Using extensive simulations, this paper showed that long-haul links were practical (using DDO-OFDM):

A. J. Lowery, L. B. Y. Du, and J. Armstrong, "Performance of optical OFDM in ultralong-haul WDM lightwave systems," J. Lightwave Technol. 25, 131-138 (2007).

The paper below used a simple analyses and simulation to show that the nonlinear limit (in a dispersion-less system) is substantially independent of the number of subcarriers. Moshe Nazarathy and Bill Shieh's groups provided more detailed analyses including dispersion.

A. J. Lowery, S. Wang, and M. Premaratne, "Calculation of power limit due to fiber nonlinearity in optical OFDM systems," Opt. Express 15, 13282-13287 (2007) http://www.opticsinfobase.org/abstract.cfm?URI=oe-15-20-13282



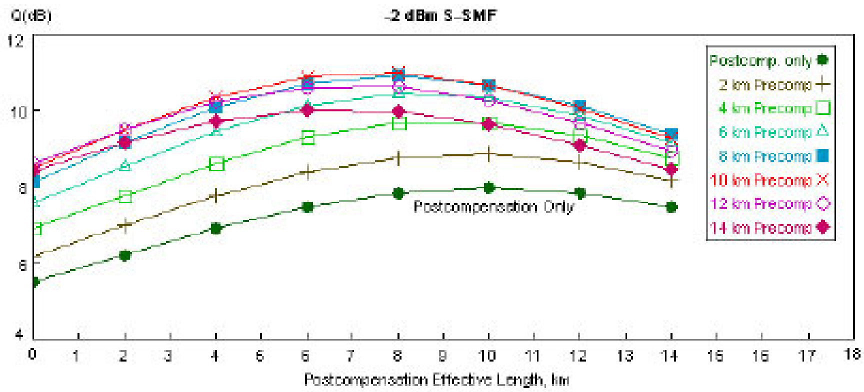
Electronic/Digital compensation **(See US Patent: 8,112,001)**

The idea was that the DSP in optical OFDM could be used for pre-compensation, post-compensating and pre/post compensation of optical OFDM signals, simply by adding intensity-dependent phase rotations at the transmitter and/or receiver.

A. J. Lowery, "Fiber nonlinearity mitigation in optical links that use OFDM for dispersion compensation," IEEE Photon. Technol. Lett. 18, 1556-1558 (2007)

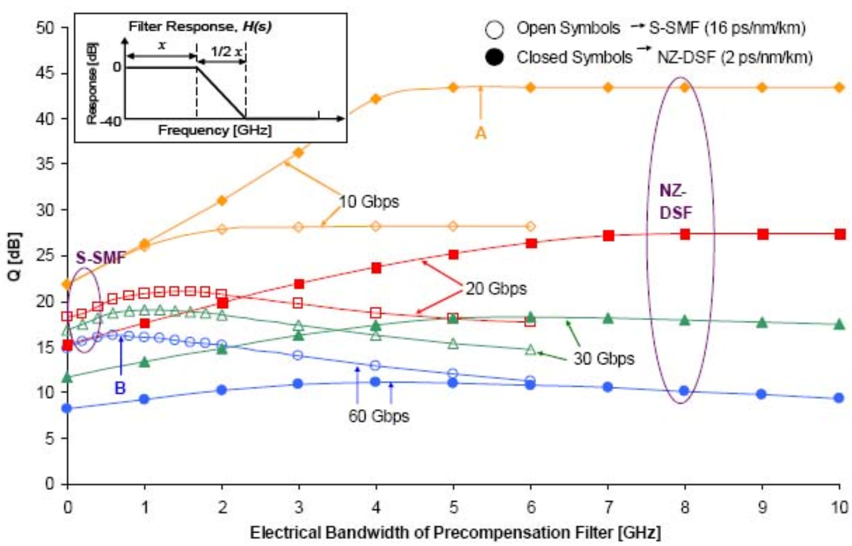
Interestingly a split between the transmitter and receiver was found to be most beneficial, in a similar way to using a symmetric split-step method to model optical fiber nonlinearities. That is, the precompensation becomes less accurate as we move along the fiber (due to dispersion evolving the 'actual' signal at any point), but the post-compensation becomes more accurate. It may be that the pre/post inaccuracies around the middle of the link might cancel out to some extent!

Arthur James Lowery, "Fiber nonlinearity pre- and post-compensation for long-haul optical links using OFDM," Opt. Express 15, 12965-12970 (2007)
https://www.osapublishing.org/oe/abstract.cfm?uri=oe-15-20-12965



After reviewing the effect of dispersion on multi-span links, the following paper showed that limiting the bandwidth of the compensation signal improves the performance of links with standard-SMF fiber.

L. B. Du and A. J. Lowery, "Improved nonlinearity precompensation for long-haul high-data-rate transmission using coherent optical OFDM," Opt. Express 16, 19920-19925 (2008)
http://www.opticsinfobase.org/oe/abstract.cfm?URI=oe-16-24-19920

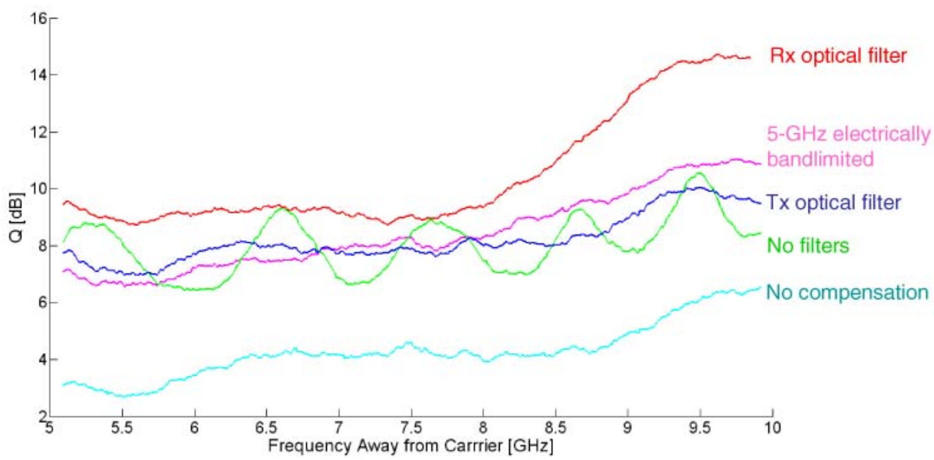


Similar pre-compensation techniques can be used for DPSK links:

Dung Dai Tran and A. J. Lowery, "SPM mitigation in 16-ary amplitude-and-differential-phase shift keying long-haul optical transmission systems," Opt. Express 18, 7790-7797 (2010)
http://www.opticsinfobase.org/oe/abstract.cfm?URI=oe-18-8-7790

The use of a strong carrier in **DDO-OFDM** creates additional nonlinear distortions that appear in the spectrum. This affects system using nonlinear precompensation. This paper showed that various filtering options helped remove the frequency-dependence of the 'carrier compensated nonlinearity', i.e. that the carrier suffers some Kerr phase modulation that is correlated with the phase modulation of the sideband, so that they cancel out, at least at low frequencies. This is similar to the compensation of XPM using pilot tones, described next.

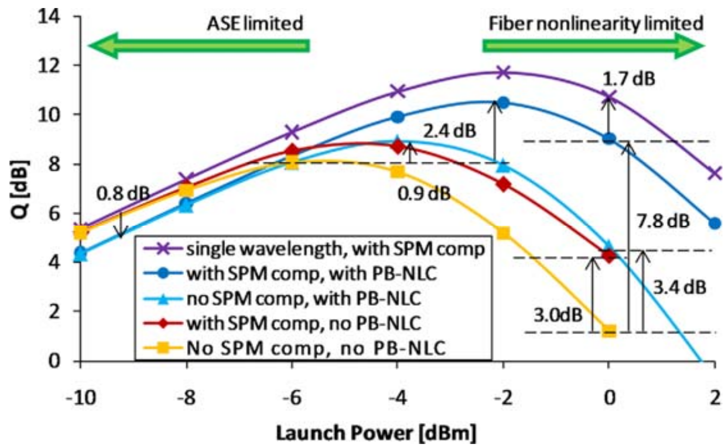
L. B. Du and A. J. Lowery, "Fiber nonlinearity precompensation for long-haul links using direct-detection optical OFDM," Opt. Express 16, 6209-6215 (2008)
http://www.opticsinfobase.org/abstract.cfm?URI=oe-16-9-6209



Compensation XPM in coherent OFDM using pilot tones **(See US Patent: 9,236,951)**

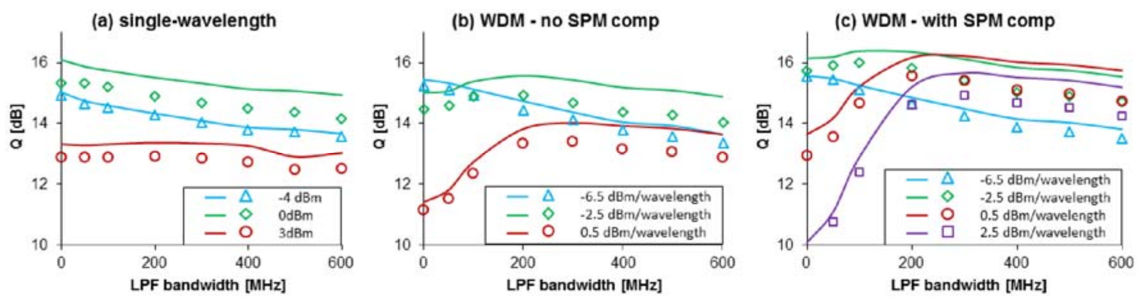
Using simulations, this paper investigated the use of a pilot for XPM compensation (PB-NLC), because the pilot and the signal-band should be affected by XPM in a similar manner. The pilots in an Optical OFDM system are used to cancel the XPM phase errors for each OFDM channel at the receiver after each channel's self-phase modulation (SPM) has been compensated, using its intensity waveform to determine its SPM. This two-step approach (SPM, then XPM with PB-NLC) yields better results than a single-step approach.

Liang B. Du and A. J. Lowery, "Pilot-based cross-phase modulation compensation for coherent optical orthogonal frequency division multiplexing long-haul optical communications systems," Opt. Lett. 36, 1647-1649 (2011)
http://www.opticsinfobase.org/ol/abstract.cfm?URI=ol-36-9-1647



This following paper is an experimental verification of the simulations in the paper above.

Liang B. Du and A. J. Lowery, "Pilot-based XPM nonlinearity compensator for CO-OFDM systems," Opt. Express, 19, pp. B862-B867 (2011)
http://www.opticsinfobase.org/oe/abstract.cfm?URI=oe-19-26-B862

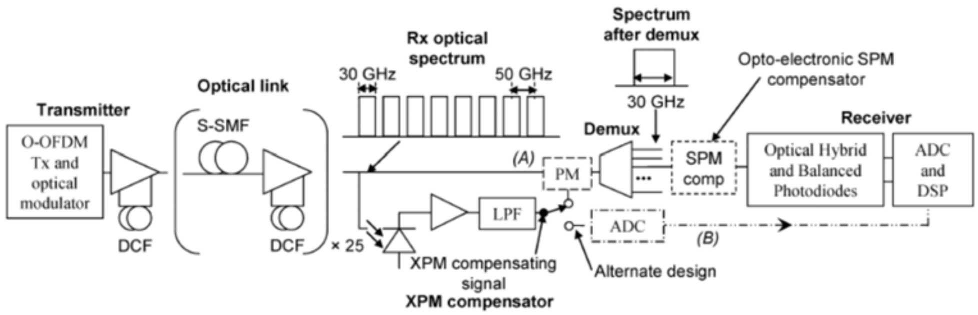


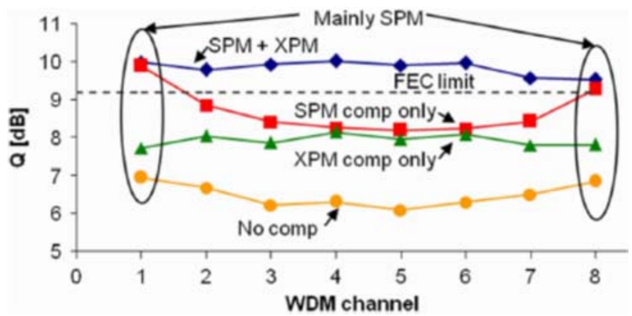
Compensating XPM by detecting many WDM channels simultaneously

(Accepted as a US Patent in Nov. 2016)

This neat way of compensating XPM uses low-bandwidth components to compensate XPM across hundreds of GHz of optical bandwidth. It is one of the examples of Electro-Photonics, where the THz bandwidth of optics works alongside the GHz bandwidth of electronics.

Liang B. Du and A. J. Lowery, "Practical XPM Compensation Method for Coherent Optical OFDM systems" Photonics Technology Letters, vol. 22(5), pp.320-322, (2009)





The following paper uses simulations to show that the XPM compensation method, above is best distributed along an optical system.

Benjamin Foo, Bill Corcoran, and Arthur Lowery, "Optoelectronic method for inline compensation of XPM in long-haul optical links," Opt. Express 23, 859-872 (2015) http://www.opticsinfobase.org/oe/abstract.cfm?URI=oe-23-2-859

The following paper examines the method for dual-polarization signals.

Ben Foo, Bill Corcoran, Chen Zhu, Arthur J Lowery "Distributed Nonlinearity Compensation of Dual-Polarization Signals Using Optoelectronics," IEEE Photonics Technology Letters 28 (20), 2141-2144

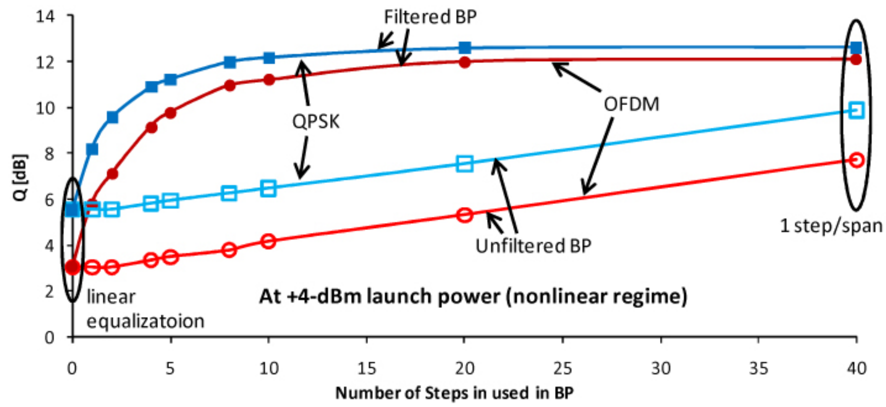
The following paper experimentally demonstrates the method using a low-bandwidth photodiode and a phase modulator.

Ben Foo *et al.*: "Compensating XPM using a Low-Bandwidth Phase Modulator" (Submitted to PTL 4th Nov 2016)

Improving Digital Backpropagation for SPM/XPM (Filtered BP) **(See US Patent: 9,002,210)**

The following paper demonstrated that it is very advantageous to filter the intensity signal in a Digital Backpropagation (DBP) system before using it to compensate Kerr phase rotation within a step of the DBP algorithm ("Filtered BP"). The advantage is that only a few steps are required over the whole length of the system, which is *far less than 1 step per span!* This is a remarkable result that could make BDP computationally practical.

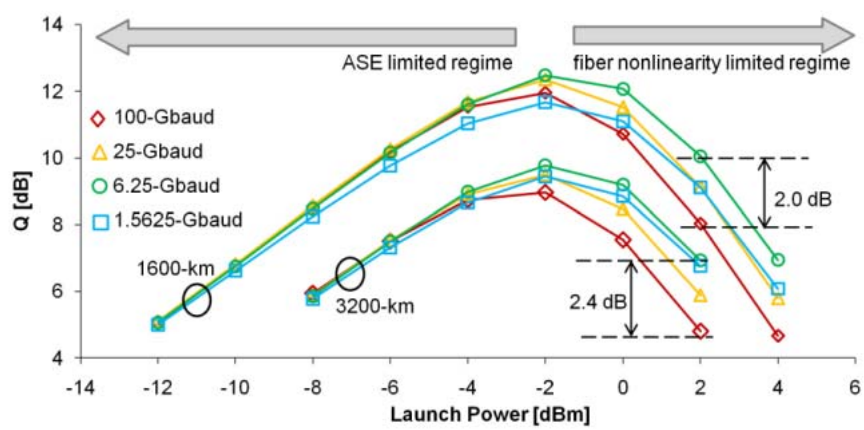
Liang B. Du and A. J. Lowery, "Improved single channel backpropagation for intra-channel fiber nonlinearity compensation in long-haul optical communication systems," Opt. Express 18, 17075-17088 (2010) http://www.opticsinfobase.org/oe/abstract.cfm?URI=oe-18-16-17075



Optimising the Baud Rate of Systems **(See US Patent: 9,294,216)**

Because of the FWM efficiency curve, only low-rate fluctuations matter. In this paper, we showed that high-baud rate systems tend to grow low-frequency intensity fluctuations along a link, faster than lower baud-rate systems, thus low-baud rate systems (paradoxically) are less sensitive to nonlinearity! This has seeded a large body of work, especially in Italy.

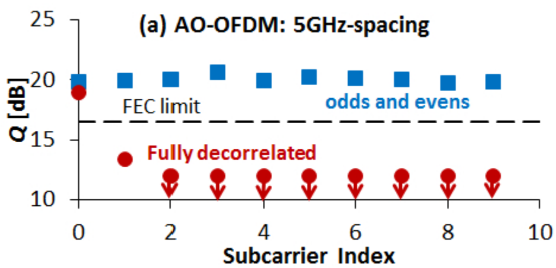
Liang B. Du and A. J. Lowery, "Optimizing the subcarrier granularity of coherent optical communications systems," Opt. Express 19, 8079-8084 (2011) http://www.opticsinfobase.org/oe/abstract.cfm?URI=oe-19-9-8079

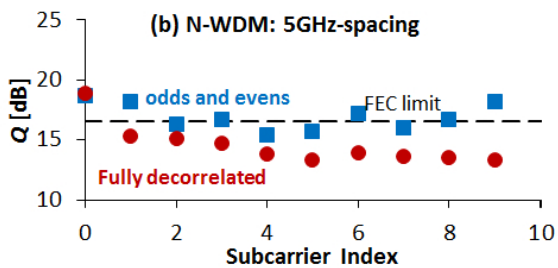


The validity of experiments using ‘odds’ and ‘evens’ wavelength channels

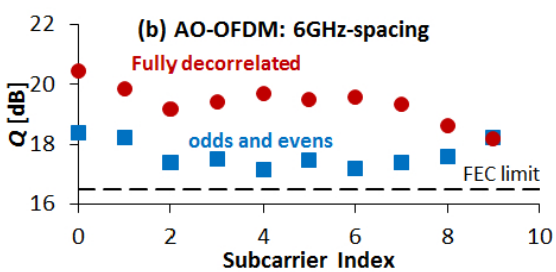
We investigate experimentally the validity of testing all-optical OFDM and Nyquist WDM systems using interleaved test channels derived from only two data sources. These “odd and even” channels are insufficiently decorrelated, so experiments underestimate the inter-carrier interference (ICI). Additionally, with a cyclic prefix, the OFDM simulations demonstrate that using odd and even channels generates stronger nonlinear distortions during transmission, causing an unrealistically large penalty in the nonlinearity-limited region. The performance of N-WDM without guard bands is overestimated using odds and evens (top left fig., below).

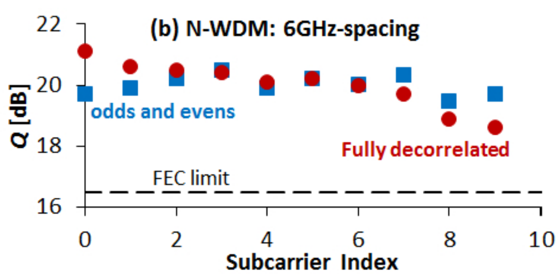
Liang Du and Arthur Lowery, “The validity of ‘Odd and Even’ channels for testing all-optical OFDM and Nyquist WDM long-haul fiber systems” Optics Express, Vol. 20 Issue 26, pp.B445-B451 (2012) http://dx.doi.org/10.1364/OE.20.00B445





The results with Cyclic Prefix (CP) or guard bands (N-WDM) are also interesting (bottom left), as this time the odds and evens have worse performance in OFDM.

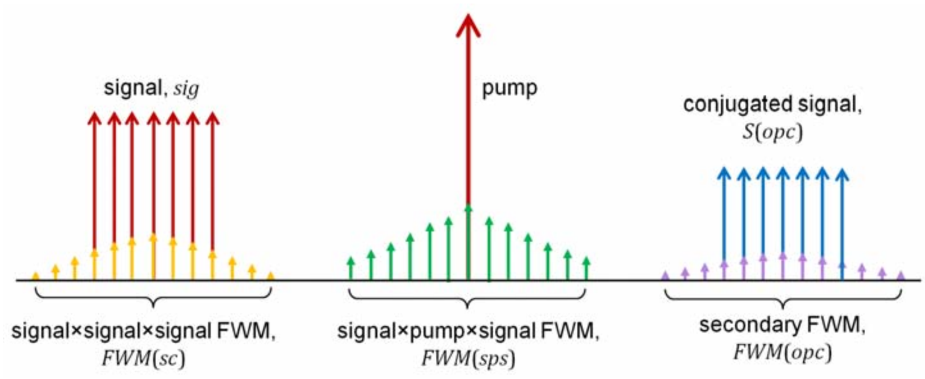




Mid-Span Spectral Inversion

MSSI uses phase conjugation half way along a link. The following experimental, analytical and numerical papers showed that mid-span spectral inversion is effective for optical OFDM.

Liang B. Du, Mohammad Monir Morshed, and Arthur J. Lowery, "Fiber nonlinearity compensation for OFDM super-channels using optical phase conjugation," Optics Express, Vol. 20, pp. 19921-19927 (2012) http://dx.doi.org/10.1364/OE.20.019921



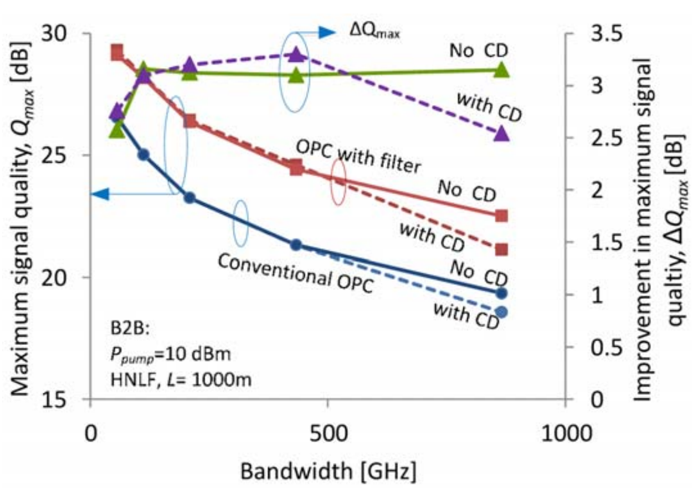
The following paper provides design rules for MSSI, based on identifying the different degradation mechanisms in the spectral domain.

Monir Morshed, Liang Du, and Arthur Lowery, "Mid-span spectral inversion for coherent optical OFDM systems: fundamental limits to performance" J. Lightwave Technol. vol. 31(1), 58-66 (2013)

This paper shows that if some of the intermediate FWM products can be removed along the nonlinear element, the performance of MSSI can be improved.

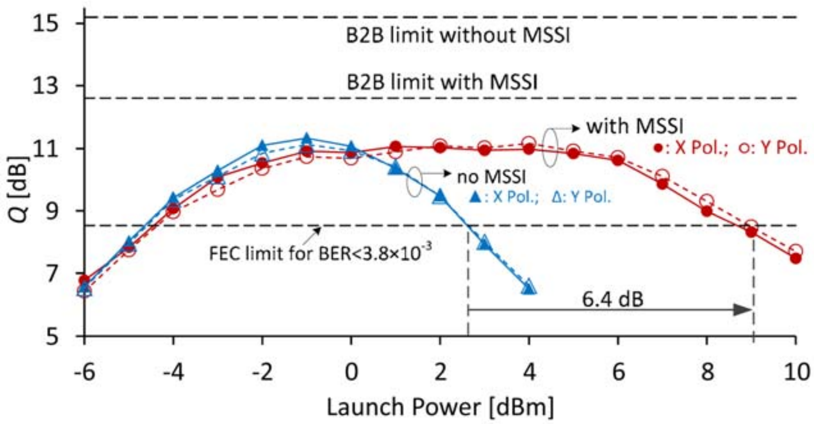
Monir Morshed, Arthur J. Lowery, and Liang B. Du, "Improving performance of optical phase conjugation by splitting the nonlinear element," Opt. Express 21, 4567-4577 (2013)

http://www.opticsinfobase.org/oe/abstract.cfm?URI=oe-21-4-4567



The following paper demonstrates that the span length in a pol-mux CO-OFDM system can be increased with MSSI. The system is more tolerant to variations in launch power.

Monir Morshed, Liang B. Du, Benjamin Foo, Mark D. Pelusi, and Arthur J. Lowery, "Experimental demonstrations of polarization multiplexed CO-OFDM systems using mid-span spectral inversion for nonlinearity compensation" Opt. Express, 22(9), 10455-10466 (2014) https://www.osapublishing.org/oe/abstract.cfm?uri=oe-22-9-10455



Review Papers

This paper was written for a special edition of the IEEE Signal Processing Magazine on Digital Signal Processing. The whole issue is worth reading.

L. Du, D. Rafique, A. Napoli, B. Spinnler, A. Ellis, M. Kuschnerov, et al., "Digital fiber nonlinearity compensation. Towards 1-Tb/s transport," IEEE Signal Proc. Mag., vol. 31, pp. 46-56, 2014.

Some other conference papers (not all, please see my web-page and Google Scholar)

L. Du and A. Lowery, "Compensating XPM for 100 Gbit/s coherent channels with 10 Gbit/s direct-detection NRZ neighbors," presented at the Proceedings of OFC/NFOEC 2010 - Optical Fiber Communication Conf. and Exposition/National Fiber Optic Engineers Conf., 2010.

L. B. Du and A. Lowery, "Improving nonlinear precompensation in direct-detection optical OFDM communications systems," in 34th European Conference on Optical Communication (ECOC 2008). , 2008, p. P4.08.

L. Du and A. Lowery, "Fiber Nonlinearity Compensation for CO-OFDM Systems with Periodic Dispersion Maps," presented at the OFC/NFOEC 2009, 2009.

Please refer to the original papers for much more detail and proper figure captions.

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