NOVEL DIGITAL NONLINEAR PHASE COMPENSATOR FOR LEGACY SUBMARINE LINKS

Pierre Mertz, Lei Zong, Mohsen Tehrani, Abdullah Karar, Atul Mathur, Scott Jackson (Infinera)

Email: pmertz@infinera.com
Infinera Corp.

Abstract: Legacy submarine links can contain dispersion management resulting in a zero-dispersion window (ZDW), or flat near-zero dispersion across the repeater bandwidth when using D+ / D- fiber. Coherent optical carriers will experience high nonlinearities in these submarine links, limiting their capacity.
To extend the life of legacy submarine links, a simple digital phase nonlinear compensator, targeted for zero dispersion, is shown to improve performance by up to 0.6 dB in a WDM environment. The circuit occurs just after the ADCs, improving the performance of the following DSP processing. The demonstrations were performed using offline processing on dispersion-managed transatlantic and transpacific length links.

1. INTRODUCTION

The dispersion compensating fiber (DCF) in legacy submarine cables is spliced as part of the cable, unlike legacy terrestrial cables where the DCF is installed as spools in the mid-state of the optical amplifiers inside accessible repeater huts. Whereas the DCF can be easily removed on terrestrial links, the fixed DCF in subsea links means the dispersion map of legacy cables designed for direct detection 10G line cards remains in place even when using modern coherent line cards that can compensate trans-pacific lengths of fiber dispersion inside the DSP. The near-zero dispersions of the legacy cables result in higher nonlinearities than in newer dispersion unmanaged cables due to neighboring channels repeatedly interacting with each other throughout the length of the cable rather than walking off from each other.

In this paper we propose a novel digital nonlinear compensator targeted for legacy low dispersion cables and evaluate its performance on two field trials. The cable on the first trans-Atlantic trial has a dispersion map that has a zero-dispersion window (ZDW) in the middle of the repeater gain bandwidth, while the cable on the second trans-Pacific trial was composed of slope matched D+/D- fiber whose net dispersion is close to zero across the entire bandwidth.

2. NONLINEARITIES IN DISPERSION MANAGED FIBERS

The Kerr nonlinearity in fibers

$$\Delta n(t) = n_2 I(t)$$

has the index of refraction proportional to the intensity pattern of the optical field. In dispersion managed links depicted in Figure 1, near the ZDW the intensity pattern can be repeated multiple times down the link as the accumulated dispersion goes back and forth between positive and negative values. Although this phase shift caused by the Kerr effect does not have much affect on legacy amplitude modulated signals, the repeated delta phase pattern creates a significant nonlinear penalty for modern coherent optical signals which include both phase and amplitude components in their constellations. The penalty can reach up to 3 dB Q between the center of the repeater gain bandwidth and the better performing red and blue edges, where the walk-off between the carriers randomizes the nonlinear phase change.

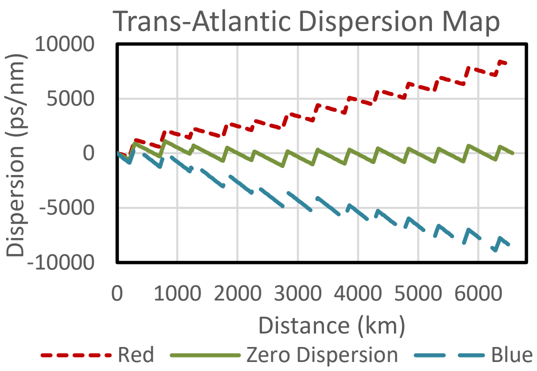

Figure 1: Dispersioned management for OOK designed trans-Atlantic cable. The center of the repeater bandwidth is designed to have zero dispersion, which induces high nonlinearities for coherent carriers.

An interesting aspect of the ZDW is that at the end of the link, the intensity pattern that caused the severe nonlinearity penalty can be measured and applied to the signal to reverse the Kerr phase shift.

3. PHOTODIODE BASED POST NONLINEAR COMPENSATORS

A simple way to measure the intensity pattern is to use a photodetector at the receiver. This technique has first been experimentally verified by using a phase modulator to apply the reverse Kerr nonlinearity[1]. There were up to 2 dB Q gains observed on single carrier, single polarization DPSK signals. The phase modulator was polarization diverse to avoid any polarization alignment requirements at the receiver. An optical filter of 10GHz was placed in front of the photodetector to reject out of band ASE.

Another experiment used a photodetector to measure the low bandwidth incoming intensity fluctuations, and then applied the reverse Kerr effect in the digital domain inside an offline implementation of the coherent DSP[2]. In this case, the optical filter allowed a band of up to 6 wavelengths into the photodetector and the RF response of the detector filtered to between 100 MHz and 600 MHz. 0.5 dB Q and 1.0 dB Q gains were observed on single polarization signals for one and six carrier passbands respectively.

However, the disadvantages of adding bandpass filters and photodiodes to a line card, along with the timing calibrations required, make this technique difficult to commercialize.

4. DSP-ONLY BASED POST NONLINEAR COMPENSATOR

Alternatively, the intensity fluctuations of the carrier can be measured using the existing photodiodes in the coherent receiver. The DSP processing can occur just after the high-speed ADC's. First the optical power is measured, aggregating the 4 lanes:

$$P(t) = XI_t^2 + XQ_t^2 + YI_t^2 + YQ_t^2$$

Where *XI*, *XQ*, *YI* and *YQ* denote real and imaginary components of the X and Y polarizations of the optical field. An adjustable low pass filter is applied

$$\bar{P}(t) = \sum_{i=-n}^{n} w_i P(t-i)$$

where the weights w_i can be adjusted to maximize the performance. A phase rotation proportional to this power is then calculated with an adjustable gain g to maximize the performance: $\varphi_P(t) = g\bar{P}(t)$. This phase rotation is then applied to the four data streams:

$$\begin{pmatrix} XI_{tc} \\ XQ_{tc} \end{pmatrix} = \begin{pmatrix} \cos(\varphi_P) & \sin(\varphi_P) \\ \sin(\varphi_P) & \cos(\varphi_P) \end{pmatrix} \cdot \begin{pmatrix} XI_t \\ XQ_t \end{pmatrix}$$

$$\begin{pmatrix} YI_{tc} \\ YQ_{tc} \end{pmatrix} = \begin{pmatrix} \cos(\varphi_P) & \sin(\varphi_P) \\ \sin(\varphi_P) & \cos(\varphi_P) \end{pmatrix} \cdot \begin{pmatrix} YI_t \\ YQ_t \end{pmatrix}$$

These nonlinear compensated data streams then go through standard coherent DSP processing.

The incoming photodiodes have a bandwidth wider than the carrier and can detect some of the neighboring ASE and carriers to compensate some cross-phase modulation. In addition, the bandwidths of the coherent photodiodes increase as baud rates go from 32 to 66 Gbaud and beyond, acting as the wider bandpass filters of the prior experiments. If the carrier is composed of lower baud rate subcarriers, the technique effectively passes through the multiple wavelengths described in Du's experiments[2].

Placing the compensator at the receiver also helps compensate for the Gordon-Mollenauer nonlinear ASE to signal interactions[3], as well as cross-subcarrier phase modulations.

5. EXPERIMENTAL VERIFICATION

The performance of this DSP based phase nonlinear compensator (PNC) is evaluated on two submarine field trials. The first is from a dispersion managed trans-atlantic cable with a dispersion map like in figure 1, containing a ZDW:

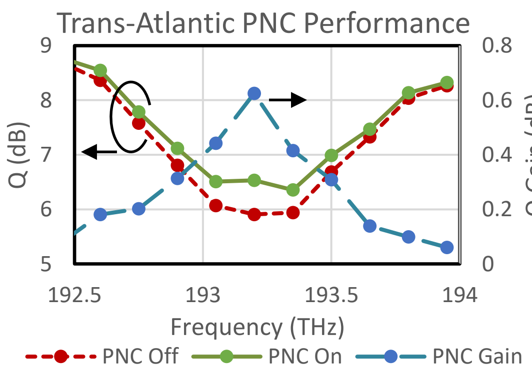

Figure 2: Phase Nonlinear Compensator performance on a dispersion managed trans-atlantic cable with a ZDW. The DWDM spectrum is fully loaded with 37.5 GHz spaced carriers.

The repeater bandwidth is fully loaded with 37.5 GHz spaced 33Gbaud carriers having an eight-dimensional (8D) modulation format with three bits per polarization multiplexed symbol (BPS) for a data rate of 75 G per carrier.

The transmitted carriers come from two modulators, each modulating a bank of tunable lasers. The carriers are further temporally decorrelated using a twin WSS whose system ports are connected together with varying length patch cables. The receiver measures a channel under test every 9 carriers by tuning its local oscillator. There is no adjustment of carrier powers while changing the channel under test during these final measurements.

Although the 8D modulation format is designed to mitigate nonlinearities[4] there is still a 2.5 dB penalty from the edge of the repeater bandwidth to the middle ZDW.

The DSP processing is performed offline on captured data from a real time oscilloscope, so the two curves come from the same waveforms with PNC turned on and off. Both the PNC filter bandwidth and the PNC gain were optimized at each frequency to maximize the Q gain.

In the ZDW, the PNC gain is up to 0.6 dB, enabling this 3 BPS to work with deployable margins across then entire ZDW. Without the PNC circuit, only 2 BPS could be used. Outside the ZDW where the dispersion is higher, the gain from the PNC circuit diminishes, but the nonlinearities also diminish netting in higher Q values, enabling higher BPS modulation formats at the edge.

The second field trial was on a trans-pacific cable dispersion managed with slope-matched D+ / D- fiber as shown in figure 3. The slope matching makes the entire spectral bandwidth end up with zero net dispersion. The dispersion map was designed to minimize nonlinearities of direct detect 10G carriers using an overall zig-zag shape to walk off neighboring carriers throughout the length of the cable. This dispersion map also helps coherent signals so that the nonlinear Q penalty is less than the ZDW of the cable in Figure 1, but still fairly high.

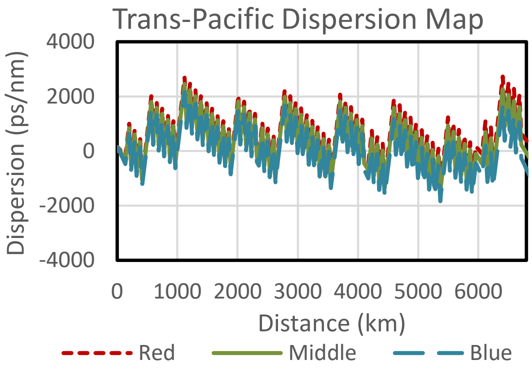

Figure 3: Dispersioned management for a slope matched D+ / D- trans-Pacific cable. The entire spectrum ends with net zero dispersion, however there is some dispersion walkoff in the middle.

The same 37.5 GHz carrier loading is used as during the transatlantic trial, as well as the same modulation format and process for determining PNC Q gain.

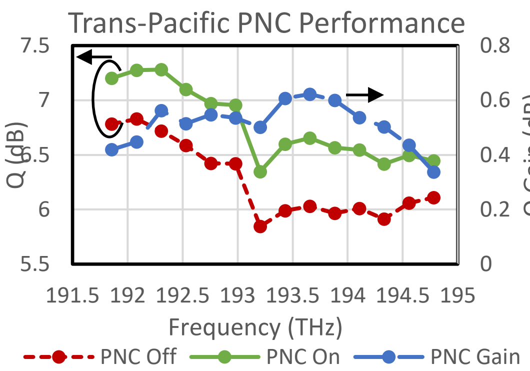

Figure 4: Phase Nonlinear Compensator performance on a slope matched D+ / D- dispersion managed trans-pacific cable. The DWDM spectrum is fully loaded with 37.5 GHz spaced carriers.

The max PNC gain is also 0.6 dB in the central region of the spectrum. However, the gain only rolls off to 0.4 dB all the way out to the very edges of this wide repeater bandwidth cable which encompasses almost the entire C band.

6. COMPLEMENTARY NONLINEAR CIRCUIT

The gain in the PNC circuit is complementary to the gain in another nonlinear circuit (NLC) that can be turned on during offline processing. The NLC is a low power circuit that correlates across polarization, frequency, and time to remove fast varying correlations caused by nonlinearities. NLC performs well for compensating the fluctuations caused by high power legacy 10G single polarization carriers.

During the trans-pacific trial, there were a number of legacy carriers with live traffic that cause higher Q fluctuations than on coherent only cables where all the carriers are polarization multiplexed.

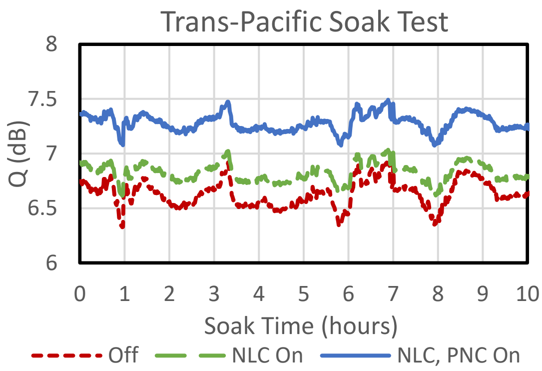

Figure 5: Soak test with live high power single pol 10G carriers creating high fluctuations on coherent carriers. The NLC circuit reduces the fluctuations and improves Q. The PNC circuit further improves Q.

The correlating nonlinear circuit (NLC) reduces the fluctuations from a 5σ of 0.6 dB down to 0.4 dB while improving the minimum Q by 0.3 dB.

The PNC circuit is complementary to this circuit by operating on the phase of the receive signal, further improving the minimum Q by 0.5 dB for a total gain of 0.8 dB.

7. CONCLUSION

This paper introduces a novel phase nonlinear compensator targeted at legacy dispersion managed cables and implemented as a low power circuit on a DSP. Maximum Q gains of 0.6 dB were observed on both a transatlantic trial with a ZDW dispersion map and a transpacific trial with a slope matched D+ / D- dispersion map, with the latter having >0.4 dB of gain across the entire repeater spectral bandwidth.

Briefly introduced were 8D modulation formats to mitigate nonlinearities, and a correlating PNC nonlinear compensator circuit. Together these low power DSP technologies can extend the lifetime of legacy submarine cables by enabling upgrades with higher capacities. Future improvements in DSP processing power will enable even more complex nonlinear algorithms such as digital back propagation and machine learning nonlinear compensation to further improve performance.

8. REFERENCES

[1] G. Zhu, L.F. Mollenauer, C. Xu, “Experimental Demonstration of Postnonlinearity Compensation in a Multi-Span DPSK Transmission,” *IEEE Photonics Technology Letters,* 18(9): 1007-1009, 2006.
[2] L. Du, A. Lowery, “Experimental Demonstration of XPM Compensation for CO-OFDM Systems with Periodic Dispersion Maps,” *Optical Fiber Communication Conference*, pp. 1-3, 2011.
[3] J. P. Gordon, L. F. Mollenauer, "Phase noise in photonic communications systems using linear amplifiers", *Opt. Lett.*, vol. 15, no. 23, pp. 1351-1353, 1990.
[4] D.S. Millar, T. Koike-Akino, “High dimensional Modulation for Optical Fiber Communications,” *Asia Communications and Photonics Conference (ACP),*

