On the Impact of Frequency Variation on Nonlinearity Mitigation using Frequency Combs

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Abstract: We investigated the impact of linewidth and dithering-induced frequency variation on the performance of nonlinearity mitigation using frequency combs. Compared to independent laser arrays, >2dB SNR gain can be achieved using comb sources.

1. Introduction

Optical frequency combs (OFCs) have been increasingly investigated in recent years as multi-wavelength sources for wavelength-division multiplexed (WDM) coherent communications systems [1]. While the original motivation was to reduce the cost and power consumption of conventional laser arrays [2], OFCs' features of equal tone spacing and coherent optical tones have opened new opportunities to enhance spectral efficiency [3] and reduce the complexity and power consumption of coherent DSP [4]. An application of particular interest is nonlinearity mitigation, where the OFC's precisely-spaced optical tones show potential to improve the performance of transmitter-side digital backpropagation (Tx-DBP) via their broadband frequency coherence [5]. Previous studies have investigated the performance of comb-based Tx-DBP schemes with static displacements between individual WDM carriers and the spectral grid, showing how the fixed frequency spacing of OFC sources can mitigate SNR penalties associated with the mismatch between the transmitter-side DBP and the signal propagation [6]. However, an aspect that has not yet been investigated is the impact of dynamic frequency variation, i.e. frequency variation that changes with time. While static frequency displacements can be corrected at the transmitter, dynamic frequency variation (such as linewidth) is intrinsic to all laser sources, and cannot be easily corrected. In addition, external frequency variation is necessary to prevent long-term center frequency drift (known as dither locking). Both of these effects dynamically modify the inter-channel spacing (and thus the inter-channel nonlinearity) and cause Tx-DBP performance degradation, but may be compensated using frequency-correlated sources, i.e. OFCs.

In this work, we numerically study and quantify the impact of both frequency dither and laser linewidth on the performance of Tx-DBP for OFCs and independent laser arrays. The dither frequency and amplitude of a commercial external cavity laser source was measured experimentally and used to inform the coherent transmission simulations. Our results show that the phase and frequency-locked carriers in an OFC can greatly mitigate the performance penalties associated with dynamic frequency variation of WDM carriers in the Tx-DBP scheme.

2. Dither Measurement

We first measured the frequency dither of a typical WDM laser array to evaluate its impact. The measurement setup is shown in Fig. 1(a). A Keysight N7714A laser source with a nominal linewidth of 100 kHz was used as the laser under test (LUT) with its frequency dither mode enabled. This was coupled together with a stable reference laser, the OEwaves OE4023 with a nominal linewidth of 20 Hz, using a polarization-maintaining 3-dB coupler. The two laser wavelengths were aligned to within a few GHz separation and detected by a 6-GHz photodiode connected to a real-time oscilloscope with 23 GHz bandwidth and 6.5-bit effective number of bits (ENOB). The spectrogram of the 1.31 GHz beat signal is shown in Fig. 1(b). An 887 Hz sinusoidal frequency modulation with a peak-to-peak amplitude of 85.5 MHz is observed on the beat note, which corresponds to the dither locking of the LUT. Any dithering of the reference laser can be neglected due to its 5000 times smaller linewidth.

3. Coherent System Simulation

We then conducted numerical simulations to investigate the performance of Tx-DBP with dynamic frequency variation, shown in Fig. 1(b). The input signal consists of four independently modulated 49.5 GBd dual-polarization (DP) 64QAM channels, each shaped by a 1% root-raised-cosine (RRC) filter and placed on an evenly-spaced 50 GHz grid. The channels were multiplexed into a 200 GHz superchannel and back-propagated through 100 km

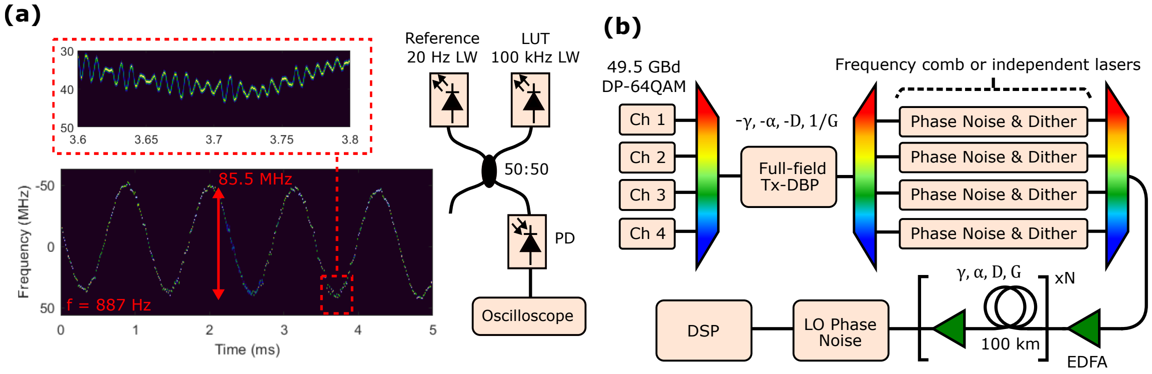

Fig. 1. (a) Laser dither measurement setup and spectrogram. (b) Simulated DWDM coherent transmission scheme. A 4x49.5 GBd 50-GHz-spaced DP-64QAM superchannel is back-propagated and launched into N spans of 100km SSMF for both correlated (OFC) and uncorrelated (independent laser) frequency variation.

spans of SSMF with nonlinearity parameter $\gamma = 1.2\,\mathrm{W}^{-1}\,\mathrm{km}^{-1}$, dispersion $D = 17\,\mathrm{ps}\,\mathrm{nm}^{-1}\,\mathrm{km}^{-1}$ and loss $\alpha = 0.2\,\mathrm{dB}\,\mathrm{km}^{-1}$ using the symmetric split-step method with 100 m steps. After full-field transmitter-side back-propagation, each channel is demultiplexed and dynamic frequency variation (linewidth and dither) is introduced. Laser phase noise is modelled as a Weiner process, while dither is modelled as a frequency drift based on a sinusoidal fit to the beat note in Fig. 1(a). For a simulated data frame of length $\sim 1\,\mu\mathrm{s}$, an equal-duration segment of the sinusoidal dither is used from the region of greatest frequency variation of the sinusoid, i.e. at its center line.

For an OFC the WDM carrier frequency variations are strongly correlated, therefore the same phase noise and dither is applied to all four channels. In the case of the independent laser array, the frequency variations are assumed uncorrelated, and thus independently-generated phase noise is applied to each channel. Uncorrelated dither is added by applying alternating rising and falling frequency dither to neighbouring channels to model the worst-case dither decorrelation. The signals are then re-multiplexed and launched into spans of 100 km SSMF (same as previously mentioned) with 5 dB noise figure erbium-doped fibre amplifiers (EDFAs). Additional local oscillator (LO) phase noise is added at the receiver (with the same linewidth as the TX source) before receiver digital signal processing (DSP). The third WDM channel is filtered out and processed using pilot-symbol-based equalisation and residual carrier phase recovery with a pilot rate of $1/2^5$ and a pilot sequence length of 2^{10} [7].

4. Results

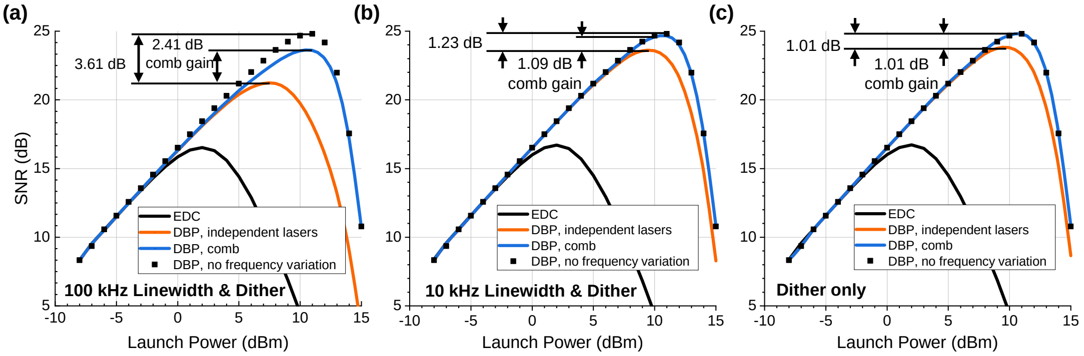

Fig. 2. SNR versus launch power per channel for 1000 km transmission distance for a carrier with (a) 100 kHz linewidth and 887 Hz dither, (b) 10 kHz linewidth and 887 Hz dither and (c) 887 Hz dither only. Four cases are simulated: electronic dispersion compensation (black), Tx-DBP using independent lasers (orange), Tx-DBP using a comb source (blue), and Tx-DBP without frequency variation (black squares).

The change in received SNR versus launch power per channel for 1000 km transmission distance is shown in Fig. 2(a) for 100 kHz linewidth and 887 Hz dither. When using an independent laser array, the Tx-DBP scheme provides approximately 4.7 dB greater maximum SNR as compared to electronic dispersion compensation at the receiver, however suffers a 3.6 dB SNR penalty compared to Tx-DBP without frequency noise due to the dynamic frequency variation modifying the signal's nonlinear interactions during propagation. Using an OFC, the correlated phase and frequency noise is able to maintain a fixed relative channel spacing, resulting in a nonlinear interaction that better matches the DBP and provides an SNR gain of 2.4 dB. It should be noted that OFCs cannot completely mitigate the frequency-variation-induced nonlinear penalty. Though the relative channel spacing is fixed, the inclusion of linewidth leads to phase-to-amplitude noise conversion induced by chromatic dispersion [8]. The additional amplitude noise modifies the nonlinear interaction in the fiber and reduces Tx-DBP performance irrespective of the frequency coherence of the WDM carriers.

Fig. 2(b) shows the change in received SNR vs launch power per channel for 10 kHz linewidth and 887 kHz dither. Comparing this to Fig. 2(a), the SNR penalty from frequency variation and comb DBP gain both decrease in magnitude as the linewidth decreases. When frequency dither is the dominant source of frequency variation (Fig. 2(c)), the comb DBP gain is only 1 dB, and any impairment due to dither is fully compensated by the use of a comb. This can be attributed to the slow 887 Hz modulation speed of the dither causing only negligible phase-to-amplitude noise conversion.

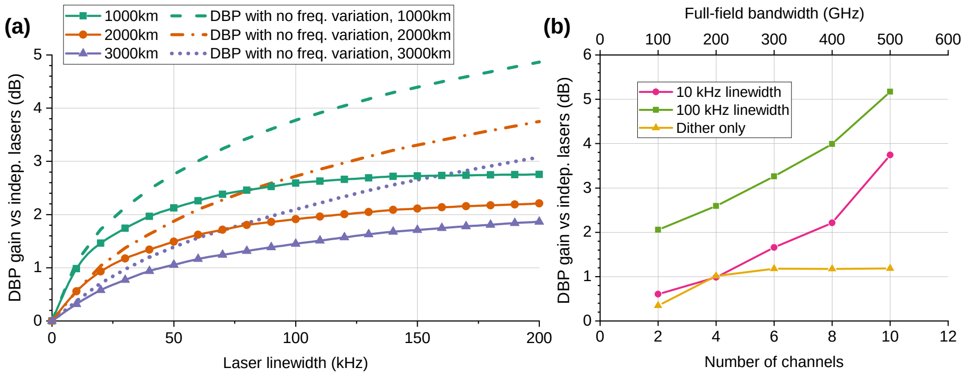

Fig. 3. (a) Comb DBP SNR gain versus linewidth at 1000 km (green), 2000 km (orange) and 3000 km (purple) for optimum launch power. The DBP gain with no frequency variation is shown as the dashed, dash-dot and dotted lines for the aforementioned distances respectively. (b) Comb DBP gain versus channel number for 10 kHz linewidth (pink), 100 kHz linewidth (light green) and dither only (yellow) for 1000km transmission and optimum launch power.

The comb DBP gain versus laser linewidth is shown in Fig. 3(a) for 1000 km, 2000 km and 3000 km transmission distances. The comb DBP gain increases with linewidth, however the phase-to-amplitude noise conversion also increases proportionally to linewidth, flattening the comb DBP gain above ∼150 kHz. Comb DBP gains are also largest at shorter distances where there is less ASE noise buildup to degrade Tx-DBP performance. Fig. 3(b) shows the comb DBP gain versus the number of channels for full-field Tx-DBP. For the laser-linewidth-only case, transmission of more channels leads to greater comb DBP gain as more frequency-variation-induced nonlinearity is compensated. In the dither-only case, the worst-case decorrelation occurs with alternating dither affecting every other channel, therefore half of all transmitted channels are always frequency correlated. Most of the nonlinear penalty therefore occurs from neighbouring channels, causing comb DBP gain to plateau with channel number.

5. Conclusion

We systematically evaluate the performance limits of comb-based transmitter-side DBP for varying laser linewidth and dither, showing that frequency combs maximise the performance of nonlinearity mitigation when $>$ 100 kHz linewidth lasers are used, gaining over 2.5 dB SNR for 4-channel 49.5 GBd 1000 km transmission. When using narrow-linewidth lasers, OFCs only provide small (about 1 dB) DBP gain compared to independent laser arrays.

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