Experimental Study of Bandwidth Loading with Modulated Signals vs. ASE Noise in 400ZR Single-Span Transmission

Steven Searcy, Thomas Richter, and Sorin Tibuleac
ADVA Optical Networking, 5755 Peachtree Industrial Blvd, Norcross, GA 30092, USA
ssearcy@adva.com

Abstract: We compare performance of a single-span 400ZR system with bandwidth loading over 2.4 THz from independent modulated signals, channelized ASE noise, or flat ASE noise bands, and quantify the impact on optimum launch power. © 2022 The Author(s)

1. Introduction

As bandwidth demands continue to grow, network and data center operators are seeking coherent optical transceivers which can achieve higher data rates at lower cost per bit. Of particular interest across the industry have been 400ZR modules, as specified by the OIF [1], using polarization-division multiplexed (PDM) 16QAM modulation at ~60 GBd, with a primary target application for amplified data center interconnect (DCI) point-to-point links ≤120 km.

When assessing performance of a system it is important to take into account all realistic transmission impairments, including fiber nonlinearity. Since the advent of digital coherent reception in dispersion-uncompensated fiber optic systems, it has become increasingly common to utilize amplified spontaneous emission (ASE) noise loading to fill the available optical spectrum in order to emulate the performance of a fully loaded system. This methodology is enabled by the basic principle that dispersed signals quickly come to resemble Gaussian noise [2], a concept that has led to significant advances in modeling fiber nonlinear effects, including the aptly-named and widely-used Gaussian Noise (GN) model [3]. For multi-span transmission systems, numerous studies have shown that the GN model assumptions are sufficiently applicable to make a good approximation of nonlinear interference and predict performance [4]. However, the underlying assumption of the signal's Gaussian characteristics may not hold for short single-span links, particularly with low-dispersion fiber types [5]. Given that 400ZR pluggable modules are primarily intended for ≤120-km links with a single amplified span, this raises the question of whether bandwidth loading using ASE noise provides a realistic emulation of fiber nonlinear effects in this scenario.

Previous studies have shown that ASE noise loading can be used as an effective method for bandwidth loading in dense wavelength-division multiplexing (WDM) transmission systems, providing an acceptable emulation of the nonlinear effects due to real modulated signals [6-8]. However, these earlier studies used relatively small WDM bandwidths (well below 1 THz) and focused primarily on longer multi-span links in contrast to the short-reach DCI applications of interest, including 400ZR. In contrast, recent demonstrations of 400ZR transmission used bandwidth loading with PDM-QPSK neighbors [9] or channelized ASE loading [10] but no previous studies have compared alternative bandwidth loading techniques with the realistic use case of ~60-GBd 16QAM channels filling the spectrum.

In this study, we examine the applicability of different bandwidth loading methods in the context of 400ZR single-span transmission. We use a commercial line system with 400ZR QSFP-DD modules as test signals and vary the bandwidth loading over 2.4 THz WDM bandwidth using ~60 GBd independently-modulated signals from commercial transponders or ASE noise loading with different types of spectral shaping. We show that ASE noise loading represents a conservative approach to assessing the system performance, with the magnitude of the difference depending on the spectral shaping of the ASE noise and the modulation order of the real transceivers.

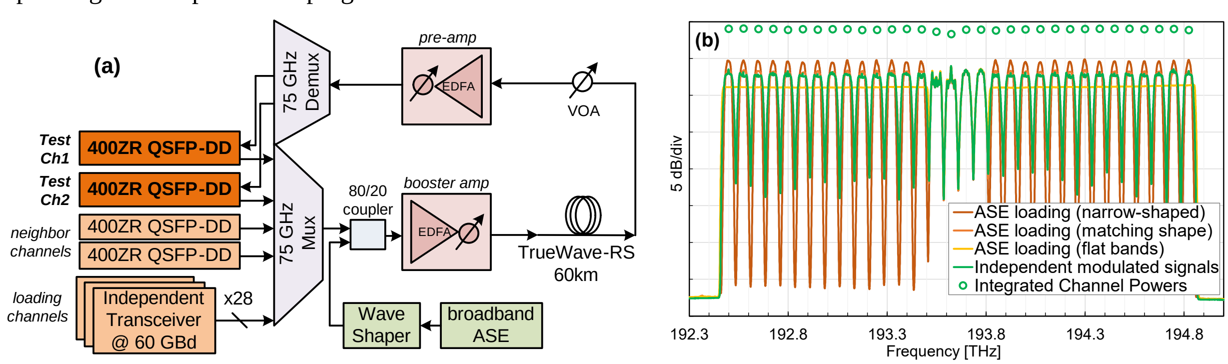

Fig. 1. (a) Experimental configuration and (b) measured optical spectrum at booster amplifier output with a resolution bandwidth of 0.02 nm.

2. Experimental Setup

Our experimental investigation used a complete commercial line system designed for 400ZR applications, including dual-EDFA booster and pre-amplifier with variable gain and output power as well as passive arrayed-waveguide grating multiplexer/demultiplexer aligned with OIF-specified 75-GHz grid (supporting 65 WDM channels) [1]. The experimental setup is depicted in Fig. 1(a). The fiber link consisted of 60-km TrueWave-RS (TW-RS), a commonly-deployed low-dispersion fiber type. The TW-RS span had α = 0.20 dB/km, D = 4.5 ps/nm/km, and A_{eff} = ~52 μm^2, with the fiber followed by a variable optical attenuator (VOA) to adjust the total span loss to 24 dB, representing the approximate maximum reach for 400ZR links. Between the mux filter and the booster amplifier we placed an 80/20-coupler to optionally insert external ASE noise bandwidth loading which was prepared using a broadband noise source and a programmable flex-grid wavelength-selective switch (Finisar WaveShaper).

As two test signals and direct adjacent neighbors we used four 400ZR-compliant QSFP-DD modules from two vendors, with different DSP chips. We placed the two test signals at the center of the spectrum at 193.625 and 193.700 THz. The surrounding spectrum was filled with 28 independent commercial transceivers, for a total WDM bandwidth of 2.4 THz (32 x 75-GHz channels). Closest to the 400ZR channels were two ZR(+) type CFP2-DCO modules. The remaining 26 loading signals came from independent transceivers supporting variable symbol rate up to 72 GBd and modulation up to 64QAM, configured with ~60 GBd and raised-cosine pulse shaping with roll-off 0.5 to closely match the optical spectrum of the 400ZR signals. The modulation of the independent loading channels was initially set to PDM-16QAM, matching the 400ZR signals, then tuned to lower or higher modulation order time-domain hybrid QAM (1.55 or 5.71 bits per symbol per polarization) at the same symbol rate.

In addition to testing with independent loading channels, the spectrum around the four central 400ZR signals was filled with ASE noise. Initially, the ASE noise loading channels were shaped to closely match the test signals. Tests were also performed with narrower-shaped ASE noise loading channels, as well as flat ASE noise bands. In all test cases, the power per 75-GHz channel slot was fixed. For each bandwidth loading condition, the launch power into the fiber span was varied using the booster amp output VOA. Measured optical spectra are shown in Fig. 1(b), for the case of +0.9-dBm launch power per channel, together with the individual integrated powers of the 32 channels for the case of independent modulated signals. The power ripple of the loading channels was +/-0.2 dB. The test channel at 193.625 THz was ~0.6-dB lower in power. For simplicity, the spectral tilt at the booster was kept at ~0 dB, i.e., no tilt optimization was applied as there was negligible performance dependence observed for the center channels. Measured receive OSNR for the test signals was ~29.5 dB at the +0.9-dBm launch condition. The pre-amp VOA was tuned to maintain receive power around -7 dBm. Pre-FEC BER of the test channels was measured and converted to Q^2 factor.

3. Results and Discussion

Measured Q values from the launch power scan are shown in Fig. 2 for each test channel. While the absolute Q levels differ for the two 400ZR modules (due to differences in transceiver performance), the optimum launch powers are similar for both, falling in the range of ~1-2 dBm, depending on the bandwidth loading condition. In the linear regime, we observe minimal variations with different bandwidth loading conditions, since the performance is dominated by linear noise with only a small component from nonlinear noise. On the other hand, in the nonlinear regime we clearly observe varying levels of nonlinear noise generated by different types of bandwidth loading – independent modulated signals with varying modulation order, or differently shaped ASE noise loading. At the highest launch power of

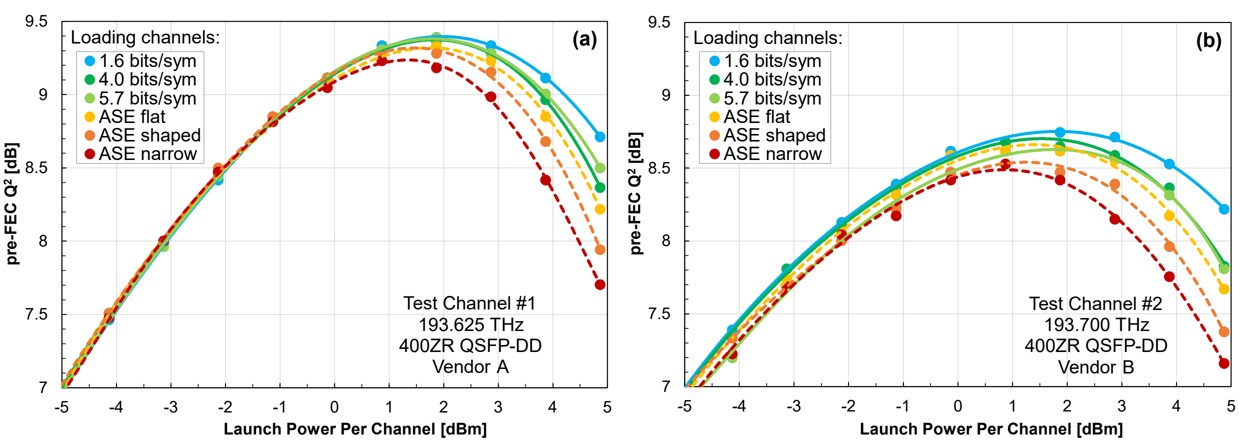

Fig. 2. Pre-FEC Q^2 for both test channels with different bandwidth loading of 2.4 THz WDM spectrum over 24 dB TW-RS fiber link.

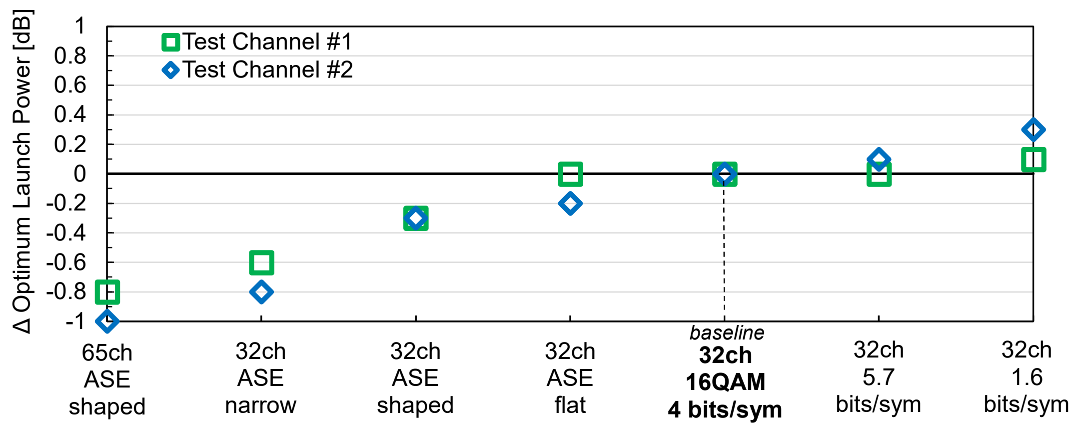

Fig. 3. Relative change in optimum launch power for different bandwidth loading conditions on 24 dB TW-RS link.

+4.9 dBm/channel, we observe a maximum difference of 1 dBQ between the best and worst case conditions (bandwidth loading with 1.6 bits/symbol/polarization modulated signals and narrow-shaped ASE noise, respectively).

In general, independent modulated loading channels produce best performance in the nonlinear regime, with weakest nonlinearity for lower-order modulated loaders (1.6 bits/symbol/polarization), but between higher-order modulated loaders (4.0 vs 5.7 bits/symbol/polarization) the difference is minimal. All tested types of ASE noise loading perform worse in the nonlinear regime compared to modulated channel loading, with flat ASE noise bands providing the closest match to modulated loaders, and narrow-shaped ASE noise loading channels producing the strongest nonlinear penalties. This highlights the importance of properly matching the spectral shape of ASE noise loading channels, if these are used to fill the spectrum in lieu of independently modulated signals, though the results indicate that flat ASE noise loading bands provide the closest match to a real system loaded with modulated signals.

The differences in optimum launch power for the various bandwidth loading scenarios are summarized in Fig. 3, showing deviations relative to the baseline case with all signals modulated with 16QAM, like the real intended system. Use of ASE noise loaders with spectrum matching the real signals' shape degrades the optimum launch power by 0.3 dB, whereas flat ASE noise loading bands match the realistic baseline case to within 0.2 dB (within the error margin for estimating the optimum power) and narrower-shaped ASE noise loaders degrade the optimum launch power up to 0.8 dB relative to 16QAM-modulated signals. It is expected that the magnitude of these differences would be smaller for standard single-mode fiber, given its higher dispersion and lower nonlinearity. As an additional point of reference, we also show the performance with fully-loaded spectrum (65 channels x 75 GHz = 4.875 THz) using ASE noise loaders matching the test signal shape. Comparing the shaped ASE noise case with 32 vs 65 channels, we see that approximately doubling the spectral occupancy from ~50% to 100% shifts the optimum launch power by an additional 0.5-0.7 dB, on a similar order to the differences between the investigated bandwidth loading conditions.

4. Conclusions

We have experimentally demonstrated the variations in optimum launch power for different bandwidth loading conditions in single-span 400ZR transmission. Bandwidth loading with ASE noise always provides conservative emulation of nonlinearity relative to modulated loaders, with strong dependence on the spectral shaping of ASE noise.

5. References

[1] OIF Implementation Agreement 400ZR, March 10, 2020. https://www.oiforum.com/wp-content/uploads/OIF-400ZR-01.0_reduced2.pdf.
[2] A. Carena, et al., "Statistical characterization of PM-QPSK signals after propagation in uncompensated fiber links," ECOC 2010, P4.07.
[3] P. Poggiolini, et al., "The GN-Model of fiber non-linear propagation and its applications," *J. Lightwave Technol.* 32(4), pp. 694-721, 2014.
[4] M. Filer, et al., "Multi-vendor experimental validation of an open source QoT estimator for optical networks," *J. Lightwave Technol.* 36(15), pp. 3073-3082, 2018.
[5] P. Poggiolini and Y. Jiang, "Recent advances in the modeling of the impact of nonlinear fiber propagation effects on uncompensated coherent transmission systems," *J. Lightwave Technol.* 35(3), pp. 458-480, 2017.
[6] D. Elson, et al, "High spectral density transmission emulation using amplified spontaneous emission noise," *Opt. Lett.*, 41(1), pp. 68-71, 2016.
[7] D. Elson, et al., "Investigation of bandwidth loading in optical fibre transmission using amplified spontaneous emission noise," *Opt. Express*, 25(16), pp. 19529-19537, 2017.
[8] T. Richter, et al., "Comparison of WDM bandwidth loading using individual transponders, shaped, and flat ASE noise," OFC 2018, W1B.2.
[9] E. Pincemin and Y. Loussouarn, "Silicon photonic ZR/ZR+ DCO-CFP2 interface for DCI and metro-regional 400G optical communications," OFC 2021, M3F.2.
[10] B. Zhu, et al., "High capacity 400Gb/s real-time transmissions over AllWave ULL fibres by 400ZR/ZR+ pluggable modules," ECOC 2021, Tu3C1.4.