Optical Noise-Loading Technique Comparison

Overview

The following report compares the performance results from an amplified optical network versus results from two laboratory noise-loading (NL) setups, given equal impairment conditions, namely chromatic dispersion. The practice of the NL techniques are validated based on the results.

Introduction

In optical fiber communications, the practice of adding broadband noise from an amplified spontaneous emission (ASE) source is often used to determine a system's tolerance, particularly the receiver, to optical signal-to-noise ratio (OSNR). This practice is referred to as NL within this context. It has been assumed that this practice is equivalent to the effect of noise build up in a real amplified transmission system making use of erbium doped fiber amplifiers (EDFA). The purpose of this experiment is to compare the results from a real network to those of two widely used NL techniques. The two techniques compared are: a) decreasing the signal-to-noise ratio (SNR) by decreasing the signal power into a single EDFA (NL-EDFA within this context), and b) coupling a broadband source (BBS) of noise to a signal (NL-BBS) in variable ratios.

Experiment

System under Evaluation

This experiment was performed at bit rates of approximately 10 Gb/s. Specifically, a synchronous optical network (SONET) OC-192 signal, encapsulated in an OTU-2 frame at a bit rate of 10.709 Gb/s, was generated by an ONT-506 10/10.7 G transport module, and transmitted to the client-side receiver (XFP) of a WaveReady™ WRT-840 transponder. A pseudorandom bit sequence (PRBS) of 2^{31}-1 bits was used in the payload to obtain the longest possible sequence of subsequent 0s or 1s. The WRT-840 transponder transparently regenerates this signal onto its line-side transmitter, a dense wavelength division multiplexer (DWDM) distributed feedback (DFB) laser at 1553.33 nm (193.0 THz) followed by a negative-chirp LiNbO3 modulator using a non-return-to-zero (NRZ) modulation format, with an average output power of +1.75 dBm. The receiver is an avalanche photodiode (APD) rated to a worst-case sensitivity level of –23 dBm for a bit error rate (BER) of 1e-12, in the absence of chromatic dispersion. Line-side received bits are transparently regenerated to the client-side transmitter, back to the ONT-506 network test set, operating as an error detector. The client-side transmission is error-free due to operation within high-margin conditions.

OTU-2 framing adds a forward error correction (FEC) code to the frame. The network test set reports how many corrected FEC errors are present, from which the BER is directly determined. As such, all BERs reported during this experiment are within the regime, where no uncorrected FEC errors occur.

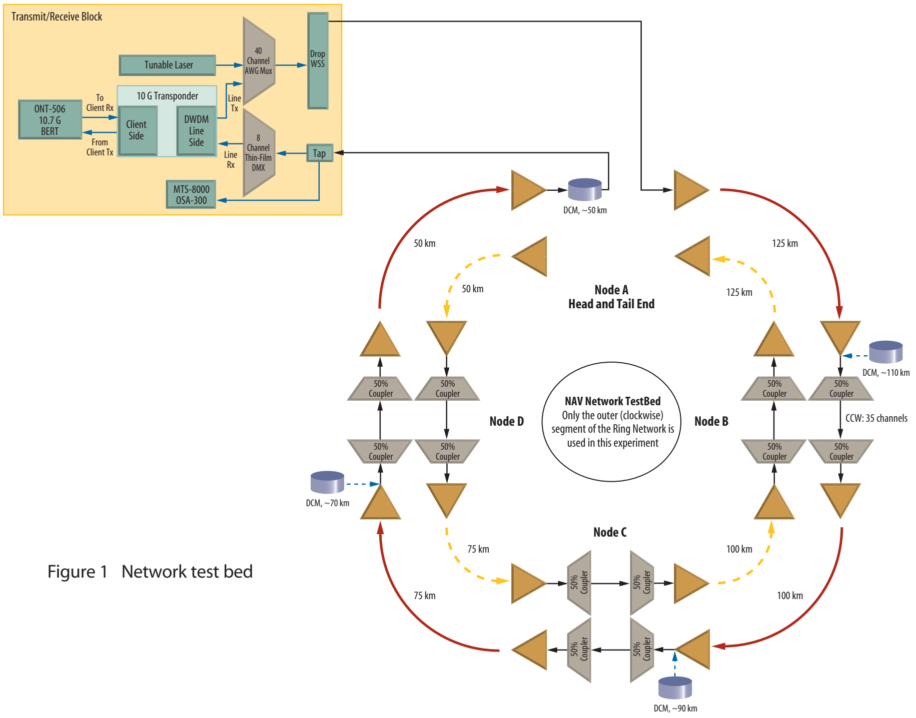

Figure 1 Network test bed

The network under test consists of four spans of ITU-T.G.652 single-mode fiber (SMF), and WaveReady network gear. The spans are 125, 100, 75, and 50 km in length in the downstream direction. A booster amplifier amplifies the signal prior to each span, operating in constant gain mode with a maximum per-channel launch power of ~0 dBm. At the tail end of each span, a pre-amplifier re-amplifies, again in constant gain mode, and injects it into a dispersion compensation fiber (DCF) of appropriate length. The launch power into each span of DCF is less than –4 dBm per channel. The launch powers into SMF and DCF spans were regulated to minimize any effects due to fiber nonlinearities. The dispersion-compensation scheme targeted approximately 90-percent compensation. Each spool of fiber (SMF and DCF) used in the network was characterized in terms of group delay and insertion loss, using the JDSU swept-wavelength measurement system (SWS-OMNI). The complete concatenation, not including patch cords and amplifiers, which have a negligible contribution, created a net dispersion of 696.1 ps/nm at the transmit wavelength of 1553.33 nm.

The amplified signal consisted of the modulated 10.7 G channel described above at 193.0 THz, and an adjacent unmodulated channel at 193.1 THz, using channel spacing of 100 GHz. For this experiment, a 40-channel arrayed waveguide (AWG) multiplexer was used to combine the two channels; while a lower-loss 8-channel thin-film filter based demultiplexer (Demux) was used to demultiplex the two channels at the receiver.

In order to obtain several OSNR points from the network test bed, additional loss was added at the input to the various booster and pre-amplifiers at different locations within the network, and compensating for loss by adding gain at the affected amplifier. As such, the receiver for the channel of interest always detected a consistent power level, even though the ratio of signal to noise at this power may have differed. Seven different OSNR samples were obtained, spanning the range of 19 to 21 dB, while maintaining a constant power level of –16.3 dBm at the receiver. The corresponding BERs were measured at each of those samples.

Noise-Loading Techniques

Comparing a simulated system to a network system is only valid if under equal conditions. In order to emulate the network dispersion in the NL simulations, a 100-GHz channelized chromatic dispersion emulator was used. With iterative measurements using the same reference instrument that was used to characterize the fiber, we found the desired setting that produced a dispersion of 700 ±4 ps, based on before-and-after measurements to ensure consistency throughout the experiment. The chromatic dispersion compensator did not present any launch power limitations that affected the experiments performed. Due to the channelized nature of the dispersion compensator, we placed it prior to any amplification or broadband noise source. Otherwise, the channelized filtering effect would suppress some noise at a distance of ±50 GHz from the 100-GHz spaced ITU channel centers, leading to erroneous OSNR measurements, because the noise is measured at half the channel spacing from the channel center by convention. The spectrum of the group delay was quite flat (ripple within ±4 ps) over a range of ±25 GHz, which covered the modulated signal spectrum (±~11 GHz) and observed any carrier drift (within 1 GHz), thus validating its emulation of fiber dispersion.

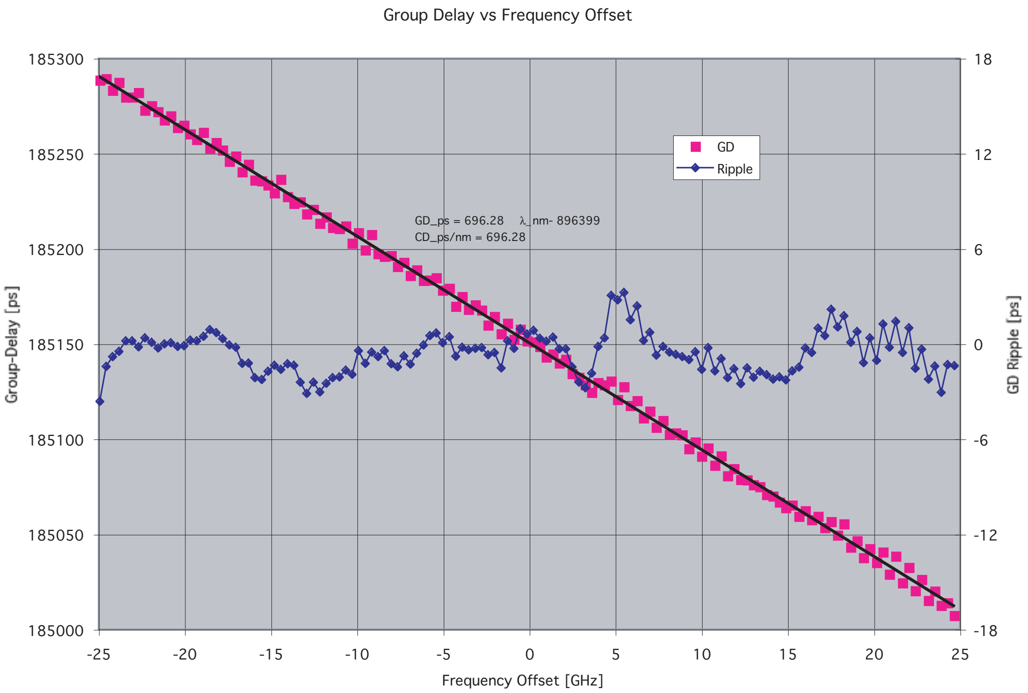

Figure 2 Chromatic dispersion emulator characteristics at wavelength of interest

In the NL-EDFA experiment, the two channels (modulated + unmodulated probe) were multiplexed, propagated through the dispersion emulator, and fed into a MAP-200 amplifier (mEDFA) via a JDSU MAP-200 variable optical attenuator (mVOA) to control the input power. The amplifier was driven to maximum output power and attenuated via a second VOA. The output of the VOA was de-multiplexed and received by the WRT-840 line-side receiver.

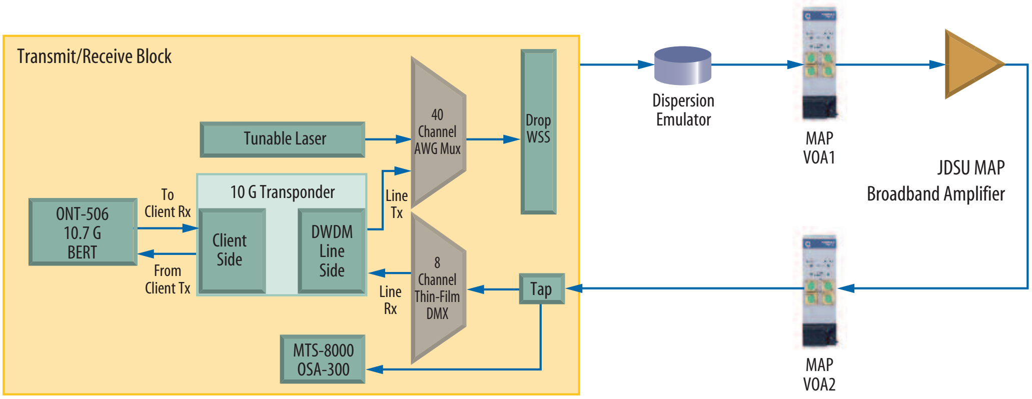

Figure 3 Noise-loading setup with mEDFA

In the NL-BBS experiment, the two channels (modulated + unmodulated probe) are multiplexed, propagated through the dispersion emulator, and fed into a WaveReady WRA-219 amplifier at 23 dB constant gain to ensure sufficient power when coupling with ASE noise. In parallel, a JDSU MAP-200 broadband noise source (mBBS) running at 100 percent was fed into an optical attenuator. The output of both the amplifier and the VOA where fed into each of the input arms of a 50/50-percent fused fiber coupler. One output terminated, the remaining coupler output was fed into a second VOA prior to de-multiplexing and connecting to the receiver.

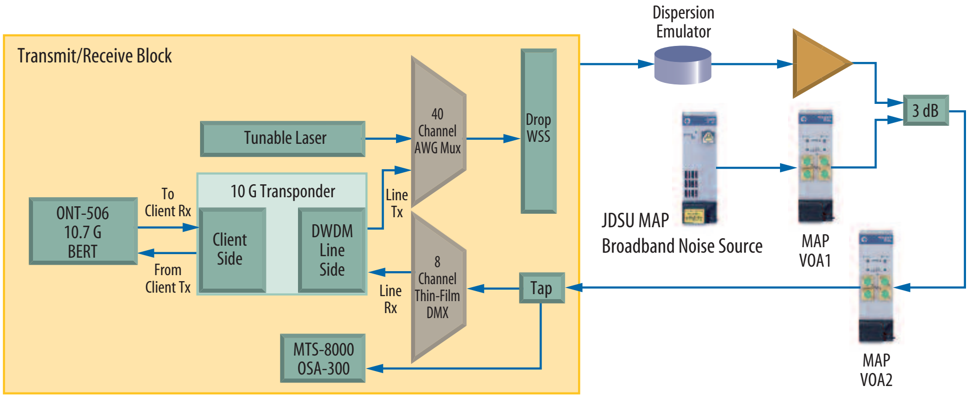

Figure 4 Noise-loading setup with mBBS

OSNR Measurements

A tap at the input of the demultiplexer allowed the evaluation of the OSNR using the following technique. Noise levels were integrated over a conventional 0.1-nm bandwidth, which were averaged to the left (–50 GHz) and right (+50 GHz) of the signal peak to sufficiently avoid interference from the signal bandwidth (for a 10 Gb/s signal) or its neighboring channels 100 GHz away. The signal level itself was evaluated using an integration bandwidth of 0.2 nm, accounting for the signal bandwidth at 10.7 GHz (2 x 10.7 GHz x 0.008 pm/GHz = 0.17 pm), and was experimentally confirmed (in the absence of ASE, smaller OSA resolution bandwidths did not capture the entire spectral power at the peak). The OSNR measurements were statistically averaged over multiple sweeps during the same time interval that bit errors were being integrated (minimum of 60 s). An uncertainty of ±0.1 dB was estimated on any OSNR measurements obtained using this method, while the repeatability remained within this range.

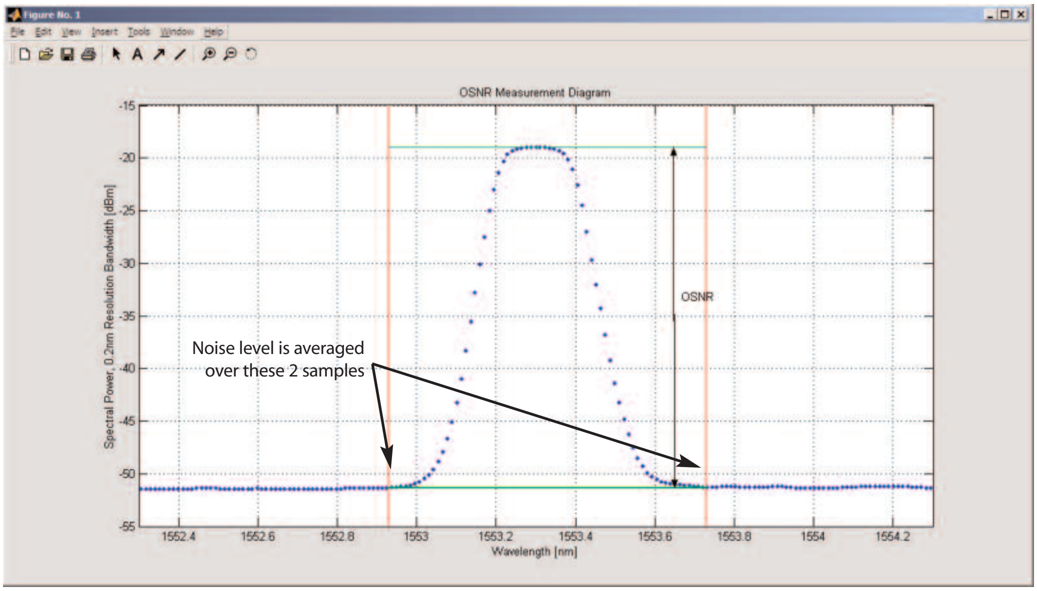

Figure 5 OSNR measurement method *(Note that ~3 dB must be removed from the NL to convert the measurement 0.2 nm integration bandwidth to the conventional 0.1 nm)*

The unmodulated probe signal was used to maintain the integrity of the OSNR evaluation of the signal of interest. Because the probe signal underwent slightly different conditions than the signal of interest (due to EDFA tilt and system wavelength-dependent loss (WDL) it could not be used to quote the exact OSNR measurment on the signal of interest; but after fewer than four amplified spans, should be reasonably close to the desired channel, provided equal launch conditions. Furthermore, OSNR measurements on the unmodulated signal are inherently less error prone due to the absence of signal sidebands to interfere with the noise power. Prior to each experiment, the two channels were set to equal launch powers by means of an OSA at the output of the multiplexer (within 0.05 dB uncertainty). The OSNR equivalence was determined at each measurement as a sanity check. It would be preferable to have two equal-power probe channels on either side of the modulated signal and average the OSNR of the two probes.

BER Measurements

In order to minimize the uncertainty on BER measurements, we adjusted the integration time as a function of the approximate BER level. For BERs above 1e-9, and between 1e-9 and 1e-11, integration times of 60 and 120 s were used, respectively, to limit the BER uncertainty to within approximately ±30 percent at a confidence level of 95 percent. For BERs less than 1e-12, the integration interval was limited to 300 s (5 min) for reasons of practicality, although this raises the BER uncertainty to a factor of ~3 at the same confidence level of 95 percent.

Although the 60-s interval used at high BERs was more than sufficient, it also enabled a longer averaging acquisition interval for the OSNR measurement.

Experimental Results

The following chart compares the results of the transmitter/receiver pair performance at a net dispersion of 696 ps/nm in the network and two NL conditions.

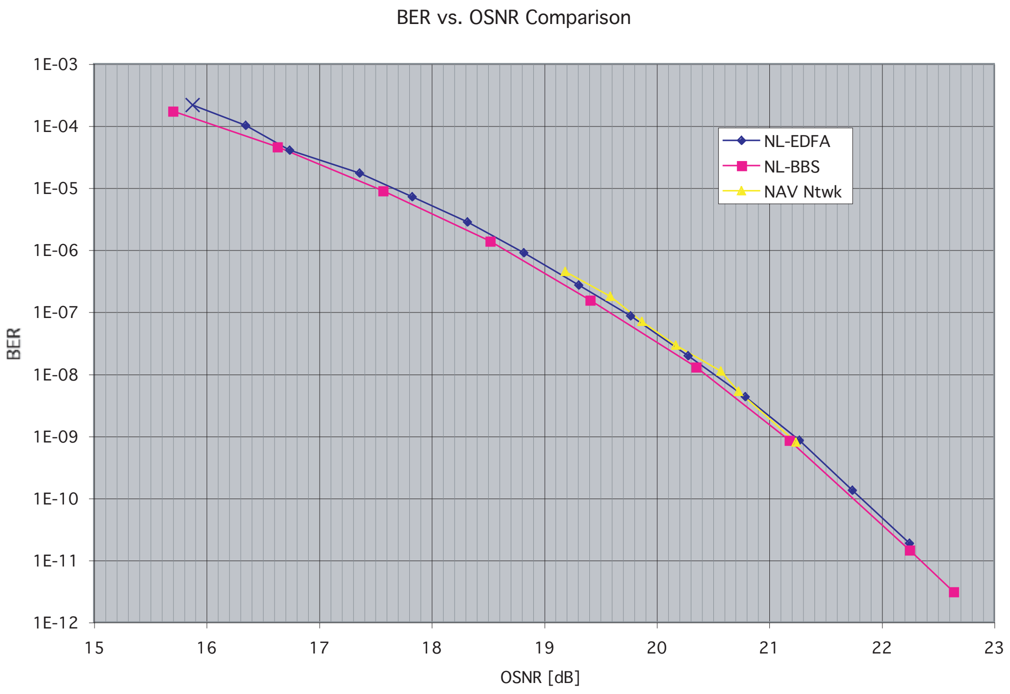

Figure 6 BER vs. OSNR waterfall curves

The results of these three setups show excellent agreement, and the same trend was reproduced in both NL simulations within 0.2 dB on the OSNR axis, which is the OSNR measurement uncertainty. The network results closely follow the general trend led by the two simulation results. This agreement supports using the two NL techniques to mimic the tolerance of a transmit/receive pair, given constant impairment (in this case, dispersion).

To further compare the two ASE simulation experiments, BER contour plots over the OSNR/Rx-Power space were obtained at BERs of 1e-5, 1e-6, and 1e-7. Due to a shut-off mechanism within the receiver when the signal dropped below a threshold of –27 dBm, a horizontal wall at this level exists (not shown). The integration time used for each of these measurements was only on the order of 5 s, which increased the uncertainty on the OSNR measurement to ±0.2 dB, with a corresponding Rx power uncertainty of -0.15 dBm. Due to the high BER in all these contours, the worst BER uncertainty over the integration interval remained below ±3 percent (at the 1e-7 contour).

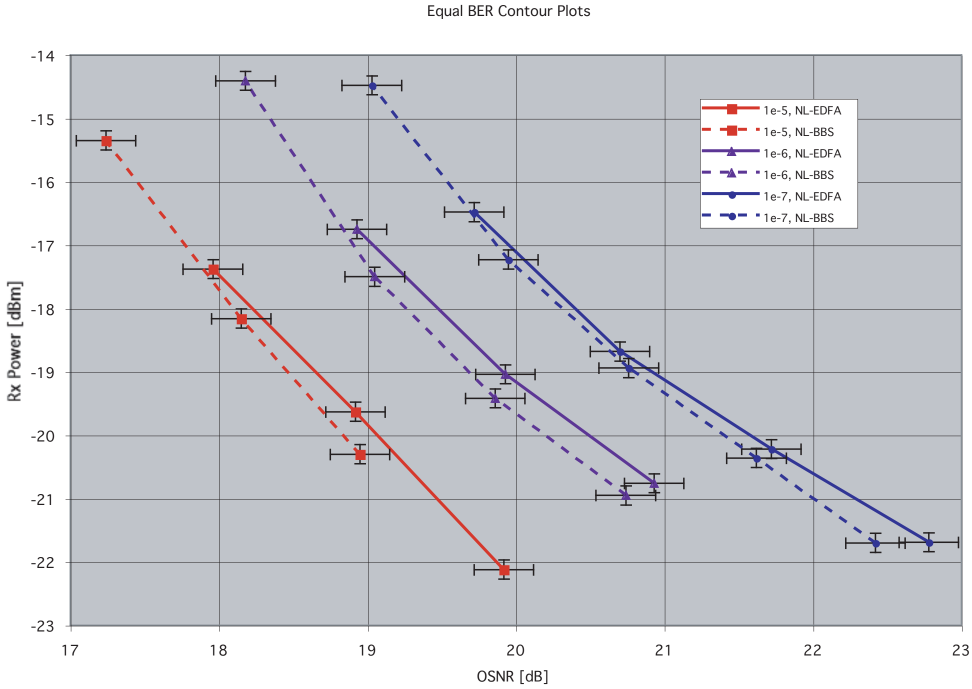

Figure 7 Contour plots of equal BER

Discussion

It is worth noting that of all three experiments, the NL-BBS technique provided the most ease and flexibility. Setting the output VOA to obtain the desired receive power under low-noise conditions required only minor tweaks when the noise level was high, and significantly contributed to the receive power. This technique allowed the largest dynamic range of OSNR while maintaining constant receive power. The NL-EDFA technique was limited in that the output power began to drop at high noise levels, which essentially limited the OSNR dynamic range that can be achieved under constant conditions. Both NL techniques have good OSNR resolution, as it is limited by the resolution of the first VOA.

In terms of setup and measurement time, the BBS technique was also the most efficient. The EDFA technique, in some cases, would require disabling of a shut-down mechanism at low input powers. The network technique, on the other hand, required inserting pads at six different points and adjusting the downstream gain to compensate. Inserting pads is not automatable unless the pads are replaced with VOAs, but using six VOAs makes this highly inefficient. Furthermore, the available dynamic OSNR range was just over 2 dB.

An offset in OSNR on the order of 0.1 to 0.2 dB appears between the two NL simulation curves, where one would expect random fluctuation. The systematic shift in OSNR between the NL-EDFA and NL-BBS curves may well be attributed to polarization effects. Both ASE simulation experiments were performed without disturbing fiber, within a reasonably short time interval. As such, the results for each experiment were obtained with somewhat constant polarization conditions. The network setup required moving patch cords to insert attenuation pads. The net movement was insignificant, but sufficient to change polarization launch conditions at various points in the network. Each of the experimental setups had a unique but unquantified net polarization dependent loss (PDL) at the wavelength of interest, while the OSA itself has an intrinsic PDL of up to 0.1 dB, such that an offset will exist between OSNR at the line-side receiver and at the OSA. Furthermore, and possibly more significantly, polarization-hole-burning (PHB) within the EDFAs may have played a role in the noise characteristics near the signal of interest, especially because only two closely-spaced wavelengths were amplified. All experiments used an EDFA in the signal path, including the NL-BBS. For further experimentation we recommend using a polarization scrambler at the transmit end to explore all EDFA polarization effects, and place another scrambler upstream from the OSA tap to scramble the ASE to average noise levels over polarization. The BER and OSNR integration times would thus average out all effects.