

Brown-Field Upgrades to 40 G Bit Rates

With the availability of 40/100 G transmission technologies, network carriers are looking to upgrade their existing 10 G DWDM systems to the higher data rate transmission formats. By improving their network spectral efficiency, they are on a path to improving the cost per bit, provided that modifying the common optical transport platform is not required.

40 G transmission technology has evolved into a “modulation format soup” from which the ideal format must be chosen to suit the specific requirement. Here, we compare a direct-detection vs. a coherent-detection technology, namely RZ-DQPSK (direct) vs. PM-QPSK (coherent).

Transponder Overview

At the transmitter, both RZ-DQPSK and PM-QPSK modulation formats use quaternary (2-bits per symbol) phase modulation, while PM-QPSK also transmits independent data streams along both orthogonally-polarized axes. Therefore, in order to transmit at the same aggregate bit rate, PM-QPSK can transmit at half the symbol rate of RZ-DQPSK, namely 10 Gbaud vs. 20 Gbaud. As such, PM-QPSK does not require as high an electrical or optical bandwidth as RZ-DQPSK.

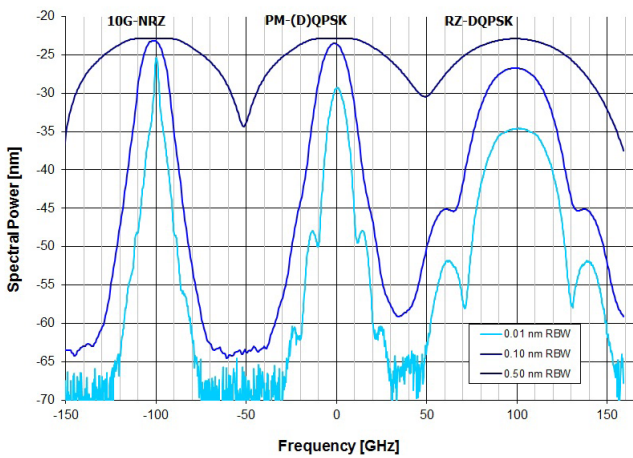


Figure 1. Spectral comparison

Both receivers are complex compared to run-of-the-mill intensity-modulated (IM) direct-detection technologies required for up to 10 G. In addition to the pairs of balanced receivers needed for phase detection, the RZ-DQPSK is complex in an optical sense when taking into account tunable dispersion compensators and tunable power compensators (also known as amplifiers), while the coherent requires complex digital signal processing.

The coherent PM-QPSK has several advantages in that it can tolerate a large range of chromatic dispersion, polarization-mode dispersion, and receiver power, and with its reduced optical bandwidth compared to RZ-DQPSK, (but on par with intensity-modulated 10 G NRZ), can tolerate a greater number of passes through 50 GHz DWDM filters (including WSS). However, although PM-QPSK has decent tolerance for self-phase modulation, its well-documented weakness is its tolerance to cross-phase modulation from adjacent intensity-modulated channels.

Typical 10 G and lower bit rate DWDM multi-span networks use dispersion compensation due to the limited dispersion tolerance of the intensity-modulated systems. In a mesh network, it is not uncommon to compensate a span's dispersion by 80-100%, while propagating channels spaced by 100 GHz (~44 channels) or even 50 GHz (~88 channels). Using this dispersion-compensating scheme and minimum span-length assumptions, a channel can travel an acceptable number of spans prior to being limited by optical signal-to-noise ratio (OSNR).

Comparison Tests

Both 40 G technologies (direct-detection RZ-DQPSK and coherent PM-QPSK) were compared in a “brown-field” deployment scenario alongside 10 G and lower data-rate signals, by using samples from a Lumentum long-haul, tunable, 40 G MSA selection. The comparison was done in the Lumentum Network Application Validation (NAV) Lab^(see end-note).

The NAV test bed consists of a 16 x 50 km span “linear” system using NDSF transmission fiber (ITU-T G.652 type). The test bed allows 16 consecutive launch points in nearly identical fiber spans. The 50 km distance is significant enough for non-linearities to accumulate at standard launch powers, and inhibits OSNR from degrading too quickly. Dispersion-compensation was performed with low-loss dispersion-matched fiber (DCF) modules. With the launch into the DCF after the 50 km of NDSF, the launch into DCF was maintained at -5 dBm or less, minimizing non-linear effects due to DCF.

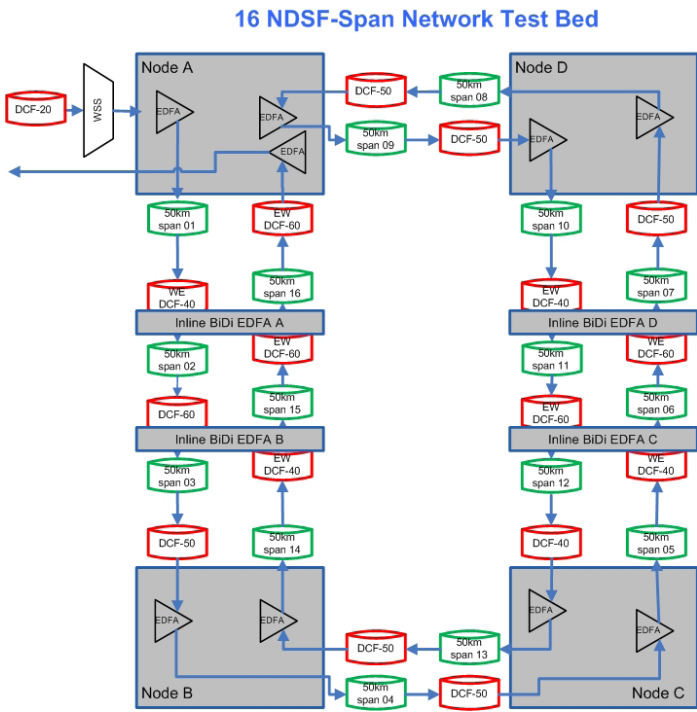


Figure 2. NAV 40 G test bed

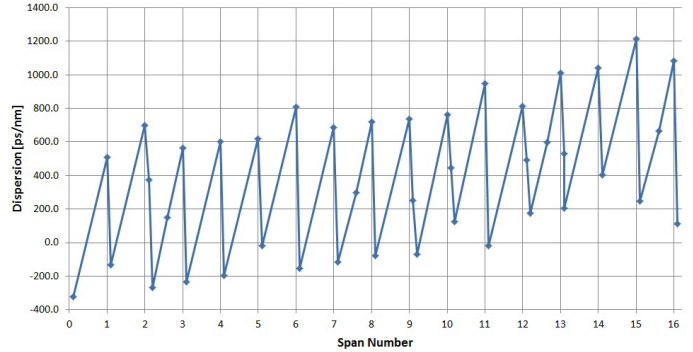


Figure 3. NAV 40 G test bed

Test Set Up

The 40 G transmitter under test passed through a slow-polarization scrambler, a tunable-dispersion compensator matched to the same pre-dispersion as its neighboring channels. It was then multiplexed using a 100 GHz or 50 GHz MEMS-based wavelength-selective switch. Neighboring, intensity-modulated channels (10 G and under) are multiplexed and then passed through a fast polarization scrambler. The WSS allowed equalization of channels at the headend of the linear system. The fast polarization scrambling of the intensity-modulated channels allows averaging of performance of the 40 G under test over neighboring polarization states, while slow polarization scrambling of the 40 G allows the averaging of performance over launch states, while still allowing the coherent receiver to recover the two states of the polarization-multiplexed signal. For fair comparison, the same setup was used for the non-polarization multiplexed 40 G RZ-DQPSK.

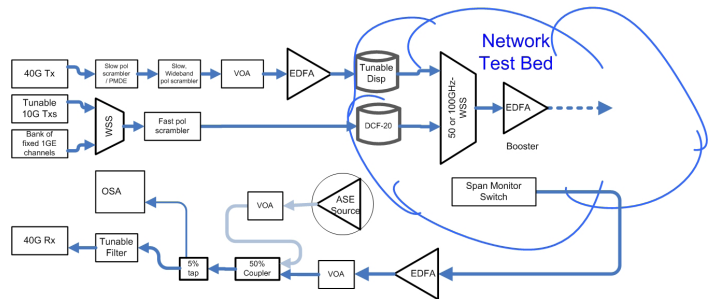


Figure 4. 40 G instrument setup

Methodology

Performance was generally measured against OSNR. At any given condition, amplified stimulated emission (ASE) was loaded onto the received signal at different levels, and the raw bit error rate (BER) was measured at each OSNR setting. The OSNR was measured with noise integrated in a 0.1 nm resolution bandwidth. Signal power was measured by integrating the power over a channel-bandwidth (typically 50 to 100 GHz) and subtracting the total noise power in the bandwidth, based on noise measurement at a fixed frequency offset from the signal center wavelength. This offset was selected on a condition-by-condition basis, and took into account pre-filtering conditions.

Receiver powers for waterfall curves were consistent across different conditions: prior to noise loading, the receiver powers were adjusted via post-amplification attenuation to levels in the middle of the optimal range. Attenuation adjustments did not occur as noise was loaded.

Performance was compared by selecting a reference BER (1e-3) and comparing the required OSNR at the specified condition versus the OSNR at a baseline condition. It is important to note that the direct-detection RZ-DQPSK had a different BER vs. OSNR baseline curve than the PM-DQPSK.

Results

Back-to-Back Performance

The RZ-DQPSK and PM-QPSK back-to-back (B2B) performance at 1545.32 nm is shown below as a baseline. The performance is compared to that of a 10 G NRZ transponder (0-Chirp TXFP). A standard receiver power level of -17 dBm was selected for further tests of the PM_QPSK, and +2 dBm for the RZ-DQPSK.

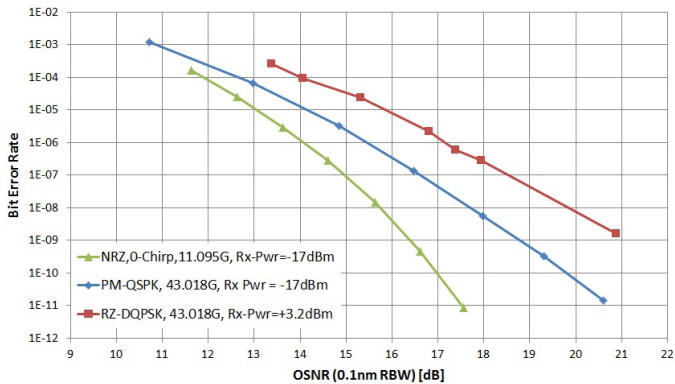


Figure 5. B2B performance baselines (OSNR waterfall)

The PM-QPSK receiver includes a narrow linewidth local oscillator (LO). The LO must be closely matched in wavelength to the received signal, and therefore to the far-end transmitter.

The electrical amplification performed by “beating” the incoming signal with the LO gives the PM-QPSK decent receiver-power sensitivity. By contrast, the RZ-DQPSK will typically be equipped with a dedicated optical amplifier to ensure a higher receiver power in the [+2, +4] dBm range. Operation outside of this range is not recommended.

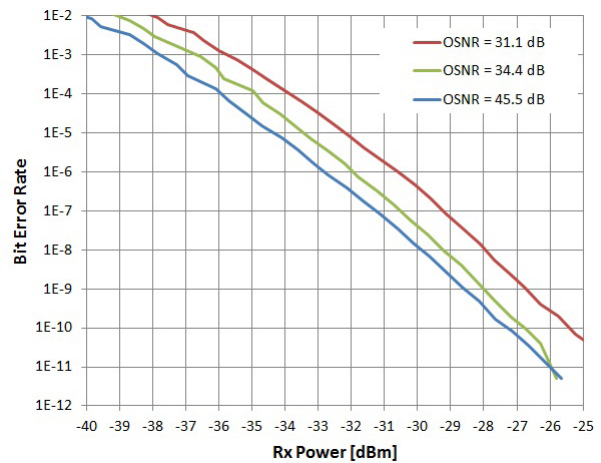


Figure 6. PM-QPSK B2B receiver power sensitivity at 1545.32 nm

Although Tx and LO tunable lasers are tuned to the ITU grid, differences in wavelength can occur due to start-of-life inaccuracy and aging. The sensitivity to LO offset is shown below from measurements. The waterfall curves are plotted on the left, while the penalty at a reference BER of 1e-3 is plotted on the right. As expected, the best performance was near 0 GHz. For a ref BER = 1e-3, LO offsets of 0.5 GHz (500 MHz) with respect to ideal show insignificant penalty. At 2 GHz offset, the penalty is on the order of 0.1 dB, while at 4.5 GHz, the penalty reaches 0.5 dB. For further tests at 1545.32 nm, the LO offset was left at optimal (0 GHz). LO offset is not applicable to the direct-detection RZ-DQPSK.

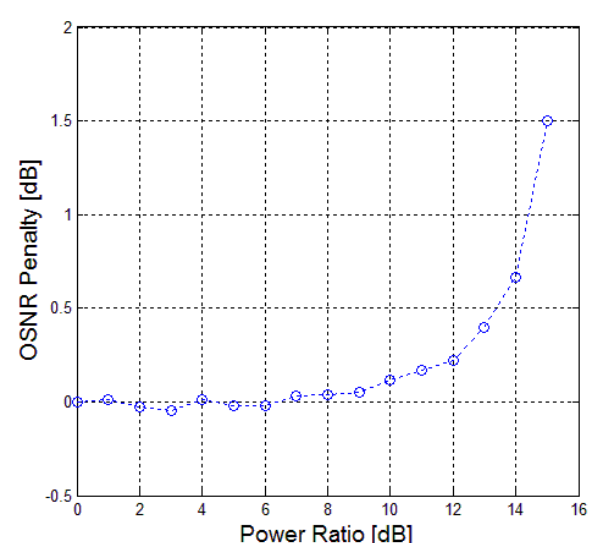
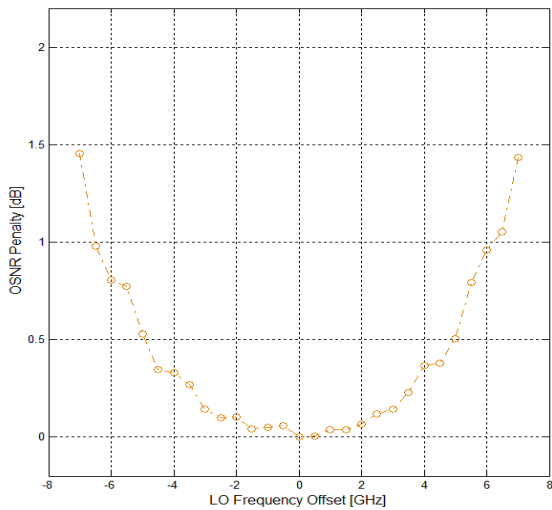
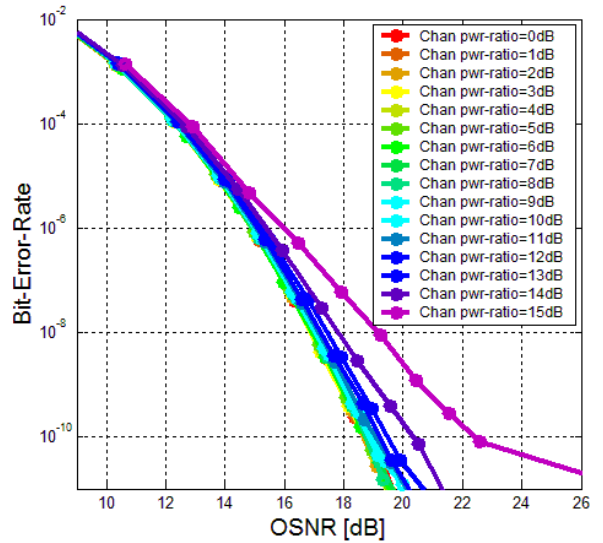
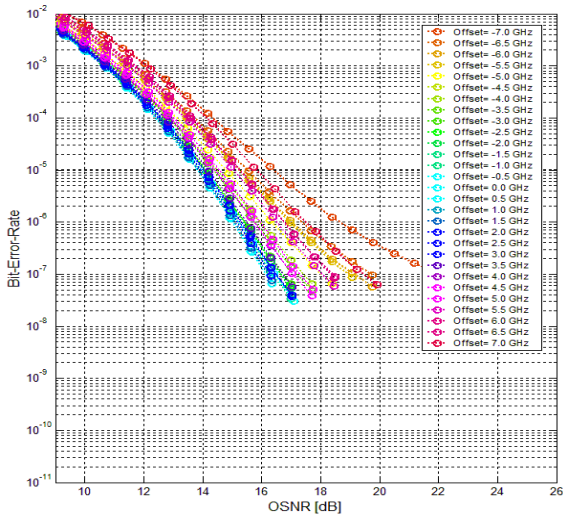


Figure 7. Sensitivity to local oscillator offset for PM-QPSK module

Figure 8. PM-QSPK performance with two adjacent 40 G channels

The LO not only has the advantage of electrically boosting the wavelength of interest at the coherent PM-QPSK receiver, but also to “electrically” filter out unwanted wavelengths. The chart below shows the tolerance to adjacent channel powers when 2 adjacent 40 G PM-QPSK channels are set 50 GHz to the left and right of the channel under test. A 0 dB adjacent-power ratio corresponds to all three channels at the same power, and power-ratio indicates the ratio of the uniform adjacent channel power to the power of the channel under test. By contrast, the RZ-DQPSK needs an optical filter similarly to 10 G channels in the brown-field scenario.

The coherent DSP is able to compensate for chromatic dispersion and polarization dispersion. The sensitivity to chromatic dispersion is experimentally very small and within OSNR measurement accuracy. The RZ-DQPSK, on the other hand, requires optical chromatic dispersion compensation, and will be equipped with a tunable dispersion compensator to mop up residual dispersion at the drop site. Its dispersion window is a narrow 200 ps/nm, equivalent to approximately ± 12.5 km of under- or over- compensated standard NDSF fiber (the figure here shows a dispersion range of 300 ps/nm for a penalty less than 1 dB).

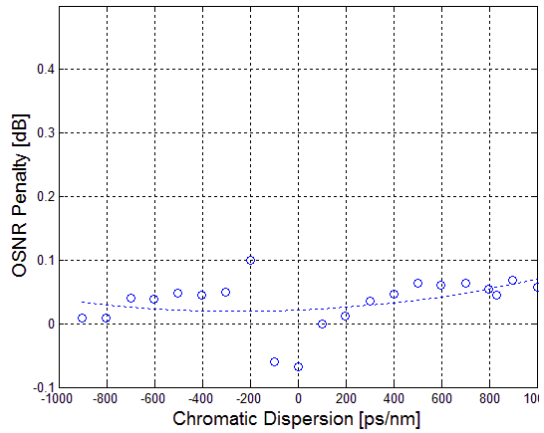
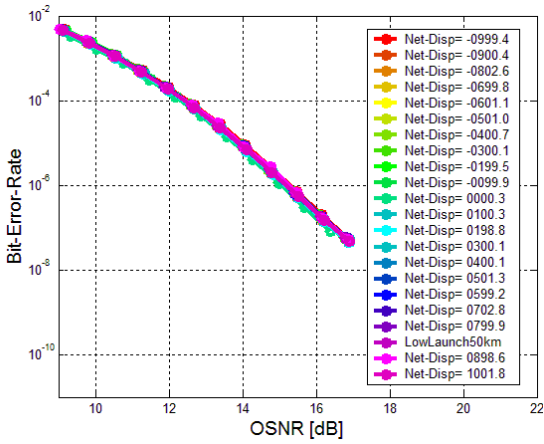


Figure 9. PM-QPSK sensitivity to chromatic dispersion

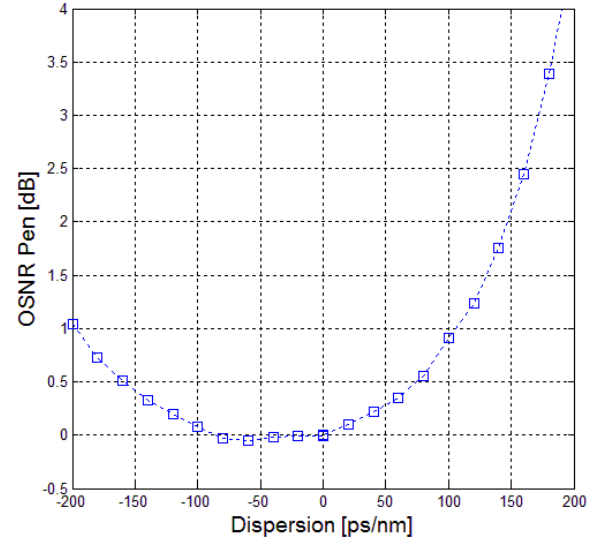
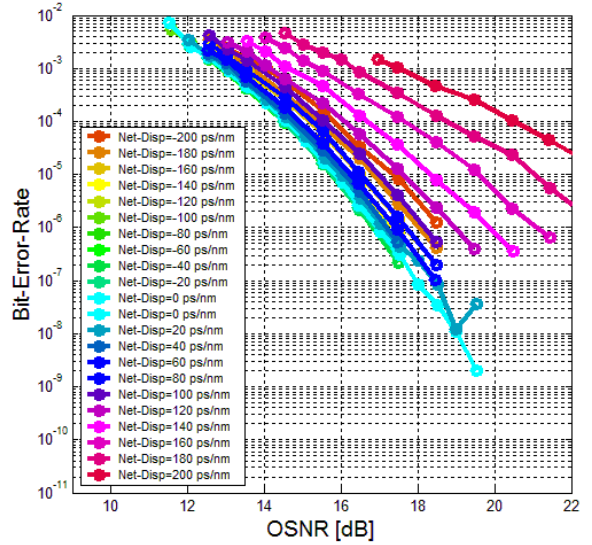


Figure 10. RZ-DQPSK sensitivity to chromatic dispersion

The PM-QPSK transmission format, at 40 G, is also very tolerant to filtering. With a spectral bandwidth not much wider than a 10 G NRZ channel, our tests show that it can tolerate filtering with a net 3 dB bandwidth of 10 GHz with less than 1 dB penalty.

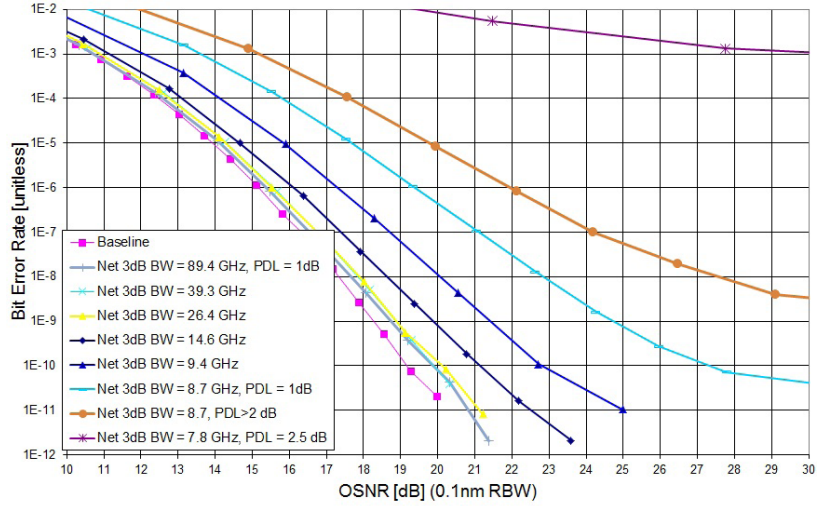


Figure 11. PXM-QSPK tolerance to filter narrowing

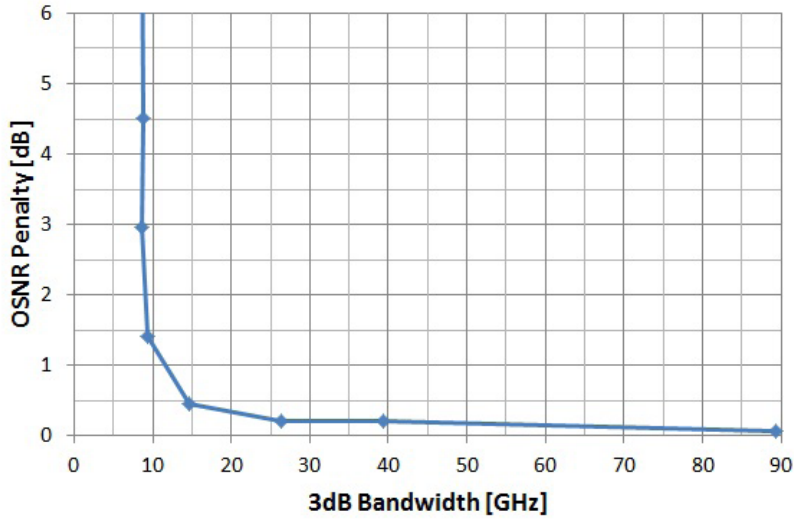


Figure 12. PM-QSPK penalty vs. filter bandwidth (3 dB)

The results above show the versatility of the coherent PM-QPSK format in terms of receiver power, OSNR, chromatic dispersion, and optical and electrical filtering. It is also very tolerant to PMD (results not shown here). These results are advantageous compared to the RZ-DQPSK, but we need to examine the performance when co-propagating with other channels.

Link Propagation: Comparison of Both 40 Gs at Launch Power of 1 dBm

PM-QPSK vs. RZ-DQPSK with Self-Phase Modulation (SPM)

Comparing the two formats at a fixed launch power of +1 dBm, both modules do not significantly increase their penalty (at 1e-3) as the number of spans increase. In the plots below, all penalties are referenced with respect to the B2B value, so the penalty at after span #0 is, by definition, 0 dB. However, it should be noted that the RZ-DQPSK does require more OSNR than the PM-QPSK. For SPM, the RZ-DQPSK penalty plotted below fluctuates more with respect to the number of spans: this is attributed to larger BER uncertainty due to the slower convergence of Rx control loops. Nevertheless, the average trend remains low and the overlaying shapes of the waterfall curves suggest little degradation with the number of spans at this launch power.

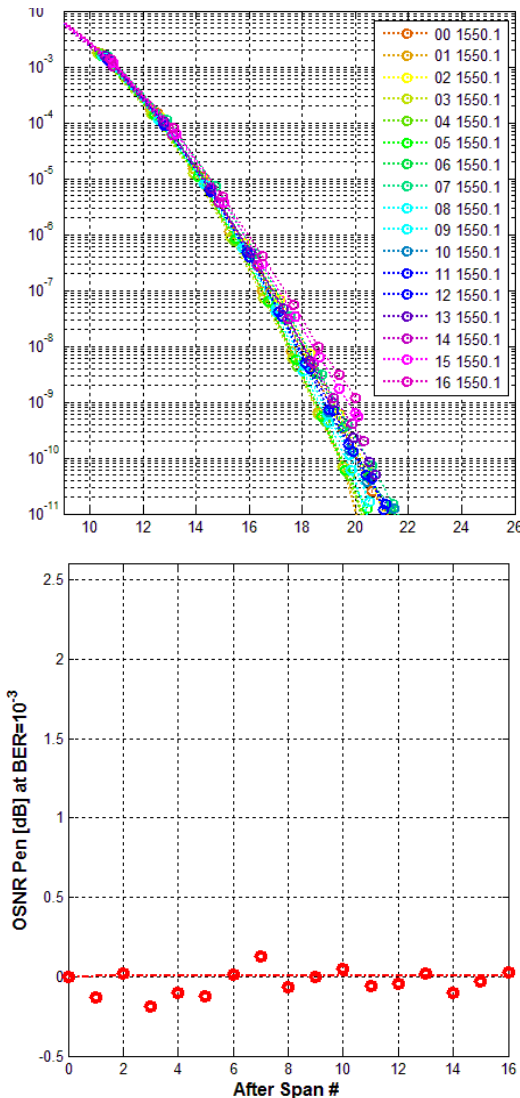


Figure 13. PM-QPSK SPM performance, 1 dBm launch power

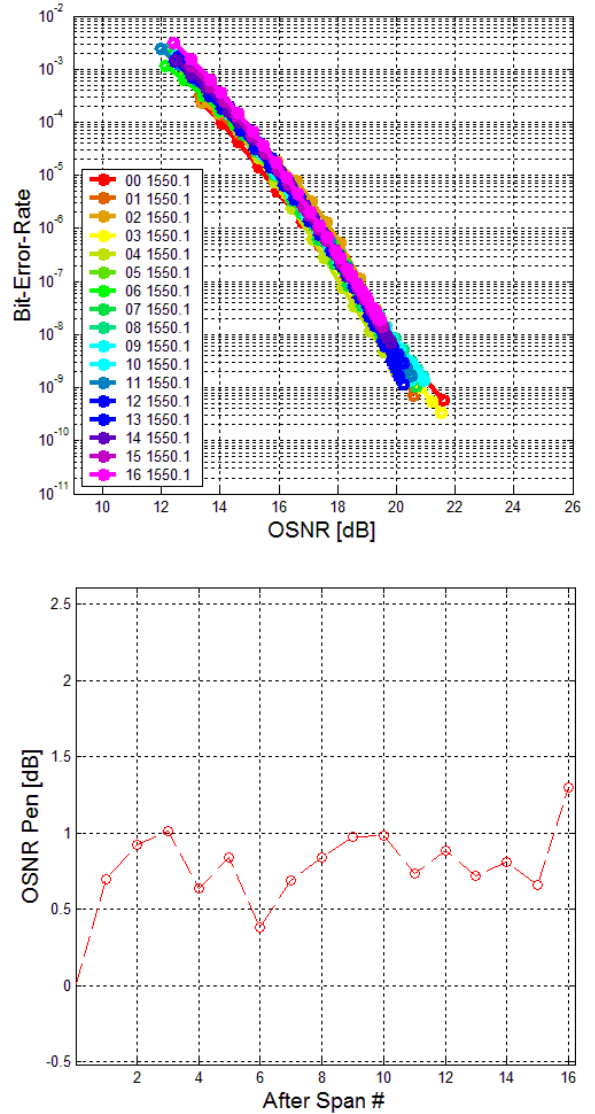


Figure 14. RZ-DQPSK SPM performance, 1 dBm launch power

PM-QPSK vs. RZ-DQPSK with Cross-Phase Modulation (XPM), 10 G

However, as soon as a co-propagating channel is added, cross-phase modulation from the aggressor channel onto the channel under test starts to manifest itself and the receiver's ability to detect the incoming signal is impaired. The channel is referred to as an aggressor since it has a detrimental effect on the channel under test. In the figures below, we compare the performance of a PM-QPSK to a RZ-DQPSK (same wavelength) in the presence of a 10 G aggressor (at a bit rate of 11.095 Gbps) spaced +100 GHz away (-0.8 nm). It is readily seen that the penalty for the PM-QPSK quickly increases with the number of spans, while it remains relatively static for the RZ-DQPSK.

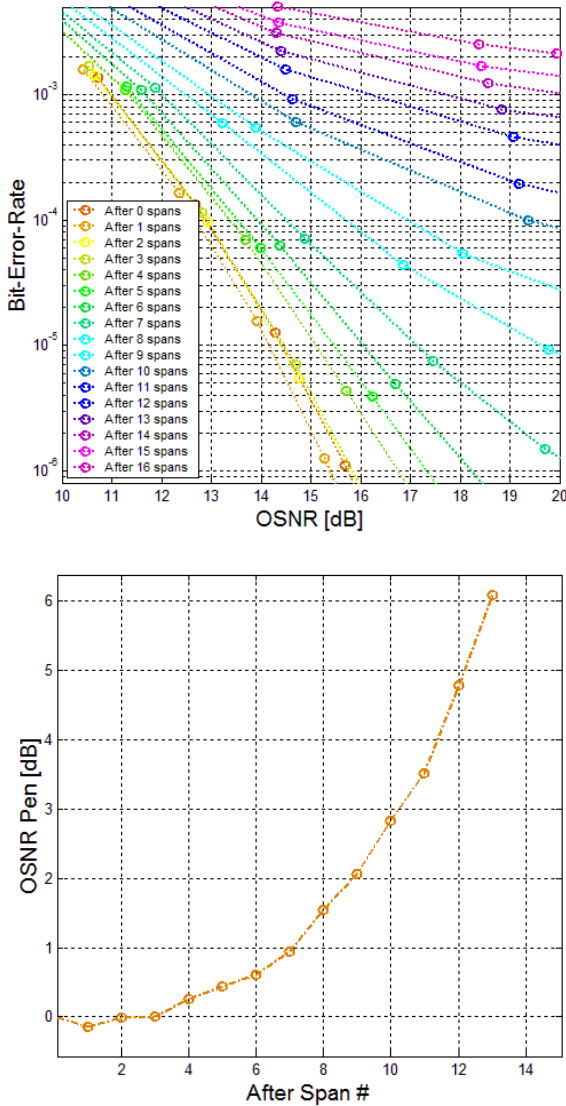


Figure 15. PM-QPSK XPM +100 GHz, 10 G

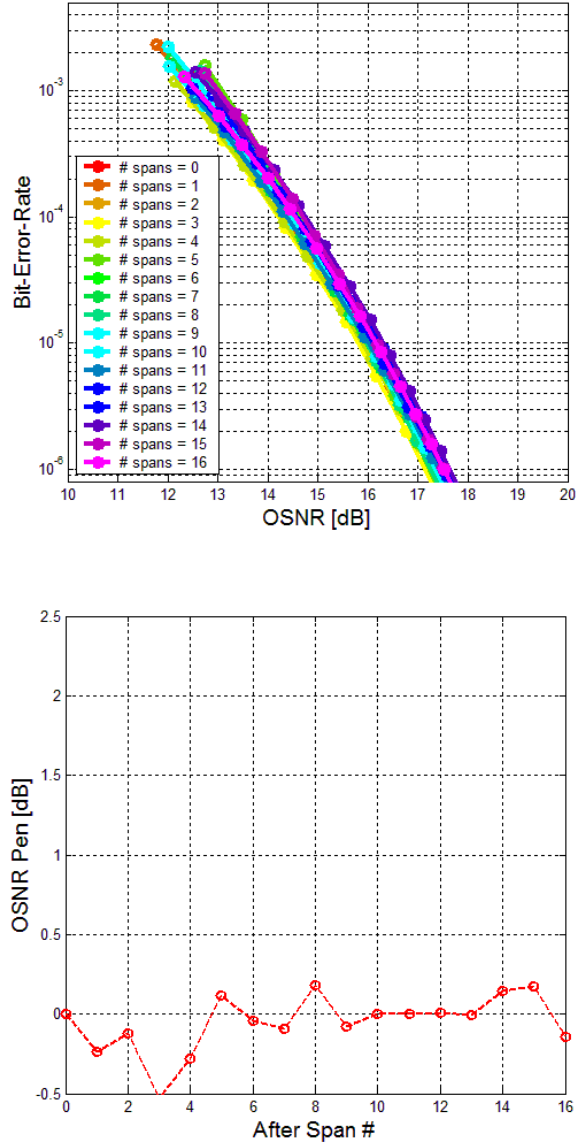


Figure 16. RZ-DQPSK XPM +100 GHz, 10 G

More experimental data demonstrates that the PM-QPSK penalty further increases as the bit rate of the intensity-modulated aggressor increases in this dispersion-compensated configuration. This also occurs for the RZ-DQPSK, however the penalty increase is limited.

Link Propagation: Characterization of PM-QPSK with Non-Linear Phase-Modulation

PM-QPSK Tolerance to SPM

To further understand the effect of non-linear phase-modulation on the PM-QPSK, we have characterized its behavior over a larger range of launch powers. Tolerance to SPM was measured by eliminating co-propagating channels, and is shown below. The results show that, in this setup, the format is fairly well behaved until a launch-power threshold of approximately +4 dBm, after which penalties quickly grow after multiple launches.

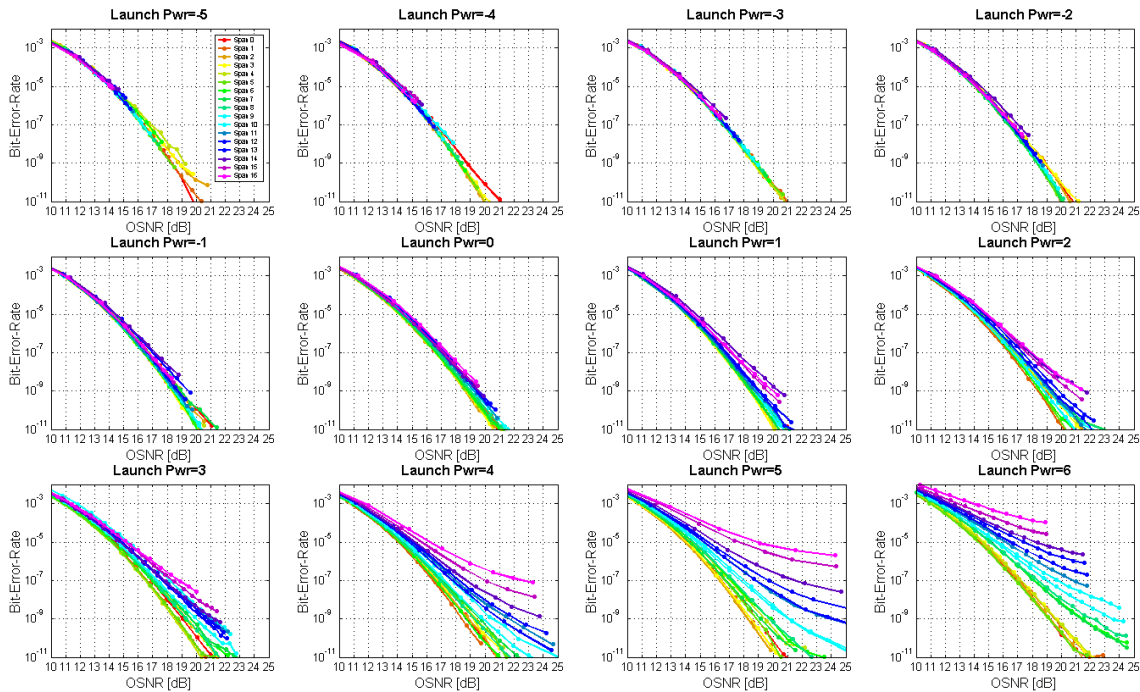


Figure 17. PM-QPSK SPM tolerance waterfalls

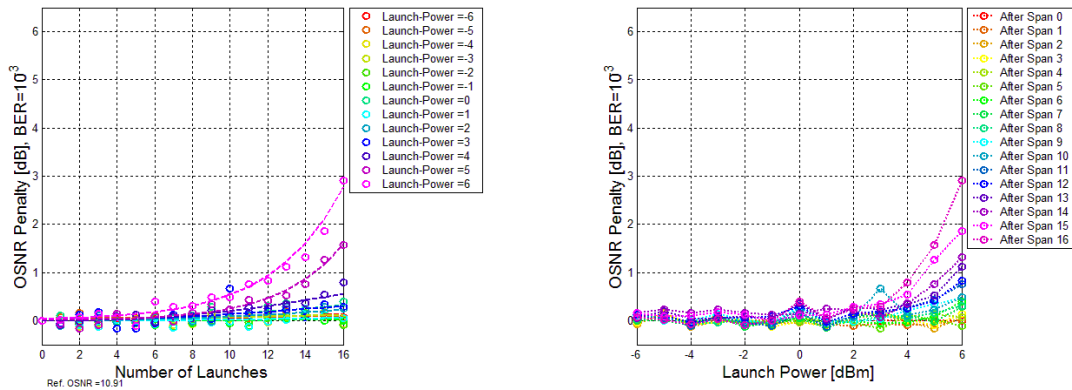


Figure 18. PM-QPSK SPM penalty

By comparison, an RZ-DQPSK signal over the same system can tolerate 16 spans at a uniform launch power of +6 dBm with only ~2 dB penalty.

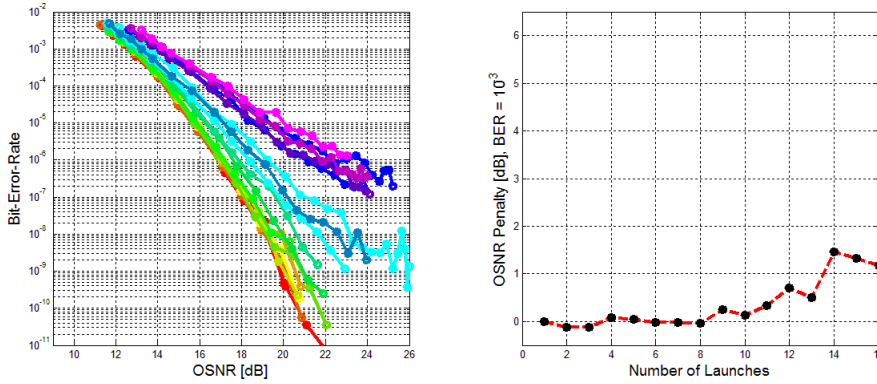


Figure 19. RZ- DQPSK SPM Penalty at +6 dBm

PM-QPSK Tolerance to Cross-Phase Modulation (XPM)

XPM impairment depends on many factors including launch power, number of spans, frequency spacing between aggressor and channel under test, dispersion mapping, and pre-dispersion conditions of both channels prior to co-propagation. Alerted to the fact that PM-QPSK is not very tolerant to XPM from adjacent channels, we show here some characterization results over this specific test bed with aggressor channels propagated near the channel under test.

For these tests, the channel under test was at 1545.32 nm, while the aggressor, carrying 11.095 Gbps negative-chirp NRZ traffic, was transmitted at a frequency offset from the channel under test ranging from +50 GHz (-0.4 nm) to +400 GHz (-3.2 nm). As per the SPM tests, the parameter space of launch power (6 to +6 dBm) and number-of-launches/spans (0 to 16) were swept.

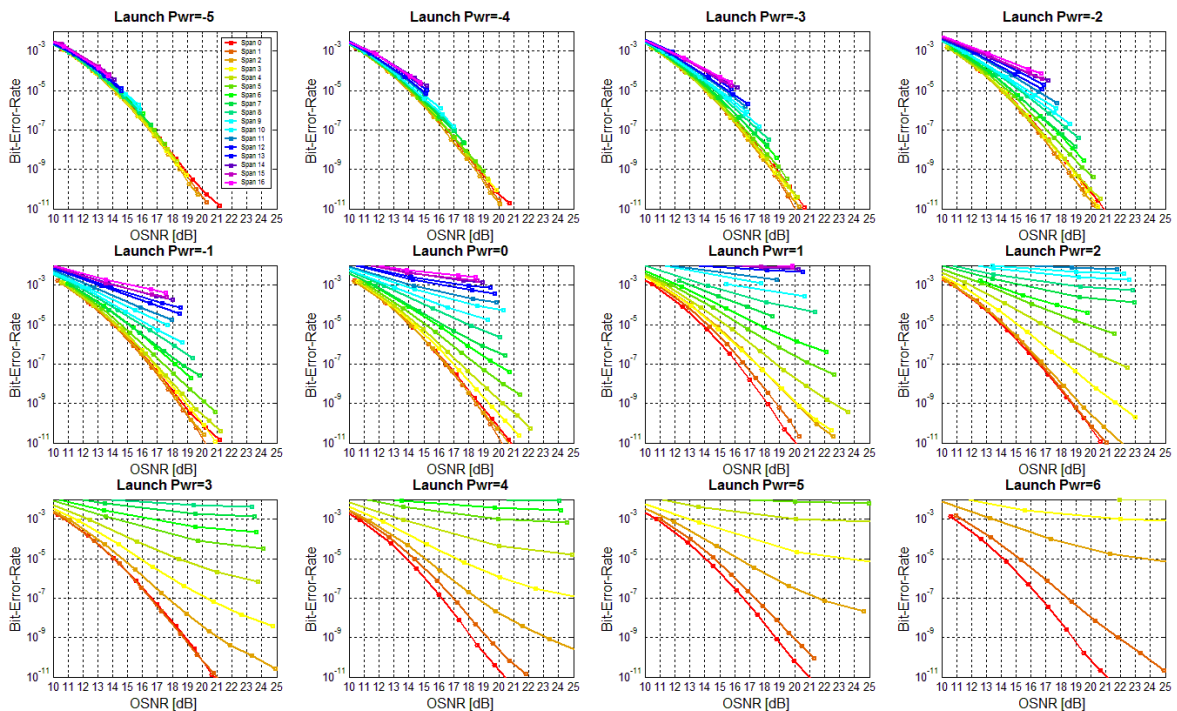


Figure 20. XPM with single co-propagating aggressor at +50 GHz (wavelength: 1544.924 nm)

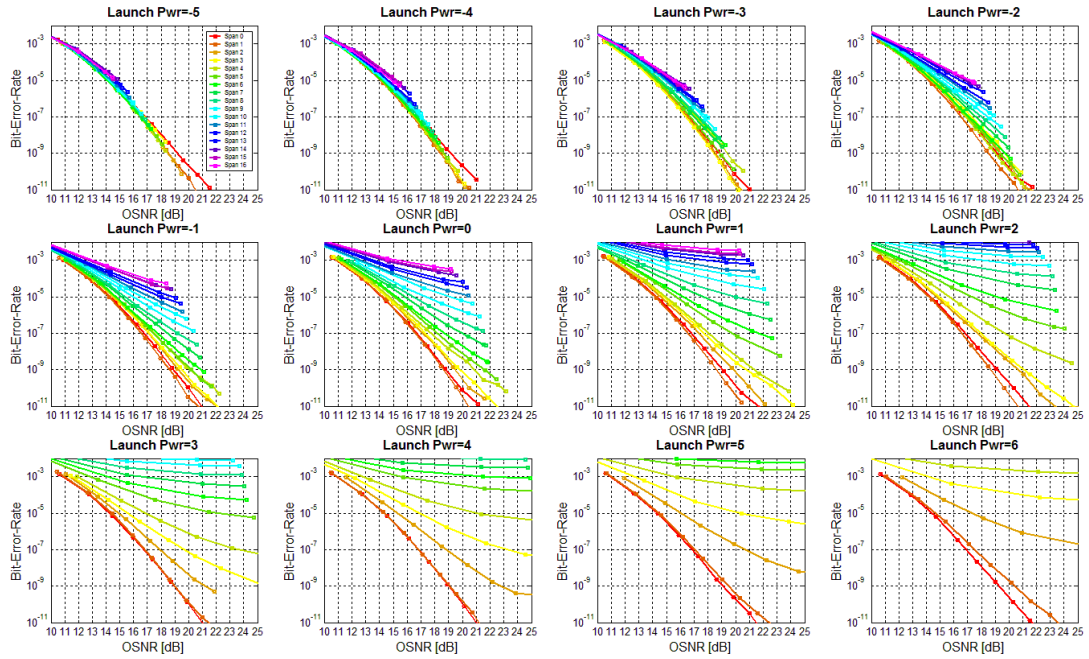


Figure 21. XPM with single co-propagating aggressor at +100 GHz (wavelength: 1544.526 nm)

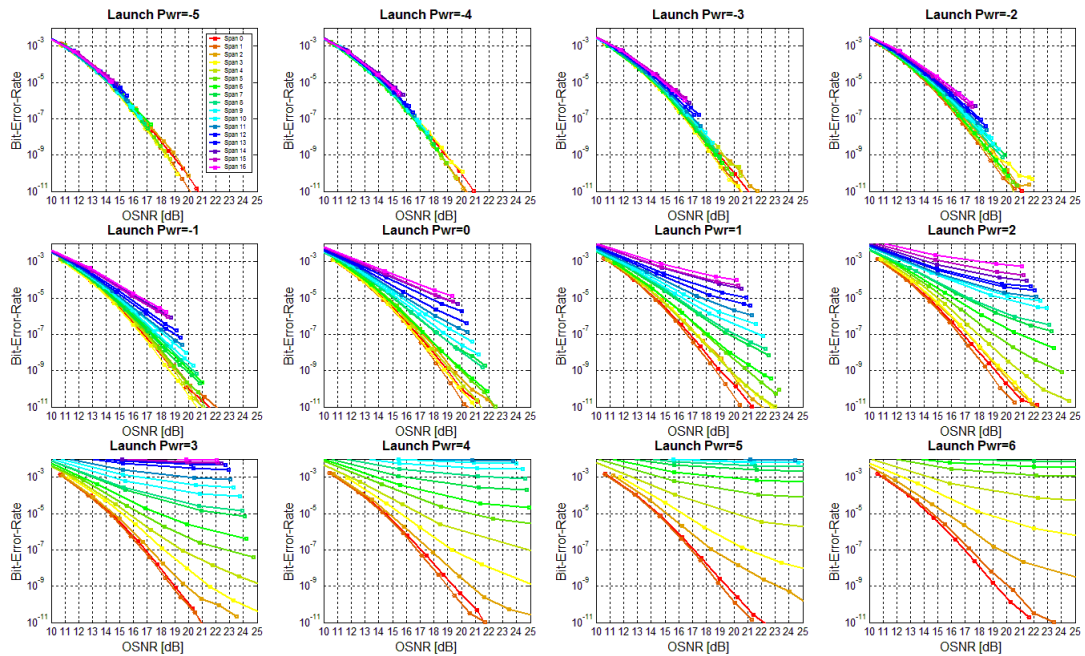


Figure 22. XPM with single co-propagating aggressor at +200 GHz (wavelength: 1543.730 nm)

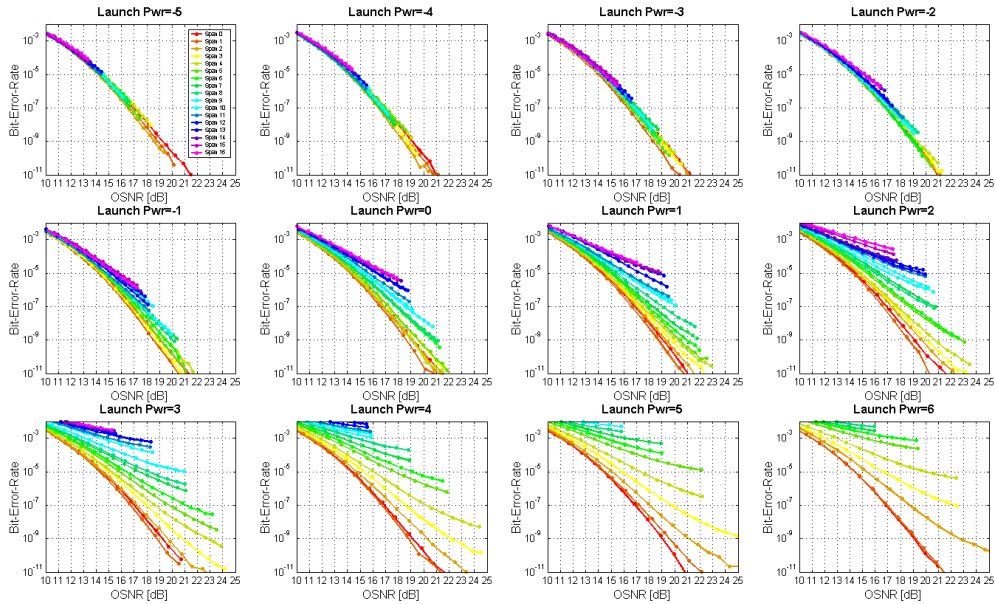


Figure 23. XPM with single co-propagating aggressor at +300 GHz (wavelength: 1542.936 nm)

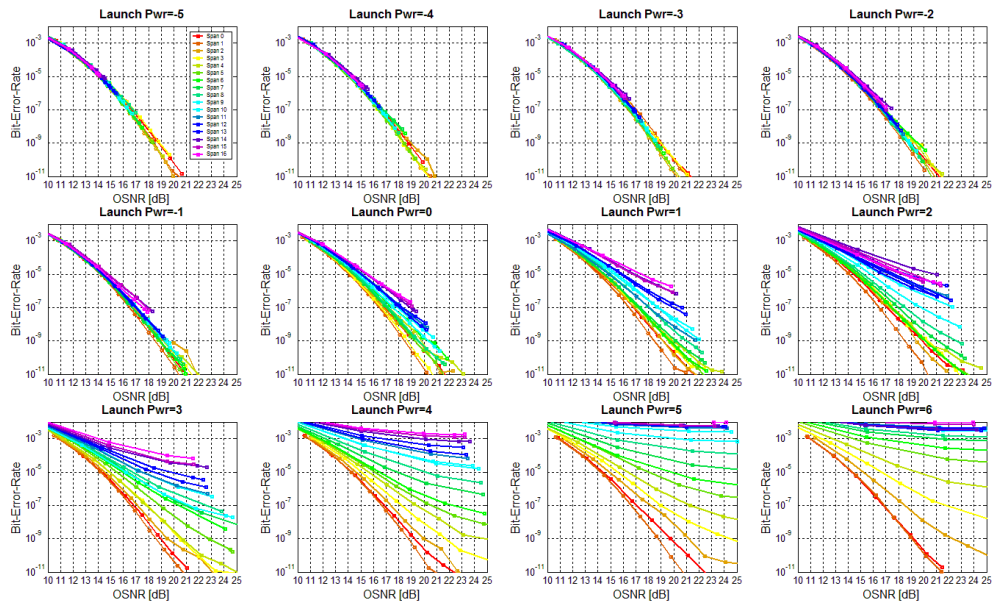


Figure 24. XPM with single co-propagating aggressor at +400 GHz (wavelength: 1542.142 nm)

The XPM OSNR waterfall charts above are summarized below by plotting only the obtained blended penalty at a BER of 1e-3 (including the SPM component) for the five conditions. It can be readily observed that the presence of a channel within 400 GHz of the channel under test causes significant penalties compared to the SPM-only condition.

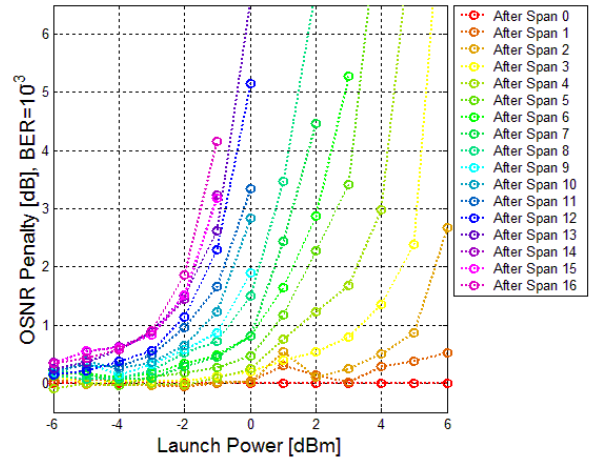
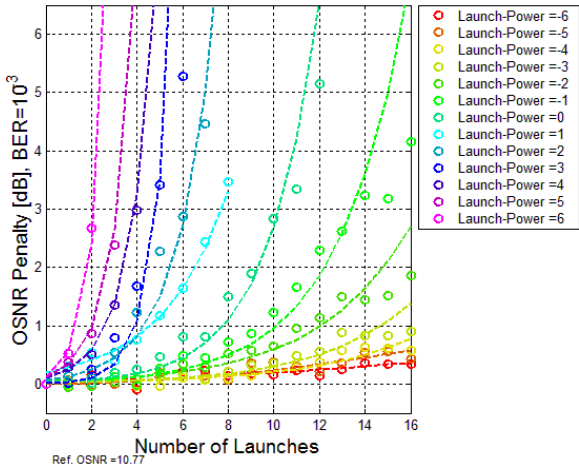


Figure 25. Co-propagating aggressor at +50 GHz, XPM penalty vs. # of launches and launch power

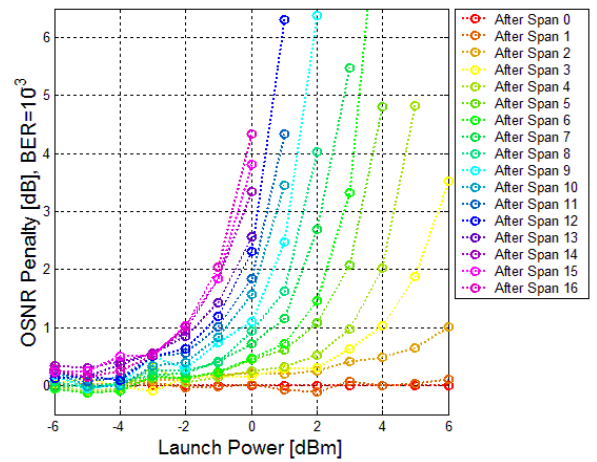
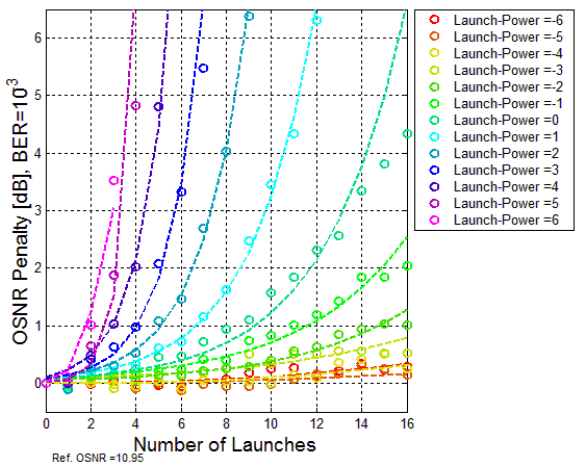


Figure 26. Co-propagating aggressor at +100 GHz, XPM penalty vs. # of launches and launch power

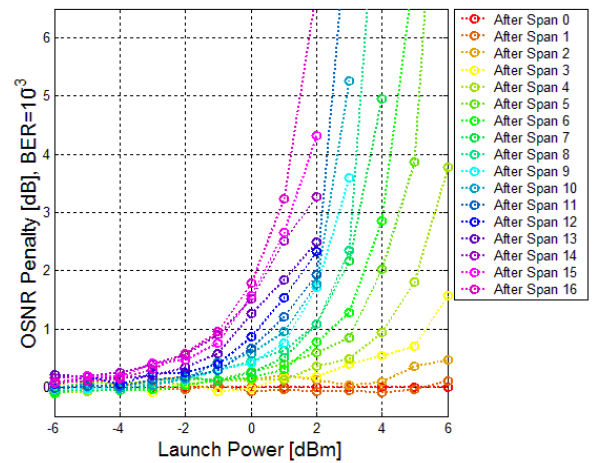
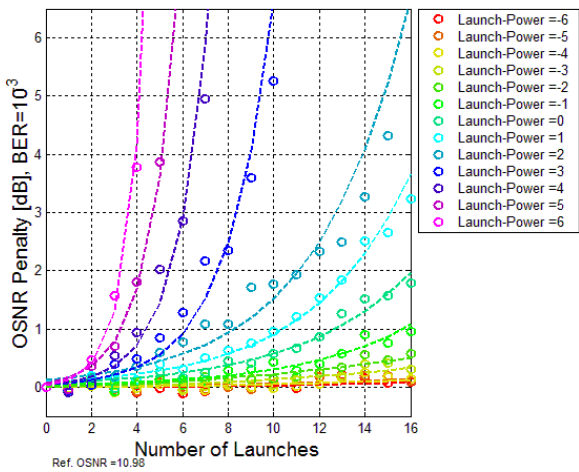


Figure 27. Co-propagating aggressor at +200 GHz, XPM penalty vs. # of launches and launch power

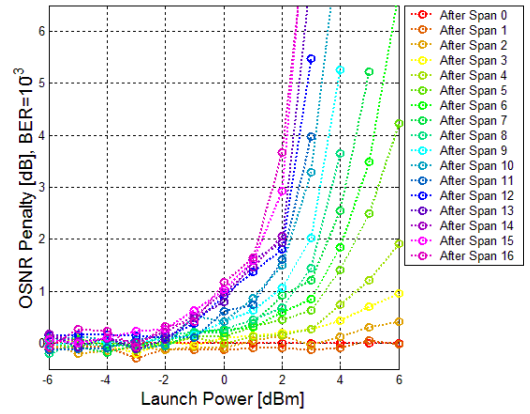
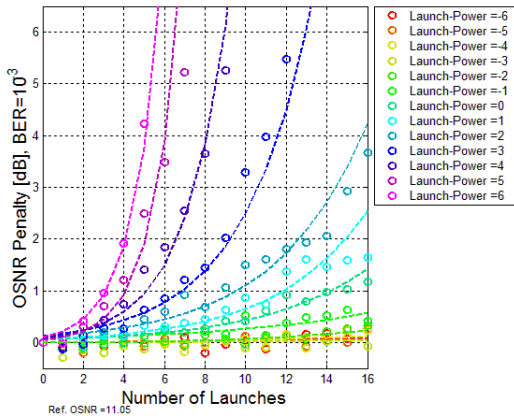


Figure 28. Co-propagating aggressor at +300 GHz, XPM penalty vs. # of launches and launch power

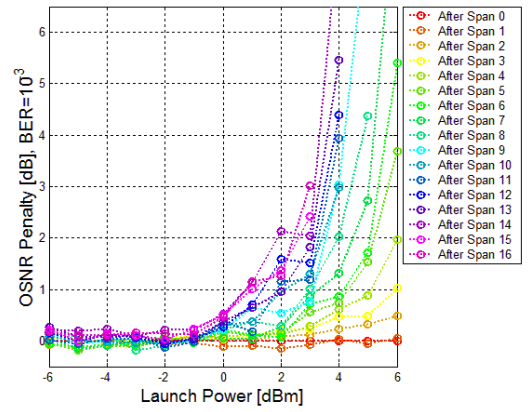
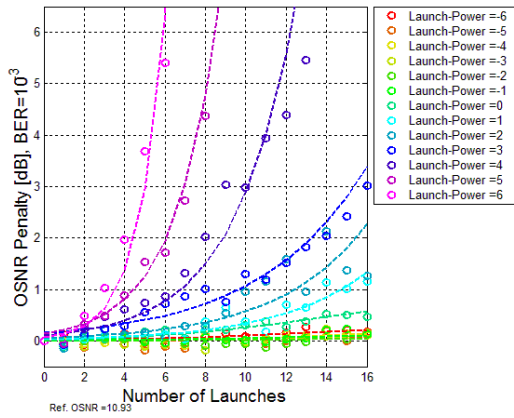


Figure 29. Co-propagating aggressor at +400 GHz, XPM penalty vs. # of launches and launch power

The penalty trend with frequency offset is shown below after 1 through 16 span launches and at select launch powers. The SPM condition is plotted to the far right of the X-axis. The trend is clear that XPM penalties are higher as the aggressor gets closer to the channel under test.

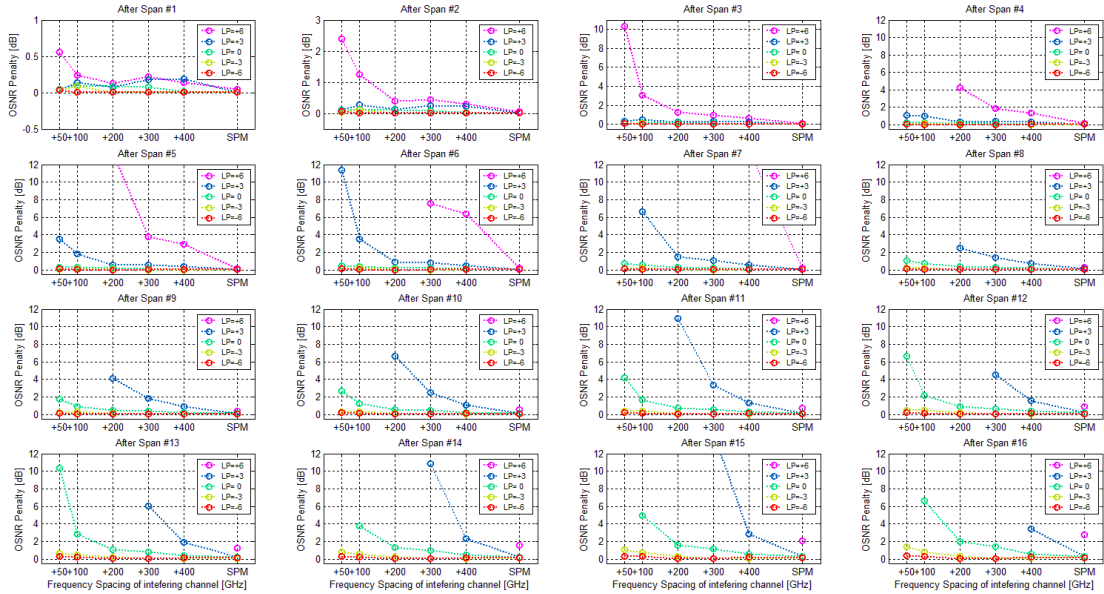


Figure 30. XPM penalty trend with frequency offset

Further PM-QPSK performance tests suggested that the XPM penalty from multiple simultaneous Intensity-modulated aggressors was not additive, and the penalty could in fact be worse (greater) than the sum of its parts. Furthermore, implementing a guard band around the PM-QPSK channel does reduce, but not eliminate, the penalty induced by XPM from the remaining channels in the spectrum, which was also shown empirically.

By comparison, the RZ-DQPSK is significantly more tolerant to XPM. Tests were conducted with four adjacent 10 G channels at -200, -100, +100 and +200 GHz spacing with respect to the channel under test. The uniform launch power of all channels over all spans was maintained at +6 dBm, where the worst penalty after 16 spans was less than 6 dB. For a uniform launch power of +3 dBm, which is more consistent with a metro transport network, the penalty was on the order of 1 dB.

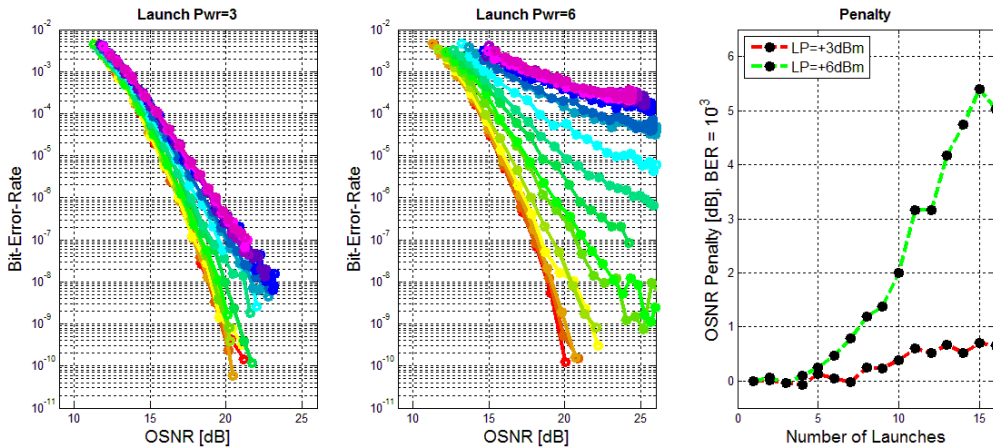


Figure 31. RZ-DQPSK XPM penalty at +3 and +6 dBm launch power, four adjacent channels on a 100 GHz grid

By contrast, XPM effects from co-propagating PM-QPSK 40 G aggressors are much less devastating (at a coherent PM-QPSK receiver), even in the same dispersion compensated test bed. However, this is less relevant in this upgrade scenario where the network operator desires to keep existing 10 G channels in place.

Mitigation of Cross-Phase Modulation (XPM)

It is important to understand that cross-phase modulation depends on the launch power of the aggressor channel, not the channel under test. There is no advantage to lowering the power of the channel under test, other than reducing self-phase-modulation penalties (if applicable).

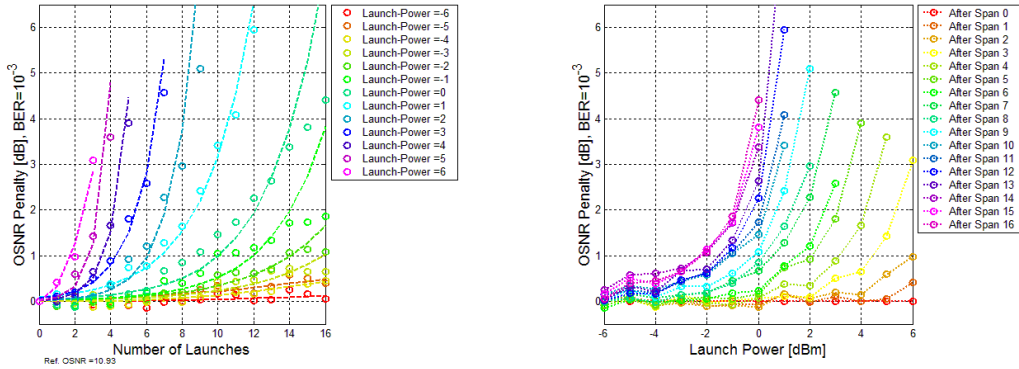


Figure 32. XPM penalty, aggressor at +100 GHz and variable launch power, DUT at fixed launch power

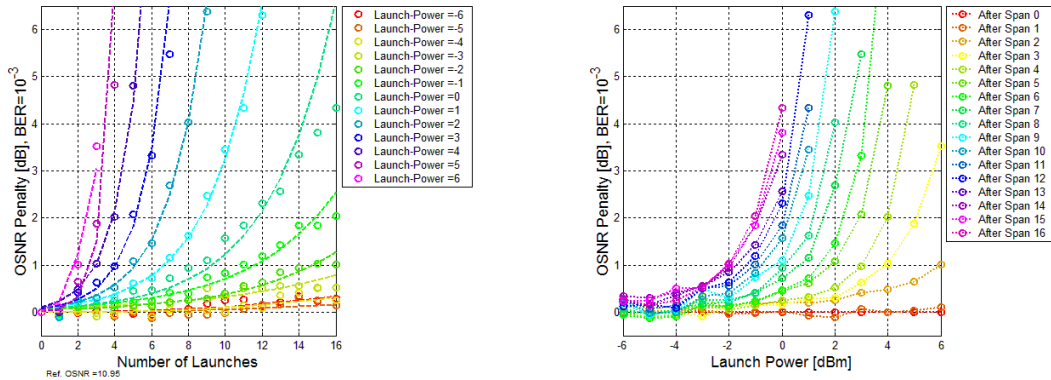


Figure 33. XPM penalty, aggressor at +100 GHz, DUT, and aggressors at same launch power

Another important fallout of the above is that the impact of an aggressor channel is, at any instant, dependent on its instantaneous power. Therefore, the instantaneous phase modulation will be worse at the aggressor’s pulse peak than during the absence of a pulse. For this reason, intensity-modulated aggressors have a worse impact than phase-modulated aggressors, because intensity-modulated aggressors will alternately cross-phase modulate the probe channel during “1” bits and not during “0” bits. By contrast, a typical phase-modulated signal at the same average power as an intensity-modulated signal only has residual amplitude modulation between successive symbols. Therefore, its cross-phase modulation will be approximately constant from symbol to symbol at half the magnitude of the intensity-modulated peaks.

Finally, over transmission fiber, the bit stream from an aggressor channel will “walk-off” from the channel under test’s bit stream due to dispersion. If dispersion-compensating fiber is used, then transmission through the DCF will gradually re-synchronize the two bit streams. Depending on the ratio of dispersion compensation being used, the number of interactions between the aggressor bit stream and the bit stream under test will grow with the number of launches, thus leaving a deeper phase “imprint” of the aggressor bit stream onto the bit stream under test.

Assuming that launch power into the DCF is low, little-to-no XPM will occur in the DCF, so the only negative effect will be bringing the two bit streams back into alignment for the next launch over transmission fiber where the XPM will be more significant.

The amount of XPM and the walk-off is identical for PM-QPSK and for RZ-DQPSK. The primary difference in impact is due to the baud difference and how the receiver detects the incoming data.

For coherent PM-QPSK, the DSP estimates the absolute signal phase at each sampling instant, while for RZ-DQPSK, the differential balanced receivers compare the phase from one symbol to the phase in the previous symbol. This latter technique can be more resilient in some regimes, since it does not rely on absolute phase. A single aggressor bit at 10 G affects two consecutive bits in the RZ-DQPSK stream at any instant, so there is a stronger correlation in XPM between consecutive bits that can be filtered out by differential detection.

Reducing the number of times the same aggressor bit-stream interacts with the same bit stream under test should reduce XPM penalties. This was done experimentally using two schemes.

The first scheme was to eliminate dispersion compensating fibers. Although this technique has little value in a real-world brown-field deployment since IM channels require compensation, the experiment lets us quantify how much can be gained by reducing the number of interactions between an aggressor bit stream and the channel under test. In a real world scenario, this can be achieved by using dispersion compensating gratings (DCGs) instead of DCF, because DCGs have a small overall group-delay, and only the slope of the group delay within the channel is matched to the desired chromatic dispersion. Thus, higher-wavelength bits do not get a chance to catch up to lower wavelength bits, as they do with DCF. DCGs would have the added benefit, compared to an uncompensated system, of reducing the peak-to-average power ratio that can occur in the propagating channels, with the aggressor channel being most relevant in this case for XPM effects. Unfortunately, very few DCGs were available for this test, so we performed the academic test of eliminating dispersion compensation entirely.

The next scheme was to use interleavers to separate the even ITU wavelengths on the 100 GHz grid (such as 194.1, 194.2 THz) from the odd ITU wavelengths (such as 194.15, 194.25 THz). The interleavers were deployed around DCF modules such that even channels propagated through DCF while odd channels did not. This implementation required careful loss balancing for all channels to keep the same channel power with respect to each other throughout the system.

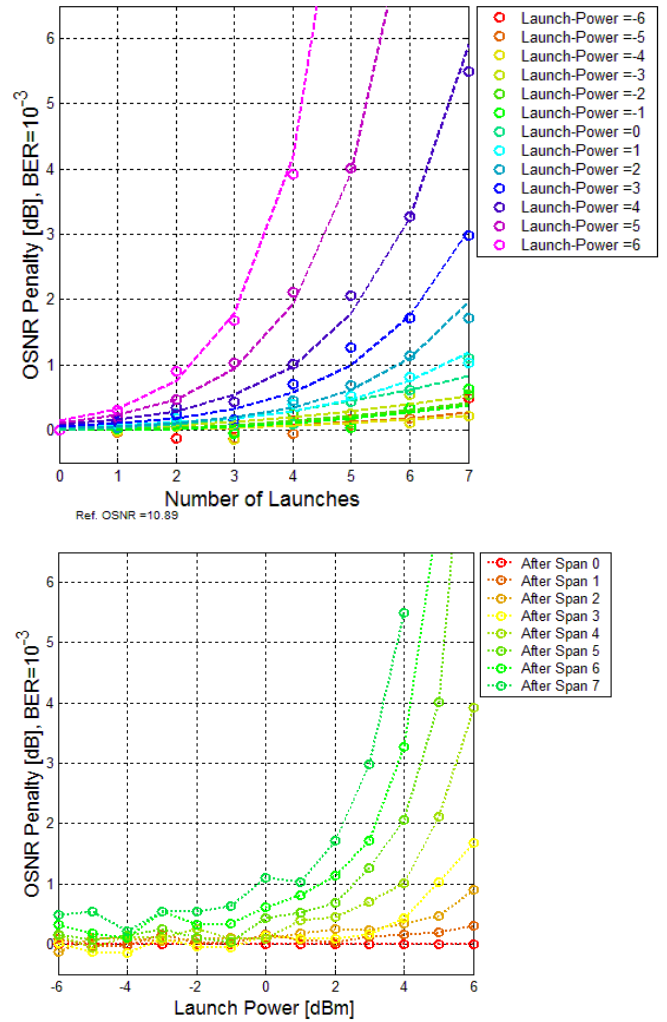


Figure 34. XPM penalty due to 100 GHz IM aggressor in baseline DCF-compensated test bed

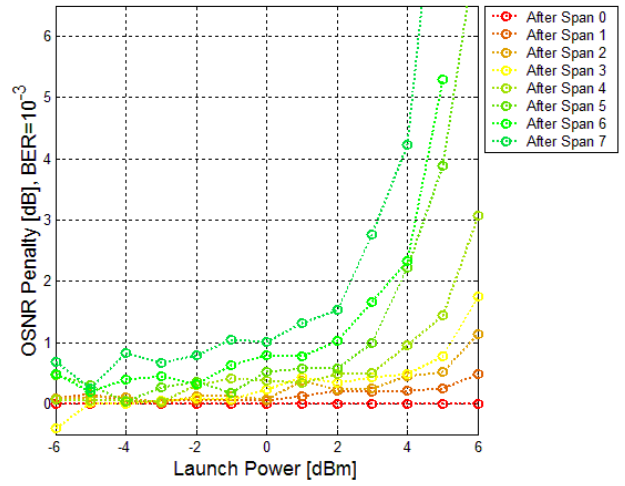
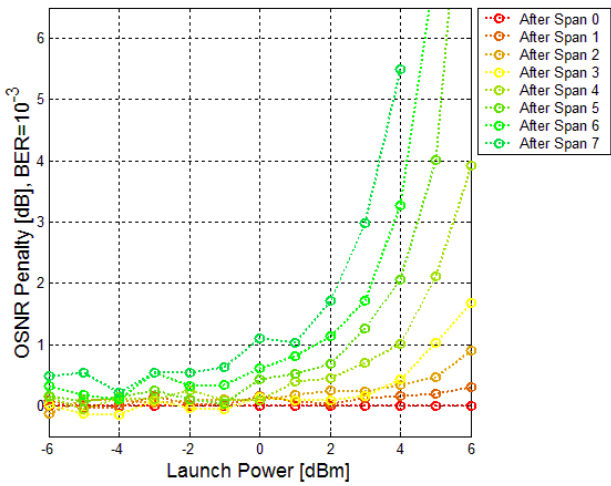
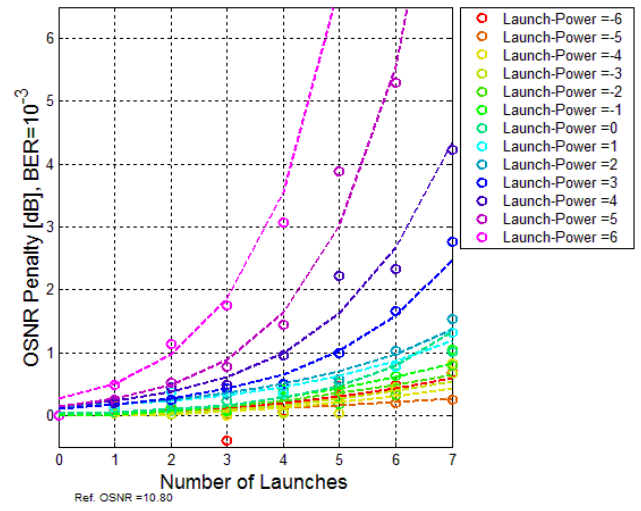
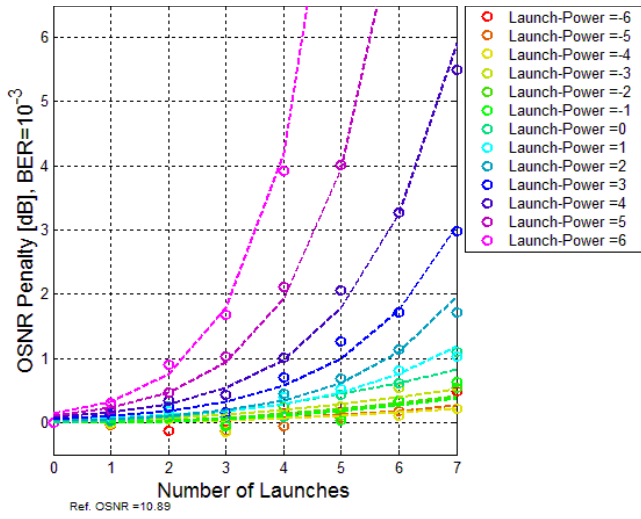


Figure 35. XPM penalty due to 100 GHz IM aggressor in uncompensated test bed

Figure 36. XPM penalty due to 50 GHz IM aggressor in split DCF test bed

The figures compare XPM effects over 7 spans in the baseline DCF-system, the same system without DCF, and finally the split-DCF (interleaver) system. Penalties for both of the latter schemes were on par, and less than for the system with DCF. However, it should also be noted that the aggressor in the split-interleaver scheme was only 50 GHz away, so in fact the penalty was better than for the no DCF scheme with respect to aggressor proximity. Both methods indeed reduced XPM penalties, but neither method tested is viable in a brown-field scenario, since the former requires removing all compensation (not in-service), while the latter method requires careful attenuation balancing for even and odd channels. Both require

- The system to go out-of-service
- Truck-rolls to various intermediate sites

However, the untested method of using DCGs may be readily available to some systems.

Pre-dispersing either the aggressor channel or the channel under-test does not mitigate the XPM impact. In our experiments, pre-distortion methods either maintained the same impact or increased penalties. It is believed that the higher peak-to-average ratio of the pre-distorted signal is responsible for this degradation.

The Lumentum Network Application Validation Lab

The lab is located in Ottawa, Ontario, Canada and serves the Lumentum Network and Service Enablement (NSE) and Communication and Commercial Optical Products (CCOP) segments. The lab has been used to validate numerous optical instruments, test gear, and network equipment in a real telecommunications network setting.

Equipment Inventory

- General Photonics PMD-Pro PMD-1000, (S/N 106800000033)
- Lumentum MAP-200 chassis (S/N 170), FW R. 2.4.18
- Lumentum MAP mBBS broadband ASE source (S/N 2014), FW R. 0.00
- Lumentum MAP mVOA, dual (Multi-Mode) (S/N KJ000340), FW R.2.10
- Lumentum MAP mTBF-A1GS0-MPOWMON-MFP, tunable filter (S/N 00003012), FW 0.00
- Lumentum MAP MLCS-A1108BD-M100-MFP 2x8 switch (S/N IS114188), FW R. 5.11Lumentum MAP Lumentum MAP mOPM, dual high-power meters (S/N 109), FW R.1.4.14
- Lumentum MAP mVOA, dual VOAs with integrated power meter (S/N 2126 and 2127), FW R. 3.021
- Lumentum TBERD/MTS-8000(S/N 7546) OSA-303 dual-input optical spectrum analyzer S/N B-0074
- JDS Fitel SC 1x40 port Switch (S/N 0), FW version 3.13
- JDS SG 8x8 matrix switch (S/N 0), FW Version 3.21
- TeraXion TDCMX-C050-EF-BS08 tunable dispersion compensator (S/N T090750), V01.01

Test instruments included:

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