WHITE PAPER

Modeling 400G-ZR and 400G-ZR+ Data Center Optics with Synopsys OptSim

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Introduction

Coherent optics is on the move—from traditional long-haul deployments to emerging data center interconnects. Pluggable transceivers—unamplified and amplified, single- and multi-wavelength—for 400G and higher speeds are being standardized and becoming commercially available to cover transmission distances from 40-km to 120-km. The Optical Internet working Forum's (OIF) 400-ZR implementation agreement (IA)[1] for 400GbE transport using coherent optics is aimed at reducing cost, complexity and advancing interoperability of optical modules from multiple vendors. And the Institute of Electrical and Electronic Engineers (IEEE) P802.3ct Task Force 400GBASE-ZR[2] is aimed at a coherent solution for 80-km.

The timing for 400G and beyond is just right, for several reasons:

- Recent advances in CMOS nodes that benefit 400G digital signal processing (DSP) and lower power consumption [3]
- Silicon photonics, which provides lower footprint, higher bandwidths and better energy efficiencies [4]
- Higher-order modulation formats, which offer better spectral efficiencies per wavelength [5]
- Forward-error-correction (FEC) techniques, which allow amplified and unamplified transmission over longer distances)[6]

Study groups, such as IEEE Beyond 400G[7] and OIF 800G Coherent[8], have been formed to explore even higher-speed connectivity standardization. However, this paper will cover 400G ZR and ZR+, since the design flow and modeling methodology for these technologies also apply to the optical interconnects operating at data rates beyond 400G and 800G.

Challenges

As with every new and emerging technology, the ability to create and test prototypes is the first step towards designing a viable solution. Modeling coherent optics of 400G-ZR and ZR+ requires the ability to employ polarization diversity, accurate modeling of the interplay between dispersion and nonlinearities in single- and multi-channel setups, capability to account for laser phase noise and line-widths, options for advanced DSP modeling for training, equalization, and FEC at the receiver. Since semi-analytic techniques often aren't as accurate for phase-modulated coherent systems, counting errors remains the most reliable option. Counting errors would require a simulator to be able to handle a large number of sampled data without incurring prohibitive computational overheads. Although 400G-ZR primarily uses a polarization multiplexed 16-QAM (PM-16QAM) modulation format, modeling ZR+ and beyond 400G requires a complex mix of advanced, multi-level modulation formats. Since all the above is in contrast to traditional intensity modulation/direct detection (IM/DD) fiber-optic system design, choosing the right simulation and analysis platform is of utmost importance. As discussed next, Synopsys OptSim[9] is the right simulation tool for the job.

Solution

A one-size-fits-all approach to choosing photonic system design software does not work efficiently for the ever-evolving nature of the applications and modeling problems. At the same time, too many software choices can be confusing. Synopsys OptSim strikes the optimal balance between the two. While traditional fiber-optic system simulators use the frequency-domain split-step (FDSS) approach, Synopsys OptSim users can choose to work either with the time-domain split-step (TDSS) simulation engine or with the FDSS simulation engine. Synopsys OptSim's circular-convolution-based FDSS method has been widely used for decades in a variety of modeling problems.

Synopsys OptSim's linear-convolution-based TDSS is especially helpful for modeling problems where periodicity assumptions don't reflect reality, such as in mixed bitrate situations, in cases when phase noise is important, and in cases when transmission of a large number of bits is required without creating exorbitant computational requirements. Coherent optics of 400G-ZR and its variants fall into this latter group, i.e., the scenario where applying the TDSS simulation engine is a better approach over FDSS.

Before we discuss the setup a 400G-ZR design in Synopsys OptSim, let us review the basic building blocks of a coherent fiber-optic system.

Overview of a Coherent Transceiver

A coherent transceiver includes a polarization-diversity transmitter and a coherent receiver.

A block diagram of a dual-polarization transmitter is shown in Figure 1. Each of the two polarizations of the light source are modulated by the I-Q modulators at the symbol rate from independent data streams. The number of bits in a symbol (and hence the number of data streams) depends upon the type of higher-level modulation format used.

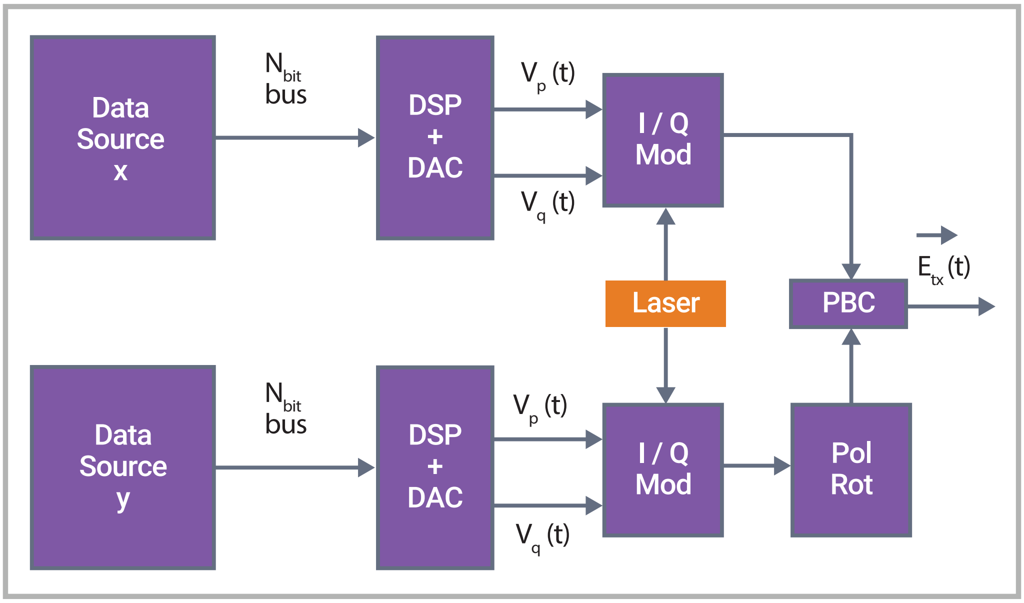

Figure 1: Block diagram of a polarization diversity transmitter

In a 400G-ZR transmitter, the symbol rate is 59.84-GBd/s per wavelength. Since the modulation format specified by the standard is 16-QAM (i.e., 4 bits per symbol in each polarization), the total data rate at the transmitter output is 478.72-Gb/s including FEC overheads.

The received, modulated optical signal at the receiver is mixed with a narrow-linewidth, CW local oscillator signal. The 90-degree hybrid outputs a down-converted, I-Q separated signal to pairs of balanced photodetectors. The block diagram of a coherent receiver is shown in Figure 2.

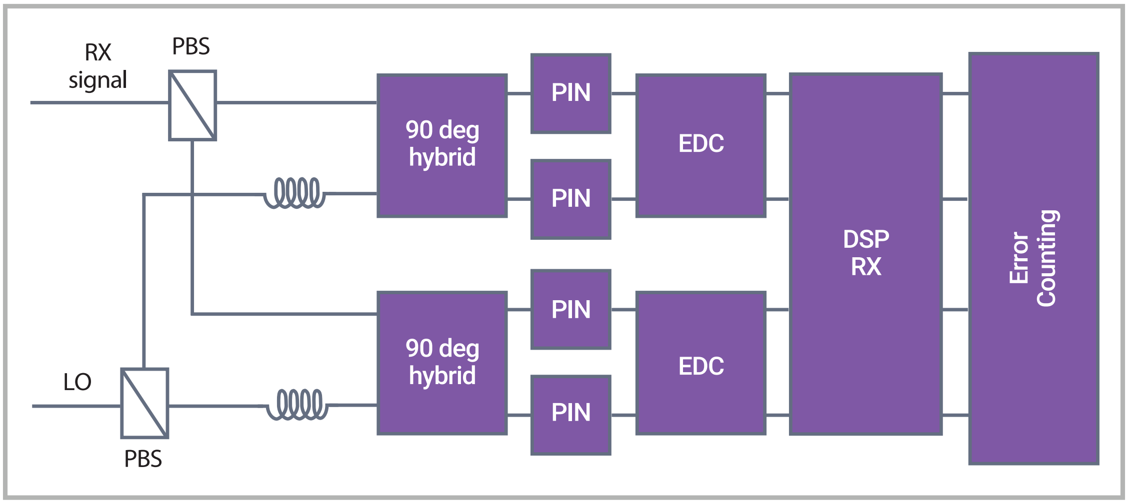

Figure 2: Block diagram of a coherent receiver

The detected electrical signal undergoes various stages of signal processing, including analog-to-digital conversion (ADC), dispersion compensation, polarization recovery, compensation of polarization mode dispersion (PMD) and polarization-dependent loss (PDL), carrier recovery, decision, and counting of errors excluding the receiver training bits. The equalization can be static or dynamically tracked and adapted post-training.

Overview of the Transmission Channel

As shown in Figure 3, the transmission channel used in 400G-ZR links is a standard singlemode fiber with a length in the 40-km-120-km range. The booster and pre-amplifier are micro-Erbium-Doped Fiber Amplifiers (EDFA) integrated into the transceiver modules.
The booster amplifier provides power gain to 400G-ZR transmitter outputs and the pre-amplifier amplifies the received signal from the fiber. The link does not use any optical compensation of fiber dispersion. The signal in the fiber experiences linear, nonlinear and polarization-dependent transmission impairments that deteriorate the optical signal-to-noise ratio (OSNR), thereby adversely affecting the link performance and the supportable distance for data transmission.

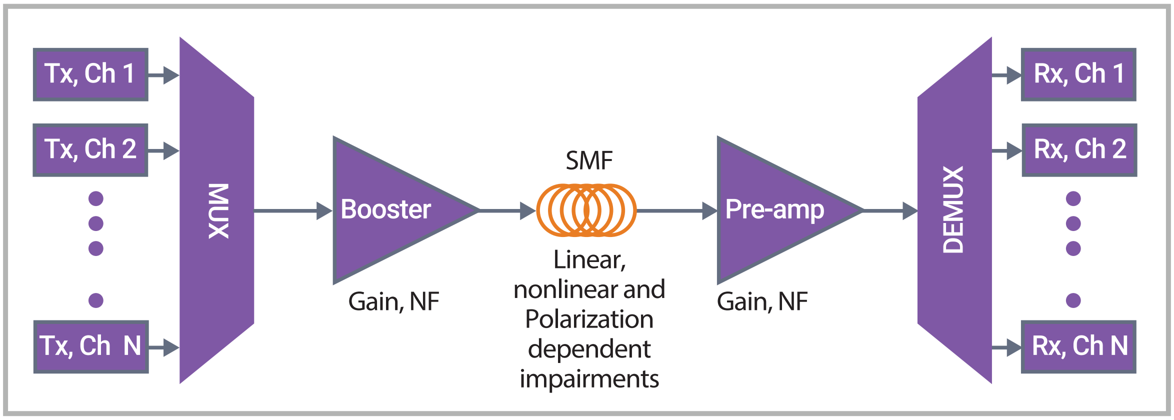

Figure 3: Block diagram of an end-to-end, DWDM multi-channel 400G-ZR interconnect

The fiber spans can also be modeled analytically via a Gaussian Noise (GN) emulator. It has been shown experimentally[10], via Synopsys OptSim-based modeling[11], and analytically[12-13] that for uncompensated, long-haul coherent systems (such as 400G-ZR and ZR+), nonlinear transmission impairments in fiber manifest as nonlinear interference (NLI) with GN power spectral density.

400G-ZR Simulation Setup in Synopsys OptSim

As we saw earlier, the OIF 400G-ZR IA specifies 400-Gb/s optical transmission over a single wavelength for a dense wavelength-division multiplexing (DWDM) implementation, resulting in a massive overall interconnect bandwidth. The standard defines optical parameters for both unamplified, single-channel (Application Code 0x02) and amplified DWDM (Application Code 0x01). The amplified, noise-limited Application Code 0x01 also includes a use case of 400-ZR point-to-point transceiver line card interface. For the sub-80-km range, normative 48 frequencies on a 100 GHz grid or optional 64 frequencies over a 75 GHz grid are defined based on Table 30 and Table 31, respectively, of the ITU-T G694.1 Section 6[14]. The link should provide an OSNR of 29dB below 80-km and the vendor modules are recommended to provide 26dB of OSNR tolerance leaving a margin of 3dB for long-term operations. The OSNR tolerance includes transmitter return loss, connector degradations, etc. but does not need to be met in the presence of fiber path penalties arising from dispersion, nonlinearities, polarization dependent loss (PDL) and dispersion (PMD). For more details, please refer to the 400ZR Implementation Agreement[1]. Synopsys OptSim is an ideal modeling tool for system integrators to evaluate OSNR tolerances and penalties form transmission impairments in 400G-ZR and beyond 400G systems.

For the Synopsys OptSim simulation study, we consider both—the unamplified single-channel and the amplified DWDM—types of 400G-ZR data center interconnect designs. The OSNR values are measured at the receiver over 0.1nm (or 12.5GHz) optical bandwidth. The pre-FEC BER values mentioned are based on the error counting per channel at the receiver excluding training and transient frames.

Single-Channel, Loss-Limited 400G-ZR (OIF Application Code 0x02)

The simulation setup in Synopsys OptSim for the single-channel 400G-ZR is shown in Figure 4. The 59.84 GBd/s PM-16QAM transmitter is centered at 193.7 THz laser frequency.

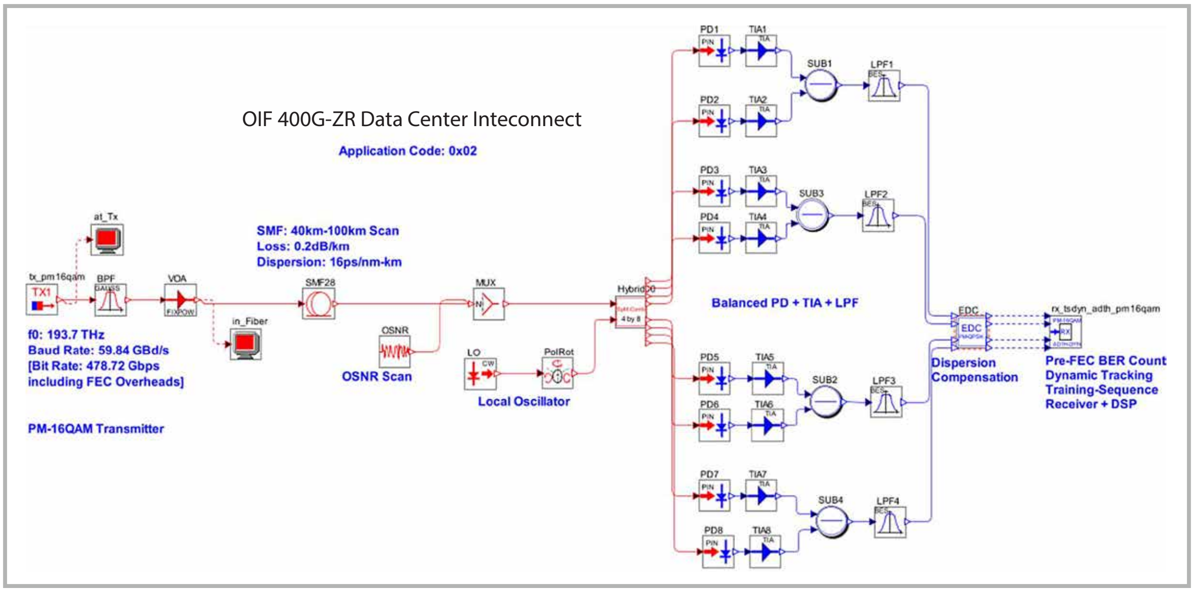

Figure 4: Schematic setup in Synopsys OptSim: Unamplified 400G-ZR

The transmitter is implemented as multi-level hierarchy, details of which are shown in Figure 5. The I-Q modulators, driven by Gray-encoded 16QAM symbols modulate each polarization of the laser source. The modulator driver levels are chosen to pre-compensate modulator nonlinearity to obtain a square 16QAM constellation at the transmitter output.

The variable optical attenuator (VOA) at the output of the transmitter facilitates tuning of transmitter power, which is set around a nominal value of 12dB above receiver sensitivity. This is to provide an industry-adopted link budget in power-limited, single-wavelength transmission for up to 40-km distance between the data centers.

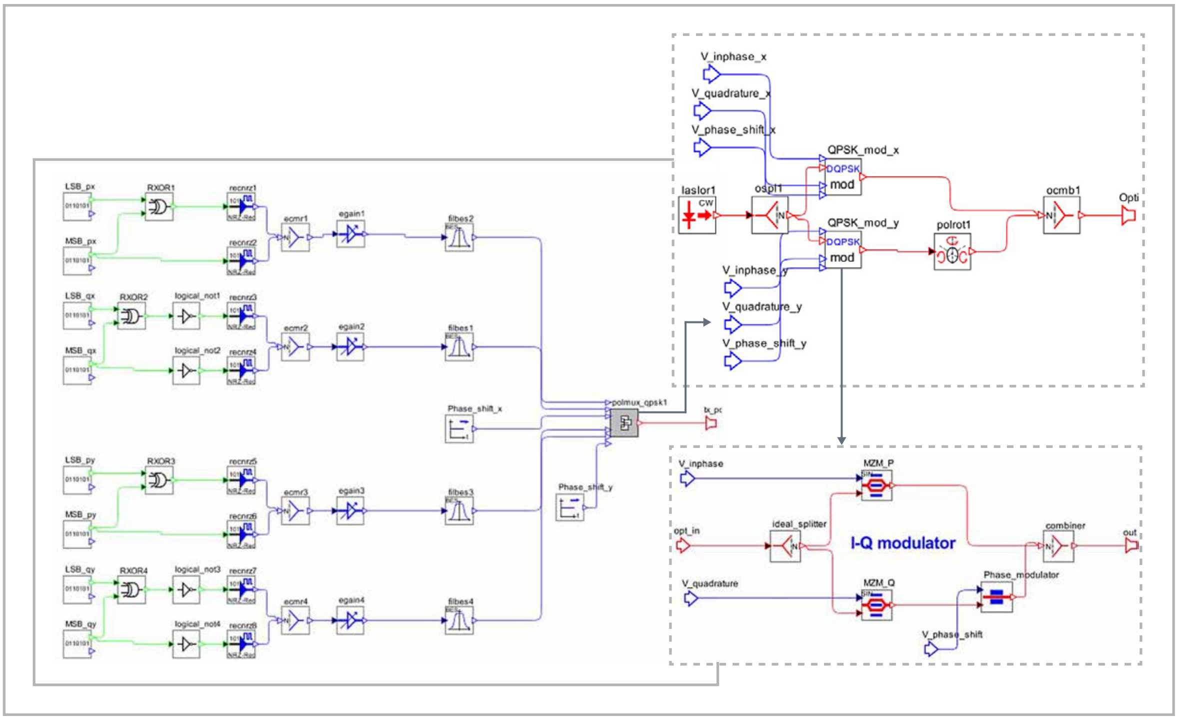

Figure 5: Details of the PM-16QAM transmitter hierarchy: Gray encoded I-Q drivers (left), polarization diversity (upper right) and an I-Q modulator (lower right) for each polarization

A scan over OSNR is set up for receiver sensitivity studies. The received signal is mixed with the local oscillator at the 90-degree hybrid input and the detected signal after balanced photodetection and I-Q separation undergoes receiver-side digital signal processing for training, tracking, equalization and pre-FEC counting of errors.

A back-to-back simulation run was carried out first to test the receiver sensitivity. Figure 6 shows selected waveforms at the modulator input, at the transmitter output and at the receiver before the DSP.

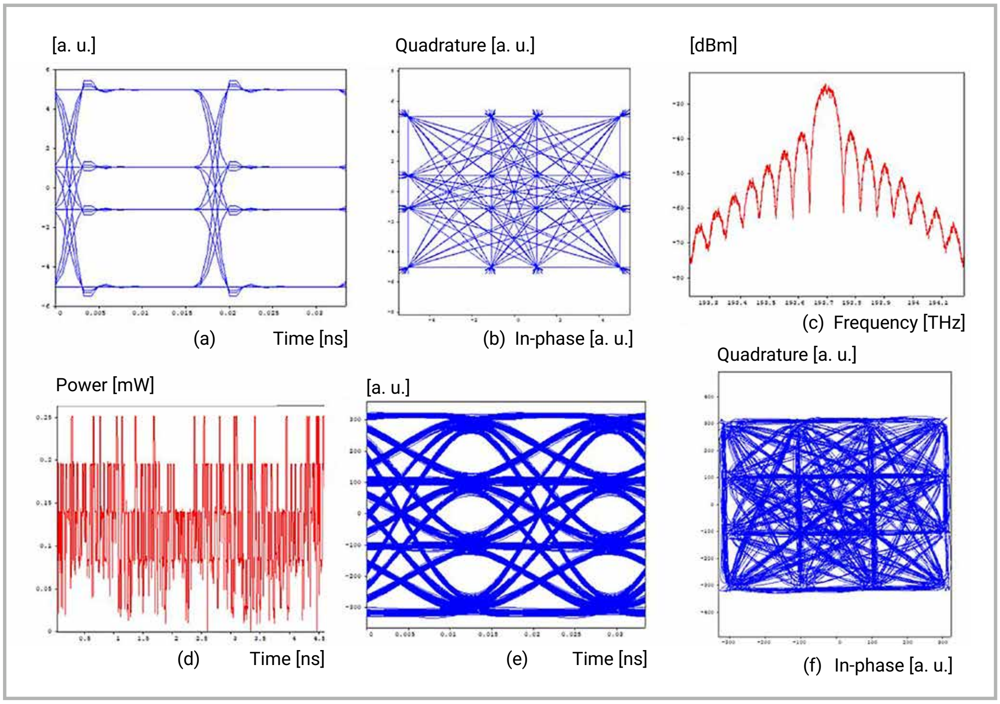

Figure 6: Waveforms for one of the polarizations from a back-to-back simulation: (a-b) electrical drive at the modulators, transmitter output spectrum (c) and signal (d), post-detection eye diagram (e) and signal constellation (f)

Next, we perform a parameter scan over OSNR at the receiver for the unamplified setup of Figure 4. Although such interconnects are designed for distances up to 40-km, the sensitivity analysis was done for transmission distances of 40-km, 60-km, 80-km, and 100-km (Figure 7). In an unamplified link, the reach is dependent on channel loss, receiver sensitivity and transmit powers.

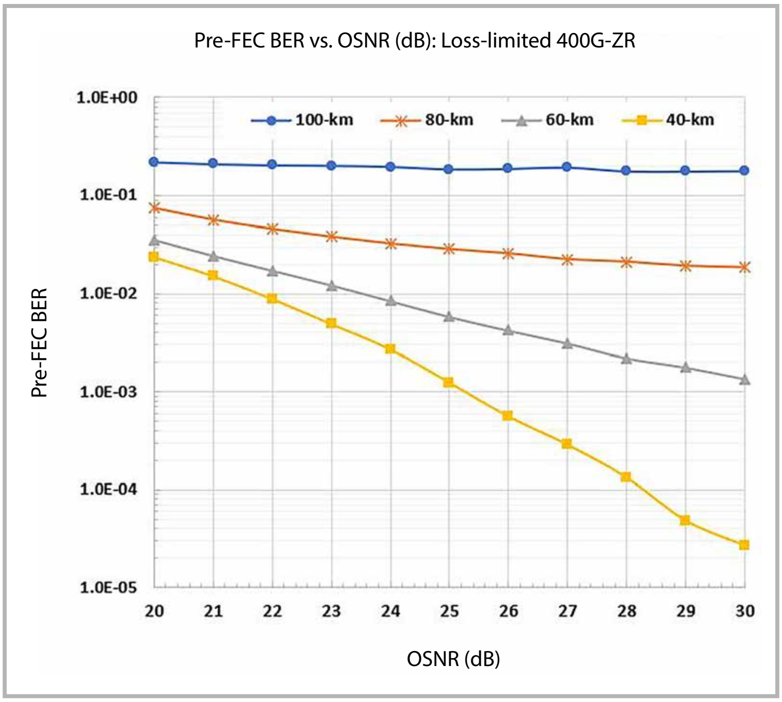

Figure 7: Pre-FEC BER vs. OSNR for the un-amplified 400G-ZR interconnect under study

As can be seen from Figure 7, the un-amplified 400G-ZR interconnect under study performs better than the pre-FEC BER of 1.25E-02 for a 40-km link. The unamplified link under study performs well even at 60-km with a slightly higher OSNR. If lower margins are acceptable, or if transmitter power can be increased, longer distances for this single-channel system can be supported.

Next, we extend the above study to an amplified, noise-limited DWDM 400G-ZR design.

DWDM, Noise-Limited 400G-ZR (OIF Application Code 0x01)

The basic principle for the setup of a DWDM 400G-ZR system is illustrated in Figure 3. These interconnects are designed to transport a much higher capacity compared to the 0x02 single-channel, unamplified links that we saw earlier. Each of the multiplexed wavelengths carries 59.84 GBd/s PM-16QAM data aided by the booster, pre-amplifier and the receiver DSP, resulting in enhanced spectral efficiency. The link aims to provide an OSNR of 29dB below 80-km and the vendor modules are recommended to provide 26dB of OSNR, leaving a margin of 3dB for long-term operations. As mentioned earlier, the specified OSNR tolerance includes transmitter return loss, connector degradations, etc. but does not need to be met in presence of fiber path penalties arising from dispersion, nonlinearities, polarization dependent loss (PDL) and dispersion (PMD).

The simulation setup in Synopsys OptSim with seven DWDM channels, each carrying 59.84GBd/s data over a 100GHz grid, is shown in Figure 8.

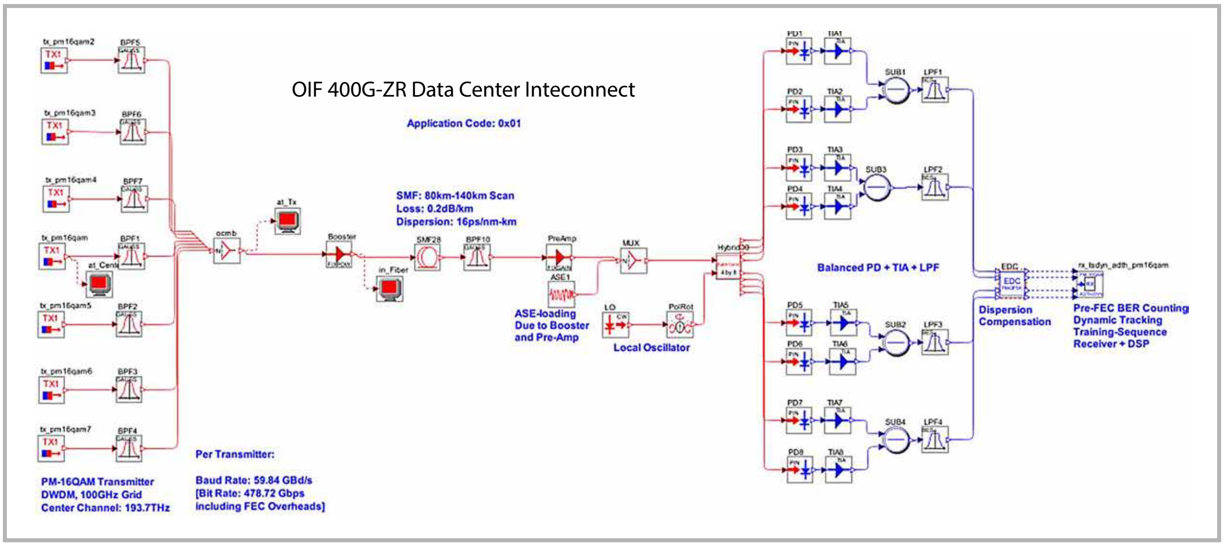

Figure 8: Schematic setup in Synopsys OptSim: DWDM 400G-ZR

Although the setup under discussion models an actual ITU-T G.652 fiber span, as mentioned earlier, from modeling perspective, the fiber span can also be replaced by a Gaussian Noise (GN) emulator available in Synopsys OptSim. GN models can provide better computational efficiency without meaningful accuracy trade-offs at optimal transmit powers.

Figure 9 includes an un-filtered signal spectrum for the center channel as well as the 100GHz DWDM signal spectrum at the transmitter for the setup shown in Figure 8.

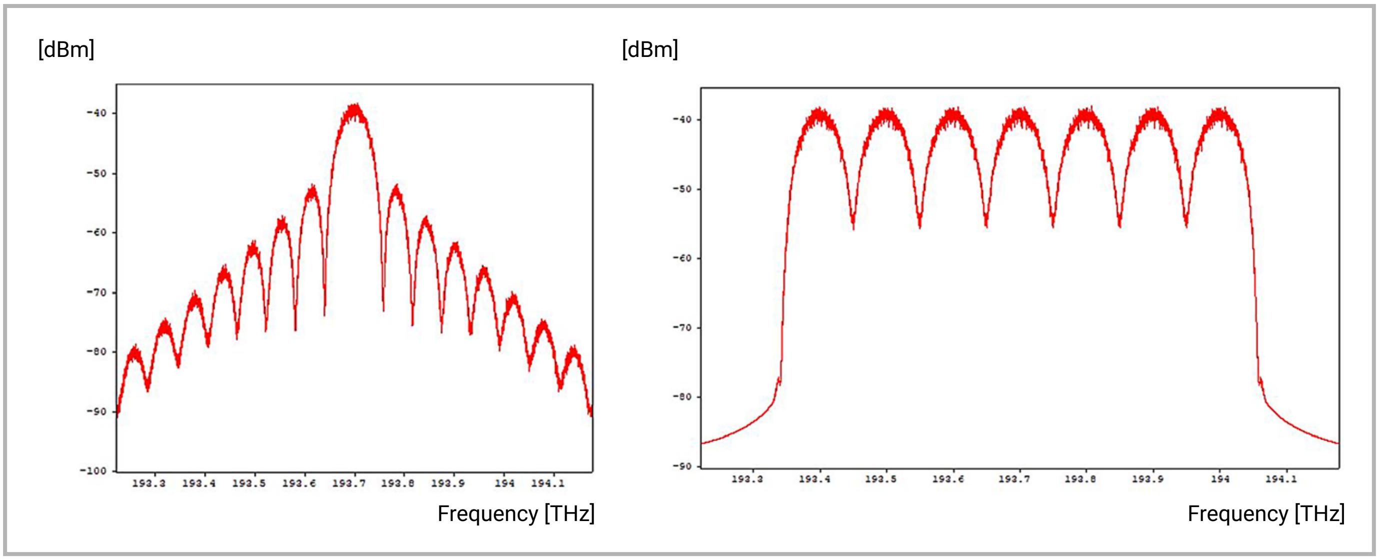

Figure 9: Spectrum of the un-filtered center channel (left) and 100GHz DWDM transmitter spectrum (right)

For amplified links, the reach is dependent on the OSNR at the receiver which, in addition to the laser, booster and pre-amplifier characteristics, is also dependent on the number of active wavelengths in the link since the nonlinear interference (NLI) in unamplified coherent links manifests as worsening of received OSNR.

To account for the amplified spontaneous emission (ASE) noise from booster and pre-amplifier, a noise-adder model is used to add an equivalent amount of optical noise to the received signal. Although each amplifier model can be specified to have its individual, wavelength dependent noise-figure, the convenience of using the noise adder model is that the noise spectral density of the noise adder model can be expressed as a function of OSNR, making it easier to carry out a parameter scan over different OSNR values, rather than having to measure OSNR from the received signal for different link margins and fiber lengths.

Figure 10 shows the receiver sensitivity for the DWDM system of Figure 8 with each of the channels carrying 400G data. The per-channel bitrate including FEC overheads is 478.72Gb/s.

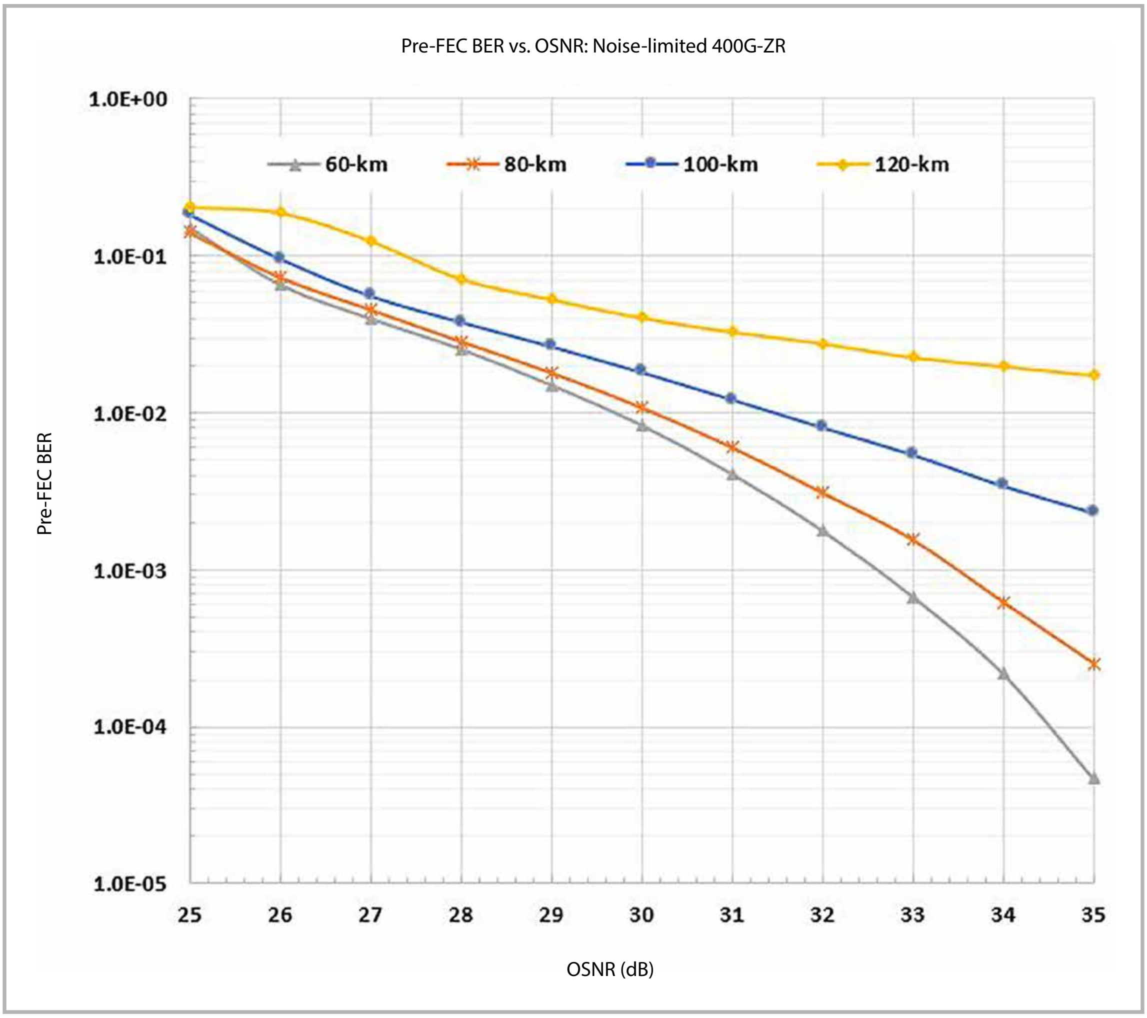

Figure 10: Pre-FEC BER vs. OSNR for the DWDM 400G-ZR interconnect under study

As can be seen from the plot, 31dB of OSNR at the receiver is required to support up to 80-km transmission with pre-FEC BER of 1.25E-02 for the seven 400G channel DWDM interconnect. To support longer distances, higher OSNR is needed due to the increasing NLI with increasing number of channels.

In order to understand the impact of penalties from the fiber path arising from dispersion, non-linearities, polarization-dependent loss (PDL) and dispersion (PMD), we carry out OSNR sensitivity studies at various transmission distances as the number of DWDM channels increases. Figure 11 shows a plot of required OSNR at the receiver to support transmission of up to 80-km.

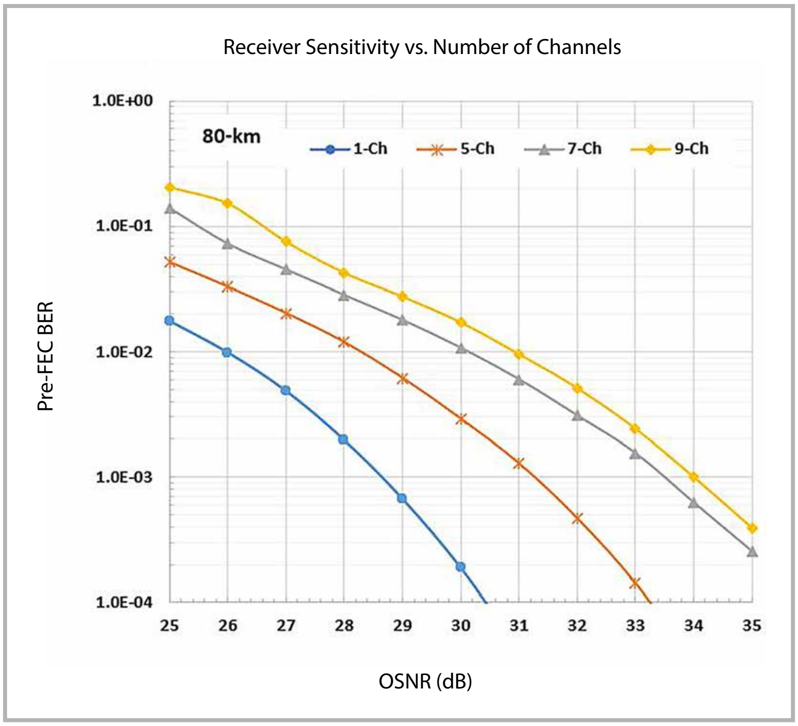

Figure 11: Pre-FEC BER vs. OSNR to support 80-km 400G-ZR DWDM transmission

As is evident from the plot, an increasing number of DWDM channels in the noise-limited amplified 400G-ZR links requires higher received OSNR for a given transmission distance. For example, in order to maintain a pre-FEC BER of 1.25E-02, a 5-channel DWDM design requires 3-dB higher OSNR while a 9-channel DWDM requires almost a 5-dB better OSNR compared to the single-channel noise-limited case.

Conclusion

The demand for bandwidth is expected to continue growing at a faster rate for the foreseeable future. The industry standards will continue evolving to keep up with the demand. On the other hand, advances in high-bandwidth components (such as lasers and modulators) at the economies of scale are expected to grow more slowly. As a result, a designer must explore innovations in silicon photonics, higher-order modulation formats, polarization diversity, and advances in DSP and FEC for achieving higher spectral efficiencies at a lower energy consumption.

Synopsys OptSim is equipped with advanced modeling capabilities that can help during development of new standards and support product design cycles for existing and emerging technologies. Synopsys OptSim helps data center architects in evaluating available and proposed vendor solutions. Beyond the product design and technology selection, Synopsys OptSim can also help business development teams in the HPC/datacenter supply chain by successfully demonstrating to their customers the standards compliance and deployment feasibility of their pluggables and near and co-packaged optics (NPO/CPO) by simulation-aided performance demonstrations.

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Reference

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