Pitfalls when Modeling High-Speed Optical Transmission Systems

André Richter, Hadrien Louchet, Igor Koltchanov
VPIphotonics (a division of VPIsystems), Germany.
andre.richter@vpisystems.com

Abstract: *We present methods for accurately modeling high-speed optical transmission systems with channel data rates beyond 40Gbit/s. We provide simulation guidelines and examples for investigating limitations of transmitter and receiver, fiber impairments, and estimating signal performances.*

Introduction

Photonic Design Automation (PDA) plays an important role in engineering complex photonic components and systems [1]. Professional PDA solutions can fully verify optical designs to identify cost savings, investigate novel technologies, and fulfill specialist requirements. Careful systems-level simulations can be used to test the performance of existing optical equipment, and define performance requirements for new equipment to ensure robust operation for all required application scenarios. However, due to modeling limitations of computer-based representations of real world problems, certain design rules should be adhered to avoid misleading simulation results and drawing unrealistic conclusions. In what follows we provide guidelines and application examples for estimating the signal performance.

Signal Representations

Optical signal representations with different degrees of abstraction are important to provide flexibility in modeling photonic networks [2, 3]. Time-domain simulations that pass individual time samples on an iteration-by-iteration basis between modeling blocks should be used to investigate the properties of integrated photonic circuits, high-speed transmitters and receivers, where the analysis of bidirectional interactions in the picoseconds range are of key importance [4]. Mixed-domain simulations passing arrays of time samples between modeling blocks can be used for unidirectional propagation applications and for bidirectional scenarios where time delays are longer than the array duration (e.g., optical switching scenarios in bidirectional ring networks), or where bidirectional interactions can be averaged in time (e.g., bidirectional Raman pumping of optical fiber). The simulation efficiency can be controlled by representing optical signals either by their complex, polarization-dependent sampled waveform, or by time-averaged parameters only. Keeping parasitic terms resulting from optical amplification, crosstalk, and scattering processes separate from the optical signal allows the investigation of their impact on the signal quality.

Equipment Modeling

Different levels of equipment modeling abstraction help to address the trade-off between detail and computation speed. Typically, detailed models require detailed parameters, whereas behavioral models operate on measured characteristics, or data from data sheets. At one extreme, detailed physical models represent components based on material and structural parameters. These parameters may be difficult to obtain, being proprietary, or difficult to derive from external measurements of a packaged device. Detailed physical models may require intensive computation, but can be used to design new devices and predict their performance. Black-Box models are based on the physics of the device, but have parameters that can be derived from external measurements. Linear devices (such as filters) or well-specified devices (such as transmitters with a digital input) can be represented by their measured performance alone. Even though novel devices cannot be designed using these models, the systems performance of a module is easily and accurately assessed using these methods. Data sheets often provide characteristics as a series of parameters fitted to measurements (such as rise-time, spectral width). Although such data is often gathered using long-term measurements, its wide availability makes it useful for systems-level simulation. Care must be taken that the long term averages do not misrepresent the worst case.

Bit Error Rate Estimation

It is quite challenging to properly estimate the BER for high-speed systems due to numerical modeling constraints and the advent of more complex modulation formats requiring specific receiver structures. For systems whose BER values of interest are 10^{-4} and higher, direct counting methods (Monte Carlo) are most accurate and also feasible. Though, significant effort is required if nonlinear fiber degradations are considered, and the impact of stochastic degradations due to PMD and PDL is evaluated. Techniques for estimating the BER are typically based on analytical models of the optical propagation channel and/or assumptions about the probability density functions of symbol amplitudes at the electrical detector. Deterministic methods are very helpful in conjunction with signal representations that distinguish between data signals, optical noise, and crosstalk, as long as mixing between signal and noise along the link can be disregarded. These methods help to avoid some of the numerical confidence problems associated with stochastic techniques, but introduce limitations due to idealized link modeling. Stochastic methods are useful for systems where the interaction between ASE noise and the optical signal are of importance, or where receiver structures are used for which no deterministic method exists yet. Stochastic methods typically require long bit streams to be transmitted to avoid numerical confidence problems when estimating the characteristic distribution measures. Advanced BER estimation methods use semi-stochastic approaches that combine the advantages of deterministic and stochastic methods [3].

Stochastic PMD

Due to polarization dependent propagation effects along the transmission link, the optical signal at the receiver may have an arbitrary random polarization state and the ASE noise may become partially polarized [5, 6]. Using a deterministic BER method

1-4244-0927-6/07/$25.00/©2007 IEEE

that accounts for non-Gaussian signal statistics and arbitrary polarization states of signal and noise at the receiver [7] in conjunction with the method described in [8] we model 4x40 Gb/s OTDM transmission over 520 km. At the OTDM-transmitter neighboring bits are either alternating polarized (AP) or single polarized (SP). Figure 1 shows the contour plots of BER versus DGD for the 40 Gb/s tributaries from 6,000 simulation trials with random PMD values. The OSNR in front of the same polarization-insensitive OTDM receiver structure was 19.3 dB what translated into a BER of $2x10^{-11}$.

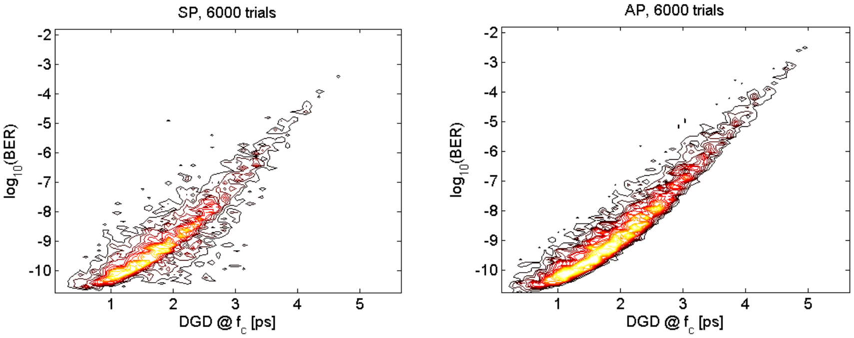

Figure 1: 4x40 Gb/s OTDM system: contour plots of BER versus DGD after propagation over a noisy link with an accumulated mean DGD of 2.1 ps for single polarization (SP, left) and alternate polarization (AP, right).

DPSK and DQPSK – Electrical Bandwidth Limitations

When investigating transmission systems using variants of D(Q)PSK formats, correct BER estimation requires methods that consider balanced receiver structures. In [7] we proposed a semi-stochastic method that determines stochastically the Moment Generating Function (MGF) due to optical amplifier noise after each photodiode, and deterministically the MGFs due to phase noise and electrical post-detection noise. For DQPSK-systems the BER for in-phase and quadrature components can be averaged [9, 10]. Figure 2 shows results of dispersion sensitivity simulations for 80 Gb/s DPSK and DQPSK systems with equal OSNR values in front of the receiver. The 3-dB bandwidth of the electrical filters after each photodiode has been set to 0.7x80 GHz for DPSK, and to 0.7x40 GHz for DQPSK. The eye diagrams in Figure 2 (left) demonstrate the impact of bandwidth limitations of the Mach-Zehnder modulators at the DPSK transmitter.

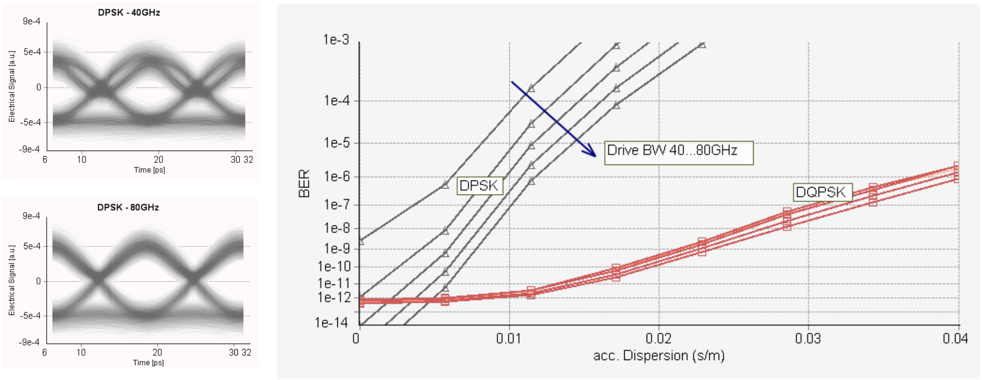

Figure 2: BER versus Dispersion for 80 Gb/s DPSK and DQPSK (right); DPSK eye diagrams for 40 GHz (left-top) and 80 GHz (left-bottom) electrical drive bandwidth.

This work was partly supported by the German Ministry for Education and Research (Eibone).

References

[1] H. Hamster, et al, “PDA: Challenges for an emerging industry”, *Lightwave*, Penwell Publishing, August 1998.
[2] A. Lowery, et al, *J. Selected Topics in Quantum Electron.*, vol. 6, pp. 282-296, 2000.
[3] VPItransmissionMaker 7.1, Reference and User’s Manuals, July 2006.
[4] J. Piprek (editor), *Optoelectronic Devices: Advanced Simulation and Analysis*, Chapter 15, Springer, 2003.
[5] E. Lichtman, *J. Lightwave Technol.*, vol. 13, pp 906-913, 1995.
[6] Y. Sun, et al, *IEEE Photon. Technol. Lett.*, vol. 13, pp 966-968, 2001.
[7] A. Richter, et al, OFC/NFOEC 2005, paper NTuH3, 2005.
[8] A. Richter, et al, NFOEC 2002, paper 073, 2002.
[9] J. Wang, et al, *J. Lightwave Technol.*, vol. 22, pp. 362-372, 2004.
[10] X. Huang, *IEEE Photon. Technol. Lett.*, vol. 17, pp. 1423-1425, 2005.