Automating Bit Error Rate Measurements of Complex Modulated Optical Signals

Application Note

Introduction

Common to all digital communications systems is the need to characterize bit error rates (BER). In radio or wireline communications, BER is usually plotted vs. signal-to-noise (SNR) ratio, resulting in "waterfall curves", log-log plots usually showing a decline in BER at some critical SNR, which becomes a benchmark in the system. Fiber communications links are also characterized by BER vs. optical signal-to-noise ratio (OSNR) or vs. received optical power (ROP).

As carriers seek to squeeze more spectral efficiency from their fiber plants while managing costs, several modulation formats beyond on-off keying (OOK) are candidates for deployment. This proliferation of formats, including differential [quadrature] phase shift keying (D[Q]PSK), coherent dual-polarization (or polarization-multiplexed) quadrature phase shift keying (DP-QPSK), quadrature amplitude modulation (QAM) and many variations of orthogonal frequency division multiplexing (OFDM), all seek to optimize among competing characteristics like reach, robustness, simplicity, and spectral efficiency.

Even though the simpler modulation schemes are usually direct-detected, all modulation schemes can be optimally characterized using coherent detection, which preserves the full electric field of the signal. Meanwhile, complex modulation of optical signals in fiber enables independent modulation of both in-phase (I) and quadrature (Q) components of each polarization, for a total of four tributaries per wavelength if the signal is polarization-multiplexed. In a full coherent system, the orthogonality of these tributaries allows each to be independently modulated; each tributary can be modulated with a different pseudo-random bit sequence (PRBS). For testing, the payload of each tributary is then examined, and different BERs measured on each tributary. Typically, only the aggregate BER for all tributaries is reported, and measured with varying experimental factors, such as OSNR, modulation format, transmitter parameters, etc.

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The Tektronix OM4106D Coherent Lightwave Signal Analyzer can be used to make automated BER measurements, performing live calculations in MATLAB[1] and using a simple LabVIEW[2] interface to control external instruments, such as an optical attenuator. To illustrate this capability, we compute the aggregate BER for each experimental condition, and write the attenuation, number of symbols received, and BER to a spreadsheet file for later analysis and plotting; OSNR or received optical power can be independently calibrated to get absolute abscissa values. Since the OM4106D offers full access to the Matlab variable space, i.e. all variables used in recovering and reporting on the quality of the optical signal, the technique illustrated here can be extended to recording the BER of each tributary, while further recording several other signal parameters, such as Q factor or constellation parameters such as phase angle, elongation, and real/imaginary bias.

Coherent Measurements of Optical Signals

Complex (quadrature) modulation with polarization diversity has the advantage of exploiting the entire electric field of the optical carrier. Access to these field quantities at the receiver enables digital filtering to compensate for impairments such as chromatic dispersion (CD) and polarization mode dispersion (PMD).

Even for differential modulation schemes that are direct-detected, such as DQPSK, a fully-coherent receiver enables full characterization of the signal, while eliminating amplitude fluctuations of the original signal and uncertainties of a hardware delay-line interferometer (DLI), since this in principle can be implemented—and even dynamically altered—in the receiver's software.

Coherent detection requires a phase reference, either from the original signal (or carrier), or from a free-running, but similar-frequency independent source; this "intradyne" method relies on real-time capture and digitizing of the difference-frequency waveform, whose bandwidth is the modulation bandwidth plus the difference frequency. Carrier phase recovery is performed by removing the frequency difference between the signal and phase reference, then applying a Wiener filter to predict the phase trajectory of the signal, since the phase variations of the carrier obey a Wiener process.

A reference receiver, such as the Tektronix Optical OM2210 Complex Modulation Receiver, takes as input two single-mode fibers, one carrying the signal (which can be polarization-multiplexed, each polarization potentially lit by an independent source) and the other the phase reference, or local oscillator (LO). For convenience, the OM2210 includes two network-tunable sources, which are controlled through the Tektronix Optical User Interface (OUI). In the receiver, the phase reference is evenly divided into both X and Y polarizations, and mixed with the signal in two branches, both I and Q. The four channels are transduced by balanced photodetectors and provided as (microwave) electrical outputs, which in turn feed a real-time oscilloscope having sufficient bandwidth to capture the difference-frequency waveform. The oscilloscope functions in burst mode, capable of measuring continuous channel data in amounts up to the memory capacity of the instrument. The burst-mode channel data are processed by Tektronix Optical software (the OUI and underlying MATLAB code) to extract the tributaries associated with the modulation scheme, report measurements on the results, and display the extracted signal in several formats, including eye diagrams of each tributary, constellation (phase) diagrams of each polarization, and a Poincaré sphere plot, indicating the state of polarization (SOP).

[1] MATLAB® is a registered trademark of The MathWorks, Inc. Other product and company names listed are trademarks and trade names of their respective companies.

[2] LabVIEW® is a trademark of National Instruments, Inc.
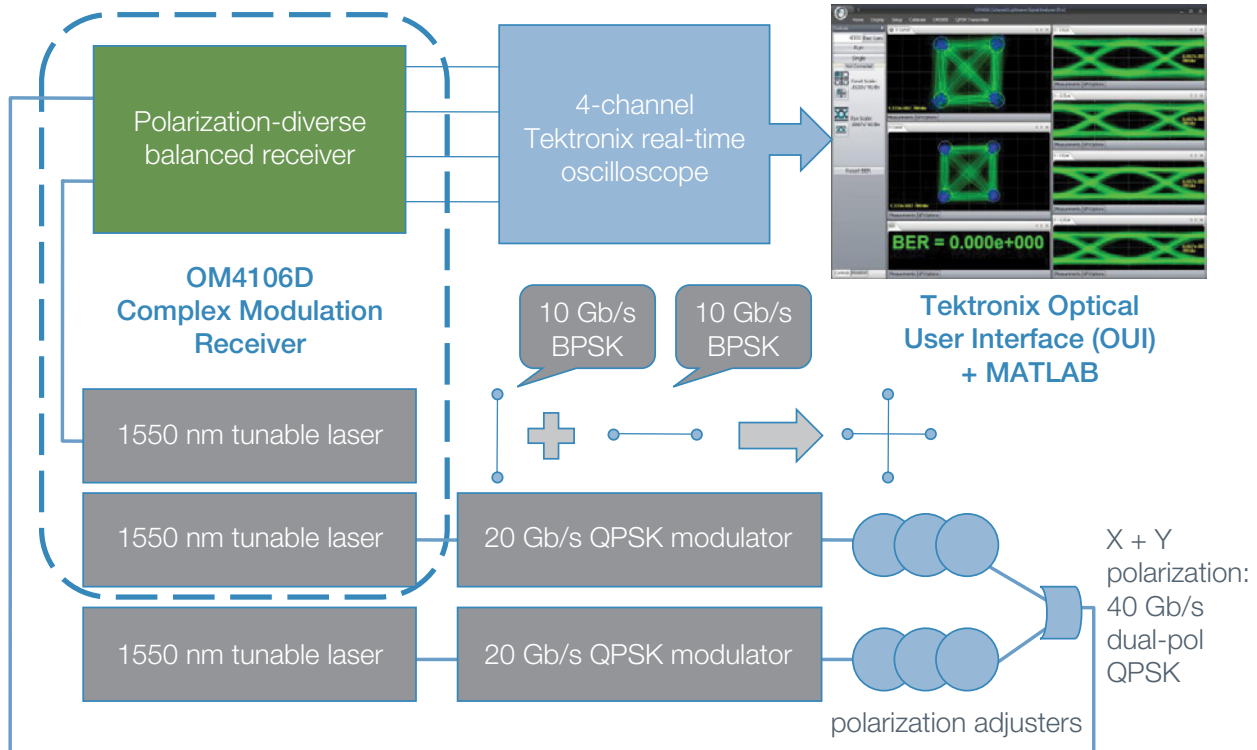
Figure 1. Dual-polarized QPSK measurement setup using 10 Gb/s tributaries and a 20 Ghz at 50 Gs/s oscilloscope. A higher-speed oscilloscope (e.g. 33 GHz at 100 Gs/s) can be used for measuring >40 Gb/s tributaries.

Since the raw data, resampled data, performance metrics, and all intermediate variables are available through the OM4106D interface to the underlying MATLAB kernel, users can create their own plots (i.e. using MATLAB graphics) or export data to other applications, such as LabVIEW. For example, spectral analysis is accomplished with a simple MATLAB command to take the Fast Fourier Transform (FFT) of a data stream.

Bit-Error-Rate (BER) Measurements

A typical dual-polarized measurement configuration for the OM4106D is show in Figure 1. Independent network-tunable external-cavity diode lasers (ECDLs) are used for each polarization, as well as for the OM2210 Complex Modulation Receiver's LO; no phase-locking among any of the lasers is employed.
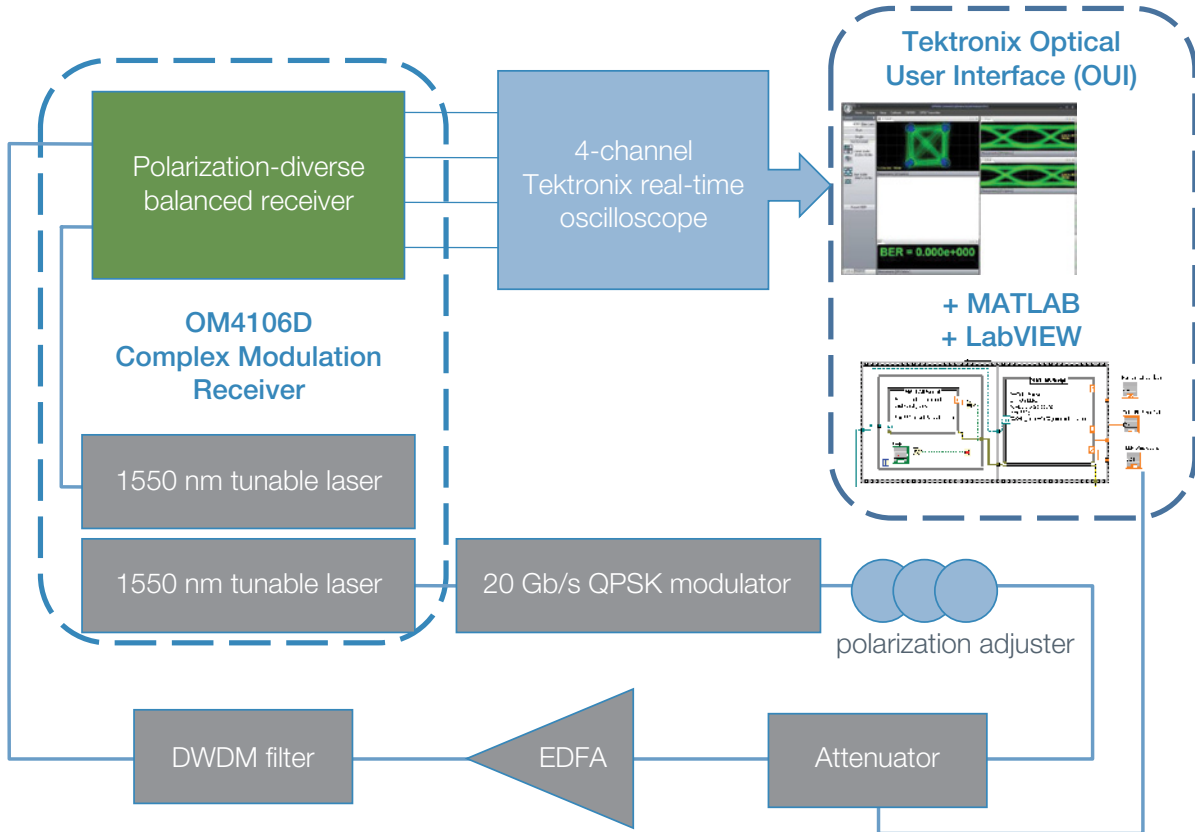
Figure 2. Experimental setup for measuring BER vs. optical signal level. As indicated by the right-hand dashed enclosure, one PC runs the OUI, MATLAB, and LabVIEW, which in turn controls the attenuator (and optionally, the gain of the EDFA).

To demonstrate measuring aggregate BER vs. signal level, we simplify the system to use one polarization, adding a variable optical attenuator (VOA), erbium-doped fiber amplifier (EDFA) and a dense wavelength-division multiplexed (DWDM) filter, as shown in Figure 2.

Variable Exchange in Matlab

In the OM4106D, automated measurement sequences can be performed by using the MATLAB variable space to exchange information with other programs running simultaneously with the OUI. One can create new variables in an OUI command or "engine" file whose values are derived from existing OM4106D variables (already present in the Matlab workspace), and these variables can be read and written while the OM4106D is running on a suitable Windows[3] platform. In particular, this application uses a flag variable to indicate when the BER calculation is ready for processing by LabVIEW. The overall process is illustrated in Figure 3.
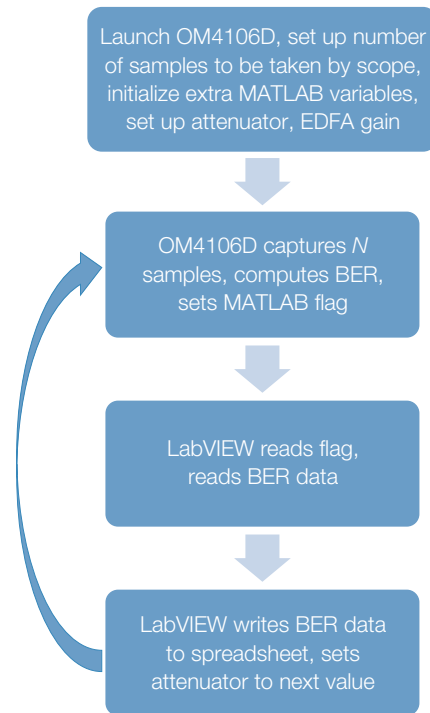
Figure 3. Flowchart for acquiring BER data.

[3] Windows is a trademark of Microsoft Corporation.

Using the OUI and Matlab with LabVIEW

When the OM4106D OUI is launched, it in turn opens a MATLAB command window, which both the OUI and LabVIEW can treat as a script server. As the OUI is executed, MATLAB variables are created to process the data collected by the real-time oscilloscope; some of these variables are in turn displayed by the OUI. New variables derived from those available in the MATLAB solution space can be created and processed, as well, extending the functionality of the OM4106D.

LabVIEW facilitates interfacing with nearly any instrument having remote-control capabilities, and because it also interfaces with MATLAB, the OM4106D can share access to the MATLAB script server with LabVIEW.

To illustrate this, we first create a bit-error-rate variable collection in MATLAB, and then acquire these variables through a MATLAB-LabVIEW script server connection. This facilitates automated measurement of waterfall curves. Our example will be for single-polarization QPSK.

First, we write a simple MATLAB script, *zeroBER.m*, to define and initialize some new variables:

```
% zeros out all bit error variables
TotalErrs = 0;
TotalBits = 0;
TotalSyms = 0;
TotalBER = 0;
BER_reset = 1; % flag to say that BER has
been reset, e.g. BER not ready
```

In the MATLAB window of the OUI, the engine file can be modified with the addition of our new variables whose values are derived from internal (pre-determined) OM4106D variables, which are shown in italics to distinguish them. Note that we choose to aggregate the number of errors from both the real and imaginary axes:

```
TotalSyms = TotalSyms + NumSyms
TotalBits = TotalSyms * 2 % for single-pol
QPSK
TotalErrs = TotalErrs+
 (NumErrs.XRe + NumErrs.XIm);
TotalBER = TotalErrs / TotalBits
%csvwrite('c:\BER.dat',TotalBER);

BER_wait_count = 0;
while (BER_wait_count <10), BER_wait_
count=BER_wait_count+1;, end;
% wait for BER to be read
BER_wait_count
BER_reset = 0; % BER calculation now done,
ready for reading
```

This set of commands includes a short wait loop, which can help synchronize the read process in the case of a slower processor. Note that we could also write the BER variable to a file `'c:\BER.dat'` if desired, though this command is commented out.
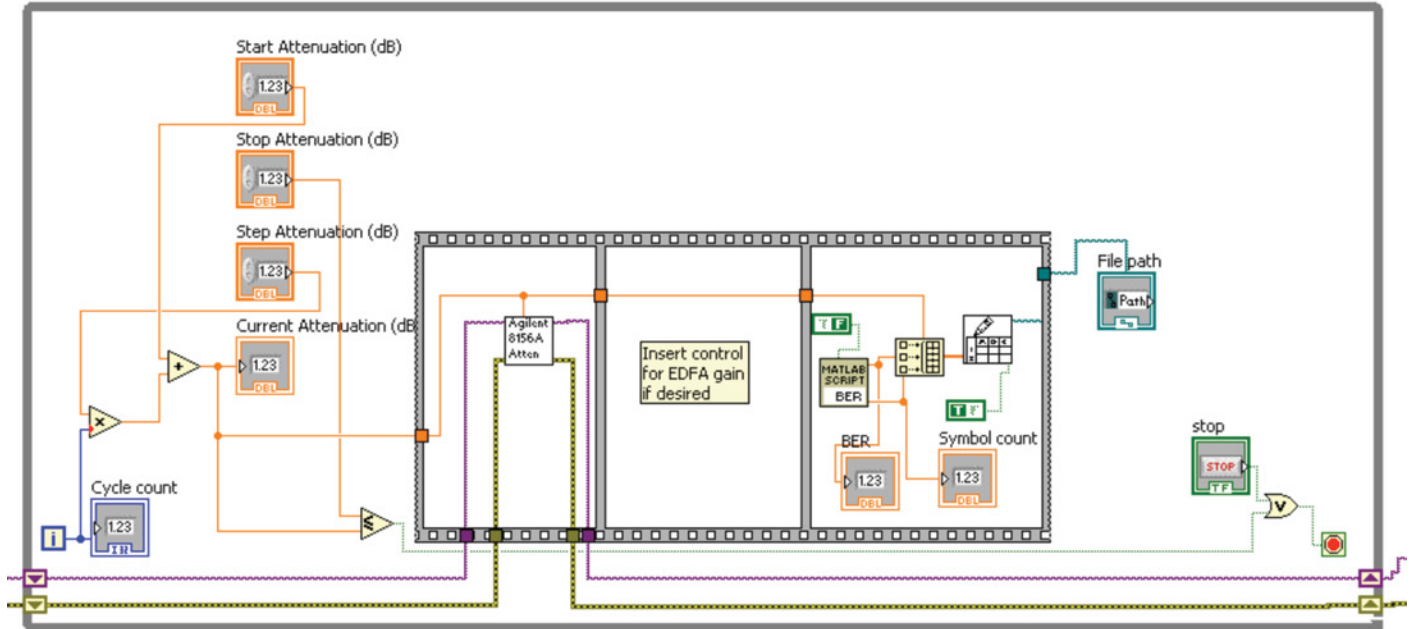
Figure 4. While loop within a LabVIEW VI for controlling attenuator and acquiring BER data. Right-hand panel calls a LabVIEW-MATLAB script, shown in Figure 5, and writes resultant data to a spreadsheet file. A simple virtual instrument (VI) was written to control an Agilent 8156A optical attenuator.

The overall LabVIEW VI to sequentially acquire BER data at each setting of the optical attenuator (and corresponding gain setting of an amplifier, such as an EDFA) can be realized as a While loop, as shown in Figure 4. The OM4106D takes a set of samples from the oscilloscope according to the user's preference (e.g. 500,000 samples as illustrated here) and notifies LabVIEW that the BER data is ready via the BER_reset flag. LabVIEW, meanwhile, continues to check the status of this flag, and when it is set to zero, LabVIEW reads the BER data and sets the attenuator value to the next one in the series determined by the user.
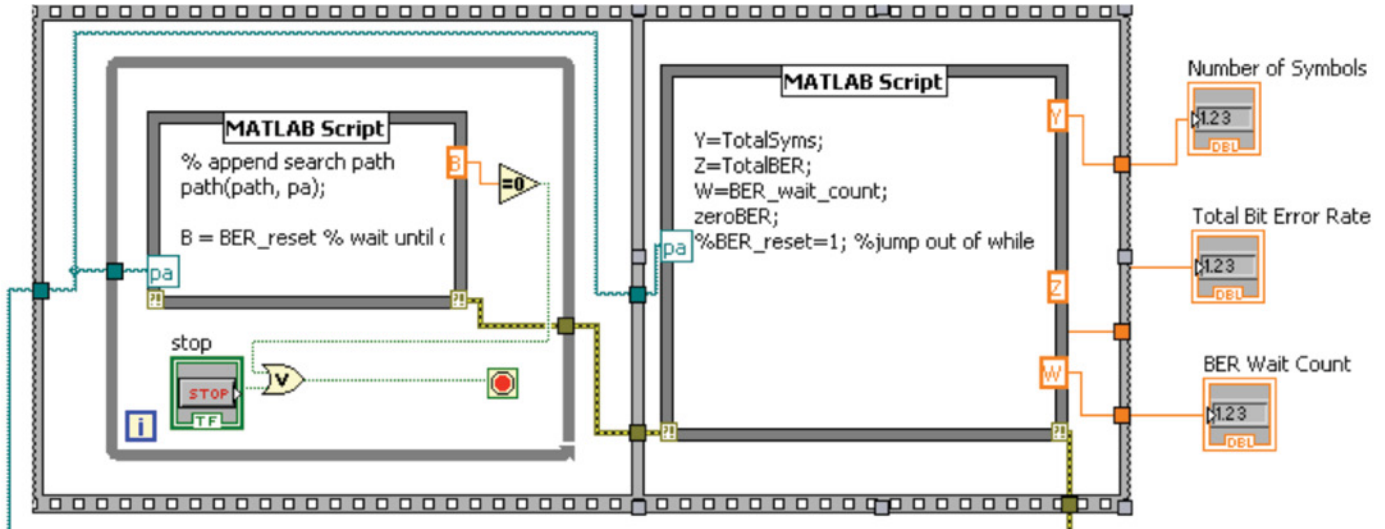
Figure 5. Details of LabVIEW Matlab Script Node to acquire BER information from Matlab. The left-hand frame waits until BER_reset is set to 0 (in the OM4106D engine file, illustrated above); it then passes control to the right-hand frame, which reads the variables and resets the BER_reset flag via the zeroBER.m command.
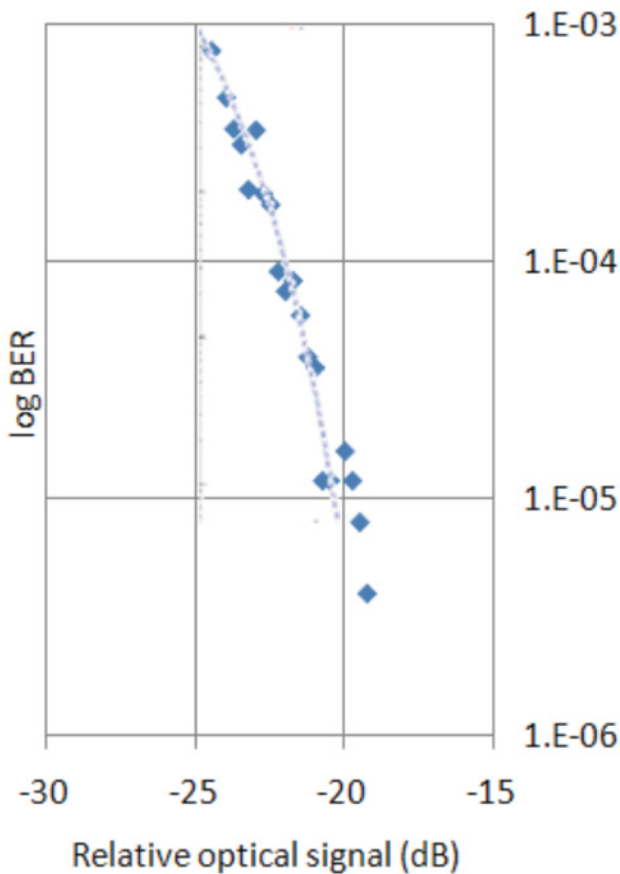

Figure 6. BER vs. relative optical signal (uncalibrated) for single-polarization coherent QPSK. Dashed line is theoretical prediction, offset horizontally to facilitate comparison of trends.

To create an interface to LabVIEW, we use the LabVIEW Matlab Script Node (Figure 5).

The sequence in Figure 5 first queries and waits for the *BER_reset* flag to be set to '0' by the engine file in the OUI, then it reads the variables *TotalSyms* and *TotalBER*, and then resets these variables by calling *zeroBER.m*. An optional *BER_wait_count* variable enables a delay (if desired) in the OUI.

Results are shown in Figure 6. Each point in the plot represents the aggregate BER from the OM4106D determined by setting 500,000 points (e.g. 125,000 symbols). The abscissa represents the (uncalibrated) optical signal power; LabVIEW could further be used to control the gain of the EDFA to obtain variable OSNR stimulus. The dashed line is the theoretical prediction, offset along the abscissa to compare data to theory.

Summary

The Tektronix OM4106D Coherent Lightwave Signal Analyzer enables access to the complete set of variables for characterizing complex optical signals on fiber. Because the OM4106D processes data using MATLAB, it enables not only creation of new functions, but also exchange of variables with other applications, such as LabVIEW. This in turn enables automated control of external instruments for acquiring BER measurements.

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