OptOlink Numerics

For Windows® systems

User Documentation

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1. Description

Optolink Numerics is a numerical tool for analyzing, evaluating and designing WDM and single-channel point-to-point and point-to-multipoint optical transmission systems.
The Optolink Numerics simulation engine has been successfully used and tested in several R&D departments of telecommunication companies, universities and research foundations.
The simulation tool runs on Personal Computers with Windows XP/7 operating system. Optolink Numerics also requires an open TCP/IP connection if a demo or temporary license is used; not required with a permanent license.

Optical devices and fiber models used by Optolink Numerics are known to be among the most accurate and fast executable in the literature. In order to obtain the fastest computational times, the Optolink Numerics simulation engine was written in Fortran source code, with optimized numerical routines; simulation tasks are launched independently from the graphical tools, and are particularly efficient in terms of computational efforts consuming. Thanks to the accurate modeling of the optical nonlinear effects, such as the Cross-Phase Modulation (XPM), and to the reduced execution times, Optolink Numerics is optimized for simulating Wavelength Division Multiplexing (WDM) transmission systems, with a large number of channels and/or simulated bandwidth.
New Optolink Numerics features include:

- a drag and drop graphical interface to let users quickly and intuitively create and modify complex systems to be simulated,
- custom transmitters and components integration,
- custom in-line and de-multiplexing optical filtering,
- optical monomodal fibers with Kerr and Raman nonlinearities,
- fibers with Raman gain and up to 10 co/counter-propagating pumps,
- multimodal fibers with user-defined differential-mode delay,
- free-space optics transmission with stored atmosphere models and link availability estimation,
- optical EDFA amplifiers with a new Polarization Hole Burning (PHB) model,
- optical modulators with dual drive design, driven by two independent electrical signals,
- user-friendly optical transmitters and receivers for Intensity Modulation with Direct Detection (IM-DD), Differential Phase Shift Keying (DPSK) and Phase and Intensity Modulation (PhIM, see the chapter “Appendix – The PhIM format”) formats,
- optical cross-connects, add&drop and cross-couplers for network simulation at the physical layer,

- laser with direct modulation for simulating access networks,
- polarization control/tracking at the receiver for polarization-multiplexed systems,
- use of averaged runs for faster and more accurate simulations.

System requirements: Optolink Numerics runs on personal computers with Pentium processor or 100% compatible, 512 MB RAM memory, Windows XP/7 operating system.
Optolink Numerics also requires an open TCP/IP connection if a demo or temporary license is used; not required with a permanent license.
The international settings for numbers must be set to a "." decimal separator (example: 134.23 instead of 134,23).

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Credits: Optolink Numerics was created by M. Zitelli, Ph.D.
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For assistance on Optolink Numerics use, please e-mail to:
software@photoneco.com

2. Starting Optolink Numerics

Optolink Numerics installation places the executable files into the directory "C:\Program files\Optolink\bin\".
First thing to do is generating a demo or permanent license. Please run the executable "InstUtility.exe" on the personal computer where Optolink Numerics is to be used. Executable will only read the computer host name, the mother board and the hard disk serial numbers; please copy those informations as they are and e-mail them to the licensor at software@photoneco.com. A license file called "License.dat" will be e-mailed to you; please copy the license file in the same "C:\Program files\Optolink\bin\" directory. Now you are ready to run Optolink Numerics.
Please remember that a demo or temporary license requires an open TCP/IP connection at Optolink Numerics startup, in order to check the expiration date. Connection may be closed after Optolink Numerics has been started. Connection is not required with a permanent license.

Once Optolink Numerics has started, an empty *design chart* will be loaded. Design chart is the white sheet where the transmission systems are designed.
Optical and electrical *components* appear at the upper side of the screen; they must be dragged and dropped on the design chart in order to design a transmission system.
Components, including optical fibers, must be connected using *link lines*; these are drawn by selecting the "Link" button on the tool bar, and clicking once on the first component and once on the second component to be connected. The "Link" button remains selected until clicking on it a second time; this lets designers connect all the components sequentially. Component input is connected on the left side, output on the right.
In order to delete components or link lines, de-select the "Link" button, click on the design chart and drag a dashed selection box around the component and/or lines to be deleted; press the "Cancel" or "Cut" button on the tool bar.
After connecting the components, de-select the "Link" button and double-click on the components to set the relative parameters; a component *dialog box* will appear.
Once finished setting the component parameters, press "Ok" to save them, close the dialog box by clicking on the "X" button otherwise. Choose the desired parameters in the "WDM" and "Simulation" menus. Now you are ready for simulating your system.
Simulation runs are launched by pressing the "Save and run" button on the tool bar.
To watch results, select the "Show graphs" button on the tool bar and double-click on the desired receiver (a "RX, IM-DD", "RX, DPSK", "RX, PhIM" or "Evaluate Performance" component), or on the "Optical filter", "Electrical filter", "Raman fiber", "Multimodal fiber", "Free-space optics" and "Laser DM" components.

For details on the transmission system design, please read the "Components library" and all other sections.
Note: selecting parameter values with non-physical sense (for example, too high or too low) may stop Optolink Numerics, or generate Not-a-Number results.

3. File menu

File menu is used to open, save and launch simulations, and to show partial or final results and graphs. Buttons corresponding to the New, Open, Save, Run and Show graph items are also present on the tool bar.
Optolink Numerics transmission system files, including all the selected parameters have extension ".olk".

New: opens an empty design chart.

Open: opens an existing transmission system.

Close: closes the current system.

Save: saves the current system; if name is not defined, the Save As window will appear.

Save As: saves system with a new name.

Run: starts simulation for the opened system. A "Run" button is present on the tool bar.
At run, a new window will appear (the *simulation window*), where the simulated system devices, parameters and performance will be sequentially described. Performance shown in the simulation window will refer to one selected channel for Q factor printing (see "WDM" and "RX" sections), although stored results will refer to all the selected channels.
After a simulation has been started, the current system may be closed, and a new one may be created or opened, and run also.
It is possible to launch an unlimited number of contemporary simulations for systems with different name.
Note: launching more contemporary simulation windows for the same system will produce unpredictable results.

Show graphs: simulation results and graphs for the current opened system are shown by the Optolink Graph Viewer; it is started by selecting the Show graphs button, and double-clicking on a system Receiver component (see the "RX, IM-DD", "RX, DPSK" or "RX, PhIM" sections), or on the "Evaluate Performance", "Optical filter", "Electrical filter", "Raman fiber", "Multimodal fiber", "Free-space optics" and "Laser DM" components. Partial results may be viewed during the simulation run, if available.

Print: prints the current window.

Exit: quits Optolink Numerics. Running simulations will not be closed. To stop a simulation, select "File-Exit" on the simulation window, or click on the usual "X" button on the simulation window.

4. Edit menu

Used to copy cut or cancel transmission system components in the design chart, or to paste them conserving the selected parameters. It is necessary to previously select some components by clicking on the design chart and dragging a dashed selection box around the components. Link lines can also be canceled with the same method. Cut, Copy, Paste and Cancel buttons are present on the tool bar.

Cut: cuts away the selected components and/or link lines.

Copy: copies the selected components with their parameters.

Paste: pastes components on the design chart.

Cancel: deletes the selected components and/or link lines.

5. WDM menu

Single-channel or WDM transmission is selected in the optical multiplexer components dialog box (see “MUX” in the components library); for WDM systems, central wavelength and channel spacing must be selected there. Correspondingly, channel wavelengths are calculated in the “WDM – Channels 1..64, 65..128, 129..192” sections for up to 192 transmitted channels.
Channels may be optically multiplexed with parallel, orthogonal or random states of polarization, by selecting the proper option in the “MUX” dialog box.
The “WDM - Channels ..” sections permit to check the option “Manually set wavelengths”; in that case, wavelengths in “WDM – Channels 1..64, 65..128, 129..192” sections can be changed manually, for systems with non-uniform channel spacing.
A random optical phase is always added to the multiplexed channels; adjacent WDM channels are transmitted with different PRBS sequences for signals de-correlation. In PhIM, amplitude and phase tributaries have different PRBS sequences as well.
When several “MUX” components are used (for, example, to multiplex different signal formats or bit-rates), the “WDM - Channels ..” automatically show the multiplexed signals in increasing order of wavelength; the optical format type is indicated assigning an order number to the “Mux input”.
For all multiplexed signals, a pre-emphasis may be chosen, and they can be selected for performance evaluation and output eye drawing.
The “MUX - Multiplexing” section permits to add an input multiplexing optical filtering to all channels.

“WDM - Channels 1..64”, “WDM - Channels 65..128”, “WDM - Channels 129..192” sections:

They have the following parameters:

Channels wavelength: [nm, default: 1550] shows or sets the optical channels wavelengths. When more than 64 channels are transmitted, remaining wavelengths are shown not only in section “WDM – Channels 1..64”, but also in “WDM – Channels 65..128” and “WDM – Channels 129..192”.

Print Q - Print Eye: check the left box below each channel when channel performance must be evaluated and saved. Check the right box to save and graph the channel received eye. For disk space savings, no more than 20 channels should be checked for performance evaluation, and no more than 10 for eye graphing.

Pre-emphasis: [dB, default: 0] excess of channel power, respect to the Input power values specified in the transmitter or laser components (see “TX, IM-DD”, “TX, DPSK”, “TX, PhIM”, “Laser CW”, “Laser DM”).

Mux input: [default: 0] shows the channel format generated by the transmitters, lasers or “MUX” components.

Note: when using "MUX" components, WDM channels are physically generated at each transmitter or laser component (see "TX, IM-DD", "TX, DPSK", "TX, PhIM", "Laser CW", "Laser DM"), according to the settings in the "MUX" dialog box and the "WDM" sections. WDM signals generated by different "MUX" are not multiplexed between them, unless an "Optical adder" or some other combiner component is used to merge the several WDM signals.
Assume, for example, a scheme including a "TX, IM-DD" transmitter (with 2 dBm/ch power) and a "TX, DPSK" transmitter (with 0 dBm/ch power). A "MUX" with 5 channels having orthogonal polarizations is added at the "TX, IM-DD" output, with 1550 nm central wavelength and 0.8 nm channel spacing; a second "MUX" is added at the "TX, DPSK" output with 5 channels, orthogonal polarizations, 1550.4 central wavelength and 0.8 nm channel spacing. The first 5 channels will be transmitted independently by the last 5, each with the assigned power. If the two WDM signals enter an "Optical adder", they will result multiplexed with orthogonal polarization, different power and interleaved with 0.4 nm channel spacing.

"WDM - Multiplexing" section:

Used to optically filter all the multiplexed channels.
"WDM - Multiplexing" selects the optical filtering experienced at the transmitters / lasers by the generated channels; filter is centered on every channel wavelength specified in the "WDM - Channels .." windows, eventually with a frequency detuning (needed, for example, in Vestigial Side Band signals). Channels generated by a single transmitter component are filtered at the transmitter and added with polarizations specified in the "MUX" dialog box. Same thing is performed for the wavelengths generated by a laser component.

The following parameters are given:

Mux filter type: [default: Gaussian] selects the multiplexing optical filter transfer function, as follows:

Gaussian filter:
The optical Gaussian filter of order M has an amplitude transfer function given by

$$H_{out}(\nu) = \exp\left[-\ln\sqrt{2}\left(2\frac{\nu-\nu_0}{B_o}\right)^{2M}\right] \quad ; \qquad (1)$$

B_o is the optical 3dB bandwidth and ν_0 the filtered channel central frequency. Eq. 1 multiplies the incoming optical field complex amplitude (for each multiplexed channel) according to

$$\tilde{A}_{out,k}(\nu) = \tilde{A}_{in,k}(\nu)H_{out}(\nu) \qquad k = x, y \quad , \qquad (2)$$

With $\tilde{A}(\nu)$ indicating the Fourier transform.
A higher order Gaussian filter could properly approximate the shape of an arrayed waveguide grating (AWG) multiplexer.

Trapezoidal filter:

The amplitude transfer function of a trapezoidal filter is $H_{out}(\nu) = 10^{H_{out,dB}(\nu)/20}$, with

$$H_{out,dB}(\nu) = \begin{cases} -Att_{dB} & |\nu| \geq \frac{\nu_c}{2} \\ Att_{dB} \dfrac{\nu + \frac{\nu_b}{2}}{\frac{\nu_c}{2} - \frac{\nu_b}{2}} & -\frac{\nu_c}{2} < \nu < -\frac{\nu_b}{2} \\ -Att_{dB} \dfrac{\nu - \frac{\nu_b}{2}}{\frac{\nu_c}{2} - \frac{\nu_b}{2}} & \frac{\nu_b}{2} < \nu < \frac{\nu_c}{2} \\ 0 & |\nu| \leq \frac{\nu_b}{2} \end{cases} . \qquad (3)$$

In eq. 3, ν is the optical frequency relative to the filter central frequency, ν_b is the 0 dB bandwidth, ν_c the cut-off bandwidth and Att_{dB} the filter attenuation, in dB. Filter shape is a trapezoid, with attenuation passing from 0 dB to $-Att_{dB}$ in the frequency range between $\nu_b/2$ and $\nu_c/2$, and between $-\nu_c/2$ and $-\nu_b/2$.

Filter from file:
A user-defined optical filter can be used for multiplexing. Filter must be passed to Optolink Numerics as a ".dat" file, selected using the "Browse" button.
Filter file must be a text file including 3 number columns (separated by commas, spaces or tabs). First column is the relative optical frequency (GHz) respect to the filter central frequency (positive and negative numbers are admitted, with "." decimal separator); second column is the filter real amplitude A_f (linear scale, between 0 and 1); third column is the filter phase ϕ_f (rad). Remember that "MUX" automatically centers the filter on each channel central frequency; thus frequencies in the first column should span around 0 GHz.
Filter amplitude transfer function is generated according to

$$H_{out}(\nu) = A_f(\nu) \exp\left[i\phi_f(\nu)\right] , \qquad (4)$$

with ν intended as the optical frequency relative to the filter central frequency. The amplitude and phase values used in eq. 4 are obtained by Optolink Numerics using a linear interpolation of the data from file, according to the

$$A_f(\nu) = A_f^j + \left(A_f^{j+1} - A_f^j\right)\frac{\nu - \nu_j}{\nu_{j+1} - \nu_j}$$

$$\phi_f(\nu) = \phi_f^j + \left(\phi_f^{j+1} - \phi_f^j\right)\frac{\nu - \nu_j}{\nu_{j+1} - \nu_j} \quad , \qquad (5)$$

with ν_j and ν_{j+1} the file relative frequencies including ν and A_f^j , ϕ_f^j the corresponding amplitude and phase from file. Transfer function is assumed to be zero outside the user-specified frequency range.

Insertion loss: [dB, default: 0] the excess optical loss introduced by the multiplexing filter.

Mux filter detuning: [GHz, default: 0] the filter detuning respect to each channel central frequency; used for the Vestigial Side Band signals.

Gaussian filter bandwidth: [GHz, default: 50] the optical 3dB bandwidth B_o in eq. 1.

Gaussian filter order: [default: 1] defines the order M for the Gaussian filter in eq. 1.

Trapezoidal filter 0 dB bandwidth: [GHz, default: 70] the optical filter bandwidth ν_b in eq. 3, corresponding to a 0 dB attenuation.

Trapezoidal filter cut-off bandwidth: [GHz, default: 100] the filter bandwidth ν_c in eq. 3, corresponding to an attenuation between 0 and Att_{dB}.

Trapezoidal filter attenuation: [dB, default: 30] the filter attenuation Att_{dB} in eq. 3.

6. Simulation menu

Defines global parameters regarding the way numerical simulation is performed.

System length: [km] shows the calculated length of the current transmission system, including optical fibers and nonlinear elements.

Reference wavelength for dispersion parameters: [nm, default: 1550] sets the wavelength λ_{ref} at which the dispersion parameters are specified. For improved accuracy, λ_{ref} should be in the same transmission window as the signal (example: 1310 nm for 2nd window, 1550 nm for 3rd window transmission).

PRBS sequences order: [between 6 an 10, default: 6] set the maximum sequence length, for transmitted channels with the maximum bit rate; the corresponding number of bits is $N_{bit} = 2^{PRBS\ order}$. Sequence length for channels with lower bit rate is calculated automatically. The ratio between different bit rates must be a power of 2; the minimum number of bits must be greater or equal to 64.

Corresponding number of bits: [default: 64] shows the number of bit N_{bit} for the channels PRBS sequences.

Include 3-bit pattern effects: [default: unchecked] if unchecked, Q factor is evaluated according to eq. 2.1 in “Appendix - The Q factor and timing jitter model” section. When box is checked, patterns (defined as the 8 combinations of 3 bits: 000, 001, 010, 011, 100, 101, 110, 111) are considered, and the Q is evaluated according to eq. 2.3.
Pattern effects should be included when inter-symbol interference (ISI) could not be neglected (for example, for high cumulated dispersion values); when 3-bit pattern effects are considered, ISI induces a smaller penalty on the evaluated performance. Note that the use of 3-bit patterns reduces the numerical accuracy for the estimated Q; to conserve the same accuracy as in the case of no pattern effects, the number of transmitted bits should be 3 times greater when using 3-bit patterns.

Use differential phase Q factor: [default: unchecked] if checked, Q factor for the phase tributary is evaluated according to the equation [X. Wei, X. Liu, C. Xu, IEEE Photonics Technology Letters 15, pp. 1636-1638, Nov. 2003]

$$Q_{diff} = \frac{\Delta\phi_{diff}}{\sigma_1 + \sigma_0} \quad ; \qquad (1)$$

in eq. 1, $\Delta\phi_{diff}$ is a differential phase eye opening (rad) selected by the user, σ_1 and σ_0 are the standard deviations for marks and spaces respectively, calculated on the differential phase received eye; this is given by

$$DiffPhase(t) = \left| Arg[A_x(t+T_B)] - Arg[A_x(t)] + Arg[A_y(t+T_B)] - Arg[A_y(t)] \right| , \quad (2)$$

with Arg() the phase (rad) of the optical signal complex amplitudes $A_x(t)$ and $A_y(t)$, for the two polarization components.

Differential phase eye opening: [deg, default: 180] the phase amplitude $\Delta\phi_{diff}$ in eq. 1.

Integration step: [m, default: 100] the integration numerical step for optical fibers (see eq. 1.1 in "Appendix - the fiber model").
A constant integration step, chosen by the user, is used in Optolink Numerics; the use of adaptive steps in WDM transmission would in fact over-estimate the XPM-induced penalties, by producing asymmetries during the optical signal pulse collisions.
Typically, in WDM systems performance increases for decreasing step, due to the asymmetry reduction in modeling the channels collisions. Numerical step should be decreased to the value corresponding to converging results; further reductions should not generate an appreciable performance improvement.
In dense WDM systems, typical step values range from 10 to 50 meters; in single-channel transmission, it is often sufficient the use of 50 to 100 meters steps.

Number of averaged runs: [default: 1] the use of repeated averaged runs is another characteristic of Optolink Numerics, which helps to reduce the computational time.
Setting the number of runs to a value N_{run}, Q factor, rms time jitter and eye closure of a transmitted channel are averaged along the repeated runs, according to

$$
\begin{aligned}
Q_{dB} &= 10\log_{10}\left(\frac{1}{N_{run}}\sum_{n=1}^{N_{run}} Q_n^2\right) \\
Rms\ jitter &= \left[\frac{1}{N_{run}}\sum_{n=1}^{N_{run}} \sigma_n^2\right]^{1/2} \\
Eye\ closure &= \left[\frac{1}{N_{run}}\sum_{n=1}^{N_{run}} Eye\ closure^2(n)\right]^{1/2}
\end{aligned}
\quad , \qquad (3)
$$

being σ_n^2 the channel time jitter variance.
At each run, the noise statistics, the PMD statistics and the transmitted PRBS sequences are changed, in order to average their effects among the repeated runs.
The use of averaged runs permits to perform simulations with considerably reduced computational times, without loss of numerical accuracy; details on the numerical accuracy are given in section "Appendix - Q factor and timing jitter models".

Seed for ASE noise in amplifiers: [<1, default: 0.5] Amplified Spontaneous Emission (ASE) generated by each amplifier is implemented adding suitable independent random Gaussian variables to the optical signal spectrum. Changing the initial seed for random variables, it varies the noise statistics. Seed is automatically changed at each repeated averaged run (see below).

Seed for PMD in fibers: [<1, default: 0.5] the seed for random variables θ_n and ϕ_n used in the birefringence axes rotation model. It is automatically changed at each repeated averaged run.

Note: Numerically transmitted pseudo-random sequences are relatively short (64 to 1024 bits). To have convergent results they should contain as much as possible equally distributed 3-bit patterns. For statistical reasons, they should also have an equal number of marks and spaces.
Sequences of this kind are quite few, and may be generated by proper pseudo-random algorithms.
Optolink Numerics uses 4 different pre-defined sequences that satisfy the above conditions (4 for each sequence length). Different sequences are transmitted in adjacent WDM channels, so that channel 1 has not the same pattern as channels 2, 3 and 4. Besides, channels patterns are cyclically changed at each repeated averaged run. This method, and the random optical phase given by default to each transmitted channel, gives a substantial de-correlation between neighboring channels. The use of uniformly distributed patterns helps to increase the convergence between simulated and experimental results.

7. Simulation window

During a simulation run, system devices, parameters and performance are sequentially described in a simulation window. Fiber dispersion, signal power and optical signal-to-noise ratio (OSNR) are shown at each simulated fiber span and amplifier. If no amplifier is present at fiber span input, power will depend on the preceding span losses, and no OSNR change will result.
Signal-to-noise ratio is evaluated as the total WDM signal power (with no amplifier noise) over the number of channels and over the Amplified Spontaneous Emission (ASE) power on a 0.1 nm bandwidth; it corresponds to an effective channel OSNR when all channels are transmitted with same power, otherwise it gives an average OSNR among the transmitted WDM channels.
In order to properly evaluate the signal-to-noise ratio even in the presence of Four Wave Mixing (FWM), Optolink Numerics transmits, independently on the signal+ASE optical field, a second field including only the ASE noise. The second field crosses all the system components, including eventual in-line filters, up to the receivers (to avoid waist of computational efforts, in optical fibers this second field experiences only losses and birefringence axis rotation). ASE noise is evaluated as the power of this second optical field.
A numerical error is also displayed at the end of each fiber span; it is defined as the normalized difference between the theoretical signal energy (evaluated by the selected fibers length and loss, and spans input power) and the numerically evaluated energy; error is cumulated over a single span length.
Numerical error is generated mainly by the integration of the nonlinear terms in Schrödinger equation (eq. 1.1 in" Appendix - The fiber model"); when relative error exceeds 0.1 % at each span, it may be necessary to reduce the integration step or the signal optical power.

Simulation results are saved as text files in the same directory as the transmission system ".olk" file (example: if system is saved in "path\system1.olk", results will be in directory "path\system1")
System components and performance are also printed on a log file named "Runlog.log", placed in the results directory.
Simulation window menus are:

File - Print/Save: prints/saves the screen text
File - Exit: quit simulation.

Edit - Select Text/Graphics/All: used to select part of the simulation window, in text or graphics format.
Edit - Copy/Paste: copies or pastes text in the simulation window.

View - Size To Fit/Full Screen: sizes text to the simulation window or screen.

State - Pause/Resume: allows the user to pause a simulation; this is particularly useful when all CPU resources are to be dedicated to another simulation and/or different tasks.

8. Optolink Graph Viewer

The Optolink Graph Viewer is a graphic tool to show the results and performance for the current opened system; it is started selecting the “Show graphs” command/button, and double-clicking on a system Receiver component (see the “RX, IM-DD”, “RX, DPSK” or “RX, PhIM” sections), an Evaluate Performance component (see “Evaluate Performance” section) or on a Raman fiber, Multimodal fiber, Free-space optics, Optical filter, Electrical filter or Laser DM component. Partial results may be viewed during the simulation run, if available.

Optical receivers (see “RX, IM-DD”, “RX, DPSK”, “RX, PhIM” and “Evaluate Performance”) automatically detect those channels selected for performance evaluation and eye printing (checking in the “WDM – Channels 1..64, 65..128, 129..192” windows). Selected channels are optically de-multiplexed by the filter specified in the “DeMUX” component (if present) and sent to the receiver.
Component “RX, PhIM” is the most complete, because it includes both an intensity receiver (evaluates the amplitude performance and eyes) and a DPSK receiver (phase performance and eyes); if an IM-DD channel is recognized, only amplitude performance is considered; if a DPSK channel, only phase performance. Component “RX, IM-DD” only includes an intensity receiver; component “RX, DPSK” only the phase DPSK receiver.
Component “Evaluate Performance” is used after one or more photodiodes, and does not include any receiver; it only evaluates the performance of the incoming electrical signal.
The above features permit to add a single receiver component to a WDM transmission system. Channel de-multiplexing and format and bit rate recognition is automatically performed. Any way, several receivers may be added to the transmission system if performance must be evaluated with different receiver parameters (splitting the output optical signal using, for example, a Splitter component).

The following menus are present when double-clicking on a “RX, IM-DD”, “RX, DPSK”, or “RX, PhIM” component:

File - Print/Save: prints/saves the current graphs or text in the Viewer window.
File - Exit: quits the Viewer.

Edit - Zoom In/Zoom Out: zoom of the current graph.
Edit - Copy Figure: copies the current graph or text to the Clipboard, in MS Chart format; graphs may be pasted as image or formatted text in other applications; in the latter case, the first column represents the abscissa values, the following columns the graph series.

Performance - Optimal: system performance at the reached distance are shown; performance parameters are (with reference to the following sections for their definitions):
- Q factor [dB] averaged among channels with selected “Print Q” box, at the optimal post-compensation value for each channel. Averaging is performed on the Q^2 factors (see “Appendix - Q factor and timing jitter models” section).

- Rms timing jitter [ps] averaged among channels, corresponding to the optimal Q post-compensation values for each selected channel.
- Eye closure [dB] averaged among channels, corresponding to the optimal Q post-compensation values for each selected channel. Eye closure is not evaluated when 3-bit patterns are used.
- OSNR (Optical Signal to Noise Ratio) [dB] over a 0.1 nm bandwidth, at the reached distance (see “Simulation window” section for details).
- The single optimal Q factors, rms timing jitter and optimal post-compensation values for the channels with selected “Print Q” box.

If simulation is still running for the currently opened system, partial results will refer to the reached distance.
When lasers, DPSK or PhIM transmitter components are used (see “Laser, CW”, “Laser, direct modulation”, “TX, DPSK” and “TX, PhIM”) performance is shown for both the amplitude and the phase tributaries (i.e. from intensity and phase receivers). For channels corresponding to IM-DD transmitters (see “TX, IM-DD”) only amplitude performance is shown.
Performance - Q factor vs. Post-comp, ampl.: graphs the Q factor [dB] vs. Post-compensation [ps/nm], for channels with selected “Print Q” box, and for the amplitude tributary of PhIM channels, or for laser modulated or IM-DD channels.
Performance - Time jitter vs. Post-comp, ampl.: shows the Rms timing jitter [ps] vs. Post-compensation [ps/nm] for the amplitude tributary of the selected channels.
Performance – Eye closure vs. Post-comp, ampl.: shows the Eye closure [dB] vs. Post-compensation [ps/nm] for the amplitude tributary of the selected channels.
Performance - Q factor vs. Post-comp, phase: Q factor [dB] vs. Post-compensation [ps/nm], for channels with selected “Print Q” box, and for the phase tributary of DPSK, laser modulated or PhIM channels.
Performance - Time jitter vs. Post-comp, phase: Rms timing jitter [ps] vs. Post-compensation [ps/nm] for the phase tributary of the selected channels.
Performance – Eye closure vs. Post-comp, phase: Eye closure [dB] vs. Post-compensation [ps/nm] for the phase tributary of the selected channels.

Eyes ampl.: shows the received eyes for the amplitude tributary of channels with selected “Print eye” box; the first 256 bits are shown for long patterns.
Eyes phase: shows the receiver eyes for the phase tributary of channels with selected “Print eye” box.

Optical power: graphs of the received Optical power [mW] vs. Time [ps], after the receiver optical de-multiplexer and the polarization controller, if used, for the specified channel in the receiver dialog box (see “RX, IM-DD”, “RX, DPSK”, “RX, PhIM”). Power is given for the two *x* and *y* polarization components, and the sum of the two (in separate windows).

Optical phase: graphs of the received Optical phase [rad] vs. Time [ps], after the receiver optical de-multiplexer (see “DeMUX”) if used, for the specified channel in the receiver dialog box. Phase is given for the two *x* and *y* polarization components, and the sum of the two.

Optical spectrum: shows the received Optical spectrum [dB, mW/nm] vs. Wavelength [nm], before any receiver optical de-multiplexer. Spectrum is given for the two *x* and *y* polarization components, and for the sum of the two. The de-multiplexer transfer function used for one channel may be viewed overlapped to the spectrum by clicking on the “Optical Filter” item.

Dynamic calculation of BER, Q-factor and optical power:

When a received eye for the amplitude or phase tributary is displayed, BER and Q-factor are calculated for any user-selected sampling instant t_0 (ps) and receiver threshold I_{th} (mA). BER is estimated using the Gaussian approximation, i.e.

$$BER = \frac{n_0}{n_0+n_1}\frac{1}{2}erfc\left(\frac{|m_0-I_{th}|}{\sqrt{2}\sigma_0}\right)+\frac{n_1}{n_0+n_1}\frac{1}{2}erfc\left(\frac{|m_1-I_{th}|}{\sqrt{2}\sigma_1}\right) \quad , \qquad (1)$$

with n_0 , n_1 the number of spaces and marks respectively, and $m_0, m_1, \sigma_0, \sigma_1$ the mean values and standard deviations for spaces and marks at the selected sampling instant; erfc(x) denotes the complementary error function.
Q-factor in calculated from BER using the inverse of

$$BER = \frac{1}{2}erfc\left(\frac{Q}{\sqrt{2}}\right) \quad , \qquad (2)$$

and the

$$Q_{dB} = 20\cdot\log_{10} Q \quad . \qquad (3)$$

When an optical spectrum is displayed, the optical power (dBm) is calculated between the user-selected lower and higher wavelength markers (nm).

The following menus are present when double-clicking on an “Evaluate Performance” component:

Performance - Optimal: system performance at the receiver, for optimal threshold and sampling instant.

Eyes ampl.: shows the received electrical signal eye.

Electrical Amplitude: graph of the received Electrical signal [mA] vs. Time [ps].

Electrical Spectrum: graph of the received Electrical power spectrum [a. u.] vs. Frequency [GHz].

Dynamic calculation of BER and Q-factor is still present for the “Evaluate Performance” component.

By selecting the “Show graphs” command/button, and double-clicking on a “Optical filter”, “Electrical filter”, “Multimodal fiber”, “Laser DM” or “Free-space optics” component, “Optolink Graph Viewer” will show the optical/electrical transfer function (dB vs. GHz) in the first three cases, the normalized response function (dB vs. GHz) in the fourth case and the link transmittance (adim. vs. μm) in the last case.
Double-clicking on a “Raman Fiber” component, the optical power evolution over the fiber length is shown as a 3-D plot for pumps, signal bins and ASE; graphs of the

optical power can be rotated by selecting the “Rotate” button, clicking on the plot and dragging horizontally or vertically. Input and output power spectra may also be compared in units of power/bin.

9. Components library

This section describes in detail the optical and electrical components used by Optolink Numerics, the implemented models and the used parameters.
All components include a “Caption” box that helps user to identify a component with an arbitrary name (example: “Fiber, D=20 ps/nm/km” for an optical fiber); caption is displayed on the design chart when mouse is positioned over the component.

TX, IM-DD (TX_IM_DD)

Optical transmitter for Intensity Modulation with Direct Detection (IM-DD) format. Generates a single-channel or WDM optical signal according to the “MUX” component and “WDM” windows settings.
For IM-DD channels, Return-to-Zero (RZ) and Non-Return-to-Zero (NRZ) formats are modeled; it may optionally be included the alternated phase or polarization among bits, the carrier suppressed, the optical modulator chirp and extinction ratio.

Inputs / Outputs: no input, 1 optical output.

Parameters:

IM-DD channel bit rate: [Gb/s, default: 10] the bit rate *R* for an IM-DD optical signal. In WDM transmission, *R* refers to a single WDM channel.

Laser linewidth: [MHz, default: 10] transmitter includes a continuous laser model (see “Laser CW”) for each generated channel. Laser optical field is initially linearly polarized over the *x* axis; it is modulated according to eqs. 1 to 11 below. Polarization is eventually rotated when multiplexing channels.

Laser wavelength: [nm, default: 1550] if a “MUX” is not used at the transmitter output, selects the optical signal central wavelength. Not considered if a “MUX” is used.

Modulation format: [default: NRZ] selects the optical format for each transmitted channel. Optical format is modeled as follows:

NRZ format:

An optical Intensity Modulator has been modeled with separately controllable Extinction Ratio *ER* and chirp parameter α_f (the alpha factor, see [F. Kodama, K. Iga, IEEE Journal of Lightwave Technology 6, pp. 87-93, Jan. 1988]).
Assuming a quadrature operating point, the output optical field is given by, over a single *x* polarization component:

$$A_{out\,x}(t) = A_{in\,x}(t)\left|\cos(\Delta\phi(t))\right|\exp\left(-j\alpha_f\Delta\phi(t)\right) \quad , \qquad (1)$$

where $A_{in\,x}(t)$ is the complex amplitude of a CW input optical field and $\Delta\phi(t)$ is the phase difference in the modulator branches; with bias $\Delta\phi_b = \pi/4$ it is given by

$$\Delta\phi(t) = \frac{\pi}{2}\left(\frac{1}{2} - er\left(norm\_sig(t) - \frac{1}{2}\right)\right)$$
$$er = 1 - \frac{4}{\pi}\arctan\left(\frac{1}{\sqrt{ER_{lin}}}\right) \quad . \qquad (2)$$

In eq. 2, *norm_sig(t)* is the normalized electrical driving signal, ranging between 0 and 1 and having finite rising and fall times; $ER_{dB} = 10\log_{10}(ER_{lin})$ is the optical extinction ratio in dB.
The desired pulse shape and rise time t_r (10% to 90%) is generated over the *norm_sig(t)* signal by filtering a step-shape PRBS signal with an electrical Gaussian filter, with transfer function in dB given by

$$H_{rise}(f) = 20\log_{10}\left\{\exp\left[-2\ln 2\left(\frac{f\,t_r}{0.562}\right)^2\right]\right\} \quad , \qquad (3)$$

with *f* the electrical frequency. The generated optical power has a complementary error function shape, with rise time very close to t_r for extinction ratios around 15 dB; for much higher *ER* values (greater than 35 dB), the rise time approaches to t_r with an error smaller than 20%.

RZ Gaussian format:
RZ pulses are experimentally generated through a shaper intensity modulator cascaded to a data modulator; the resulting pulse shape is strongly dependent on the chosen bias and modulation currents. In order to overcome the uncertainties encountered in using cascaded modulators, RZ signals are generated by exact shape functions.
The RZ optical pulses with Gaussian shape are typical of dispersion managed solitonic systems. Optical field is modeled by the

$$A_x(t) = \sum_j code(j)A_{in,x}(t)\exp\left[-\frac{(t - jT_B)^2}{2T_0^2}\right] \qquad j = 0,1,2\ldots \; , \qquad (4)$$

for a signal transmitted with co-polarized bits. In eq. 4, T_0 is bound to the pulse full width at a half maximum by $T_0 = T_{FWHM}/1.665$, *code(j)* equals $1/\sqrt{ER+1}$ or $\sqrt{ER/(ER+1)}$ for transmitted spaces or marks, *ER* is the linear extinction ratio, $A_{in,x}(t)$ is an input optical field generated by the CW laser and $T_B = 1/R$ the bit period.
For bits transmitted with alternated polarizations (like, for example, in polarization multiplexed solitons), the optical field for the *x* and *y* polarization components is given by

$$A_x(t) = \sum_j code(j) A_{in}(t) \exp\left[-\frac{(t - jT_B)^2}{2T_0^2}\right] \qquad j = 0,2,4...$$
$$A_y(t) = \sum_j code(j) A_{in}(t) \exp\left[-\frac{(t - jT_B)^2}{2T_0^2}\right] \qquad j = 1,3,5... \quad , \quad (5)$$

with $A_{in}(t)$ a scalar laser field.

RZ cosine format:
Cosine format is typical of chirped RZ transmission, and commonly used in submarine systems. The complex amplitude for co-polarized pulses is

$$A_x(t) = \sum_j code(j) A_{in,x}(t) \cos\left[\frac{\pi}{2}\sin(\pi Rt)\right] rect(t - jT_B) \qquad j = 0,1,2... \quad , \quad (6)$$

with *rect()* the rectangular function of width $T_B = 1/R$. For alternated polarization bits, optical fields equations are similar to the above eq. 5.

RZ sech format:
Hyperbolic secant shape is typical of solitonic systems with uniform fiber dispersion. Complex amplitude for co-polarized bits is given by

$$A_x(t) = \sum_j code(j) A_{in,x}(t) \operatorname{sech}\left[\frac{(t - jT_B)}{T_0}\right] \qquad j = 0,1,2... \quad , \quad (7)$$

with $T_0 = T_{FWHM}/1.763$. For alternated polarization bits, equations similar to eq. 5 hold.

Channel power: [dBm, default: 0] the optical power for each modulated channel.

Extinction ratio: [dB, default: 15] sets the extinction ratio ER_{dB} for each optical channel.

Rise time: [ps, default: 20] it is the electrical NRZ rise and fall time t_r, defined in eq. 3. Optical rise and fall times are very close to t_r for extinction ratios around 15 dB; for much higher *ER* values (greater than 35 dB), the rise time approaches to t_r with an error smaller than 20%.

Alpha chirp factor: [default: 0] is the modulator chirp α_f, defined by eq. 1. If $\Delta\theta(t) = -\alpha_f \Delta\phi(t)$ and $P_{out}(t)$ is the modulator output power, alpha-factor is given by

$$\alpha_f = 2\frac{\frac{d\Delta\theta}{dt}}{\frac{1}{P_{out}}\frac{dP_{out}}{dt}} \quad , \qquad (8)$$

Alpha chirp is available for NRZ signals.

FWHM pulsewidth: [ps, default: 30] the RZ pulses full width at a half maximum T_{FWHM} ; it refers to the optical power.

Alternated polarizations bits: [default: unchecked] check this box for RZ bits with alternated polarizations.

Synchronous phase modulation amplitude: [radians, default: 0] when non-zero, optical field complex amplitudes are multiplied for a synchronous phase modulation term, with the specified amplitude ϕ_{mod} (the phase modulation index), according to [E. A. Golovchenko, A. N. Pilipetskii, N. S. Bergano, proc. of OFC 2000, FC3, pp. 38-40]

$$A_k(t)\exp\left[i\phi_{\mathrm{mod}}\cos(2\pi Rt)\right] \qquad k = x, y \qquad . \qquad (9)$$

Applies to both NRZ and RZ format; typical of RZ cosine.

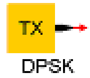
Initial phase between bits: [degrees, default: 0] sets an initial optical phase $\Delta\phi_{in}$ between adjacent bits. Bit phase is alternated between $\pm\Delta\phi_{in}/2$ with negligible rise time, according to the

$$A_k(t)\exp\left[i\frac{\Delta\phi_{in}}{2}\mathrm{sign}\left(\cos(\pi Rt)\right)\right] \qquad k = x, y \qquad . \qquad (10)$$

Carrier suppressed: [default: unchecked] if checked, optical field complex amplitudes are multiplied for a sinusoidal phase term with frequency $R/2$ and amplitude $\Delta\phi_{in} = \pi$, to generate a carrier suppressed optical signal [Y. Miyamoto, A. Hirano, K. Yonenaga, A. Sano, H. Toba, K. Murata, O. Mitomi, Electronics Letters 35, pp. 2041-2042, Nov. 1999]; eq. 10 is replaced by

$$A_k(t)\exp\left[i\frac{\pi}{2}\cos(\pi Rt)\right] \qquad k = x, y \ . \qquad (11)$$

TX, DPSK (TX__DPSK)



Optical transmitter for Differential Phase Shift Keying format.
Generates a single-channel or WDM optical signal according to the “MUX” component and “WDM” windows settings.
Continuous wave (CW) and Return-to-Zero (RZ) carriers are modeled; it may optionally be included the alternated polarization among bits, the carrier suppressed, the optical pulses extinction ratio.

Inputs / Outputs: no input, 1 optical output.

Parameters:

DPSK tributary bit rate: [Gb/s, default: 10] the bit rate *R* for a DPSK signal.

Laser linewidth: [MHz, default: 10] transmitter includes a continuous laser model (see “Laser CW”) for each generated channel. Laser optical field is initially linearly polarized over the *x* axis; it is modulated according to the equations below. Polarization is eventually rotated when multiplexing channels.

Laser wavelength: [nm, default: 1550] if a “MUX” is not used at the transmitter output, selects the optical signal central wavelength. Not considered if a “MUX” is used.

Amplitude shape: [default: CW] selects the shape of the optical carrier, as follows:

CW amplitude:
The optical amplitude shape equals the optical field $A_{in,x}(t)$ generated by a CW laser. Optical amplitude is then phase modulated (see below).

RZ Gaussian amplitude:
Optical amplitude shape is modeled as

$$B_x(t) = A_{in,x}(t)\left\{\frac{1}{\sqrt{ER+1}} + \sum_j \frac{\sqrt{ER}-1}{\sqrt{ER+1}}\exp\left[-\frac{(t-jT_B)^2}{2T_0^2}\right]\right\} \qquad j = 0,1,2\ldots, \quad (1)$$

for a signal transmitted with co-polarized bits. In eq. 1, T_0 is bound to the pulse full width at a half maximum by $T_0 = T_{FWHM}/1.665$, *ER* is the linear extinction ratio, $A_{in,x}(t)$ is an input optical field generated by the CW laser and $T_B = 1/R$ the bit period.
For bits transmitted with alternated polarizations, the optical field for the *x* and *y* polarization components is given by

$$B_x(t) = A_{in}(t)\left\{\frac{1}{\sqrt{ER}+1} + \sum_j \frac{\sqrt{ER}-1}{\sqrt{ER}+1}\exp\left[-\frac{(t-jT_B)^2}{2T_0^2}\right]\right\} \qquad j = 0,2,4...$$
$$B_y(t) = A_{in}(t)\left\{\frac{1}{\sqrt{ER}+1} + \sum_j \frac{\sqrt{ER}-1}{\sqrt{ER}+1}\exp\left[-\frac{(t-jT_B)^2}{2T_0^2}\right]\right\} \qquad j = 1,3,5... \quad , \quad (2)$$

with $A_{in}(t)$ a scalar laser field.

RZ cosine amplitude:
The complex amplitude shape for co-polarized pulses is

$$B_x(t) = A_{in,x}(t)\left\{\frac{1}{\sqrt{ER}+1} + \sum_j \frac{\sqrt{ER}-1}{\sqrt{ER}+1}\cos\left[\frac{\pi}{2}\sin(\pi R t)\right] rect(t-jT_B)\right\} \qquad j = 0,1,2... \quad , \quad (3)$$

with *rect()* the rectangular function of width $T_B = 1/R$. For alternated polarization bits, optical field equations are similar to the above eq. 2.

RZ sech amplitude:
Complex amplitude shape for co-polarized bits is given by

$$B_x(t) = A_{in,x}(t)\left\{\frac{1}{\sqrt{ER}+1} + \sum_j \frac{\sqrt{ER}-1}{\sqrt{ER}+1}\operatorname{sech}\left[\frac{(t-jT_B)}{T_0}\right]\right\} \qquad j = 0,1,2... \, , \quad (4)$$

with $T_0 = T_{FWHM}/1.763$. For alternated polarization bits, equations similar to eq. 2 hold.

Phase type: [default: NRZ] selects the phase modulation format, NRZ or pulsed.
Phase modulation for the DPSK phase tributary is modeled as proportional to the driving electrical signal. PRBS driver may be of NRZ type, generated according to eqs. 1 to 3 in “TX, IM-DD”, or pulsed with positive and negative pulses respect to an average value. In the latter case, let *NRZ(t)* and *clock(t)* be a normalized NRZ PRBS signal and a normalized clock, both with step-shape; the signal $sig\_norm(t) = clock(t)(NRZ(t) - 0.5)$ is passed through an electrical Gaussian filter according to eq. 3 in “TX, IM-DD”, to generate the desired phase rise time t_r (10% to 90%). The optical phase with amplitude $\Delta\phi_{DPSK}$, on a given polarization component, is generated by the

$$A_{out,x}(t) = B_x(t)\exp[i\Delta\phi_{DPSK}\, sig\_norm(t)] \quad . \qquad (5)$$

Channel power: [dBm, default: 0] the optical power for each modulated DPSK channel.

Amplitude extinction ratio: [dB, default: 15] it is the ER_{dB} for the amplitude shape, *ER* in linear scale is used in eqs. 1 to 4.

Pulsed amplitude FWHM pulsewidth: [ps, default: 30] the T_{FWHM} in eqs. 1 to 4, for the amplitude pulsed shape.

Phase modulation amplitude: [degrees, default: 180] the phase amplitude $\Delta\phi_{DPSK}$ (in degrees) in eq. 5.

Phase rise time: [ps, default: 20] the rise time t_r (10% to 90%) for the DPSK phase in both NRZ and pulsed cases.

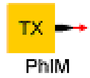
Carrier suppressed: [default: unchecked] if checked, a sinusoidal phase modulation is added to the phase tributary, according to the

$$A_{out,x}(t)\exp\left\{i\frac{\pi}{2}\cos(\pi Rt)\right\} \quad , \quad (6)$$

with R the tributary bit rate.

Bits with alternated polarizations: [default: unchecked] if checked, amplitude shape has alternated polarization pulses (only for pulsed shape).

TX, PhIM (TX__PhIM)



Optical transmitter for Phase and Intensity Modulation (PhIM) format, described in section “PhIM format”.

Inputs / Outputs: no input, 1 optical output.

Parameters:

PhIM tributaries bit rate: [Gb/s, default: 10] the bit rate *R* for each tributary in a PhIM optical signal (amplitude and phase). The total bit rate for a PhIM signal with no polarization domain multiplexing is 2x*R*.

Laser linewidth: [MHz, default: 10] transmitter includes a continuous laser model (see “Laser CW”) for each generated channel. Laser optical field is initially linearly polarized over the *x* axis; it is modulated according to the equations below. Polarization is eventually rotated when multiplexing channels.

Laser wavelength: [nm, default: 1550] if a “MUX” is not used at the transmitter output, selects the optical signal central wavelength. Not considered if a “MUX” is used.

Amplitude type: [default: NRZ] selects the amplitude tributary modulation format, as follows:

NRZ amplitude:
In NRZ case, dark pulse PhIM is generated using the transmitter scheme in Fig. 2 of “PhIM format” section; optical dark pulses in the PhIM amplitude tributary are generated on a given polarization component by an intensity modulator, according to

$$\begin{aligned} A_{out\,x}(t) &= A_{in\,x}(t)\left|\cos\left(\Delta\phi(t)\right)\right| \\ \Delta\phi(t) &= \frac{\pi}{2}\left(\frac{1}{2} - er\left(\frac{1}{2} - norm\_sig(t)\right)\right) \\ er &= 1 - \frac{4}{\pi}\arctan\left(\frac{1}{\sqrt{ER_{lin}}}\right) \end{aligned} \quad . \qquad (1)$$

$ER_{dB} = 10\log_{10}\left(ER_{lin}\right)$ is the optical extinction ratio in dB; *norm_sig(t)* is a normalized RZ electrical driving signal, ranging between 0 and 1 and having finite rising and fall times. RZ electrical PRBS is generated as the AND operation of an NRZ step-shape signal and a clock; the obtained step-shaped RZ pulses, with 50% duty-cycle, are passed through an electrical Gaussian filter with transfer function in dB given by eq. 3 in “TX, IM-DD”, to generate the desired pulse shape and amplitude rise time t_r (10% to 90%).

Tanh amplitude:

In tanh case, dark pulse PhIM is generated again using the scheme in Fig. 2 of "PhIM format" section; optical dark pulses on a given polarization component are generated according to the

$$A_x(t)=\sum_{j=1}^{N_{bit}} A_{in,x}(t)A_0\left[\frac{1}{B_o^2}-code(j)\cdot\mathrm{sech}^2\left(1.763\cdot Cadj\cdot A_0\,\frac{t-jT_B}{T_{FWHM}}\right)\right]^{1/2}+$$
$$-(N_{bit}-1)\sqrt{P_{peak}}\sqrt{\frac{ER_{lin}}{ER_{lin}+1}}$$
$$A_0=\sqrt{\frac{ER_{lin}-1}{ER_{lin}+1}}\qquad B_0=\sqrt{\frac{ER_{lin}-1}{ER_{lin}}}\qquad ,\ (2)$$
$$Cadj=\begin{cases}-3.341\times10^{-7}ER_{dB}^5+4.092\times10^{-5}ER_{dB}^4-1.839\times10^{-3}ER_{dB}^3+\\ +0.0386ER_{dB}^2-0.389ER_{dB}+2.594 & ER_{dB}\le 20\text{ dB}\\ 1 \quad ER_{dB}>20\text{ dB}\end{cases}$$

with ER_{dB} and ER_{lin} the amplitude tributary extinction ratio in dB and linear scale, $A_{in,x}(t)$ and P_{peak} the CW laser complex amplitude and average power respectively, T_{FWHM} the dark pulses full width at half maximum, and *code(j)* a PRBS code with N_{bit} bits and equal number of marks and spaces. For high extinction ratio, eq. 2 reduces to a tanh shape.

Dual drive amplitude:
Dark pulse PhIM is transmitted using the scheme in Fig. 3 and eqs. 2 of "PhIM format" section, here generalized as

$$\begin{aligned}
&d_A(t)=NRZ_A(t)\oplus d_A(t-T_B)\\
&b_\phi(t)=NRZ_A(t)\oplus NRZ_\phi(t)\\
&d_\phi(t)=b_\phi(t)\oplus d_\phi(t-T_B)\\
&V_A(t)=d_A(t)\cdot V_\pi\\
&V_\phi(t)=\left[d_\phi(t)\cdot V_\pi-\frac{V_\pi}{2}\right]\frac{\Delta\phi_{PhIM}}{\pi}\\
&V_1(t)=V_A(t)+V_\phi(t)\\
&V_2(t)=-V_A(t)+V_\phi(t)
\end{aligned}\qquad .\qquad (3)$$

Driving voltages $V_1(t)$ and $V_2(t)$ are applied to a modulator with dual drive design, modeled as

$$A_{outx}(t)=A_{in\,x}(t)\left\{\frac{1}{2}\exp\left[i\pi\frac{V_1(t)}{V_\pi}\right]+\frac{\gamma}{2}\exp\left[i\pi\frac{V_2(t)}{V_\pi}\right]\right\}\qquad ,\qquad (4)$$
$$\gamma=\frac{\sqrt{ER_{lin}}-1}{\sqrt{ER_{lin}}+1}$$

with V_π the modulator inversion voltage, ER_{lin} the extinction ratio in linear scale. Eqs. 3 and 4 generate both a dark pulse amplitude modulation and an independent phase modulation with NRZ shape and amplitude $\Delta\phi_{PhIM}$.
Finite rise and fall times are applied to the driving signals $V_A(t)$ and $V_\phi(t)$ in eqs. 3, passing the signals through an electrical Gaussian filter with transfer function in dB given by eq. 3 in "TX, IM-DD".

RZ amplitude:
Sets the bright pulse PhIM transmitter, using the scheme in Fig. 4 of "PhIM format" section. Shaper modulator generates a train of Gaussian pulses of selected pulsewidth T_{FWHM}. Pulses with intensity data modulation are generated over the *x* transmitted polarization component, according to eq. 4 in "TX, IM-DD"; pulses with phase data modulation are generated over the *y* polarization component using the

$$A_{out,y}(t) = B_y(t)\exp\left[i\Delta\phi_{PhIM}\, sig\_norm(t)\right] \quad , \qquad (5)$$

with $\Delta\phi_{PhIM}$ the selected phase modulation amplitude, $B_y(t)$ the pulse train to the phase modulator, $sig\_norm(t)$ the normalized NRZ driving signal, supposed with negligible rise and fall times and with differential pre-encoding.
The generated RZ and RZ-DPSK signals are then polarization interleaved. Output signal SOP may be rotated when multiplexed.

Phase type: [default: Pulsed] selects the phase modulation format, NRZ or with positive and negative pulses respect to an average value. It is used only for the transmitter scheme in Fig. 2, "PhIM format".
When using the transmitter in Fig. 2, phase modulation for the PhIM phase tributary is modeled as proportional to the driving electrical signal. PRBS driver may be of NRZ type, generated according to eqs. 1 to 3 in "TX, IM-DD", or pulsed with positive and negative pulses respect to an average value. In the latter case, let *NRZ(t)* and *clock(t)* be a normalized NRZ PRBS signal and a normalized clock, both with step-shape; the signal $sig\_norm(t) = clock(t)(NRZ(t) - 0.5)$ is passed through an electrical Gaussian filter according to eq. 3 in "TX, IM-DD", to generate the desired phase rise time t_r (10% to 90%). The optical phase with amplitude $\Delta\phi_{PhIM}$, on a given polarization component, is generated by the

$$A_{out,x}(t)\exp\left[i\Delta\phi_{PhIM}\, sig\_norm(t)\right] \quad . \qquad (6)$$

Channel power: [dBm, default: 0] the optical power for each modulated PhIM channel.

Extinction ratio: [dB, default: 15] it is the ER_{dB} for the amplitude tributary, both for dark and bright PhIM.

Amplitude tributary FWHM pulsewidth: [ps, default: 30] the T_{FWHM} in eq. 2 for the amplitude tributary with tanh shape, or for the pulse train in bright pulse PhIM.

Phase tributary modulation amplitude: [degrees, default: 180] the phase amplitude in eqs. 3, 5 and 6.

Amplitude-Phase tributaries delay: [ps, default: 50] amplitude and phase tributaries are delayed in PhIM format, the best performance is usually given for a delay equal to half a baud time slot. Not used with dual drive dark pulse PhIM.

Amplitude tributary rise time: [ps, default: 20] the rise time t_r (10% to 90%) for the PhIM amplitude in NRZ and dual drive case.

Phase tributary rise time: [ps, default: 20] the rise time for the optical phase applied to the PhIM signal. Used with NRZ, tanh and dual drive amplitude.

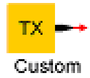
RZ PhIM splitting ratio: [default: 1] used in bright PhIM of Fig. 4 , "PhIM format"; it is the ratio *s* between the RZ and the RZ-DPSK pulses peak power.

Carrier suppressed: [default: unchecked] if checked, a sinusoidal phase modulation is added to the phase tributary, according to the

$$A_x(t)\exp\left\{i\frac{\pi}{2}\cos(\pi R t)\right\} \quad , \qquad (7)$$

with *R* the tributary bit rate.

TX, Custom (TXCustom)



Optical transmitter for user-defined format.
Designers may want to integrate their executable files into Optolink Numerics; this is possible for both optical components with 1 optical input and 1 optical output (see "Custom Component") and for the custom transmitter described here. "TX, Custom" is used to generate a single-channel or WDM optical field.
Executable file can be compiled in any programming language able to generate an ".exe" file; the executable must be placed in a dedicated subdirectory (we will refer to it as the "path\" directory). Optolink Numerics writes the parameters selected for "TX, Custom" in a file called "path\Parameters.dat"; this is a text file with a single column of 16 numbers, in order: the channel bit rate *R* (Gb/s), 12 user parameters for the transmitter (with user-defined dimensions), the number of simulated points *N*, the number of simulated bits N_{bits}, the simulation time window $\Delta t = N_{bits}/R$ (in seconds).
The user-defined executable must be able to read the "path\Parameters.dat" file and use the 16 numeric parameters for generating the single-channel optical field

$$A_k(t_j) = \mathrm{Re}\left[A_k^{(j)}\right] + i\,\mathrm{Im}\left[A_k^{(j)}\right] \qquad k = x, y \qquad j = 1,2,..N \qquad . \qquad (1)$$

The generated *x* polarization complex amplitude must be recorded in a file called "path\Ax.dat", containing 2 columns of *N* numbers separated by commas, spaces or tabs: the first column is the real part of the complex amplitude $\mathrm{Re}\left[A_x^{(j)}\right]$ (in $W^{1/2}$), the second is the imaginary part $\mathrm{Im}\left[A_x^{(j)}\right]$ (in $W^{1/2}$); the generated *y* polarization must be recorded in file "path\Ay.dat" in the same way.
Optolink Numerics will read those file for integrating the user-defined signal into the system scheme; WDM signals may be also generated using the "MUX" and the "WDM" windows, exactly like the other "TX" components.
Numbers written to or read from file must be compatible with the Fortran REAL data type.
Executable is launched by Optolink Numerics with a command line

"path\executable_file.exe path\"   ,   (2)

i.e. the "path\" string is passed to the executable as a command parameter. To show an example, command parameter may be read in a Fortran executable using the CALL GETARG(1,sfile) instruction; it will result TRIM(sfile)= "path\".

Inputs / Outputs: no input, 1 optical output.

Parameters:

Executable file: use the "Browse" button to search for the user-defined executable.

Channel bit rate: [Gb/s, default: 10] the bit rate for the generated signal, to be used by the executable.

Parameter 1 .. Parameter 12: [default: 0] up to 12 numeric parameters to be used by the executable for generating the signal.

Different executables must be recorded in separated subdirectories, in order to avoid unpredictable results.
“TX, Custom” may also be used to read from file stored optical fields, and integrate them within the Optolink Numerics design chart.

Laser CW (Laser_CW)

Optical continuous wave laser. If external optical modulators are used, a “Laser CW” is needed to generate the wavelengths to be modulated. “Laser CW” is used in conjunction with “MUX” and the “WDM menu” just like the “TX” components; if a WDM transmission is selected for the laser, it generates all the selected wavelengths, multiplexed with the desired polarizations. Those wavelengths will be modulated in a following modulator using the same driving signal.
A laser with linewidth $\Delta\nu$, generates a continuous wave optical field (one for each wavelength) affected by the noise

$$A_{out,x}(t) = \sqrt{P}\exp\left[i\int_{-\infty}^{t}\omega_0(t')dt'\right] \quad , \qquad (1)$$

with *P* the average power and $\omega_0(t)$ a white Gaussian noise with zero average and standard deviation $\sigma_{\omega 0} = 2\pi\Delta\nu$.
Polarization is eventually rotated at the “Laser CW” by the wavelength multiplexing.

Inputs / Outputs: no input, 1 optical output.

Parameters:

Laser power: [dBm, default: 0] the power *P* in eq. 1 for each generated wavelength.

Linewidth: [MHz, default: 10] the laser linewidth $\Delta\nu$ for eq. 1.

Wavelength: [nm, default: 1550] if a “MUX” is not used at the laser output, selects the laser central wavelength. Not considered if a “MUX” is used.

Laser, direct modulation (Laser_DM)

The component models a realistic semiconductor laser with direct modulation, integrating the complete rate equations. It also includes a design tool for extracting the laser rate equation parameters, starting from the measured frequency response. Input to the “Laser DM” must be an “Electrical Driver”, eventually followed by other electrical components.

Direct problem; the semiconductor laser rate equations:

The laser model accounting for spontaneous emission, gain compression and linewidth enhancement is given by [J. C. Cartledge, R. C. Srinivasan, IEEE Journal of Lightwave Technology 15, pp. 852-860, May 1997]

$$\begin{aligned}
\frac{dN(t)}{dt} &= \frac{I(t)}{qV} - \frac{N(t)}{\tau_n} - g_0[N(t)-N_t]\frac{S(t)}{1+\varepsilon S(t)} \\
\frac{dS(t)}{dt} &= \Gamma g_0[N(t)-N_t]\frac{S(t)}{1+\varepsilon S(t)} - \frac{S(t)}{\tau_p} + \frac{\Gamma\beta N(t)}{\tau_n} \\
\frac{d\phi(t)}{dt} &= \frac{1}{2}\alpha\left\{\Gamma g_0[N(t)-N_t] - \frac{1}{\tau_p}\right\}
\end{aligned} \quad . \qquad (1)$$

In eq. 1, the following laser parameters have been used:
$N(t)$, $S(t)$ and $\phi(t)$ are respectively the carrier density, photon density and optical phase; Γ the mode confinement factor, N_t the carrier density at transparency, τ_p and τ_n the photon and electron lifetime, β the spontaneous emission factor, $I(t)$ the injected current, V the active layer volume, g_0 the gain slope constant, α the linewidth enhancement factor, ε the gain compression factor and q the electron charge. If η_0 is the differential quantum efficiency, h the Planck’s constant and ν the unmodulated optical frequency, the laser output power is given by

$$P(t) = S(t)\frac{V\eta_0 h\nu}{2\Gamma\tau_p} \quad . \qquad (2)$$

The laser threshold current is evaluated by

$$I_{th} = \frac{q}{\tau_n}\left(VN_t + \frac{V}{\Gamma g_0 \tau_p}\right) \quad , \qquad (3)$$

and the laser linewidth at the steady state

$$\Delta\nu = \frac{\beta\Gamma}{\tau_n}(N - N_t)\frac{1+\alpha^2}{4\pi S} \qquad . \qquad (4)$$

The rate equations 1 are numerically solved by a Runge-Kutta method, finding the laser output optical phase and amplitude also using eq. 2.
Laser emission is affected by a relative intensity noise (RIN) caused by the spontaneous emission and the shot noise; RIN is added to the photon density spectrum using random variables with variance $\sigma_{RIN}^2 = \int RIN(\omega)d\omega$, the spectral density being given by [G. P. Agrawal, *Fiber Optics Communications Systems*, Wiley, NY, 1992]

$$RIN(\omega) = \frac{2\Gamma\beta N_{av}}{\tau_n} \cdot \frac{\Gamma_N^2 + \omega^2 + g_0 S_{av}\left[g_0 S_{av}\left(1 + \frac{1}{\Gamma\beta V S_{av}}\right) - 2\Gamma_N\right]}{S_{av}\left[(\Omega_R - \omega)^2 + \Gamma_R^2\right]\left[(\Omega_R + \omega)^2 + \Gamma_R^2\right]} \quad , \quad (5)$$

with Ω_R and Γ_R respectively the frequency and damping rate of relaxation oscillation, given by

$$\begin{aligned}
\Omega_R &= \left[g_0^2(N_{av} - N_t)\frac{S_{av}}{1+\varepsilon S_{av}} - \frac{(\Gamma_p - \Gamma_N)^2}{4}\right]^{1/2} \\
\Gamma_R &= \frac{\Gamma_p + \Gamma_N}{2} \\
\Gamma_p &= \frac{\Gamma\beta N_{av}}{\tau_n S_{av}} + \varepsilon g_0 (N_{av} - N_t)\frac{S_{av}}{1+\varepsilon S_{av}} \\
\Gamma_N &= \frac{1}{\tau_n} + g_0 S_{av}
\end{aligned} \qquad . \qquad (6)$$

In eqs. 5 and 6, N_{av} and S_{av} stand for time averaged carrier and photon density respectively.

Inverse problem; finding the semiconductor laser parameters:

The “Laser DM” component includes a powerful tool for estimating the laser rate equation parameters from the measured small-signal intensity modulation frequency response.
The normalized frequency response of a semiconductor laser is given by [J. E. Bowers, Solid State Electron. 30, pp. 1-11, 1987]

$$H(f,Y,Z)=\frac{Z}{(i2\pi f)^2+i2\pi fY+Z}$$
$$Y=g_0\frac{S}{1+\varepsilon S}+\frac{1}{\tau_n}-\Gamma g_0(N-N_t)\frac{1}{(1+\varepsilon S)^2}+\frac{1}{\tau_p} \quad . \quad (7)$$
$$Z=g_0\frac{S}{1+\varepsilon S}\frac{1}{\tau_p}+\frac{1}{\tau_n\tau_p}+(\beta-1)\frac{\Gamma g_0}{\tau_n}(N-N_t)\frac{1}{(1+\varepsilon S)^2}$$

In eqs. 7, N and S are evaluated at steady state from eqs. 1, Y is the damping factor of the frequency response, and the resonance frequency is given by

$$f_r=\frac{1}{2\pi}\sqrt{Z-\frac{Y^2}{2}} \quad . \quad (8)$$

If Y_0, Z_0 are the values at bias current just above the threshold current I_{th} and Y_1, Z_1 are given at bias well above the threshold, laser parameters may be estimated measuring at several frequencies the subtracted frequency response

$$S(f)=20\log_{10}\left|\frac{H(f,Y_1,Z_1)}{H(f,Y_0,Z_0)}\right| \quad . \quad (9)$$

Optolink Numerics fits eq. 9 and the first of eqs. 7 to the measured values of the subtracted frequency response, finding the optimal parameters Y_0, Z_0, Y_1, Z_1. Laser parameters used in rate eqs. 1 are then found by minimizing the sum of squared errors for Y_0, Z_0, Y_1, Z_1 and for I_{th} and the optical power P_1 at bias, as found fitting eq. 9, and those calculated from eqs. 2, 3 and 7; minimization involves the 9 rate equation parameters Γ, N_t, τ_p, τ_n, β, V, g_0, ε and η_0. The result of the minimization is not sensitive to the initial estimate of the solution which is chosen within reasonable bounds. The 9 rate equation parameters show a weak dependence on the bias current, that must be selected before the parameter estimation. Since there are 4 equations to satisfy and 9 parameters to specify, more than one set of 9 parameters may yield similar laser behaviors.

Inputs / Outputs: 1 electrical input, 1 optical output. Input to the “Laser DM” must be an “Electrical Driver”, eventually followed by other electrical components.

Parameters:

Wavelength: [nm, default: 1550] sets the laser emission wavelength.

Bias current: [A, default: 2.6E-2] the laser bias current. Must equal the input electrical offset voltage, divided by the input resistance.

Threshold current: [A, default: 1.51E-2] the evaluated I_{th}, according to eq. 3.

Output power at bias: [W, default: 2.61E-3] the evaluated optical power at bias current, according to eq. 2. The photon density S is evaluated using eqs. 1 at steady state.

Laser linewidth: [Hz, default: 1.0E8] the unmodulated laser linewidth, from eq. 4; N and S are evaluated from eqs. 1 at steady state.

Linewidth enhancement factor: [default: 5] the parameter α in eqs. 1.

Active layer volume: [m^3, default: 5.0e-17] the parameter V.

Mode confinement factor: [default: 3.0E-1] the Γ factor.

Gain slope constant: [m^3 s^-1, default: 6.0E-13] the parameter g_0.

Differential quantum efficiency: [default: 6.0E-1] the η_0 parameter.

Photon lifetime: [s, default: 2.0E-12] the τ_p lifetime.

Carrier lifetime: [s, default: 2.0E-9] the τ_n value.

Gain compression factor: [m^3, default: 3.0E-23] the parameter ε.

Spontaneous emission factor: [default: 1.0E-4] the β factor.

Carrier density at transparency: [m^-3, default: 1.0E24] the N_t density.

Input resistance: [Ohm, default: 50] the laser electrical resistance. Bias current must equal the selected input electrical offset voltage, divided by the input resistance.

Frequency: [GHz, default: 0] used for the inverse problem. Set up to 16 modulation frequencies where the subtracted frequency response has been measured.

Normalized response: [dB, default: 0] up to 16 measured subtracted frequency response values, as defined in eq. 9, at several modulation frequencies.

The rate equation parameters have default values typical for a 2.5 GHz DFB laser. By pressing the “Evaluate” button in the “Measured frequency response” frame, the measured subtracted frequency response values will be used for the inverse problem. First frequency is always zero; the subtracted frequency response must be normalized to 0 dB at 0 GHz. The following frequencies will be considered in the inverse problem only if positive and non-zero. The “Measured frequency response” may be viewed after a simulation run using the “Optolink Graph Viewer”.

MUX (MUX__WDM)

Optical multiplexer for Wavelength Division Multiplexing (WDM) systems. “MUX” is a powerful component used to simplify the selection of single-channel or WDM transmission, and to generate a WDM signal without the need of drag-dropping a transmitter component for each WDM channel.
If used, “MUX” must be linked at the output of a transmitter or laser component (“TX, IM-DD”, “TX, DPSK”, “TX, PhIM”, “TX, Custom”, “Laser CW”, “Laser DM”). The incoming optical signal is then replicated at the selected wavelengths, generating a WDM signal.
For WDM systems, number of channels, central wavelength and channel spacing must be selected at the “MUX”; correspondingly, channel wavelengths are calculated in the “WDM – Channels 1..64, 65..128, 129..192” windows for up to 192 transmitted channels.
The generated channels may be optically multiplexed with parallel, orthogonal or random states of polarization, by selecting the proper option. Channels are transmitted with different PRBS sequences for signals de-correlation. In PhIM, amplitude and phase tributaries have different PRBS sequences as well. A random optical phase is automatically added to the multiplexed channels.
“MUX” components must be used in conjunction with the “WDM” windows. The “WDM - Multiplexing” window selects the optical multiplexing filtering experienced at the transmitters / lasers by the generated channels; filter is centered on every channel wavelength specified in the “WDM” windows, eventually with a frequency detuning (needed, for example, in Vestigial Side Band signals). Channels generated by a single transmitter component are filtered at the transmitter and added with polarizations specified in the “MUX” dialog box. Same thing is performed for the wavelengths generated by a laser component. The “WDM - Channels ..” windows may also be used to select the channel pre-emphasis.
A “MUX” component may be used at the output of each transmitter / laser to generate a complex WDM signal with channels modulated with different formats and/or channel spacing. Please refer to the “WDM - Multiplexing” and “WDM - Channels .. “ for further details.

Inputs / Outputs: 1 optical input, 1 optical output. “MUX” must be linked at the output of a transmitter or laser component (“TX, IM-DD”, “TX, DPSK”, “TX, PhIM”, “TX, Custom”, “Laser CW”, “Laser DM”).

Parameters:

Transmission of single-channel / WDM: [default: single-channel] selects the transmission of a single-channel or a WDM signal.

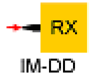
Spectrum centered at wavelength: [nm, default: 1550] central wavelength λ_0 for the WDM or single-channel signal.

Channels multiplexed with polarizations: [default: parallel] selects if multiplexed channels are co-polarized or cross polarized at the transmitters, or if channels state of polarization (SOP) is randomly rotated (it is the case of a non polarization-preserving multiplexer). Transmitted WDM channels have random optical phase shift among them.

Channel spacing: [nm, default: 0.8] sets the wavelength spacing between multiplexed channels.

Number of channels: [default: 2] sets the number of generated WDM optical channels.

RX, IM-DD (RX_IM_DD)



Optical receiver for Intensity Modulation with Direct Detection format.

Optolink Numerics optical receivers (“RX, IM-DD”, “RX, DPSK” and “RX, PhIM”) use the parameters set in “MUX” components and “WDM” windows to automatically detect those channels selected for performance evaluation and eye printing (in the “WDM – Channels 1..64, 65..128, 129..192” windows). Selected channels are optically de-multiplexed by the filter specified in the “DeMUX” component (if present) and elaborated by the receiver.
These powerful tools permit to use a single receiver component in the transmission system scheme, to evaluate the performance for all the selected channels. Several receivers may be used if performance must be calculated with different receiver parameters.
For details on the performance parameters, see “Appendix - Q factor and timing jitter models” section.

IM-DD receiver is composed by cascaded: PIN photodiode, electrical filter, clamping and decision circuit with optimal sampling instant and threshold.

Inputs / Outputs: 1 optical input, no output.

Parameters:

PIN responsivity: [A/W, default: 1] the incoming optical field is detected by a PIN photodiode with responsivity R_{PIN} ; the generated photocurrent is proportional to the incoming optical power P_{in} as

$$I_p(t) = R_{PIN} P_{in}(t) + I_d + n_{sh}(t) + n_{th}(t) \quad ; \qquad (1)$$

in eq. 1, receiver dark current, shot noise and thermal noise have been included (see below).

Include PIN shot noise: [default: unchecked] if checked, photodiode shot noise $n_{sh}(t)$ is added to the generated photocurrent; n_{sh} is modeled adding to the instantaneous photocurrent a random Gaussian current, with zero average and variance [G. P. Agrawal, *Fiber Optics Communications Systems*, Wiley, NY, 1992]

$$\sigma_{sh}^2 = 2q(I_p + I_d)B_e \quad , \qquad (2)$$

with I_d the receiver dark current (see below), q the electron charge, B_e the receiver cut-off frequency and $I_p(t)$ the instantaneous photocurrent.
Shot noise mainly affects the transmitted marks, being almost negligible for spaces.

PIN dark current: [A, default: 0] sets the photodiode dark current I_d, due to residual light or thermal generation.

Receiver thermal noise spectral density: [A/Hz^0.5 default: 0] thermal noise current is generated by electrons thermal motion in the receiver load resistor. It is modeled by a Gaussian random process n_{th}, adding Gaussian variables to the real and imaginary parts of the current spectrum. Random variables have zero average and variance

$$\sigma_{th}^2 = \frac{S_{th}^2 B_e}{N} \quad , \qquad (3)$$

being *N* the number of simulated points, B_e the receiver cut-off frequency and S_{th} the specified one-sided thermal noise spectral density [A/Hz^0.5]; a commonly used value for this parameter is 1.0E-11 A/Hz^0.5.

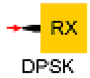
Electrical low-pass filter: [default: Bessel 4th order] selects the receiver low-pass electrical filter type. Filter is inserted after the PIN photodiode. See "Electrical Filter" for details on its models.

Electrical filter 3 dB cut-off frequency: [GHz, default: 7.5] the electrical filter cut-off frequency, used for eqs. 1 to 3 in "Electrical Filter"; it corresponds to the receiver front-end bandwidth.

Graph optical power and phase for channel: [default: 1] selects the channel whose optical power and phase will be shown by the Optolink Graph Viewer.

After the electrical filter, the received pattern is clamped at the first received mark, sampled and compared with a decision threshold.
Performance is always evaluated at the optimal threshold and sampling instant in the received eye.

RX, DPSK (RX__DPSK)



Optical receiver for Differential Phase-Shift Keying or Differential Quadrature Phase-Shift Keying formats.
DPSK phase receiver is based on a delay-and-add Mach-Zehnder interferometer and a PIN photodiode couple in differential configuration (balanced detector). It is composed by cascaded: delay-and-add interferometer, balanced PINs, electrical filter, clamping and decision circuit with optimal sampling instant and threshold.
The “RX, DPSK” component differs from the phase receiver in “RX, PhIM” because it includes an arbitrary phase shift at one arm of the Mach-Zehnder interferometer, it models also the presence of thermal noise generated by the phase receiver front-end and the electrical signal polarity is not inverted like in PhIM.

Inputs / Outputs: 1 optical input, no output.

Parameters:

PIN responsivity: [A/W, default: 1] signal phase tributary is revealed by a polarization independent phase receiver, generating the photocurrent

$$I_\phi(t) = R_{PIN}\left\{\mathrm{Re}\left[E_x(t)e^{i\phi}E_x^*(t-T_{Arm})\right] + \mathrm{Re}\left[E_y(t)e^{i\phi}E_y^*(t-T_{Arm})\right]\right\} + n_{th}(t) \quad , (1)$$

with R_{PIN} the PIN responsivity, E_x and E_y the optical field to the phase receiver, T_{Arm} the delay in one arm of the receiver interferometer and ϕ the phase shift at the other arm of the interferometer; DPSK usually works with $T_{Arm} = T_B$, the tributary bit-time slot and $\phi = 0$; a DQPSK decoder is obtained setting $T_{Arm} = T_B$ and $\phi = \pm 45°$. In eq. 1, $n_{th}(t)$ is a thermal noise generated by the electrical front-end.
Any circuit implementing eq. 1 works as a phase receiver, with no need for a polarization controller. The generated photocurrent is then passed through the electrical filter specified by the user. Performance is evaluated on the phase tributary eyes in the same way as for the IM-DD format.

Receiver thermal noise spectral density: [A/Hz^0.5 default: 0] thermal noise is modeled by a Gaussian random process n_{th}, adding Gaussian variables to the real and imaginary parts of the current spectrum. Random variables have zero average and variance

$$\sigma_{th}^2 = \frac{S_{th}^2 B_e}{N} \quad , \qquad (2)$$

being *N* the number of simulated points, B_e the receiver cut-off frequency and S_{th} the specified one-sided thermal noise spectral density [A/Hz^0.5]; a commonly used value for this parameter is 1.0E-11 A/Hz^0.5.

Electrical low-pass filter: [default: Bessel 4th order] selects the receiver low-pass electrical filter type. Filter is inserted after the PIN photodiodes. See "Electrical Filter" component for the models.

Electrical filter 3 dB cut-off frequency: [GHz, default: 7.5] the electrical filter cut-off frequency; it corresponds to the receiver front-end bandwidth the phase detector.

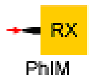
Graph optical power and phase for channel: [default: 1] selects the channel whose optical power and phase will be shown by the Optolink Graph Viewer.

Phase receiver optical arm delay: [ps, default: 100] the delay T_{Arm} in eq. 1, produced by one arm of the receiver interferometer; DPSK usually works with $T_{Arm} = T_B$, the tributary bit-time slot.

Phase receiver shift at other arm: [deg, default: 0] the phase shift ϕ in eq. 1, produced by the other arm of the receiver interferometer; DPSK works with $\phi = 0$, DQPSK with $\phi = \pm 45°$.

After the electrical filter, the received pattern is clamped at the first received mark, sampled and compared with a decision threshold.
Performance is always evaluated at the optimal threshold and sampling instant in the received eye.
If the "Use differential phase Q factor" option is selected in "Simulation menu", the phase tributary Q factor is evaluated according to eqs. 1 and 2 in "Simulation menu"; the differential phase eye opening must be set equal to the phase tributary modulation amplitude to obtain correct results. The printed eye in this case is generated by the said eq. 2, with no shot, dark or thermal noise added. Signal is given in (rad) instead of (mA).
The use of differential phase has given in some cases more accurate results for phase modulated signals respect to the traditional Q evaluation [X. Wei, X. Liu, C. Xu, IEEE Photonics Technology Letters 15, pp. 1636-1638, Nov. 2003]. Conversely, the generated eye is not the one obtained by a realistic DPSK receiver.

RX, PhIM (RX__PhIM)



Optical receiver for Phase and Intensity Modulation format.
PhIM receiver is the most complete, because it includes both an intensity and a phase detector.
PhIM amplitude tributary receiver is the same as for IM-DD format, with an electrical polarity inversion after the electrical filter. It is composed by cascaded: PIN photodiode, electrical polariry inversion, electrical filter, clamping and decision circuit with optimal sampling instant and threshold.
PhIM phase tributary receiver is composed by the same cascaded components as for “RX, DPSK”, with no thermal noise, and includes an electrical polarity inversion too; DPSK receiver is also described in section “PhIM format”.
Electrical polarity inversion for both the amplitude and the phase tributary is performed only for PhIM transmitted channels; it is not included for channels generated by “TX, IM-DD”, “TX, DPSK”, or “Laser CW” sources.

Inputs / Outputs: 1 optical input, no output.

Parameters:

PIN responsivity: [A/W, default: 1] amplitude tributary is detected by a PIN photodiode of responsivity R_{PIN}; the generated photocurrent is proportional to the incoming optical power P_{in} as

$$I_p(t) = -\left[R_{PIN} P_{in}(t) + I_d + n_{sh}(t) + n_{th}(t)\right] \quad ; \qquad (1)$$

in eq. 1, receiver dark current, shot noise and thermal noise have been included (see below).
The polarity inversion shown in eq. 1 is in reality performad after the electrical filtering, and only for PhIM channels.
Phase tributary is revealed by a polarization independent DPSK receiver (“PhIM format”), generating the photocurrent

$$I_\phi(t) = -R_{PIN}\left\{\mathrm{Re}\left[E_x(t)E_x^*(t-T_{Arm})\right] + \mathrm{Re}\left[E_y(t)E_y^*(t-T_{Arm})\right]\right\}, \qquad (2)$$

with R_{PIN} the same PIN responsivity as in eq. 1, E_x and E_y the optical field to the phase receiver, and T_{Arm} the specified interferometer arm delay; DPSK usually works with $T_{Arm} = T_B$, the tributary bit-time slot. Polarity inversion in eq. 2 is in reality performed after the electrical filter, and only for PhIM channels.
Any circuit implementing eq. 2 works as a DPSK receiver, with no need for a polarization controller if using PhIM with 2 tributaries. The generated photocurrent is then passed through the electrical filter specified by the user. Performance is evaluated on the phase tributary eyes in the same way as for the amplitude tributary or the IM-DD format.

Include PIN shot noise: [default: unchecked] if checked, photodiode shot noise $n_{sh}(t)$ is added to the generated photocurrent; n_{sh} is modeled adding to the instantaneous photocurrent a random Gaussian current, with zero average and variance [G. P. Agrawal, *Fiber Optics Communications Systems*, Wiley, NY, 1992]

$$\sigma_{sh}^2 = 2q(I_p + I_d)B_e \quad , \qquad (3)$$

with I_d the receiver dark current (see below), *q* the electron charge, B_e the receiver cut-off frequency and $I_p(t)$ the instantaneous photocurrent.
In phase receiver, shot noise is not considered.

PIN dark current: [A, default: 0] sets the photodiode dark current I_d , due to residual light or thermal generation.
In phase receiver, dark current is not included, because two PIN photodiodes in differential configuration are used (see the "PhIM format" section).

Receiver thermal noise spectral density: [A/Hz^0.5 default: 0] thermal noise is modeled by a Gaussian random process n_{th} , adding Gaussian variables to the real and imaginary parts of the current spectrum. Random variables have zero average and variance

$$\sigma_{th}^2 = \frac{S_{th}^2 B_e}{N} \quad , \qquad (4)$$

being *N* the number of simulated points, B_e the receiver cut-off frequency and S_{th} the specified one-sided thermal noise spectral density [A/Hz^0.5]; a commonly used value for this parameter is 1.0E-11 A/Hz^0.5.
In PhIM phase receiver, thermal noise is not included.

Electrical low-pass filter: [default: Bessel 4th order] selects the receiver low-pass electrical filter type. Filter is inserted after the PIN photodiode. See "Electrical Filter" component for the models.

Electrical filter 3 dB cut-off frequency: [GHz, default: 7.5] the electrical filter cut-off frequency; it corresponds to the receiver front-end bandwidth for both the amplitude and the phase detectors.

Graph optical power and phase for channel: [default: 1] selects the channel whose optical power and phase will be shown by the Optolink Graph Viewer.

Phase receiver optical arm delay: [ps, default: 100] the delay T_{Arm} in eq. 2, produced by one arm of the DPSK receiver interferometer; DPSK usually works with $T_{Arm} = T_B$, the tributary bit-time slot.

After the electrical filter, the received pattern is clamped at the first received mark, sampled and compared with a decision threshold.
Performance is always evaluated at the optimal threshold and sampling instant in the received eye.

If the “Use differential phase Q factor” option is selected in “Simulation menu”, the phase tributary Q factor is evaluated according to eqs. 1 and 2 in “Simulation menu”; see also “RX, DPSK”.

DeMUX (DeMuxWDM)

Optical de-multiplexer. Must be eventually used before a receiver component (“RX, IM-DD”, “RX, DPSK” or “RX, PhIM”) in order to de-multiplex the WDM channels according to the settings in the “WDM” windows. “DeMUX” optically filters the channels selected in the “WDM” windows for performance evaluation; filter is centered on every channel wavelength. Channels are filtered one by one, and successively elaborated by the receiver. Optical filtering applies also to single-channel systems.
“DeMUX” is used together with the receiver components as a powerful tool for easily selecting the channels for performance evaluation. A “DeMUX” component must be added before every receiver component, if optical de-multiplexing is desired.

Inputs / Outputs: 1 optical input, 1 optical output. “DeMUX” output must be directly linked to a “RX, IM-DD”, “RX, DPSK”, “RX, PhIM” receiver component, or to a “Post-Compensator” component.

Parameters:

Filter type: [default: Gaussian] selects the de-multiplexing optical filter transfer function, as follows:

Gaussian filter:
The optical Gaussian filter of order M has an amplitude transfer function given by

$$H_{out}(\nu) = \exp\left[-\ln\sqrt{2}\left(2\frac{\nu-\nu_0}{B_o}\right)^{2M}\right] \qquad ; \qquad (1)$$

B_o is the optical 3dB bandwidth and ν_0 the filtered channel central frequency. Eq. 1 multiplies the incoming optical field complex amplitude according to

$$\tilde{A}_{out,k}(\nu) = \tilde{A}_{in,k}(\nu) H_{out}(\nu) \qquad k = x, y \qquad , \qquad (2)$$

With $\tilde{A}(\nu)$ indicating the Fourier transform.
A higher order Gaussian filter could properly approximate the shape of an arrayed waveguide grating (AWG) de-multiplexer.

Trapezoidal filter:

The amplitude transfer function of a trapezoidal filter is $H_{out}(\nu) = 10^{H_{out,dB}(\nu)/20}$, with

$$H_{out,dB}(\nu)=\begin{cases} -Att_{dB} & |\nu|\geq \frac{\nu_c}{2} \\ Att_{dB}\dfrac{\nu+\frac{\nu_b}{2}}{\frac{\nu_c}{2}-\frac{\nu_b}{2}} & -\frac{\nu_c}{2}<\nu<-\frac{\nu_b}{2} \\ -Att_{dB}\dfrac{\nu-\frac{\nu_b}{2}}{\frac{\nu_c}{2}-\frac{\nu_b}{2}} & \frac{\nu_b}{2}<\nu<\frac{\nu_c}{2} \\ 0 & |\nu|\leq \frac{\nu_b}{2} \end{cases} \quad . \qquad (3)$$

In eq. 3, ν is the optical frequency relative to the filter central frequency, ν_b is the 0 dB bandwidth, ν_c the cut-off bandwidth and Att_{dB} the filter attenuation, in dB. Filter shape is a trapezoid, with attenuation passing from 0 dB to $-Att_{dB}$ in the frequency range between $\nu_b/2$ and $\nu_c/2$, and between $-\nu_c/2$ and $-\nu_b/2$.

Filter from file:
A user-defined optical filter can be used for de-multiplexing. Filter must be passed to Optolink Numerics as a ".dat" file, selected using the "Browse" button.
Filter file must be a text file including 3 number columns (separated by commas, spaces or tabs). First column is the relative optical frequency (GHz) respect to the filter central frequency (positive and negative numbers are admitted, with "." decimal separator); second column is the filter real amplitude A_f (linear scale, between 0 and 1); third column is the filter phase ϕ_f (rad). Remember that "DeMUX" automatically centers the filter on each channel central frequency; thus frequencies in the first column should span around 0 GHz.
Filter amplitude transfer function is generated according to

$$H_{out}(\nu)=A_f(\nu)\exp[i\phi_f(\nu)] \quad , \qquad (4)$$

with ν intended as the optical frequency relative to the filter central frequency. The amplitude and phase values used in eq. 4 are obtained by Optolink Numerics using a linear interpolation of the data from file, according to the

$$\begin{aligned} A_f(\nu)&=A_f^j+\left(A_f^{j+1}-A_f^j\right)\frac{\nu-\nu_j}{\nu_{j+1}-\nu_j} \\ \phi_f(\nu)&=\phi_f^j+\left(\phi_f^{j+1}-\phi_f^j\right)\frac{\nu-\nu_j}{\nu_{j+1}-\nu_j} \end{aligned} \quad , \qquad (5)$$

with ν_j and ν_{j+1} the file relative frequencies including ν and A_f^j , ϕ_f^j the corresponding amplitude and phase from file. Transfer function is assumed to be zero outside the user-specified frequency range.

Insertion loss: [dB, default: 0] the excess optical loss introduced by the filter.

Gaussian filter bandwidth: [GHz, default: 50] the optical 3dB bandwidth B_o in eq. 1.

Gaussian filter order: [default: 1] defines the order M for the Gaussian filter in eq. 1.

Trapezoidal filter 0 dB bandwidth: [GHz, default: 70] the optical filter bandwidth ν_b in eq. 3, corresponding to a 0 dB attenuation.

Trapezoidal filter cut-off bandwidth: [GHz, default: 100] the filter bandwidth ν_c in eq. 3, corresponding to an attenuation between 0 and Att_{dB}.

Trapezoidal filter attenuation: [dB, default: 30] the filter attenuation Att_{dB} in eq. 3.

Fiber (OptFiber)

Optical monomodal fiber, accounting for Group Velocity Dispersion (GVD), dispersion slope, attenuation, Polarization Mode Dispersion (PMD), Kerr and Raman nonlinearities. Details on the “Fiber” model are given in “Appendix – The fiber model”. “Fiber” output includes informations on the propagated Jones matrix; this is used by the “Polarization Controller” to recover the birefringence axis rotation and the PMD at the receiver.

Inputs / Outputs: 1 optical input, 1 optical output.

Parameters:

Span length: [km, default: 0] the optical fiber span length; must be greater than zero.

Dispersion: [ps/nm/km, default: 0] the group velocity dispersion $D(\lambda_{ref})$ in “Appendix – The fiber model”, eq. 1.3. Reference wavelength for dispersion is selected in the “Simulation menu”. Eq. 1.3 is repeated here for clarity.

$$D(\lambda) = D(\lambda_{ref}) + (\lambda - \lambda_{ref})S(\lambda_{ref})$$

$$\beta_2(\omega) = -\frac{\lambda^2}{2\pi c} D(\lambda)$$

$$\beta_3(\omega) = \left[S(\lambda_{ref}) + \frac{2}{\lambda} D(\lambda) \right] \left(\frac{\lambda^2}{2\pi c} \right)^2 \quad . \qquad (1)$$

Dispersion Slope: [ps/nm^2/km, default: 0] the slope $S(\lambda_{ref})$ in eq. 1. Dispersion and dispersion slope are constant in a fiber span.

Attenuation: [dB/km, default: 0] the fiber linear attenuation α in “Appendix – The fiber model”, eq. 1.1, supposed constant in a fiber span.

PMD: [ps/km^0.5, default: 0] polarization mode dispersion is modeled by rotating the fiber birefringence axes every L_c meters, the PMD correlation length, according to eq. 1.4 in “Appendix – The fiber model”; PMD is given by eq. 1.5.

PMD correlation length: [m, default: 100] the said L_c length. If you wish to avoid the birefringence axis rotation, this length must be set to a value greater than the system length.

Effective area: [um^2, default: 1.0E9] the fiber Kerr nonlinearity is accounted for by the parameter $\gamma = n_2\omega_0/(cA_{eff})$ in “Appendix – The fiber model”, eq. 1.1, with n_2 [m^2/W] the Kerr nonlinear index coefficient and A_{eff} [um^2] the fiber modal effective area. Model accounts for the Self Phase Modulation (SPM), Cross Phase Modulation (XPM) and Four

Wave Mixing (FWM) altogether and with no approximations. To model a linear fiber, effective area should be set to a very high value.

Fiber nonlinear coefficient: [W/m^2, default: 2.6E-20] the Kerr nonlinear index coefficient n_2.

Include Raman nonlinearity: [default: unchecked] if checked, the fiber Raman nonlinearity is included using the molecular Raman delay time T_R [fs]; it is responsible for a red shift in the signal energy. Raman self and cross-effect between polarization components are properly modeled in "Appendix – The fiber model", eq. 1.1, for optical signals with pulsewidth greater than 0.1 ps.

Fiber Raman delay: [fs, default: 0] the molecular Raman delay time T_R; a commonly used value is 3 fs for standard monomodal fibers, although a value up to 5 fs has been observed. The γ and T_R parameters are supposed constant in a fiber span.

Note: A PMD emulator may be modeled using a "Fiber", setting the PMD, the correlation length L_c and the fiber length to the desired value, setting to zero the dispersion and dispersion slope and to a very high value the effective area.

Raman Fiber (RamFiber)

Optical monomodal fiber with Raman gain and with up to 10 co/counter-propagating pumps. It also accounts for Group Velocity Dispersion (GVD), dispersion slope, attenuation, Polarization Mode Dispersion (PMD), Kerr and Raman nonlinearities. Details on the fiber propagation equations are given in "Appendix – The fiber model". Fiber output includes information on the propagated Jones matrix; this is used by the "Polarization Controller" to recover the birefringence axis rotation and the PMD at the receiver.

Raman gain is included into the fiber model calculating the frequency-dependent attenuation/gain coefficient $\alpha(z,\nu)$ over the fiber length z. Gain is previously calculated dividing the signal spectrum into $N=256$ frequency bins. Let $P(j)$ be the optical power for the pumps and the signal bins ($j=1..N_c$: counter-propagating pumps, $j=N_c+1..M$: co-propagating pumps, $j=M+1..N$: signal bins); Raman gain evolution is modeled by the coupled equations [V. E. Perlin, H. G. Winful, J. Lightwave Tech. 20, pp. 409-419, Mar. 02]

$$\pm\frac{dP(k)}{dz}=-\alpha_k P(k)+\sum_{j=1,\,j\neq k}^{N*M} g(\nu_j,\nu_k)P(k)P(j) \qquad k=1,2..N+M \quad . \qquad (1)$$

In eqs. 1, the plus sign on the left-hand side is for co-propagating signals/pumps, the minus sign for counter-propagating pumps, α_k and ν_k are the passive attenuation coefficient and the optical frequency (assumed in decreasing order for the signal bins) for the kth wave respectively, and the gain coefficients $g(\nu_j,\nu_k)$ are given by

$$g(\nu_j,\nu_k)=\begin{cases}\dfrac{g_R(\nu_j-\nu_k)}{K_{eff}A_{eff}}\dfrac{\nu_j}{\nu_0} & \nu_j>\nu_k\\[2ex] -\dfrac{g_R(\nu_k-\nu_j)}{K_{eff}A_{eff}}\dfrac{\nu_k}{\nu_j}\dfrac{\nu_k}{\nu_0} & \nu_j<\nu_k\end{cases} \quad , \qquad (2)$$

with $K_{eff}=2$ for depolarized signal/pumps, A_{eff} the fiber effective area and $g_R(\Delta\nu)$ the Raman gain spectrum (m/W) at frequency ν_0 (in Optolink Numerics, ν_0 is assumed equal to the central spectrum frequency, and $K_{eff}=2$).

Amplified spontaneous emission (ASE) noise is generated over the fiber length according to the

$$\pm\frac{dP_{ASE}(k)}{dz}=-\alpha_k P_{ASE}(k)+\sum_{j=1,\,j\neq k}^{N*M} g(\nu_j,\nu_k)P(j)\left[P_{ASE}(k)+h\nu_k\Delta\nu F_{phon}(\nu_j,\nu_k)\right] \quad , \qquad k=1,2..N+M$$

(3)

with the spontaneous scattering term for the Stokes and anti-Stokes waves

$$F_{phon}(\nu_j,\nu_k)=\begin{cases}1+\dfrac{1}{\exp\left[h(\nu_j-\nu_k)/k_BT\right]-1} & \nu_j>\nu_k\\ -\dfrac{1}{\exp\left[h(\nu_k-\nu_j)/k_BT\right]-1} & \nu_j<\nu_k\end{cases}\quad . \quad (4)$$

In eq. 3, Rayleigh scattering is assumed to be negligible, and $\Delta\nu$ is the bandwidth for the ASE power evaluation; in eqs. 3 and 4, h is the Plank's constant, k_B the Boltzman's constant and T the fiber temperature.
In Optolink Numerics, Raman gain spectrum is calculated using the multiple-vibrational-mode model described in [D. Hollenbeck, C. Cantrell, J. Opt. Soc. Am. B 19, pp. 2886-2892, Dec. 02] with normalized peak value; gain spectrum is then multiplied by the user-specified peak gain g_{Rp} (m/W); an example of calculated gain spectrum is shown in fig. 1 with $g_{Rp}=0.8\times10^{-13}$ m/W.

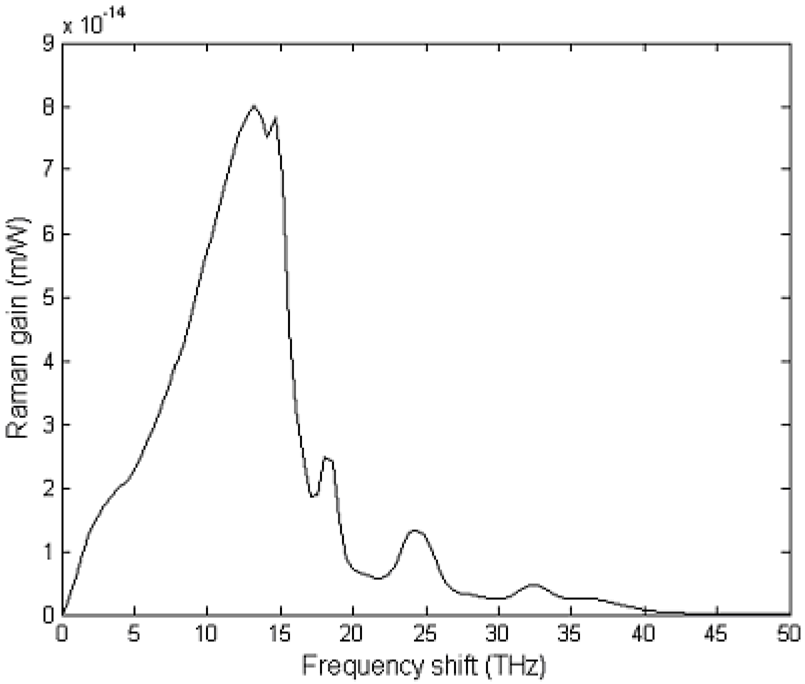


Fig. 1

Eqs. 1 are solved for the powers $P^{\pm}(z,j)$, with $\pm$ denoting co/counter-propagating waves, using iterative methods and the following mid-point shooting algorithm for the n-th iteration:

1) Assume certain boundary conditions at the fiber input $P_{in}(N_c+1..M+N) = P^+(0, N_c+1..M+N)$ and at the output (in $z = L$) $P_{out}(1..N_c) = P^-(L,1..N_c)$.

Assume guess boundary conditions $P_{in}(1..N_c) = P^+(0,1..N_c)$ and $P_{out}(N_c+1..M+N) = P^-(L, N_c+1..M+N)$.

2) Integrate eqs. 1 from $z=0$ to $z = L/2$ and from $z = L$ to $z = L/2$ using fourth-order Runge-Kutta methods, with the boundary conditions of step 1).

3) Calculate the iteration relative error

$$Err(1..M+N) = \left| \frac{P^+(L/2,1..M+N) - P^-(L/2,1..M+N)}{P^+(L/2,1..M+N) + P^-(L/2,1..M+N)} \right| \quad ; \qquad (5)$$

if one of the errors is greater than 10^{-2} continue with step 3), if all errors are smaller stop the iterations.

4) Modify the guess boundaries assuming the calculated $P^+(L/2, N_c+1..M+N)$ and $P^-(L/2,1..N_c)$ as certain values, and applying linear interpolations, i.e. assuming

$$\begin{aligned} B_n^c(1..N_c) &= P^-(L/2,1..N_c) \\ B_n^c(N_c+1..M+N) &= P^+(L/2, N_c+1..M+N) \end{aligned} \qquad (6a)$$

as certain, reference values,

$$\begin{aligned} B_n(1..N_c) &= P^+(L/2,1..N_c) \\ B_n(N_c+1..M+N) &= P^-(L/2, N_c+1..M+N) \end{aligned} \qquad (6b)$$

as calculated from guess values,

$$\begin{aligned} A_n(1..N_c) &= P^+(0,1..N_c) \\ A_n(N_c+1..M+N) &= P^-(L, N_c+1..M+N) \end{aligned} \qquad (6c)$$

as guess values for iteration n. The modified guess values for iteration n+1 are evaluated by [X. Liu, B. Lee, Opt. Expr. 11, pp. 1452-1461, Jun 03]

$$A_{n+1} = \begin{cases} A_n \dfrac{B_n^c}{B_n} & n = 1 \\ A_{n-1} + \dfrac{B_n^c - B_{n-1}}{B_n - B_{n-1}}(A_n - A_{n-1}) & n > 1 \end{cases} \quad . \qquad (7)$$

5) Modify the guess boundaries $P_{in}(1..N_c) = A_{n+1}(1..N_c)$, $P_{out}(N_c+1..M+N) = A_{n+1}(N_c+1..M+N)$ and go to step 2).

The proposed shooting algorithm is convergent for overall signal/pump powers overcoming 1 W.
Once the signal bin powers are known, the net attenuation coefficients are given by

$$\alpha(z, M+1..M+N) = -\frac{1}{\Delta z}\ln\left[\frac{P(z+\Delta z, M+1..M+N)}{P(z, M+1..M+N)}\right] \quad ; \quad (8)$$

attenuations are assumed equals for all simulated samples into the same bin.
Co-propagating ASE power is added at the fiber end using suitably normalized independent Gaussian variables added to the optical field complex spectrum.

Inputs / Outputs: 1 optical input, 1 optical output.

Parameters:

Span length: [km, default: 0] the optical fiber span length; must be greater than zero.

Dispersion: [ps/nm/km, default: 0] the group velocity dispersion $D(\lambda_{ref})$ in "Appendix – The fiber model", eq. 1.3. Reference wavelength for dispersion is selected in the "Simulation menu".

Dispersion Slope: [ps/nm^2/km, default: 0] the slope $S(\lambda_{ref})$ in eq. 1.3. Dispersion and dispersion slope are constant in a fiber span.

PMD: [ps/km^0.5, default: 0] polarization mode dispersion is modeled by rotating the fiber birefringence axes every L_c meters, the PMD correlation length, according to eq. 1.4 in "Appendix – The fiber model"; PMD is given by eq. 1.5.

PMD correlation length: [m, default: 100] the said L_c length. If you wish to avoid the birefringence axis rotation, this length must be set to a value greater than the system length.

Effective area: [um^2, default: 1.0E9] the fiber Kerr nonlinearity is accounted for by the parameter $\gamma = n_2\omega_0/(cA_{eff})$ in "Appendix – The fiber model", eq. 1.1, with n_2 [m^2/W] the Kerr nonlinear index coefficient and A_{eff} [um^2] the fiber modal effective area. Model accounts for the Self Phase Modulation (SPM), Cross Phase Modulation (XPM) and Four Wave Mixing (FWM) altogether and with no approximations. To model a linear fiber, effective area should be set to a very high value.

Fiber nonlinear coefficient: [W/m^2, default: 2.6E-20] the Kerr nonlinear index coefficient n_2.

Include Raman nonlinearity: [default: unchecked] if checked, the fiber Raman nonlinearity is included using the molecular Raman delay time T_R [fs]; it is responsible for a red shift in the signal energy. Raman self and cross-effect between polarization components are properly modeled in “Appendix – The fiber model”, eq. 1.1, for optical signals with pulsewidth greater than 0.1 ps.

Fiber Raman delay: [fs, default: 0] the molecular Raman delay time T_R; a commonly used value is 3 fs for standard monomodal fibers, although a value up to 5 fs has been observed. The γ and T_R parameters are supposed constant in a fiber span.

Attenuation: [dB/km, default: 0] the fiber passive attenuations used in eqs. 1, α_s for signals and α_p for pumps.

Attenuation from file: [default: unchecked] if checked, passive attenuation is read from a user-supplied “.dat” file, selected using the “Browse” button.
Attenuation file must be a text file including 2 number columns (separated by commas, spaces or tabs). First column is the optical wavelength (nm) (positive numbers are admitted, with “.” decimal separator); second column is the passive attenuation coefficient (dB/km), supposed constant over the fiber length. The attenuation values are obtained by Optolink Numerics using a linear interpolation of the data from file, according to the

$$\alpha(\lambda) = \alpha_j + \left(\alpha_{j+1} - \alpha_j\right)\frac{\lambda - \lambda_j}{\lambda_{j+1} - \lambda_j} \quad , \qquad (9)$$

with λ_j and λ_{j+1} the file wavelengths including λ and α_j, the corresponding attenuations from file (converted to m^{-1}).

Peak Raman gain: [m/W, default: 0.8E-13] the peak gain multiplying the normalized Raman gain spectrum (see the example in Fig.1).

Temperature: [K, default: 300] the fiber temperature used in eq. 4 for ASE power calculation.

Wavelength: [nm, default: 0] selects the wavelength for up to 10 co/counter-propagating pumps; wavelengths should be smaller than the signal ones in order to obtain Raman gain.

Power: [mW, default: 0] the launch powers for up to 10 co/counter-propagating pumps. Pump is not used if power equals zero.

Co/Counter-propagating: [default: unchecked] default pump is counter-propagating, check the box for co-propagating pumps.

To check the Raman fiber optical power evolution for pumps, signal bins and ASE, and the input and output power/bin spectra, use the “Optolink Graph Viewer”, i.e. select the “Show graphs” button and double-click over the component after a simulation run. 3-D graphs of the optical power can be rotated by selecting the “Rotate” button, clicking on the plot and dragging horizontally or vertically.

Multimodal Fiber (MulFiber)

Optical multimodal fiber, accounting for Chromatic Dispersion (CD), dispersion slope, attenuation, Polarization Mode Dispersion (PMD), birefringence. Differential-Mode Delay (DMD or modal dispersion) is also included in two alternative ways: by selecting a modal dispersion value or by reading from file the fiber impulse response function.
All the optical linear effects with exception of the modal impulse response are modeled as in the monomodal fiber case, neglecting the nonlinear effects (see "Appendix – The fiber model"). "MulFiber" output includes information on the propagated Jones matrix; this is used by the "Polarization Controller" to recover the birefringence axis rotation and the PMD at the receiver.
When a user-defined DMD impulse response is used, a ".dat" file must be passed to Optolink Numerics, selected using the "Browse" button. DMD file must be a text file including 2 number columns (separated by commas, spaces or tabs). First column is the time delay per unit length (ps/m); second column is the corresponding optical power fraction (in arbitrary units) at the fiber output; time delays must be given in increasing order. Optolink Numerics automatically calculates the DMD transfer function for a given fiber length, normalized to conserve the average optical power and linearly interpolated.
DMD transfer function filters the optical field complex amplitude according to the

$$\begin{aligned}\tilde{A}_{out,k}(\nu) &= \tilde{A}_{in,k}(\nu) H_{DMD}(\nu) \qquad k = x, y \\ H_{DMD}(\nu) &= \Im\left[\sqrt{I_{DMD}(t)}\right]\end{aligned} \quad , \qquad (1)$$

with $\tilde{A}(\nu)$ and $\Im$ indicating the Fourier transforms and $I_{DMD}(t)$ the user-defined DMD power impulse response. In the WDM case, DMD transfer function is replicated at each transmitted channel wavelength.
DMD filtering technique reduces the out band ASE noise, if present; consequently, the received eyes will not correctly show the ASE effects when a "MulFiber" is used. OSNR is on the contrary correctly evaluated, because it is based on the transmission simulation of a second optical field including only the ASE noise (see "Simulation window" section for details).

Inputs / Outputs*:* 1 optical input, 1 optical output.

Parameters:

Span length: [m, default: 0] the optical fiber span length; must be greater than zero.

Modal Dispersion: [ps/nm/km, default: 0] the modal dispersion D_{MOD}, selected if the "DMD Impulse Response from file" is checked.

Chromatic Dispersion: [ps/nm/km, default: 0] the chromatic dispersion $D(\lambda_{ref})$ in "Appendix – The fiber model", eq. 1.3. Reference wavelength for dispersion is selected in the "Simulation menu". Eq. 1.3 is repeated here for clarity.

$$D(\lambda) = D(\lambda_{ref}) + (\lambda - \lambda_{ref})S(\lambda_{ref})$$
$$\beta_2(\omega) = -\frac{\lambda^2}{2\pi c}D(\lambda)$$
$$\beta_3(\omega) = \left[S(\lambda_{ref}) + \frac{2}{\lambda}D(\lambda)\right]\left(\frac{\lambda^2}{2\pi c}\right)^2 \quad . \qquad (2)$$

Modal dispersion is added to chromatic dispersion if a DMD file is not used.

Dispersion Slope: [ps/nm^2/km, default: 0] the slope $S(\lambda_{ref})$ in eq. 2. Dispersion and dispersion slope are constant in a fiber span.

Attenuation: [dB/km, default: 0] the fiber linear attenuation α in "Appendix – The fiber model", eq. 1.1, supposed constant in a fiber span.

PMD: [ps/km^0.5, default: 0] polarization mode dispersion is modeled by rotating the fiber birefringence axes every L_c meters, the PMD correlation length, according to eq. 1.4 in "Appendix – The fiber model"; PMD is given by eq. 1.5.

PMD correlation length: [m, default: 100] the said L_c length. If you wish to avoid the birefringence axis rotation, this length must be set to a value greater than the system length.

DMD Impulse Response from file: [default: unchecked] if unchecked, a DMD ".dat" file must be selected using the "Browse" button.

DMD files are provided for typical 50/125 μm and 62/125 μm fibers at 850 nm and 1310 nm, measured under radially over-filled launch conditions (ROFL) with 1 dB coupling loss; files are located in directory:
"C:\Program Files\Optolink\demos\custom\MMF ".
Other files may be found, for example, at http://www.ieee802.org/3/z/mbi/index.html.
DMD power transfer function (dB) vs. relative frequency (GHz) may be viewed using the "Optolink Graph Viewer", by selecting the "Show graphs" button and double-clicking over the component after a simulation run. Modal dispersion cut-off frequency may be checed by the graph.

Free-Space Optics (FSOptics)

FSO

Free-space point-to-point optical link.
Typical free-space optical systems are composed by a laser or LED source directly or externally modulated at high data rates, a transmitting telescope lens to transmit the laser beam through the atmosphere, a receiving telescope lens to collect and focus the intercepted laser signal onto a PIN or APD photodiode. Usual transmission distances are of the order of a fraction to a few kilometers.
Optolink Numerics "FSOptics" component simulates the transmission impairments produced by the diffractive optics, the atmosphere attenuation (extinction) caused by the absorption, Rayleigh and Mie scattering with molecules and aerosol particles in the air [D. Killinger, "Free-space optics", Optics and Photonics News, Oct. 2002]. Rain extinction is also included at variable rain rates.
Optolink Numerics further comprises a tool for evaluating the availability of the free-space optics link, caused by the beam scintillation.
"FSOptics" is usually inserted between a "Laser, direct modulation" and a "PIN/APD photodiode", although boost EDFA amplifiers and other optical components may be directly linked to it.
Optical beam power loss caused by the signal diffraction and the limited receiver aperture is accounted by the transmittance term

$$T_{GEOM} = \frac{\pi\left(d_{RX}/2\right)^2}{\pi\left(\theta L/2\right)^2} \quad , \qquad (1)$$

with L the link range, θ (rad) the beam divergence angle and d_{RX} the receiver collector lens diameter.
If a LED is used in place of a laser source, T_{GEOM} is further multiplied by a factor concerning the focusing of noncoherent light, i.e.

$$K = \frac{d_{detect}^{\ 2}}{d_{LED}^{\ 2}} \quad , \qquad (2)$$

with d_{detect} and d_{LED} the photodiode and LED diameters (or dimensions) respectively.
A LED source is, to a first approximation, modeled using a directly modulated laser with 40-50 nm bandwidth.
Attenuation in the atmosphere is modeled according to the Beer-Lambert law with transmittance [D. C. Robertson, L. S. Bernstein, L. S. Haimes, R. Wunderlich, J. Vega, "5 cm-1 band model option to Lowtran 5", appl. Opt. 20, pp.3218 (1981)]

$$T_{AEROSOL} = \exp\left[-\alpha(\lambda, VIS)L\right] \quad , \qquad (3)$$

with

$$\alpha = \left(\frac{3.912}{VIS} - \beta_{Rayleigh} \right) k_{ext}(\lambda) \quad . \qquad (4)$$

in eqs. 3 and 4, VIS is the aerosol visibility (km) or Meteorological Range, $\beta_{Raileigh} = 0.012\ km^{-1}$ is the Rayleigh scattering coefficient and $k_{ext}(\lambda)$ the aerosol extinction coefficient, conventionally normalized to the value assumed at $0.55\ \mu m$ and wavelength dependent.
Rain extinction is accounted by the Marshall-Palmer model

$$T_{RAIN} = \exp\left(-0.365 \cdot RR^{0.63} L\right) \quad , \qquad (5)$$

with RR (mm/hr) the rain rate at the transmission time and L measured in kilometers.
The overall transmission is dependent on the wavelength, visibility, rain rate, aerosol type as well as the geometrical parameters.
Optolink Numerics is able to read from file the aerosol extinction coefficient $k_{ext}(\lambda)$; a ".dat" file must be passed to Optolink Numerics, selected using the "Browse" button. Aerosol file must be a text file including 2 number columns (separated by commas, spaces or tabs). First column is the wavelength (microns), second column is the corresponding aerosol extinction coefficient $k_{ext}(\lambda)$ normalized at $\lambda = 0.55\,\mu m$.
Wavelengths must be given in increasing order. Optolink Numerics automatically linearly interpolates the read values according to the transmitter wavelengths.
Aerosol files are provided for typical conditions in urban, rural and marine areas and in conditions of light or heavy fog; files are measured at 15 °C (a weak temperature dependence is assumed) at the boundary layer (up to 1 km altitude), for atmospheres considered as a standard in the literature. Files are located in directory: "C:\Program Files\Optolink\demos\custom\FSO ".
Table 1 summarizes the stored files, and the relative typical visibilities.

Aerosol type, description	File name	Visibility (km)
Rural (continental areas, clean air with dust)	Rural_Extinction.dat	25
Urban (rural + combustion / industrial pollution)	Urban_Extinction.dat	5
Marine (sea-salt particles, offshore aerosol)	Marine_Extinction.dat	25
Light fog (radiational cooling fog)	FogLight_Extinction.dat	0.5
Heavy fog (advective fog)	FogHeavy_Extinction.dat	0.2

Table 1

Evaluating the link availability:

Atmospheric turbulence due to the wind and temperature gradients causes temporal and spatial random variation of the detected optical power; such effect is called scintillation.
"FSOptics" component includes a tool for evaluating the availability of the free-space optics link, caused by the beam scintillation.
In conditions of weak turbulence, the optical beam power fluctuations follow a statistical log-normal distribution; the signal attenuation, expressed in dB, due to the atmosphere aerosol and to rain, i.e.

$$Att_{dB} = 10\log_{10}\left(\frac{1}{T_{AEROSOL}T_{RAIN}}\right) \quad (6)$$

is a random variable with Gaussian distribution, mean given by eq. 6 and standard deviation σ_{dB}.
The link availability is defined as the probability that $Att_{dB} \le Att_{Sens}$, being Att_{Sens} the maximum attenuation tolerable, in dB, to obtain a given receiver BER (or a given sensitivity). For a Gaussian distribution, availability is given by

$$Avail = \frac{1}{2}erfc\left(\frac{Att_{dB} - Att_{Sens}}{\sqrt{2}\sigma_{dB}}\right) \quad . \quad (7)$$

System availability is commonly increased using *M* redundant lasers/LEDs at the transmitter; availability becomes

$$Avail_M = 1-(1-Avail)^M \quad , \quad (8)$$

being *Avail* the availability for a single-laser system.

Inputs / Outputs: 1 optical input, 1 optical output.

Parameters:

Link range: [km, default: 0] the link distance L in eqs. 1, 3 and 5.

Beam divergence: [deg, default: 1] the divergence θ used in eq. 1.

Receiver lens diameter: [mm, default: 100] the collecting lens diameter d_{RX} .

Use a LED: [default: no] if checked, eq. 2 is included to account for noncoherent light focusing at the receiver.

Aerosol extinction from file: [default: yes] if checked, a user-defined aerosol extinction is used in place of eqs. 3 and 4.

Aerosol extinction: [dB/km, default: 0] sets the aerosol attenuation in place of eqs. 3 and 4; visibility is not used.

Aerosol from file: [default: urban aerosol] reads from file the aerosol normalized extinction coefficient, and applies eqs. 3 and 4 according to the transmitter wavelength(s) and the selected visibility.

Visibility: [km, default: 5] the meteorological range for the selected aerosol.

Rain rate: [mm/hr, default: 0] sets the rain falling rate RR in eq. 5.

Link attenuation: [dB, default: 0] the average attenuation Att_{dB} in eq. 7, used for evaluating the link availability. Attenuation may be read after a simulation run in the transmittance graph, dividing by the geometrical transmittance given by eq. 1.

Attenuation standard deviation: [dB, default: 0] the estimated (or experimentally measured) standard deviation σ_{dB} of the variable Att_{dB}.

Attenuation to sensitivity: [dB, default: 0] the maximum tolerable attenuation Att_{Sens}.

Number of Lasers/LEDs: [default: 1] the number of lasers/LEDs *M* in eq. 8.

The overall atmosphere transmittance vs. wavelength (μm) may be viewed using the "Optolink Graph Viewer", by selecting the "Show graphs" button and double-clicking over the component after a simulation run.

EDFA (Amp_EDFA)

Optical Erbium Doped Fiber Amplifier.
Optolink Numerics uses both power-controlled and gain-controlled models for optical amplifiers. Gain spectrum is supposed to be flat over the simulated bandwidth. In order to generate a wavelength-dependent gain, an "Optical Filter" may be used at the amplifier input or output.
A new feature proposed by Optolink Numerics is the amplifier Polarization Hole Burning (PHB) model, whose transmission impairments can be considerable in long-haul systems. Details for the "EDFA" are given in "Appendix – The amplifier model".

Inputs / Outputs*:* 1 optical input, 1 optical output.

Parameters:

Amplifier controlled by output power or gain: [default: Output power] if "Output power" is selected, gain *G* equals the selected "Amplifier output power" over the calculated optical power at the amplifier input. If "Gain" is selected, *G* equals the selected "Amplifier gain". In both cases, the effective output power is

$$P_{out} = G \cdot \left(P_{in,x} + P_{in,y}\right) + P_{ASE,loc} \quad , \qquad (1)$$

with $P_{in,x}$, $P_{in,y}$ the amplifier input power on the 2 polarization components, $P_{ASE,loc}$ the amplified spontaneous emission noise (ASE) generated by this amplifier. "Amplifier output power" then includes the amplified input power (with the ASE noise of previous EDFA), but does not include the ASE noise produced by this "EDFA" (i.e. the effective output power will be negligibly higher than the selected, because it includes the locally generated ASE power). In the presence of PDL or PDG, eq. 1 still holds (see below and "Appendix – The amplifier model").

Amplifier output power: [dBm, default: 0] used when "Output power" is selected to evaluate the gain *G*.

Amplifier gain: [dB, default: 0] it is the gain *G*, used when "Gain" is selected.

Noise figure: [dB, default: 0] the ASE noise figure *NF*, used in "Appendix – The amplifier model", eq. 3.8; noise is added to the 2 polarization components also considering the presence of PDL and PDG (eq. 3.7). To turn-off the amplifier noise, set this parameter to a very low value (example: -1000 dB).

Amplifier input PDL: [dB, default: 0] polarization dependent loss is modeled at the amplifier input according to "Appendix – The amplifier model", eq. 3.1; total gain accounts for PDL, in order to satisfy eq. 1.

Amplifier PDG by polarization hole burning: [dB, default: 0] polarization hole burning introduces a polarization dependent gain weighted by the state of polarization of the input field. Optolink Numerics implements a new model for this effect, described in “Appendix – The amplifier model”, eq. 3.2 to 3.7. Total gain accounts for PDG, in order to satisfy eq. 1.

Nonlinear Element (NL__Elem)

Optical Kerr and Raman nonlinear element.
The “Fiber” component uses the vectorial nonlinear Schrödinger equation to account for the Kerr and Raman nonlinearity. A more complete equation should also include the self-stepeening term, originating from the intensity dependence of the group velocity and responsible of asymmetry in the signal spectrum; self-steepening is considerable in signals with ultrashort pulses (< 1 ps).
In order to account for all the nonlinear effects, it has been introduced the “Nonlinear Element”, modeled by the equations [G. P. Agrawal, *Nonlinear fiber optics*, New York, Academic Press, 1995]

$$
\begin{aligned}
&\frac{\partial A_x}{\partial z} + \beta_{1x}(z)\frac{\partial A_x}{\partial t} + \frac{\alpha(z)}{2}A_x = i\gamma(z)\left(|A_x|^2 + \frac{2}{3}|A_y|^2\right)A_x - \\
&-\frac{\gamma(z)}{\omega_0}\frac{\partial}{\partial t}\left[\left(|A_x|^2 + \frac{2}{3}|A_y|^2\right)A_x\right] - i\gamma(z)T_R A_x \frac{\partial}{\partial t}\left(|A_x|^2 + \frac{2}{3}|A_y|^2\right) \\
&\frac{\partial A_y}{\partial z} + \beta_{1y}(z)\frac{\partial A_y}{\partial t} + \frac{\alpha(z)}{2}A_y = i\gamma(z)\left(|A_y|^2 + \frac{2}{3}|A_x|^2\right)A_y - \\
&-\frac{\gamma(z)}{\omega_0}\frac{\partial}{\partial t}\left[\left(|A_y|^2 + \frac{2}{3}|A_x|^2\right)A_y\right] - i\gamma(z)T_R A_y \frac{\partial}{\partial t}\left(|A_y|^2 + \frac{2}{3}|A_x|^2\right)
\end{aligned}
\quad , \quad (1)
$$

with the same notations as in “Appendix – The fiber model”. In eqs. 1, the group velocity dispersion, dispersion slope and PMD are not included; second term on the right-hand side accounts for the self-steepening effect.
Eqs. 1 are numerically solved by the symmetrical split-step method [G. P. Agrawal, *Nonlinear fiber optics*, New York, Academic Press, 1995. J. A. Fleck, J. R. Morris, M. D. Feit, Applied Physics 10, pp.129-160, 1976], with a constant integration step selected by the user.

Inputs / Outputs: 1 optical input, 1 optical output.

Parameters:

Insertion loss: [dB, default: 0] the excess loss introduced by the component at the input.

Span length: [km, default: 0] the component length (considered similar to a fiber span). Must be greater than zero.

Effective area: [um^2, default: 1.0E9] the component Kerr nonlinearity is accounted for by the parameter $\gamma = n_2\omega_0/(cA_{eff})$ in eq. 1, with n_2 [m^2/W] the Kerr nonlinear index coefficient and A_{eff} [um^2] the component modal effective area (assuming it as a fiber). Model accounts for the Self Phase Modulation (SPM), Cross Phase Modulation (XPM) and Four Wave Mixing (FWM) altogether and with no approximations.

Nonlinear coefficient: [W/m^2, default: 2.6E-20] the Kerr nonlinear index coefficient n_2.

Raman delay: [fs, default: 0] the molecular Raman delay time T_R in eq. 1; a commonly used value is 3 fs for standard monomodal fibers, although a value up to 5 fs has been observed. The γ and T_R parameters are supposed constant in a fiber span.

Step: [m, default: 100] the integration step for solving eq. 1; it must be chosen for every "Nonlinear Element" component

Loss: [dB/km, default: 0] the attenuation α experienced over the component length.

Attenuation, Kerr and Raman parameters are assumed constant in a "Nonlinear Element".

Dispersion Compensator (DispComp)

Optical dispersion compensation element. Adds an amount of group velocity dispersion (GVD, [ps/nm]) and dispersion slope. It may model, for example, a Fiber Bragg Grating (FBG) component.
Dispersion and dispersion slope are added according to the

$$\tilde{A}_{out,k}(\nu) = \tilde{A}_{in,k}(\nu)\exp\left[\frac{i}{2}\beta_2 z(\omega-\omega_0)^2 + \frac{i}{6}\beta_3 z(\omega-\omega_0)^3\right] \qquad k = x,y \; ; \qquad (1)$$

in eq. 1, $\tilde{A}(\nu)$ indicates the complex amplitude Fourier transform, $\beta_2 z$ is the GVD (in s^2) re-calculated at frequency ω (see “Fiber”, eq. 1), $\beta_3 z$ is the dispersion slope (in s^3), ω_0 is the WDM signal central frequency.

Inputs / Outputs: 1 optical input, 1 optical output.

Parameters:

Insertion loss: [dB, default: 0] the excess loss introduced by the component at the input.

Dispersion: [ps/nm, default: 0] the GVD introduced by the component at the reference wavelength selected in the “Simulation menu”.

Dispersion Slope: [ps/nm^2, default: 0] the introduced dispersion slope, in proximity of the reference wavelength.

Post-Compensator (PostComp)

Optical dispersion compensation sweep at the receiver.
In transmission systems where group velocity dispersion is cumulated along the line, such as dispersion managed systems [I. Gabitov, E. G. Shapiro, S. K. Turitsyn, Optics Communications 134, pp.317-329, Jan. 1997], it is useful to evaluate the performance over a given post-compensation dispersion range, to find the highest performance for each transmitted channel.
This is automatically performed by Optolink Numerics when a “Post-Compensator” is used. “Post-Compensator” must be directly linked to a “RX, IM-DD”, “RX, PhIM” or “RX, DPSK” receiver; a “DeMUX” may be eventually linked at the input of the “Post-Compensator”.
The use of “Post-Compensator” is equivalent to calling a “Dispersion Compensator” several times, with no dispersion slope, and elaborating the obtained signal in the linked receiver. Insertion loss is introduced only at the first call of “Dispersion Compensator”, in order to evaluate the performance on a received signal with different amounts of cumulated GVD but same optical power.
The results stored at the receiver will include the performance vs. post-compensation, and the eyes and graphs at the post-compensation value corresponding to the highest Q factor (on a channel-by-channel basis).

Inputs / Outputs: 1 optical input, 1 optical output. Must be directly linked to a “RX, IM-DD”, “RX, PhIM” or “RX, DPSK”.

Parameters:

Insertion loss: [dB, default: 0] the “Post-Compensator” device insertion loss.

Initial dispersion value for all channels: [ps/nm, default: 0] sets the initial value for the post-compensation dispersion sweep. Dispersion sweep values are the same for all channels.

Final dispersion value: [ps/nm, default: 0] the final dispersion sweep value.

Number of steps for dispersion sweep: [default: 1] the number of dispersion values in the sweep range.

Optical Delay (OptDelay)

Optical delay with optical phase shift. It is modeled by

$$A_{out,k}(t) = A_{in,k}(t - \Delta t)\exp(-i2\pi\nu_0\Delta t + i\phi) \qquad k = x, y \quad , \qquad (1)$$

where ν_0 is the WDM signal central frequency, Δt the selected time delay. Signal experiences a phase shift corresponding to the optical delay, plus a selected value ϕ, in order to use the component as a phase shifter. Optical signal exiting from one side of the simulation time window enters in the other side.

Inputs / Outputs: 1 optical input, 1 optical output.

Parameters:

Insertion loss: [dB, default: 0] the component insertion loss.

Optical delay: [ps, default: 0] the delay Δt in eq. 1.

Phase shift: [deg, default: 0] the additional phase shift ϕ in eq. 1.

Splitter (Splitter)

Optical splitter, polarization-independent. It is used as a real power splitter with variable splitting ratio *s*, i.e. the ratio between the two output powers, or as an ideal splitter. The model for the real splitter is

$$\begin{aligned} A_{out1,k}(t) &= A_{in,k}(t)\sqrt{\frac{s}{1+s}} \\ A_{out2,k}(t) &= A_{in,k}(t)\sqrt{\frac{1}{1+s}} \qquad k = x, y \end{aligned} \quad . \qquad (1)$$

The first output in eq. 1 is the one linked to a component with the upper position in the design chart, respect to the one linked to the second output.

Inputs / Outputs: 1 optical input, 2 optical outputs.

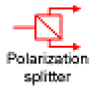
Parameters:

Insertion loss: [dB, default: 0] the component insertion loss (not included in eq. 1).

Splitting ratio: [dB, default: 0] the ratio *s* (selected in dB scale) in eq. 1.

Use ideal splitter: [default: unchecked] if checked, the two outputs equal the input signal, with the selected insertion loss.

Polarization Splitter (PolSplit)



Optical splitter, polarization-dependent. It is equivalent to 2 optical polarizers at angle θ and $\theta+\pi/2$ respect to the *x* polarization axis in the *x*-*y* plane. A polarizer at angle θ is modeled by the Jones matrix

$$Pol(\theta)=\begin{bmatrix}\cos^2\theta & \cos\theta\sin\theta\\ \cos\theta\sin\theta & \sin^2\theta\end{bmatrix} \quad ; \qquad (1)$$

the “Polarization Splitter” gives the output optical fields:

$$\begin{aligned}\begin{bmatrix}A_{out1,x}(t)\\ A_{out1,y}(t)\end{bmatrix} &= Pol(\theta)\begin{bmatrix}A_{in,x}(t)\\ A_{in,y}(t)\end{bmatrix}\\ \begin{bmatrix}A_{out2,x}(t)\\ A_{out2,y}(t)\end{bmatrix} &= Pol\left(\theta+\frac{\pi}{2}\right)\begin{bmatrix}A_{in,x}(t)\\ A_{in,y}(t)\end{bmatrix}\end{aligned} \quad . \qquad (2)$$

The first output in eq. 1 is the one linked to a component with the upper position in the design chart.

Inputs / Outputs: 1 optical input, 2 optical outputs.

Parameters:

Insertion loss: [dB, default: 0] the component insertion loss.

Polarizer angle: [deg, default: 0] the angle θ in eq. 1.

Optical Adder (OptAdder)

Optical adder, polarization-independent. The two incoming optical fields are added according to

$$A_{out,k}(t) = A_{in1,k}(t) + A_{in2,k}(t) \qquad k = x, y \qquad . \tag{1}$$

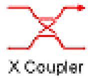
The first input in eq. 1 is the one linked to a component with the upper position in the design chart.

Inputs / Outputs: 2 optical inputs, 1 optical output.

Parameters:

Insertion loss: [dB, default: 0] the component insertion loss.

X Coupler (XCoupler)



Optical cross-coupler, polarization-independent. Input optical fields are coupled according to the

$$A_{out,k}(t) = \sqrt{1-\alpha}A_{in1,k} + i\sqrt{\alpha}A_{in2,k} \qquad k = x, y \qquad , \qquad (1)$$

with α the device coupling factor.
The first input in eq. 1 is the one linked to a component with the upper position in the design chart, respect to the one linked to the second input.

Inputs / Outputs: 2 optical inputs, 1 optical output.

Parameters:

Insertion loss: [dB, default: 0] the component insertion loss.

Coupling factor: [default: 0] the factor α in eq. 1, selected in linear scale.

Polarization Combiner (Pol_Comb)

Optical coupler, polarization-dependent. It is equivalent to 2 optical polarizers at angle θ and $\theta+\pi/2$ respect to the *x* polarization axis in the *x-y* plane, and a power combiner. The 2 input optical fields are coupled according to the

$$\begin{bmatrix} A_{out,x}(t) \\ A_{out,y}(t) \end{bmatrix} = Pol(\theta) \begin{bmatrix} A_{in1,x}(t) \\ A_{in1,y}(t) \end{bmatrix} + Pol\left(\theta+\frac{\pi}{2}\right) \begin{bmatrix} A_{in2,x}(t) \\ A_{in2,y}(t) \end{bmatrix} , \qquad (1)$$

with $Pol(\theta)$ given in “Polarization Splitter”, eq. 1.
The first input in eq. 1 is the one linked to a component with the upper position in the design chart.
“Polarization Combiner” can be used for the Polarization Domain Multiplexing (PDM) of 2 optical signals; it is sufficient to rotate through an angle $\pi/2$ the polarization of the second signal and set $\theta=0$. At the receiver, a “Polarization Controller” should be used in this case. WDM channels should be multiplexed with parallel polarizations when using PDM, otherwise the polarizers at the “Polarization Combiner” inputs may cut away the optical field of some channel.

Inputs / Outputs: 2 optical inputs, 1 optical output.

Parameters:

Insertion loss: [dB, default: 0] the component insertion loss.

Polarizer angle: [deg, default: 0] the angle θ in eq. 1.

Optical Cross Connect (XConnect)

Optical Cross Connector for network applications, with two optical inputs, N wavelengths per input. The component scheme is reported in Fig. OXC-1; it includes: a multiplexer section, implemented with tunable optical filters separating the WDM wavelengths at each input; a switching section with one space switch matrix for each wavelength, accounting for channel cross-talk and phase shift; an output multiplexer section adding the switched output channels. The component insertion loss is also included at input.

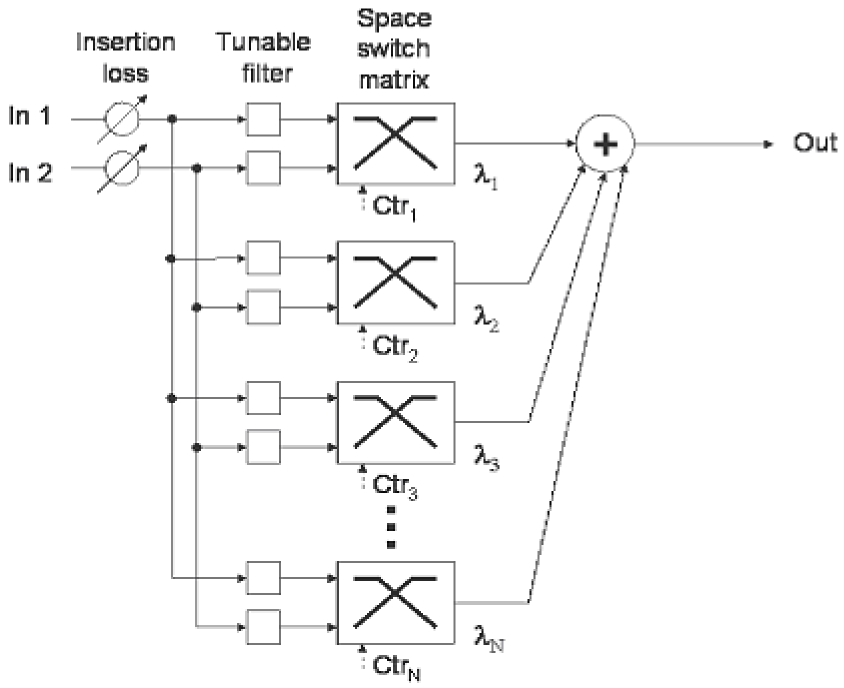


Fig. OXC-1

Tunable filters transfer function may be chosen between Gaussian, trapezoidal or used-defined, as explained for the "Optical filter" component.
Space switch matrixes may assume the cross or bar state, and include the cross-talk between the two inputs and an optical phase shift due to the space switching; the implemented scheme is given in Fig. OXC-2.

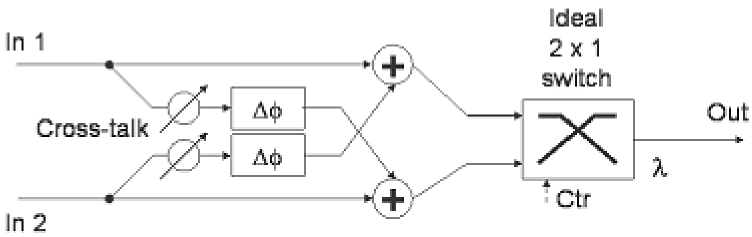


Fig. OXC-2. The space switch matrix scheme.

Inputs / Outputs: 2 optical inputs, 1 optical output.

Parameters:

Insertion loss: [dB, default: 0] the component insertion loss for both inputs.

Number of space-switching matrixes: [default: 1] sets the number of used matrixes N; must equal the number of incoming wavelengths at each input.

Central wavelength: [nm, default: 1550] the N tunable filter operation wavelengths are calculated with uniform channel spacing, according to the

$$\lambda_j = \lambda_0 + \left(j - \frac{N+1}{2} \right) \Delta\lambda \quad , \qquad (1)$$

with λ_0 and $\Delta\lambda$ the selected central wavelength and wavelength spacing.

Wavelength spacing: [nm, default: 0] the channel spacing in eq. 1, assumed uniform for the incoming signals.

Operation wavelength: [nm] shows the evaluated operation wavelengths for each tunable filter, according to eq. 1.

Bar - Cross state: [default: unchecked] sets the control Ctr_j for the j-th matrix; if unchecked, the upper input in Fig. OXC-2 is transmitted, if checked the lower input is passed.

Cross-talk: [dB, default: 0] sets the signal cross-talk, caused by the space switch matrix in fig. OXC-2.

Phase shift: [deg, default: 0] selects the optical phase shift experienced by the input signals in the space switch matrix.

Filter type: [default: Gaussian] selects the tunable optical filter transfer function. See the "Optical filter" component for further details.

Gaussian filter bandwidth: [GHz, default: 50] the optical 3dB bandwidth B_o in eq. 1, "Optical filter" section.

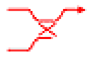
Gaussian filter order: [default: 1] defines the order M for the Gaussian filter in eq. 1, “Optical filter” section.

Trapezoidal filter 0 dB bandwidth: [GHz, default: 70] the optical filter bandwidth ν_b in eq. 3, “Optical filter” section, corresponding to a 0 dB attenuation.

Trapezoidal filter cut-off bandwidth: [GHz, default: 100] the filter bandwidth ν_c in eq. 3, “Optical filter” section, corresponding to an attenuation between 0 and Att_{dB}.

Trapezoidal filter attenuation: [dB, default: 30] the filter attenuation Att_{dB} in eq. 3, “Optical filter” section.

Add Filter (Add_Filt)



Add function by an Add&Drop filter. Component adds wavelengths to a WDM signal according to the scheme in Fig. Add&Drop-1.

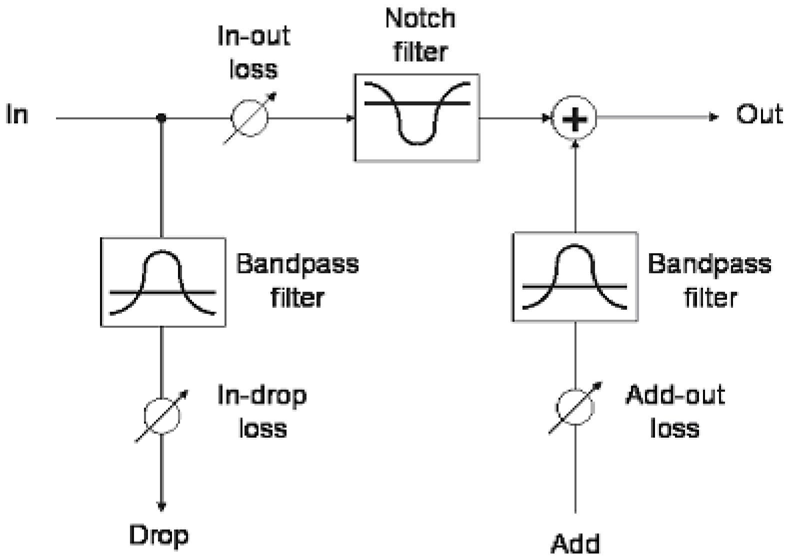


Fig. Add&Drop-1

If $T(\nu)$ is the bandpass filter transfer function for the incoming optical complex amplitude, the notch filter transfer function is given by $\left[1-T^2(\nu)\right]^{1/2}$.
Optical losses from input to output and from add to output are separately selected.

Inputs / Outputs: 2 optical inputs, 1 optical output.

Parameters:

Add filter type: [default: Gaussian] selects the bandpass optical filter transfer function. See the “Optical filter” component for further details.

Input-to-output loss: [dB, default: 0] sets the insertion loss from input to output.

Add-to-output loss: [dB, default: 0] the optical loss from add to output.

Add wavelength: [nm, default: 1550] selects the central wavelength for the bandpass and the notch filters.

Gaussian filter bandwidth: [GHz, default: 50] the optical filter 3dB bandwidth B_o in eq. 1, “Optical filter” section.

Gaussian filter order: [default: 1] defines the order M for the Gaussian filter in eq. 1, “Optical filter” section.

Trapezoidal filter 0 dB bandwidth: [GHz, default: 70] the optical filter bandwidth ν_b in eq. 3, “Optical filter” section, corresponding to a 0 dB attenuation.

Trapezoidal filter cut-off bandwidth: [GHz, default: 100] the filter bandwidth ν_c in eq. 3, “Optical filter” section, corresponding to an attenuation between 0 and Att_{dB}.

Trapezoidal filter attenuation: [dB, default: 30] the filter attenuation Att_{dB} in eq. 3, “Optical filter” section.

Drop Filter (DropFilt)

Drop function by an Add&Drop filter. Component drops wavelengths from a WDM signal according to the scheme in Fig. Add&Drop-1.
If $T(\nu)$ is the drop bandpass filter transfer function for the incoming optical complex amplitude, the notch filter transfer function is given by $\left[1-T^2(\nu)\right]^{1/2}$.
Optical losses from input to output and from input to drop are separately selected.

Inputs / Outputs: 1 optical input, 2 optical outputs.

Parameters:

Drop filter type: [default: Gaussian] selects the bandpass optical filter transfer function. See the “Optical filter” component for further details.

Input-to-output loss: [dB, default: 0] sets the insertion loss from input to output.

Input-to-drop loss: [dB, default: 0] the optical loss from input to drop.

Drop wavelength: [nm, default: 1550] selects the central wavelength for the bandpass and the notch filters.

Gaussian filter bandwidth: [GHz, default: 50] the optical filter 3dB bandwidth B_o in eq. 1, “Optical filter” section.

Gaussian filter order: [default: 1] defines the order M for the Gaussian filter in eq. 1, “Optical filter” section.

Trapezoidal filter 0 dB bandwidth: [GHz, default: 70] the optical filter bandwidth ν_b in eq. 3, “Optical filter” section, corresponding to a 0 dB attenuation.

Trapezoidal filter cut-off bandwidth: [GHz, default: 100] the filter bandwidth ν_c in eq. 3, “Optical filter” section, corresponding to an attenuation between 0 and Att_{dB}.

Trapezoidal filter attenuation: [dB, default: 30] the filter attenuation Att_{dB} in eq. 3, “Optical filter” section.

Polarization Attenuator (PolAtten)

Optical attenuator, polarization-dependent. Input optical field can be attenuated differently on the 2 polarization components, according to

$$A_{out,k} = \frac{A_{in,k}}{Att_k} \qquad k = x, y \qquad . \qquad (1)$$

Inputs / Outputs: 1 optical input, 1 optical output.

Parameters:

Behave as PDL element: [default: unchecked] if checked, attenuation for *x* and *y* polarizations can be changed separately.

Attenuation for x polarization: [dB, default: 0] the attenuation $Att_{dB,x}$, with $Att_x = 10\wedge\left(Att_{dB,x}/20\right)$ in eq. 1.

Attenuation for y polarization: [dB, default: 0] the attenuation $Att_{dB,y}$, with $Att_y = 10\wedge\left(Att_{dB,y}/20\right)$ in eq. 1.

Optical Filter (OpFilter)

Optical filter

Optical in-line filter. Can be used along the transmission line as a Gain Flattening Filter (GFF), or to introduce wavelength dependence to the amplifier gain, or simply to limit the optical noise. “Optical Filter” differs from the “DeMUX” in that the former may be used as an in-line component; conversely, it does not use the “WDM menu” and “MUX” settings to perform an optical de-multiplexing.

Inputs / Outputs: 1 optical input, 1 optical output.

Parameters:

Filter type: [default: Gaussian] selects the optical filter transfer function, as follows:

Gaussian filter:
The optical Gaussian filter of order M has an amplitude transfer function given by

$$H_{out}(\nu) = \exp\left[-\ln\sqrt{2}\left(2\frac{\nu-\nu_0}{B_o}\right)^{2M}\right] \quad ; \qquad (1)$$

B_o is the optical 3dB bandwidth and ν_0 the filter central frequency. Eq. 1 multiplies the incoming optical field complex amplitude according to

$$\tilde{A}_{out,k}(\nu) = \tilde{A}_{in,k}(\nu) H_{out}(\nu) \qquad k = x, y \quad , \qquad (2)$$

With $\tilde{A}(\nu)$ indicating the Fourier transform.

Trapezoidal filter:

The amplitude transfer function of a trapezoidal filter is $H_{out}(\nu) = 10^{H_{out,dB}(\nu)/20}$, with

$$H_{out,dB}(\nu)=\begin{cases}-Att_{dB} & |\nu|\geq\frac{\nu_c}{2}\\ Att_{dB}\frac{\nu+\frac{\nu_b}{2}}{\frac{\nu_c}{2}-\frac{\nu_b}{2}} & -\frac{\nu_c}{2}<\nu<-\frac{\nu_b}{2}\\ -Att_{dB}\frac{\nu-\frac{\nu_b}{2}}{\frac{\nu_c}{2}-\frac{\nu_b}{2}} & \frac{\nu_b}{2}<\nu<\frac{\nu_c}{2}\\ 0 & |\nu|\leq\frac{\nu_b}{2}\end{cases} \quad . \qquad (3)$$

In eq. 3, ν is the optical frequency relative to the filter central frequency ν_0, ν_b is the 0 dB bandwidth, ν_c the cut-off bandwidth and Att_{dB} the filter attenuation, in dB. Filter shape is a trapezoid, with attenuation passing from 0 dB to $-Att_{dB}$ in the frequency range between $\nu_b/2$ and $\nu_c/2$, and between $-\nu_c/2$ and $-\nu_b/2$.

Filter from file:
A user-defined optical filter can be used as an in-line filter; it must be passed to Optolink Numerics as a ".dat" file, selected using the "Browse" button.
Filter file must be a text file including 3 number columns (separated by commas, spaces or tabs). First column is the relative optical frequency (GHz) respect to the filter central frequency ν_0 (positive and negative numbers are admitted, with "." decimal separator); second column is the filter real amplitude A_f (linear scale, between 0 and 1); third column is the filter phase ϕ_f (rad).
Filter amplitude transfer function is generated according to

$$H_{out}(\nu)=A_f(\nu)\exp[i\phi_f(\nu)] \quad , \qquad (4)$$

with ν intended as the optical frequency relative to the filter central frequency ν_0. The amplitude and phase values used in eq. 4 are obtained by Optolink Numerics using a linear interpolation of the data from file, according to the

$$\begin{aligned}A_f(\nu)&=A_f^j+\left(A_f^{j+1}-A_f^j\right)\frac{\nu-\nu_j}{\nu_{j+1}-\nu_j}\\ \phi_f(\nu)&=\phi_f^j+\left(\phi_f^{j+1}-\phi_f^j\right)\frac{\nu-\nu_j}{\nu_{j+1}-\nu_j}\end{aligned} \quad , \qquad (5)$$

with ν_j and ν_{j+1} the file relative frequencies including ν and A_f^j, ϕ_f^j the corresponding amplitude and phase from file.
Filter transfer function is supposed to be zero outside the frequency range defined in the filter file.

Insertion loss: [dB, default: 0] the excess optical loss introduced by the filter.

Central wavelength: [nm, default: 1550] sets the transfer function central wavelength, and consequently the frequency ν_0 in eqs. 1 to 5.

Gaussian filter bandwidth: [GHz, default: 50] the optical 3dB bandwidth B_o in eq. 1.

Gaussian filter order: [default: 1] defines the order M for the Gaussian filter in eq. 1.

Trapezoidal filter 0 dB bandwidth: [GHz, default: 70] the optical filter bandwidth ν_b in eq. 3, corresponding to a 0 dB attenuation.

Trapezoidal filter cut-off bandwidth: [GHz, default: 100] the filter bandwidth ν_c in eq. 3, corresponding to an attenuation between 0 and Att_{dB}.

Trapezoidal filter attenuation: [dB, default: 30] the filter attenuation Att_{dB} in eq. 3.

To check the optical filter power transfer function, use the “Optolink Graph Viewer”, i.e. select the “Show graphs” button and double-click over the component after a simulation run.

Polarization Rotator (PolRotat)

Optical polarization rotation, including a phase shift between the polarization components, according to

$$\begin{bmatrix} A_{out,x}(t) \\ A_{out,y}(t) \end{bmatrix} = \begin{bmatrix} \cos\theta\, e^{i\Delta\phi/2} & \sin\theta\, e^{i\Delta\phi/2} \\ -\sin\theta\, e^{-i\Delta\phi/2} & \cos\theta\, e^{-i\Delta\phi/2} \end{bmatrix} \cdot \begin{bmatrix} A_{in,x}(t) \\ A_{in,y}(t) \end{bmatrix} . \qquad (1)$$

“Polarization Rotator” may be used together with the “Polarization Combiner” to generate polarization multiplexed signals (one signal is rotated through $\theta = \pi/2$).

Inputs / Outputs: 1 optical input, 1 optical output.

Parameters:

Insertion loss: [dB, default: 0] the component insertion loss.

Rotation angle: [deg, default: 0] the angle θ in eq. 1.

Phase between polarizations: [deg, default: 0] the angle $\Delta\phi$ in eq. 1.

Polarization Controller (PolContr)

Optical polarization control/tracking and polarizer are a powerful instrument for the study of polarization multiplexed signals (PDM). “Polarization Controller” must be inserted in proximity of the receiver (eventually preceding a “Post-Compensator” and a “DeMUX”); no splitter or combiner should be placed between a controller and the receiver.
“Polarization Controller” works in a logical way; polarization tracking is physically performed in the receiver component “RX, IM-DD”, “RX, PhIM” or “RX, DPSK”, for every channel and after the eventual de-multiplexing and post-compensation. Controller is modeled as the inverse of the Jones matrix, cumulated over the transmission system fibers and centered on the received channel wavelength.
The Jones matrix used by “Polarization Controller” is modified only in “Fiber” components, when PMD and birefringence axis rotation is present. For a “Fiber” span, the cumulated Jones matrix is given by

$$\prod_{n=1}^{N_{rot}} Jones(\omega_k, n) \quad , \qquad (1)$$

with N_{rot} the number of birefringence axes rotations along the fiber, ω_k the de-multiplexed channel central frequency, and the Jones matrix given by [A. O. Dal Forno, A. Paradisi, R. Passy, J. P. von der Weid, IEEE Photonics Technology Letters 12, pp. 296-298, 2000]

$$Jones(\omega_k, n) = \begin{bmatrix} \exp\left(i\frac{\Delta\beta_1}{2}(\omega_k - \omega_0)L_c\right) & 0 \\ 0 & \exp\left(-i\frac{\Delta\beta_1}{2}(\omega_k - \omega_0)L_c\right) \end{bmatrix} \cdot \begin{bmatrix} \cos\theta_n & sen\theta_n \exp(i\phi_n) \\ -sen\theta_n \exp(-i\phi_n) & \cos\theta_n \end{bmatrix} \quad , \qquad (2)$$

with ω_0 the WDM signal central frequency, θ_n, ϕ_n the birefringence axis rotation, L_c the PMD correlation length and $\Delta\beta_1 = \beta_{1x} - \beta_{1y}$.
For other system components, the Jones matrix is transmitted unmodified; when components with 2 or more inputs are encountered, the Jones matrix corresponding to the first input (the higher component in the design chart) is transmitted. For this reason, signals multiplexed in polarization should preferably enter to combiner components as first input.
The modeled polarization controller is able to ideally recover the PMD and birefringence axis rotation experienced in fibers at the filtered channel central frequency, yet PMD is not ideally recovered at the channel spectrum frequencies different from ω_k.

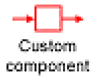
After the polarization controller, the transmitted channels are recovered along the *x* polarization axis; the polarization rotation performed by the transmitter multiplexer is in fact also recovered. If a “Polarization Rotator” is used in-line, the rotation is not recovered; for that reason, signals multiplexed in polarization by means of a “Polarization Rotator” and “Polarization Combiner” are recovered one along the *x* and one along the *y* axis.
If a polarizer is used, the optical field along *y* is cut away; at the receiver, performance is evaluated without the *y* components; any way, the received optical power and phase is displayed also for the *y* (i.e. after the polarization tracking and before the polarizer).

Inputs / Outputs: 1 optical input, 1 optical output.

Parameters:

Include polarizer: [default: unchecked] if checked, a polarizer is used after the polarization control. The *y* polarization component is cut away, setting $A_{out,y} = 0$.

Custom Component (CompCust)



Optical user-defined component.
Designers can integrate their own optical components into Optolink Numerics, in the form of executable files; this is possible for optical components with 1 optical input and 1 optical output using “Custom Component”.
Executable file can be compiled in any programming language able to generate an “.exe” file; the executable must be placed in a dedicated subdirectory (we will refer to it as the “path\” directory). Optolink Numerics writes the parameters selected for “Custom Component” in a file called “path\Parameters.dat”; this is a text file with a single column of 16 numbers, in order: 14 user parameters for the component (with user-defined dimensions), the number of simulated points *N*, the simulation time window Δt (in seconds). We recall that the simulated optical bandwidth equals $N/\Delta t$.
The user-defined executable must be able to read the “path\Parameters.dat” file and use the 16 numeric parameters to elaborate the optical field at the input of “Custom Component”

$$A_k(t_j) = \mathrm{Re}\left[A_k^{(j)}\right] + i\,\mathrm{Im}\left[A_k^{(j)}\right] \qquad k = x, y \qquad j = 1,2,..N \quad . \qquad (1)$$

The input field, *x* polarization, is written by Optolink Numerics in a file called “path\Ax.dat”, containing 2 columns of *N* numbers separated by commas, spaces or tabs: the first column is the real part of the complex amplitude $\mathrm{Re}\left[A_x^{(j)}\right]$ (in $W^{1/2}$), the second is the imaginary part $\mathrm{Im}\left[A_x^{(j)}\right]$ (in $W^{1/2}$); the input *y* polarization is written in file “path\Ay.dat” in the same way. The user-defined executable must read the input field files also, elaborate the optical signal using the 16 input parameters and write the two files “path\Ax.dat” and “path\Ay.dat” with the output optical field, replacing the old files. Input field may be a WDM signal.
Optolink Numerics will read the new files and integrate the user-calculated signal into the system scheme.
Numbers written to or read from file must be compatible with the Fortran REAL data type.
Executable is launched by Optolink Numerics with a command line

“path\executable_file.exe path\” , (2)

i.e. the “path\” string is passed to the executable as a command parameter. To show an example, command parameter may be read in a Fortran executable using the CALL GETARG(1,sfile) instruction; it will result TRIM(sfile)= “path\”.

Inputs / Outputs: 1 optical input, 1 optical output.

Parameters:

Executable file: use the “Browse” button to search for the user-defined executable.

Parameter 1 .. Parameter 14: [default: 0] up to 14 numeric parameters to be used by the executable for elaborating the optical signal.

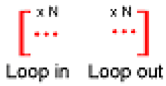
Different executables must be recorded in separated subdirectories, in order to avoid unpredictable results.

Null Component (CompNull)

Optical null termination. Used to terminate the optical output of a component without any calculation. The incoming optical field will be lost. “Null Component” may be used, for example, at one output of the “Splitter” or “Polarization Splitter”, or to evaluate the transmission system OSNR evolution (written in file “Runlog.log”) without evaluating the performance.

Inputs / Outputs: 1 optical input, no output.

Loop in, Loop out (Loop__In, Loop_out)



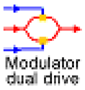
Loop for optical or electrical components. The sequence of optical components inserted between a “Loop in” and “Loop out” component is repeated *n* times, being *n* the “Number of loops” selected in “Loop out”. This is particularly useful when a dispersion managed system is simulated, constituted by a dispersion map repeated several times. A sequence of electrical component can also be inserted in a loop; this is useful, for example, to generate higher order electrical filters.
The sequence of components in a loop must be all optical or all electrical; it is not possible to insert components with more inputs or outputs, nor a “PIN/APD photodiode”.

Inputs / Outputs: 1 optical (electrical) input, 1 optical (electrical) output.

Parameters:

Number of loops: [default: 0] the number *n* of loop repetitions. Specified in “Loop out”.

Modulator, dual-drive (Modul_dd)



Optical modulator with dual-drive design. This component models a Mach-Zehnder modulator with z-cut geometry and 2 distinct electrical driving inputs. The general equation is

$$
\begin{aligned}
A_{out,k}(t) &= A_{in,k}(t)\cos\left(\frac{\Delta\phi_1-\Delta\phi_2}{2}\right)\exp\left(i\frac{\Delta\phi_1+\Delta\phi_2}{2}\right) \qquad k=x,y\\
\Delta\phi_j &= \frac{2\pi L n_0}{\lambda}+\pi\frac{V_j}{V_\pi} \qquad j=1,2 \qquad\qquad .\ (1)\\
V_\pi &= \frac{\lambda}{2\eta L}
\end{aligned}
$$

In eqs. 1, η, *L*, n_0 are respectively the index change per volt term, the interferometer interaction length and index of refraction; λ is the incoming wavelength, V_π the inversion voltage and $V_1=V_1(t)$, $V_2=V_2(t)$ the 2 applied driving voltages. By neglecting the constant phase term in eq. 1 and adding a modulator extinction ratio *er*, we obtain the “Modulator, dual-drive” model [S. Walklin, J. Conradi, IEEE Journal of Lightwave Technology 17, pp. 2235-2248, Nov. 1999]

$$
\begin{aligned}
A_{out,k}(t) &= A_{in,k}(t)\left\{\frac{1}{2}\exp\left(i\pi\frac{V_1(t)}{V_\pi}\right)+\frac{\gamma}{2}\exp\left(i\pi\frac{V_2(t)}{V_\pi}\right)\right\} \qquad . \qquad (2)\\
\gamma &= \frac{\sqrt{er}-1}{\sqrt{er}+1}
\end{aligned}
$$

In eq. 2, extinction ratio *er* is the ratio between the maximum and the minimum power transmission.

Inputs / Outputs: 1 optical input, 2 electrical inputs, 1 optical output.

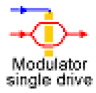
Parameters:

Insertion loss: [dB, default: 0] the excess power loss at the modulator input.

Inversion voltage: [V, default: 1] the voltage V_π in eq. 2.

Modulator extinction ratio: [dB, default: 15] the extinction ratio er_{dB}. In eq. 2 it is $er = 10\wedge(er_{dB}/10)$.

Modulator, single-drive (Modul_sd)



Optical modulator with single-drive design, typical of a Mach-Zehnder modulator with x-cut geometry and 1 electrical driving input. The implemented models are for both a cosine and a linear modulator response. In the cosine response case, it is

$$
\begin{aligned}
&A_{out,k}(t) = A_{in,k}(t)\cos[\Delta\phi(t)]\exp[i\theta_c(t)] \qquad k = x, y \\
&\Delta\phi(t) = \frac{\pi}{2}\left\{\frac{1}{2} - \gamma\cdot\left[norm\_sig(t) - \frac{1}{2}\right]\right\} \\
&\gamma = 1 - \frac{4}{\pi}\arctan\left(\frac{1}{\sqrt{er}}\right)
\end{aligned}
\quad . \qquad (1)
$$

In eqs. 1, modulator is supposed to be biased in $V_\pi/2$; *er* is the extinction ratio, $\theta_c(t)$ the modulator chirp and *norm_sig(t)* is the driving electrical signal normalized between 0 and 1. In "Modulator, single-drive" the input electrical signal may have any voltage levels; normalization between 0 and 1 is automatically performed inside the modulator.
Chirp is calculated solving the

$$
\frac{d\theta_c}{dt} = \frac{\alpha}{2P_{out}}\frac{dP_{out}}{dt} \quad , \qquad (2)
$$

with $P_{out}(t)$ the modulator output power and α the chirp parameter.
In a modulator with linear response, it is

$$
\begin{aligned}
&A_{out,k}(t) = A_{in,k}(t)\,f(V_{in})\exp[i\theta_c(t)] \qquad k = x, y \\
&f(V_{in}) = \left(\sqrt{\frac{er}{er+1}} - \sqrt{\frac{1}{er+1}}\right)\cdot norm\_sig(t) + \sqrt{\frac{1}{er+1}}
\end{aligned}
\quad , \qquad (3)
$$

with the same notations of eqs. 1. Chirp is evaluated solving eq. 2 as well.

Inputs / Outputs: 1 optical input, 1 electrical input, 1 optical output.

Parameters:

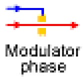
Modulator response: [default: cosine] selects between eq. 1 or eq. 3 models.

Insertion loss: [dB, default: 0] the excess power loss at the modulator input.

Extinction ratio: [dB, default: 15] the extinction ratio er_{dB}. In eqs. 1 and 3 it is $er = 10\wedge\left(er_{dB}/10\right)$.

Chirp parameter: [default: 0] the chirp α in eq. 2.

Modulator, phase (Modul_ph)



Optical phase modulator, with a generic inversion voltage V_π (i.e. the voltage corresponding to a π phase shift). Model is

$$A_{out,k}(t) = A_{in,k}(t)\exp\left[i\pi\frac{V(t)}{V_\pi}\right] \qquad k = x, y \qquad , \qquad (1)$$

with $V(t)$ the applied driving voltage.

Inputs / Outputs: 1 optical input, 1 electrical input, 1 optical output.

Parameters:

Insertion loss: [dB, default: 0] the excess power loss at the modulator input.

Inversion voltage: [V, default: 1] the voltage V_π in eq. 1.

Electrical Driver (ElDriver)

Electrical driving signal generator. It must be used with the modulator components, for generating electrical signals (voltages) with NRZ or RZ shape. Signal PRBS code may include a differential pre-encoding to be used for DPSK optical signals. Clock or constant signals may also be generated.

Inputs / Outputs: 1 electrical input, 1 electrical output.

Parameters:

Driver bit rate: [Gb/s, default: 10] the bit rate *R* for the electrical signal.

Electrical signal format: [default: NRZ] selects the format for the generated driving signal. Formats are modeled as follows:

NRZ format:
A Non-Return-to-Zero signal is generated with levels V_{offset}, the signal offset, and $V_{offset} + V_{amp}$, being V_{amp} the signal amplitude. The desired NRZ shape and rise time t_r (10% to 90%) is generated by filtering a step-shape PRBS signal with an electrical Gaussian filter, with transfer function in dB given by

$$H_{rise}(f) = 20\log_{10}\left\{\exp\left[-2\ln 2\left(\frac{f t_r}{0.562 \cdot 1.22}\right)^2\right]\right\} \quad , \qquad (1)$$

with *f* the electrical frequency. Factor 1.22 in eq. 1 is needed to generate at the modulator an optical signal with rise time very close to t_r.

RZ Gaussian format:
The RZ electrical signal with Gaussian shape is modeled by the

$$V(t) = V_{amp}\left\{\sum_j code(j)\exp\left[-\frac{(t - jT_B)^2}{T_0^2}\right]\right\} + V_{offset} \qquad j = 0,1,2... \quad . \qquad (2)$$

In eq. 2, T_0 is bound to the pulse full width at a half maximum by $T_0 = T_{FWHM}/1.665$, *code(j)* equals 0 or 1 for spaces and marks respectively, $T_B = 1/R$ is the bit period.

RZ cosine format:
The electrical signal is given by

$$V(t) = V_{amp}\left\{\sum_j code(j)\cos\left[\frac{\pi}{2}\sin(\pi Rt)\right]rect(t - jT_B)\right\} + V_{offset} \qquad j = 0,1,2... \quad ,$$
(3)

with *rect()* the rectangular function of width $T_B = 1/R$.

RZ sech format:
Hyperbolic secant shape signal is given by

$$V(t) = V_{amp}\left\{\sum_j code(j)\text{sech}^2\left[\frac{(t - jT_B)}{T_0}\right]\right\} + V_{offset} \qquad j = 0,1,2... \quad , \quad (4)$$

with $T_0 = T_{FWHM}/1.763$. Sech is squared to give a correct pulsewidth to the modulated optical field.

Signal offset: [V, default: 0] the offset voltage V_{offset} added to the 4 signal formats.

Signal amplitude: [V, default: 1] the amplitude voltage V_{amp} in the 4 signal formats. A 0 V value is not accepted; set to a negligible value (for example: 1.0E-20) for generating a constant signal, to be used with the “Electrical Operator” component.

For NRZ, rise time: [ps, default: 20] it is the electrical NRZ rise and fall time t_r, defined in eq. 1. Optical rise and fall times are very close to t_r for extinction ratios around 15 dB; for much higher *ER* values (greater than 35 dB), the rise time approaches to t_r with an error smaller than 20%.

For RZ, FWHM pulsewidth: [ps, default: 30] the RZ pulses full width at a half maximum T_{FWHM}.

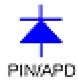
Differential pre-encoding: [default: unchecked] if checked, the used PRBS code is differentially pre-encoded according to

$$PRBSdiff(t) = PRBSdiff(t - T_B) \oplus PRBS(t) \qquad ; \qquad (5)$$

this is needed for DPSK phase modulation.

Clock signal: [default: unchecked] if checked, the generated signal is a clock. In NRZ case, signal has the selected risetime with 50% duty-cycle; in RZ case, the above pulse shapes are used as clock pulses; in RZ cosine case, a sinusoidal signal is generated.

PIN/APD photodiode (PhotDiod)



PIN/APD photodiode with dark current, shot and thermal noise. Noise is evaluated over the entire simulation bandwidth. For this reason, shot and thermal noises are physically meaningful if "PIN/APD photodiode" is followed by an "Electrical Filter".

***Inputs / Outputs**:* 1 optical input, 1 electrical output.

Parameters:

Responsivity: [A/W, default: 1] the incoming optical field is detected by a PIN or APD photodiode with responsivity R_p; the generated photocurrent is proportional to the incoming optical power P_{in} as

$$I_p(t) = GR_p P_{in}(t) + GI_d + n_{sh}(t) + n_{th}(t) \quad ; \qquad (1)$$

in eq. 1, APD avalanche gain G, receiver dark current I_d, shot noise and thermal noise have been included (see below).
For a PIN photodiode, the APD avalanche gain must be set to 0 dB.

Include shot noise: [default: unchecked] if checked, photodiode shot noise $n_{sh}(t)$ is added to the generated photocurrent; n_{sh} is modeled adding to the instantaneous photocurrent a random Gaussian current, with zero average and variance [G. P. Agrawal, *Fiber Optics Communications Systems*, Wiley, NY, 1992]

$$\sigma_{sh}^2 = q(R_p I_p + I_d)G^2 F \Delta\nu_{tot} \quad , \qquad (2)$$

with I_d the receiver dark current with no avalanche gain (see below), *q* the electron charge, $I_p(t)$ the instantaneous photocurrent, G the APD avalanche gain, F the avalanche noise figure, and $\Delta\nu_{tot}$ the simulation bandwidth. $\Delta\nu_{tot}$ should be reduced to a receiver equivalent bandwidth $2B_e$ by connecting the photodiode to an "Electrical Filter" with cut-off frequency B_e.
Shot noise mainly affects the transmitted marks, being almost negligible for spaces.
For a PIN photodiode, both the APD avalanche gain and noise figure must be set to 0 dB.

Dark current: [A, default: 0] sets the photodiode dark current before the avalanche gain I_d, due to residual light or thermal generation.

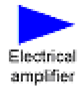
Receiver thermal noise spectral density: [A/Hz^0.5 default: 0] thermal noise current is generated by electrons thermal motion in the receiver load resistor. It is modeled by a

Gaussian random process n_{th} , adding Gaussian variables to the real and imaginary parts of the current spectrum. Random variables have zero average and variance

$$\sigma_{th}^2 = \frac{S_{th}^2 \Delta\nu_{tot}}{2N} , \qquad (3)$$

being *N* the number of simulated points, S_{th} the specified one-sided thermal noise spectral density [A/Hz^0.5], and $\Delta\nu_{tot}$ the simulation bandwidth. $\Delta\nu_{tot}$ should be reduced to a receiver equivalent bandwidth $2B_e$ by connecting the photodiode to an “Electrical Filter” with cut-off frequency B_e .

Electrical Amplifier (El_Ampli)



Electrical amplifier with Gaussian noise. Electrical signal is multiplied for a gain *G*, and an electrical white Gaussian noise $n_{th}(t)$ is added according to

$$V_{out}(t) = GV_{in}(t) + n_{th}(t) \quad . \qquad (1)$$

Inputs / Outputs: 1 electrical input, 1 electrical output.

Parameters:

Electrical gain: [dB, default: 0] the gain G_{dB} in dB scale. Linear gain is given by $G = 10^{\wedge}(G_{dB}/20)$.

Gaussian noise spectral density: [A/Hz^0.5 default: 0] noise current is modeled by a Gaussian random process n_{th}, adding Gaussian variables to the real and imaginary parts of the current spectrum. Random variables have zero average and variance

$$\sigma_{th}^2 = \frac{S_{th}^2 \Delta\nu_{tot}}{2N} \quad , \qquad (3)$$

being *N* the number of simulated points, S_{th} the specified one-sided thermal noise spectral density [A/Hz^0.5], and $\Delta\nu_{tot}$ the simulation bandwidth. $\Delta\nu_{tot}$ should be reduced to an equivalent bandwidth $2B_e$ by connecting the amplifier to an “Electrical Filter” with cut-off frequency B_e.

Electrical Filter (ElFilter)

Electrical filter; is commonly used after a photodiode or an electrical amplifier, or into an electrical driving circuit.

Inputs / Outputs: 1 electrical input, 1 electrical output.

Parameters:

Electrical low-pass filter: [default: Bessel 4th order] selects the receiver low-pass electrical filter type.
Bessel-Thomson 4th order electrical filter is characterized by the current transfer function [ITU-T Recommendation G.957 (06/99)]

$$H_{Bessel}(f) = \frac{105}{105 + 105p + 45p^2 + 10p^3 + p^4} \qquad p = 2.1140 i \frac{f}{B_e} \quad , \quad (1)$$

with B_e the receiver 3dB cut-off frequency and *f* the electrical frequency.
Gaussian filter is defined by

$$H_{Gauss}(f) = \exp\left[-\ln\sqrt{2}\left(\frac{f}{B_e}\right)^2 \right] \quad . \quad (2)$$

Butterworth 2nd order filter is given by [Zverev A. I., *Handbook of Filter Synthesis*, Wiley, NY, 1967]

$$H_{Butterworth}(f) = \frac{1}{1 + \sqrt{2}p + p^2} \qquad p = i\frac{f}{B_e} \quad . \quad (3)$$

Filter from file:
A user-defined electrical filter can be used as an in-line filter; it must be passed to Optolink Numerics as a ".dat" file, selected using the "Browse" button.
Filter file must be a text file including 3 number columns (separated by commas, spaces or tabs). First column is the electrical frequency around 0 (GHz, positive and negative numbers are admitted, with "." decimal separator); second column is the filter real amplitude A (linear scale, between 0 and 1); third column is the filter phase ϕ (rad).
Filter amplitude transfer function is generated according to

$$H_{el}(f) = A(f)\exp[i\phi(f)] \quad , \quad (4)$$

with f intended as the electrical frequency. The amplitude and phase values used in eq. 4 are obtained by Optolink Numerics using a linear interpolation of the data from file, according to the

$$A(f) = A_j + (A_{j+1} - A_j)\frac{f - f_j}{f_{j+1} - f_j}$$
$$\phi(f) = \phi_j + (\phi_{j+1} - \phi_j)\frac{f - f_j}{f_{j+1} - f_j} \quad , \qquad (5)$$

with f_j and f_{j+1} the file frequencies including f and A_j , ϕ_j the corresponding amplitude and phase from file.
Filter transfer function is supposed to be zero outside the frequency range defined in the filter file.

Electrical filter 3 dB cut-off frequency: [GHz, default: 7.5] the electrical filter cut-off frequency, used in eqs. 1 to 3; it corresponds to the receiver front-end bandwidth.

Electrical filter transfer function may be viewed after a simulation run using “Optolink Graph Viewer”, i.e. by selecting the “Show graphs” button and double-clicking over the component.

Electrical Delay (El_Delay)

Electrical signal delay, according to

$$V_{out}(t) = V_{in}(t - \Delta t) \quad , \qquad (1)$$

with Δt the selected delay.

Inputs / Outputs: 1 electrical input, 1 electrical output.

Parameters:

Electrical delay: [ps, default: 0] the delay Δt in eq. 1.

Evaluate Performance (PerfEval)

Performance evaluation for the incoming electrical signal. “Evaluate Performance” only calculates the Q factor, timing jitter and eye opening penalty for the input electrical signal; it also stores the relative eye. See the “Appendix – Q factor and timing jitter models” for details on the performance calculation.
Performance and eye can be viewed by selecting the “Show graphs” command/button, and double-clicking the component. The evaluated signal will be referred to as “Channel 0”.
“Evaluate Performance” cannot use the “Post-Compensation” sweep.

Inputs / Outputs: 1 electrical input, no output.

Parameters:

Bit rate: [Gb/s, default: 10] specify the electrical signal bit rate, for bit sampling.

Input signal units: [default: Ampere] selects the input signal electrical units. If “Volt” is selected, signal is divided by the “Input resistance”.

Input resistance: [Ohm, default: 50] divides the electrical signal if Volt units are selected.

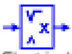
“Evaluate Performance” must be set to Ampere units when the electrical signal is generated by a photodiode (intended as an electrical current). Conversely, it must be set to Volt when used at the output of an “Electrical driver” (whose signal is intended as an electrical voltage).

Electrical Splitter (El_Split)

Electrical ideal splitter. The input electrical signal is ideally split into 2 outputs, with no attenuation.

Inputs / Outputs: 1 electrical input, 2 electrical outputs.

Electrical Arithmetics (ElArithm)



Electrical arithmetic operator with single input. Performs arithmetics for a single input electrical signals. Input and output are in Volt or Ampere units.

Inputs / Outputs: 1 electrical input1, 1 electrical output. Input must be a current (generated by a photodiode) or a voltage (generated by a driver).

Parameters:

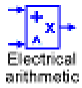
Arithmetical operation for 1st input: [default: +] selects the operator; if $V_{in}(t)$ is the input voltage or current, the output is given by the following operations

$$\begin{array}{llll} V_{in}(t)+C, & V_{in}(t)*C, & V_{in}(t)\wedge C, & \\ \ln[V_{in}(t)], & \log[V_{in}(t)], & \exp[V_{in}(t)], & 10^{V_{in}(t)} \end{array} \quad . \qquad (1)$$

In eqs. 1, C is a constant set by the user, using the text box next to the corresponding arithmetical operation.

As an example, if a square root of the incoming signal is requested, select the "1st ^" option and set "0.5" into the corresponding text box. Operations are performed in Volt or Ampere units.

Electrical Operator (ElOperat)



Electrical arithmetic operator. Performs arithmetics between 2 input electrical signals. Inputs and output are in Volt or Ampere units.

Inputs / Outputs: 2 electrical inputs, 1 electrical output. The first electrical input is the one linked to the upper component in the design chart. Inputs must be both currents (generated by photodiodes) or voltages (generated by drivers).

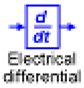
Parameters:

Operator between first and second input: [default: +] selects the operator; if $V_1(t)$ and $V_2(t)$ are the input voltages or currents, the output is given by the following operations

$$\begin{array}{lll} V_1(t)+V_2(t), & V_1(t)-V_2(t), & V_1(t)\cdot V_2(t), \\ V_1(t)/V_2(t), & V_1(t)^{V_2(t)}, & \exp[V_1(t)+V_2(t)], \\ \ln[V_1(t)+V_2(t)], & 10^{V_1(t)+V_2(t)}, & \log[V_1(t)+V_2(t)] \end{array} . \qquad (1)$$

A constant input signal can be generated using an “Electrical Driver” with negligible amplitude. A complemented voltage may be, for example, generated using a driver with negligible amplitude and zero offset as first input, another driver as second input, and selecting the subtraction operator; when using this method, it is preferable to set the bit rates of the two drivers to a common value.

Electrical Differential (El__Diff)



Electrical derivative; used for generating a differentially pre-encoded signal. Component performs a logical operation over electrical signals with finite rise and fall times; it previously samples the input signal extracting the logical pattern $codein(j),\ j=1,2..N_{bit}$, N_{bit} being the number of bits; output pattern is then evaluated according to the XOR operation

$$codeout(j) = codeout(j-1) \oplus codein(j) \qquad j = 1,2,..N_{bit} \quad . \qquad (1)$$

The output pattern modulates an electrical signal with the desired output format, rise and fall times. Component also performs a reshaping, re-amplification and retiming of the input signal. Output signal is synchronized to the input.

Inputs / Outputs: 1 electrical input, 1 electrical output.

Parameters:

Output electrical signal format: [default: NRZ] selects the format for the generated output signal. Formats are modeled like in the “Electrical Driver” component.

Bit rate: [Gb/s, default: 10] the bit rate *R* for the input and output electrical signals.

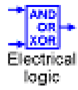
Signal offset: [V, default: 0] the offset voltage V_{offset} added to the 4 signal formats; see “Electrical Driver” for details.

Signal amplitude: [V, default: 1] the amplitude voltage V_{amp} in the 4 signal formats. A 0 V value is not accepted.

For NRZ, rise time: [ps, default: 20] the output electrical NRZ rise and fall time t_r, defined in eq. 1, “Electrical Driver”. Optical rise and fall times are very close to t_r for extinction ratios around 15 dB; for much higher *ER* values (greater than 35 dB), the rise time approaches to t_r with an error smaller than 20%.

For RZ, FWHM pulsewidth: [ps, default: 30] the RZ pulses full width at a half maximum T_{FWHM}.

Electrical Logic (El_Logic)



Performs a logical operation of the incoming electrical signals.
Component previously samples the two input signals, extracting the logical patterns $codein_1(j),\quad codein_2(j),\quad j=1,2..N_{bit},\ N_{bit}$ being the number of bits; signals are clamped at the same instant, corresponding to the first incoming mark in the first input (i.e. the upper one in the design chart). Output pattern is then evaluated according to the logical operation LO

$$codeout(j)=codein_1(j)\,LO\,codein_2(j)\qquad j=1,2,..N_{bit}\quad . \qquad (1)$$

The following logical operators are implemented, being NOT the logical negation operator:

LO	Operator	Description
$\bullet$	AND	$codein_1$ AND $codein_2$
$+$	OR	$codein_1$ OR $codein_2$
$\oplus$	XOR	$codein_1$ Exclusive OR $codein_2$
$\uparrow$	NAND	NOT($codein_1$ AND $codein_2$)
$\downarrow$	NOR	NOT($codein_1$ OR $codein_2$)
/	Inhibition	$codein_1$ AND NOT($codein_2$)
$\odot$	Equivalence	($codein_1$ AND $codein_2$) OR (NOT($codein_1$) AND NOT($codein_2$))
$\subset$	Implication	$codein_1$ OR NOT($codein_2$)

The output pattern modulates an electrical signal with the desired output format, rise and fall times. Component also performs a reshaping, re-amplification and retiming of the input signals. Output signal is synchronized to the inputs.

Inputs / Outputs: 2 electrical inputs, 1 electrical output.

Parameters:

Logical operation: [default: AND] selects the logical operator, according to the table above.

Output electrical signal format: [default: NRZ] selects the format for the generated output signal. Formats are modeled like in the "Electrical Driver" component.

Bit rate: [Gb/s, default: 10] the bit rate *R* for the input and output electrical signals.

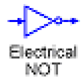
Signal offset: [V, default: 0] the offset voltage V_{offset} added to the 4 signal formats; see "Electrical Driver" for details.

Signal amplitude: [V, default: 1] the amplitude voltage V_{amp} in the 4 signal formats. A 0 V value is not accepted.

For NRZ, rise time: [ps, default: 20] the output electrical NRZ rise and fall time t_r, defined in eq. 1, “Electrical Driver”. Optical rise and fall times are very close to t_r for extinction ratios around 15 dB; for much higher *ER* values (greater than 35 dB), the rise time approaches to t_r with an error smaller than 20%.

For RZ, FWHM pulsewidth: [ps, default: 30] the RZ pulses full width at a half maximum T_{FWHM}.

Electrical Complement (El_Compl)



Performs a logical complement, or negation, of the incoming electrical signal. Component previously samples the input signal, extracting the logical pattern $codein(j)$, $j = 1,2..N_{bit}$, N_{bit} being the number of bits. Output pattern is then logically complemented

$$codeout(j) = NOT[codein(j)] \qquad j = 1,2,..N_{bit} \qquad . \qquad (1)$$

The output pattern modulates an electrical signal with the desired output format, rise and fall times. Component also performs a reshaping, re-amplification and retiming of the input signal. Output signal is synchronized to the input.

Inputs / Outputs: 1 electrical input, 1 electrical output.

Parameters:

Output electrical signal format: [default: NRZ] selects the format for the generated output signal. Formats are modeled like in the "Electrical Driver" component.

Bit rate: [Gb/s, default: 10] the bit rate *R* for the input and output electrical signals.

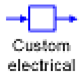
Signal offset: [V, default: 0] the offset voltage V_{offset} added to the 4 signal formats; see "Electrical Driver" for details.

Signal amplitude: [V, default: 1] the amplitude voltage V_{amp} in the 4 signal formats. A 0 V value is not accepted.

For NRZ, rise time: [ps, default: 20] the output electrical NRZ rise and fall time t_r, defined in eq. 1, "Electrical Driver". Optical rise and fall times are very close to t_r for extinction ratios around 15 dB; for much higher *ER* values (greater than 35 dB), the rise time approaches to t_r with an error smaller than 20%.

For RZ, FWHM pulsewidth: [ps, default: 30] the RZ pulses full width at a half maximum T_{FWHM}.

Electrical Custom Component (El__Cust)



Electrical user-defined component.
Designers can integrate their own electrical components into Optolink Numerics, in the form of executable files; component must have 1 electrical input and 1 electrical output.
Executable file can be compiled in any programming language able to generate an ".exe" file; the executable must be placed in a dedicated subdirectory (we will refer to it as the "path\" directory). Optolink Numerics writes the parameters selected for "Electrical Custom Component" in a file called "path\Parameters.dat"; this is a text file with a single column of 16 numbers, in order: 14 user parameters for the component (with user-defined dimensions), the number of simulated points *N*, the simulation time window Δt (in seconds).
The user-defined executable must be able to read the "path\Parameters.dat" file and use the 16 numeric parameters to elaborate the electrical current (Ampere) at the input of "Electrical Custom Component"

$$I(t_j) = \mathrm{Re}\left[I^{(j)}\right] + i\,\mathrm{Im}\left[I^{(j)}\right] \qquad j = 1,2,..N \quad . \qquad (1)$$

The input current is written by Optolink Numerics in a file called "path\Z.dat", containing 2 columns of *N* numbers separated by commas, spaces or tabs: the first column is the real part of the current $\mathrm{Re}\left[I^{(j)}\right]$ (A), the second is the imaginary part $\mathrm{Im}\left[I^{(j)}\right]$ (A). The user-defined executable must read the input current file also, elaborate the electrical signal using the 16 input parameters and write the file "path\Z.dat" with the output current, replacing the old file.
Optolink Numerics will read the new file and integrate the user-calculated signal into the system scheme.
Numbers written to or read from file must be compatible with the Fortran REAL data type.
Executable is launched by Optolink Numerics with a command line

"path\executable_file.exe path\"   ,   (2)

i.e. the "path\" string is passed to the executable as a command parameter. To show an example, command parameter may be read in a Fortran executable using the CALL GETARG(1,sfile) instruction; it will result TRIM(sfile)= "path\".

Inputs / Outputs: 1 electrical input, 1 electrical output.

Parameters:

Executable file: use the "Browse" button to search for the user-defined executable.

Parameter 1 .. Parameter 14: [default: 0] up to 14 numeric parameters to be used by the executable for elaborating the electrical signal.

Different executables must be recorded in separated subdirectories, in order to avoid unpredictable results.

10. Appendix: Models and Demos

10.1 The fiber model:

In Optolink Numerics, single-mode optical fibers are modeled by the full vectorial nonlinear Schrödinger equation [G. P. Agrawal, *Nonlinear fiber optics*, New York, Academic Press, 1995]

$$\begin{aligned}
&\frac{\partial A_x}{\partial z}+\beta_{1x}(z)\frac{\partial A_x}{\partial t}+\frac{i}{2}\beta_2(z)\frac{\partial^2 A_x}{\partial t^2}-\frac{1}{6}\beta_3(z)\frac{\partial^3 A_x}{\partial t^3}+\frac{\alpha(z)}{2}A_x=\\
&=i\gamma(z)\left(|A_x|^2+\frac{2}{3}|A_y|^2\right)A_x-i\gamma(z)T_R A_x\frac{\partial\left(|A_x|^2+\frac{2}{3}|A_y|^2\right)}{\partial t}\\
&\frac{\partial A_y}{\partial z}+\beta_{1y}(z)\frac{\partial A_y}{\partial t}+\frac{i}{2}\beta_2(z)\frac{\partial^2 A_y}{\partial t^2}-\frac{1}{6}\beta_3(z)\frac{\partial^3 A_y}{\partial t^3}+\frac{\alpha(z)}{2}A_y=\\
&=i\gamma(z)\left(|A_y|^2+\frac{2}{3}|A_x|^2\right)A_y-i\gamma(z)T_R A_y\frac{\partial\left(|A_y|^2+\frac{2}{3}|A_x|^2\right)}{\partial t}
\end{aligned} \quad , \quad (1.1)$$

where $A_k(z,t)$ (k=x,y) are the complex amplitudes for the WDM signal polarization components, z it is the transmission distance and α the fiber loss coefficient at the signal wavelength. Losses are supposed with flat spectrum in the signal bandwidth. The propagation constants for the two polarization axes are expanded as

$$\beta_k(\omega)=\beta_0+\beta_{1k}(\omega_0)\cdot(\omega-\omega_0)+\frac{1}{2}\beta_2(\omega_0)\cdot(\omega-\omega_0)^2+\frac{1}{6}\beta_3(\omega_0)\cdot(\omega-\omega_0)^3 \quad , \quad (1.2)$$

with $\omega_0=2\pi c/\lambda$ bound to the signal central wavelength λ.
Once given the group velocity dispersion $D(\lambda_{ref})$ [ps/nm/km] and the dispersion slope $S(\lambda_{ref})$ at reference wavelength λ_{ref}, the dispersion parameters in eq. 1.2, at the signal wavelength λ, are evaluated as

$$\begin{aligned}
&D(\lambda)=D(\lambda_{ref})+(\lambda-\lambda_{ref})S(\lambda_{ref})\\
&\beta_2(\omega)=-\frac{\lambda^2}{2\pi c}D(\lambda)\\
&\beta_3(\omega)=\left[S(\lambda_{ref})+\frac{2}{\lambda}D(\lambda)\right]\left(\frac{\lambda^2}{2\pi c}\right)^2
\end{aligned} \quad . \quad (1.3)$$

The fiber Kerr nonlinearity is accounted for by the parameter $\gamma = n_2\omega_0/(cA_{eff})$, with n_2 [m^2/W] the Kerr nonlinear index coefficient and A_{eff} [μm^2] the fiber modal effective area.
In eqs. 1.1, a WDM signal is represented as a single optical bandwidth transmitted through the fiber; thus, Kerr terms in eqs. 1.1 are able to model with no approximations all of the Kerr nonlinearities (self-phase modulation SPM, cross-phase modulation XPM, and four-wave mixing FWM).
Fiber Raman nonlinearity is included by the molecular Raman delay time T_R [fs]; Raman self and cross-effect between polarization components are properly modeled by eqs. 1.1, for optical signals with pulsewidth greater than 0.1 ps.

Equations 1.1 are numerically solved by the symmetrical split-step method [G. P. Agrawal, *Nonlinear fiber optics*, New York, Academic Press, 1995. J. A. Fleck, J. R. Morris, M. D. Feit, Applied Physics 10, pp.129-160, 1976], undoubtedly the most commonly used and tested method for optical fibers modeling. A constant integration step, chosen by the user, is adopted; the use of adaptive steps in WDM transmission would in fact over-estimate the XPM-induced penalties, by producing asymmetries during the optical signal pulse collisions.

Polarization mode dispersion is modeled by rotating the fiber birefringence axes every L_c meters, the PMD correlation length; the n-th axes rotation is given by [P. K. A. Wai, C. R. Menyuk, H. H. Chen, Optics Letters 16, pp. 1231-1233, Aug. 1991]

$$\begin{bmatrix} A_x' \\ A_y' \end{bmatrix} = \begin{bmatrix} \cos\theta_n & sen\theta_n \exp(i\phi_n) \\ -sen\theta_n \exp(-i\phi_n) & \cos\theta_n \end{bmatrix} \cdot \begin{bmatrix} A_x \\ A_y \end{bmatrix} \quad , \qquad (1.4)$$

with θ_n and ϕ_n random angles with uniform distribution between 0 and 2π. The relation between the fiber PMD [ps/km^0.5] and L_c is

$$PMD = \sqrt{2L_c}(\beta_{1x} - \beta_{1y}) \quad . \qquad (1.5)$$

If a polarization controller is used at the receiver, the optical field is multiplied with the inverse of the Jones matrix, cumulated over the transmission link and centered at the channel wavelength; assuming a system including only consecutive fiber spans, the polarization control is given by

$$\left(\prod_{n=1}^{N_{rot}} Jones(\omega_k, n)\right)^{-1} \cdot \begin{bmatrix} A_x \\ A_y \end{bmatrix} \quad . \qquad (1.6)$$

In eq. 1.6, N_{rot} is the number of birefringence axes rotations along the link, ω_k is the de-multiplexed channel central frequency, and the Jones matrix is given by [A. O. Dal Forno, A. Paradisi, R. Passy, J. P. von der Weid, IEEE Photonics Technology Letters 12, pp. 296-298, 2000]

$$Jones(\omega_k, n) = \begin{bmatrix} \exp\left(i\frac{\Delta\beta_1}{2}(\omega_k - \omega_0)L_c\right) & 0 \\ 0 & \exp\left(-i\frac{\Delta\beta_1}{2}(\omega_k - \omega_0)L_c\right) \end{bmatrix} \cdot \begin{bmatrix} \cos\theta_n & sen\theta_n \exp(i\phi_n) \\ -sen\theta_n \exp(-i\phi_n) & \cos\theta_n \end{bmatrix} \quad , \quad (1.7)$$

with ω_0 the WDM signal central frequency and $\Delta\beta_1 = \beta_{1x} - \beta_{1y}$.
The modeled polarization controller is able to ideally recover the PMD and birefringence axis rotation at the filtered channel central frequency, yet PMD is not ideally recovered at the channel spectrum frequencies different from ω_k.

10.2 Q factor and timing jitter models:

Q factor and timing jitter definitions:

System performance is commonly estimated by the Q factor and the Eye Closure (EC), defined as [D. Marcuse, IEEE Journal of Lightwave Technology 9, pp. 505-513, Apr. 1991]

$$Q = \frac{|m_1 - m_0|}{\sigma_1 + \sigma_0} \quad , \quad (2.1)$$

$$EC = \frac{m_1 - m_0}{min_1 - max_0}$$

with m_i, σ_i (*i*=1,0) the average and standard deviation of the received marks and spaces, min_1 and max_0 the minimum of received marks and the maximum of received spaces respectively, at optimal threshold and sampling instant.
Q factor in decibel units is evaluated as $20 \cdot \log_{10} Q$, eye closure is given by $20 \cdot \log_{10} EC$.
Q factor by eq. 2.1 holds when the noise affecting the received signal can be assumed with Gaussian distribution on both marks and spaces. Under this assumption, bit error rate is given by

$$BER = \frac{1}{2}\mathrm{erfc}\left(\frac{Q}{\sqrt{2}}\right) \approx \frac{1}{\sqrt{2\pi}Q}\exp\left(-\frac{Q^2}{2}\right) \quad . \quad (2.2)$$

When inter-symbol interference (ISI) is present, the Gaussian approximation that brings to eq. 2.1 is no longer valid; Q factors evaluated using eq. 2.1 are in that case under-estimated. If ISI is considerable, a better Q estimate is given evaluating the bit error rate for bits belonging to the same pattern (referring to the central bit of 3-bit patterns); BERs evaluated in this way are not pattern dependent, and the Gaussian approximation assumption is still valid. The overall BER is given by [C. J. Anderson, J. A. Lyle, Electronics Letters 30, pp. 71-72, Jan. 1994]

$$BER = \min_{Ith}\left[\frac{1}{N_{bit}}\sum_{j=1}^{8} N_{patt}(j)\, erfc\left(\frac{m_j - I_{th}}{\sqrt{2}\sigma_j}\right)\right] \quad , \qquad (2.3)$$

with $N_{patt}(j)$ the occurrences for the j-th pattern, $N_{bit} = \sum N_{patt}(j)$ the total number of bits, m_j and σ_j the average and standard deviation for the central bit in the j-th pattern. BER is minimized with respect to the decision threshold I_{th}, and also respect to the sampling instant. Q factor is then evaluated using the inverse of eq. 2.2.

Timing jitter is evaluated taking the instant $t_m(j)$ corresponding to the maximum electrical current in the j-th bit pulse; only transmitted marks are considered. Jitter is defined as the standard deviation of $t_m(j) - t(jT_B)$, being $t(jT_B)$ the sampling instant; it is evaluated on the received electrical current, after the electrical filter.
For NRZ format, timing jitter gives values with no physical sense.

Averaged runs:

If the number of averaged runs in the “Advanced” section is set to a value N_{run}, simulation is repeated for N_{run} runs, and Q factor and rms timing jitter of a transmitted channel are averaged over the repeated runs according to

$$Q_{dB} = 10\log_{10}\left(\frac{1}{N_{run}}\sum_{n=1}^{N_{run}} Q_n^2\right)$$

$$Rms\ jitter = \left[\frac{1}{N_{run}}\sum_{n=1}^{N_{run}} \sigma_n^2\right]^{1/2} \quad , \qquad (2.4)$$

$$Eye\ closure = \left[\frac{1}{N_{run}}\sum_{n=1}^{N_{run}} Eye\ closure^2(n)\right]^{1/2}$$

being σ_n^2 the channel timing jitter variance.
At each run, the noise statistics, the PMD statistics and the transmitted PRBS sequences are changed, in order to average their effects over the repeated runs.
The use of averaged runs permits to perform simulations with reduced computational times, without loss of numerical accuracy.
As will be shown in the next section, by performing a single-run simulation with a number of transmitted bits equal to N_{bit1}, it is given the same accuracy on the Q estimation as by performing N_{run} averaged runs with $N_{bit2} = N_{bit1}/N_{run}$ transmitted bits.
The split-step Fourier algorithm used by the Optolink Numerics requires computation efforts that increase more than linearly with the number of transmitted bits. Thus, simulation involving, for example, 1024 transmitted bits and THz WDM bandwidths may not be feasible

even on a single run, since too much time and CPU resources would be required. On the contrary, the repeated simulation of a smaller number of bits may work properly.
Using averaged runs may scale the overall computational time by several times with respect to a simulations involving a single run and having the same numerical error over the Q factor estimate.

Q factor estimation accuracy:

Using the basic error theory, it may be shown that the Q factor defined by eq. 2.1 has variance

$$Var\left[\hat{Q}\right] \approx \frac{Q^2}{2N_{bit1}} \quad , \qquad (2.5)$$

with N_{bit1} the number of transmitted bits. Considering the Q as a random variable with Gaussian distribution, there is a 95% probability that the relative error on the Q estimation falls into the interval

$$\pm\frac{\Delta Q}{Q} = \pm 2\frac{\sqrt{Var\left[\hat{Q}\right]}}{Q} = \pm\sqrt{\frac{2}{N_{bit1}}} \quad . \qquad (2.6)$$

It is useful to evaluate the relative error for the Q^2 factor, as $Q_{dB} = 10\log_{10}\left(Q^2\right)$; this is given by

$$\pm\frac{\Delta Q^2}{Q^2} = \pm 2\frac{\Delta Q}{Q} = \pm 2\sqrt{\frac{2}{N_{bit1}}} \quad . \qquad (2.7)$$

If averaged runs are used, the Q^2 factor is estimated as

$$\hat{m}_{Q^2} = \frac{1}{N_{run}}\sum_{n=1}^{N_{run}} Q_n^2 \quad , \qquad (2.8)$$

whose variance is

$$Var\left[\hat{m}_{Q^2}\right] = Var\left[\hat{\Psi}_Q^2\right] = \frac{2}{N_{run}}Var\left[\hat{Q}\right]^2 + \frac{4}{N_{run}}Var\left[\hat{Q}\right]E\left[\hat{Q}\right]^2 \quad ; \qquad (2.9)$$

in eq. 2.9 E[ ] is the expectation value, and the squared average definition $\Psi_Q^2 = Var\left[\hat{Q}\right] + E\left[\hat{Q}\right]^2$ has been used. Using eq. 2.5, for a number of bits N_{bit2}, we get

$$Var\left[\hat{m}_{Q^2}\right] \approx \frac{2E\left[\hat{Q}\right]^4}{N_{run}N_{bit2}} \quad . \qquad (2.10)$$

The relative error for the average Q^2 estimation is

$$\pm\frac{\Delta m_{Q^2}}{m_{Q^2}} = \pm 2\frac{\sqrt{Var\left[\hat{m}_{Q^2}\right]}}{m_{Q^2}} \approx \pm 2\frac{\sqrt{Var\left[\hat{m}_{Q^2}\right]}}{m_Q^2} = \pm 2\sqrt{\frac{2}{N_{run}N_{bit2}}} \quad , \qquad (2.11)$$

where we used $m_{Q^2} = \Psi_Q^2 \approx E\left[\hat{Q}\right]^2 = m_Q^2$.

By comparing eqs. 2.7 and 2.11, it results that the same accuracy on the Q^2 estimation is obtained, when the number of transmitted bits is $N_{bit2} = N_{bit1} / N_{run}$.
In fig. 2.1 it is reported an example of back-to-back transmission simulated by Optolink Numerics (the demo file “QvsNrun.olk”). An optical fiber has been used in place of the attenuator, in order to randomly change the state of polarization using the birefringence axis rotation; fiber introduces a 37 dB loss and no dispersion or nonlinearity. Transmitter has 10 Gb/s bit rate, NRZ format, 20 ps rise time, 30 dB extinction ratio. Amplifiers have 0 dBm output power and 6 dB noise figure; receiver includes 40 GHz optical filter of order 1 and 7.5 GHz electrical filter. Received OSNR is 15.0 dB.
Numerical curves correspond to transmitted $N_{bit} = 128$ bit sequences, with $N_{run} = 8$ averaged runs, and to a 1024 bit sequence transmitted only once. Theoretical curve is evaluated according to equations 4.1-4.3 given in “Appendix - Comparison of simulation with theory”, including only the ASE noise contribution.
When varying the initial ASE seed, the Q factor fluctuations in the two cases are comparable, and are contained in a range of approximately +/- 0.4 dB with respect to the theoretical value.

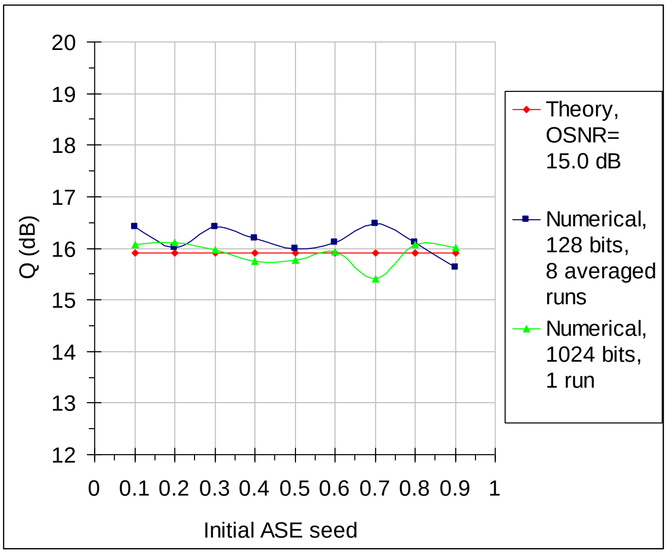


Fig. 2.1

The computational time required for the case of 8 averaged runs with 128 bits has resulted considerably shorter than the case of a single run with 1024 bits.

Differential-phase Q factor:

In Optolink Numerics, it is possible to evaluate performance for phase-modulated systems using the differential-phase Q factor method [X. Wei, X. Liu, C. Xu, IEEE Photonics Technology Letters 15, pp. 1636-1638, Nov. 2003]. By checking the “Use differential phase Q factor” box in “Simulation menu”, Q factor for the phase tributary is evaluated according to the equation

$$Q_{diff} = \frac{\Delta\phi_{diff}}{\sigma_1 + \sigma_0} \quad ; \qquad (2.12)$$

in eq. 2.12, $\Delta\phi_{diff}$ is a differential phase eye opening (rad) selected by the user, σ_1 and σ_0 are the standard deviations for marks and spaces respectively, calculated on the differential phase received eye; this is given by

$$DiffPhase(t) = \left| Arg[A_x(t+T_B)] - Arg[A_x(t)] + Arg[A_y(t+T_B)] - Arg[A_y(t)] \right| , \qquad (2.13)$$

with Arg() the phase (rad) of the optical signal complex amplitudes $A_x(t)$ and $A_y(t)$, for the two polarization components.
Differential phase Q-factor has shown in some DPSK systems a better agreement with the experimental results, if compared to the standard Q evaluation according to eq. 2.1. Conversely, the eye diagram generated using eq. 2.13, is considerably different from the one physically generated by the DPSK receiver. “Optolink Graph Viewer” shows the eye according to eq. 2.13 if differential-phase Q is used.

10.3 The optical amplifier model:

Optolink Numerics uses both power-controlled and gain-controlled models for optical amplifiers. Gain spectrum is supposed to be flat over the simulated bandwidth.
A new feature proposed by Optolink Numerics is the amplifiers Polarization Hole Burning (PHB) model, whose transmission impairments may be considerable in long-haul systems. PHB produces a gain saturation along the signal polarization ellipse major axis, for strongly polarized signals; amplified spontaneous emission thus experiences greater gain along the component orthogonal to the signal.
PHB main effects are an amplifier Polarization Dependent Gain (PDG) and an excess noise along the polarization component orthogonal to the signal.
It is also included a Polarization Dependent Loss (PDL) element at the amplifiers input, that may be produced by amplifier components like the internal isolators, or may model an equivalent PDL generated by in-line elements.
Let $E_{in\,x}$ and $E_{in\,y}$ be the WDM optical field complex amplitudes at the amplifier input, including the optical phases, along the *x* and *y* polarization axes; the input PDL is modeled as

$$E_{1x} = E_{in\,x}$$
$$E_{1y} = \frac{E_{in\,y}}{\sqrt{PDL}} \quad , \qquad (3.1)$$

with $PDL = 10^{(PDL_{dB}/10)}$, PDL_{dB} the selected polarization dependent loss, in dB scale.
PHB is modeled as a polarization dependent gain weighted by the signal State Of Polarization (SOP); this is defined by the Stokes parameters as [E. L. O'Neill, *Introduction to Statistical Optics*, Dover, 1992]

$$S_0 = |E_{1x}|^2 + |E_{1y}|^2$$
$$S_1 = |E_{1x}|^2 - |E_{1y}|^2$$
$$S_2 = E_{1x}E_{1y}^* + E_{1y}E_{1x}^* \quad , \qquad (3.2)$$
$$S_3 = i\left(E_{1x}E_{1y}^* - E_{1y}E_{1x}^*\right)$$
$$SOP = \frac{\sqrt{\langle S_1\rangle^2 + \langle S_2\rangle^2 + \langle S_3\rangle^2}}{\langle S_0\rangle}$$

where < > stands for time averaging.
The angle ψ between the field polarization ellipse major axis and the *x* polarization axis is, with reference to fig. 3.1

$$\psi = \frac{1}{2}\arctan\frac{\langle S_2\rangle}{\langle S_1\rangle} \quad . \qquad (3.3)$$

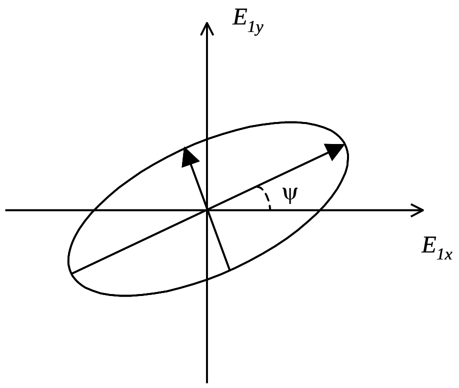


Fig. 3.1

To account for PHB-induced PDG, field is rotated with the major axis along the *x* polarization axis:

$$\begin{bmatrix} E_{2x} \\ E_{2y} \end{bmatrix} = \begin{bmatrix} \cos\psi & \sin\psi \\ -\sin\psi & \cos\psi \end{bmatrix} \begin{bmatrix} E_{1x} \\ E_{1y} \end{bmatrix} \quad , \qquad (3.4)$$

optical field is then amplified with polarization dependent gain, according to

$$E_{3x} = \sqrt{G_x} E_{2x}$$
$$E_{3y} = \sqrt{G_y} E_{2y} \quad ; \qquad (3.5)$$

PHB is introduced by setting [E. Lichtman, IEEE Journal of Lightwave Technology 13, pp. 906-913, May 1995]

$$G_y = G_x G_{PDG} = G_x \cdot 10^{PDG_{dB} \cdot SOP / 10} \quad , \qquad (3.6)$$

with PDG_{dB} the selected polarization dependent gain, in dB scale, weighted by the evaluated field SOP, from eq. 3.2.
Once PDG is introduced, field is anti-rotated by the inverse of eq. 3.4.
In order to have the required amplifier output power P_{out}, gain must satisfy

$$G_x = \frac{P_{out}}{P_{in\,x}\left(\cos^2\psi + G_{PDG}\sin^2\psi\right) + \frac{P_{y\,in}}{PDL}\left(\sin^2\psi + G_{PDG}\cos^2\psi\right) + S_{2\,in}\frac{\sin\psi\cos\psi}{\sqrt{PDL}}\left(1 - G_{PDG}\right)} \quad , \qquad (3.7)$$

with $S_{2in} = E_{in\,x}E^*_{in\,y} + E_{in\,y}E^*_{in\,x}$ and $P_{in\,k} = \left|E_{in\,k}\right|^2$ (*k*=*x*,*y*).
Amplified spontaneous emission noise (ASE) is modeled by adding to the field complex spectrum, suitably normalized independent Gaussian variables; j-th amplifier generates the noise power [D. Marcuse, IEEE Journal of Lightwave Technology 10, pp.273-278, Feb. 1992]

$$N_x(j) = N_{sp} h\nu (G_x - 1)\Delta\nu$$
$$N_y(j) = N_{sp} h\nu (G_y - 1)\Delta\nu \quad , \qquad (3.8)$$

with $N_{sp} = 10^{NF/10}/2$, *NF* the selected noise figure in dB scale, *h* the Plank constant and $\Delta\nu$ the simulated optical bandwidth; noise is added before the optical field is anti-rotated.

10.4 Comparison of simulations with theory:

In the following sections, comparisons are performed among the Optolink Numerics simulations and the most complete theory in the literature. System penalties are evaluated isolating for each case the main causes of impairment, like amplifiers ASE noise, transmitter and receiver limitations, cross phase modulation (XPM) induced signal distortion. Amplifiers PDG effect is also investigated, using the new Optolink Numerics model for polarization hole burning.

Back-to-back case:

For NRZ IM-DD systems comprising only transmitter, loss element, optical amplifier and receiver (i.e. with no dispersion, PMD and nonlinearities), performance penalties are due to the transmitter extinction ratio (supposed with no chirp), the amplifier ASE noise and the receiver dark current, shot and thermal noise. Powers [A^2] for the noise at receiver side are given by [R. C. Steele, G. R. Walker, N. G. Walker, IEEE Photonics Technology Letters 3, pp. 545-547, Jun. 1991]

$$\begin{aligned}
\sigma_{SH\,k}^2 &= 2q\left(RP_k + I_d\right)B_e \\
\sigma_{SIG-SP\,k}^2 &= 4R^2 P_k S_{sp} B_e \\
\sigma_{SH-SP}^2 &= 4qRS_{sp} B_o B_e \qquad (k=0,\ 1); \qquad (4.1) \\
\sigma_{SP-SP}^2 &= 4R^2 S_{sp}^2 B_o B_e \\
\sigma_{TH}^2 &= S_{TH}^2 B_e
\end{aligned}$$

in eqs. 4.1, q is the electron charge, R the PIN photodiode responsivity, I_d the dark current, B_o and B_e the receiver optical bandwidth and electrical cut-off frequency, $S_{sp} = N_{sp} h\nu(G-1)$ the amplifier ASE spectral density, S_{TH} [A/Hz^0.5] the selected thermal noise one-sided spectral density. SH stands for shot noise, SIG-SP is the beating between signal and ASE, SP-SP the ASE-ASE beating, SH-SP the shot noise-ASE beating and TH the thermal noise. Eqs. 4.1 evaluate the receiver noise for both marks (k=1) and spaces (k=0). P_1 and P_0 are the optical powers for transmitted marks and spaces respectively, with

$$P_1 = 2P_{aver}\frac{er}{er+1}, \qquad P_0 = 2P_{aver}\frac{1}{er+1} \qquad (4.2)$$

being *er* the transmitter extinction ratio, in linear scale, and P_{aver} the optical signal average power.
Using eqs. 4.1 and 4.2, theoretical Q factor may be estimated by the

$$Q = \frac{R(P_1 - P_0)}{\sigma_1 + \sigma_0} \qquad . \qquad (4.3)$$

$$\sigma_k = \sqrt{\sigma^2_{SH\,k} + \sigma^2_{SIG-SP\,k} + \sigma^2_{SH-SP} + \sigma^2_{SP-SP} + \sigma^2_{TH}} \qquad (k = 0,1)$$

Back-to-back with ASE noise only:

This first demo simulation shows the effects of ASE noise on NRZ signals, in a back-to-back scheme.
Open file “QvsASE.olk” in “C:\Program Files\Optolink\demos” folder. System parameters represent a 10 Gb/s NRZ system, with 30 dB extinction ratio and 0 dBm power. An optical attenuator is inserted between 2 EDFA amplifiers with variable Att [dB] attenuation; amplifiers are power controlled, with 6 dB noise figure in order to produce the desired ASE noise. Receiver includes a 40 GHz optical Gaussian filter (at the “DeMUX”) and 7.5 GHz electrical Bessel filter; no dark current, no shot and thermal noise are considered; PIN responsivity is *R*=1. OSNR may be varied by changing the attenuation from 28 to 43 dB. Theoretical performance may be evaluated by eqs. 4.1 to 4.3, considering only the SIG-SP and SP-SP noise terms.

Fig. 4.1 shows a comparison of theory and numerical results; simulations were performed using 256 transmitted bits and a single run, both including the 3-bit pattern effects or not (that is the 1-bit patterns case).

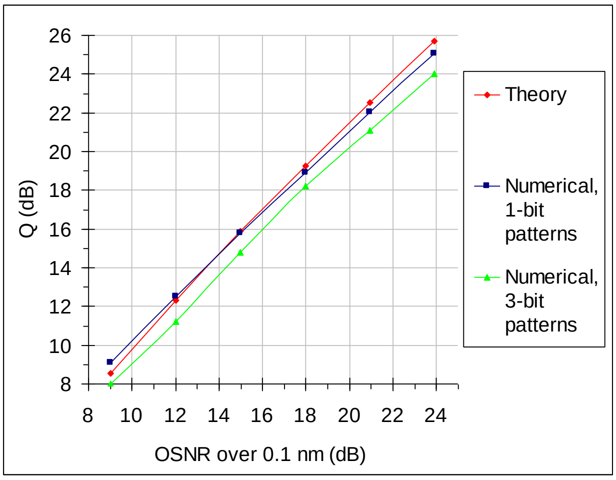


Fig. 4.1

Results with 3-bit patterns show a greater error respect to the theory (they would require a greater number of bits). The numerical error may be reduced using averaged runs or increasing the number of transmitted bits.

Back-to-back with extinction ratio only:

The effects of transmitter extinction ratio on NRZ signals are shown by the “QvsER.olk” demo. System parameters are similar to the previous example, representing a 10 Gb/s NRZ system with variable extinction ratio and 0 dBm power. A 30 dB attenuator is inserted for obtaining the desired OSNR; the receiver pre-amplifier has 6 dB noise figure. Receiver includes a 40 GHz optical Gaussian filter and 7.5 GHz electrical Bessel filter; no dark current, no shot and thermal noise are considered.

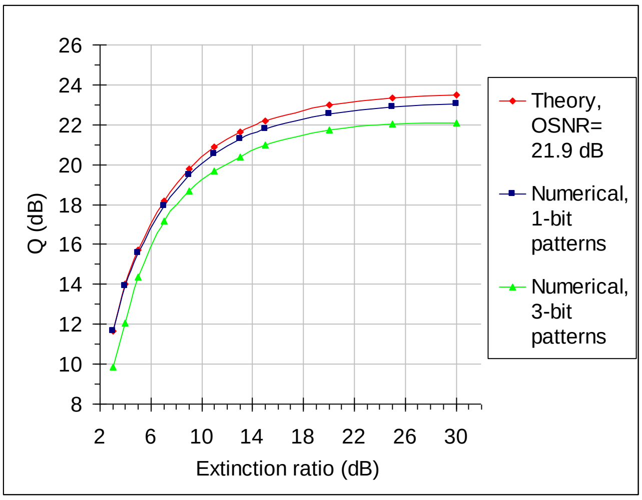


Fig. 4.2

Again, only the SIG-SP and SP-SP noise terms are considered in eqs. 4.1 to 4.3.
Fig 4.2 shows the obtained theory and numerical results, for extinction ratios varied between 3 and 30 dB; 256 transmitted bits and a single run have been used, both including or not the 3-bit pattern effects. Good agreement is obtained, especially in the Q range of interest, between 12 and 18 dB.
Performance starts to fall rapidly for extinction ratios below 14 dB.

Back-to-back with shot noise only:

Open system “QvsSH.olk”; it corresponds to a NRZ transmitter directly linked to a receiver, with no ASE, dark current and thermal noise. In receiver, shot noise box is checked, the used cut-off frequency is 7.5 GHz. Transmitter extinction ratio is 30 dB, i.e. a value producing unimportant penalties, as seen in fig. 4.2.
In order to observe significant shot noise-induced penalties, transmitter optical power must be decreased to values between -47 and -35 dBm.
Theoretical performance is obtained by eqs. 4.1-4.3 including only the SH noise term.
Fig. 4.3 reports a comparison between theory and numerical results, with 256 transmitted bits and 1 run. It is shown that shot noise is substantially negligible for commonly used receiver optical power levels.

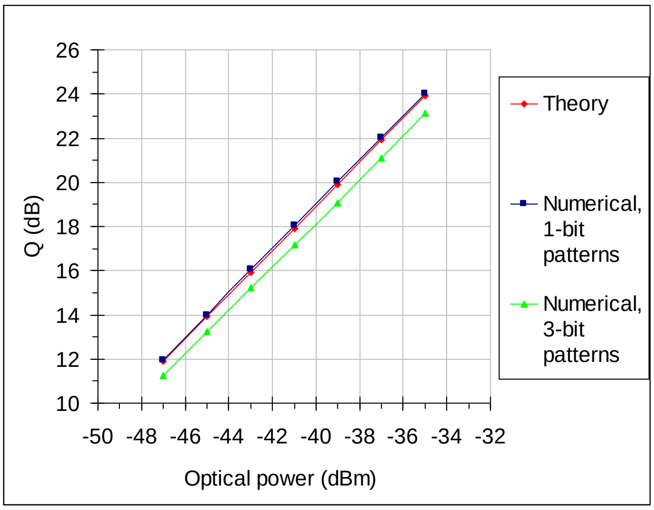


Fig. 4.3

Back-to-back with thermal noise only:

The effects of thermal noise are investigated by the demo “QvsTH.olk”; system has no ASE noise, no shot noise and dark current. Transmitter power is set to 0 dBm, and extinction ratio is 30 dB. Receiver electrical cut-off frequency is 7.5 GHz. Thermal noise one-sided spectral density may be varied between 10e-10 and 24e-10 A/Hz^0.5 to obtain relevant penalties. Theory eqs. 4.1-4.3 are used including the TH noise term only. Results are shown in fig. 4.4, together with 256 bits single-run numerical simulations.
Since thermal spectral densities for commonly used receivers are of the order of 1e-11 A/Hz^0.5, thermal noise also is usually negligible.

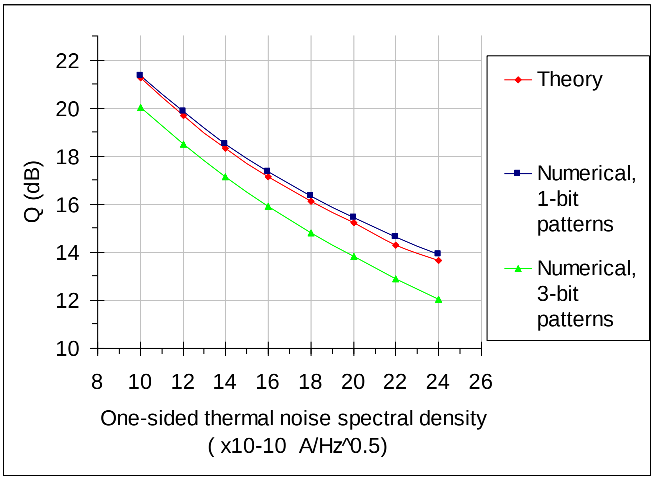


Fig. 4.4

Amplifiers Polarization Hole Burning (PHB):

Demo file "QvsPDG_WDM.olk" investigates the effects of amplifiers PHB-induced polarization dependent gain (PDG) in long-haul systems.
A last generation submarine system is considered, with 50 km long dispersion map, composed by 30 km of Pure Silica Fiber followed by 20 km of low-loss Dispersion Compensating Fiber. Transmission line is composed by 126 amplified dispersion maps, for a total distance of 6300 km.
Transmitted channels have Carrier-Suppressed Return to Zero format (CS-RZ), with Gaussian shape and 40 ps pulsewidth; power per channel is -6 dBm; bit rate is 10.66 Gb/s, accounting for a Forward Error Correction (FEC) overhead. Ten channels are multiplexed with 0.2 nm spacing, with 1550 nm central wavelength; input filtering by the multiplexer is substantially negligible.
In order to have approximately solitonic transmission for all channels, an optimal channel-by-channel pre-compensation is inserted , with dispersion given by $-800-30\cdot(\lambda_j-1550)$ [ps/nm], with λ_j the j-th channel wavelength [nm].
Amplifiers have 4 dBm output power, 4 dB noise figure and variable PDG.
At receiver side, channels are de-multiplexed by a 12.5 GHz Gaussian filter, and an 8 GHz electrical Bessel filter is used; shot and thermal noise are included. Optimal post-compensation is in the range -200 to 200 ps/nm.
Three cases are considered in order to evaluate the impact of amplifiers PDG: co-polarized channels at input, cross-polarized or multiplexed with random state of polarizations.
Performance is evaluated on 64 bit sequences, with 6 averaged runs, not including 3-bit pattern effects.
Fig. 4.5 reports the Q factor averaged among channels # 1, to 10 for several amplifiers PDG values. According to the PDG model implemented in Optolink Numerics, system with cross-polarized channels at input (i.e. with strongly de-polarized WDM signal) is the less sensitive to PHB, with only a 0.2 dB average Q penalty at PDG=2.0 dB. At the same PDG value, channels randomly polarized at input are affected by a 0.7 dB penalty; co-polarized channels have 0.9 dB, because WDM signal is strongly polarized at input. Reduced penalties have been observed because of the random birefringence introduced by the fibers.

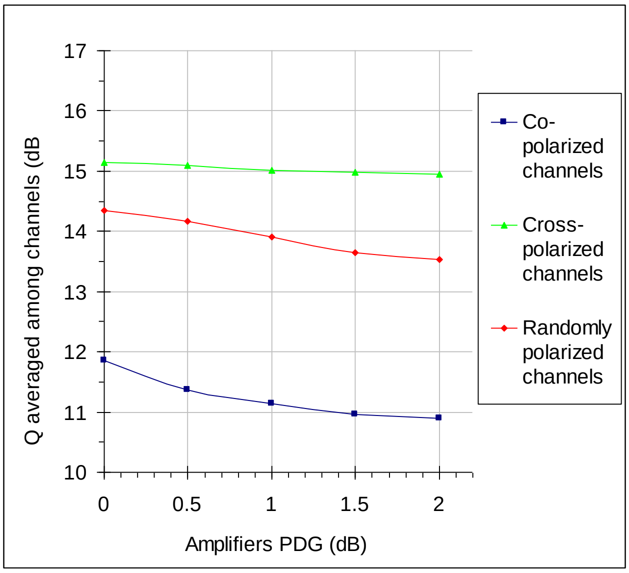


Fig. 4.5

It is also noteworthy the effect of linear cross-talk between channels in the co-polarized case, and of cross phase modulation (XPM) and four wave mixing (FWM) in the three cases; for co-polarized channels, Kerr nonlinear cross effects have higher efficiency than in the cross-polarized case. When no PDG is present a 3.2 penalty is observed in the co-polarized case respect to the cross-polarized; in the random polarization case penalty is reduced to 0.7 dB.

Cross Phase Modulation (XPM) penalty:

An important feature for WDM systems simulators is the proper estimate of cross phase modulation (XPM) impairments, due to intensity noise and timing jitter generated by the collisions among channels; XPM is usually the main source of penalty in modern WDM optical systems.
Demo file “QvsXPM_WDM.olk” shows the effects of XPM on a typical long-haul terrestrial system, with an 82.5 km dispersion map composed by 80 km of Non-Zero Dispersion Shifted fiber, and by 2.5 km of Dispersion Compensating Fiber with partial slope compensation. Amplifiers are inserted at the input of both fibers; power at DCF input is 8 dB smaller than at NZ-DSF input, in order to reduce the nonlinearity and have equal gain for all amplifiers. Transmission line is composed by 6 dispersion maps, for a distance of 495 km. An optimal pre-compensation of -400 ps/nm is inserted for all transmitted channels; a 32 dB loss is also added at input to get a realistic OSNR at output; the required post-compensation is around 0-100 ps/nm.
Channels have NRZ format at 10 Gb/s, with 40 ps rise time, 15 dB extinction ratio, 0.4 nm spacing and are multiplexed with parallel polarizations.
PMD and birefringence are excluded (setting L_c to 1000 km and PMD=0), in order to increase the collisions effects and directly compare the numerical results with the theory.
At receiver side, channels are de-multiplexed by a 25 GHz Gaussian filter, and a 7.5 GHz electrical Bessel filter; shot noise, thermal noise and dark current are not included.
Theory used for comparison [G. Bellotti, M. Varani, C. Francia, A. Bononi, IEEE Photonics Technology Letters 10, pp. 1745-1747, Dec. 1998] is able to predict the XPM-induced intensity noise of modulated systems, constituted by multiple amplifiers and an arbitrary sequence of fibers. Assuming a scalar case (i.e. co-polarized channels, no PMD and birefringence) the XPM-induced intensity noise over a probe channel, assumed as a continuous wave, by a modulated interfering channel is evaluated as

$$\frac{\Delta P_{XPM}(\omega)}{P_{pr}} = P_{sig}(0,\omega)\sum_{k=1}^{M} C_{sig}^{(k)} H_{XPM}^{(k)}(\omega)$$

$$C_{sig}^{(k)} = \prod_{i=1}^{k-1} \exp\left[\left(-\alpha_i + j\omega d_i\right)l_i\right]G_i$$

$$H_{XPM}^{(k)}(\omega) = -2\gamma_k\, j\exp\left(j\frac{\lambda^2}{4\pi c}D_r^{(k)}\omega^2\right)\frac{1-\exp\left(-\alpha_k + j\left(d_k\omega - \frac{\lambda^2}{4\pi c}D_k\omega^2\right)\right)L_k}{\alpha_k - j\left(d_k\omega - \frac{\lambda^2}{4\pi c}D_k\omega^2\right)} + \quad ;$$

$$+2\gamma_k\, j\exp\left(-j\frac{\lambda^2}{4\pi c}D_r^{(k)}\omega^2\right)\frac{1-\exp\left(-\alpha_k + j\left(d_k\omega + \frac{\lambda^2}{4\pi c}D_k\omega^2\right)\right)L_k}{\alpha_k - j\left(d_k\omega + \frac{\lambda^2}{4\pi c}D_k\omega^2\right)} \tag{4.4}$$

in eqs. 4.4, the parameters $l_k, D_k, \alpha_k, \gamma_k$ are the k-th fiber span length, dispersion, attenuation and nonlinear parameter, $d_k = D_k\left(\lambda_{sig} - \lambda_{pr}\right)$ is the walk-off parameter between the interfering signal and the probe, *M* the number of amplified spans, $D_r^{(k)} = \sum_{i=k}^{M} D_i l_i$ the accumulated dispersion from the k-th fiber to the end of the link, $L_k = \sum_{i=1}^{k-1} l_i$, G_k the gain for the k-th fiber amplifier, P_{pr} the probe signal average power, $P_s(0,\omega)$ the interfering channel power spectrum at input and $\Delta P_{XPM}(\omega)$ the evaluated intensity noise power spectrum. XPM-induced noise by several interfering channels is obtained adding the noise terms evaluated for each channel.

Eqs. 4.4 have been applied to the investigated system, assuming as input interfering channels several NRZ modulated signals at 10 Gb/s and with 40 ps rise time; the resulting optical field in time domain, $P_{pr}\left(1 + \Delta P_{XPM}(t)\right)$, is a continuous wave affected by XPM-induced noise whose standard deviation is σ_{XPM} [W].

In order to evaluate the system performance, σ_{XPM} is added to the noise terms for the marks in eqs. 4.1-4.3, i.e. to the σ_1 standard deviation. This is done because the XPM-induced noise may be considered as an intensity modulation over the signal marks. ASE noise is also included choosing an equivalent gain *G*=32.5 dB, to have the same OSNR as in simulations. The shot and thermal noise terms are neglected.

Fig. 4.6 shows the Q factor vs. the number of transmitted channels, at 3 different channel powers; Q is always given for the central WDM channel. Numerical performance is evaluated on 64 bit sequences, with 6 averaged runs, not including the 3-bit pattern effects.

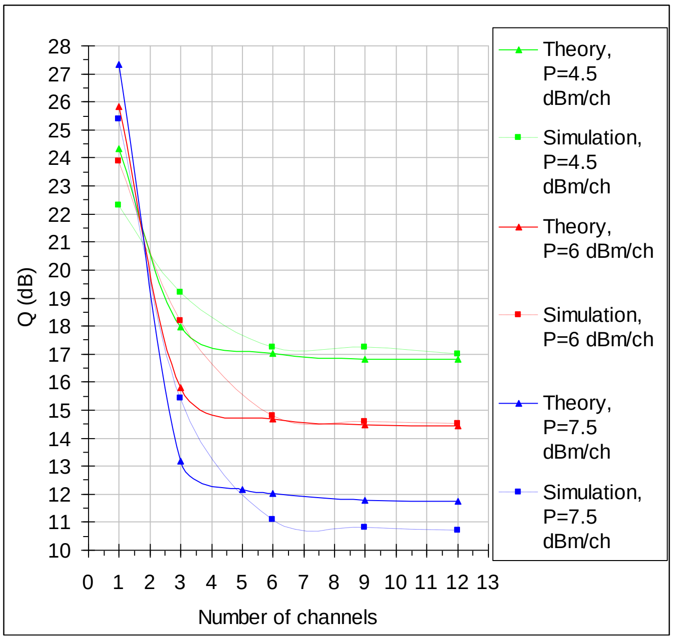


Fig. 4.6

Dotted lines represent the simulated Q factors for the central channel; solid lines are evaluated theoretically.
A good agreement with the theory has been observed for power levels of interest in system design, i.e. for XPM penalties up to 10 dB. For higher power (7.5 dBm/ch), other nonlinear effects arise, like FWM and timing jitter induced by the XPM itself, which are not taken into account by the theory.
Fig. 4.7 gives the evaluated Q vs. post-compensation, for a 6 channel system at 7.5 dBm/ch; it is shown how central channels are affected by XPM more than the external channels. Fig. 4.8 is the transmitted eye for ch. 3 at optimal post-compensation, showing a strong intensity noise and timing jitter.
In fig. 4.7 it is also clear the importance of performing a post-compensation sweep to correctly evaluate the optimal transmitted performance on a channel-by-channel basis.

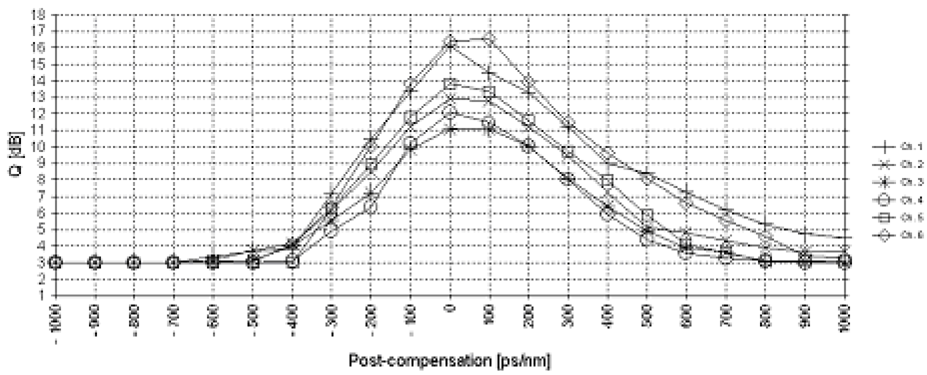


Fig. 4.7

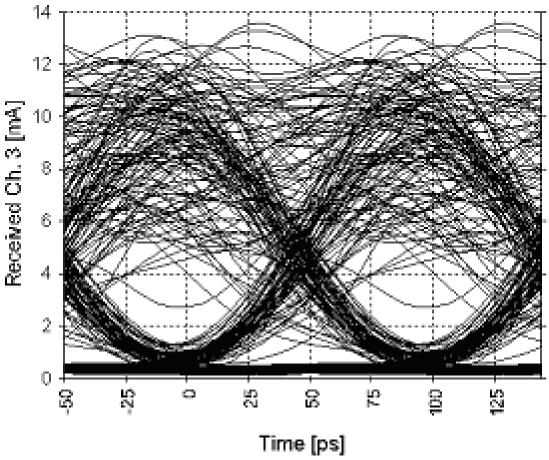


Fig. 4.8

Optical solitons with Raman nonlinearity:

Solitonic transmission is a good example for testing the Kerr and Raman nonlinearity models, because a complete theory is available. Traditional solitons in uniform dispersion systems are generated by the balancing of a positive frequency chirp, produced by the Kerr nonlinearity, and a negative chirp due to the anomalous group velocity dispersion of the transmission fiber. In the ideal case of a fiber with no loss, optical solitons are pulses with sech shape and peak power given by [G. P. Agrawal, *Fiber Optics Communications Systems*, Wiley, NY, 1992]

$$P_0 = \frac{|\beta_2|}{\gamma T_0^2} \quad , \tag{4.5}$$

where β_2 is the dispersion parameter from eq. 1.3, $\gamma = n_2\omega_0/(cA_{eff})$ is the nonlinear parameter and $T_0 = T_{FWHM}/1.763$ a measure of the pulsewidth. When pulses are launched in a fiber with the proper power, its time and frequency shape is conserved through unlimited distances, therefore producing improved performance.

Raman nonlinearity typically produces a red shift on the transmitted spectrum (Stimulated Raman Scattering, SRS). In WDM case, optical power is transferred from channels at lower to the ones at higher wavelength. In single-channel solitonic case, the signal is able to conserve its original shape in frequency, and the optical spectrum central frequency is red-shifted during transmission (Raman Self-Frequency Shift), according to [P. V. Mamyshev, *Optical Solitons - Theory and Experiment*, Edited by J. R. Taylor, Cambridge University Press, pp. 286, 1992]

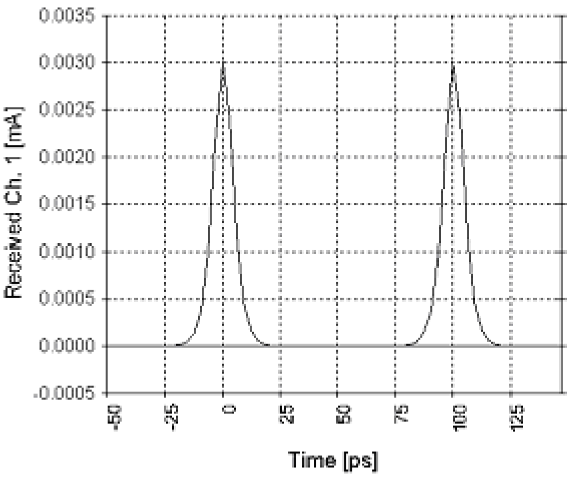
$$\frac{d\omega_0}{dz} = -\frac{8}{15} T_R \frac{|\beta_2|}{T_0^4} \quad , \tag{4.6}$$

with T_R the molecular Raman delay time; correspondingly, a time delay is experienced by soliton pulses in the anomalous dispersion fiber, given by

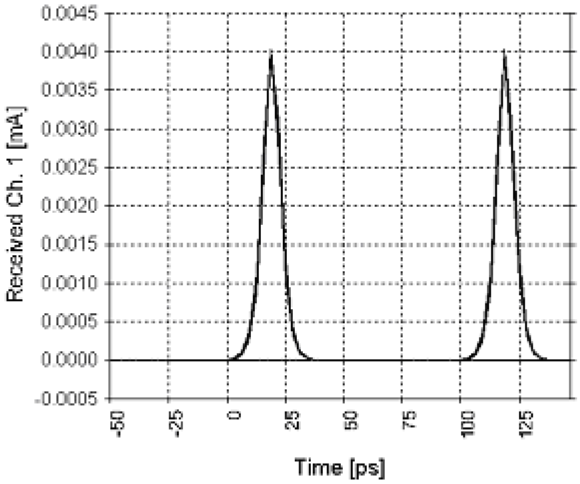
$$\Delta t_R(z) = \frac{4}{15} T_R \frac{\beta_2^2}{T_0^4} z^2 \quad . \tag{4.7}$$

Demo file “Kerr_Raman.olk” investigates the effects of Raman nonlinearity in ideal solitonic transmission. Fibers with D=2 ps/nm/km are used with no loss, 40 μm^2 effective area and 5 fs Raman delay time; soliton pulses with 10 ps width are transmitted at 10 Gbit/s, with power corresponding to eq. 4.5; due to the high power used, a 20 m step is necessary to avoid numerical error; several receivers are used with 1000 GHz cut-off frequency and a 40 dB split ratio, in order to observe the received optical power at 0, 1500, 2000 and 2500 km transmission distance.
Figs. 4.9 shows the received eyes at 3 distances; eyes correspond to the optical power, because a very large bandwidth receiver has been used. Kerr nonlinearity perfectly balances the cumulated dispersion, therefore no post-compensation is required and the initial solitonic shape is conserved. According to eq. 4.7, pulses delay due to Raman nonlinearity is 19.0, and 52.8 ps for distances z=1500 and 2500 km respectively; this agrees with 10% accuracy to the observed numerical delays in the figure.

z=0 km:



z=1500 km:



z=2500 km:

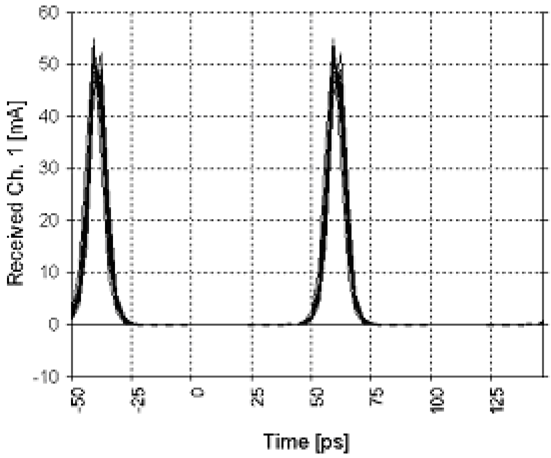


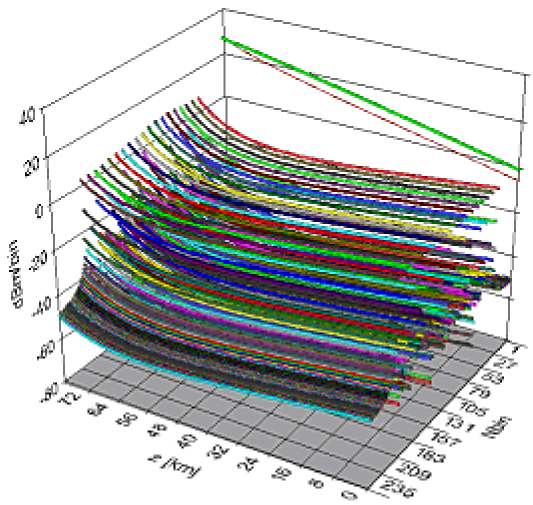
Fig. 4.9

10.5 *Other demos*

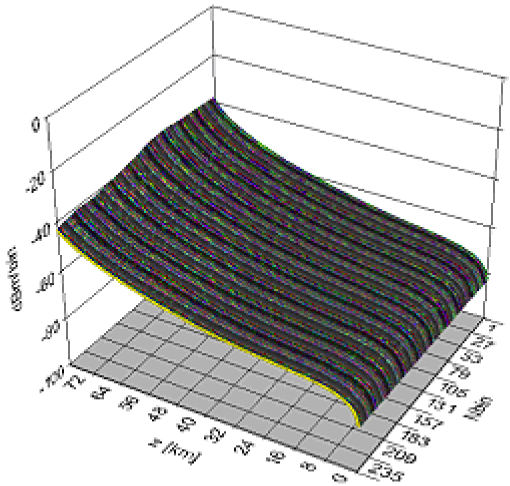
In directory “C:\Program files\Optolink\demos” several other demos are stored by way of example on the components usage. A summary description is given here.

Fiber with Raman gain:

Demo file “RamanFiber.olk” illustrates the behavior of a Raman fiber (“RamFiber”) component with 2 high power counter-propagating pumps; the example is reported for comparison from [X. Liu, B. Lee, Opt. Expr. 11, pp. 1452-1461, Jun. 03]. 19 signal channels are transmitted with 1.6 nm channel spacing between 1558.8 and 1587.6 nm and 0 dBm/ch power, over a 80 km SMF span; 2 counter-propagating pumps at 1455 and 1475 nm are applied, with 500 mW power each. Peak Raman gain is $g_{rp} = 0.8 \times 10^{-13}$ m/W and attenuation for signals and pumps are respectively 0.2 and 0.35 dB/km. 4 simulation runs are performed with 64 transmitted bit patterns.
Fig. 5.1 shows the calculated power/bin (a) for pumps and signal bins (see the “RamFiber” component for details) and the generated ASE power (b) over the fiber length.



a)



b)

Fig. 5.1

Multimodal fiber:

File “MMFiber.olk” shows an example of optical LAN simulation, consisting in the physical layer of a Gigabit Ethernet network. 4 wavelengths are transmitted at 3.125 Gb/s and 10 dB extinction ratio each, using directly modulated lasers; transmission wavelength is around 1310 nm. A 62/125 multimodal fiber is used with DMD impulse response read from file (modal bandwidth is 130 MHz km). Simulation shows performance degradations for transmission distances over 100 m, mostly due to modal dispersion.

Free-space optics link:

File “FSOptics.olk” reports a typical high power free-space optics system transmitting at the rate of 1 Gb/s in urban area. A directly modulated laser at 1550 nm is boosted by an EDFA amplifier; beam is transmitted over a 3 km free-space link with urban aerosol, 5 km visibility and 2 mm/hr rain. Receiver is affected by thermal noise with $2\times10^{-10}\ A/\sqrt{Hz}$ spectral density. Received signal is still unaffected by the thermal noise after 3 km transmission, while it would become very noisy after 5 km transmission.
Example is also given of the estimated channel availability for an aerosol and rain attenuation of 10.4 dB.

DPSK transmitters:

Demo file “TX_DPSKvsModul.olk” shows a comparison between DPSK signals generated by the “TX, DPSK” component, those generated by a “Modulator, dual-drive” in push-pull configuration and those from a “Modulator, phase”.
“TX, DPSK” transmits a 10 Gb/s signal with CW amplitude and NRZ phase, 20 ps rise time and 180° amplitude for the phase modulation.
“Modul_dd” is driven by a 10 Gb/s NRZ electrical signal with 0 V and 1 V levels, and 20 ps rise time; the “Differential pre-encoding” option must be checked in order to properly evaluate the performance at the DPSK receiver. At the second input the same signal is applied, with 0 V and –1 V levels; this is obtained using a second driver at 10 Gb/s with 0 V offset and 1.0E-20 V amplitude (corresponding to a ≈0 V constant signal), and subtracting to it the NRZ electrical signal. Inversion voltage for the modulator is also 1 V; in this configuration, dual-drive modulator acts as a phase modulator, generating a CW amplitude with NRZ phase.
“Modul_ph” is driven by a 10 Gb/s NRZ signal with levels 0 V and 1 V, and 20 ps rise time; modulator inversion voltage is also 1 V.
An optical fiber is used as a lossy element with birefringence, in order to show the functionality of the DPSK receiver with any incoming state of polarization.
A “RX, PhIM” receiver is used, in order to show the received eye for the amplitude also.
If the “Use differential phase Q factor” is selected in “Simulation menu”, differential-phase eyes will be displayed instead of the “physical” ones; obtained Q factors and eyes show that not always the differential phase Q method is acceptable for performance evaluation.

Duobinary transmitter:

Demo file “TX_Duobinary.olk” gives an example of a low-pass filter duobinary transmitter at 10 Gbit/s. A dual-drive modulator and two Bessel filter with 2.8 GHz cut-off frequency are used to generate the proper signal; a common IM-DD receiver is also used. The “Evaluate Performance” component shows the multilevel drivers eye. Duobinary is tested vs. uncompensated SMF fiber span length.

Custom components:

Demo file “CustomPhaseConjug.olk” is an example on the use of custom optical components. An RZ-DPSK signal at 10 Gb/s is transmitted in back-to-back configuration (“Optical Fiber” is used to add a random birefringence); at receiver side, signal is displayed with and without the use of a custom optical phase conjugator. Custom “Parameter 1” sets the insertion loss (dB). The component is simulated by the executable “C:\Program files\Optolink\demos\custom\CustomPhaseConjug\CustmPhaseConjug.exe”, compiled in Visual Basic language; the source code is reported here by way of example:

```
‘ Start of code

Private Sub Form_Load()

Dim Param(1 To 14), DeltaT, Temp1, Temp2, Temp3, Temp4, InsLoss As Double
Dim Tau, Npoints As Long
Dim ReAx(), ImAx(), ReAy(), ImAy() As Double
Dim sFile As String
```

```
' Reads the command line parameter (directory for files)
 sFile = TrimCommandLine(Command())

' Reads Parameters file
 Open Trim(sFile) & "Parameters.dat" For Input As #1
 For j = 1 To 14
    Input #1, Param(j)
 Next
 Input #1, Npoints
 Input #1, DeltaT
 Close (1)

 ' Reads the input optical field files
 ReDim ReAx(1 To Npoints)
 ReDim ImAx(1 To Npoints)
 ReDim ReAy(1 To Npoints)
 ReDim ImAy(1 To Npoints)
 Open Trim(sFile) & "Ax.dat" For Input As #1
 For j = 1 To Npoints
    Input #1, ReAx(j), ImAx(j)
 Next
 Close (1)
 Open Trim(sFile) & "Ay.dat" For Input As #1
 For j = 1 To Npoints
    Input #1, ReAy(j), ImAy(j)
 Next
 Close (1)

 ' Elaborates the optical fields (phase conjugation)
 InsLoss = 10# ^ (Param(1) / 20#)
 For j = 1 To Npoints
  ReAx(j) = ReAx(j) / InsLoss
  ImAx(j) = -ImAx(j) / InsLoss
  ReAy(j) = ReAy(j) / InsLoss
  ImAy(j) = -ImAy(j) / InsLoss
 Next

 ' Writes the output optical fields
 Open Trim(sFile) & "Ax.dat" For Output As #1
 For j = 1 To Npoints
    Write #1, ReAx(j), ImAx(j)
 Next
 Close (1)
 Open Trim(sFile) & "Ay.dat" For Output As #1
 For j = 1 To Npoints
    Write #1, ReAy(j), ImAy(j)
 Next
 Close (1)

 Unload Me

End Sub


Function TrimCommandLine(CommString As String) As String

   Dim C, CmdLnLen, InArg, i, NumArgs, MaxArgs
```

```
  Dim ArgArray As String
  NumArgs = 0
  MaxArgs = 250
  InArg = False
  ArgArray = ""
  'Get command line arguments.
  CmdLnLen = Len(CommString)
  'Go thru command line one character at a time.
  For i = 1 To CmdLnLen
    C = Mid(CommString, i, 1)
      'Concatenate character to current argument.
      NumArgs = NumArgs + 1
      ArgArray = ArgArray & C
      If NumArgs = MaxArgs Then Exit For
  Next i
  'Return Array in Function name.
  TrimCommandLine = Trim(ArgArray)

End Function

‘ End of code
```

Code must be pasted into a Visual Basic form and compiled as standard .exe.
Received optical field after the custom component shows conjugated optical phase, and attenuation due to the insertion loss.
Optical signal-to-noise ratio may be not correctly evaluated after a custom component, if it introduces some losses.

Custom filters:

Demo file “OpFilter_WDM.olk” shows how custom in-line filters can be used to implement optical amplifiers with arbitrary gain spectra. Transmission system dispersion map is composed by an 80 km NZ-DSF fiber span, compensated by a 2.5 km span of DCF fiber; EDFA amplifiers are inserted at fiber inputs. An “OpFilter” component is used together with the first amplifier to add a linear gain tilt at the amplifier output; this is generated by the custom filter stored in “C:\Program files\Optolink\demos\custom\OpFilter_WDM\CustomFilter.dat”. Filter transfer function may be checked using “Optolink Graph Viewer”, by selecting the filter in the “DeMUX” component.
Six channels with RZ format are transmitted with 0.4 nm channel spacing; after 6 dispersion map repetitions, gain tilt increases the power of channels 1, 2 and 3, causing considerable nonlinear impairments in the form of intensity noise. Received Q factors are 13.4, 15.2, 15.8, 20.3, 19.4 and 20.8 dB for channel 1 to 6 respectively.
The impairments may be reduced in two ways:

- Inserting a second user-defined in-line filter as a Gain Flattening Filter (GFF).
- Adding a power pre-emphasis at input to balance the gain wavelength dependence.

This second method can be tested by setting in the “WDM menu” a pre-emphasis of –2.5, -2, -1.5, 0, 0 and 0 dB for channels 1 to 6 respectively; received Q factors in this way are equalized between 16.2 and 17.8 dB for all channels. Fig. 5.2 shows the received spectra without (upper figure) and with pre-emphasis (lower figure).

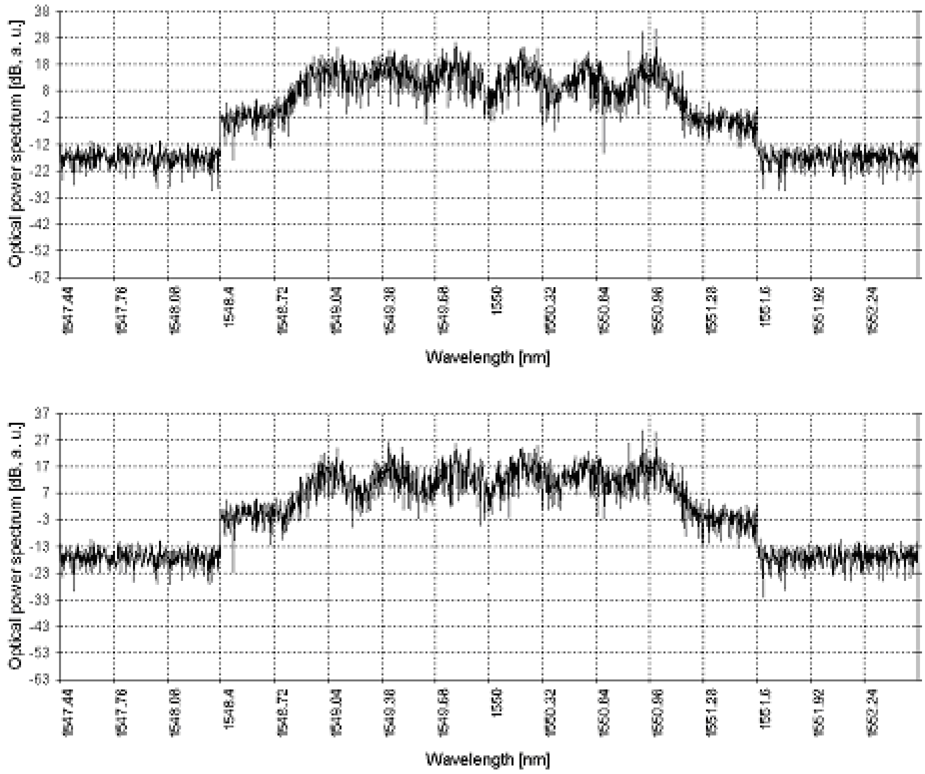


Fig. 5.2

Custom receivers:

Demo file “CustomRX.olk” shows a DPSK receiver scheme alternative to the “RX, DPSK”. An “Optical Splitter”, a 100 ps optical delay (at 10 Gb/s bit rate), a “Polarization Combiner” with 45° polarizer angle and a “Polarization Splitter” are used to generate the optical fields

$$\begin{array}{l}\frac{1}{2}\left[A_x(t)+A_x(t-\Delta t)\right]\\ \frac{1}{2}\left[A_x(t)-A_x(t-\Delta t)\right]\end{array}, \qquad (5.1)$$

with $A_x(t)$ the output field at the splitter. Eq. 5.1 corresponds to the optical field generated by a Mach-Zehnder delay-and-add interferometer; when the two fields are revealed by two photodiodes in differential configuration, the optical differential phase is revealed.

11. Appendix: The PhIM format

Dark pulse and bright pulse Phase and Intensity Modulation (PhIM) are two new, patent pending modulation formats (US 10/732,404 and US 10/345,244), belonging to the class of orthogonal ASK-DPSK signals. In both cases an amplitude and a phase tributary are independently modulated in a same optical signal, doubling the transport capacity with a modest increase in the optical bandwidth, and with no need to reduce the modulators extinction ratio.
At the receiver, the optical signal is sent to a common intensity receiver and a DPSK receiver for the detection of the optical intensity and the phase. The generated photocurrents for the intensity and the phase are respectively, neglecting the noise terms:

$$I_A(t) = -R_{PIN}\left\{\left|E_x(t)\right|^2 + \left|E_y(t)\right|^2\right\}$$
$$I_\phi(t) = -R_{PIN}\left\{\mathrm{Re}\left[E_x(t)E_x^*(t-T_B)\right] + \mathrm{Re}\left[E_y(t)E_y^*(t-T_B)\right]\right\} \qquad (1)$$

with R_{PIN} the PIN responsivity, E_x and E_y the optical field to the intensity or the phase receiver, and T_B the tributary bit time slot. Electrical front-ends with cut-off frequency comparable with *R* are also used in the receivers. In eqs. 1, an electrical polarity inversion is included; this is needed both for graphical and for decoding reasons, as will be clear later.

Dark Pulse PhIM

PhIM format using dark pulses has been described in detail in [M. Zitelli, “Optical phase and intensity modulation using dark pulses”, *IEEE Photon. Technol. Lett.*, vol 16, pp. 1972-1974, Aug. 2004.]. With reference to Fig. 1, intensity modulation generates a coded dark pulse sequence with bit rate *R* (Gb/s), representative of a first Amplitude Tributary (Fig. 1a); if $T_B = 1/R$ is the tributary bit time slot, the bit time portion $T_B - \Delta t$ between one bit and the following is characterized by having nearly unperturbed optical power (power always recovers to the maximum value). A phase modulation with bit rate *R*, representative of a second Phase Tributary, is added to the dark pulse sequence using the unperturbed bit time portion, i.e. the optical phase level in the time interval $T_B - \Delta t$ shall be 0 or $\Delta\phi \le \pi$. The phase tributary is delayed by half bit time slot respect to the amplitude tributary; it may have NRZ format (Fig. 1b), or upward and downward impulses respect to an average value (Fig. 1c). The optical phase is generally encoded using the common DPSK format, thus requiring a differential pre-encoding for the phase tributary.

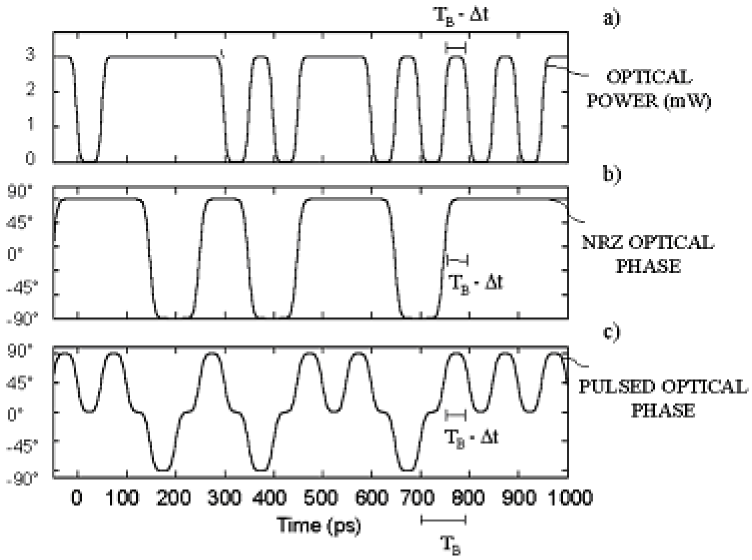


Fig. 1. Example of transmitted PhIM optical signal with *R*=10 Gb/s: a) optical power; b) optical phase with NRZ format; c) optical phase with pulsed format. Phase code is delayed by half bit-slot respect to the dark pulse code.

Fig. 2 shows a possible scheme for a dark pulse PhIM transmission system. Transmitter includes one intensity and one phase modulator with electrical bandwidth comparable with *R* (GHz). The electrical driving signal V_A for the intensity modulator must be of pulsed type, and may be generated by an AND operation between a first electrical tributary with NRZ format and a clock (Fig. 2b); an optical dark pulse is then generated in correspondence of a driver impulse. The phase modulator is driven by a second electrical tributary V_ϕ with NRZ format, or with positive and negative impulses respect to an average value; in this second case, the driving circuit may be the one in Fig. 2c; the generated optical phase is proportional to the phase driver. Electrical delay lines τ_A and τ_ϕ or flip-flop gates can be used to properly synchronize the intensity and the phase modulation, with the required half bit-slot delay. Signal is transmitted with arbitrary state of polarization (SOP).

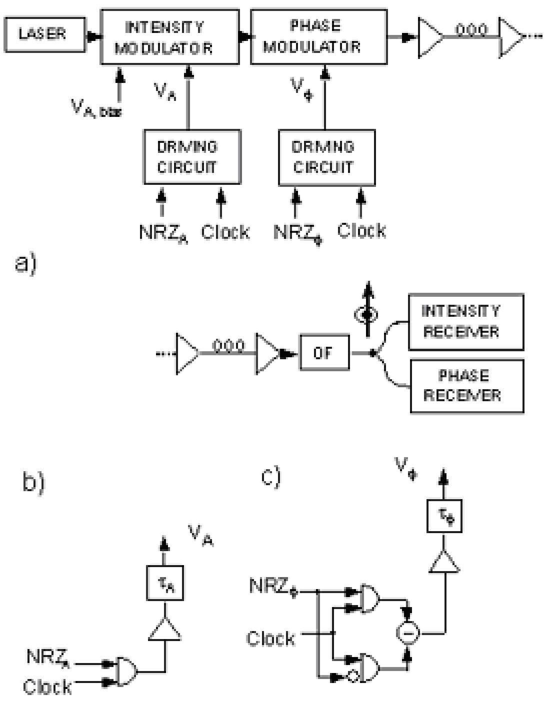


Fig. 2

A simplified transmitter is by the way possible, requiring a single optical modulator with dual drive design, that generates both the orthogonal amplitude and phase modulations. Dual drive modulator with a finite extinction ratio is modeled here using eq. 7 in [S. Walklin, J. Conradi, "Multilevel signaling for increasing the reach of 10 Gb/s lightwave systems," *IEEE J. Lightwave Technol.*, vol. 17, pp. 2235-2247, Nov. 1999.]; if NRZ_A and NRZ_ϕ are the normalized electrical amplitude and phase tributaries and V_π is the modulator inversion voltage, both the amplitude and phase optical signals are generated applying to the modulator the driving voltages $V_1(t)$ and $V_2(t)$ obtained as

$$\begin{aligned}
d_A(t) &= NRZ_A(t) \oplus d_A(t-T_B) \\
b_\phi(t) &= NRZ_A(t) \oplus NRZ_\phi(t) \\
d_\phi(t) &= b_\phi(t) \oplus d_\phi(t-T_B) \\
V_A(t) &= d_A(t) \cdot V_\pi \\
V_\phi(t) &= d_\phi(t) \cdot V_\pi - V_\pi/2 \\
V_1(t) &= V_A(t) + V_\phi(t) \\
V_2(t) &= -V_A(t) + V_\phi(t)
\end{aligned} \quad . \qquad (2)$$

The corresponding transmitter scheme is shown in Fig. 3. The electrical amplitude tributary is differentially pre-encoded in order to produce fast transitions around the modulator zero transmission point, i.e. optical dark pulses, in correspondence of a

tributary mark; this method also produces π phase jumps at each generated optical dark pulse. The phase tributary performs an XOR operation with the amplitude tributary in order to subtract the π phase jumps to the phase modulation; optical signal thus results also phase modulated by a signal proportional to NRZ_ϕ, which is differentially pre-encoded to produce a DPSK code. Driving signals $V_1(t)$ and $V_2(t)$ are obtained as the sum and the difference of the elaborated tributaries, producing orthogonal amplitude and phase terms into the modulator transfer function. The two buffers in Fig. 3 are needed to produce the desired voltage levels to the modulator; the upper buffer is also used to delay the amplitude tributary by an amount equivalent to one logic gate, in order to recover the input synchronization between tributaries; buffers may be replaced by clocked gates.
The generated optical signal is similar to the one shown in Fig. 1, with a NRZ optical phase. Fig. 5b shows an example of received eyes (left: amplitude, right: phase tributary) at 2x42.7 Gb/s. Both the eyes show polarity-inverted currents; this is needed for the amplitude tributary to recover the logical conjugation produced by the dark pulses, while for the phase it is used just for graphical purposes; amplified spontaneous emission (ASE) noise is visible in the lower levels of the amplitude tributary.

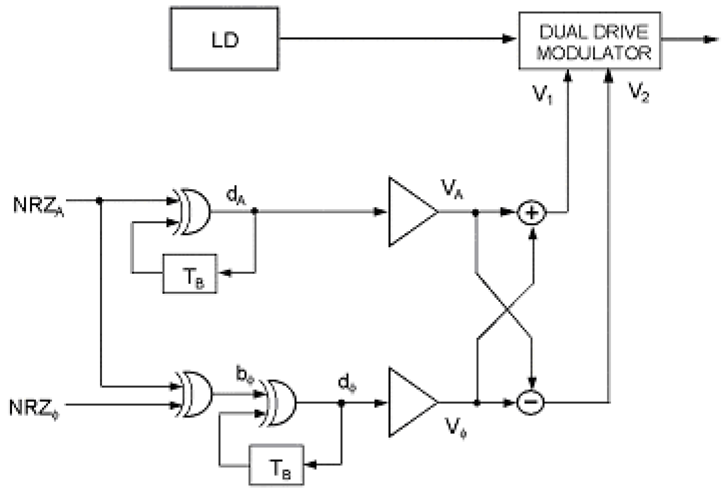


Fig. 3. Dark pulse PhIM transmitter scheme. LD is the laser diode.

Bright Pulse PhIM

PhIM using bright pulses is implemented as the polarization interleaving of a return-to-zero (RZ) signal and a return-to-zero differential phase shift-keying (RZ-DPSK) signal. As shown in Fig. 4, a shaper modulator is needed to generate a pulse train that is split in two portions; the former is intensity modulated by the amplitude tributary NRZ_A, the latter is phase modulated by a differentially pre-encoded phase tributary NRZ_ϕ and is delayed by half bit slot before being polarization multiplexed with the RZ signal. The ratio s between the RZ and the RZ-DPSK pulses peak power should preferably fall between 1 and 2 (an optimal value of 1.5 is found later).

The basic advantage of bright pulse PhIM respect to other polarization-interleaved signals is that a polarization controller is not needed at the receiver (the receiver scheme is identical to the one for dark pulse PhIM). In terms of received amplitude tributary, this feature is explained observing that the received optical power eye is formed by a central RZ-like shape, added to two smaller side lobes representing the DPSK signal pulses; once the overall signal is detected and electrically filtered, a received eye like the example shown in the left Fig. 5c is obtained, for any received state of polarization (SOP). Electrical polarity has been inverted in the figure for graphical reasons; in this case a logically conjugated NRZ_A at the transmitter is needed. ASE noise is visible in the lower eye levels. In terms of received phase tributary, the RZ signal does not contribute to the received DPSK eye, because it adds a constant phase to the signal; phase eye thus shows the phase information carried only by the RZ-DPSK signal independently on the received SOP; the DPSK detector produces a received eye like the one shown in right Fig. 5c, where polarity is also inverted for graphical purposes.

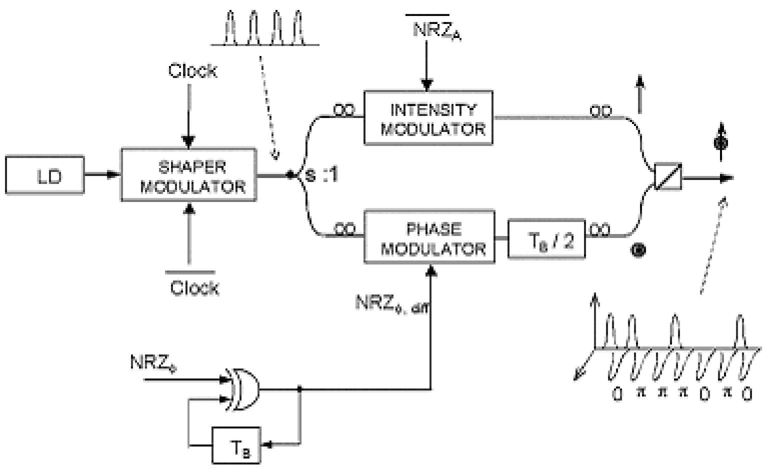


Fig. 4. Bright pulse PhIM transmitter scheme. An output signal is shown by way of example.

Numerical Results

Numerical simulations have been performed using Optolink Numerics, making a direct comparison between pulsed PhIM and the common NRZ format. Three cases have been considered, with optimized parameters:

i) NRZ optical signal at 85.4 Gb/s bit rate, i.e. including a forward error correction (FEC) overhead; signal has 15 dB extinction ratio and 5.8 ps rise and fall times (equal to half the bit time slot), corresponding to 57 GHz cut-off frequency for the modulator and the transmitter electronics. At the receiver, a PIN photodiode and a front-end with 70 GHz cut-off frequency are used.

ii) Dark pulse PhIM at $2\times R = 85.4$ Gb/s capacity, and $R = 42.7$ Gb/s tributary bit rate; the dual drive modulator scheme is used; extinction ratio is 15 dB and optimal rise and fall times for both the amplitude and phase are found to be 14 ps (60% the bit time slot), corresponding to electronics with 24 GHz cut-off frequency at the transmitter. Both the intensity receiver and the DPSK balanced detector have 35 GHz cut-off front-ends.

iii) Bright pulse PhIM at $2 \times R = 85.4$ Gb/s; the pulse train has 7.8 ps full-width at half-maximum (33% duty cycle); an optimal value for the the split ratio is *s*=1.5; the intensity data modulator has 15 dB extinction ratio; the phase modulator is with linear response and π phase modulation amplitude; the intensity and DPSK receivers have 35 GHz cut-off front-ends.

Fig. 5a shows the transmitted spectra for cases i) (left), ii) (middle) and iii) (right). Fig. 5b represents the received eyes (left: amplitude, right: phase tributary) for case ii) with large optical filtering and with ASE noise. Fig. 5c gives the received eyes in case iii).

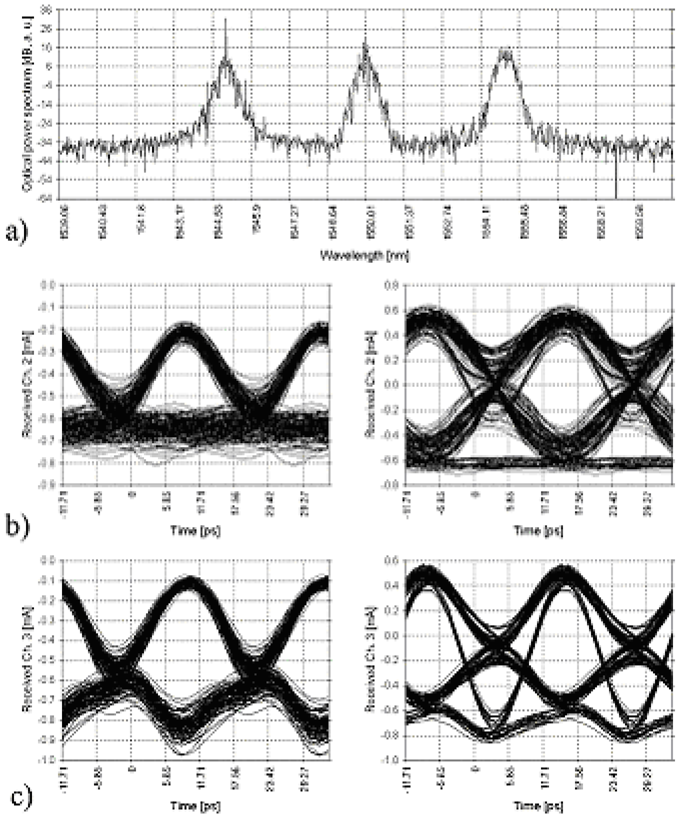


Fig. 5. a): transmitted spectra for the 3 cases described in the text. b): received amplitude (left) and phase (right) eyes for dark pulse PhIM. c): received amplitude (left) and phase (right) eyes for bright pulse PhIM.

A back-to-back test has been performed in the 3 cases, simulating a transmission line composed by a lossy and birefringent element between two erbium doped fiber amplifiers (EDFAs); birefringence is used to produce a random output SOP. At the receiver, a 2nd order Gaussian optical filter is used with 300 GHz bandwidth. Fig. 6a shows the obtained Q factors vs. OSNR for the NRZ signal and for the amplitude and phase tributaries of the pulsed PhIMs. In the following, the worse result between amplitude and phase will be considered for the comparison with the NRZ; Gaussian approximation has been used to evaluate the Q. At Q=10 dB (corresponding to approximately a BER=10^{-9} when FEC is considered) the sensitivity for dark pulse PhIM is reduced by 2.2 dB respect to NRZ, while for bright pulse PhIM it is on the contrary increased by 1.2 dB.

Tolerance to CD is tested using a linear dispersive element in place of the lossy element; again birefringence is used, and no ASE noise is included. Fig. 6b shows the eye closure penalty (ECP, the eye closure is defined as the ratio between the average and the minimum eye opening) vs. CD: the 1 dB penalty for cases i), ii) and iii) is obtained at –10 to 10, –14 to 14, –20 to 20 ps/nm respectively.

Tolerance to DGD is simulated rotating the transmitted polarization by 45° and introducing a delay between the two principal states of polarization. Fig. 6c shows 1 dB penalty for cases i), ii) and iii) at 6.5, 8 and 4.5 ps respectively, and 5 dB penalty at 10, 16.5 and 12.5 ps. Bright pulse PhIM has lower tolerance respect to dark pulse because it is a polarization interleaved format.

WDM behavior is simulated transmitting 3 channels for each case, with variable channel spacing. Channels are multiplexed with orthogonal polarizations, and a birefringent line with no loss is used to generate a random output SOP. De-multiplexing optical filter is a 2nd order Gaussian with bandwidth equal to 75% the channel spacing. Fig. 6d gives the obtained ECP for the middle channel vs. channel spacing. Cases i), ii) and iii) experience a 1 dB penalty at 145, 120 and 100 GHz respectively, showing the possibility to transmit pulsed PhIM with spectral efficiencies over 0.8 bit/s/Hz.

Numerical results show that dark pulse PhIM presents significant advantages respect to NRZ in terms of DGD tolerance and spectral efficiency; transmitter in Fig. 3 requires a single dual drive modulator and electronics with cut-off frequency around $0.55 \cdot R$, while the required NRZ modulator bandwidth is over $1.3 \cdot R$; receiver sensitivity is on the contrary reduced by 2.2 dB. Bright pulse PhIM shows improved tolerances to CD, greater spectral efficiency and increased sensitivity by 1.2 dB respect to NRZ; conversely it requires two modulators and a shaper with cut-off frequencies comparable to *R*.

Dark pulse PhIM is compatible with the polarization domain multiplexing (PDM) technique.

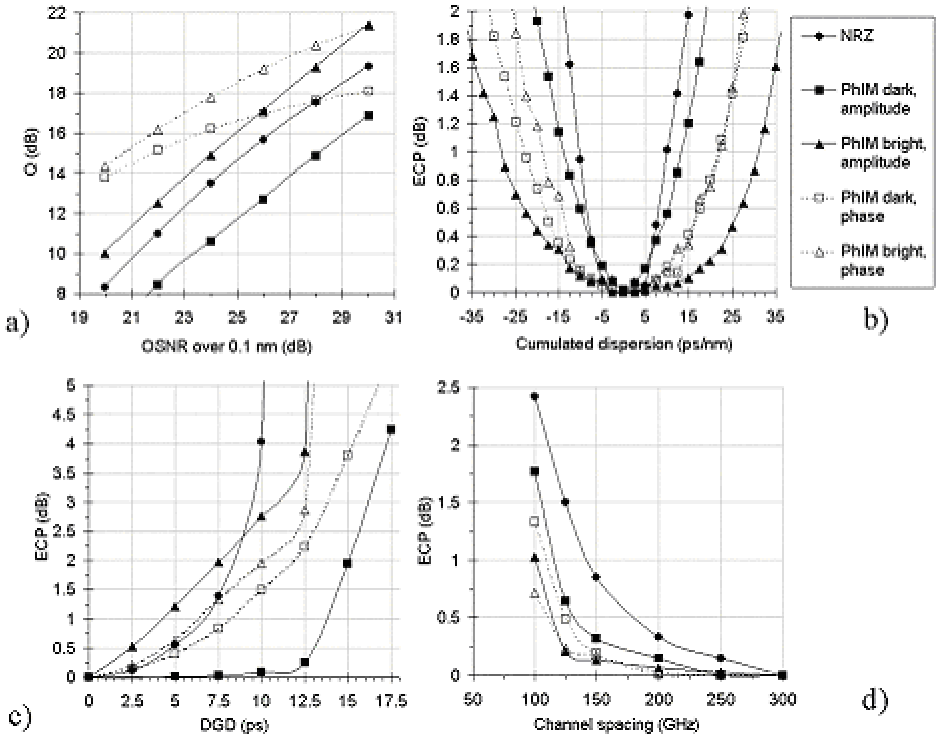


Fig. 6. a): Q factor vs. OSNR in the 3 cases described in the text. b): eye closure penalty vs. cumulated dispersion. c): eye closure penalty vs. DGD. d): eye closure penalty vs. channel spacing in WDM transmission.

In Optolink Numerics, phase tributary has differential encoding, and phase receiver is of DPSK type. The PRBS electrical sequences used for the phase encoding are then pre-encoded by an XOR operation, according to the

$$PRBSdiff\,(t) = PRBSdiff\,(t - T_B) \oplus PRBS(t)\ , \qquad (3)$$

with *PRBS(t)* a pseudo-random sequence with equal number of marks and spaces and uniformly distributed 3-bit patterns.
The phase receiver used in Optolink Numerics is of DPSK type, with an electrical polarity inversion at the output. A possible scheme is shown in Fig. 7.

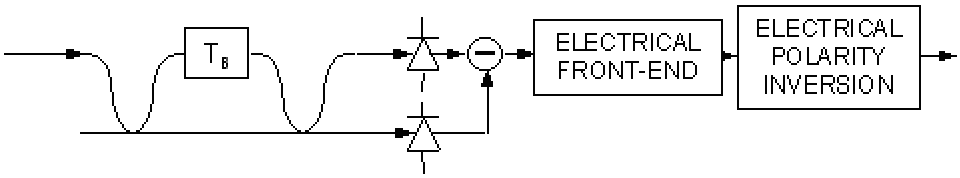


Fig. 7

Optolink Numerics uses a polarization independent DPSK phase receiver, modeled by the generated photocurrent

$$I_{\phi}(t) = -R_{PIN}\left\{\mathrm{Re}\left[E_x(t)E_x^*(t-T_{Arm})\right] + \mathrm{Re}\left[E_y(t)E_y^*(t-T_{Arm})\right]\right\} \quad , \qquad (4)$$

with R_{PIN} the PIN responsivity, E_x and E_y the optical field to the phase receiver, and T_{Arm} the delay in one arm of the receiver interferometer; DPSK usually works with $T_{Arm} = T_B$, the tributary bit-time slot.
Any circuit implementing eq. 4 works as a DPSK receiver, with no need for a polarization controller. The generated photocurrent is then passed through the electrical filter specified by the user. Performance is evaluated on the phase tributary eyes in the same way as for the amplitude tributary or the IM-DD format.