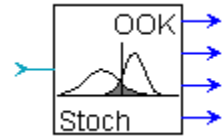




BER_OOK_Stoch

BER Estimation (Chi2 or Gaussian Assumption, using Logical Channel)



Purpose

This module estimates the error probability, or bit error ratio (BER) in digital direct detection optical transmission systems. The Q-factor, effective Q-factor and absolute decision threshold used to perform the calculations are also output. The estimation can be performed assuming Gaussian or Chi-squared (χ^2) statistics for the optical beat noise. Post-detection thermal noise, shot noise, and intersymbol interference (ISI) can also be taken into account within the module.

The module uses the bit sequence contained in a specified logical channel to determine the marks and spaces in the received signal.

Keywords

Error Ratio, BER, Stochastic, Chi-squared, Gaussian, Noise, Instrumentation.

Inputs

input = Electrical signal input
(signal type: *ElectricalBlocks*)

Outputs

ber = Output BER estimate
(signal type: *Float*)

q = Output Q-factor estimate
(signal type: *Float*)

threshold = Output absolute decision threshold
(signal type: *Float*)

q_eff = Output effective Q-factor estimate
(signal type: *Float*)

Physical Parameters

Name and Description	Symbol	Unit	Type	Volatile	Value Range	Default Value
EstimationMethod Specifies the method used for BER estimation.	-	-	enum	yes	Gauss, Gauss_ISI, Chi2, Chi2_ISI	Gauss

ISI_Prebites Specifies the number of bits preceding the current bit to be considered in the ISI calculation. (context sensitive)	-	-	int	yes	[0, 16]	1
ISI_Postbits Specifies the number of bits following the current bit to be considered in the ISI calculation. (context sensitive)	-	-	int	yes	[0, 16]	1
SampleType Specifies the method used to determine the sampling instant.	-	-	enum	yes	Optimum, Relative	Optimum
SampleTime For SampleType = Relative, specifies the sampling instant as a fraction of the bit period. (context sensitive)	t_s	-	float	yes	[0, 1[0.5
SampleRange For SampleType = Relative, specifies the sampling range as a fraction of the bit period. (context sensitive)	-	-	float	yes	[0, 2[0
ThresholdType Specifies the method used to calculate the decision threshold.	-	-	enum	yes	Optimum, Relative, Absolute	Optimum
Threshold For ThresholdType = Relative, specifies the decision threshold as a fraction of the difference between the mean one and zero levels. For ThresholdType = Absolute, specifies the decision threshold current in ampere. (context sensitive)	D	-	float	yes	-	1.0e-3
DetectorType Specifies the type of detector used in receiver, either PIN or APD	-	-	enum	yes	PIN, APD	PIN
DarkCurrent For DetectorType = PIN specifies the value of dark current to be added to the input photocurrent. (context sensitive)	i_d	A	float	yes	[0, ∞ [0.0
DarkCurrentMult For DetectorType = APD specifies part of the internally generated photocurrent when there is no light incident upon the photodiode. This current is multiplied by the avalanche gain. (context sensitive)	i_{dm}	A	float	yes	[0, ∞ [0.0
DarkCurrentNonMult For DetectorType = APD specifies part of the internally generated photocurrent when there is no light incident upon the photodiode. This current is NOT multiplied by the avalanche gain. (context sensitive)	i_{dnm}	A	float	yes	[0, ∞ [0.0
AvalancheMult For DetectorType = APD specifies the avalanche multiplication factor. The photocurrent and DarkCurrentMult are multiplied by this factor. (context sensitive)	M	-	float	yes	[0, ∞ [1.0
IonizationCoefficient For DetectorType = APD is used to calculate excess shot noise during avalanche multiplication. (context sensitive)	k	-	float	yes	[1e-3, 1]	1.0
IncludeShotNoise Specifies whether shot noise should be added. (context sensitive)	-	-	enum	yes	No, Yes	Yes
ThermalNoise Specifies the power spectral density of additive Gaussian noise.	S_{th}	$\frac{A}{\sqrt{Hz}}$	float	yes	[0, ∞ [10.0e-12
ElecNoiseBandwidth Equivalent electrical noise bandwidth of the receiver (as determined by the post-detection 'noise limiting' filter). Used to calculate the total additive noise variance due to shot and thermal noise sources.	B_e	Hz	float	yes	[0, ∞ [10.0e9

Enhanced Parameters

Name and Description	Symbol	Unit	Type	Volatile	Value Range	Default Value
ChannelLabel The label of the logical channel on the electrical signal input containing the original transmitted bit sequence.	-	-	string	yes	-	-
ChannelIndex The index of the logical channel on the electrical signal input containing the original transmitted bit sequence. A value of -1 specifies that the logical channel with the highest index should be used.	-	-	int	yes]-∞,∞[-1
IgnoreBits Allows a group of consecutive bits to be excluded from the calculation of BER. Settings are: include all bits in the calculation (IgnoreBits = No); ignore bits only once in a multiple-block run (IgnoreBits = ApplyOnce); or ignore bits in every block of a multiple-block run (IgnoreBits = Repeat).	-	-	enum	no	No, ApplyOnce, Repeat	No
StartTimeToIgnore Specifies the start time of the group of bits to exclude from the calculation of BER, if IgnoreBits = ApplyOnce or IgnoreBits = Repeat. (context sensitive)	-	s	float	no	[0,∞[0.0
NumberOfBitsToIgnore Specifies the number of bits to exclude from the calculation of BER, if IgnoreBits = ApplyOnce or IgnoreBits = Repeat. (context sensitive)	-	-	int	no	[0,∞[0
MultipleBlockMode In IndependentBlocks mode, a new BER calculation is performed for each input block received in a multiple-block simulation. In AccumulateOverBlocks mode, statistics are accumulated over all blocks received, and cumulative values are output after each block.	-	-	enum	no	IndependentBlocks, AccumulateOverBlocks	IndependentBlocks
VisualizationMode Defines whether simulation result is displayed after simulation automatically, or is stored and can be visualized later by demand, or is not generated at all.	-	-	enum	yes	StartAutomatically, StartOnDemand, None	None
Title Title used to identify internal visualizer plots.	-	-	string	yes	-	-
BERvsSampeTime Defines whether to select BER vs. sample time for visualization.	-	-	enum	yes	On, Off	Off
BERvsThreshold Defines whether to select BER vs. threshold for visualization.	-	-	enum	yes	On, Off	Off
QvsSampeTime Defines whether to select Q value vs. sample time for visualization.	-	-	enum	yes	On, Off	Off
EyeOpeningvsSampeTime Defines whether to select Eyeopening vs. sample time for visualization.	-	-	enum	yes	On, Off	Off
PDFs Defines whether to select PDFs for visualization.	-	-	enum	yes	On, Off	Off
Active Defines if the module is active or not.	-	-	enum	yes	On, Off	On

Description

The *BER_OOK_Stoch* module combines stochastic and deterministic approaches for BER estimation. The variance of the detected optical beat noise, and the mean values of 'one' and 'zero' signals are determined from the statistics of the input signal. The variance of post-detection electrical noise can be either calculated deterministically from the user-specified power density and electrical bandwidth of the receiver, or taken into account stochastically by including them into the input electrical signal. In the

latter case, the results will only be correct for the Gaussian estimation method.

The *BER_StochasticNoRef* module estimates the BER of the incoming electrical signal by using either a Gaussian approximation, or a Chi-squared fitting procedure. It can account for the influence of ISI in either case. The estimation method is set by the **EstimationMethod** parameter. The Chi-squared fit is valid when the dominant noise processes are signal-spontaneous beat noise, and spontaneous-spontaneous beat noise generated when an optical signal accompanied by optical spontaneous emission noise is received. However, if the input contains significant noise contributions from other sources, such as shot noise or post-detection electrical noise, then the statistics of the input samples may deviate from the χ^2 distribution, in which case a more reliable estimate of the BER may be obtained using conventional Gaussian approximation.

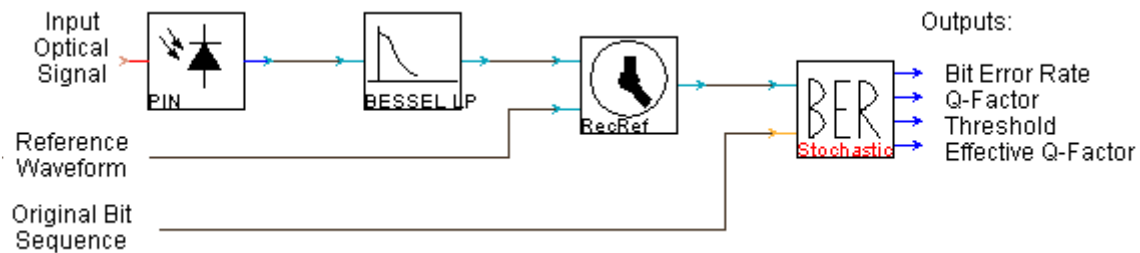


Figure 1. Schematic illustrating a typical application of the *BER_OOK_Stoch* module

[Figure 1](#) shows a schematic illustrating a typical application of the *BER_OOK_Stoch* module. When the Input Optical Signal contains significant optical noise, such as amplified spontaneous emission (ASE) noise introduced in optical amplifiers, the *BER_OOK_Stoch* module can be used to calculate estimates of the BER that are superior to those obtained using conventional Gaussian approximation methods. To ensure that the optical beat noise components are dominant at the input of the *BER_OOK_Stoch* module, thermal noise, dark current and shot noise of the receiver should be specified in the *BER_OOK_Stoch* module and set to zero in the photodetector.

For example, in the setup shown in [Figure 1](#), the PIN photodiode should be configured with **ThermalNoise** = 0.0, **DarkCurrent** = 0.0 and **ShotNoise** = OFF. These quantities should instead be specified using the corresponding **ThermalNoise**, **DarkCurrent** and **IncludeShotNoise** parameters of the *BER_OOK_Stoch* module. Analogously, if an APD is used as the photodetector, then it should be configured with **ThermalNoise** = 0.0, **DarkCurrentMult** = 0.0, **DarkCurrentNonMult** = 0.0, **IonizationCoefficient** = 1.0, **ShotNoise** = OFF. All these quantities should be specified in the corresponding parameters of the *BER_OOK_Stoch* module. The avalanche multiplication factor should be specified in both *BER_OOK_Stoch* and the photodetector. That is, the **AvalancheMult** parameters of *BER_OOK_Stoch* and APD should both be set to the same value. Additionally, the **ElecNoiseBandwidth** parameter should be set equal to the bandwidth of the low pass filter used in the setup of [Figure 1](#). In such configurations, the *BER_OOK_Stoch* module incorporates the effects of the post-detection noise processes into the BER estimate using deterministic rather than statistical methods.

The method used to include the effects of thermal noise and shot noise depends upon the analysis method chosen. When performing a Gaussian analysis, the variances corresponding to these parameters are simply added to the variances estimated for the incoming samples. When performing a χ^2 analysis, the parameters of the χ^2 fit are first estimated from the incoming samples. Then the overall non-Gaussian probability density functions are calculated, including the contributions from the Gaussian thermal noise and a Gaussian approximation of the shot noise. Finally, the probabilities of error for data 'ones' and 'zeros' are computed from the probability density functions. Further details are provided below in the [Theory](#) section.

Important: The χ^2 analysis uses several numerical approximations when performing the BER calculation. These approximations are extremely accurate in most cases, and significantly improve the speed and efficiency of the algorithms. However, they are not valid at very high values of BER, on the order of 10^{-2} and above. Therefore calculated BER values that are in this range should not be

considered to be precise. This limitation is not very restrictive in practice, because such high values of BER are in any case unacceptable in a real system.

Theory

In this section:

[BER Calculation](#)
 [\$\chi^2\$ Analysis](#)
[Gaussian Analysis](#)
[Calculation of Post-Detection Noise Variance](#)
[Q-factor Calculation](#)
[Calculation of Effective Q-factor](#)
[Calculation of Eye-Opening](#)
[Taking into account intersymbol interference \(ISI\)](#)
[Other Parameters and Features](#)

BER Calculation

The overall probability of error is calculated as:

$$(1) \quad BER = P_0 P_{0/1} + P_1 P_{1/0}$$

where:

P_1 is the probability of receiving a 'one' bit.

P_0 is the probability of receiving a 'zero' bit.

$P_{0/1}$ is the probability of deciding that a received bit is 'zero' when actually a 'one' was sent.

$P_{1/0}$ is the probability of deciding that a received bit is 'one' when actually a 'zero' was sent.

The probabilities P_1 and P_0 are calculated from the transmitted bit sequence (supplied at the bits input) according to:

$$(2) \quad P_1 = \frac{n_1}{n_1 + n_0}, \quad P_0 = \frac{n_0}{n_1 + n_0}$$

where n_1 and n_0 are the number of 'one' and 'zero' bits sent, respectively.

To calculate the conditional error probabilities $P_{0/1}$ and $P_{1/0}$ the probability density functions W_0 and W_1 of the 'one' and 'zero' signal levels must be known, as well as the decision threshold D . The conditional error probabilities are then obtained by integrating the density functions from the decision threshold according to:

$$(3) \quad P_{0/1} = \int_{-\infty}^D W_1(x) dx$$

$$(4) \quad P_{1/0} = \int_D^{\infty} W_0(x) dx$$

The exact method used to obtain the density functions W_0 and W_1 depends upon the analysis method used, i.e., either χ^2 or Gaussian, as described in greater detail in the following sections.

χ^2 Analysis

It is well known that in a baseband, direct-detection optical communications system, the statistics of a received optical signal accompanied by optical noise (such as ASE noise from optical amplifiers) are non-Gaussian [1]. In fact, since the total optical field in this case consists of a signal field accompanied by a noise field with Gaussian-distributed amplitude, the statistics of the electrical current after square law detection will follow one of a family of χ^2 probability densities. This probability density function will be affected also by the process of electrical low-pass filtering that typically follows detection. In the special case of the ideal integrate-and-dump receiver (where the filtering action is performed by the integrator), it has been established that the statistics of the electrical signal retain the χ^2 form [1],[5]. It is therefore reasonable to assume that in a wide range of receiver configurations, in which the ideal integrate-and-dump system is approximated by a low pass filter followed by a sampling circuit, a χ^2 model for the received optical beat noise statistics will be more suitable than the common Gaussian approximation. This assumption is the basis of the χ^2 analysis method employed in this module.

The general non-central χ^2 probability density function representing a detected optical signal accompanied by optical noise can be fully described by three parameters [5]: the non-centrality parameter, the number of degrees of freedom, and a scaling factor. If post-detection Gaussian noise is also included, the resulting distribution is a "hybrid" which can be obtained mathematically by convolving the χ^2 distribution of the detected signal with the Gaussian distribution of the post-detection noise. This distribution can be fully described by the addition of a fourth parameter, namely the variance of the Gaussian noise. Numerical means are available to calculate this hybrid distribution, and the resulting error probabilities [2], however all four parameters must be known in order to employ these methods. In principle, standard techniques such as the Method of Moments can be used to estimate the parameters, however in practice it is necessary to simulate an excessively large number of bits in order to obtain good estimates.

For this reason, the *BER_OOK_Stoch* module employs more efficient methods to estimate the parameters of the probability density functions, and to calculate the error probabilities. In order to reduce the number of unknown parameters to only three (those of the χ^2 distribution), it is assumed that the input signal does not contain any additive post-detection Gaussian noise. Instead, the BER is estimated by a two-step process:

1. The three parameters of the non-central χ^2 distribution are estimated by performing a statistical analysis of the input signal samples. A separate analysis is performed for 'one' and 'zero' bits in the received bit sequence.
2. The probability density functions $W_0(x)$ and $W_1(x)$, and the corresponding error probabilities $P_{1/0}$ and $P_{0/1}$ are then computed, including the effect of post-detection noise processes (as described

below), using the numerical methods described in [2].

The noise processes are defined depending on the type of the photodetector used. For both APD and PIN detector types, the parameters **ThermalNoise**, **IncludeShotNoise** and **ElecNoiseBandwidth** should be specified. The latter defines the equivalent noise bandwidth of the post-detection electrical filter. For the PIN photodetector, the **DarkCurrent** parameter should be additionally specified. In case of the APD photodetector, the **AvalancheMult**, **DarkCurrentMult**, **DarkCurrentNonMult** and **IonizationCoefficient** parameters should be specified.

To avoid including the noise processes twice (that would invalidate the results produced by the *BER_OOK_Stoch* module), the photodetector module used in combination with the *BER_OOK_Stoch* module should be configured as follows:

The PIN photodetector: **ThermalNoise** = 0.0; **DarkCurrent** = 0.0; **ShotNoise** = OFF.

The APD photodetector: **DarkCurrentMult** = 0.0; **DarkCurrentNonMult** = 0.0; **IonizationCoefficient** = 1.0; **AvalancheMult** should be set to the same value in both *BER_OOK_Stoch* and *APD* modules.

Gaussian Analysis

Sometimes the χ^2 analysis may not be appropriate, or the additional accuracy obtained by using a more sophisticated (and computationally expensive) analysis may not be required. Alternatively, it may be desirable to compare the results obtained using the χ^2 method with those obtained using the common Gaussian approximation. For these reasons, the module is also capable of performing an analysis based on a Gaussian approximation for the statistics.

The Gaussian analysis method uses a simpler two-step process to estimate the BER:

1. The mean and variance of the received 'one' and 'zero' bits are estimated using the usual sample estimators. This step is identical to the method used by the *BER Estimation (Gaussian Approximation)* module.
2. The dark current is then added to the computed means, and the thermal noise and shot noise variances added to the computed variances. The probability density functions $W_0(x)$ and $W_1(x)$, and the corresponding error probabilities $P_{1/0}$ and $P_{0/1}$ are then assumed to be those of Gaussian distributions with the total mean and variance values calculated.

Note that in this case, since all statistics are assumed to be Gaussian and only the means and variances of the input marks and spaces are calculated, the results will be the same (within statistical variations) whether the post-detection noise is added at the receiver, or using the module parameters. Thus, when using the Gaussian analysis modes, the *BER_OOK_Stoch* module may usually be used instead of the *BER Estimation (Gaussian Assumption)* module if desired. However, you should be careful not to include the noise in both the optical receiver and the *BER_OOK_Stoch* module, otherwise the total noise power will be doubled!

Calculation of Post-Detection Noise Variance

The post-detection noise includes contributions from both thermal and shot noise, with variances given by σ_{th}^2 and σ_s^2 respectively. Thus the total post-detection noise variance is given by:

$$(5) \quad \sigma_p^2 = \sigma_{th}^2 + \sigma_s^2$$

The thermal noise variance is given by:

$$(6) \quad \sigma_{th}^2 = N_{th}^2 B_e$$

where N_{th} is the noise spectral density, as specified by the parameter **ThermalNoise**.

The shot noise variance is calculated depending on the type of photodetector used.

For the PIN detector, it is calculated according to:

$$(7) \quad \sigma_s^2 = 2q(\mu_k + i_d)B_e$$

where μ_k is the mean value of the data samples representing either a 'one' ($k=1$) or 'zero' ($k=0$) symbol; q is the electron charge; B_e is the electrical noise bandwidth, as specified by the **ElecNoiseBandwidth** parameter; and i_d is the detector dark current, as specified by the **DarkCurrent** parameter.

For the APD detector, it is calculated as:

$$(8) \quad \sigma_s^2 = 2q((\mu_k + M \cdot i_{dm})F \cdot M + i_{dnm})B_e$$

$$(9) \quad F = kM + (1 - k)\left(2 - \frac{1}{M}\right)$$

where M is the avalanche multiplication factor specified by the **AvalancheMult** parameter; i_{dm} is the detector multiplied dark current specified by **DarkCurrentMult**; i_{dnm} is the detector non-multiplied dark current specified by **DarkCurrentNonMult** and k is the ionization coefficient specified by the **IonizationCoefficient** parameter.

Note: A contribution of the responsivity and avalanche multiplication of the APD to μ_k is already taken into account by the photodetector module, while the *BER_OOK_Stoch* module accounts for the additional noise only.

Q-factor Calculation

The Q-factor is calculated from the mean and standard deviation of the 'zero' and 'one' levels using the conventional formula [3].

$$(10) \quad Q = \frac{\mu_1 - \mu_0}{\sigma_0 + \sigma_1}$$

Calculation of Effective Q-factor

The effective Q-factor Q_{eff} is a measure of system performance that is equivalent to, and commonly used in place of, the BER [6]. In the *BER_OOK_Stoch* module Q_{eff} is calculated as follows: First the BER for the optimum threshold is evaluated, then the effective Q-factor is found as a root of the defining equation:

$$(11) \quad BER = \frac{1}{2} \operatorname{erfc}\left(\frac{Q_{\text{eff}}}{\sqrt{2}}\right)$$

Note that Q_{eff} is, by definition, completely determined by the BER value. It can, in principle, be computed externally from the BER output of the module, however it is generated internally for convenience since its calculation requires the numerical solution of a transcendental equation.

Calculation of Eye-Opening

The eye-opening EO is calculated from the mean and standard deviation of the 'zero' and 'one' levels using the formula [3]

$$(12) \quad EO = (\mu_1 - 3\sigma_1) - (\mu_0 + 3\sigma_0)$$

Taking into account intersymbol interference (ISI)

Intersymbol interference is the dependence of the signal representing the current bit on the preceding and following bits. The effect of ISI on stochastic BER estimation is to overestimate the BER. However, this overestimation can be reduced by grouping identical patterns of bits before estimating the pdf's and hence their BERs. The numbers of preceding and following bits to be grouped in a pattern are specified by the parameters *ISI_Prebits* and *ISI_Postbits*. Such a bit pattern is referred to as a *metasymbol*. There are $M = 2^{ISI_Prebits + 1 + ISI_Postbits}$ possible different metasymbols. If only one preceding and one following bit is considered, there are eight possible metasymbols: four corresponding to a logical 'one' (010, 011, 110, 111) and four metasymbols corresponding to a logical zero (000, 001, 100, 101). It is convenient to associate each metasymbol with a number in the range 0 to $M-1$ according to binary notation. As with the case of simple 'one' and 'zero' symbols, the probability of error BER_i can be calculated for each metasymbol $i=0\dots M-1$. The total error probability is then calculated as:

$$(13) \quad BER(D) = \frac{\sum_{i=0}^{M-1} NMS_i}{\sum_{i=0}^{M-1} NMS_i} BER_i(D)$$

where NMS_i is the total number of metasymbols i occurring in the transmitted bit sequence.

Other Parameters and Features

For a description of the parameters **IgnoreBits**, **StartTimeToIgnore** and **NumberOfBitsToIgnore**, refer to [Ignoring bits in the input sequence](#).

The use of the **MultipleBlockMode** parameter to perform cumulative BER estimates over multiple firings of the module is discussed in [Improving BER estimates over multiple blocks](#).

Generating Visualizer Plots

The *BER_OOK_Stoch* module is capable of generating a number of plots that appear in pop-up visualizer windows. Two levels of output data are available. The first level is basic output data, equivalent to the plots that can be generated by the Gaussian approximation BER modules. The second level is advanced output data, which visualizes the quality of the statistical fitting process used by the *BER_OOK_Stoch* module, and displays the differences between the Gaussian and χ^2 fits. These advanced plots are very useful when assessing the suitability of the different fitting processes for a specific simulation setup.

Basic output data can be visualized by setting parameters **BERvsSampleTime**, **BERvsThreshold**, **QvsSampleTime**, **EyeOpeningvsSampleTime** to **On**. Four visualizer windows will be shown.

The first visualizer shows

- BER vs. sample time (without the influence of ISI).
- BER ISI vs. sample time.

The second visualizer shows

- Q-factor vs. sample time

The third visualizer shows

- Eye Opening vs. sample time.

The fourth visualizer shows

- BER vs. threshold (without the influence of ISI).
- BER for transmitted data 'one' symbols vs. threshold (without the influence of ISI)
- BER for transmitted data 'zero' symbols vs. threshold (without the influence of ISI)
- BER ISI vs. threshold.

If the **PDFs** parameter is set to **On**, a number of advanced plots are displayed.

If ISI is not considered in the current estimation method, two visualizer windows open.

The first window shows:

- the histogram obtained from data samples corresponding to 'one' symbols
- the Gaussian fit to the input PDF for 'one' symbols
- the χ^2 fit to the input PDF for 'one' symbols

and the second window shows similar data for 'zero' symbols.

If ISI is considered, the number of visualizers is $M = 2^{ISI\text{Prebits} + 1 + ISI\text{Postbits}}$, which corresponds to the number of metasymbols considered. Each visualizer displays histogram, Gaussian and χ^2 PDF fits for one particular metasymbol.

Boundary Conditions

The boundary condition setting effects the metasymbol definition if ISI is considered. When boundary conditions are "periodic", the preceding symbol for the first symbol of the bit sequence shall be equal to the last symbol of the bit sequence, and the succeeding symbol for the last symbol of the bit sequence shall be equal to the first symbol of the bit sequence. When boundary conditions are "aperiodic", the preceding symbol for the first symbol of the bit sequence and the succeeding symbol for the last symbol of the bit sequence shall be assumed to be a 'zero'.

Re-initialization Behavior

Multiple runs

If the **MultipleBlockMode** = `AccumulateOverBlocks`, the data samples from previous iterations are stored in memory, and output results are cumulative over multiple runs. If **MultipleBlockMode** = `IndependentBlocks`, the module performs a full initialization at the start of each run, and output results are dependent upon the inputs for the current run only.

Restart of Simulation or Reset during Simulation

Full reinitialization is performed.

Inactive Behavior

When set inactive, the module will perform no calculations and will not open any visualizers, regardless of the settings of the corresponding parameters. The output values in this case will be $ber = 1$, $q = 0.0$, $q_{eff} = 0.0$, $threshold = 0.0$.

Comments

Extensive testing has shown that the χ^2 analysis methods used in this module produce better estimates than the Gaussian approximation for the BER in most simulated baseband direct-detection systems with significant additive optical noise such as ASE noise from optical amplifiers. However, in some circumstances the χ^2 analysis may not be appropriate, or should be used with care. Before using the χ^2 analysis methods, consider the following:

- Although the statistical analysis methods used by the module to estimate the parameters of the χ^2 distribution are more sophisticated than the Method of Moments, it is still generally necessary to have more information in order to estimate the values of a larger number of parameters. Therefore, you should expect that it will be necessary to simulate a larger number of bits when using the χ^2 analysis method than when using the Gaussian analysis method, in order to obtain results that do not exhibit excessive statistical variation. As a guide, typically 2048 bits (i.e., 1024 marks and 1024 spaces) is the minimum requirement to obtain reasonable results using the Gaussian approximation. At least twice this number of bits may be required using the χ^2 analysis, especially if very low error probabilities are being estimated. In return for this additional simulation cost, the χ^2 analysis will produce a better estimate of the actual system performance than the Gaussian approximation.
- The χ^2 fitting procedure may be unsuccessful in some cases—for example when the optical signal to noise ratio is very high, or the data samples have a distribution with two or more widely separated peaks (which may occur when the sampling instant is close to bit frame margins). This will result in warning messages. In particular, when the basic visualizers are enabled, or the **SampleType** parameter is set to `Optimum`, the module performs calculations for all possible sample instants, including those near the edge of the bit frame, which may cause several warning messages to be issued. In these cases it is recommended to use the internal module visualizers to decide whether the obtained result is acceptable.

If for any reason the module fails to calculate a required quantity, it issues an appropriate warning message and sets the output value of this quantity to -1.

When the basic visualizers are enabled, or the **SampleType** is set to *Optimum*, the module performs calculations for all possible sample instants and consequently the calculation time increases. When the estimation includes the effect of ISI, the calculation time is approximately four times longer than with the non-ISI calculation method.

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