**Subject:  Example PAM4 SerDes System Using Behavioral Models**
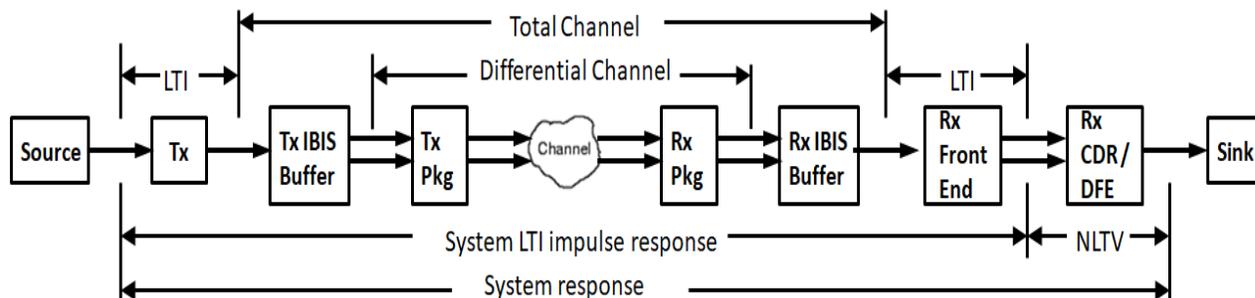
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This paper discusses features on the web site:  **https://www.serdesdesign.com**

A SerDes system for a single channel has the typical structure shown in this figure.



See details in **About the SerDes System Single Channel Tool...**

Many of the features available in the SerDesDesign.com tools are free others are available for a fee.  This document is on the modeling and simulation of a SerDes system using PAM4 signaling, Tx/Rx behavioral models, S4P data for the channel, and using the SerDesDesign.com channel simulator.

## Top Level Web Page Overview

The top-level channel simulator used is at this web page:
**https://www.serdesdesign.com/home/serdes-system-tool/**

One must be registered to use this web page.  Registration is free and available on the home page.

For this example, this top-level page has these values:
- Define Transmitter section:
    - TransmitterType =1; This defines a feed forward equalizer (FFE).
- Define Channel section:
    - ChannelType = 2; This defines differential channel using four port S-parameters.
- Define Receiver section:
    - ReceiverFEType = 1; this defines a continuous time linear equalizer (CTLE) with automatic gain control (AGC).
    - ReceiverNLType = 1; this defines a nonlinearity.
    - ReceiverNLTVType = 2; this defines a clock and data recovery circuit (CDR) and decision feedback equalizer (DFE).
- Setup Analysis section:
    - SymbolRate = 12.5e9; this defines the PAM4 baud rate
    - SetupBitByBitMode = 1; this is used to set the PAM4 mode and the number of

analysis symbols.

The resultant top-level web page will appear as shown here:

**1. Define Analysis Name**

| Description and Name Prefix | Name | Status | Comment | Action | Action |
|---|---|---|---|---|---|
| Analysis name: Serdes_ | SystemTest | ✓ | Alpha-numeric characters or underbar - case sensitive - start with alpha character | Recall | Info... |

**2. Define Transmitter** - nonlinear and/or time variant (NL/NLTV) model forces Bit-by-Bit Analysis mode.

| Name | Description | Entry Value(s) | Status | Type | Limits | Comment | Action |
|---|---|---|---|---|---|---|---|
| TransmitterType | Transmitter type | 1 | ✓ | Integer | [0, 5] | 0 = None<br>1 = FFE<br>2 = FFE Black Box<br>3 = FFE with Registers<br>4 = CTLE<br>5 = Tx LTI AMI model<br>6 = Tx NLTV AMI model | Open... |

**3. Define Channel** - model is linear and time invariant (LTI).

| Name | Description | Entry Value(s) | Status | Type | Limits | Comment | Action |
|---|---|---|---|---|---|---|---|
| ChannelType | Channel specification type | 2 | ✓ | Integer | [0, 3] | 0 = None<br>1 = Channel impulse data<br>2 = Channel S-parameter data<br>3 = Channel + Tx/Rx IBIS/pkg | Open... |
| EnableChAntiAliasing | Enable channel impulse anti-alising | 0 | | Integer | [0, 1] | 0 = No; 1 = Yes<br>Used only when ChannelType=1 | |
| ChAntiAliasingFc | Channel anti-alising filter corner frequency | 0 | | Real | >= SymbolRate | Value in Hz; Used only when ChannelType=1 and EnableChAntiAliasing=1 | |

**4. Define Receiver** - nonlinear and/or time variant (NL/NLTV) model forces Bit-by-Bit Analysis mode.

| Name | Description | Entry Value(s) | Status | Type | Limits | Comment | Action |
|---|---|---|---|---|---|---|---|
| ReceiverFEType | Receiver LTI front end type | 1 | ✓ | Integer | [0, 7] | 0 = None<br>1 = 1 section CTLE<br>2 = 2 section CTLE<br>3 = 3 section CTLE<br>4 = 4 section CTLE<br>5 = Rx FFE<br>6 = Rx FFE Black Box<br>7 = Rx LTI IBIS-AMI model | Open... |
| ReceiverNLType | Receiver NL type | 1 | ✓ | Integer | [0, 1] | 0 = None<br>1 = Gain with nonlinearity | Open... |
| ReceiverNLTVType | Receiver NLTV type | 2 | ✓ | Integer | [0, 3] | 0 = None<br>1 = CDR<br>2 = CDR + DFE<br>3 = Rx NLTV IBIS-AMI model | Open... |

**5. Setup Analysis** - Analysis uses Statistical or Bit-by-Bit mode based on the selected models.

| Name | Description | Entry Value(s) | Status | Type | Limits | Comment | Action |
|------|-------------|----------------|--------|------|--------|---------|--------|
| SymbolRate | Symbol rate (same as bit rate for NRZ) | 12.5e9 | ✅ | Real | > 0 | Symbols per second (same as bits per second for NRZ) | |
| SamplesPerSymbol | Samples per symbol (same as samples per bit for NRZ) | 32 | ✅ | Integer | [4, 128] | | |
| SetupOptions | Setup analysis options | 0 | ✅ | Integer | [0, 1] | 0 = No<br>1 = Yes | Open... |
| SetupBitByBitMode | Setup bit-by-Bit mode | 1 | ✅ | Integer | [0, 1] | 0 = No<br>1 = Yes | Open... |
| GenerateModels | Generate IBIS-AMI models<br>Generate models after Run with satisfactory results | 0 | ✅ | Integer | [0, 1, 2, 3] | 0 = No<br>1 = Yes: Tx only<br>2 = Yes: Rx only<br>3 = Yes: Tx and Rx | Info... |

## Setting Up the Transmit Model

In the 'Define Transmitter' section, select the TransmitterType 'Open…' button.

The Tx dialog box is displayed.  This page is used as-is.

Select the HELP button at the bottom of this page for more detail on this Tx model.
Select the APPLY button to verify the settings.  If they are good, then each parameter will have a green circle with a check mark will appear in its 'Status' field.
Select the OK button to close this dialog box.  If the box was setup properly, then a green circle with a check mark will appear in the TransmitterType 'Status' field.

## Setting Up the Channel Model

In the 'Define Channel' section, select the ChannelType 'Open…' button.

The Channel dialog box is displayed.  This page is used as-is.

Select the HELP button at the bottom of this page for more detail on this Channel model.
Select the APPLY button to verify the settings.  If they are good, then each parameter will have a green circle with a check mark will appear in its 'Status' field.
Select the OK button to close this dialog box.  If the box was setup properly, then a green circle with a check mark will appear in the ChannelType 'Status' field.

## Setting Up the ReceiverFEType Model

In the 'Define Receiver section, select the ReceiverFEType 'Open…' button.

The Rx FE dialog box is displayed.  This page is used as-is.

Select the HELP button at the bottom of this page for more detail on this Rx model.
Select the APPLY button to verify the settings.  If they are good, then each parameter will have a green circle with a check mark will appear in its 'Status' field.
Select the OK button to close this dialog box.  If the box was setup properly, then a green circle with a check mark will appear in the ReceiverFEType 'Status' field.

## Setting Up the ReceiverNLType Model

In the 'Define Receiver section, select the ReceiverNLType 'Open…' button.

The Rx NL dialog box is displayed.  This page is used as-is.

Select the HELP button at the bottom of this page for more detail on this Rx model.
Select the APPLY button to verify the settings.  If they are good, then each parameter will have a green circle with a check mark will appear in its 'Status' field.
Select the OK button to close this dialog box.  If the box was setup properly, then a green circle with a check mark will appear in the ReceiverNLType 'Status' field.

## Setting Up the ReceiverNLTVType Model

In the 'Define Receiver section, select the ReceiverNLTVType 'Open…' button.

This page is changed from the default values to these settings:
- CDR_OJTS_Fc = 5.0e6; this sets the CDR Observed Jitter Transfer Function corner frequency.  For detail discussion on a CDR OJTF see this reference:  **CDR_OJTF**

Select the HELP button at the bottom of this page for more detail on this Rx model.
Select the APPLY button to verify the settings.  If they are good, then each parameter will have a green circle with a check mark will appear in its 'Status' field.
Select the OK button to close this dialog box.  If the box was setup properly, then a green circle with a check mark will appear in the ReceiverNLTVType 'Status' field.

## Setting Up the Analysis Bit-by-Bit Mode

In the 'Setup Analysis section, select the SetupBitByBitMode 'Open…' button.

The setup dialog box is displayed.  This page is changed from the default values to these settings:
- EnablePAM4 = 1; this turns on the PAM4 mode.
- AnalysisSymbols = 1000000; this set the number of analysis symbols recorded after the system defined ignore sysmbols.

Select the HELP button at the bottom of this page for more detail on this setup dialog.
Select the APPLY button to verify the settings.  If they are good, then each parameter will have a green circle with a check mark will appear in its 'Status' field.
Select the OK button to close this dialog box.  If the box was setup properly, then a green

circle with a check mark will appear in the SetupBibByBitMode 'Status' field.

## Run the Analysis

In the 'Run Analysis section, select the Run button.  If the SerDes design was setup properly, then each top-level web page parameter will have a green circle with a check mark will appear in its 'Status' field.

As the simulation is run, the number of seconds run will display to the right of the Run button.

During simulation the following steps will be performed.
- The total channel will be analyzed and will be represented with a single ended impulse response.
- The Tx model will be setup and initialized.
- The Rx model will be setup and initialized.
- The simulator will determine how many 'IgnoreSymbols' are required and will run the simulation for the AnaysisSymbols after these IgnoreSymbols.
  - The AnalysisSymbols will be rounded up to a power of 2; 1,048,576in this case.
- The simulator will run a time domain simulation using a time step = 1/SampleRate = 1/SymbolRate/SamplesPerSymbol = 1/12.5e9/32 = 2.5e-12 sec in this case.
  - The simulator will create PAM4 symbols using bits from a PRBS bit generator. The PRBS generator length will be the default value since the Analysis setup used the default PRBS_Len = 0.  The value 20 is used because 2^20 = 1,048,576/2.
- The simulator will collect a histogram database of amplitude vs time values.  This database will be post processed after the simulation run to derive all metrics, include eye density and BER plots.

At the end of the simulation run, the 'Analysis log file' will open at the bottom of the web-page.

Observe in the log file:
- The Tx FFE taps were set to their optimal values.
- The Rx front-end set its gain to achieve its target level.
- The Rx CDR phase was automatically adjusted during the simulation ignore symbols.
- The Rx DFE tap value were continuously adjusted during simulation.
- The simulation of 1,048,576 symbols plus the ignore symbol took 103 sec.

## Observe Quick Results

On this top-level web page, the 'Display Results' section provides the ability to see quick results.

For example, this is a quick display of the eye best and worst case contours.  Note:  This does not show the eye detail.
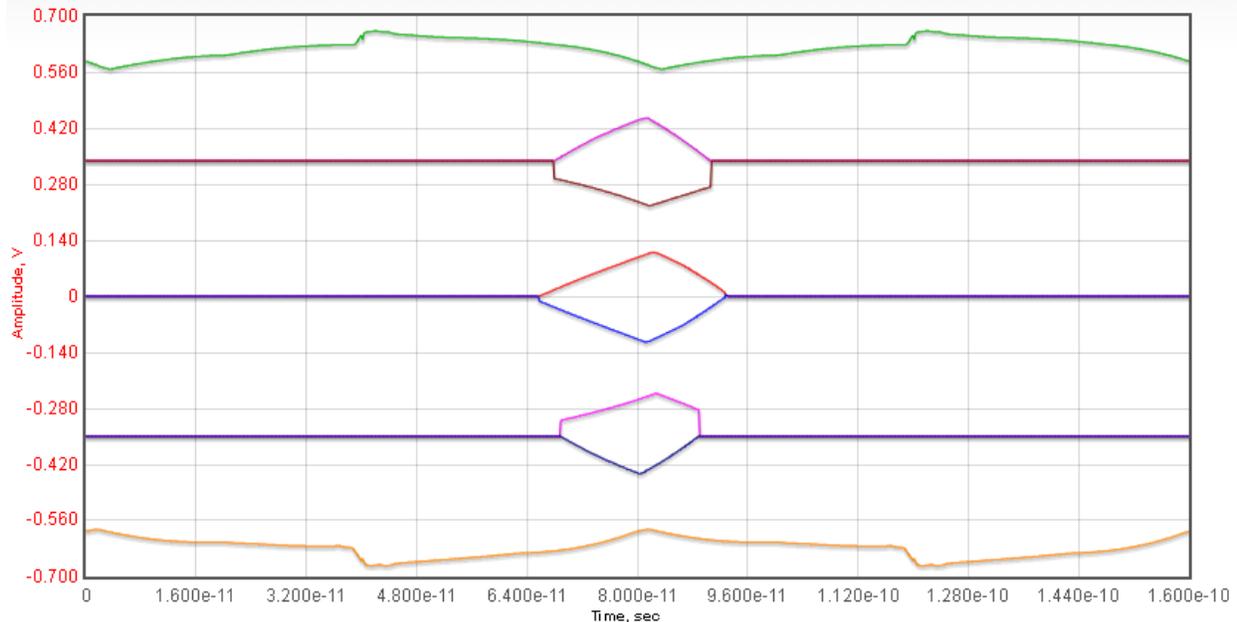
For detail results for eye density, BER and more, open the Eye Analysis web page:
**https://www.serdesdesign.com/home/eye-analysis-tool/**

In this web-page, one can set up many ways to post process the channel simulation output data.  To do this, as a minimum, set the 'ChAnalysisName' to the same Analysis name used in the prior web-page; Serdes_ChannelTest in this case.

Recommendation:  Set MaxEyeColorSize to 120000 (the default is 40000).  A larger value gives the eye density more detail at the cost of more data traffic between the server and ones computer.

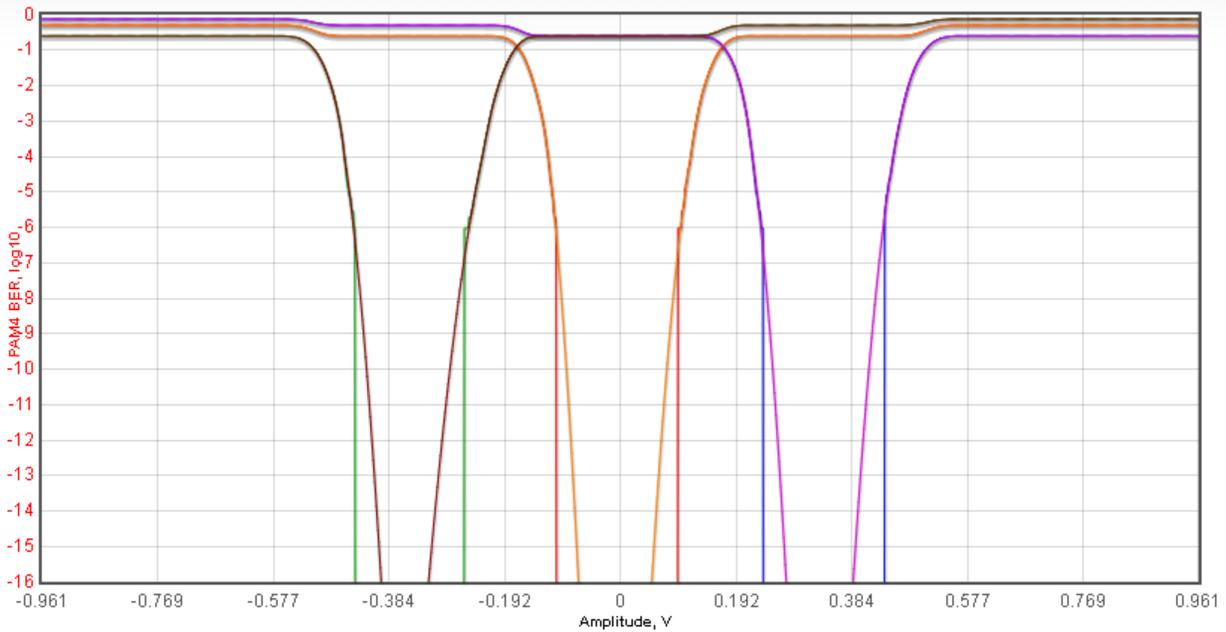After setup, run the Eye Analysis by selecting the Run button.
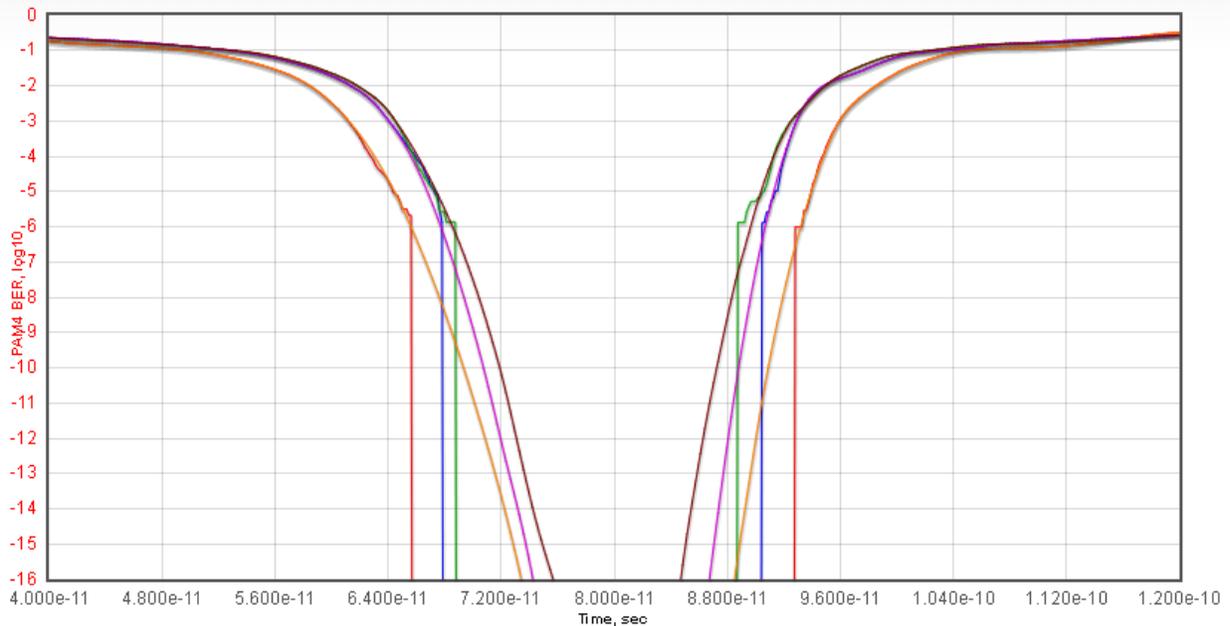
Here is the resultant Eye Density plot:
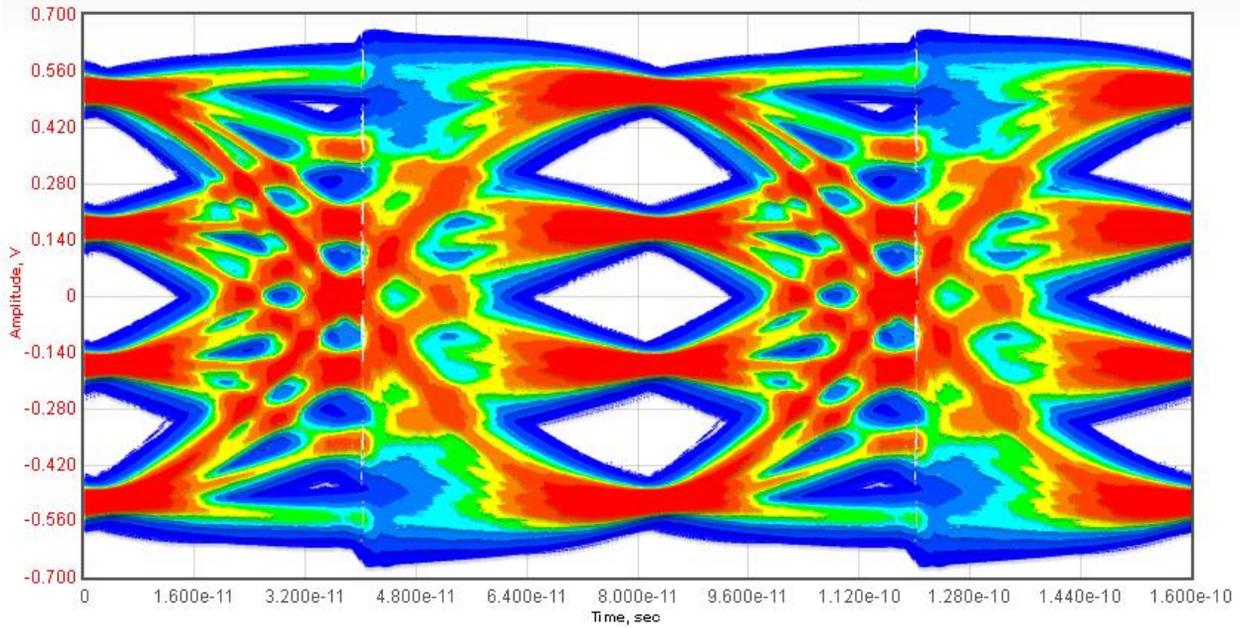
Redish colors are for higher densities.  Bluish colors are for lower densities.

Here is the resultant Amplitude Waterfall BER plot.



Here is the resultant Timing Waterfall BER plot (with a zoom into the center ½ UI).

BER curves are shown for the upper, middle, and lower eyes. The raw (Monte-Carlo based) BER curves are shown along with the extrapolated BER curves. The raw BER goes down to the level of 10^(-6) for this case. The extrapolated BER goes down to 10^(-16). The display of both shows that the extrapolated BER curves overlap the raw BER data very well above 10^(-6).

In all plots, one can zoom into any portion of the plot as desired.

Many ways of displaying the channel simulation data are possible.

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