SerDesDesign.com Example Rx Circuit CTLE/CDR/DFE Model 2020/02/13

By John Baprawski
johnb@serdesdesign.com
Web Site
www.serdesdesign.com

About SerDesDesign.com

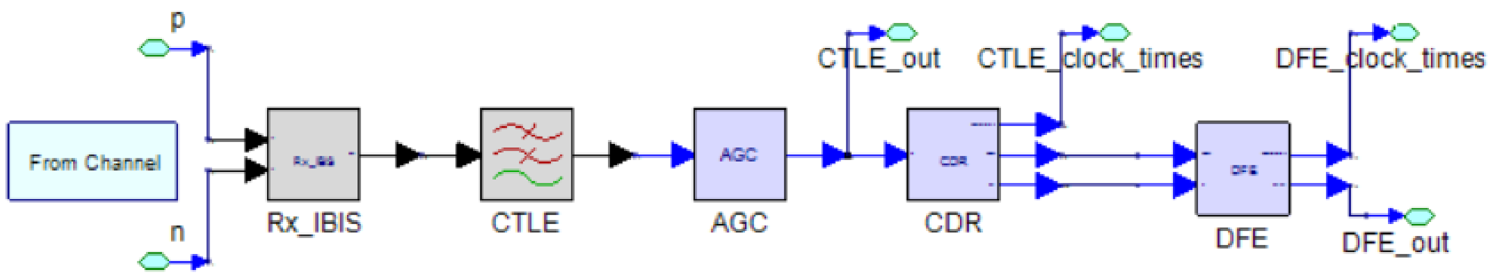
- Focused on Cloud based behavioral modeling and simulation of multi-gigabit high speed digital (HSD) integrated circuits (ICs) used in serializer/deserializer (SerDes) channels/systems.
- Features: Details at IntroductionToSerDesDesign.com
  - Free and subscription-use of on-line tools.
  - Tools for creating custom SerDes system IBIS-AMI models and SystemVue models.
    - IBIS-AMI models are portable for use in any standards compliant SerDes system channel simulator.
  - Consulting and training for custom IBIS-AMI modeling.
- SerDesDesign.com provides quick, efficient, accurate and cost effective modeling for SerDes systems.

What this training is and is not:

- First what this training is not:
  - Not focused on understanding SerDes systems in general.
  - Not for understanding details in SerDes system modeling.
  - Not an introduction to Channel Simulation or the IBIS-AMI standard.
  - Not an introduction to SerDesDesign.com
- What this training is:
  - The training is focused on modeling and testing SerDes system applications using tools on SerDesDesign.com.
  - The Rx circuit contains a CTLE/CDR/DFE for use with NRZ data
  - The Rx CTLE circuit is based on input/output waveforms.
  - The objective is to give SerDesDesign.com users an understanding on how to model a SerDes Rx circuit using SerDesDesign.com tools, generate an IBIS-AMI model for their Rx circuit, and use the generated IBIS-AMI model in the SerDesDesign.com Channel Simulator.

Modeling an Rx Circuit

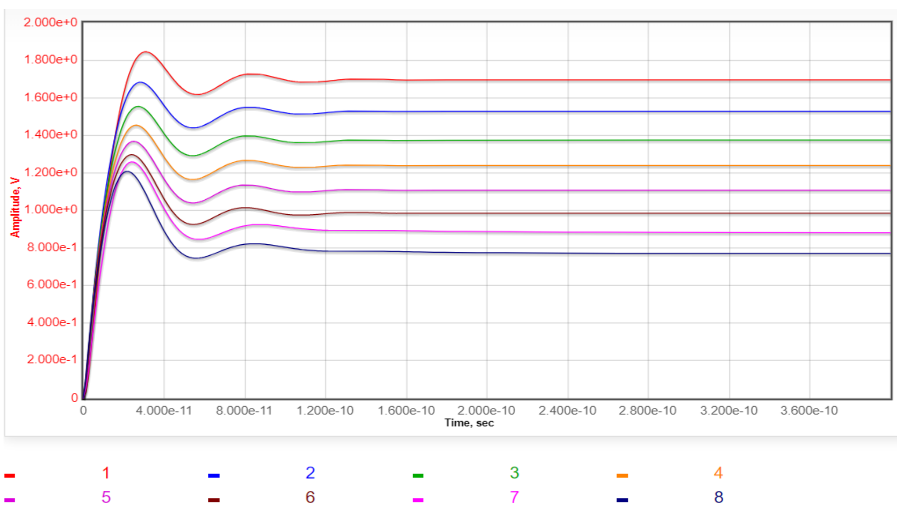
- The Rx circuit of interest is used for receiving a low voltage differential signal (LVDS), contains a continuous time linear equalizer (CTLE), clock and data recovery (CDR) and decision feedback equalizer (DFE).
- The Rx circuit is defined as shown in this figure.

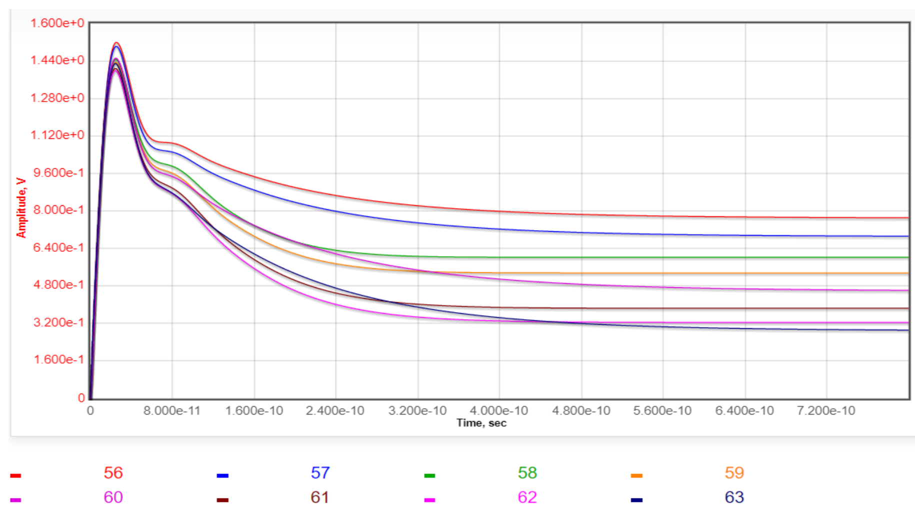


- The bit rate at and about 25 Gbps using NRZ signals.
- The Rx IBIS is a differential resistance (100 Ohms).
- The Rx CTLE has 64 states; the AGC targets the DFE operating level.
- The Rx CDR is defined with its OJTF corner frequency.
- The Rx 5 tap DFE has a nominal peak eye level with quantized taps, each with 30 states, defined with codes.

Example Rx: CTLE Waveforms

- The CTLE characteristic can be captured over its full set of 64 states.
- Waveform capturing requirement:
  - Use the highest bit rate: 25 Gbps in this case; with Tstep = 1/25e9/32 = 1.25e-12 sec.
  - Use repeating NRZ waveform with N 0's and N 1's; in this case N = 20
  - Capture data from Tstart = time when the rising edge starts; to Tstop = Tstart + 20 UI.
  - Normalize the data for Tstart = 0 and Vstart = 0.
  - Group data in file with 65 columns: Time, CTLE 1, CTLE 2, …, CTLE 63, CTLE 64
- Waveforms are displayed for CTLE index = 1 to 8 and 56 to 63.



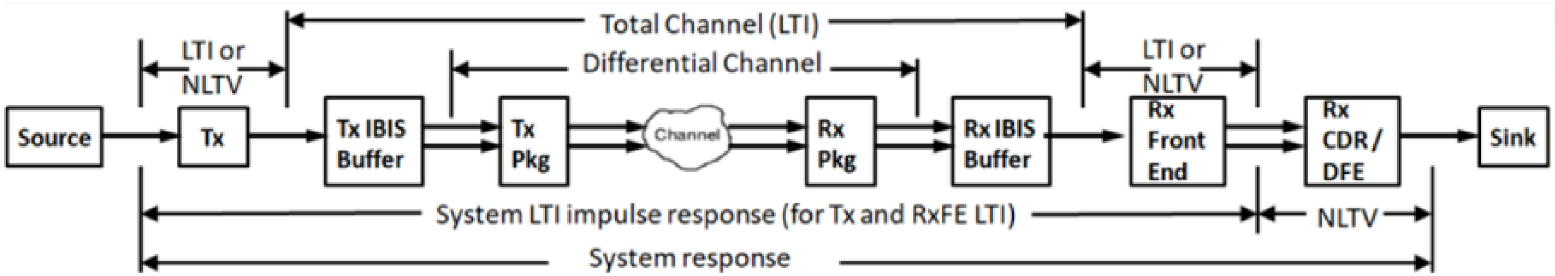


Example Rx: IBIS/AGC/CDR/DFE

- The IBIS buffer is defined with a differential load resistance of 100 Ohms.
- The AGC is used to set the level after the CTLE to the targeted DFE single sided eye level of 0.125 V.
- The CDR is set to the circuit observed jitter transfer function (OJTF) corner frequency; 20 MHz in this case.
- The DFE has its 5 taps quantized with min/max values = 0.006/0.180 with 0.006 steps and each tap is indexed with codes from -30 to +30.

Use the SerDes.com Channel Simulator

- **Single channel SerDes system:** [serdes-system-single-channel-tool]



- Source: NRZ or PAM4 data source
- Tx: Transmiter equalization; typically an FFE; see **Note** below.
- Tx/Rx IBIS Buffers: IBIS buffer to the differential channel; defines the on-die impedance; see **Note** below.
- Tx/Rx Pkg: Package characteristic defined in SnP files.
- Channel: SerDes channel defined in a SnP file.
- Rx Front End: Receiver equalization; typically a CTLE; see **Note** below.
- Rx CDR/DFE: Receiver timing/eq; typically a CDR and DFE; see **Note** below.
- **Note**: Can be a built-in model or a user defined IBIS-AMI model.

Rx Example: Set the CTLE/AGC

- The CTLE/AGC data is used in the SerDesDesign.com Rx Front End model.
- Set ReceiverFEType=1; open the dialog box; set ModelType=3.
- Set the other ReceiverFE parameters as shown here for initial tests:

Name	Description	Entry Value(s)	Status	Type	Limits	Comment
ModelType	Model type	3		Integer	[0, 4]	0 = AGC only 1 = List of peaking dBs 2 = File with set of poles and zeros 3 = File with set of step responses 4 = File with set of spectrums
InputGain	Input scalar gain	1.0		Real	> 0	Scalar gain
AutoGainControl	Automatic gain control at Rx FE output	0		Integer	[0,1]	0 = No 1 = Peak-to-peak eye level
EnableCorners	Enable corner cases	0		Integer	[0,1]	0 = No 1 = Yes
NumData1	Number of data sets in file1 or dB list	64		Integer	> 0	
DataColumnType1	Data column type for file 1	1		Integer	[0,1]	0 = t1,v1,t2,v2,...,tN,vN 1 = t,v1,v2,...,vN
DataFile1	Data file 1 (typical corner). Alpha-numeric or underbar; start with alpha	CTLEStepResp.csv Choose File No f...osen		File		Upload a file (Step Response Data format or Pole-Zero Data format) or list previously uploaded file.
AdaptForChannel	Auto adapt to equalize the channel	0		Integer	[0,1]	0 = No 1 = Yes
DataIndex1	Data set index used for file1 or dB list	8		Integer	[1,NumData1]	PHP error alert: If the integer entered (ie. 7) fails, put a zero in front of it (ie. 07).

AutoGainControl will be changed to 1 for a later test with AGC_Level = 0.25.

Use the 'Choose File' button to upload the data file.

AdaptForChannel will be changed to 1 for a later test.

Rx Example: Set the rest of the system

- The initial tests are for the Rx only without a channel or receiver.
- Set ChannelType = 0:

ChannelType	Channel specification type	0

- Set ReceiverFrontEndType = 0

ReceiverFEType	Receiver front end type	0

- Set ReceiverCDRDFEType = 0:

ReceiverCDRDFEType	Receiver CDR/DFE type	0

- Set the BitRate and SamplesPerBit:

SymbolRate	Symbol rate (same as bit rate for NRZ)	2.50E+10
SamplesPerSymbol	Samples per symbol (same as samples per bit for NRZ)	32

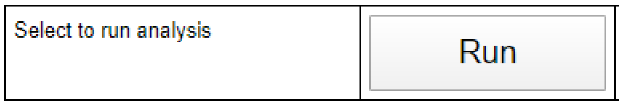
- Use the SetupOptions to use a NRZ stream with 20 repeating 1's and 0's collecting 200 symbols with zero ignore symbols.

DisplaySourceType	Source type	1
DisplaySourceN	Source N value	20

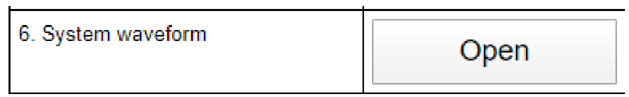
DisplayIgnoreSymbols	Ignore initial output symbols (same as bits for NRZ)	0
DisplaySymbols	Symbols (same as bits for NRZ) to display after DisplayIgnoreSymbols	200

Rx Example: Observe the Model Data

- Run the Channel Simulation by selecting the 'Run' button.



- Open the System waveform:



- Observe the that graph displays a waveform that agrees with the original data on slide 5 for curve 8, the black curve:

- This Rx model is usable at any BitRate about 25 Gbps at other SamplesPerBit.

Rx Example: Use with a Channel

- Use default built-in channel; ChannelType = 1; 24.5 dB loss at Nyquist.
- Set Rx AdaptForChannel = 1.

AdaptForChannel	Auto adapt to equalize the channel	1

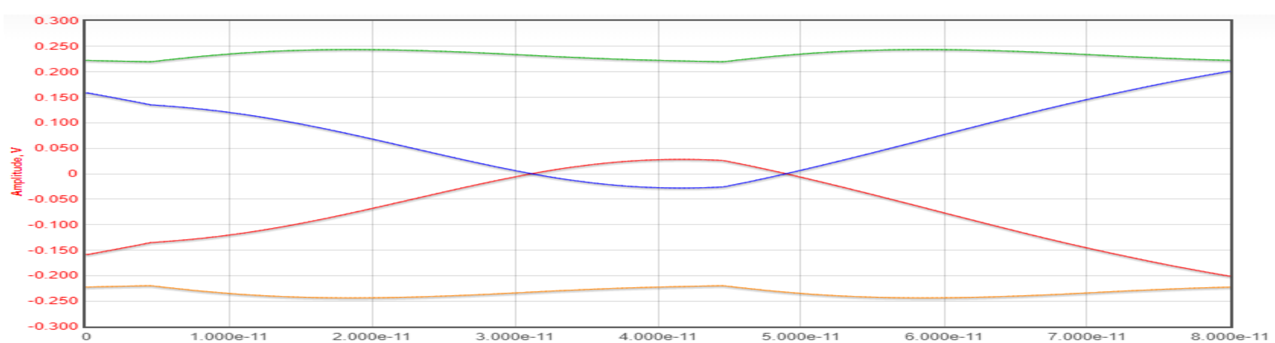
- Set AutoGainControl = 1; AGC_Level = 0.25.

AutoGainControl	Automatic gain control at Rx FE output	1
AGC_Level	AGC level	0.25

- Run the Channel Simulator and observe the message output:

Generating Receiver front end (RxFE) model based on step response data.
Optimization of EQ over count = 64 states resulting in max open eye ratio = 0.122444 with optimized states
EQ1_StepRespIndex = 16
For the selected EQ states the open eye ratio = 0.122444
To adapt channel+equalizer loss for peak to peak eye level (0.25), a gain of 3.67993 dB is added at the equalizer output.

- This shows the DataIndex1 and Gain values selected for the optimal eye and eye level at the channel output.
- Open and observe the 'System worst/best case eye contours':



The CTLE opened the eye a bit.
The DFE will open the eye much more.

Rx Example: Add CDR/DFE

- The CDR/DFE data is used in the SerDesDesign.com Rx CDR/DFE model.
- Set ReceiverCDRDFEType=5; open the dialog box.
- Set the other ReceiverCDRDFE parameters as shown here:

InputGain	Rx input gain	1.0
NonlinearityType	Nonlinearity type	0
CDR_OJTS_Fc	CDR observed jitter transfer spec approximate corner frequency	20e6
CDR_SamplerUIDelay	CDR sampler UI delay; 0=AutoSet	-0.03125
NumTaps	Number of DFE taps	5
Level	Nominal DFE input eye peak level	0.125

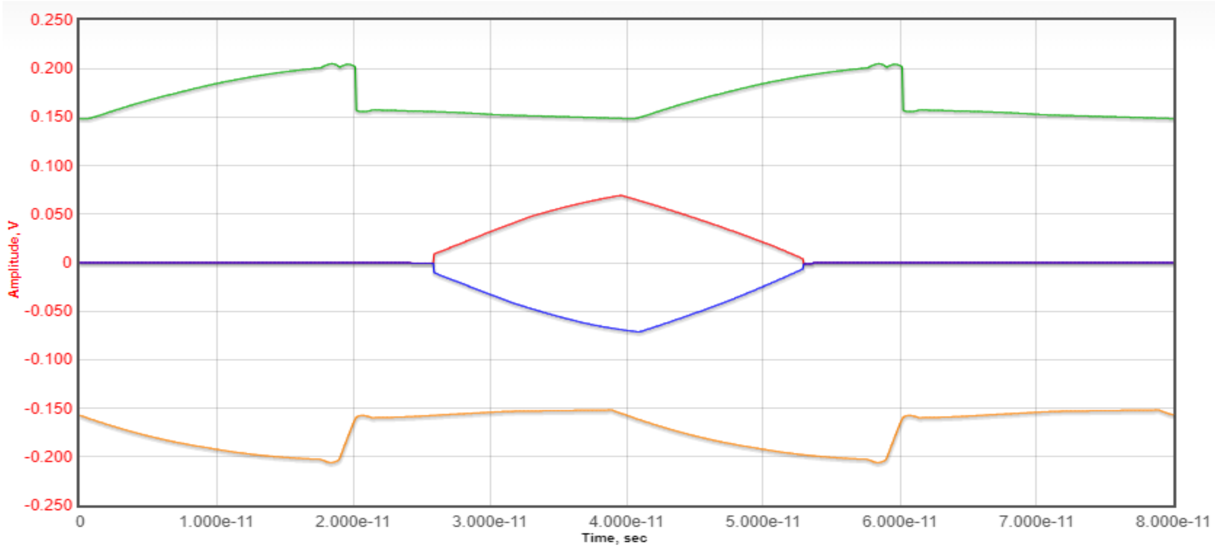
MinRange	Minimum magnitude value for taps	0.006,0.006,0.006,0.006
MaxRange	Maximum magnitude value for taps	0.18,0.18,0.18,0.18,0.18
NumRange	Number of tap values from min to max (inclusive)	30, 30, 30, 30, 30

Rx Example: Set the rest of the system

- The tests include the channel and Rx CTLE/AGC/CDR/DFE using 25 Gbps with 32 SamplesPerBit.
- Use the SetupBitByBitMode to set the AnalysisSymbols to 100,000.

AnalysisSymbols	Number of analysis symbols (same as bits for NRZ) after IgnoreSymbols/Bits	100000

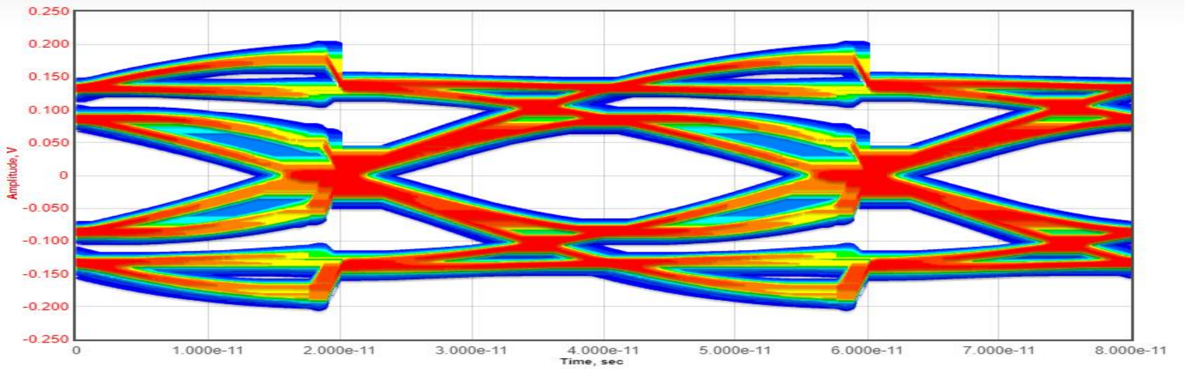
- Run the Channel Simulator and Open and observe the 'System worst/best case eye contours':



The DFE opened the eye much more than the CTLE alone.

Rx Example: Observe the Detail Eye

- Since the Channel Simulation saved a statistical data set from its analysis, that statistical data can be further post processed in the Eye Analysis tool to observe the detail eye analysis.
- Open the Eye Analysis Tool: eye-analysis-tool
- Set the ChAnalysisName to the AnalysisName used with the Channel Simulator and select Run.
- Open the System Eye Density plot.

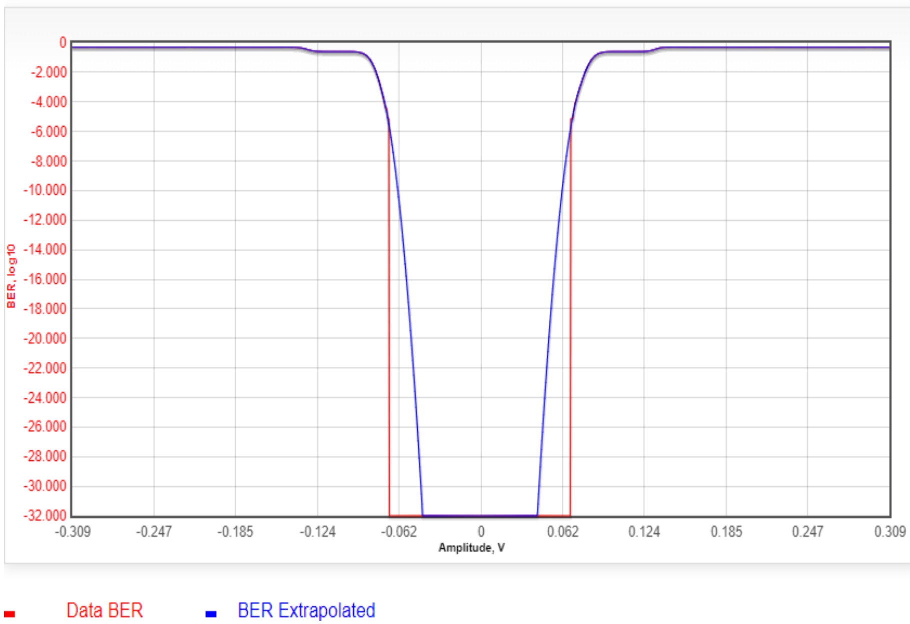


- The eye contours from the prior page overlap this detail Eye plot.
- Additional metrics are available: eye width/height, BER and more

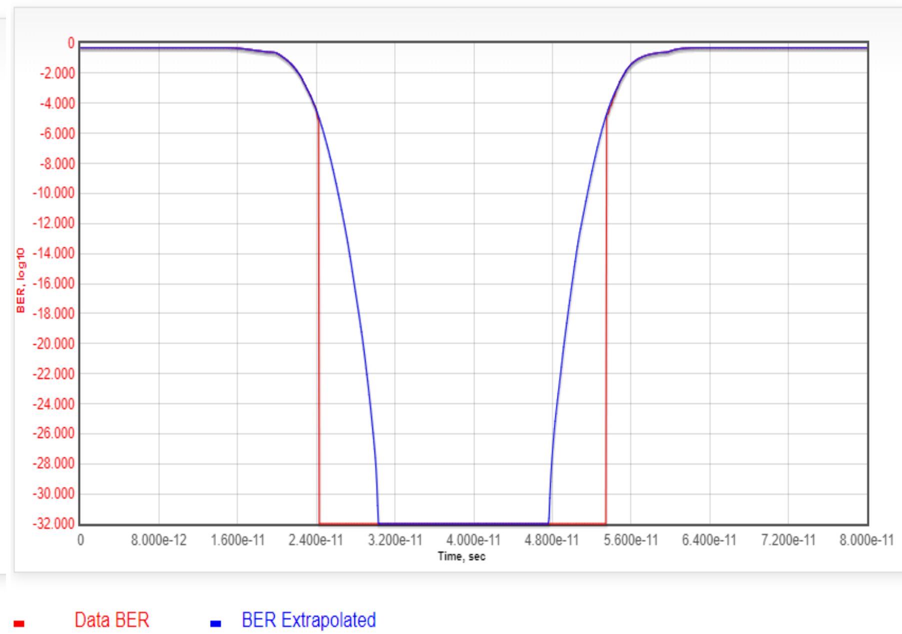
Rx Example: Observe the Detail BER

- Open the System eye amplitude and eye timing bathtub BER plots.

Eye amplitude bathtub BER for system



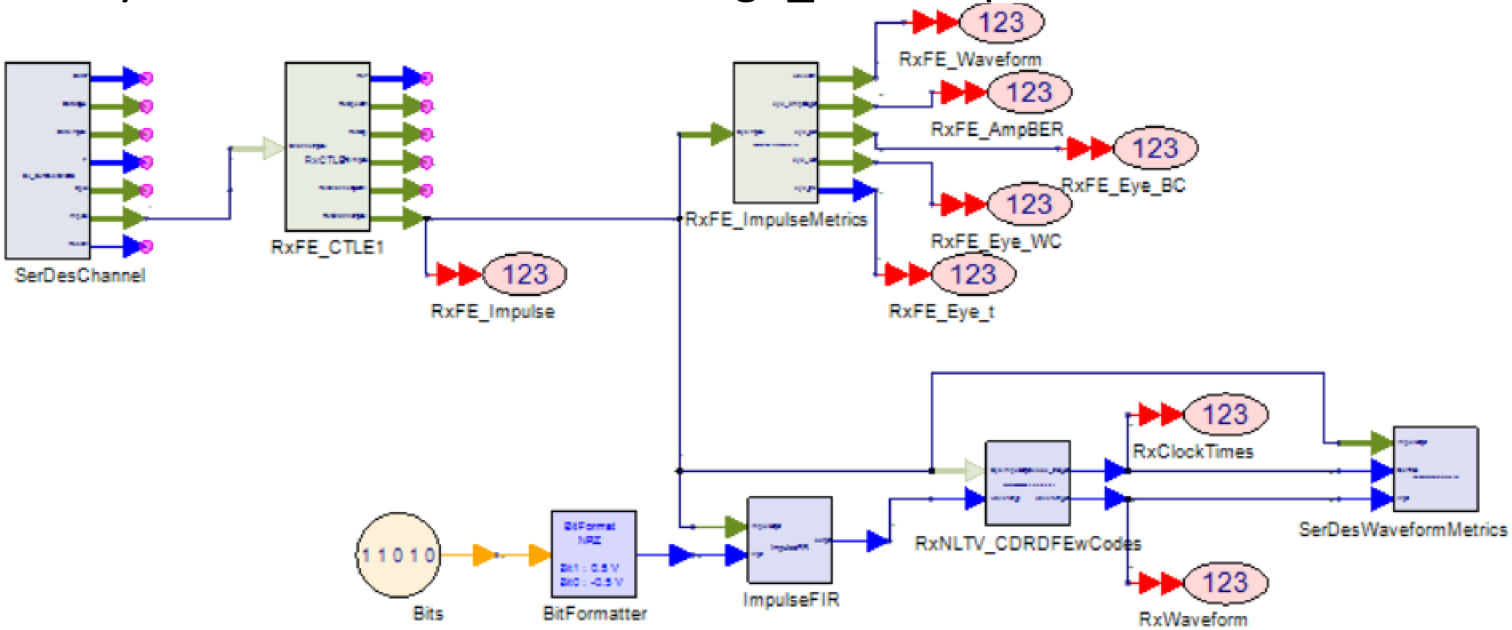
Eye timing bathtub BER for system vs time



- In both BER plots, the extrapolated BER is overlaid on top of the BER from the raw channel simulation collected histogram data.
- There is an excellent match between the BER Extrapolated and Data BER.

Define and use as a SystemVue model

- The Rx model in the prior slides can also be defined/used in SystemVue.
  - Use the SerDesDesign.com SystemVue add-on library (SerDesDesign).
- The SystemVue model SerDesDesign_RxExample is used here.



- SerDesChannel: SV model that converts an SNP file
  - Generates Impulse h21dd and s21dd response.
  - Generates S-parameter data h21dd and s21dd response.

Define and use as a SystemVue model

- RxFE_CTLE1 : SV model that converts RxFE input impulse.
  - Generates Rx and Rx+Ch impulse and spectrum response.
- RxFE_ImpulseMetrics: SV model that converts RxFE impulse to eye metrics:
  - Eye best and worst contours vs time (for 2 UI)
  - Waveform for defined bit source; Eye amplitude waterfall BER.
- RxNLTV_CDRDFEwCodes: SV model with CDR and DFE
  - Generates Rx output waveform and clock_times.
- SerDesWaveformMetrics: SV model that converts Rx output waveform and clock_times to metrics:
  - Eye best and worst contours vs time (for 2 UI)
  - Waveform for defined bit source; Eye amplitude waterfall BER.
- Same results in SystemVue as shown on SerDesDesign.com.

Define and use as a SystemVue model

- SerDesEyeMetricsNRZ/PAM4: SV models that convert eye histogram data to eye metrics.
  - Ability to change the eye amplitude and timing slicing levels for BER analysis.
  - BER extrapolation for Bit-by-Bit analysis.
  - Outputs eye metrics: eye width, jitter rms, jitter p2p, more.
- Use of SystemVue models in SystemVue provides more flexible SerDes system topologies, Channel Simulations, displays, and pre- and post-processing.

Rx Example: Iterate Analyses

- The Channel Simulator and the Eye Analysis tools can be used to test various Rx Model and Channel configurations and observe eyes, BER results and more.
- When one is comfortable with the results obtained, one can then generate the Rx IBIS-AMI model – as discussed next.

Rx Example: Generate IBIS-AMI Model

- When one is ready, an Rx IBIS-AMI model can be generated.
- Use the Channel Simulator with 'Setup Analysis' GenerateModels = 2 to generate the Rx IBIS-AMI model for the defined analysis set up.
- When Run is selected, the analysis is run and the files needed to generate the Rx IBIS-AMI model are saved.
- The Analysis log file displays this message:

```
==========================================================================================

You have requested that a Rx IBIS-AMI model be generated.

The files associated with this successful analysis have been saved with reference number:
      user-37_1583718589

The saved files will be used to generate the IBIS-AMI models and for validation testing.

Use this log file as your IBIS-AMI model ordering form.
Copy, paste and complete this form into your email (same email used to register for SerDesDesign.com) and email to:  admin@serdesdesign.com

  |...

Pricing for delivery of this generated Rx IBIS-AMI model is: $2000 USD for 1 OS or $3000 USD for 2 OSs.

Include any additional custom requirements for creation and delivery of your model.  List it into your email:

_ _ _< list additional requirements >  _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _

Your additional requirments may be included at no extra charge or you will be informed of any incremental additional cost if any.
==========================================================================================
```

Rx Example: Order IBIS-AMI Model

- The form on the prior page can be sent to admin@serdesdesign.com to order you IBIS-AMI model.
- The '…' lines can be filled-in as shown here in **bold**.

```
Order Windows 64 bit models: ____Yes______ (Yes or No)
Order Linux 64 bit models:   ____Yes______ (Yes or No)

The settable NLTV Rx model parameters (fill in the user defined names):
    RxFE_InputGain; _____RxInputGain_____________; Rx front end input scalar gain.
    RxFE_AutoGainControl; _____EnableAGC_____________; Enable Rx front auto gain control; 1=yes.
    RxFE_AGC_Level; _____AGC_Level_____________; Rx front end output target AGC peak-to-peak eye level; used when EnableAGC=1.
    RxFE_AdaptForChannel; ____AutoInitCTLE_________; Auto adapt Rx front end CTLE to equalize the channel; 1 = Yes.
    RxFE_DataIndex1; ____CTLE_Index______________; CTLE index value in the range [1, 64]; used when AutoInitCTLE = 0.
    CDR_OJTS_Fc; __________________; Rx CDR observed jitter transfer spec approximate corner frequency in the range [0.00005*SymbolRate, 0.005*SymbolRate].
    CDR_SamplerUIDelay; __________________; Rx CDR sampler delay in the range [-0.5, +0.5] UI.
    DFE_Adapt; __________________; Adapt DFE taps during simulation; 1 = Yes
    DFE_Alpha; __________________; DFE taps update factor; used when DFE_Adapt = 1
    DFE_AutoInitTaps; __________________; Auto init DFE tap codes to equalize the channel; 1 = Yes
    DFE_TapCodes; __________________; Comma separated list of initial 5 DFE integer tap codes; used when DFE_AutoInitTaps = 0.
    DFE_OutputUIDelay; __________________; DFE output delay in the range [-0.5, +0.5] in UI units.

 Default 'rx_model_name' = Serdes_RxExample2_Rx;    User defined 'rx_model_name' = ___RxExample_______

 Optional deliverable:  Include SystemVue model:  ___No________ (Yes or No)
```

Rx Example: Finalize the Model Order

- <list additional requirements> as required.
- Email your order to admin@serdesdesign.com
- You will receive an email response confirming your order and pricing.
- The listed price may be increased based on any additional requirements.
- If you agree to the price quote, then deposit your funds using PayPal from the Store web site.
- In this case select:

  4. D. Single Tx or Rx IBIS-AMI model with 2 OS: $3,000.00

  Add to Cart

- In this case, there are no additional requirement costs, but if there were then select with the needed Hourly quantity.

  1. A. HSD IBIS-AMI Consulting Hourly Rate: $250.00

  Add to Cart

…

Rx Example: Include Order Options

- Besides ordering the IBIS-AMI model, Web based Training can be ordered
  - Includes the model source code and instructions on how the model can be further modified on Windows and/or Linux.
  - Training is required for source code delivery.
  - Web based training is for 4 remote hours plus up to 2 hours post training support.
  - This training is available from SerDesDesign.com for $8000 USD with up to 12 attendees.
  - The price can be reduced if post training support in not required, typically because the new training is with a customer that had prior training.
- Additionally, a custom Linux build machine can be ordered
  - The machine plugs into a PC and is fully loaded with all software required including the model software and build environment.
  - Pricing is $2000 USD

Rx Example: IBIS-AMI Model Delivery

- The purchased model ordered will be provided via DropBox link within 1-2 business.
- Each IBIS-AMI model delivered includes these deliverable files:
  - <name>.ibs (IBIS buffer specification file)
  - <name>.ami (Model definition based on the IBIS standard)
  - <name>_x64.dll (64 bit Windows dynamic linked library file)
  - <name>.so (64 bit Linux shared object file)
  - <name>.pdf (custom model documentation)
  - where <name> is the customer specified name for the model.

Rx Example: Using this IBIS-AMI Model

- This Rx IBIS-AMI model can be used in any Channel Simulator based on the IBIS standard.
- Discussed here is the use in the SerDesDesign.com Channel Simulator at: [serdes-system-single-channel-tool]
- We will use the RxExample model.
- Set the ReceiverFEType=0
- Set the ReceiverCDRDFEType=6, open the dialog box; set UseIBS_File = 1.

UseIBS_File	Use Rx *.ibs file for IBIS-AMI NLTV model	1

- Upload the RxExample.ibs file:

RxCDRDFE_IBS_FileName	Rx IBIS-AMI NLTV model *.ibs file. Alpha-numeric or underbar; start with alpha	RxExample.ibs Choose File No …sen

- We will use the default channel S-parameter file with ChannelType = 3 which has 34 dB loss at Nyquist.

ChannelType	Channel specification type	3

Rx Example: Run Channel Simulation

- Set BitRate = 25.0e9 Gbps and SamplesPerBit = 32.

SymbolRate	Symbol rate (same as bit rate for NRZ)	2.50E+10
SamplesPerSymbol	Samples per symbol (same as samples per bit for NRZ)	32

- Run the analysis and observe the resulting log file message displayed for the Rx IBIS-AMI model:

```
Begin Message returned by AMI_Init():
Generating Receiver front end (RxFE) model based on step response data.
Optimization of EQ over count = 64 states resulting in max open eye ratio = 0.122444 with optimized states
EQ1_StepRespIndex = 16
For the selected EQ states the open eye ratio = 0.122444
To adapt channel+equalizer loss for peak to peak eye level ( 0.25 ), a gain of 3.67993 dB is added at the equalizer output.
End Message returned by AMI_Init().
```

- This shows that CTLE1_Index = 16 for the optimal eye at the receiver front end output.
- Additional messages are displayed in SystemVue during run time.

Rx Example: Run Channel Simulation

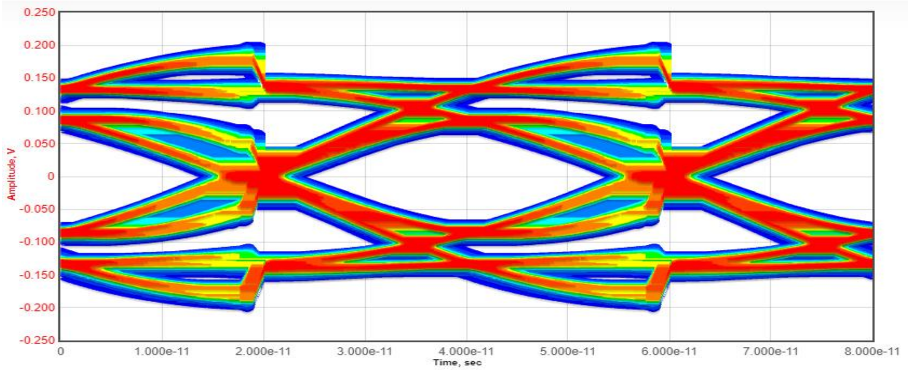
- During run time, these are some of the additional messages displayed in SystemVue.

```
Initial additional scalar gain estimate of 4 is applied to achieve the required level into the CDR.
Initialization for optimal DFE TapCodes[0: 4] = 2, 1, 2, 2, 1
TapValues[0: 4] = 0.012, 0.006, 0.012, 0.012, 0.006
AnalysisIgnoreSymbols is set to 13102.  AnalysisSymbols is set to 131072 and are recorded after these ignore symbols.
CDR settling UIs = 11102;  Ignore UIs = 13102
At UI count = 5551:  Revised additional scalar gain of 4.19219 is applied to achieve the required level into the CDR.
At UI count = 11102:  Manually set CDR sampler UI delay = -0.03125 UI.
At UI count = 11102:  Revised additional scalar gain of 3.95174 is applied to achieve the required level into the CDR.
At UI count = CDR settling UIs = 11102:
DFE TapValues[0: 4] = -0.0257583, 0.0161819, 0.022354, 0.0113575, 0.00817308
At UI count = 13102:  Revised additional scalar gain of 4.01384 is applied to achieve the required level into the CDR.
At UI count = IgnoreBits = 13102:
DFE TapCodes[0: 4] = -5, 2, 4, 2, 1
DFE TapValues[0: 4] = -0.03, 0.012, 0.024, 0.012, 0.006
Waveform for eye analysis = 100% done.
At final UI count:
DFE TapCodes[0: 4] = -5, 2, 4, 2, 1
DFE TapValues[0: 4] = -0.03, 0.012, 0.024, 0.012, 0.006
```

- These show the initial, intermediate and final states for the DFE tap codes.

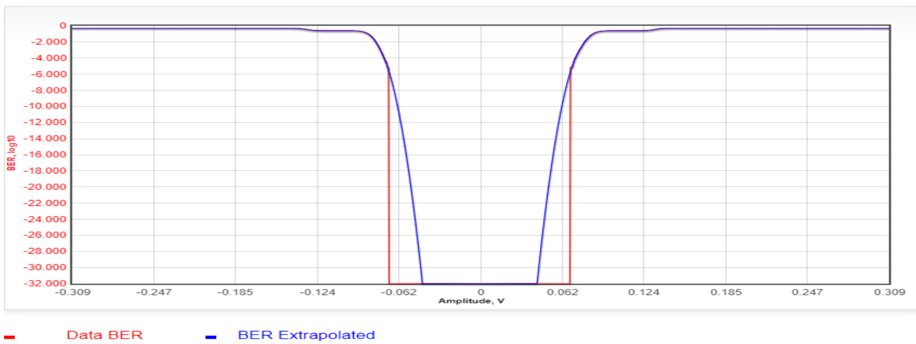
Rx Example: Observe Eye Metrics

- Open the Eye Analysis tool and observe the IBIS-AMI model 'System eye density plot' which is the same as for the original model.

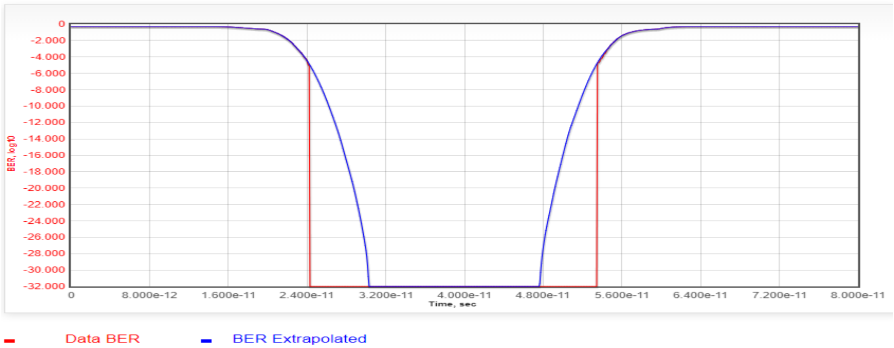


- Open and observe the IBIS-AMI model 'Eye amplitude and timing bathtub BER' plots which are the same as for the original model.

Eye amplitude bathtub BER for system



Eye timing bathtub BER for system vs time



Rx Example: Conclusion

- This presentation provided details on creating a Rx IBIS-AMI model by using the Rx circuit CTLE circuit simulation response waveforms data and using data on the Rx circuit CDR and DFE in the built-in CDR/DFE models.
  - The Rx circuit was discussed.
  - The Rx circuit CTLE waveforms were defined.
  - The Rx modeling approach was discussed.
  - The Rx circuit data was used in the Rx model.
  - The Rx model was simulated in a channel simulator.
  - The Rx model was exported as a Rx IBIS-AMI model.
  - The Rx IBIS-AMI models was used in a channel simulator.
- The presentation demonstrated just one of the many types of SerDes system Tx or Rx models that can be created using SerDesDesign.com.

Appendix

IBIS-AMI Modeling Flow – Model Development

- Use SerDesDesign.com for IBIS-AMI model development
- Construct the IBIS-AMI models in the SerDes Systems Tool
  - https://www.serdesdesign.com/home/serdes-system-single-channel-tool
  - Iterate as needed to achieve desired performance.
- Generate the Tx or Rx IBIS-AMI model from the web site.
  - Typical cost is as low as $2K per model.
- There is no need for the IBIS-AMI model developer to be an expert on the IBIS standard, C/C++ coding, or in setting up the compile and linking rules in the Microsoft Visual Studio or Linux tools.
- IBIS-AMI Tx and Rx models can be created by users in this SerDes System Tool.