

## SerDes\_Channel\_Impulse\_Modeling\_with\_Rambus

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### Introduction

This paper discusses SerDes channel impulse modeling for SerDes system simulation using Channel Simulators. The focus is on modeling SerDes channels using S-Parameters and the problem inherent in Channel Simulators when converting frequency domain S-Parameters into their equivalent time domain impulse responses. A solution is offered to the problems encountered. The solution is based on converting an S-Parameter file into Causal S-Parameters. By using Causal S-Parameters in a Channel Simulator, one avoids encountering impulse modeling problems in a Channel Simulator and will inherently obtain consistent impulse modeling among different Channel Simulators.

### Problem Statement

High speed digital (HSD) integrated circuits (ICs) are used in Serializer/Deserializer (SerDes) systems. In such systems, a lossy channel exists between the transmitter (Tx) circuit and the receiver (Rx) circuit. At high data rates the received data stream is severely distorted and requires reconstruction (equalization) before use. For system design, there is often the need to model the SerDes system in a custom simulator called a Channel Simulator that provides high speed simulation of millions of bits and tailored statistical analysis to determine the SerDes system metrics which include symbol eye diagrams and bit error rate (BER) characteristics.

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Modeling work for SerDes systems in a Channel Simulator is typically done by signal integrity (SI) engineers. A key step in this process is to convert HSD IC input and output buffer circuits into Input/Output Buffer Information Specification (IBIS) models using the IBIS AMI (Algorithmic Modeling Interface) standard to achieve fast simulations for evaluation and system performance prediction.

A SerDes system channel typically is a differential signal transmission channel. A hardware SerDes channel is typically characterized by measuring its N-port S-parameters versus frequency and is typically a 4-port. The 4-port differential input ports are typically port 1 (+) and port 3 (-). The associated differential output ports are typically port 2 (+) and port 4 (-). Other port assignments can be used. The differential characteristic (Port 1 – Port 3 vs. Port 2 – Port 4) is the channel transmission characteristic.

**S-Parameters are commonly used to represent a SerDes channel in a Channel Simulator.**

A key Channel Simulator process is to convert the frequency domain S-Parameters to their equivalent time domain impulse response.

**Problem: S-Parameters inherently cause problems when used in a time domain simulation.**

S-parameters, though measured on actual hardware, actually deviate from constraints for physical realizability such as passivity, reciprocity, and causality or include noise in the measured S-parameters for various reasons. For physical realizability, the S-parameters should ideally be measured continuously from 0 Hz to infinity and with no noise or distortion. For practical reasons, the S-parameters are band limited, are tabulated only at discrete frequencies, and are corrupted by measurement noise. These measurement limitations typically cause the S-parameters to be non-causal, non-reciprocal, and non-passive. Thus, to achieve a physically realizable transmission characteristic, the S-parameters must have corrections applied. These corrections must be achieved when converting S-Parameters to equivalent impulses in the time domain.

All SerDes system channel simulators convert the frequency domain S-parameter characteristics into time domain impulse characteristics. While doing this, all such simulators attempt to correct for all impairments in the S-parameters. However, some are less successful than others.

**In fact, all of the top 6 EDA channel simulation tools have problems in doing this.** As has been observed by many and especially reported by Romi Mayder of Xilinx Inc. at the 2015 DesignCon conference, Jan 27-30, Santa Clara Convention Center, Santa Clara CA, the top 6 EDA Channel Simulators in the industry gave widely varying impulse modeling of S-parameters as well as widely varying channel BER performance. See this link: > [DesignCon 2015 Technical Papers.](#)

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**Solution:** The key to obtaining consistent S-Parameter use with any time domain based tool, including any channel simulator, is to convert S-Parameter data into what is called “Causal S-Parameters”.

Causal S-Parameters for an N-port are based on the frequency domain equivalent of the NxN causal impulse responses generated from the original NxN S-Parameters. Causal S-Parameters will typically provide better eye and BER results while also providing close agreement with the frequency domain response of the original S-Parameters. Causal S-parameters will typically provide faster simulations. Causal S-parameters typically result in impulse responses that have a smaller number of data points. A 2x shorter impulse length results in a 4x faster convolution time.

The following discussion in this paper considers the S-Parameters for typical channels and their use in the Keysight Technologies Advanced Design System (ADS) Channel Simulator, ADS 2016.01

- The channel frequency domain characteristics are shown.
- Conversion of S-parameters into Causal S-Parameters is discussed.
- The ADS channel impulse modeling is discussed.
- Problems inherent in the ADS channel impulse responses are discussed.
- Use of Causal S-parameters provides better fidelity in the channel impulse responses.
- Use of SerDesDesign.com for better SerDes system modeling.

### **Example S-Parameter Test Cases**

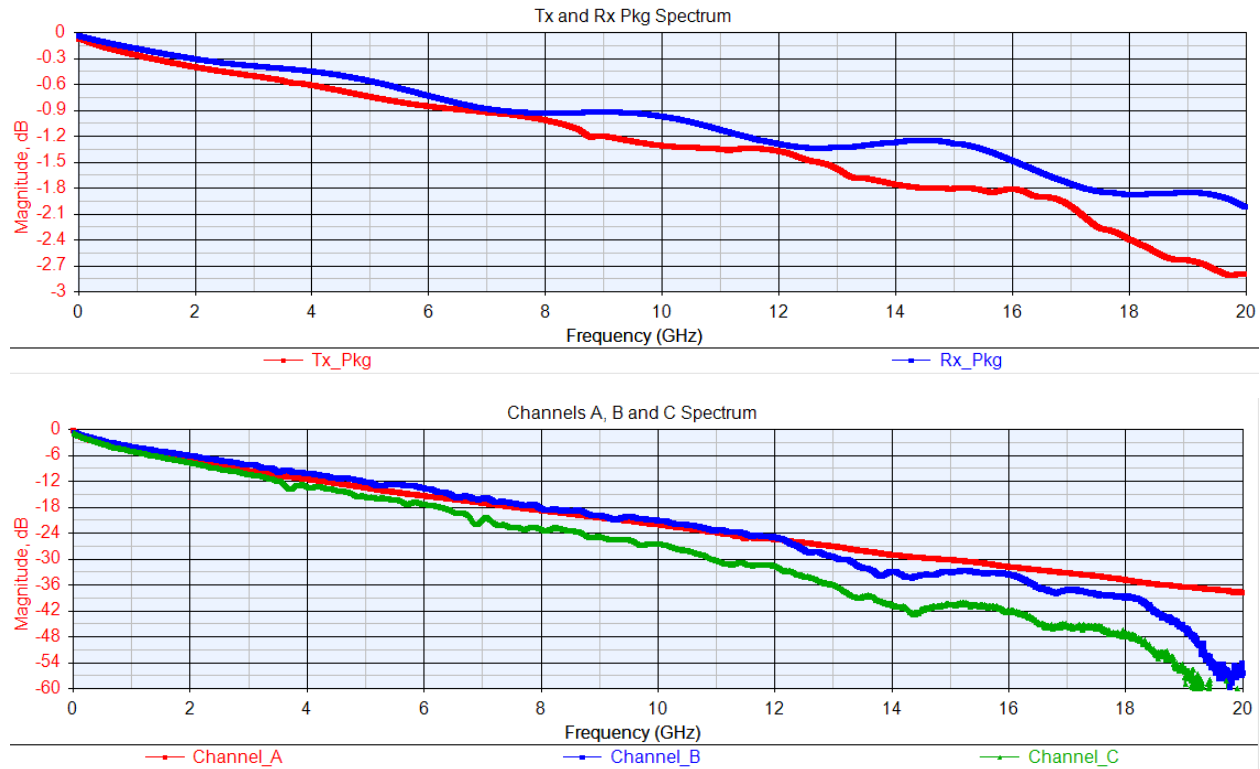
For test purposes, the SerDes system will use a bit pattern with a 28.125 Gbps bit rate and sampled at 32 samples per bit. Here is a listing of channels used as test cases.

Channel	Filename	Comment
Tx_Pkg	Tx_Pkg.s4p	Hardware measured transmit package S4P file
Rx_Pkg	Rx_Pkg.s4p	Hardware measured receive package S4P file
A	Channel_A.s4p	Hardware measured channel S4P file. Loss at 14.0625 GHz is -29.8 dB.
B	Channel_B.s4p	Hardware measured channel S4P file. Loss at 14.0625 GHz is -42.5 dB.
C	Channel_C.s4p	Hardware measured channel S4P file. Loss at 14.0625 GHz is -52.1 dB

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The S-parameter files represent hardware measured S-parameters for frequencies up to 20 GHz.

The frequency domain differential channel characteristics for these S4P files is shown here:



Loss in dB for each channel at 14.0625 GHz.

Channel	3.75 GHz	7.5 GHz	12.89 GHz	14.06 GHz
Tx_Pkg	-0.58	-0.96	-1.53	-1.76
Rx_Pkg	-0.43	-0.92	-1.33	-1.26
Channel_A	-11.05	-17.90	-26.80	-29.00
Channel_B	-9.73	-17.20	-28.70	-33.00
Channel_C	-13.50	-22.60	-35.60	-40.70

## Converting S-Parameters to Causal S-Parameters

The S-parameters for the channels were converted to Causal S-parameters using tools on the web site: <https://www.serdesdesign.com>.

See discussion at [About the Generate Causal SParameters Tool...](#) and [Typical Causal SParameters Characteristics and Displays...](#) to understand the problem inherent in using S-parameter files with time domain simulations and the benefits of using causal S-parameters and associated causal

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impulse response for portable and consistent S-parameter simulation results across different time domain simulation tools.

Using [www.serdesdesign.com/home/generate-causal-sparameters](http://www.serdesdesign.com/home/generate-causal-sparameters), each of the s4p files listed above were converted to causal s4p files using BitRate = 28.125 Gbps and SamplesPerBit = 32.

The resultant causal s4p files are:

Tx\_Pkg.s4p.causal.s4p

Rx\_Pkg.s4p.causal.s4p

Tx\_Pkg\_Rx\_Pkg.s4p.causal.s4p

Channel\_A.s4p.causal.s4p

Channel\_B.s4p.causal.s4p

Channel\_C.s4p.causal.s4p

Using [www.serdesdesign.com/home/generate-causal-sparameters](http://www.serdesdesign.com/home/generate-causal-sparameters), the original s4P and causal s4p frequency domain responses as well as their impulse responses can be compared.

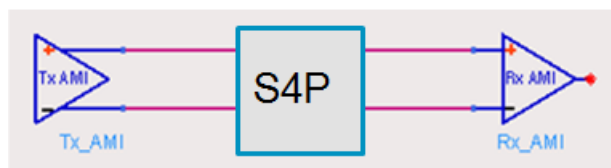
The Causal S-parameters are based on converting the S-parameters first to their causal impulse responses which are then converted into their Causal S-parameters. Thus, a s4p file is based on  $4 \times 4 = 16$  causal impulse responses which are then used to create the new Causal s4p.

The differential channel impulse response and frequency domain response for these Causal S-parameters will be discussed in the sections below in comparison with the original S-parameter data and the ADS generated impulse responses.

### **Modeling the Channel Impulse Response in ADS**

The ADS Channel Simulator, like all channel simulators, is based on the IBIS-AMI standard ([IBIS 6.1](#) ratified Sept 11, 2015) which defines the modeling of HSD IC Tx and Rx input/output buffers and the algorithmic model interface (AMI) for SerDes Tx and Rx equalization algorithms.

A simple SerDes system with Tx block, S4P channel and Rx block is shown here:

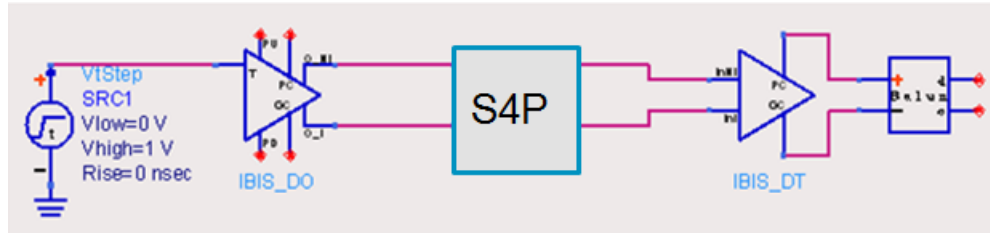


The Tx block includes a DSP based equalization input portion and a differential analog buffer output buffer portion. The Rx block includes a differential analog input buffer input portion and a DSP based equalization output portion. The combination of the Tx output analog buffer,

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channel (S4P), and Rx input analog buffer is assumed to be linear and time invariant (LTI). As a combined LTI block it can be modeled with an equivalent single ended impulse waveform.

Conceptually, ADS models this system internally with a Tx IBIS analog circuit, physical channel (S4P), Rx IBIS analog circuit and a balun:



The (unofficial) approach ADS takes to create the impulse model is as follows:

- A transient circuit simulation is performed with a step stimulus input to the Tx. Threshold crossing of the step function triggers the Tx IBIS model to transmit a rising edge into the channel.
- The step response is captured at the balun's differential output. When the response settles, the transient simulation is terminated.
- The impulse response is computed from the derivative of the step response.
- The Tx IBIS analog model includes rise/fall edge times and Tx impedance.
- The Rx IBIS analog model includes the Rx load/termination impedance.
- Reflections due to impedance mismatch, edge swing and shape, and common-differential mode conversion are included in the channel impulse response.

Key to this process is the conversion of the S4P data to its equivalent impulse response. Thus a 4 port S-parameter files has associated with it  $4 \times 4 = 16$  impulse responses.

Errors in the S-parameter impulse modeling results in errors in the channel impulse modeling.

### **ADS Impulse Models for the Example S-Parameter Test Cases**

For test case S4P files, an ADS impulse response was generated.

Within the ADS ChannelSim (channel simulation controller) one enables it to export the channel impulse models to text files by setting the 'Status Level' to 4 (by default it is 2 and no impulse model text file is produced).

Using BitRate = 28.125 Gbps and SamplesPerBit = 32, and an ideal Tx IBIS buffer, and an ideal Rx IBIS buffer, these ADS impulse response files were generated:

- ADS\_Impulse\_Tx\_Pkg.txt for Tx\_Pkg.s4p
- ADS\_Impulse\_Rx\_Pkg.txt for Rx\_Pkg.s4p
- ADS\_Impulse\_Channel\_A.txt for Channel\_A.s4p
- ADS\_Impulse\_Channel\_B.txt for Channel\_B.s4p
- ADS\_Impulse\_Channel\_C.txt for Channel\_C.s4p

### **Impulse responses in the time and frequency domains**

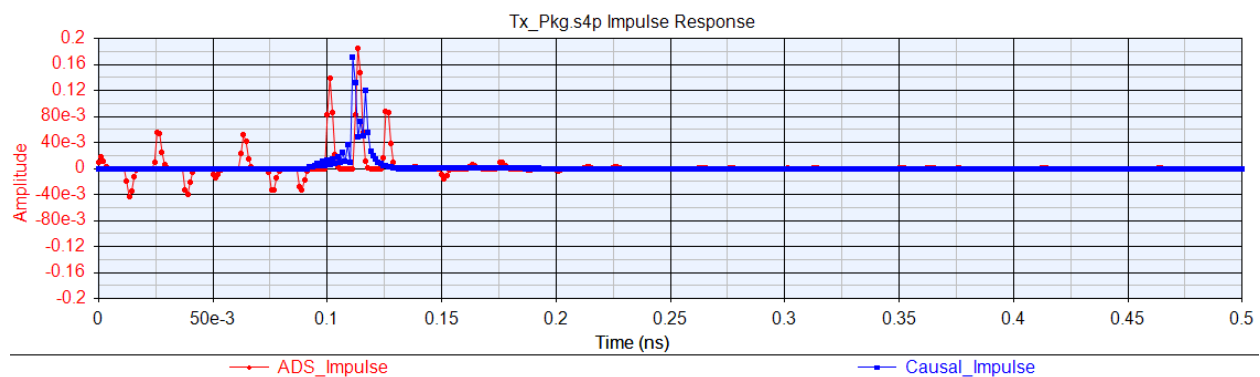
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These ADS channel impulse responses listed above are shown here for their time and frequency domain characteristics. Their responses are compared with the time domain response derived from the Causal S-parameters and with the frequency domain response from the original S4P files.

With BitRate = 28.125 Gbps and SamplesPerBit = 32, the maximum frequency content in the impulse response is one half the sample rate (time step) =  $0.5 \cdot \text{BitRate} \cdot \text{SamplesPerBit} = 450$  GHz. Though the S-parameters are measured up to 20 GHz. The process of creating the impulse response for that data results in higher frequency content in the impulse above 20 GHz.

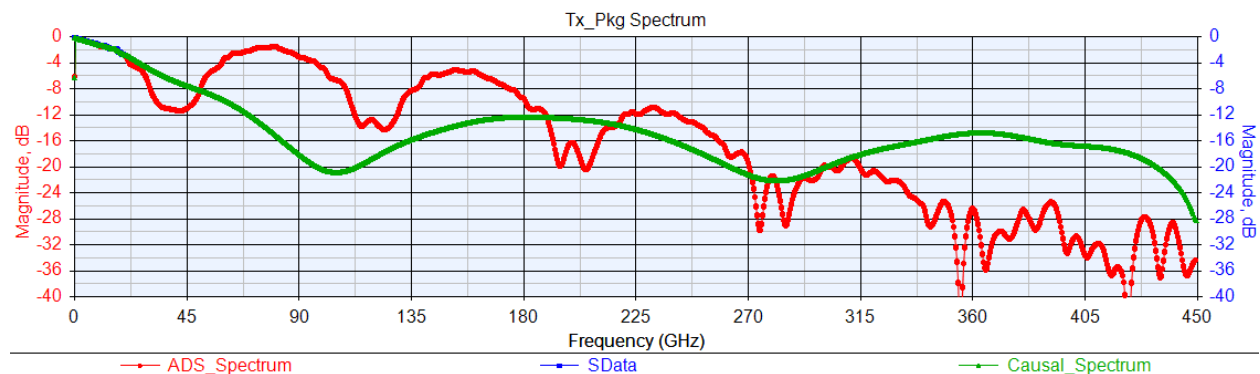
The frequency domain plots below will show the response up to 450 GHz as well as the response to the data upper limit of 20 GHz.

### Tx\_Pkg impulse time domain response



The ADS\_Impulse (red) has a lot of non-causal and high frequency artifacts before its peak. The Causal\_Impulse (blue) is zero up to 0.75 ns. Notice that the Causal\_Impulse is much shorter in length than the ADS\_Impulse.

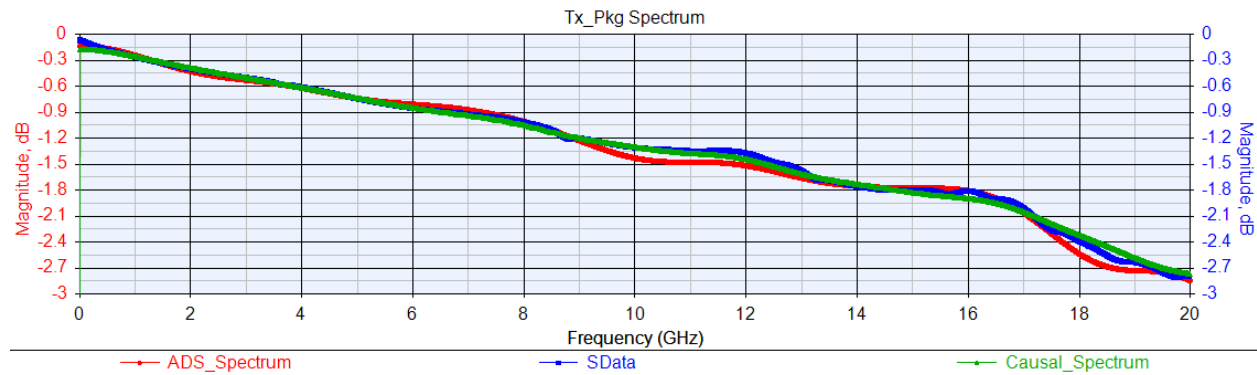
### Tx\_Pkg impulse frequency domain response (up to SampleRate/2 = 450 GHz)



Above the 20 GHz data limit, the ADS\_impulse (red) has high frequency aliasing. The Causal\_impulse (green) has a smooth roll off above 20 GHz.

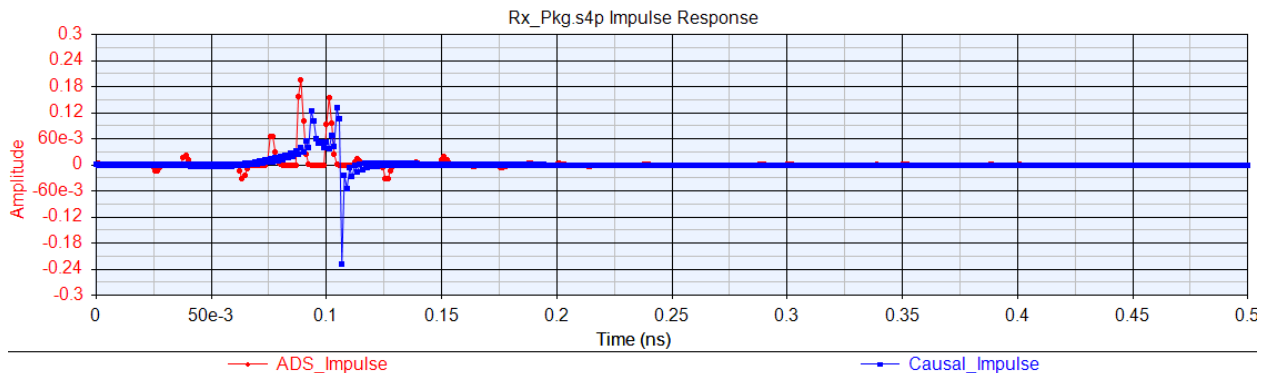
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### Tx\_Pkg impulse frequency domain response (up to 20 GHz)



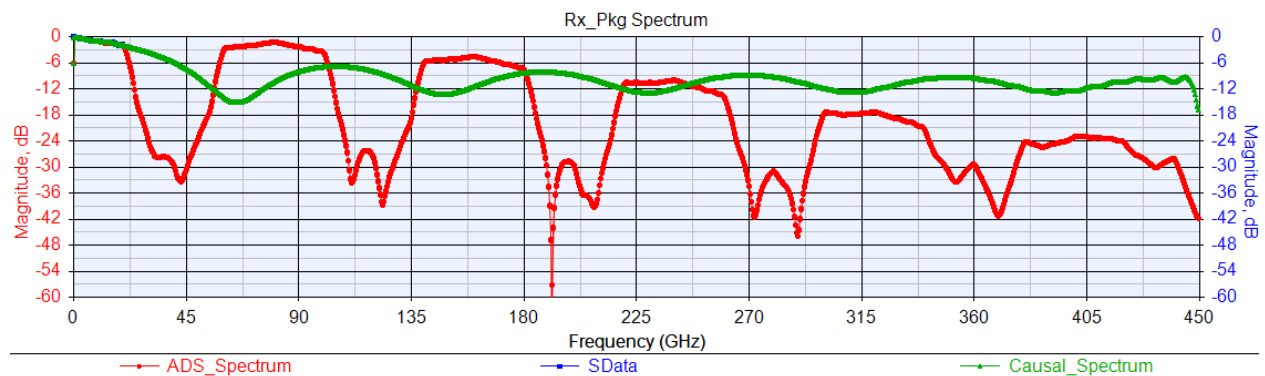
The raw SData is in blue. The ADS impulse (red) and the Causal\_Impulse (green) both align well with the SData. The Causal\_Impulse data better aligns with the SData.

### Rx\_Pkg impulse time domain response



The ADS\_Impulse (red) has a lot of non-causal and high frequency artifacts before its peak. The Causal\_Impulse (blue) is zero up to 0.65 ns. Notice that the Causal\_Impulse is much shorter in length than the ADS\_Impulse.

### Rx\_Pkg impulse frequency domain response (up to SampleRate/2 = 450 GHz)

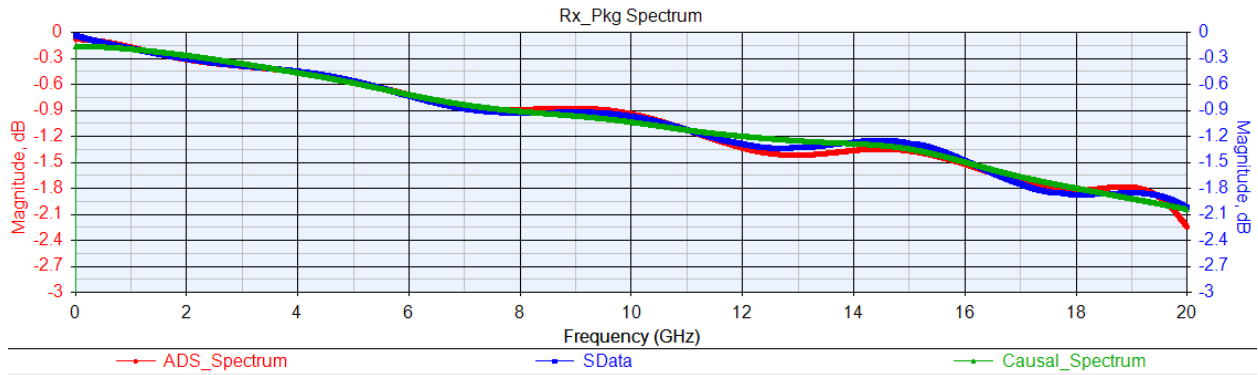


Above the 20 GHz data limit, the ADS\_impulse (red) has high frequency aliasing. The Causal\_impulse (green) has a smooth roll off above 20 GHz.



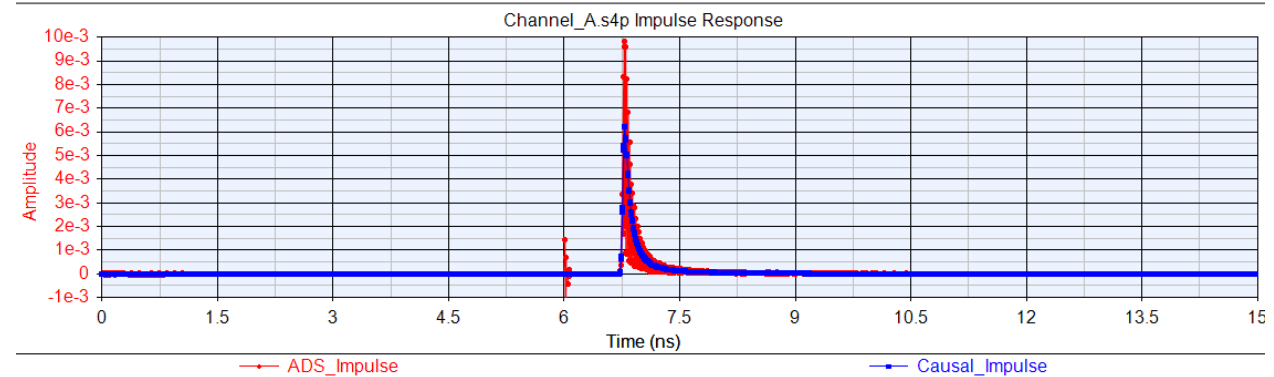
## SerDes\_Channel\_Impulse\_Modeling\_with\_Rambus

### Rx\_Pkg impulse frequency domain response (up to 20 GHz)



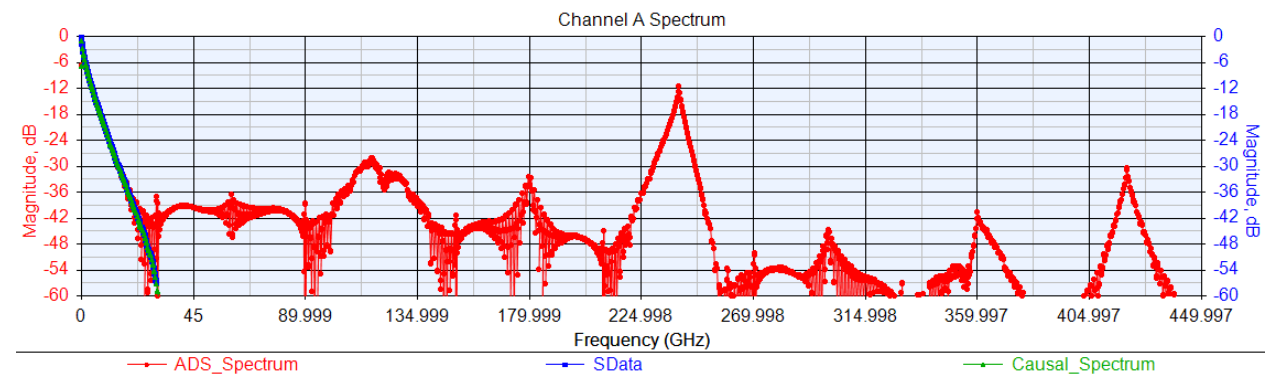
The raw SData is in blue. The ADS impulse (red) and the Causal\_Impulse (green) both align well with the SData. The Causal\_Impulse data better aligns with the SData.

### Channel\_A impulse time domain response



The ADS\_Impulse (red) has a lot of non-causal and high frequency artifacts before its peak. The Causal\_Impulse (blue) is zero up to 6.5 ns. Notice that the Causal\_Impulse is much shorter in length than the ADS\_Impulse.

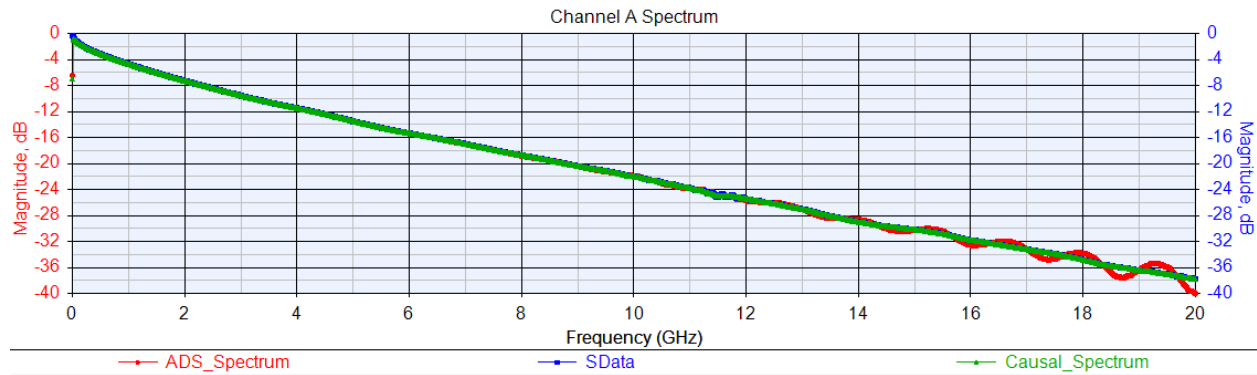
### Channel\_A impulse frequency domain response (up to SampleRate/2 = 450 GHz)



Above the 20 GHz data limit, the ADS\_impulse (red) has high frequency aliasing. The Causal\_impulse (green) has a smooth roll off above 20 GHz.

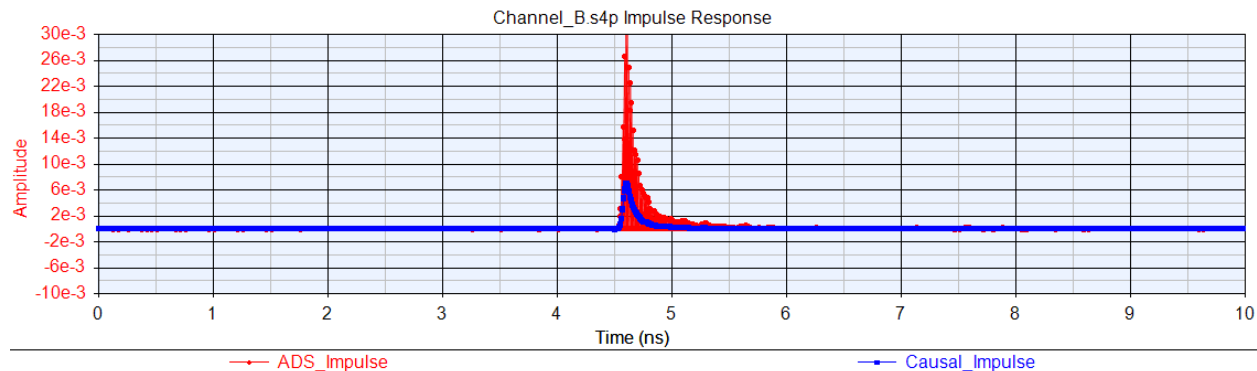
# SerDes\_Channel\_Impulse\_Modeling\_with\_Rambus

## Channel\_A impulse frequency domain response (up to 20 GHz)



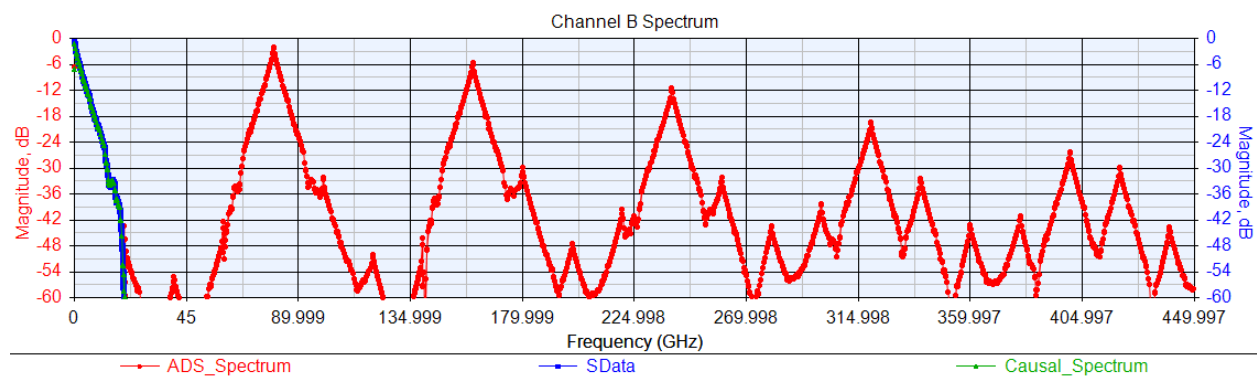
The raw SData is in blue. The ADS impulse (red) and the Causal\_Impulse (green) both align well with the SData. The Causal\_Impulse data better aligns with the SData.

## Channel\_B impulse time domain response



The ADS\_Impulse (red) has a lot of non-causal and high frequency artifacts. The Causal\_Impulse (blue) is zero up to 4.5 ns. Notice that the Causal\_Impulse is much shorter in length than the ADS\_Impulse.

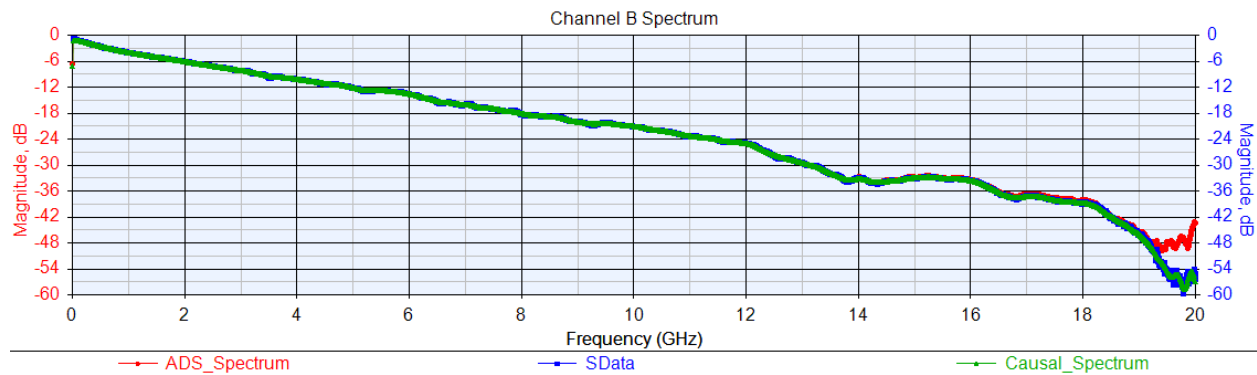
## Channel\_B impulse frequency domain response (up to SampleRate/2 = 450 GHz)



Above the 20 GHz data limit, the ADS\_impulse (red) has high frequency aliasing. The Causal\_impulse (green) has a smooth roll off above 20 GHz.

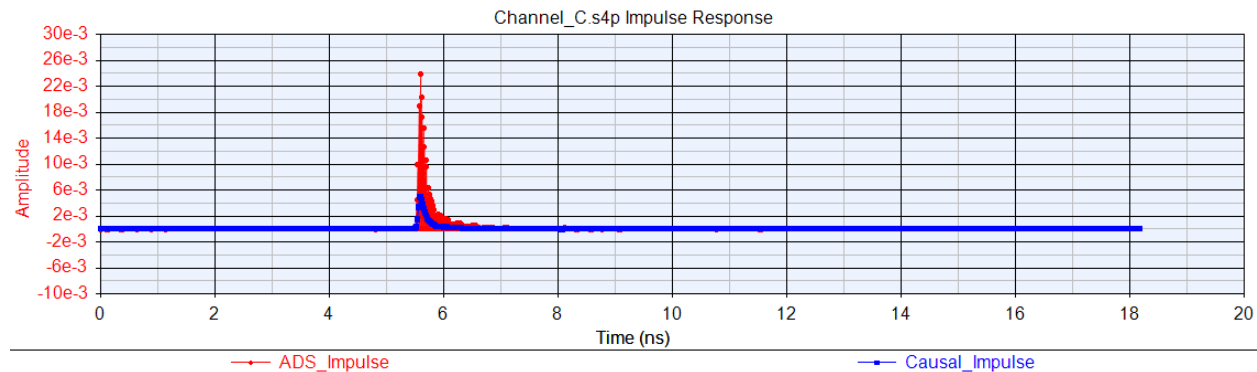
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## Channel\_B impulse frequency domain response (up to 20 GHz)



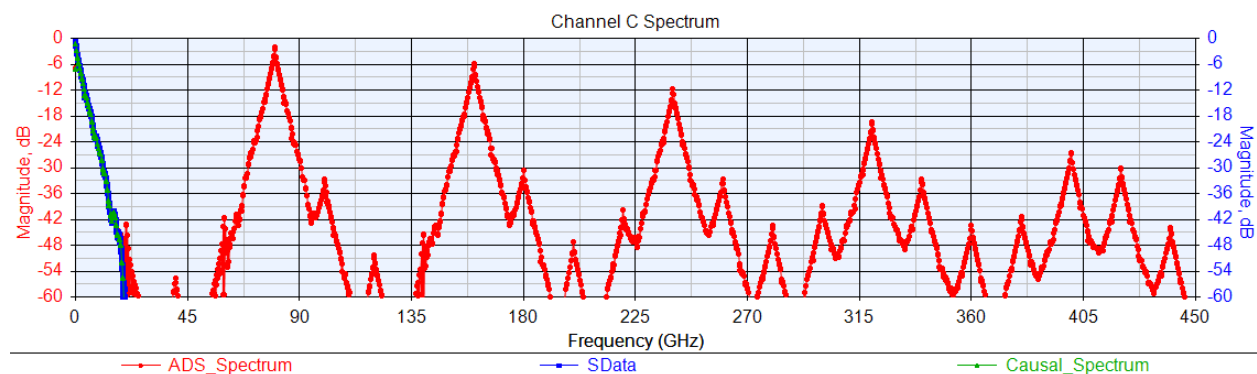
The raw SData is in blue. The ADS impulse (red) and the Causal\_Impulse (green) both align well with the SData. The Causal\_Impulse data better aligns with the SData.

## Channel\_C impulse time domain response



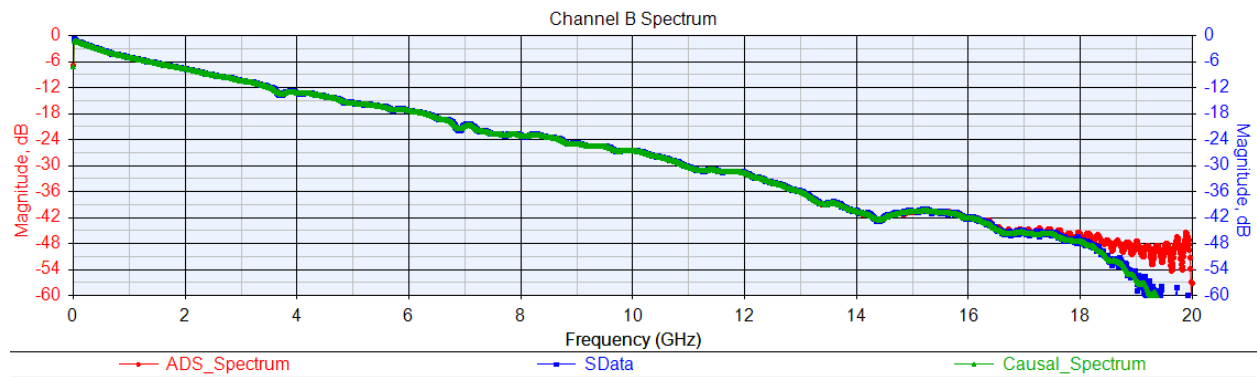
The ADS\_Impulse (red) has a lot of non-causal and high frequency artifacts. The Causal\_Impulse (blue) is zero up to 5.5 ns. Notice that the Causal\_Impulse is much shorter in length than the ADS\_Impulse.

## Channel\_C impulse frequency domain response (up to SampleRate/2 = 450 GHz)



Above the 20 GHz data limit, the ADS\_impulse (red) has high frequency aliasing. The Causal\_impulse (green) has a smooth roll off above 20 GHz.

## Channel\_C impulse frequency domain response (up to 20 GHz)



The raw SData is in blue. The ADS impulse (red) and the Causal\_Impulse (green) both align well with the SData. The Causal\_Impulse data better aligns with the SData.

The above shows that the Causal S-parameters align very well with the original S-parameters up to its high frequency limit and additionally, beyond that high frequency limit, rolls off smoothly and does not have any high frequency aliasing. The time domain impulse responses shows that the Causal Impulse responses are smoothly varying with no high frequency artifacts and with zero level for the transit delay of the differential channel.

The use of the Causal S-parameters in ADS will result in realistic and accurate eye and BER performance.

## High Frequency Aliasing Effects on Eye Diagrams and BER Plots

The prior section showed that the ADS impulse response for frequency band limited S-parameters results in high frequency aliasing. This is visible in the time and frequency domain representations of the impulse response. Furthermore, it was shown that the use of Causal S-Parameters does not result in any high frequency aliasing.

Though the ADS band limited impulse and the Causal S-Parameters impulse both overlap the differential channel frequency domain characteristic over the limited frequency band of the original S-parameters, a key questions is: **What impact does the high frequency aliasing have on eye diagrams and BER plots?**

This question will be investigated with various test conditions.

Test 1. Tx Pkg alone: Impulse for band limited differential S-parameters low loss.

Test 2. Tx Pkg + Rx AFE: Tx Pkg with low loss plus Rx AFE IBIS-AMI model relying on AFE state optimization for the channel impulse response provided by the ADS Channel Simulator.

Test 3. Tx Pkg + Tx FFE: Tx Pkg with low loss plus Tx FFE IBIS-AMI model relying on a FFE state optimization for the channel impulse response provided by the ADS Channel Simulator.

Test 4. Channel A + Tx FFE: Channel A with high loss plus Tx FFE IBIS-AMI model relying on FFE state optimization for the channel impulse response provided by the ADS Channel Simulator.

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Test will be performed using the Rambus Tx FFE and Rx AFE IBIS-AMI models.

The Rambus Tx IBIS-AMI model is an LTI (linear time invariant) model with a three tap FFE (feed forward equalizer) followed by a low pass filter. FFE tap optimization is based on a MMSE (minimum mean square error) approach that samples the impulse at one sample per bit and mathematically derives the optimal tap values to provide the closest approximation to optimal raised cosine filtering. The tap value are then reset to the closest values in the defined tap code tables. The noise in the model was turned off for these tests.

The Rambus Rx IBIS-AMI model is for an LTI AFE (analog front end) with four sections defining the cascade of an Attenuator, CTLE (continuous time linear equalizer), VAGC1 (voltage automatic gain control) and VAGC2. Each of these four LTI sections have multiple states defining various gain and filtering options. Combined, the AFE has over 65,000 possible state combinations. AFE state optimization is based on a multi-pass optimization approach that filters the full impulse sequentially with each section to obtain the optimal state settings for each section that provides the best eye opening. The noise in the model was turned off for these tests.

Tests were done using these sets of tool configurations.

1. ADS using band limited Channel S-parameter file.
2. ADS using Causal S-parameter exported from SerDesDesign.com

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## Test 1: Tx Pkg.

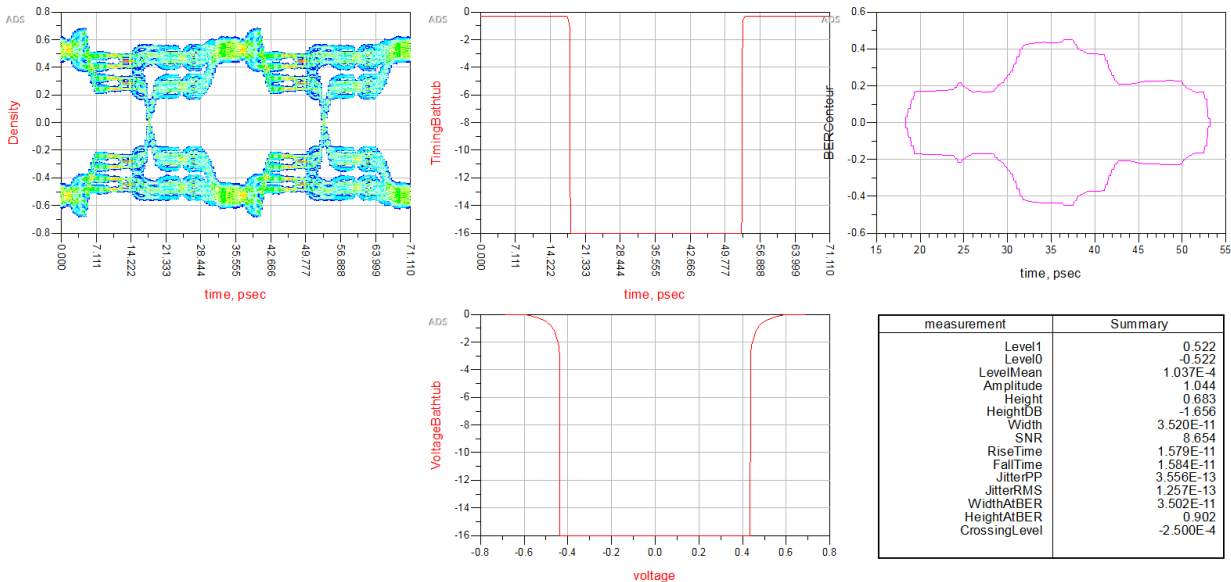
Tx Pkg is used to test the ADS impulse effects on the eye diagram. Tx Pkg represents a typical low loss channel.

The Tx Pkg s-parameters are band limited to 20 GHz and the associated ADS impulse response has high frequency aliasing, as shown earlier, at frequencies above 20 GHz up to 450 GHz (which is half the sample rate for 28.125 Gbps with 32 samples per bit).

The Tx Pkg Causal S-Parameters, as shown earlier, do not have high frequency aliasing.

### Using ADS with bandlimited S-Parameters

ADS eye diagram and BER plots using band limited Tx Pkg (impulse model contains high frequency aliasing):

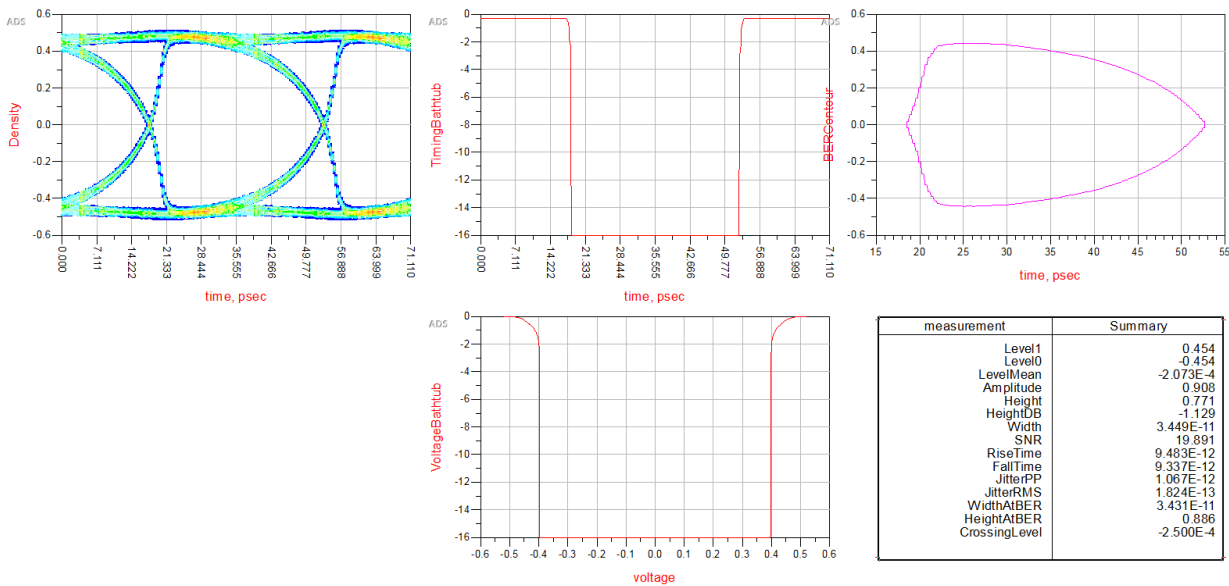


This eye diagram clearly has unrealistic artifacts. This is typical for the impulse model generated by ADS for a low loss channel. If the eye diagram has distortions, then the BER plots are also questionable since they are derived from the eye density plots.

### Using ADS with Causal S-Parameters

ADS eye diagram and BER plots using Tx Pkg Causal S-Parameters (impulse model does not contain high frequency aliasing). The Causal S-Parameters were obtained from SerDesDesign.com:

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This eye does not have the distortions shown by ADS when using the band limited S-Parameters. Also, since the eye does not have distortions, the BER plots are good since they are derived from the eye density plot.

### Test 2: Tx Pkg + Rx AFE.

Tx Pkg is used to test the ADS impulse effects on the eye diagram with the Rx IBIS-AMI model. Tx Pkg represents a typical low loss channel.

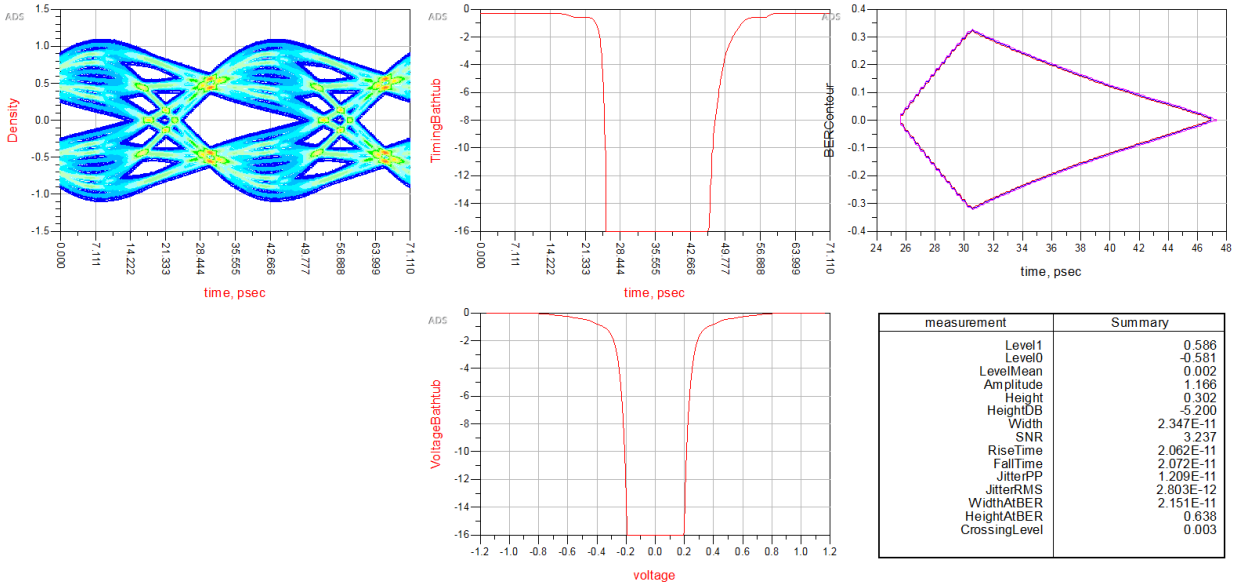
The Tx Pkg s-parameters are band limited to 20 GHz and the associated ADS impulse response has high frequency aliasing, as shown earlier, at frequencies above 20 GHz up to 450 GHz (which is half the sample rate for 28.125 Gbps with 32 samples per bit).

The Tx Pkg Causal S-Parameters, as shown earlier, do not have high frequency aliasing.

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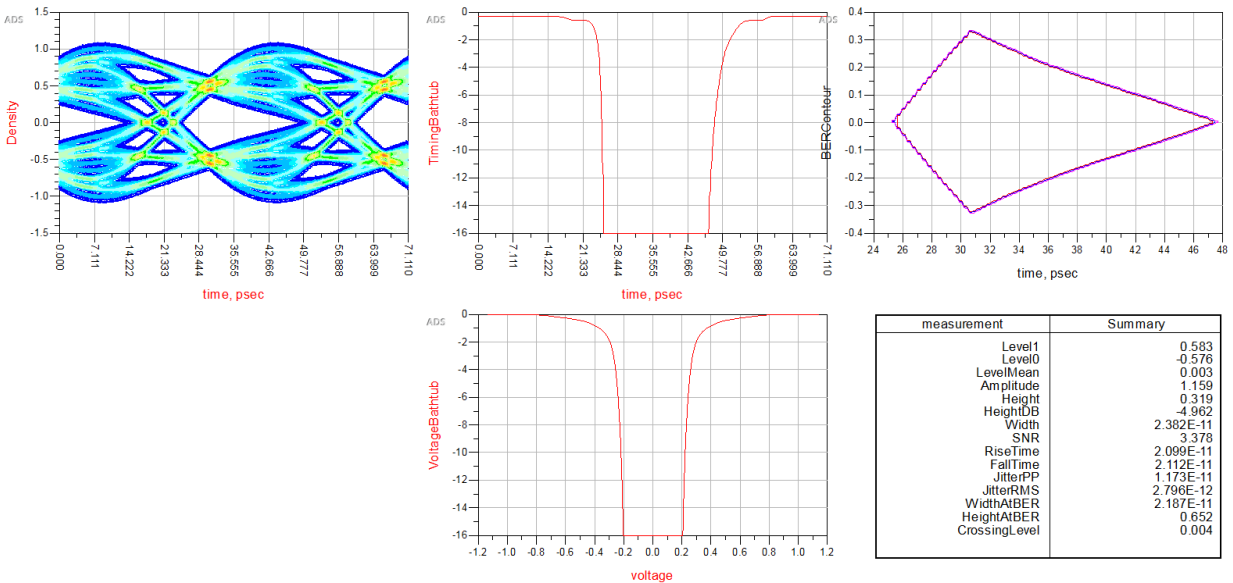
## Using ADS with bandlimited S-parameters

ADS eye diagram, BER plots using band limited Tx Pkg S-Parameters (impulse model contains high frequency aliasing) with Rx AFE:



## Using ADS with Causal S-Parameters

ADS eye diagram, BER plots using Tx Pkg Causal S-Parameters (impulse model does not contain high frequency aliasing) with Rx AFE. The Causal S-Parameters were obtained from SerDesDesign.com:



The eye diagram and metrics for the band-limited S-parameters are similar to that achieved with use of the Causal S-Parameters.

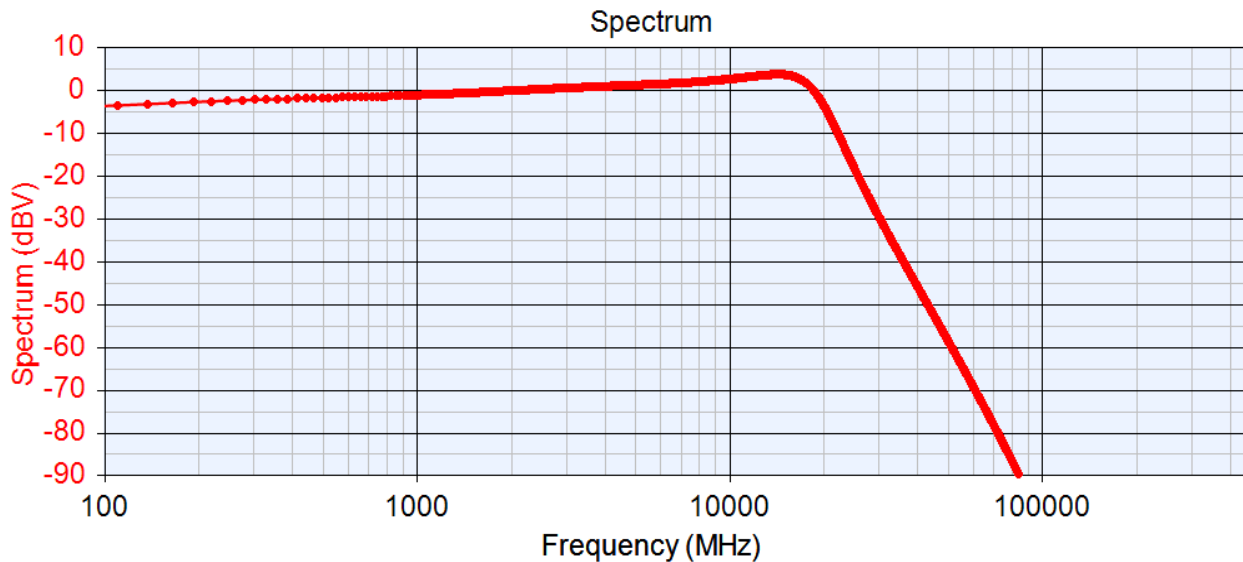


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The Rx AFE optimized states differ from those optimized with use of the band limited S-Parameters. When there is greater concern about the actual optimized Rx AFE states, then use of the Causal S-Parameters is recommended.

The Rx IBIS-AMI model frequency domain response with the equalizer state settings is shown here:



As can be seen, the Rx AFE has a sharp roll off above Nyquist (14 GHz). Thus the Rx AFE substantially filters out the ADS high frequency aliasing when the band limited Tx Pkg s-parameters are used.

### **Test 3: Tx Pkg + Tx FFE.**

Tx Pkg is used to test the ADS impulse effects on the eye diagram with the Tx IBIS-AMI model. Tx Pkg represents a typical low loss channel.

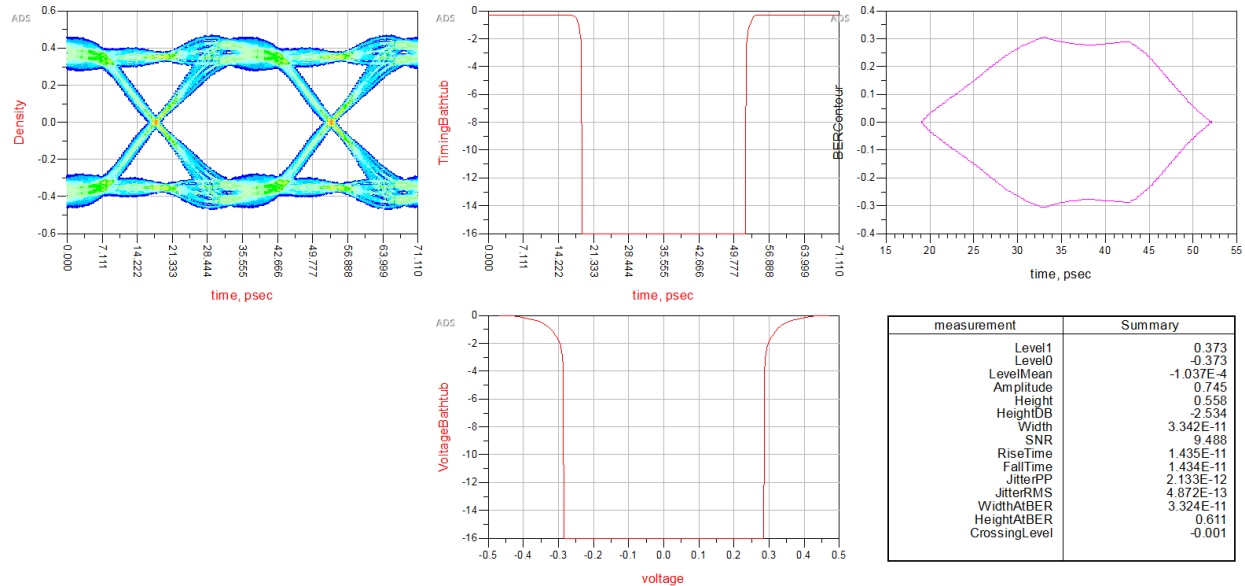
The Tx Pkg s-parameters are band limited to 20 GHz and the associated ADS impulse response has high frequency aliasing, as shown earlier, at frequencies above 20 GHz up to 450 GHz (which is half the sample rate for 28.125 Gbps with 32 samples per bit).

The Tx Pkg Causal S-Parameters, as shown earlier, do not have high frequency aliasing.

# SerDes\_Channel\_Impulse\_Modeling\_with\_Rambus

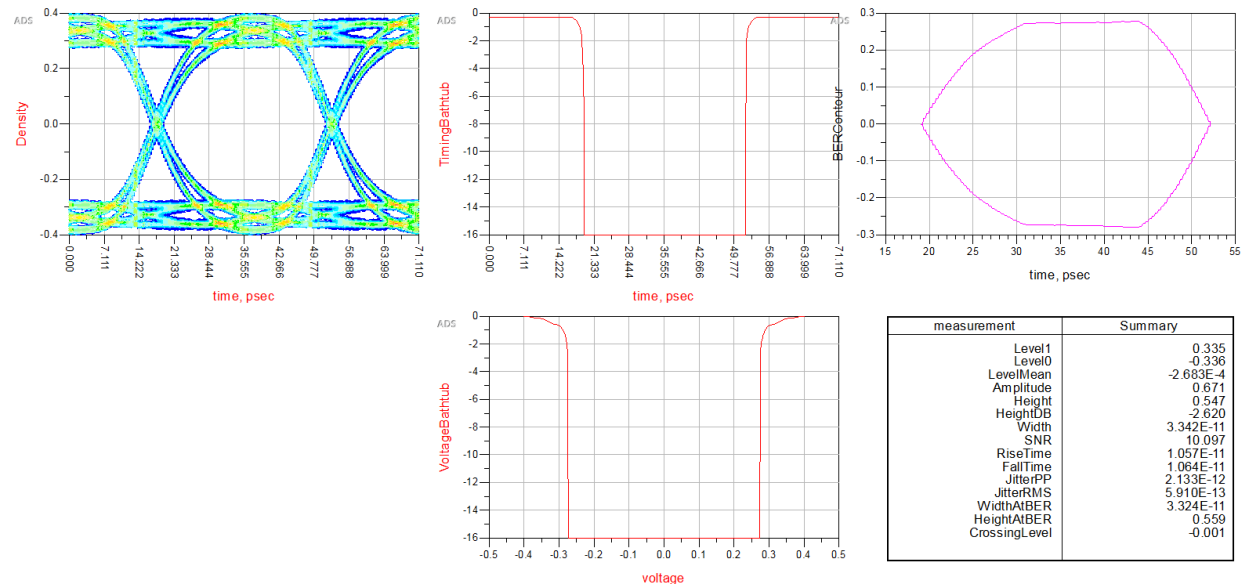
## Using ADS with bandlimited S-Parameters

ADS eye diagram, BER plots using band limited Tx Pkg S-Parameters (impulse model contains high frequency aliasing) with Tx FFE:



## Using ADS with Causal S-Parameters

ADS eye diagram, BER plots using Tx Pkg Causal S-Parameters (impulse model does not contain high frequency aliasing) with Tx FFE. The Causal S-Parameters were obtained from SerDesDesign.com:



## SerDes\_Channel\_Impulse\_Modeling\_with\_Rambus

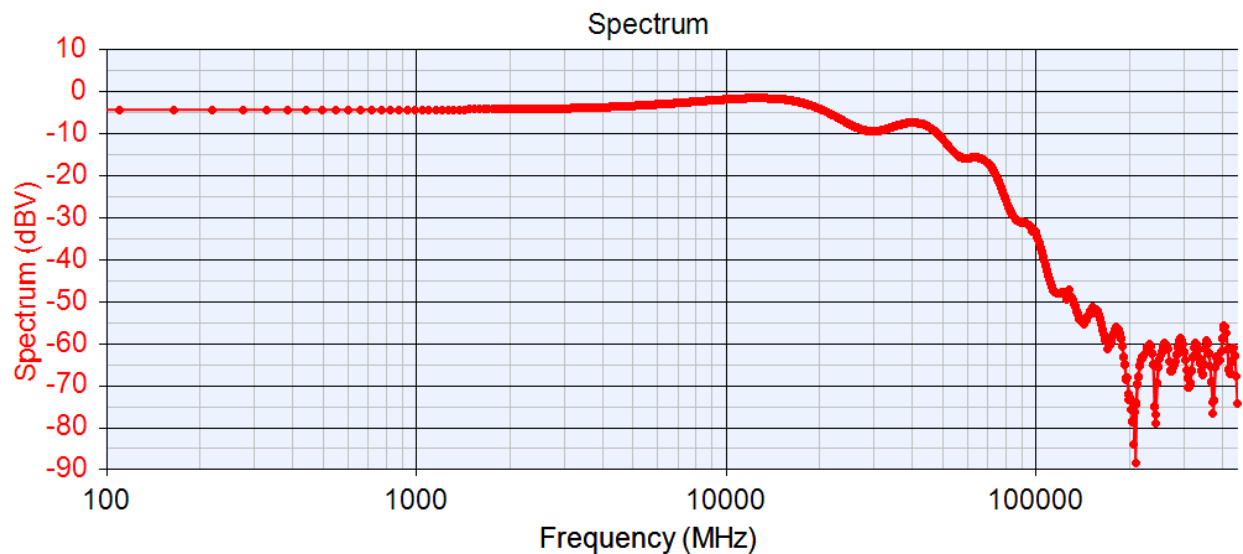
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The eye diagram and metrics for the band-limited S-parameters are similar, but noticeably different, than that achieved with use of the Causal S-Parameters. The ADS eye using the band limited S-Parameters is lacking the fidelity seen in the ADS eye using the Causal S-Parameters.

The BER plots using the Causal S-Parameters would be better than that obtained using the band limited S-Parameters since the BER data is derived from the eye histogram data.

The Tx FFE optimized states differ from those optimized with use of the band limited S-Parameters. When there is greater concern about the actual optimized Tx FFE states, then use of the Causal S-Parameters is recommended.

The Tx IBIS-AMI model frequency domain response with the listed FFE tap settings is shown here:



As can be seen, the Tx FFE does have some roll off above Nyquist (14 GHz). Thus the Tx FFE filters out only some of the ADS high frequency aliasing when the band limited Tx Pkg s-parameters are used.

# SerDes\_Channel\_Impulse\_Modeling\_with\_Rambus

## Test 4: Channel A + Tx FFE.

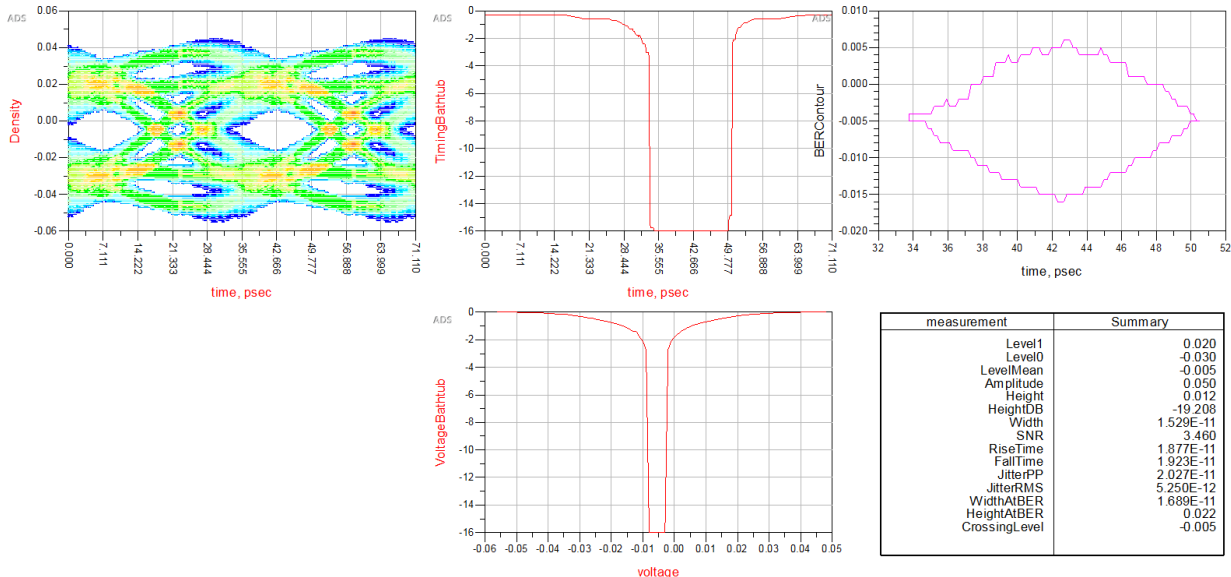
Channel\_A is used to test the ADS impulse effects on the eye diagram with the Tx IBIS-AMI model. Channel\_A represents a typical medium loss channel.

The Channel\_A s-parameters are band limited to 20 GHz and the associated ADS impulse response has high frequency aliasing, as shown earlier, at frequencies above 20 GHz up to 450 GHz (which is half the sample rate for 28.125 Gbps with 32 samples per bit).

The Channel\_A Causal S-Parameters, as shown earlier, do not have high frequency aliasing.

### Using ADS with bandlimited S-Parameters

ADS eye diagram, BER plots using band limited Channel\_A S-Parameters (impulse model contains high frequency aliasing) with Tx FFE:



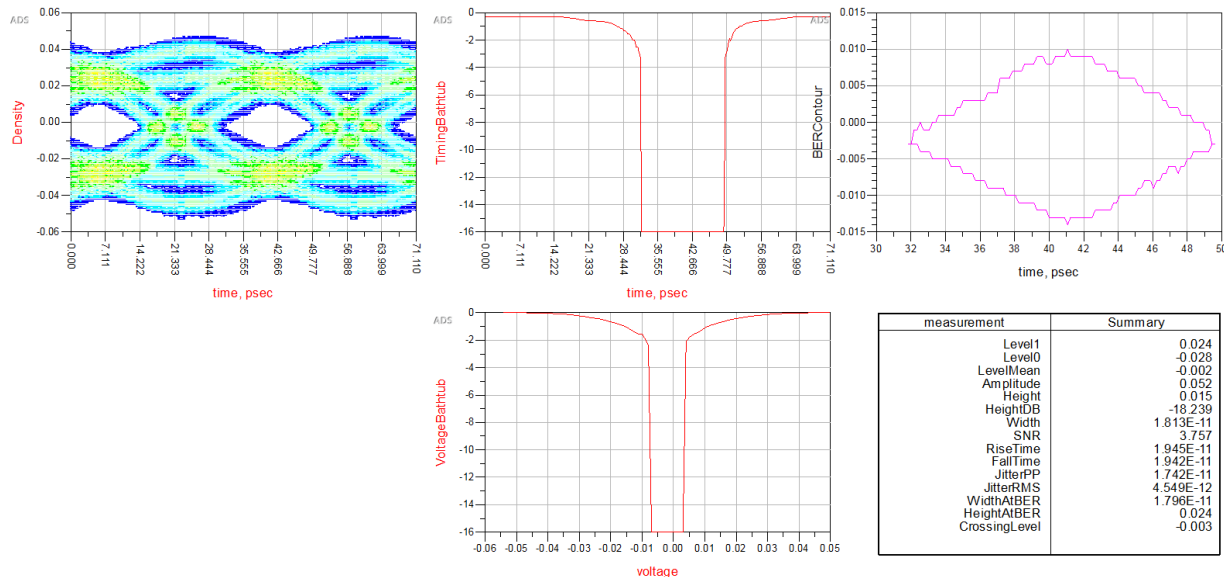
The ADS eye diagram has a vertical offset from the y-axis zero volts. This is an artifact of the ADC Channel Simulator and not the S-Parameters. This error in the ADS eye diagram is apparent in the Voltage Bathtub BER curve which shows the low BER totally to the left of the x-axis zero volts.

Additionally, the eye diagram is not centered in the time domain (x-axis). The ADS Channel Simulator appears to have a problem with this channel and offsets the eye to the right of the x-axis midpoint of 35.6 psec.

# SerDes\_Channel\_Impulse\_Modeling\_with\_Rambus

## Using ADS with Causal S-Parameters

ADS eye diagram, BER plots using Channel\_A Causal S-Parameters (impulse model does not contain high frequency aliasing) with Tx FFE. The Causal S-Parameters were obtained from SerDesDesign.com:



Again, for this case with the Causal S-Parameter, the eye diagram is not centered in the time domain (x-axis). The ADS Channel Simulator appears to have had a problem with this channel and offset the eye to the right of the x-axis midpoint of 35.6 psec.

This is an ADS Channel Simulator artifact and is not due to the S-Parameters.

Since errors exist in the eye histogram data, then the BER data cannot be considered to be high fidelity either since they are derived from the eye histogram data.

As shown in this section, ADS can provide good eye diagram and BER results under these conditions.

- Channels modeled using Causal S-Parameters
- Channels modeled using band limited S-Parameters with IBIS-AMI models that have substantial filtering above the Nyquist frequency

However, also shown in this section, ADS DOES NOT provide best eye diagram or BER results under these conditions.

- Channels modeled using band limited S-Parameters with IBIS-AMI models that DO NOT have substantial filtering above the Nyquist frequency.
- Some channel conditions (either with band limited or Causal S-Parameters) that result in the ADS Channel Simulator introducing offsets in the eye diagram horizontal (time, x-axis) or vertical (voltage, y-axis) dimensions.

## SerDes\_Channel\_Impulse\_Modeling\_with\_Rambus

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Additionally, when there is greater concern about the actual optimized Tx FFE and Rx AFE states, then use of the Causal S-Parameters is recommended.

The next sections discusses the same four test cases with results from SerdesDesign.com which does not have any of the ADS limitations noted above.

## Eye and BER Plots from SerDesDesign.com

The simulations run in ADS using the band limited S-parameters were also run on SerDesDesign.com. As discussed above, this web site inherently converts band limited S-parameter data into its causal time domain representation with no high frequency aliasing.

Shown here are the SerDesign.com results for the same test cases:

Test 1. Tx Pkg alone

Test 2. Tx Pkg + Rx AFE

Test 3. Tx Pkg + Tx FFE

Test 4. Channel A + Tx FFE

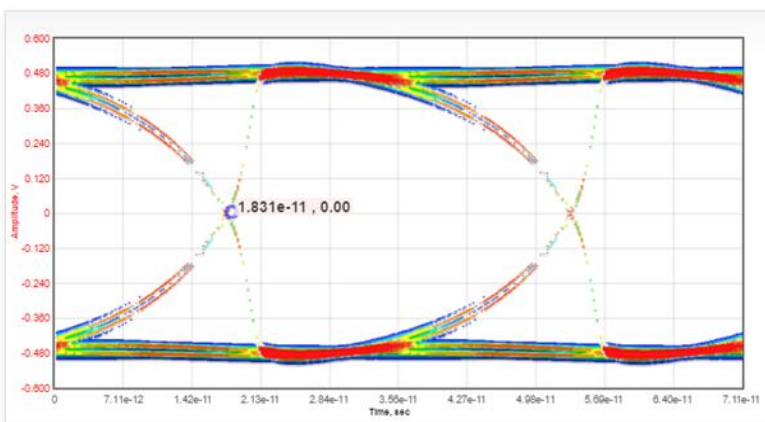
### Test 1: Tx Pkg alone.

The Tx Pkg s-parameters are band limited to 20 GHz.

### Using SerDesDesign.com with bandlimited S-parameters

Eye diagram and BER plots and eye metrics using band limited Tx Pkg S-Parameters.

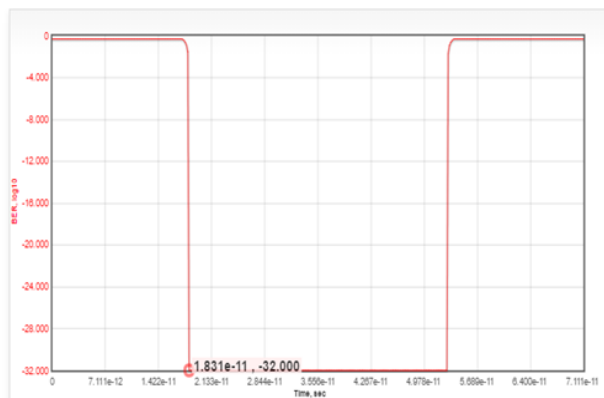
Eye density plot vs time



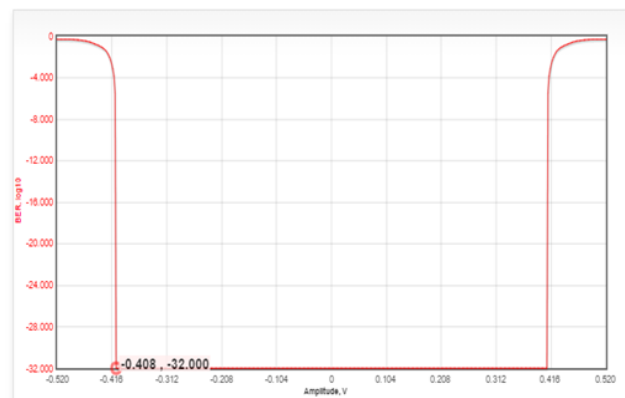
Eye metrics:

Level0 = -0.455321  
Level1 = 0.455323  
LevelMean = 1.1892e-06  
LevelPP = 0.910644  
Height3Sigma = 0.828326  
Height6Sigma = 0.820001  
Width3Sigma = 3.48444e-11 in sec.  
Width6Sigma = 3.48444e-11 in sec.  
Jitter3Sigma = 3.55556e-13 in sec.  
Jitter6Sigma = 3.55556e-13 in sec.  
RiseTime = 8.60084e-12 in sec.  
FallTime = 8.5587e-12 in sec.

Eye bathtub BER vs time



Eye bathtub BER vs amplitude



## SerDes\_Channel\_Impulse\_Modeling\_with\_Rambus

The eye and BER plots are much better than the ADS results when both use band limited S-Parameters.

However, the ADS eye and BER plots obtained using the Causal S-Parameters generated by SerDesDesign.com agree with the SerDesDesign.com results using the band limited S-Parameters.

This shows the portability of the Causal S-Parameters to another Channel Simulator, ADS in this case, to achieve consistent eye and BER results.

Note that the SerDesDesign.com BER plots show performance down to  $10^{-32}$  whereas the default for ADS is to show BER performance down to  $10^{-16}$ .

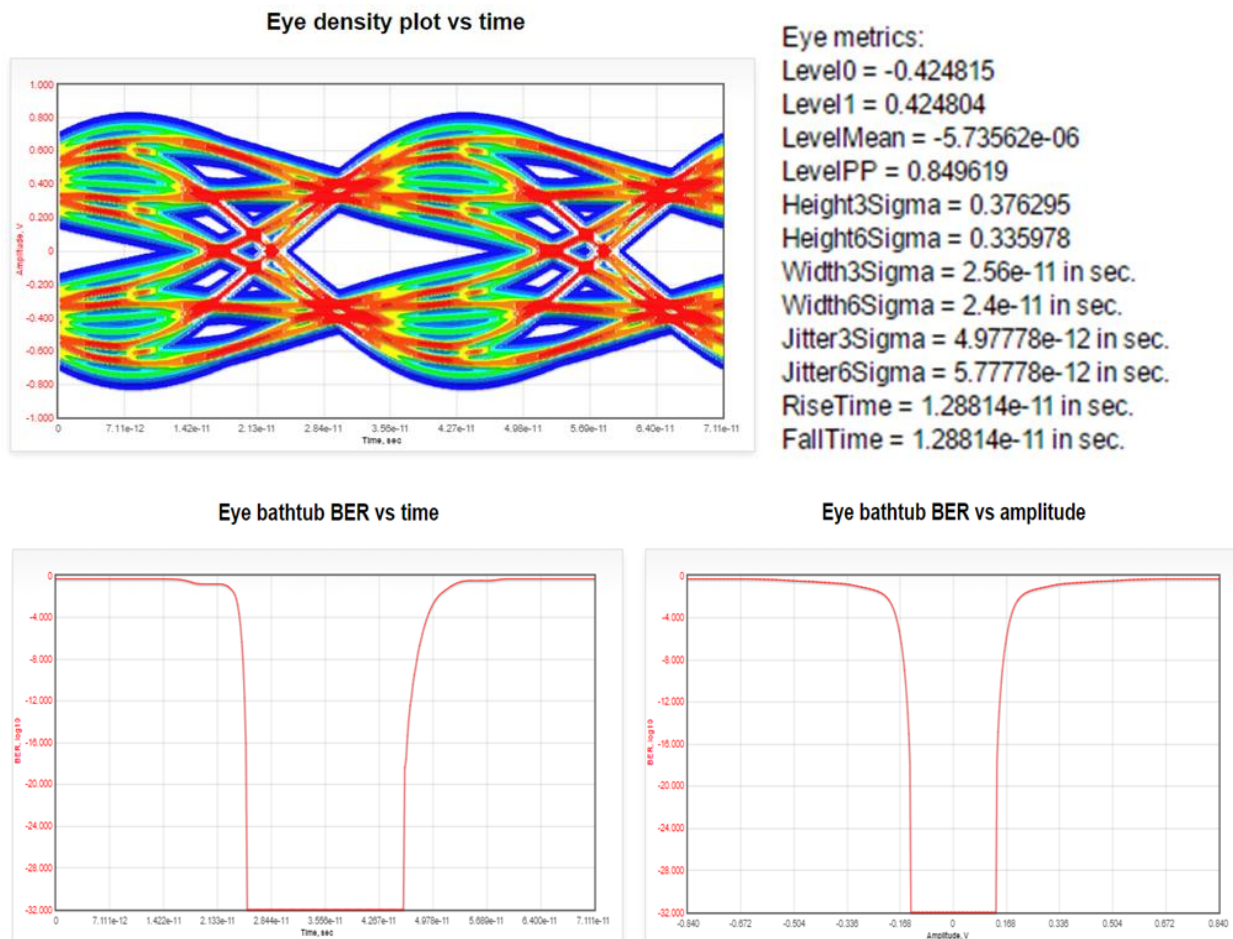
Note also that the SerDesDesign.com eye plot shows more color differentiation than does the ADS eye plot.

### **Test 2: Tx Pkg + Rx AFE.**

The Tx Pkg s-parameters are band limited to 20 GHz.

#### Using SerDesDesign.com with bandlimited S-parameters

Eye diagram, BER plots and eye metrics using band limited Tx Pkg S-Parameters and Rx AFE:





## SerDes\_Channel\_Impulse\_Modeling\_with\_Rambus

The eye and BER plots are much better than the ADS results when both use band limited S-Parameters.

However, the ADS eye and BER plots obtained using the Causal S-Parameters generated by SerDesDesign.com agree with the SerDesDesign.com results using the band limited S-Parameters.

This shows the portability of the Causal S-Parameters to another Channel Simulator, ADS in this case, to achieve consistent eye and BER results.

Note that the SerDesDesign.com BER plots show performance down to  $10^{-32}$  whereas the default for ADS is to show BER performance down to  $10^{-16}$ .

Note also that the SerDesDesign.com eye plot shows more color differentiation than does the ADS eye plot.

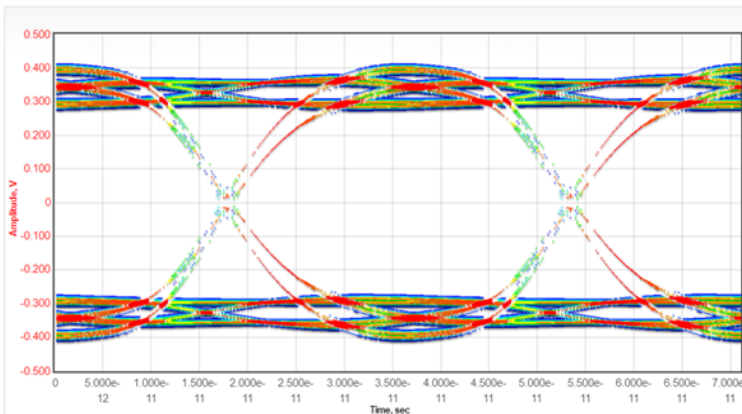
### Test 3: Tx Pkg + Tx FFE.

The Tx Pkg s-parameters are band limited to 20 GHz.

#### Using SerDesDesign.com with bandlimited S-parameters

Eye diagram, BER plots and eye metrics using band limited Tx Pkg S-Parameters and Tx FFE:

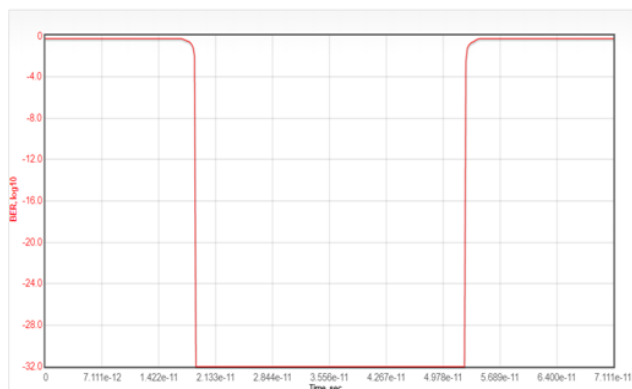
Eye density plot vs time



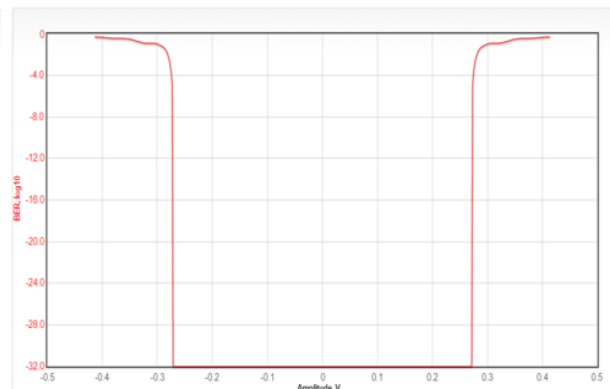
Eye metrics:

Level0 = -0.342768  
Level1 = 0.342765  
LevelMean = -1.17007e-06  
LevelPP = 0.685533  
Height3Sigma = 0.552599  
Height6Sigma = 0.545981  
Width3Sigma = 3.39556e-11 in sec.  
Width6Sigma = 3.39556e-11 in sec.  
Jitter3Sigma = 8e-13 in sec.  
Jitter6Sigma = 8e-13 in sec.  
RiseTime = 1.08529e-11 in sec.  
FallTime = 1.0853e-11 in sec.

Eye bathtub BER vs time



Eye bathtub BER vs amplitude



## SerDes\_Channel\_Impulse\_Modeling\_with\_Rambus

The eye and BER plots are much better than the ADS results when both use band limited S-Parameters.

However, the ADS eye and BER plots obtained using the Causal S-Parameters generated by SerDesDesign.com agree with the SerDesDesign.com results using the band limited S-Parameters.

This shows the portability of the Causal S-Parameters to another Channel Simulator, ADS in this case, to achieve consistent eye and BER results.

Note that the SerDesDesign.com BER plots show performance down to  $10^{-32}$  whereas the default for ADS is to show BER performance down to  $10^{-16}$ .

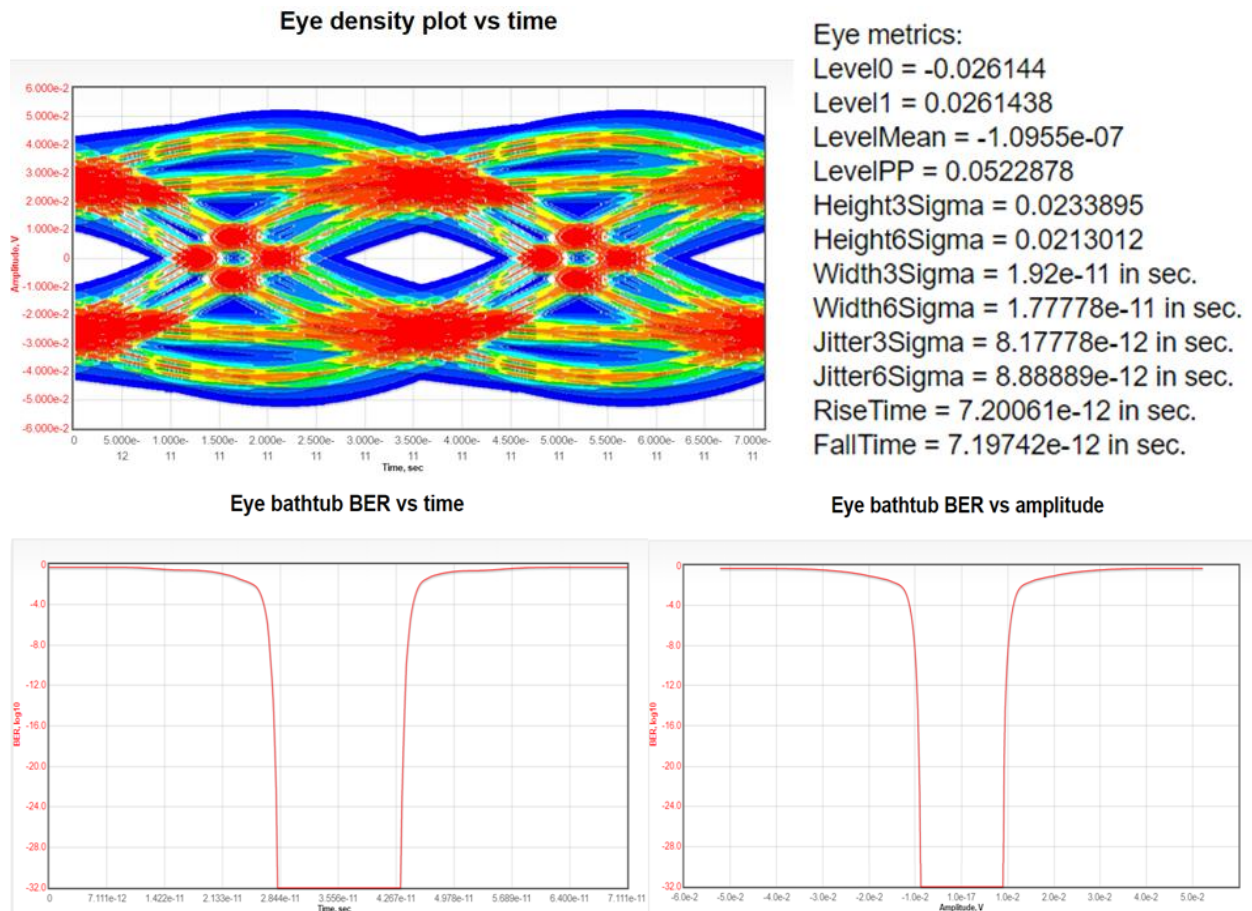
Note also that the SerDesDesign.com eye plot shows more color differentiation than does the ADS eye plot.

### **Test 4: Channel A + Tx FFE.**

The Channel\_A s-parameters are band limited to 20 GHz.

#### Using SerDesDesign.com with bandlimited S-parameters

Eye diagram, BER plots and eye metrics using band limited Channel\_A S-Parameters and Tx FFE:



# SerDes\_Channel\_Impulse\_Modeling\_with\_Rambus

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The eye and BER plots are much better than the ADS results when both use band limited S-Parameters.

Additionally, the ADS eye plot obtained using the Causal S-Parameters generated by SerDesDesign.com inherently has x and y axis offsets as an artifact of the ADS Channel Simulator and not due to the S-Parameters.

Thus, the ADS results using the Causal S-Parameters, though closer to the SerDesDesign.com results, are different due to the ADS induces eye offsets.

Nonetheless, this test still shows the portability of the Causal S-Parameters to another Channel Simulator, ADS in this case, to achieve better eye and BER results.

Note that the SerDesDesign.com BER plots show performance down to  $10^{-32}$  whereas the default for ADS is to show BER performance down to  $10^{-16}$ .

Note also that the SerDesDesign.com eye plot shows more color differentiation than does the ADS eye plot.

## **Topics for further study**

The use of Keysight ADS to generate channel impulse responses was performed in collaboration with Rambus using their ADS copy. Not all of the channel configurations of interest were studied. For further study, it is desirable to record additional impulse responses from industry channel simulators including Keysight ADS, Cadence Sigrity, Mentor Graphics Hyperlynx, and SiSoft Quantum Designer. These can then be evaluated for their performance compared to Causal S-Parameter versions of the band limited channel S-parameters.

Testing Causal S-Parameters with various time domain simulators, such as Channel Simulators, is desirable. It is expected that such tests will show that Causal S-Parameters provide a common reference point to achieve repeatable results, including eye and BER performance, in various tools.

## **Summary**

This document reports on SerDes channel impulse modeling. Various channels were defined using S-parameter files based on hardware measurements. Such S-parameters, though measured on physical devices, inherently have non-physical distortions due to frequency band limiting, non continuous frequency domain characteristics, non reciprocity, non passivity, non causality and noise. Such distortions must be corrected when using S-parameters in the time domain such as with SerDes system Channel Simulators. The Keysight ADS Channel Simulator, using bit rate 28.125 Gbps and 32 samples per bit, was used to generate channel impulse responses for various test case band limited S-parameter files. These impulse responses were shown to have non-causal and high frequency artifacts in the time domain and high frequency aliasing in the frequency domain. The high frequency aliasing in impulses were shown to have limitations when used with IBIS-AMI models without substantial filtering above the Nyquist frequency. An approach for generating Causal S-Parameters from the original S-parameter files was presented. It was shown that the Causal S-Parameters have associated impulse responses that have none of the problems observed in the ADS generated channel impulse responses. Causal S-Parameters accurately track the original S-parameters while meeting the constraints of physical realizability including causality, with no aliasing.

Further testing Causal S-Parameters with various time domain simulators, such as Channel Simulators, is desirable. It is expected that such tests will show that Causal S-Parameters provide a common reference point to achieve repeatable results, including eye and BER performance, in various tools.

### **Acknowledgment**

Thanks to Wendem Beyene from Rambus Inc. for his collaboration in the work leading to this paper. Wendem provided the hardware measured channel S-parameter files used in this work. He also provided use of Keysight ADS for investigations of the performance of these S-parameter files using the ADS Channel Simulator.