SerDes_Channel_Impulse_Modeling_with_SignalMetrics

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Date: Sept. 24, 2016; Updated Jan. 17, 2017

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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.

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.

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 28.16825 Gbps bit rate and sampled at 32 samples per bit. Here is a listing of channels used as test cases.

Channel	Filename	Max freq.	Comment
1boutput	1boutput1se22ghzNOscdsdcKeysightSmoothedCORRECTED.s4p	22 GHz	Hardware measured transmit package S4P file;
0binput	0binput1se18ghzNOscdsdcKeysightSmoothed.s4p	18 GHz	Hardware measured receive package S4P file
SFP_5dB	SFP_5dB_14GHz_Megtron6_13hcb_mcb24_20150818.s4p	40.96 GHz	Hardware measured channel S4P file. Loss at 14 GHz is -4.9 dB.
SFP_10dB	SFP_10dB_14GHz_Megtron6_13hcb_mcb24_20150818.s4p	40.96 GHz	Hardware measured channel S4P file. Loss at 14 GHz is -9.8 dB.

The S-parameter files represent hardware measured S-parameters for frequencies up to the maximum frequency listed.

The frequency domain differential channel characteristics for these S4P files are shown here:
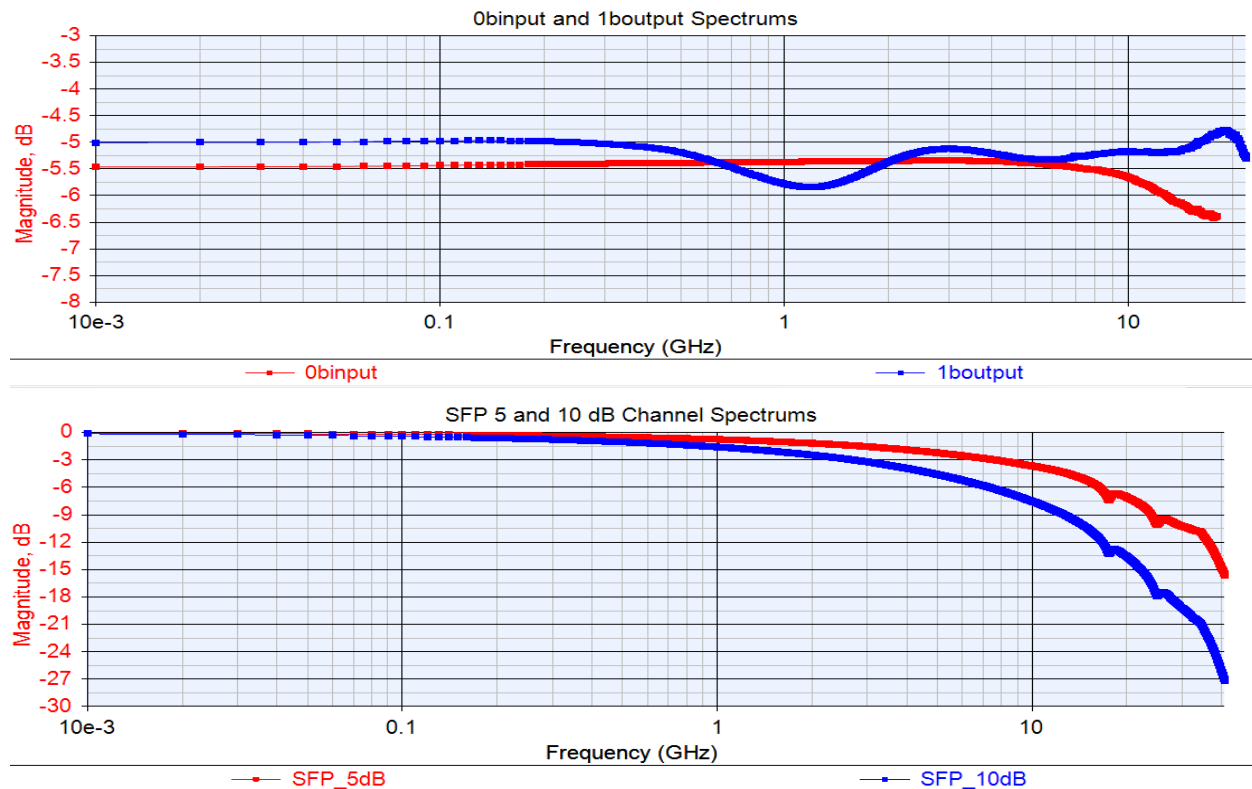
Converting S-Parameters to Causal S-Parameters

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

Using 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:

  1boutput1se22ghzNOscdsdcKeysightSmoothedCORRECTED.s4p.causal.s4p

  0binput1se18ghzNOscdsdcKeysightSmoothed.s4p.causal.s4p

  SFP_5dB_14GHz_Megtron6_13hcb_mcb24_20150818.s4p.causal.s4p

  SFP_10dB_14GHz_Megtron6_13hcb_mcb24_20150818.s4p.causal.s4p

Using 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 4x4 = 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:
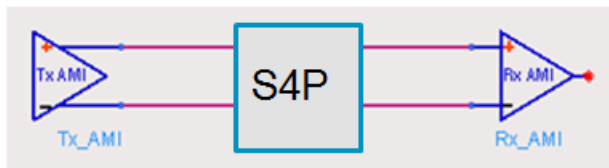
The Tx block includes a DSP based equalization input portion and a differential analog buffer output buffer portion. The Rx block includes a differential analog input buffer input portion and a DSP based equalization output portion. The combination of the Tx output analog buffer, channel (S4P), and Rx 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:
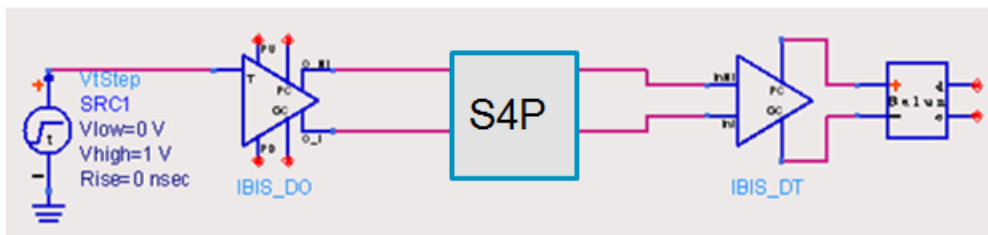
The (unofficial) approach ADS takes to create the impulse model is as follows:

- 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 4x4 = 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 = 28.16825 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_1boutput.txt for 1boutput
- ADS_Impulse_0binput.txt for 0binput
- ADS_Impulse_SFP_5dB.txt for SFP_5dB
- ADS_Impulse_SFP_10dB.txt for SFP_10dB

Impulse responses in the time and frequency domains

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 = 28.16825 Gbps and SamplesPerBit = 32, the maximum frequency content in the impulse response is one half the sample rate (time step) = 0.5*BitRate*SamplesPerBit = 450.692 GHz. Though the S-parameters are measured up to 18 to 40 GHz, the process of creating the impulse response for that data results in higher frequency content in the impulse above file maximum frequency.

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

1boutput impulse time domain response
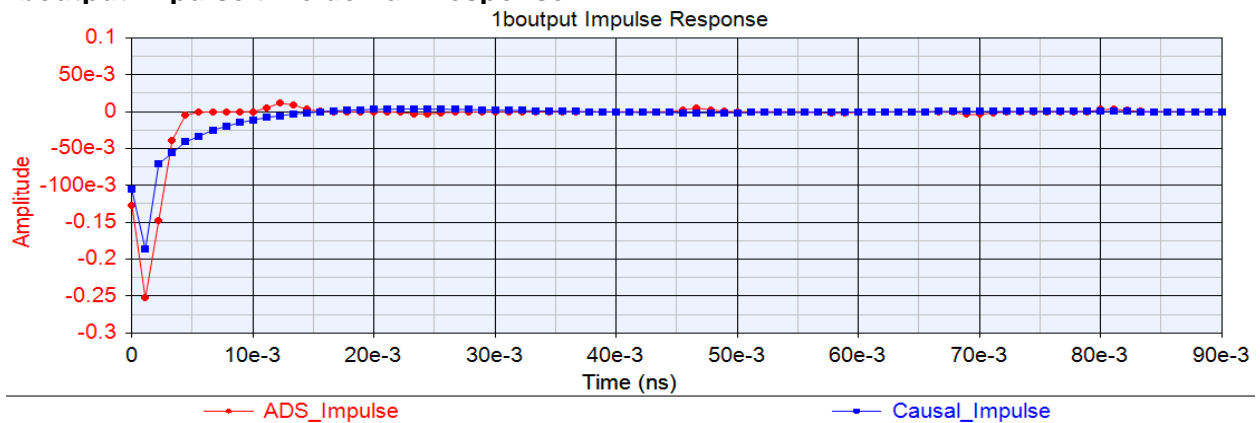
The ADS_Impulse (red) has 20,982 points. The Causal_Impulse (blue) has 7,004 points which is much shorter in length than the ADS_Impulse.

1boutput impulse frequency domain response (up to SampleRate/2 = 450 GHz)
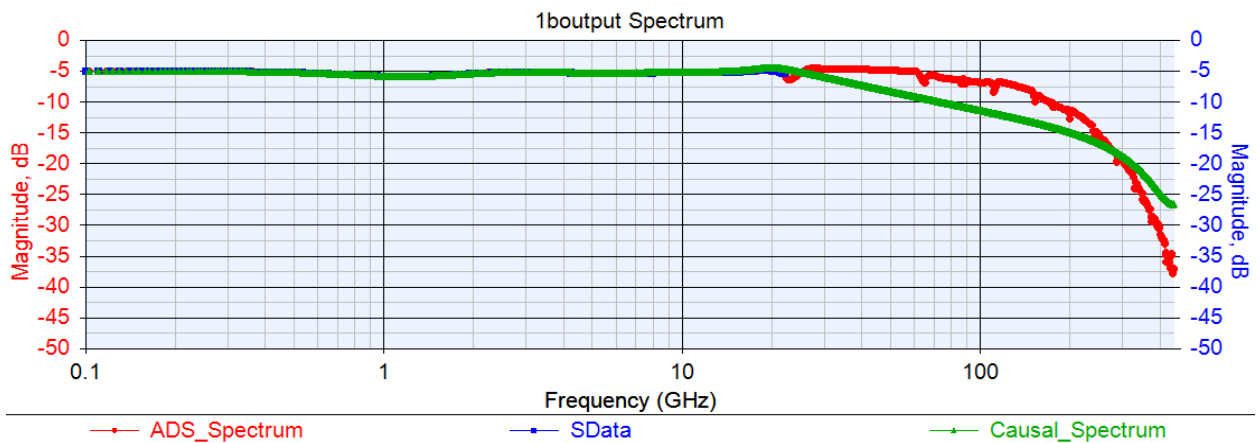
Above the 22 GHz data limit, the ADS_impulse (red) has an irregular roll off. The Causal_impulse (green) has a smooth roll off above 22 GHz.

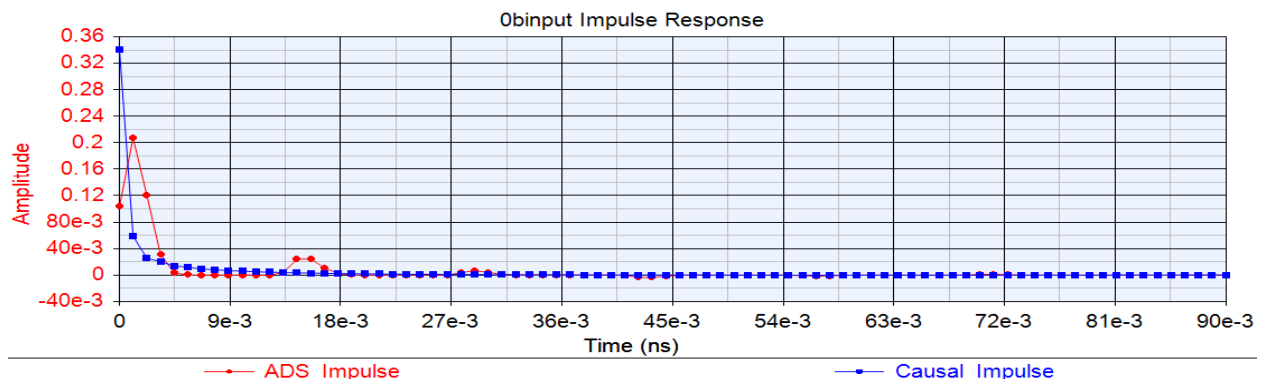**1boutput impulse frequency domain response (up to 22 GHz)**
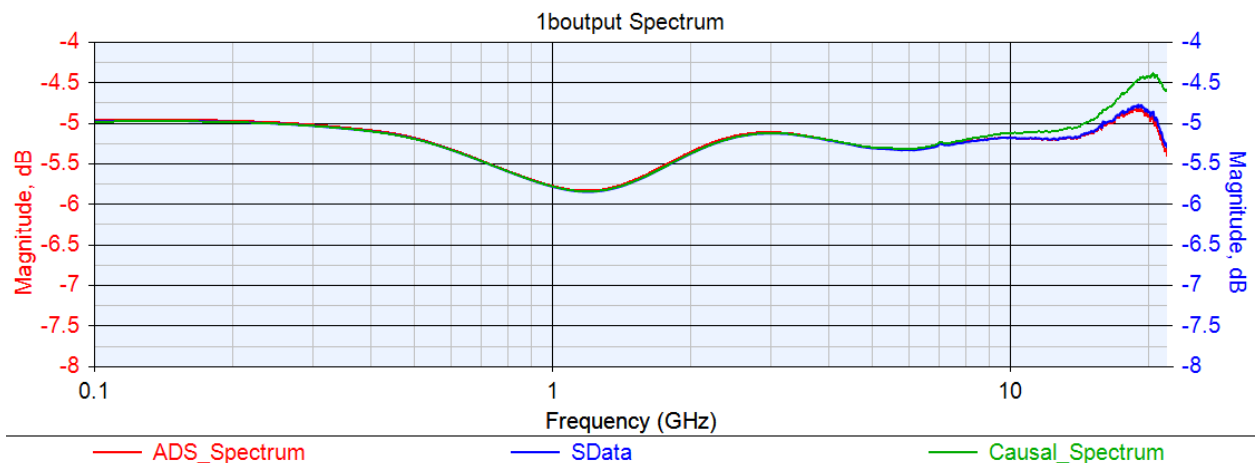
The raw SData is in blue. The ADS impulse (red) and the Causal_Impulse (green) both align well with the SData up to the Nyquist frequency. The ADS impulse aligns with the original SData up to 22 GHz where as the Causal_Impulse is higher by up to 0.75 dB at 22 GHz.

To better understand what is happening at 22 GHz, the following view was made from 10 to 40 GHz.
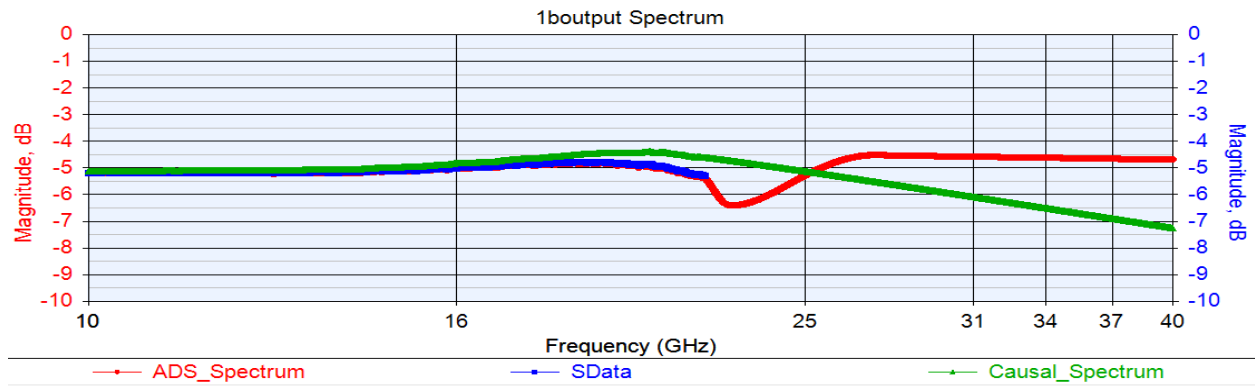
As can be seen, the ADS impulse response abruptly goes down then up after 22 GHz, then continues flat to 40 GHz. The Causal impulse response is smoothly varying beyond 22 GHz sloping down is a manner consistent with the SData slope at 22 GHz. One can argue that either the ADS or Causal impulse is a better representation. From this author's point of view, the non-abrupt characteristic of the Causal impulse is preferable.
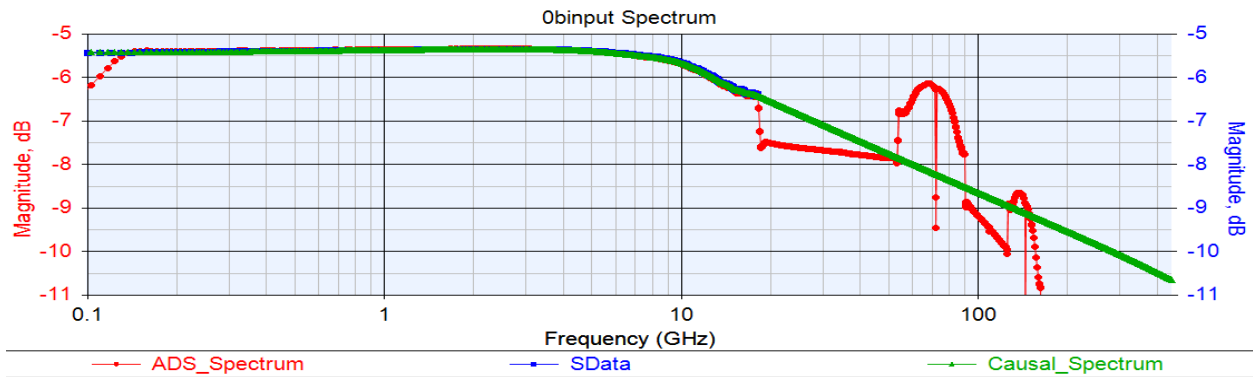
0binput impulse time domain response

The ADS_Impulse (red) has 12,825 points. The Causal_Impulse (blue) has 872 points which is much shorter in length than the ADS_Impulse.
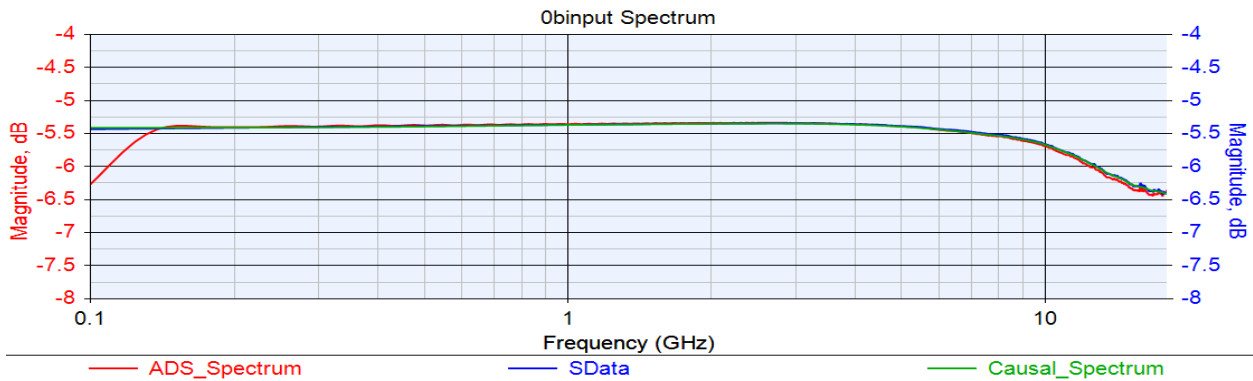
0binput impulse frequency domain response (up to SampleRate/2 = 450 GHz)

Above the 40 GHz data limit, the ADS_impulse (red) has high frequency aliasing. The Causal_impulse (green) has a smooth roll off above 40 GHz.

0binput impulse frequency domain response (up to 18 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 at low frequency.

SFP_5dB impulse time domain response

The ADS_Impulse (red) has a lot of non-causal and high frequency artifacts. It also has non-causal ringing near time 0. The Causal_Impulse (blue), is zero up to 0.6 ns and is smoothly varying.

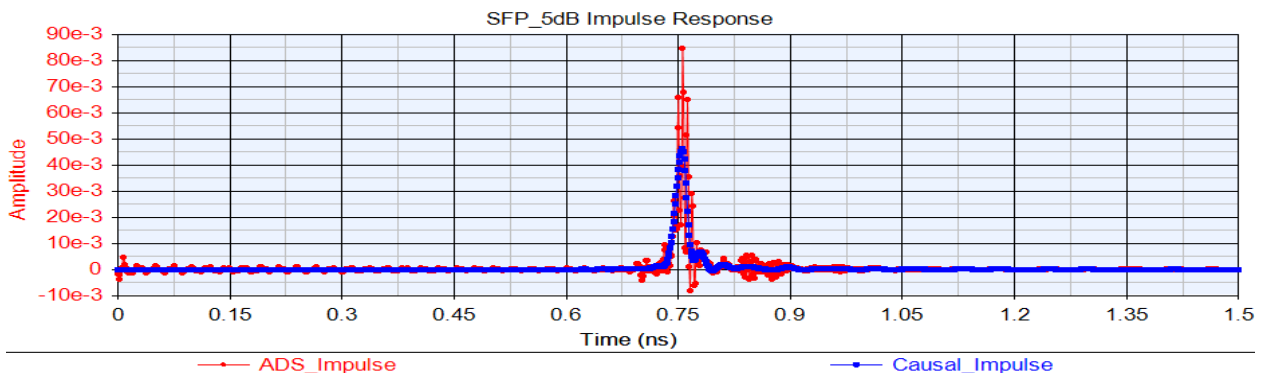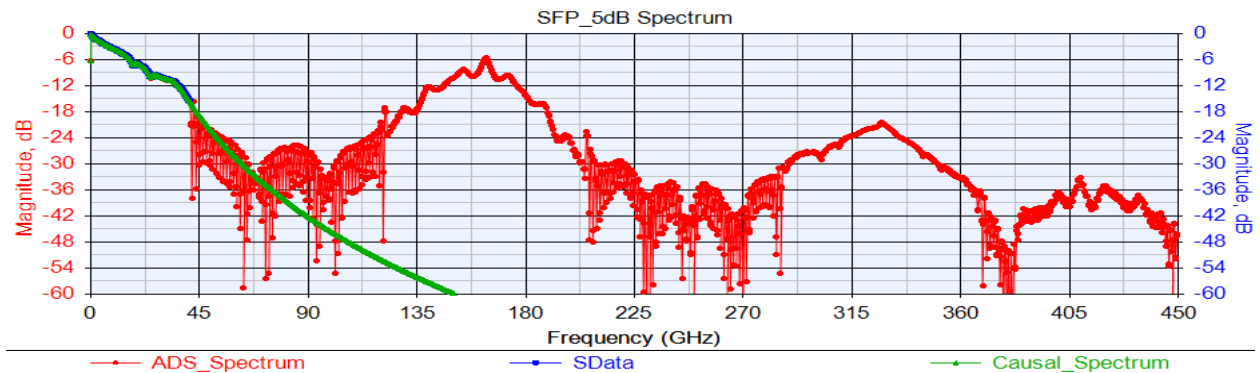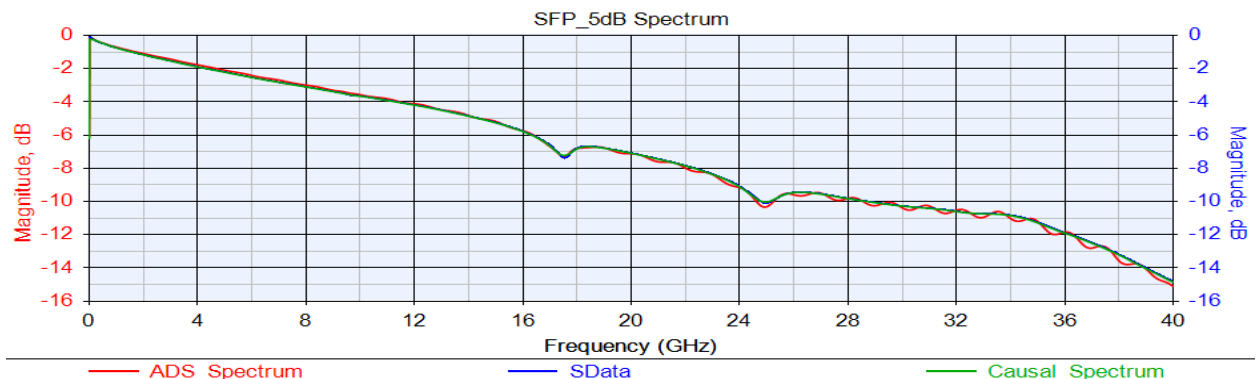**SFP_5dB impulse frequency domain response (up to SampleRate/2 = 450 GHz)**

Above the 40 GHz data limit, the ADS_impulse (red) has high frequency aliasing. The Causal_impulse (green) has a smooth roll off above 40 GHz.

SFP_5dB impulse frequency domain response (up to 40 GHz)

The raw SData is in blue. The ADS impulse (red) and the Causal_Impulse (green) both align well with the SData. The ADS impulse response has a low level ripple about the SData.

SFP_10dB impulse time domain response

The ADS_Impulse (red), with 11,963 points, has a lot of non-causal and high frequency artifacts. The Causal_Impulse (blue), with 2,589 points, is zero up to 1.4 ns. The Causal_Impulse is much shorter in length than the ADS_Impulse.

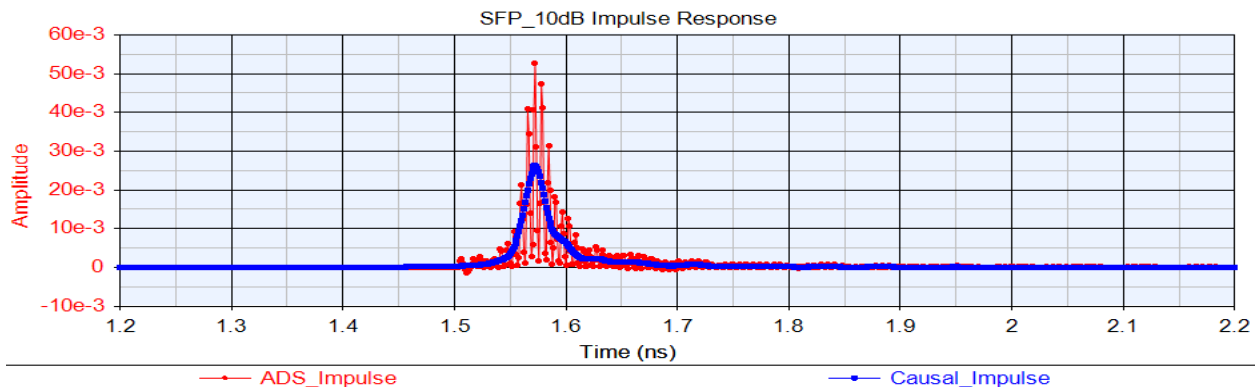**SFP_10dB impulse frequency domain response (up to SampleRate/2 = 450 GHz)**

Above the 40 GHz data limit, the ADS_impulse (red) has high frequency aliasing. The Causal_impulse (green) has a smooth roll off above 40 GHz.

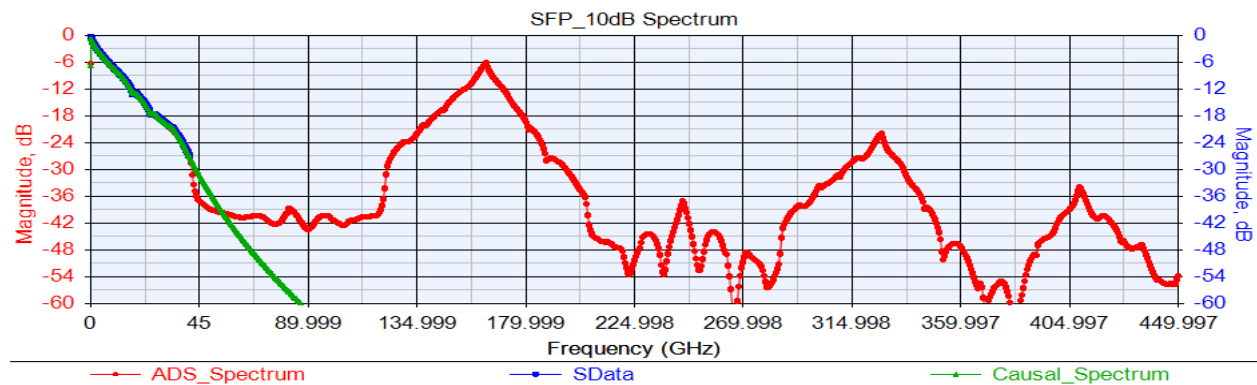**SFP_10dB impulse frequency domain response (up to 40 GHz)**
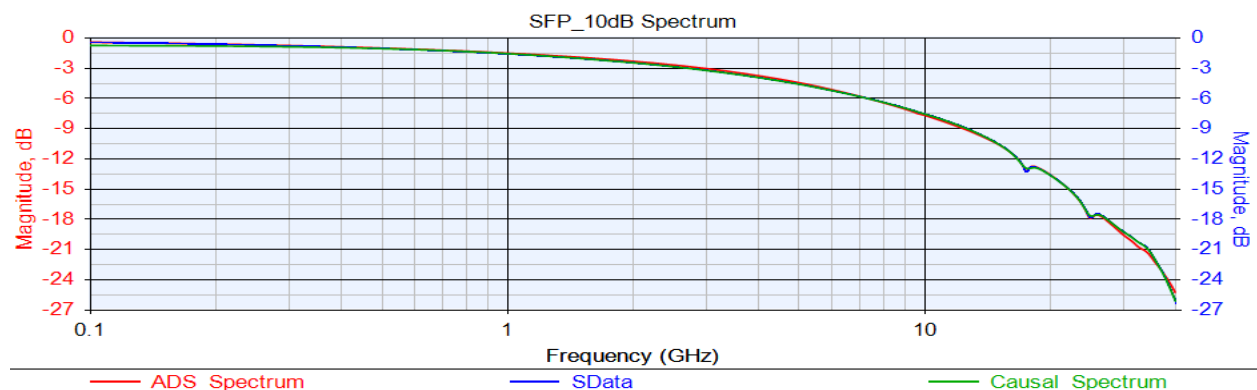
The raw SData is in blue. The ADS impulse (red) and the Causal_Impulse (green) both align well with the SData.

1boutput_SFP_10dB_0binput impulse time domain response
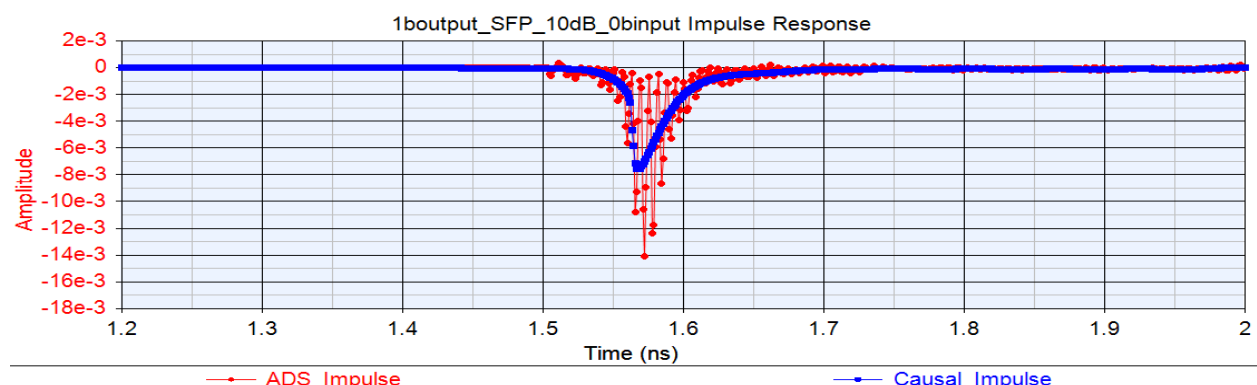
The ADS_Impulse (red) has a lot of non-causal and high frequency artifacts. The Causal_Impulse (blue) is zero up to 1.45 ns. The Causal_Impulse is smoothly varying.

1boutput_SFP_10dB_0binput impulse frequency domain response (up to SampleRate/2 = 450 GHz)

Above the SData max frequency, the ADS_impulse (red) has high frequency aliasing. The Causal_impulse (green) has a smooth roll off.

1boutput_SFP_10dB_0binput impulse frequency domain response (up to 18 GHz)
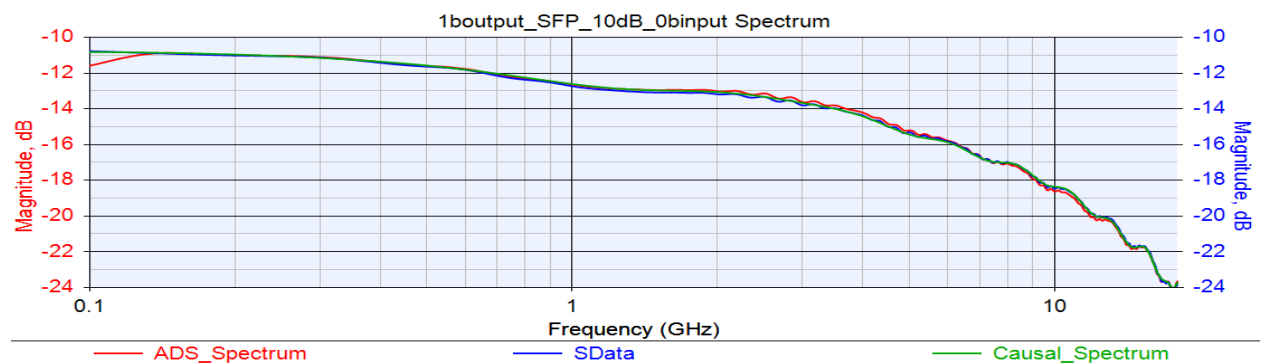
The raw SData is in blue. The ADS impulse (red) and the Causal_Impulse (green) both align well with the SData.
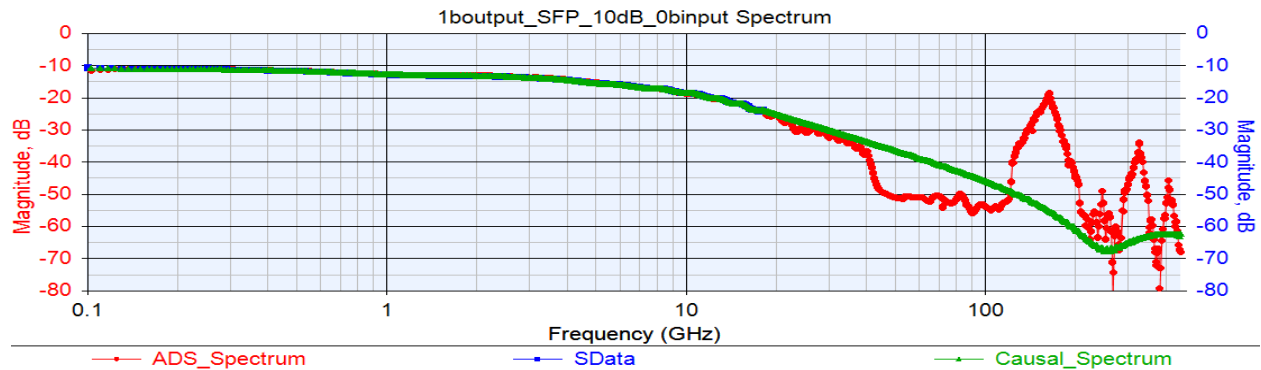
The above shows that the ADS impulse has high frequency aliasing. The time domain views show high frequency artifacts and sometimes has a non-causal ringing response at time zero.

The above shows that the Causal impulse 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 more 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 these test conditions.

Test 1. SFP 10 dB channel

Test 2. 1boutput S4P + SFP 10dB S4P + 0binput S4P

Test 1: SFP 10 dB channel.

SFP_10dB is used to test the ADS impulse effects on the eye diagram and BER plots. SFP_10dB represents a typical medium loss channel.

The SFP_10dB s-parameters are band limited to 40 GHz and the associated ADS impulse response has high frequency aliasing, as shown earlier at frequencies above 40 GHz up to 450 GHz (which is half the sample rate for 28.16825 Gbps with 32 samples per bit).

The SFP_10dB Causal impulse, as shown earlier, does not have high frequency aliasing.

The ADS eye diagram and BER plots using the SFP_10dB Causal S-Parameters defines a reference point against which the ADS performance using the band limited SFP_10dB is compared.

ADS eye diagram and BER plots for SFP_10dB using Causal S-Parameters (ADS impulse model does not contain high frequency aliasing):

measurement	Summary
Level1	0.271
Level0	-0.276
LevelMean	-0.003
Amplitude	0.547
Height	0.170
HeightDB	-7.696
Width	2.414E-11
SNR	3.260
RiseTime	2.180E-11
FallTime	2.178E-11
JitterPP	1.136E-11
JitterRMS	2.211E-12
WidthAtBER	2.396E-11
HeightAtBER	0.181
CrossingLevel	-0.003
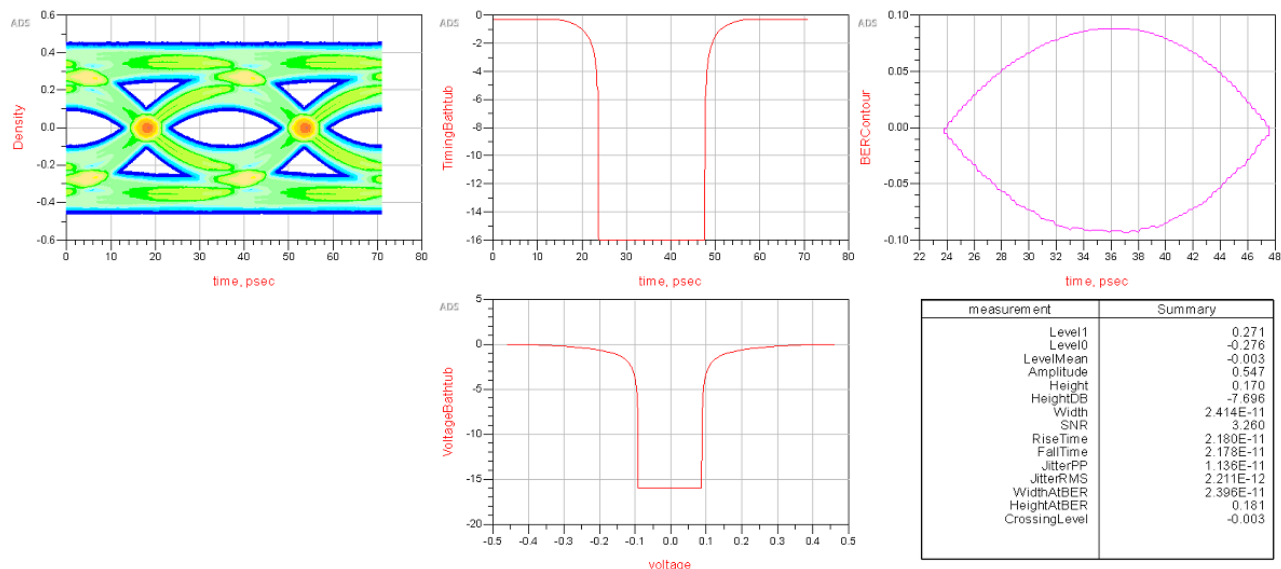
This eye diagram and BER plots are typical of what would be expected from a medium loss channel.

ADS eye diagram and BER plots for SFP_10dB using band limited S-parameters (ADS impulse model contains high frequency aliasing):

measurement	Summary
Level1	0.267
Level0	-0.282
LevelMean	-0.008
Amplitude	0.549
Height	0.122
HeightDB	-9.136
Width	2.343E-11
SNR	3.204
RiseTime	2.133E-11
FallTime	2.143E-11
JitterPP	1.580E-11
JitterRMS	2.016E-12
WidthAtBER	1.828E-11
HeightAtBER	0.164
CrossingLevel	-0.008

Observe the impact of the ADS impulse model high frequency aliasing on the eye diagram and BER plots.

The eye diagram and the BER plots using the Causal S-Parameters do not have these ADS high frequency aliasing artifacts.

Test 2: 1boutput S4P + SFP 10dB S4P + 0binput S4P channel.

1boutput S4P + SFP 10dB S4P + 0binput S4P is used to test the ADS impulse effects on the eye diagram and BER plots. 1boutput S4P + SFP 10dB S4P + 0binput S4P represents a typical medium loss channel including Tx and Rx packages.

The output, SFP 10 dB and input S4P s-parameters are band limited to 22, 40 and 18 GHz respectively and for each the associated ADS impulse response has high frequency aliasing, as shown earlier at frequencies above the maximum file frequency up to 450 GHz (which is half the sample rate for 28.16825 Gbps with 32 samples per bit).

The 1boutput S4P + SFP 10dB S4P + 0binput S4P Causal impulse, as shown earlier, does not have high frequency aliasing.

The ADS eye diagram and BER plots using the SFP_10dB Causal S-Parameters defines a reference point against which the ADS performance using the band limited SFP_10dB is compared.
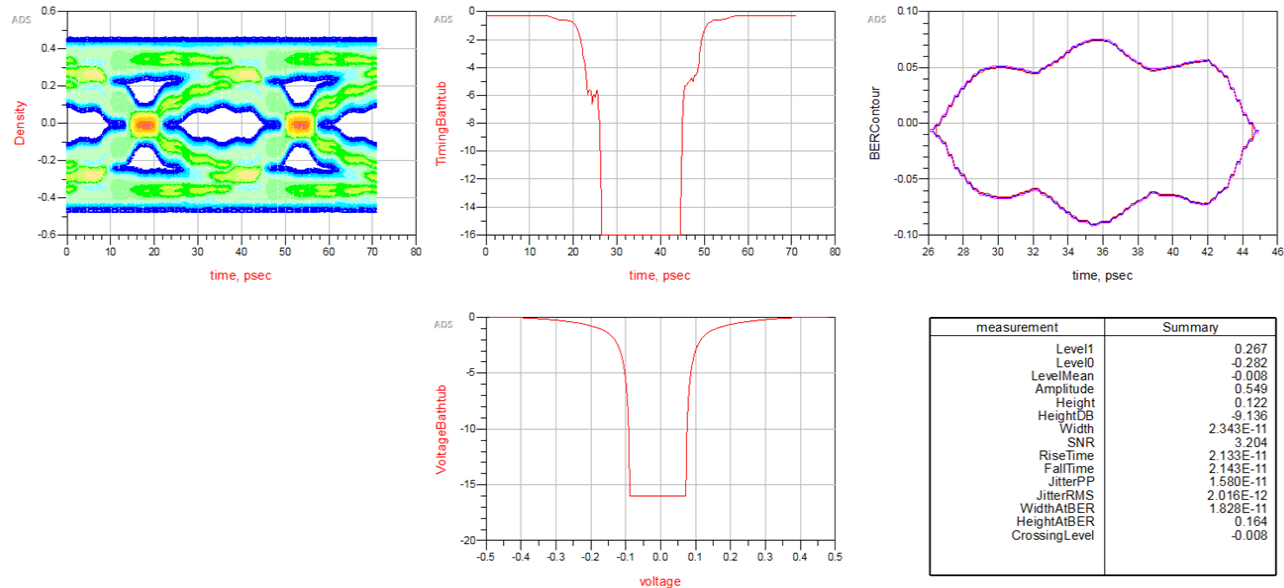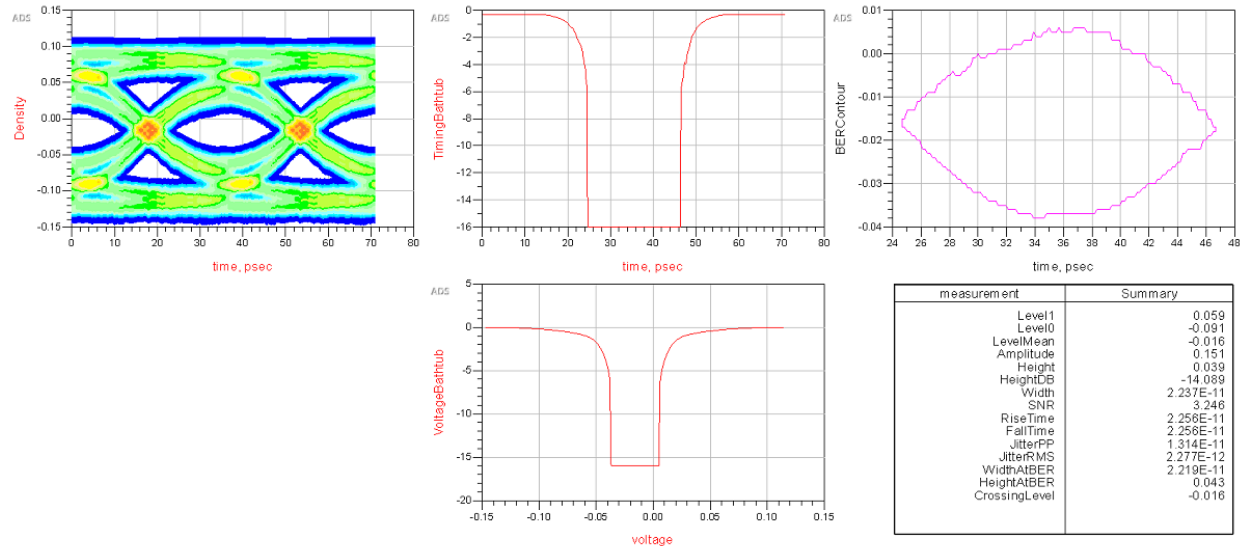
ADS eye diagram and BER plots for 1boutput S4P + SFP 10dB S4P + 0binput using Causal S-Parameters (ADS impulse model does not contain high frequency aliasing):
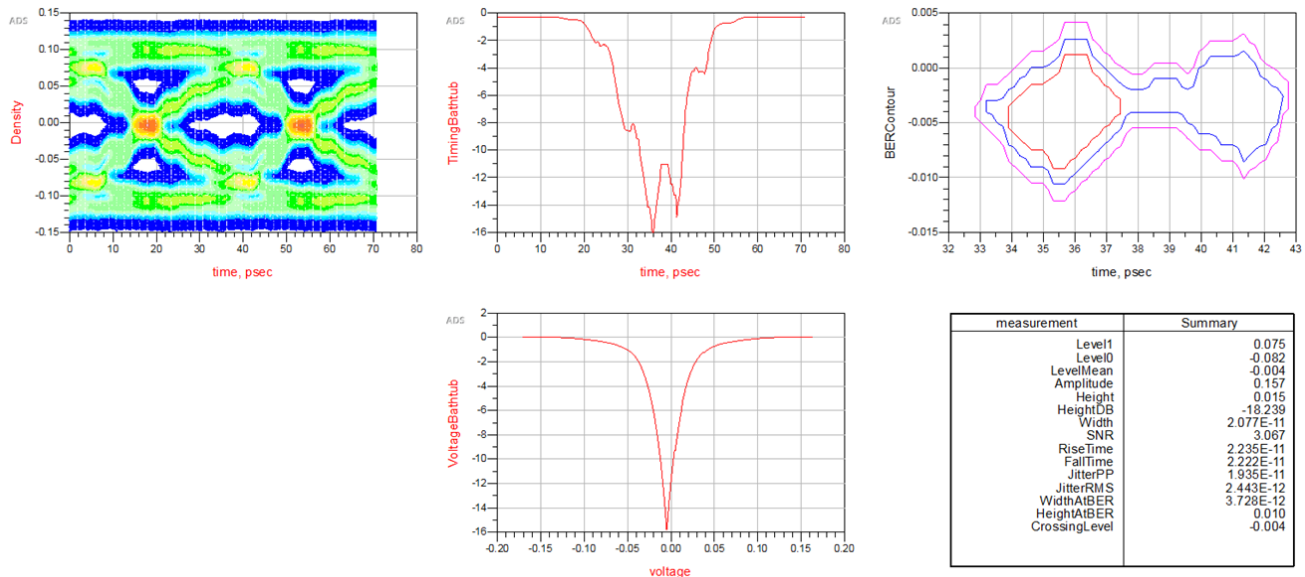
measurement	Summary
Level1	0.059
Level0	-0.091
LevelMean	-0.016
Amplitude	0.151
Height	0.039
HeightDB	-14.089
Width	2.237E-11
SNR	3.246
RiseTime	2.256E-11
FallTime	2.256E-11
JitterPP	1.314E-11
JitterRMS	2.277E-12
WidthAtBER	2.219E-11
HeightAtBER	0.043
CrossingLevel	-0.016

This eye diagram and BER plots are for a medium loss channel.

However, notice that the ADS eye diagram has vertical offset from the y-axis zero value. This is an unrealistic and unwanted artifact of the ADS Channel Simulator. It is not an artifact of the Causal S-Parameters. This unwanted ADS Channel Simulator artifact results in the Voltage Bathtub BER curve being greatly unsymmetrical about its x-axis zero value.

ADS eye diagram and BER plots for 1boutput S4P + SFP 10dB S4P + 0binput using band limited S-parameters (ADS impulse model contains high frequency aliasing):

measurement	Summary
Level1	0.075
Level0	-0.082
LevelMean	-0.004
Amplitude	0.157
Height	0.015
HeightDB	-18.239
Width	2.077E-11
SNR	3.067
RiseTime	2.235E-11
FallTime	2.222E-11
JitterPP	1.935E-11
JitterRMS	2.443E-12
WidthAtBER	3.728E-12
HeightAtBER	0.010
CrossingLevel	-0.004

Observe the impact of the ADS impulse model high frequency aliasing on the eye diagram and BER plots. The eye is significantly closed and the BER is greatly degraded compared to the eye diagram and the BER plots using the Causal S-Parameters.

As shown in this section, ADS high frequency aliasing in their impulse modeling of band limited S-parameters can significantly affect eye diagrams and BER plots for medium loss channels.

Unrealistic and unexpected results with ADS impulse modeling are essentially eliminated when Causal S-Parameters are used in place of band limited S-Parameters. However, as shown in Test 2, even with use of Causal S-Parameters, the ADS Channel Simulator has unwanted eye and BER offsets that are not due to the Causal S-Parameters.

Cadence Sigrity Channel Simulator Impulse Modeling

The Cadence Sigrity Channel Simulator was used to compare its impulse modeling with the ADS impulse modeling.

The SFP_10dB channel was used as the test case.

The following show the ADS Causal S-Parameters impulse response with the Sigrity impulse response using the band limited SFP_10dB data.
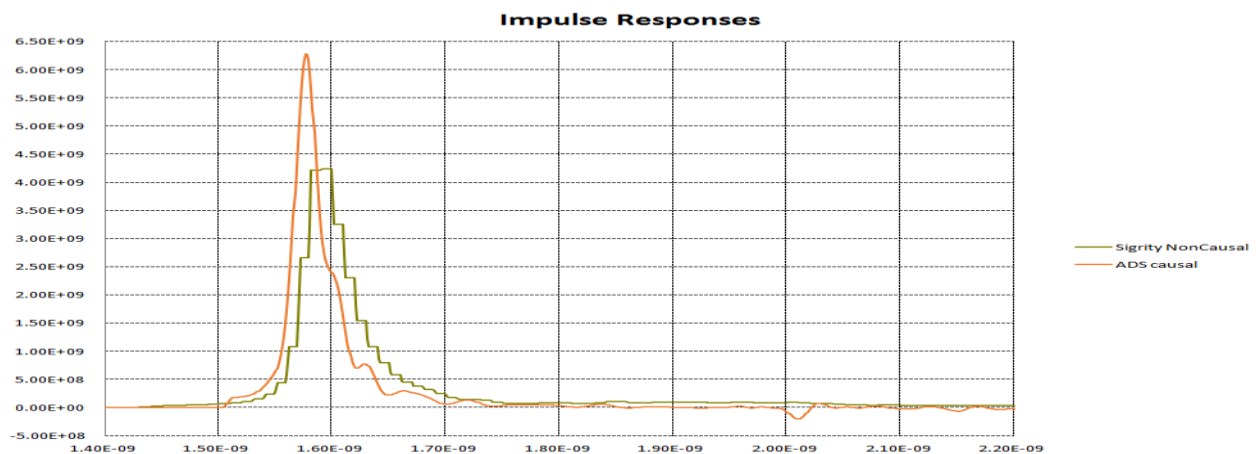
Sigrity uses a different S-parameter to impulse algorithm than ADS.

As seen here, the Sigrity approach causes the band limited S-parameter impulse response to have steps in it.

Clearly, the impulse response using the Causal S-Parameters is a better representation for the SFP_10dB channel.
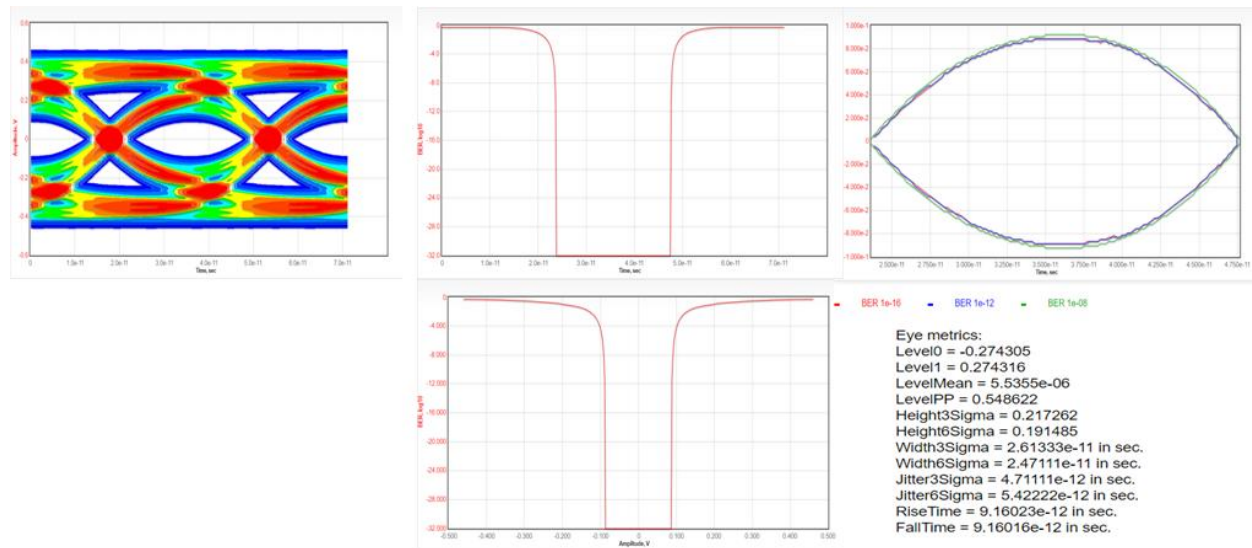
Eye and BER Plots from SerDesDesign.com

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 two test cases:

1. SFP 10 dB channel

2. 1boutput S4P + SFP 10dB S4P + 0binput S4P

Test 1: SFP 10 dB channel.

The band limited (to 40 GHz) SFP_10dB S-Parameter file is used by SerDesDesign.com to obtain its eye diagram and BER plots. SFP_10dB represents a typical medium loss channel.

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: 1boutput S4P + SFP 10dB S4P + 0binput S4P channel

These three band limited (to 40 GHz) S-Parameter files are used by SerDesDesign.com to obtain its eye diagram and BER plots. These files represents a typical medium loss channel.
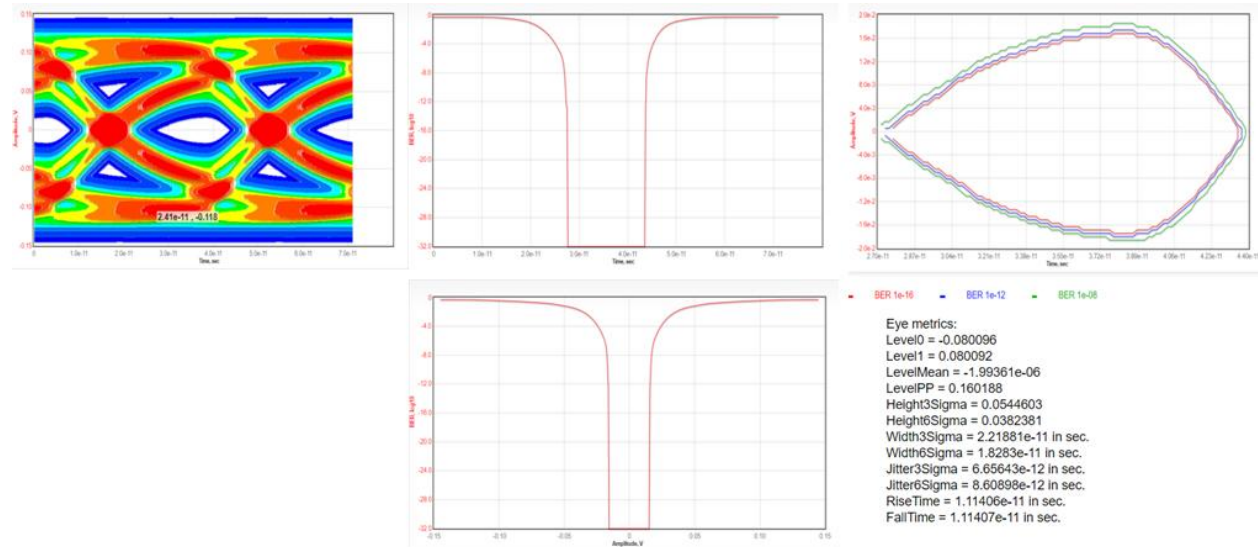
The eye and BER plots are much better than the ADS results when both use the band limited S-Parameters.

Though the ADS eye and BER plots obtained using the Causal S-Parameters generated by SerDesDesign.com are more in agreement with the SerDesDesign.com results using the band limited S-Parameters, the ADS results using Causal S-Parameters have some ADS Channel Simulator related unwanted artifacts.

Note that the ADS eye plot using the Causal S-Parameters has a vertical offset and has some loss of eye shape fidelity compared to the eye from SerDesDesign.com. These are ADS Channel Simulator related unwanted artifacts and are not due to the Causal S-Parameters.

Note that the ADS BER plots using the Causal S-Parameters have differences from the SerDesDesign.com BER plots due to the ADS eye differences.

This test shows that though the Causal S-Parameters are portable to another Channel Simulator, ADS in this case, inherent issues in the ADS Channel Simulator may result in differences compared to the results from SerDesDesign.com.

Topics for further study

The use of Keysight ADS to generate channel impulse responses was performed in collaboration with SignalMetrics 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 Quantuum Desiger. 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 28.16825 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 was shown to have significant effects on eye diagrams and BER plots for medium loss channels. 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