A Better Anti-Aliasing Process (Rev1)

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INTRODUCTION

High Speed Digital (HSD) transmit (Tx) and receive (Rx) circuits are modelled as IBIS-AMI models per the IBIS standard which are used with associated SerDes channels in SerDes channel simulators to evaluate their system margins. Oftentimes, the SerDes channel is defined with S-parameters which may result in the channel simulator modeling the channel with an impulse response that has excessive high frequency aliasing. An original and better anti-aliasing process is defined for use in channel simulators to eliminate the negative effects of high frequency aliasing without compromising the integrity of the channel characterization. This process preserves the fidelity of the S-parameters up to their highest frequency while eliminating high frequency aliasing at higher frequencies with no added delay.

This paper first gives an overview of high frequency aliasing issues in context with industry standards compliance testing, SerDes systems examples without and with the proposed anti-aliasing algorithm (AAA), and then the AAA is discussed.

HIGH FREQUECY ALIASING IN CHANNEL SIMULATORS

SerDes systems are represented in channel simulators with SerDes channels and IBIS-AMI models per the IBIS Open Forum standard (currently at revision 7.1).

Figure 1 shows a typical SerDes system block diagram to be simulated using a channel simulator.

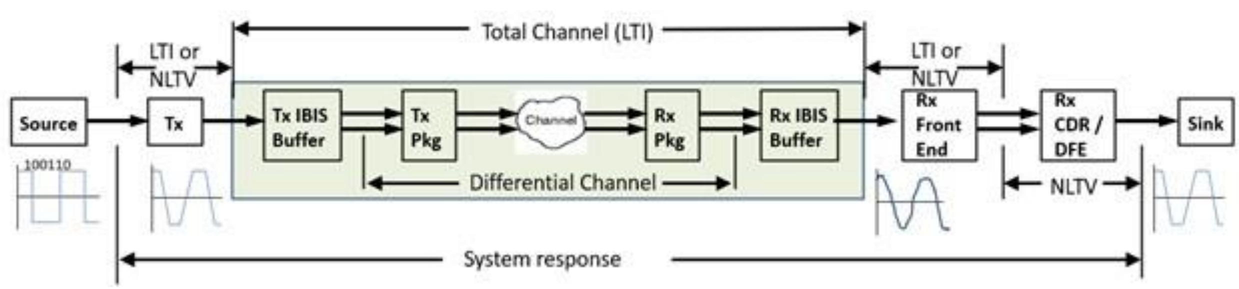

Figure 1: Typical SerDes System Representation in a channel simulator

This block diagram is generic for any channel simulator (CS), but each tool has its specific way to represent this block diagram.

All channel simulators convert the total channel into an impulse response (IR). One of the key problems when setting up a SerDes system design in different CS tools is that each CS tool does not generate the same IR. This fact has been observed by many and especially reported by Romi Mayder of Xilinx Inc. at the 2015 DesignCon conference for the top 6 EDA channel simulators in the industry. Though this paper is dated, it still applies today. Additional observations have been posted on the web [2][3][4].

Some CS tools produce an IR that has a high level of high frequency aliasing. This is not of concern when an Rx IBIS-AMI model is used which has an input continuous time linear equalizer (CTLE) that attenuates the high frequency aliasing low enough so as to not affect Rx IBIS-AMI output results.

However, there are my SerDes system that require characterization with a pass-through Rx IBIS-AMI model so that the Tx IBIS-AMI model can be evaluated per industry testing requirements.

For example, consider the Universal Serial Bus 4 (USB4™) Router Assembly Electrical Compliance Test Specification [5]. It's Figure 1 is shown here as Figure 2.

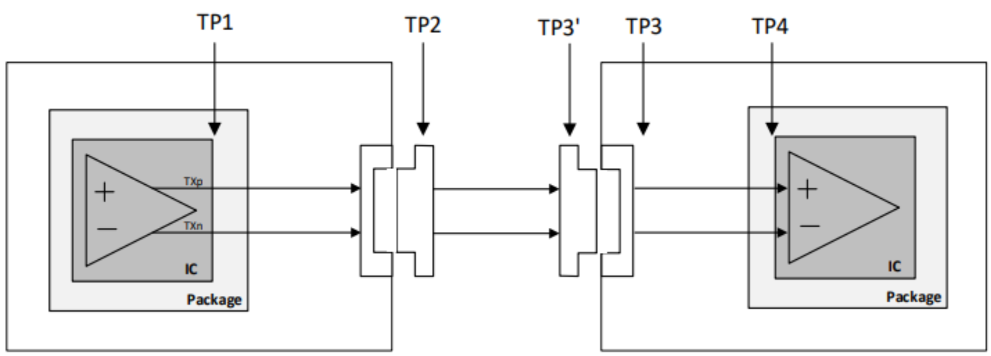

Figure 2. USB4 Tx Compliance Test Points

Also, consider the VESA DisplayPort™ PHY Compliance Test Standard [6]. It's Figure 2-1 is shown here as Figure 3.

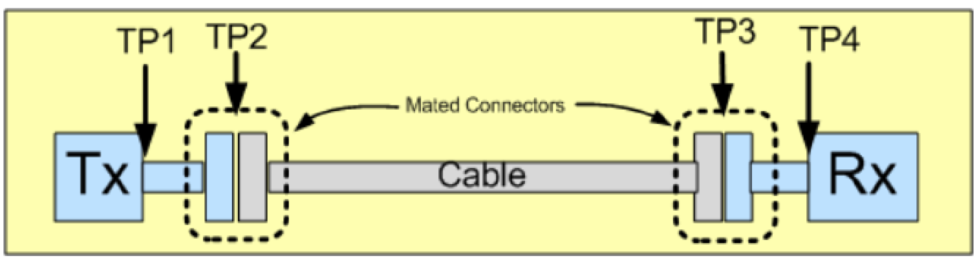

Figure 3. The Four Ideal Measurement Points in a DisplayPort Interconnect System

In both of these figures, the four test points are identified as follows:

TP1 - Reference measurement point at the Tx IBIS buffer output.

TP2 - Reference measurement point located at the USB Type-C plug connected to the Router Assembly TX output. Used as a reference point for defining Router Assembly TX.

TP3 – Reference measurement point located at USB Type-C receptacle output on the far-end side of passive cable. Used as a reference point for passive installations.

TP4 – Reference measurement point located at Rx IBIS buffer input.

All of these test points do not include the Rx circuit which would have included low pass filtering of any high frequency aliasing.

Thus, testing within a SerDes CD tool that exhibits high frequency aliasing in its IR can lead to misleading CS results and possible non-compliance to the industry standards requirements.

SERDES SYSTEM EXAMPLES

Three SerDes system examples are considered. Since the focus in on the SerDes total channel IR, all systems use a pass-through Tx and Rx IBIS-AMI model and S-parameter files to define the Tx IBIS buffer, Tx router assembly output, and channel passive cable.

All examples use NRZ signaling with 20 Gbps and 32 samples per bit. This implies a sample rate = 640 GHz with maximum frequency 320 GHz. The IR for each example is obtained from one commercial channel simulator and its time domain impulse, impulse frequency domain characteristic and its eye density plot is observed without and with AAA. Without AAA, the high frequency aliasing is visible in the IR. With AAA, the high frequency aliasing is eliminated with no delay to the IR while retaining the IR characteristics below the S-parameters maximum frequency. All IR displays have time domain data normalized such that a unity impulse is defined by unity amplitude and frequency domain data normalized such a unity impulse has 0 dB gain at 0 Hz. The IBIS-AMI standard reference unity impulse in the context with unity area in a one time step interval. All IR responses collected from the CS tool, along with the applied AAA, are displayed in the Keysight SystemVue tool for consistent comparison.

The AAA process converts the CS IR to the frequency domain and matches the characteristics below the maximum S-parameter frequency (20 GHz in this case) and reformulates the characteristics above this frequency to eliminate high frequency aliasing while retaining a causal time domain response.

Example 1: Tx with IBIS buffer defined with S-parameters with maximum frequency at 20 GHz and with 1.3 dB loss at Nyquist (10 GHz).

Figure 4 shows the CS IR in the time domain and frequency domain without and with AAA.

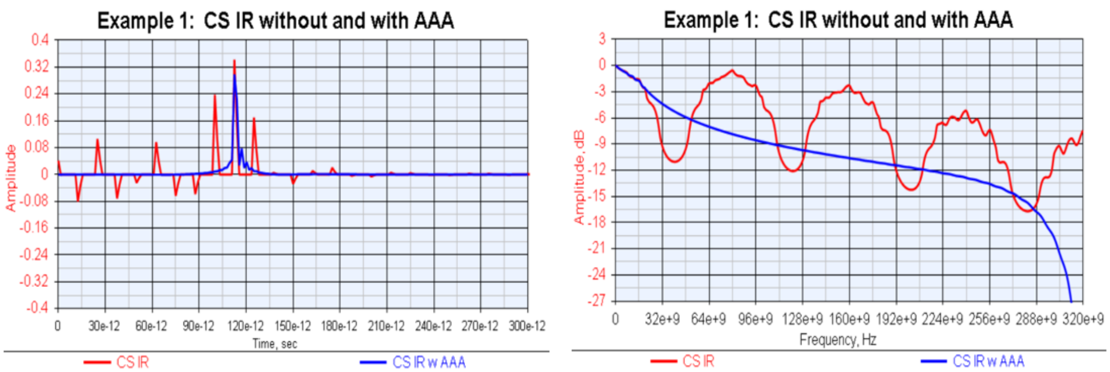

Figure 4: Example 1: CS IR in time (left)/frequency (right) domains without and with AAA.

As can be seen, there is a lot of high frequency aliasing in the IR. However, the IR w AAA has no high frequency aliasing and has no additional processing time delay.

Figure 5 shows the CS IR eye density plots without and with AAA.

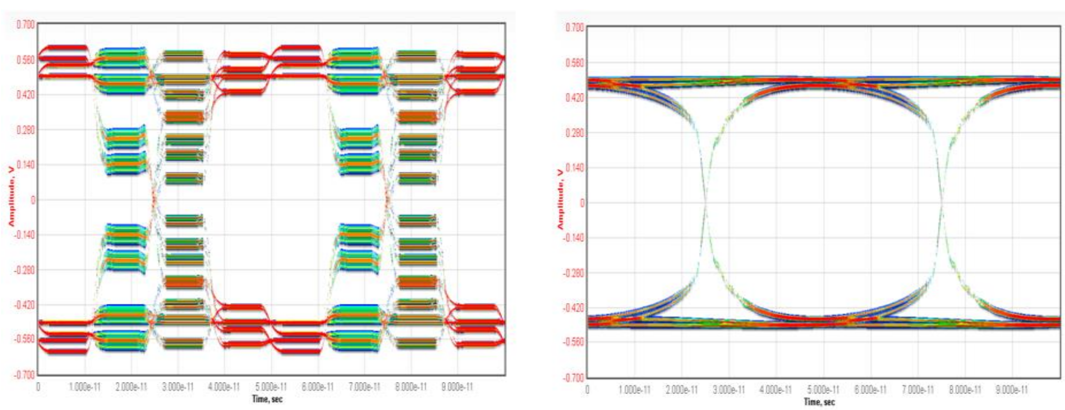

Figure 5: Example 1 CS IR eye density plots without (left) and with AAA (right).

As can be seen, the IR eye density without AAA has high frequency aliasing that makes the eye density unusable. The IR with AAA has a much cleaner and usable eye density plot.

Figure 6 compares the AAA response to the CS tool IR using the CS tool anti-aliasing filter (AAF) set to have a filter with number of time points = BR*SPB/BW = 32; where BR = BitRate (20 Gbps), SPB = SamplesPerBit (32) and BW = Max S-parameter frequency (20 GHz).

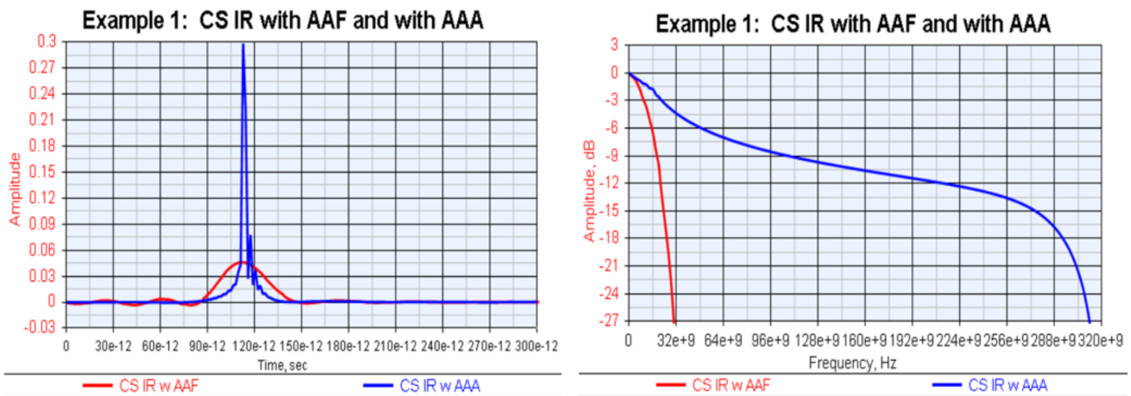

Figure 6: Example 1: CS IR in time (left)/frequency (right) domains with AAF and with AAA.

As can be seen, the CS IR with AAF has excessive rolloff and reduced fidelity in the time domain impulse as compared to the CS IR with AAA.

Figure 7 shown the eye density plots for these two cases.

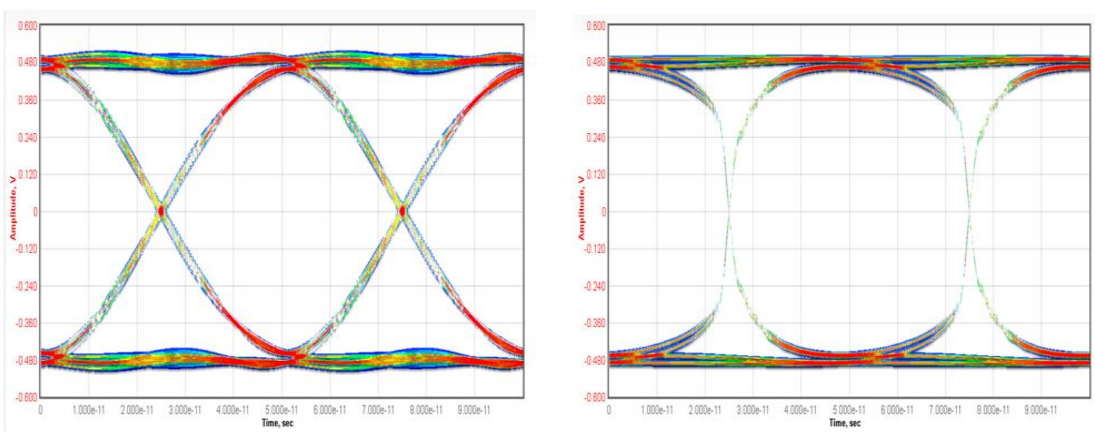

Figure 7: Example 1 CS IR eye density plots with AAF (left) and with AAA (right).

As can be seen, though the CS IR with AAF has reduced high frequency aliasing, its eye density plot has misleading fidelity.

Example 2: Tx with IBIS buffer and Tx router assembly output both defined with S-parameters with maximum frequency at 20 GHz and with 7.5 dB loss at Nyquist (10 GHz).

Figure 8 shows the CS IR in the time domain and frequency domain without and with AAA.

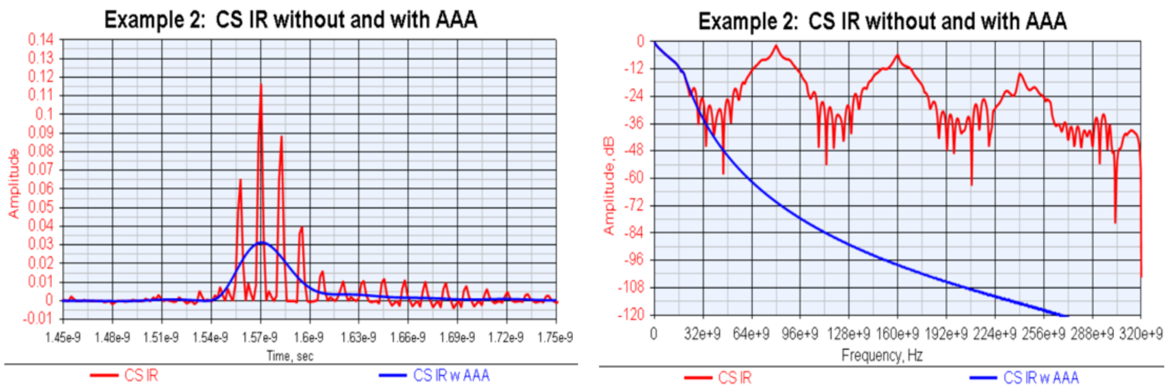

Figure 8: Example 2: CS IR in time (left)/frequency (right) domains without and with AAA.

As can be seen, there is a lot of high frequency aliasing in the IR. However, the IR w AAA has no high frequency aliasing and has no additional processing time delay.

Figure 9 shows the CS IR eye density plots without and with AAA.

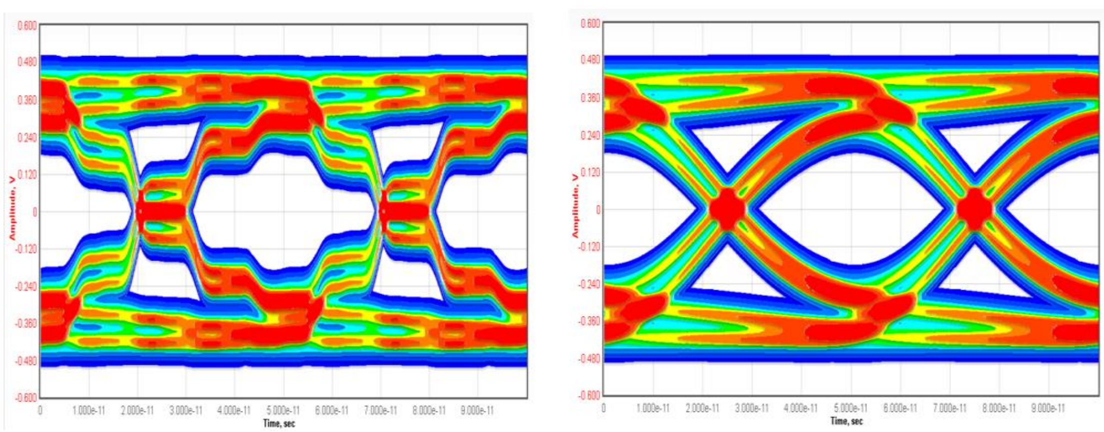

Figure 9: Example 2 CS IR eye density plots without (left) and with AAA (right).

As can be seen, the IR eye density without AAA has high frequency aliasing that makes the eye density unusable. The IR with AAA has a much cleaner and usable eye density plot.

Example 3: Tx with IBIS buffer and Tx router assembly output and channel passive cable all defined with S-parameters with maximum frequency at 20 GHz and with 21 dB loss at Nyquist (10 GHz).

Figure 10 shows the CS IR in the time domain and frequency domain without and with AAA.

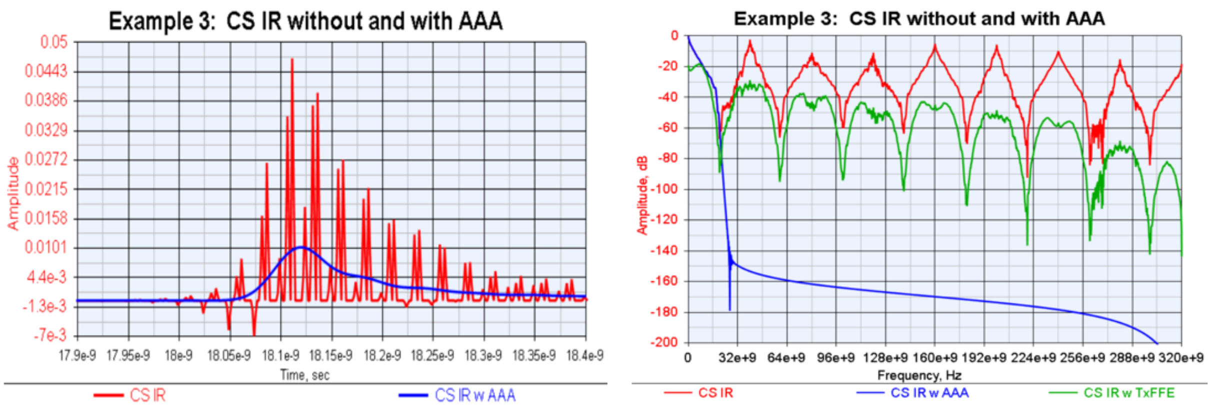

Figure 10: Example 3: CS IR in time (left)/frequency (right) domains without and with AAA.

As can be seen, there is a lot of high frequency aliasing in the CS IR. However, the CS IR w AAA has no high frequency aliasing and has no additional processing time delay. The spectrum view on the right also shows the spectrum for the CS IR with a TxFFE model applied (the green curve). As can be seen the TxFFE model output attenuates most of the high frequency aliasing.

With this high loss channel and no equalization, the eye is closed. Equalization is required to open the eye. Thus, a Tx IBIS-AMI model is used which is a feed forward equalizer (FFE) with two precursors and two post-cursors and low pass filtering with corner frequency at the bit rate which attenuates most of the high frequency aliasing. The Tx FFE auto sets its taps for optimal output eye opening.

Figure 11 shows the CS IR eye density plots without and with AAA with the TxFFE model applied.

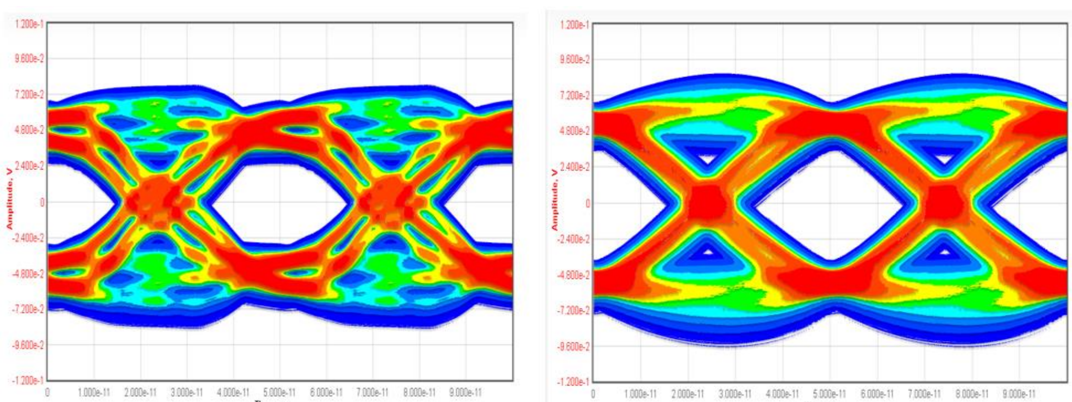

Figure 11: Example 3 CS IR eye density plots without (left) and with AAA (right).

As can be seen, the CS IR eye density without AAA has an eye that has noticeable distortion even though most of the high frequency aliasing was attenuated. The CS IR eye density with AAA shows the eye wide open as expected. Without AAA, the Tx model gives performance that is misleading and unacceptable.

The examples above were focused on SerDes systems that used a pass-through Rx IBIS-AMI model since the test points of interest were before any Rx circuit as is typically required per various industry standards. The examples are for test cases at the Tx IBIS buffer output, the Tx router assembly output, or the output of a far end passive cable before the receiver.

These examples show the effects of high frequency aliasing and the use of AAA to eliminate those high frequency aliasing effects without compromising the fidelity for the S-parameter based channel.

In all examples, the AAA process matches the CS IR characteristics below the maximum S-parameter frequency (20 GHz in this case) and reformulated the CS IR characteristics above this frequency to eliminate high frequency aliasing while retaining a causal time domain response with no additional delay.

As has been mentioned, when an Rx IBIS-AMI model is used in which the Rx CTLE attenuates the high frequency aliasing, then this AAA approach is not needed for viewing the Rx output performance.

ANTI-ALIASING ALGORITHM (AAA) DISCUSSION

The AAA has been in use for over 10 years with the technology from SerDesDesign.com for channels using S-parameter data. It has been used to provide free high quality channel simulations and free tools for overcoming inherent S-parameter file limitations.

S-parameter data, though measured on physical devices, is non-causal in the time domain due to limited spectral bandwidth, discrete spectrum frequencies and possible measurement noise. All time domain tools that use S-parameter data need to correct for these non-causal/non-physical effects in the S-parameter data to obtain meaningful causal time domain representation of the frequency domain data. Unfortunately, many companies take a frequency domain to time domain conversion approach that can result in undesirable high frequency aliasing.

One approach used by Keysight Technologies that does not result in high frequency aliasing is described in [7]. The Keysight approach and AAA have similarities and differences. The AAA approach has been discussed in numerous reports [2][3][4].

Both approaches rely on extrapolating the S-parameter magnitude data beyond the maximum S-parameter frequency (F-smax) to the desired sampling Nyquist frequency (F-max). In our examples above the S-parameter maximum frequency was 20 GHz and the sampling Nyquist frequency was 20e9*32/2 = 320 GHz.

They differ in their extrapolation approach. The Keysight approach uses a 4th order polynomial to extrapolate the data from F-smax to F-max. AAA replies on extrapolating the final slope of the S-parameter data and deriving the phase based on a scientific approach.

They both rely on using the Kramers-Kronig relations that state that the real and imaginary parts of a causal response are related by the following Hilbert transforms:

$$u(\omega) = \frac{1}{\pi} P\int_{-\infty}^{\infty} \frac{v(\omega')}{\omega - \omega'} d\omega' \qquad v(\omega) = -\frac{1}{\pi} P\int_{-\infty}^{\infty} \frac{u(\omega')}{\omega - \omega'} d\omega'$$

Figure 11: Kramers-Kronig relations.

where:

- u and v are real and imaginary parts of the spectrum
- P is the Cauchy principal value.

However, they differ in the approach used to convert the extrapolated data to causal data.

The Keysight approach relies on an iterative approach for optimizing the extrapolated data with a 4^{th} order polynomial to result in a minimum in the error between the Hilbert transform of the real spectrum and the imaginary part of the extrapolated data.

AAA derives the phase in the extrapolated region from the magnitude response. As the above Kramers-Kronig relations show, the real and imaginary parts of a causal response are related. Similarly, it can also be shown that under certain conditions the magnitude and phase of a causal response are related. Such a relationship shows that phase shift is obtained by integrating the product of the slope of the logarithmic magnitude plot with a weighting factor that decreases as the integration frequency is further from the evaluation frequency. The real and imaginary parts of the spectrum are adjusted to ensure that the requirements of the Kramers-Kronig relations are met as well.

AAA has been in use for over 10 years with technology from SerDesDesign.com for use in converting S-parameter data to its equivalent causal representation in the time domain. AAA preserves the fidelity of the S-parameters up to their highest frequency while eliminating high frequency aliasing at higher frequencies with no added delay.

CONCLUSION

High Speed Digital (HSD) transmit (Tx) and receive (Rx) circuits are modelled as IBIS-AMI models per the IBIS standard which are used with associated SerDes channels in SerDes channel simulators to evaluate their system margins. Oftentimes, the SerDes channel is defined with S-parameters which may result in the channel simulator modeling the channel with an impulse response that has excessive high frequency aliasing. An original and better anti-aliasing process was defined for use in channel simulators to eliminate the negative effects of high frequency aliasing without compromising the integrity of the channel characterization. The process preserves the fidelity of S-parameters up to their highest frequency while eliminating high frequency aliasing at higher frequencies with no added delay.

This paper first gave an overview of high frequency aliasing issues in context with industry standards compliance testing, SerDes systems examples were presented without and with the proposed anti-aliasing algorithm (AAA), and then the AAA was discussed.

This paper showed an effective approach (AAA) to eliminate high frequency aliasing without compromising the inherent characteristics in S-parameter based channels.

With AAA, any channel simulator can remove high frequency aliasing and provide their users a better environment for SerDes system simulation.

ACKNOWLEDGEMENT

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Link to the Signal Integrity Journal article:

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