DesignCon 2013

Validation & Analysis of Complex Serial Bus Link Models

Version 1.0

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Abstract

This paper highlights an application framework for performing serial data link modeling and analysis using live waveforms on a real-time oscilloscope. It then introduces a method for re-sampling S-parameters in a manner that prevents aliasing when combining multiple sets. In high speed serial data link systems and in RF systems, S-parameters are often used to describe the characteristic behavior [1, 2]. A complex system may be composed of multiple subsystems. Each subsystem can be represented by one S-parameter set. There is a need to combine these S-parameter sets to obtain the model for the complete system. It is required that S-parameter data covers a specific bandwidth of interest. It is also required that the S parameter data has frequency resolution that is fine enough to prevent phase aliasing in the frequency domain [3]. This means that the frequency resolution needs to be fine enough to provide a time interval long enough to cover the impulse response duration plus the reflections duration. Even though all the S-parameter data for an individual block may have appropriate frequency resolution, the same frequency resolution may become inadequate when combining them together in a cascade.

Author(s) Biography

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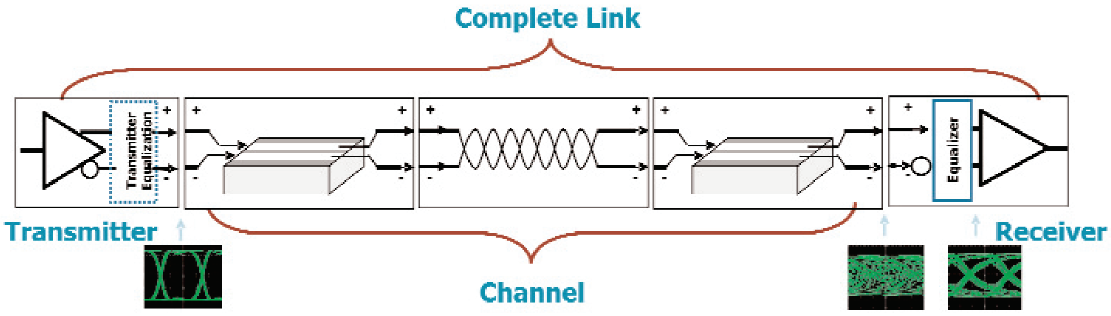
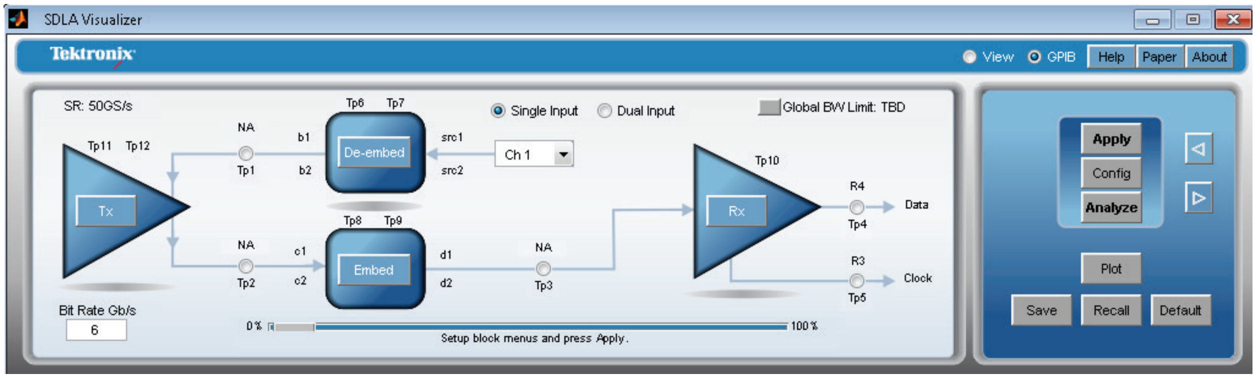


Figure 1. Diagram of a serial data link system.

Introduction

In todays' competitive environment for serial data link analysis and evaluation, there is a need for applications that perform modeling, measurement, and simulation on live waveforms in a real-time oscilloscope. Such applications are setup to allow the user to load circuit models for the test and measurement fixtures and instruments that are used to acquire the waveforms from the DUT. This allows the fixtures and test equipment such as the probe and scope to be de-embedded from the test point waveforms. It also provides test point waveforms with the equipment present. In addition, the application allows the user to load models for the serial data link system in order to evaluate performance without the need for actual link hardware to be present.

One such application would be to acquire waveforms through fixtures from an actual transmitter circuit that is to be evaluated. The system then allows for observation of waveforms out of the transmitter with the test equipment removed, and with an ideal load simulated. Also, the serial data link *simulated* models can be connected to the transmitter to evaluate how the signal with eye closed can be recovered through the receiver model using CTLE equalization, clock recovery, and FFE/DFE equalization. The resulting live waveforms output from various test points in the modeled system can then be output into other applications for various measurements for quality, and to provide eye diagrams.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● Single Input ○ Dual Input

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Setup block menus and press Apply.

Figure 2. This is an application that performs real-time de-embedding of test equipment, and simulation of serial data link components on live waveforms in a real-time oscilloscope.

An example of such a modeling setup is shown above in Figure 2. The system acquires input waveform(s) from the oscilloscope and applies transfer function, filters, to obtain test point waveforms. These test points are the outputs from the simulation system and appear as live waveforms on the oscilloscope display.

- **The De-embed block represents the measurement system** used to acquire the waveforms. It is made up of ***cascade and branches*** of S-parameter models. Other models such as RLC and lossless transmission lines can be assigned.
- **The Tx block is the Thevenin equivalent model for the transmitter** of the serial data link system. The nominal, or S-parameter model for its impedance can be loaded. The application will compute transfer functions from the S-parameter models that can be applied to the input waveforms to obtain the Thevenin equivalent voltage. The Thevenin equivalent model then drives the simulation side of the circuit represented by the embed block.

- **The Embed block represents the simulated system** model for the serial data link. It is made up of ***cascade*** of S-parameter models. Other models such as RLC and lossless transmission lines can be assigned.
- **The complete 4-port S-parameter system is modeled.** It includes all reflection, cross coupling, and transmission characteristics.
- **Test Point Waveforms.** Each test point consists of two lines, A and B. Therefore, any test point can be assigned up to four waveforms simultaneously. These are A, B, (A – B) for differential, and (A + B) / 2 for common mode.
- **The Rx, receiver block:** This is where the S-parameter modeling ends and the linear and non-linear signal processing models begin. It contains CTLE equalization, clock recovery, FFE/DFE equalization, and IBIS-AMI models.

S-Parameter Modeling

RF design engineers commonly use the scattering parameters to mathematically model RF and microwave multi port networks. The basic two port S-parameter model for a network is shown below in Figure 3. Where Z_S is the source impedance of the generator that drives the network and Z_L is the load impedance attached to the output of the network.

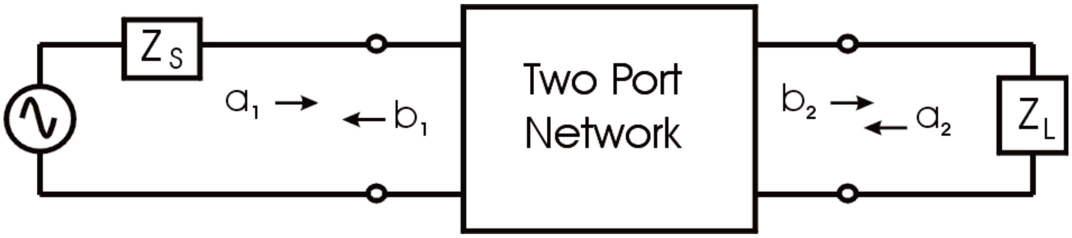

Figure 3. S-parameter two port network model

The value of a_1 is the incident signal traveling into port one of the network. The value of b_1 is the reflected signal from the input of the network due to impedance mismatch when port two is terminated with $Z_L = Z_0$. The value of Z_0 is the reference impedance used during the measurement process of the S-parameters. The value is commonly 50 ohms. Likewise, if port one is terminated in Z_0 and port two is driven by a generator then a_2 is incident into port two then b_2 would be the reflected signal. When considering transmission through the network a_1 into port one may result in contribution to b_2 out of port two. Likewise, a_2 into port two may result in contribution to b_1 out of port one.

Assume that Ea_1 is a traveling wave into port one and that E_{b1} is a traveling wave reflected back out from port one. Also, assume that E_{a2} is a traveling wave into port two and that E_{b2} is the reflected wave from port two.

The values of *a* and *b* may be characterized as follows and described in [1].

$$a_1 = \frac{E_{a1}}{\sqrt{Z_0}} \qquad a_2 = \frac{E_{a2}}{\sqrt{Z_0}} \qquad b_1 = \frac{E_{b1}}{\sqrt{Z_0}} \qquad b_2 = \frac{E_{b2}}{\sqrt{Z_0}}$$

The S-parameters relate to the four waves in the equations above in the following manner:

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \cdot \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

The S-parameters are then defined as follows:

$$S_{11} = \frac{b_1}{a_1} \quad \text{when} \quad a_2 = 0 \qquad\qquad S_{12} = \frac{b_1}{a_2} \quad \text{when} \quad a_1 = 0$$

$$S_{21} = \frac{b_2}{a_1} \quad \text{when} \quad a_2 = 0 \qquad\qquad S_{22} = \frac{b_2}{a_2} \quad \text{when} \quad a_1 = 0$$

The value of a_1 is zero when the input port one is terminated with Z_0 and port two is driven with the test signal. The value of a_2 is zero when the load impedance, Z_L, equals Z_0 and port one is driven with the test signal. These are the conditions that a VNA or TDR system provide when measuring S-parameters.

The S-parameters are each a vector of complex numbers that are a function of frequency. The value of S_{11} and S_{22} are called reflection coefficients and S_{21} and S_{12} are called transmission coefficients.

The same procedure is applied for models with 3, 4 or more ports. The dimensions of the resulting S-parameter matrix are (N, N, M) where N is the number of ports and M is the number of frequencies at which the measurements or calculations were made.

S-parameter cascade

An example of a cascade of 4-port S-parameter blocks is shown below in Figure 4. The circuit connections are defined by port numbers assignments. S-parameter reference impedance for the ports that are connected must be the same.

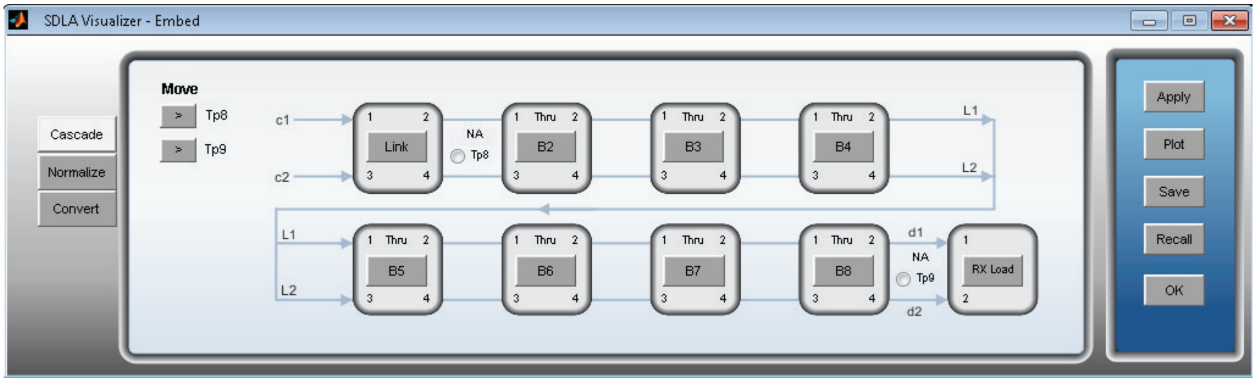

Figure 4. An example of a cascade of 4-port S-parameter blocks for modeling the simulated link model.

The 4-port magnitude plots ordered in the relative matrix positions provide a quick way to view the characteristics of a component, from a single view as shown in Figure 5. The reflection coefficients, S11, S22, S33, and S44 are shown down the diagonal of the matrix. The transmission terms S21, S12, S34, and S43 are on 2x2sub matrix diagonal. The remaining terms are cross coupling terms between various ports. For passive circuits the forward and reverse transmission terms are identical. If they are not, then there are errors in the measurements.

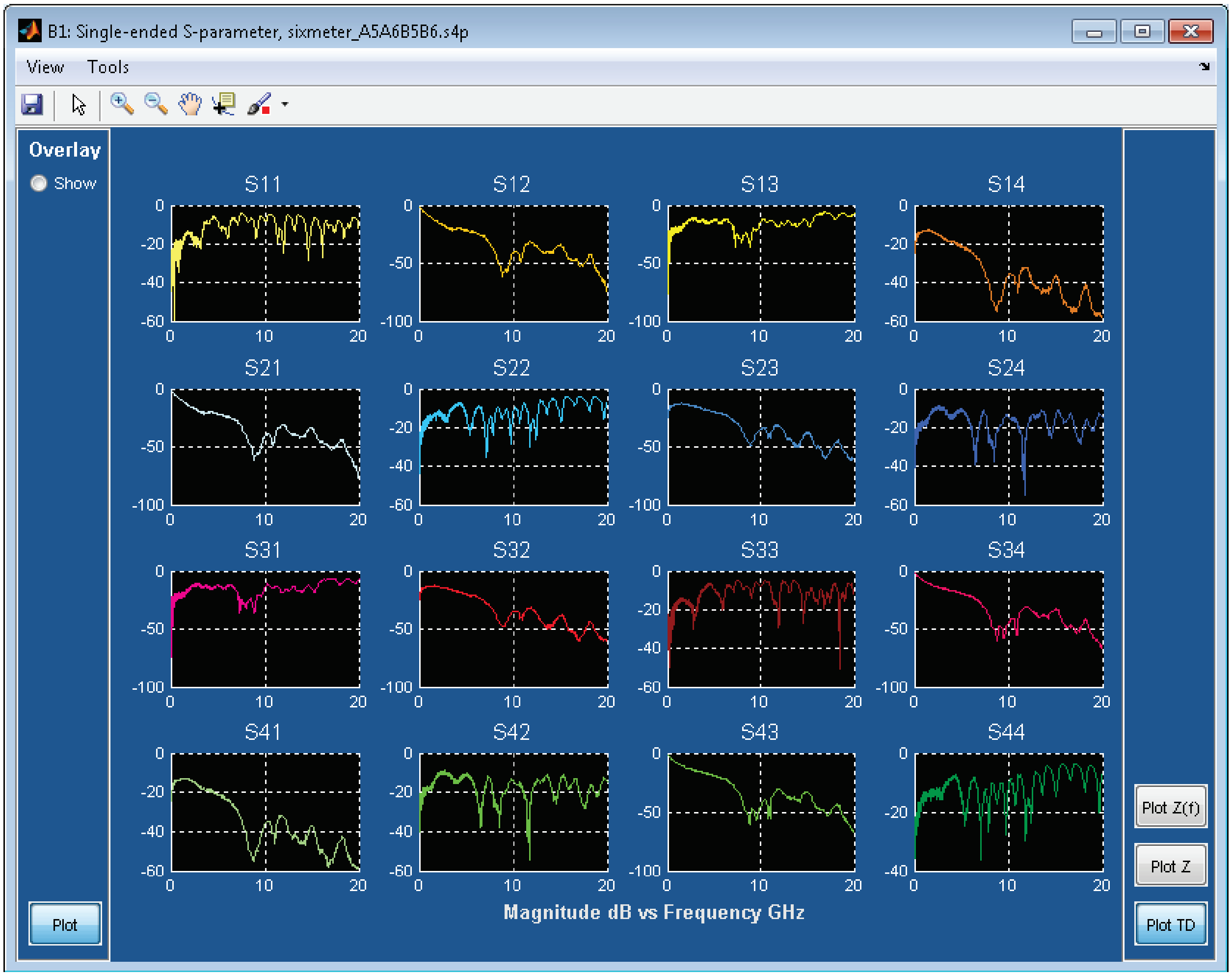

Figure 5. Frequency domain plots for a 4-port S-parameter set for a serial data cable pair and circuit board.

The time domain impulse response representation of each of the above S-parameter vectors is shown below in Figure 6. This is also a valuable view. It readily shows time delays of the transmission terms. It also indicates whether the data is settled over the time interval as it should be for a valid set of S-parameters. These plots are obtained by computing an IFFT of the frequency domain S-parameter data. This often requires extrapolating frequency domain data to DC, and sometimes requires extrapolation to a higher desired Nyquist frequency.

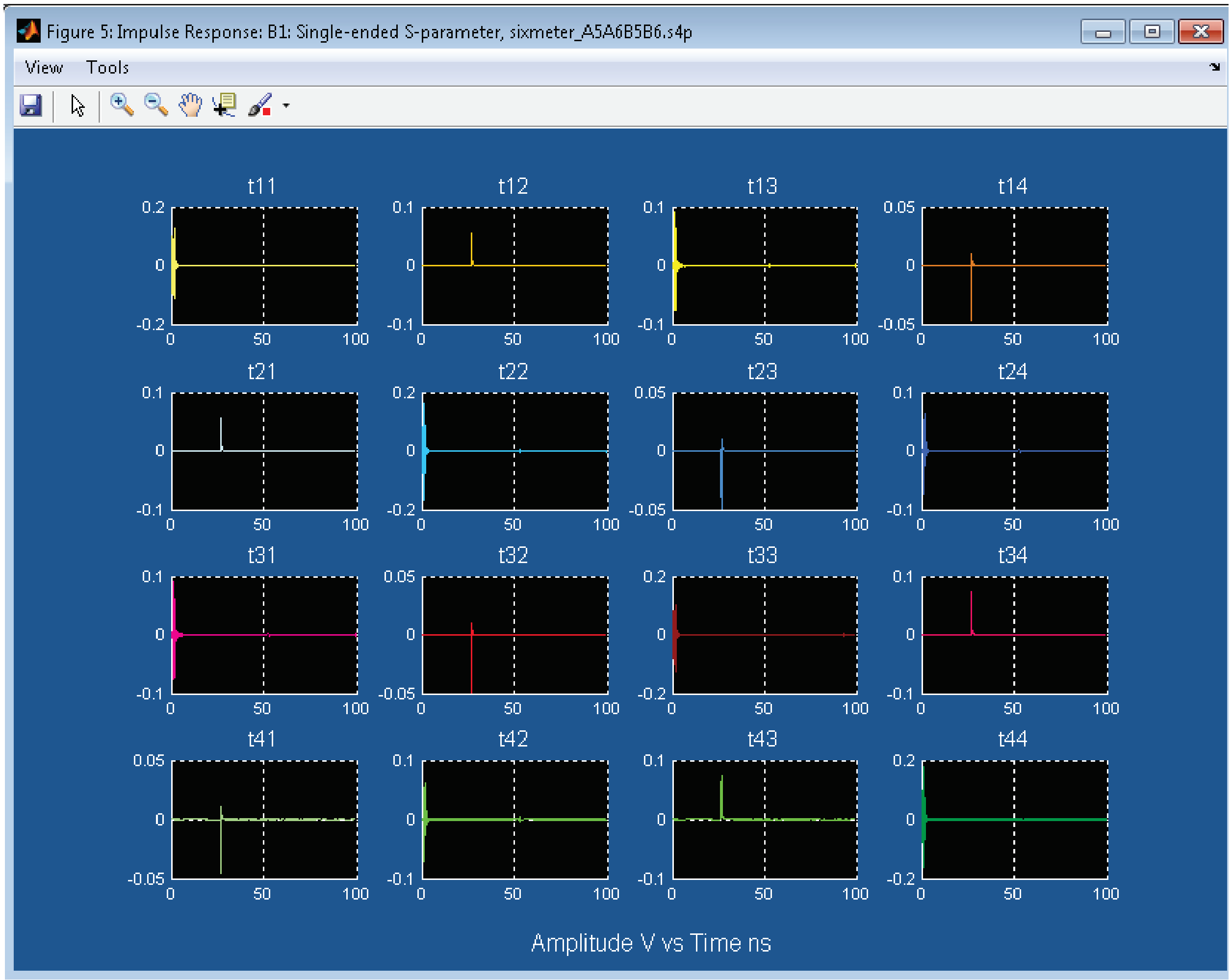

Figure 6. Time domain representation of a set of 4-port S-parameters for a data link.

Measurement of S-parameters:

When a set of S-parameters is measured using a VNA, a sine wave incident signal is placed on a port. For reflection coefficients the reflected sine wave magnitude and phase are measured. All other ports must be terminated with the reference impedance. The ratio of the reflected and the incident signals is represented as S11, S22, S33, or S44. This is done for many frequencies. For S21 a sine wave is placed on port 1 and measured on port 2 and their ratio becomes S21. ***This requires that the sine waves are at steady state after all reflections and transmissions have settled to steady state.***

S-parameters may also be measured and computed in the time domain using step generators for TDR or TDT responses. The step contains all frequencies simultaneously applied to the device that is being measured.

VNA frequency spacing and time response duration

The frequency spacing of the VNA measured data will determine the number of samples up to the desired sample rate frequency at which the time domain waveforms are to be represented. The smaller the frequency spacing, the more frequency samples there are, and the longer the time interval will be. If the frequency spacing is too large and the resulting time interval is too short for the time domain data to be settled, then aliasing occurs. This results in the time domain signal being wrapped to incorrect positions. The equation to determine the time interval is given below:

$$T = 1 / \Delta f$$

Where T is the time interval covered by the S-parameter set, and Δf is the frequency spacing. This inverse relationship infers that in order to cover a longer T, the Δf needs to be smaller. This results in a finer frequency resolution which in turn results in a larger number of frequency domain samples up to the desired sample rate frequency.

The number of samples, N, may be computed from the following equation.

$$N = 0.5 fs / \Delta f$$

Where fs is the sample rate. The number of frequency domain samples covering the range of DC up to the sample rate frequency is equal to the number of time domain samples when the IFFT is computed to obtain the time domain response.

Therefore, the time interval is longer for a given sample rate when Δf is made smaller.

Cascading S-parameters and aliasing:

The cascading of blocks represented by S-parameters is a key operation in the serial data link simulation and analysis system. To understand several of the issues involved consider the cascade shown in Figure 4. The model in each block is represented by a set of 4-port S-parameters. In order to compute transfer functions for the system test points, it is necessary to combine several cascaded blocks into a single block. Consider three blocks with 4 x 4 S-parameters matrices named B1, B2, and B3.

These may be converted to T-parameter matrices. Then they may be multiplied together to obtain a single T-parameter matrix, T_T, for the total system. The T_T matrix may then be converted back to an S-parameter set. In order to combine the matrix sets they must be consistent:

- Frequency spacing must be the same, thus time interval represented must be the same.
- Start and stop frequencies must be the same.
- Reference impedance must be the same for any two ports connected together.

- The final combined matrix will cover the same time interval of each block matrix. Thus if the system delay of the cascaded blocks is greater than the time interval covered by the individual block S-parameters then aliasing will occur. In the time domain the aliasing results in pulse response features occurring in the wrong time position and they may be reversed in time order. This is the result of phase aliasing in the frequency domain where there are less than 2 samples per revolution.

An example:

To illustrate the problems involved consider the following example where three blocks are to be cascaded, and all of the blocks are the same. The s12 data has the impulse response shown in Figure 7. It is observed from the graph that the propagation delay is about 10ns. The S-parameter's frequency spacing of 50MHz covers a time duration of 20ns. It is sufficient for this s12 data set.

However, when three of these S-parameter blocks have been cascaded, the total propagation delay would be 30ns. This would result in the impulse aliased to a delay of 10ns rather than the correct 30ns position. For this case, using the same frequency spacing is no longer sufficient to cover the combined blocks. This example demonstrates the first requirement to be addressed:

> **Requirement 1:** Resample the individual S-parameters for each block to provide smaller frequency spacing to cover the increased time interval for the combined S-parameters. A plot showing the data set after resampling is shown in Figure 8.

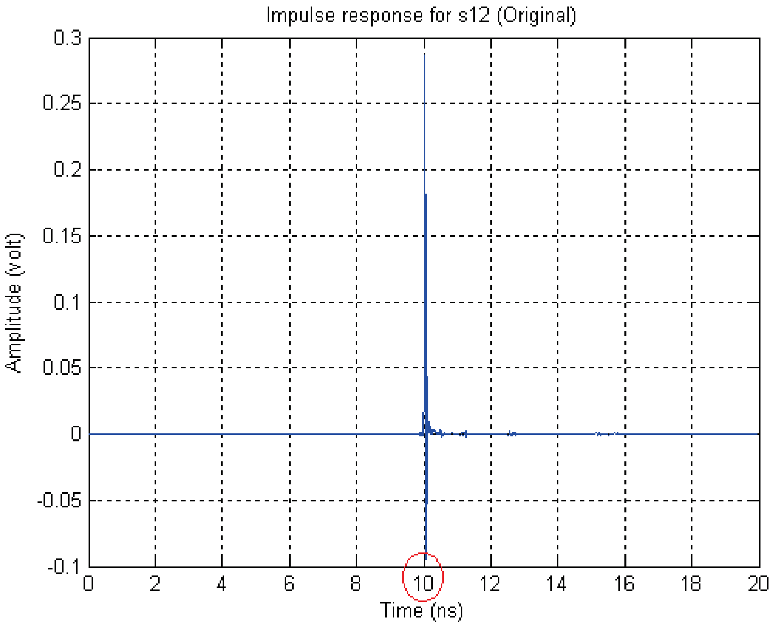

Figure 7. Impulse response of s12. Propagation delay of 10ns.

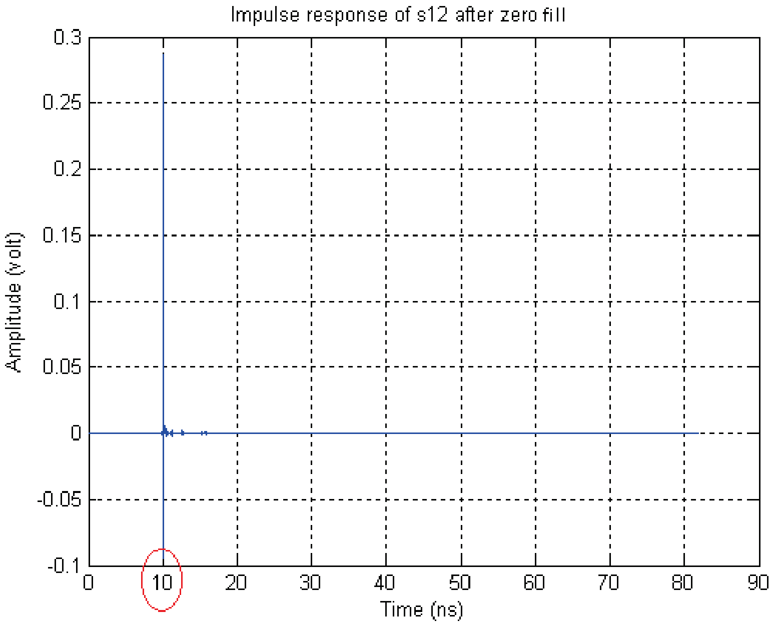

Figure 8. Impulse response of resampled s12. Covers longer time interval

The plot shown below in Figure 9 demonstrates that the interpolation does not significantly change the response of the S-parameter.

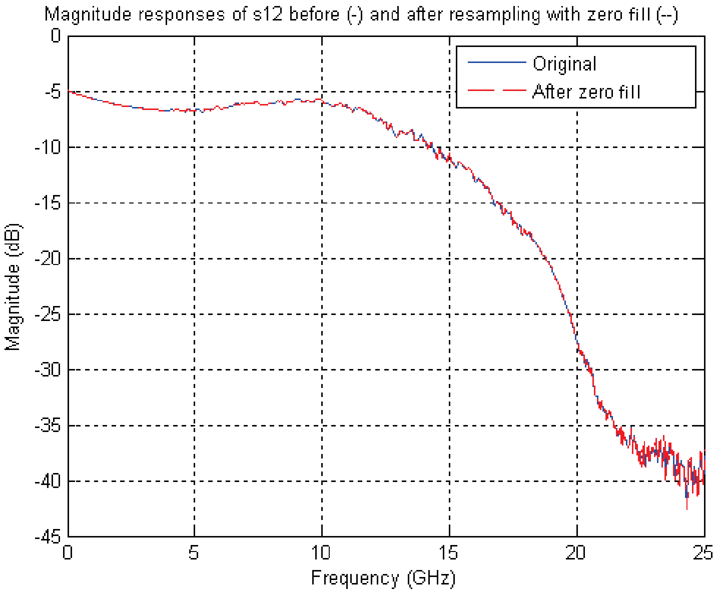

Figure 9. Magnitude responses of s12 before and after re-sample.

Various approaches can be taken to address requirement 1. For example, one approach is to perform interpolation in the frequency domain. This may be done by either interpolating the real and imaginary components, or it may be done by interpolating the magnitude and phase components [3]. This approach can be done with linear interpolation but this can result in significant errors unless the frequency spacing is sufficiently small. Using higher order interpolation may result in transient errors at the start and stop frequencies where there is a discontinuity in the data set.

A different approach would be to resample multiple S-parameters that potentially have different frequency spacing and different bandwidth.

Note: A patent disclosure has been submitted for this overall algorithm.

1. **Extrapolate all S-parameters data to DC** if the S-parameters don't have DC value. S-parameters measured from VNA do not have a DC value. TDR measured S-parameters have a DC value.
2. **Determine the common maximum frequency** for all of the S-parameter sets. This value can be the maximum frequency of all of the S-parameter sets in the cascade. Extrapolate each S-parameter set to beyond the maximum common frequency.
3. **Convert extrapolated frequency domain S-parameters** to obtain the time domain impulse responses using an IFFT.
4. **Determine the actual common sample period** between the impulse responses. The actual common sample period can be taken as the minimum of sample periods of the impulse responses. Then resample the impulse responses so they all have the same sample rate.
5. **Zero fill the impulse responses** at proper positions, as described below, to get increased time interval. The increased time interval can be determined as multiples of the sum of all the time intervals represented by each S-parameter.
6. **Convert time domain zero filled** impulses to frequency domain using FFT.
7. **Truncate the lower frequency and high frequency points** that are extrapolated. (This step is optional.)
8. **At this step all S-parameters have been resampled at the same frequency points with sufficient frequency resolution.** For each frequency point, combine the S-parameters for each block to be cascaded. Do this directly [2] or through T-parameters [1] to get the combined S parameter.

The zero fill algorithms:

In step 5, the position of zero filling is not arbitrary and it is not necessarily started at the end of the right side of the time domain response.

For all of the impulse responses in the S-parameter set the, the zero phase time reference position is at the beginning of the time record. If the data were all ideal the zero fill would be added to the right side of the record. However, the leakage from IFFT calculations can sometimes result in ringing from the beginning of the time record being wrapped to the end of the time record.

Therefore, the impulse responses obtained from converting to the time domain can have some ringing at the end of the time record. This ringing at the end the impulse response is caused by band limited nature of S-parameters [3], and is affected by sample offset [4]. For example, the impulse response for an s11 data obtained in step 4 is shown in Figure 10. The small ringing at the end is wrapped from the left end to the right end. Regular zero padding, where zeros are padded to the right end of the impulse response would yield an S-parameter result with errors. This example demonstrates the second issue to be addressed:

Requirement 2: Zeros are filled at proper position to maintain the wrapped ringing at the end of the impulse response.

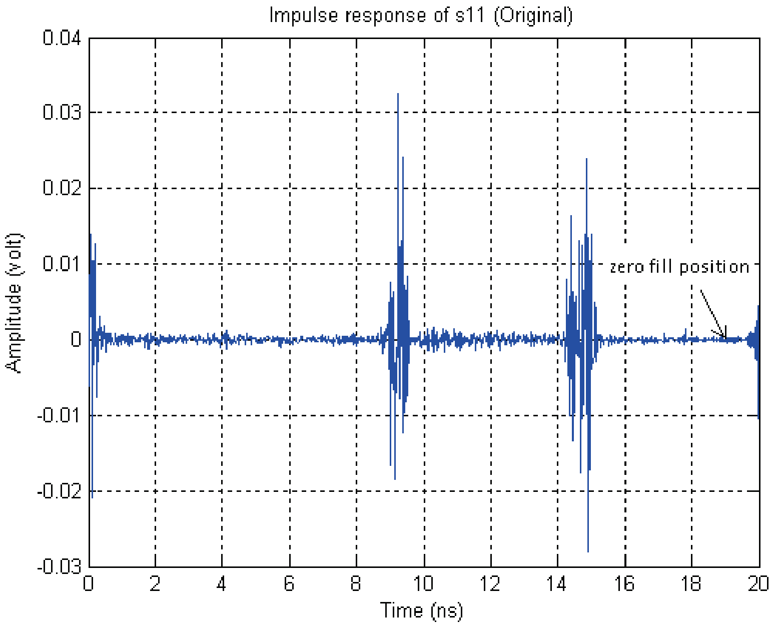

Figure 10. Impulse response of s11. Early ringing wrapped to the end.

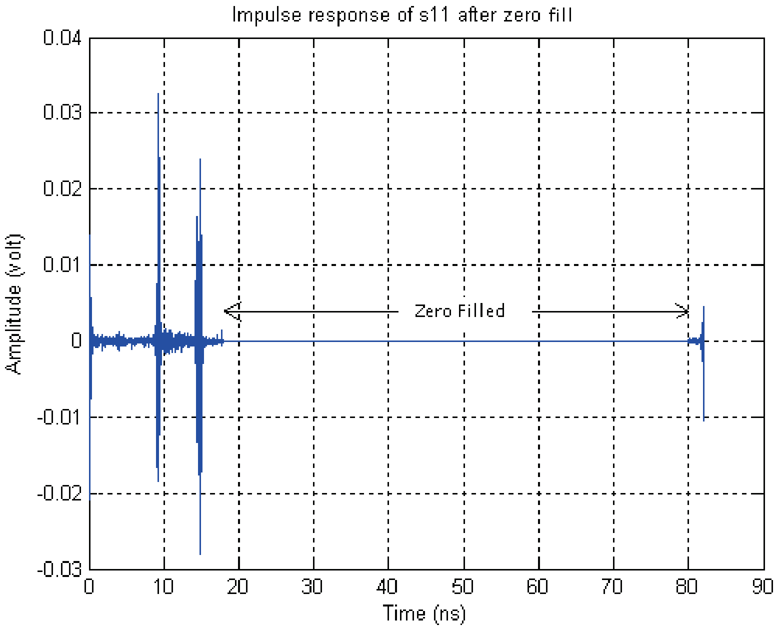

Figure 11. Impulse response of resampled s11. Early ringing preserved at the end.

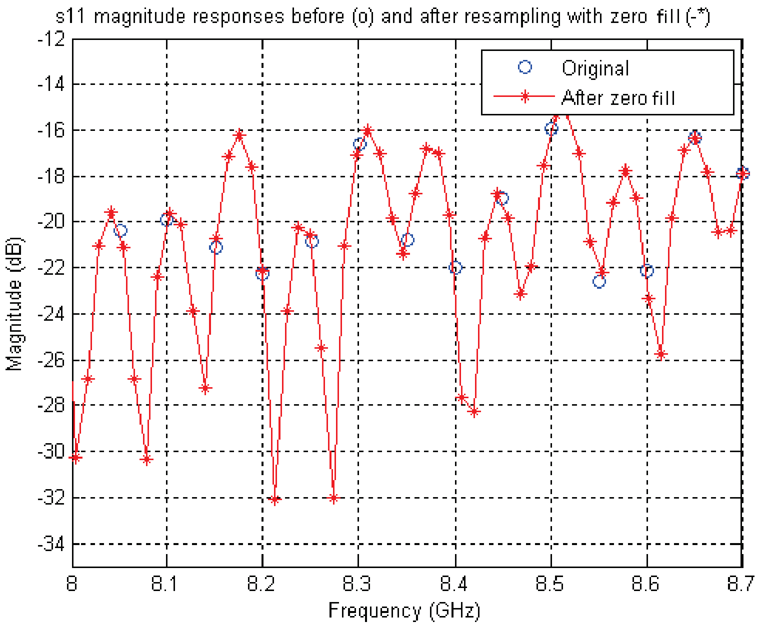

Figure 12. Zoomed in magnitude responses of s11 before and after re-sample.

To address requirement 2, there are two options to find the proper position:

Option 1: Starting from the end the impulse response, check if there is ringing at the end. If there is no ringing, then the zeros can be filled right after the last point of the impulse response. If there is ringing, then search backwards to find the position where the ringing is settled. Zeros can be filled in the settled position as shown in **Figure 11**.

Option 2: Always pick a certain percentage of the impulse response to fill zeros. For example, zero fill at a position of 5% from the end. **Figure 10** and **Figure 11** show the results of option 2. The resampled S-parameters are matched well with the original S-parameters, as shown in **Figure 12** .

De-embedding Example With a Large Reflection

In the photo in Figure 13, a step generator is driving a balun to provide a differential step signal. Two 5X attenuators are connected to the two outputs of the balun where the green cables are connected. These insure minimum reflections from the generator at the reference plane for de-embedding. In order to provide a large reflection for the purpose of this example, the opposite ends of the green cables are each connected to a T and coupler combination with an open circuit.

A VNA was used to measure 2-port S-parameters for each green cable and for of the two T's combined with open circuit couplers. These 2-port s-parameter sets for the green cables can be loaded into block 1 of the cascade and treated as a 4-port model. The 2-port S-parameters for the two T's can be loaded into block 2 of the cascade. These blocks are in the de-embed system block to define the measurement circuit into the scope. Nominal 50 ohms is defined as the scope impedance and for the balun combined with the step generator for this example.

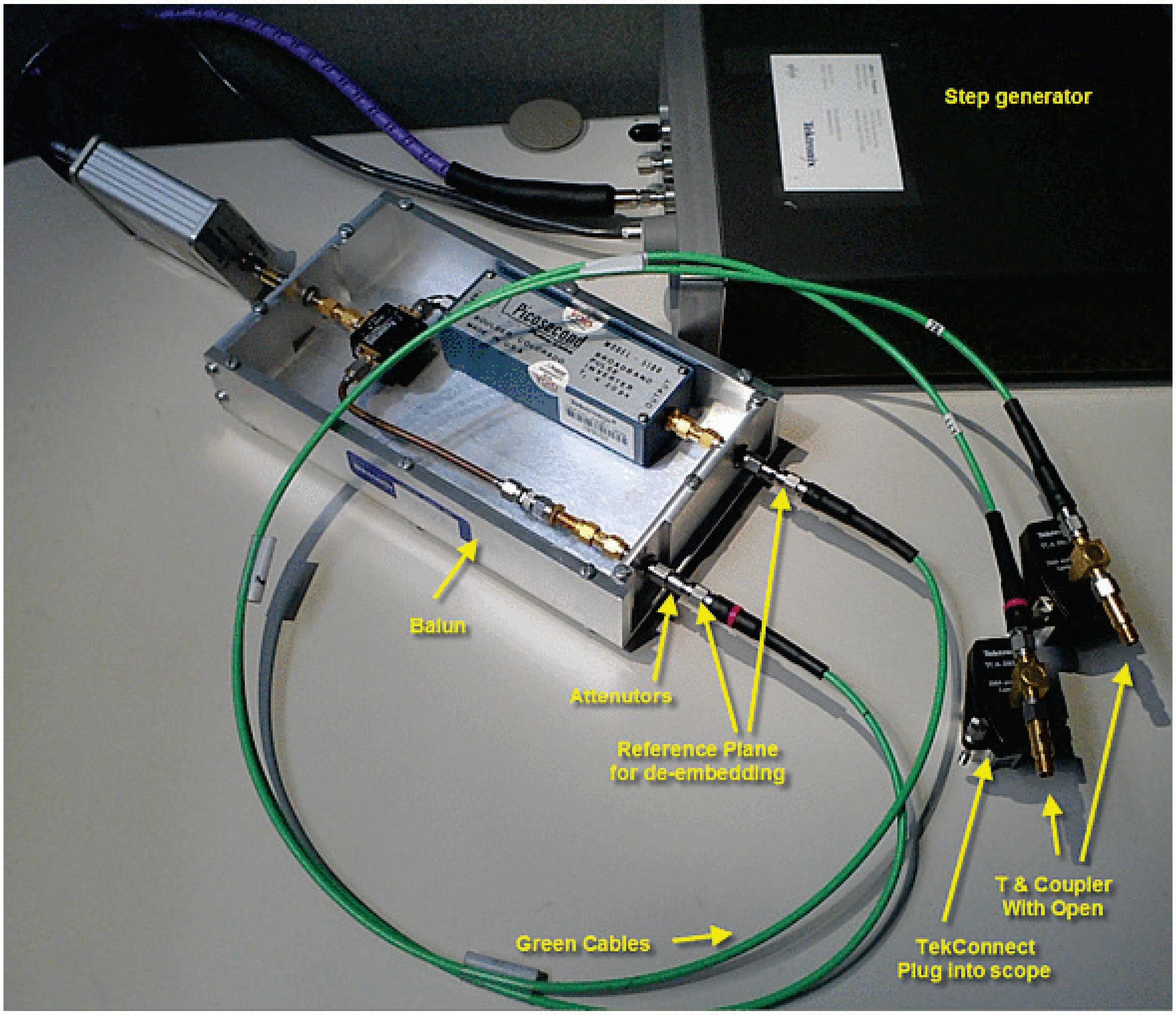

Figure 13. Test setup for de-embedding the green cables and a T connector with an open circuit coupler.

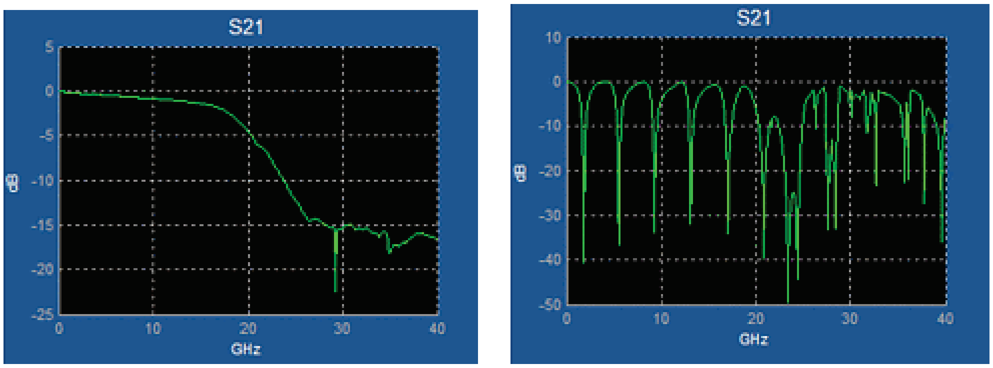

Figure 14. S21 for one the green cable is shown at the left. S21 for one T and coupler is shown at the right.

The green cables have relatively small loss over the range of 10GHz as shown in Figure 14. However, the T with open circuit coupler has dropouts of up to -40 dB in the same range! This is a difficult de-embedding situation since the transfer function will end up with inverse response of up to 40 dB peaks. The oscilloscope will be operated in average acquisition mode for this example in order to increase the bits of resolution and eliminate noise from the large boost.

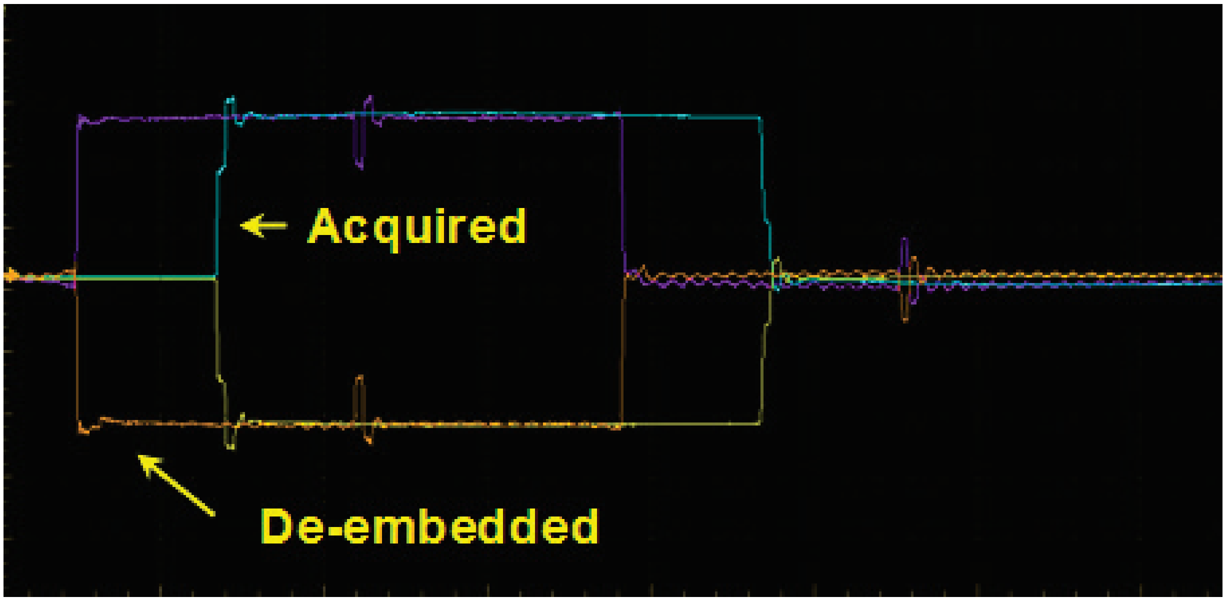

Figure 15. De-embedded waveforms with cables and T's connected to the balun, at Tp1 as shown in Figure 2.

The image above in Figure 15 shows the **Tp1** waveforms, which are the outputs of the balun with the cables and T coupler combination still loading the step generator. The waveforms acquired on the scope are in yellow and Cyan. The waveforms de-embedded to the reference plane with the cables still loading that point are shown in purple and orange.

The resulting reflections and time delays are correctly represented in the de-embedded waveforms.

The reflections due to the open circuit of the coupler can be seen on the acquired waveform at the rising and falling edges where the steps entered the oscilloscope (yellow and cyan). On the de-embedded waveforms (purple and orange), the rising and falling edges have the reflections removed, and the shape of the pulse is as expected at the reference plane into the cables. There is a delay of approximately 4.1 ns through the cable. At 8.2 ns, the round trip time of 8.2 ns, the reflection arrives back at the reference plane input to the green cables. Also, when the pulses (purple and orange) go back to zero, another round trip reflection off of the input side to the scope arrives back to the reference plane 8.2 ns later. (Figure 15)

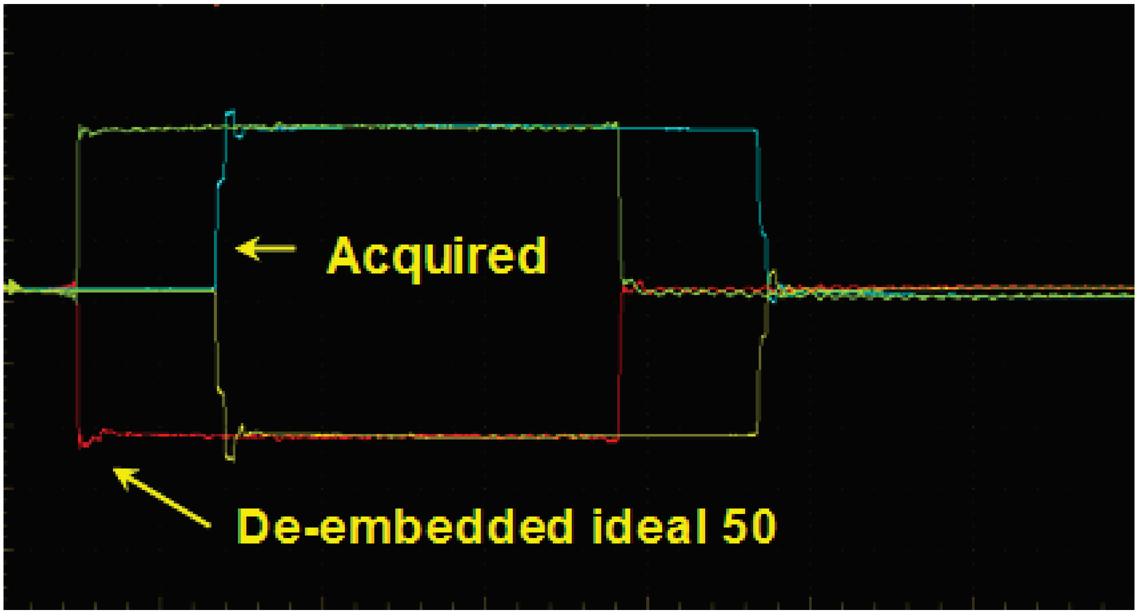

Figure 16. De-embedded waveforms with cables and T's replaced by ideal 50 ohms, at Tp2 as shown in Figure 2.

The image above in Figure 16 shows **Tp2,** which provides the waveforms with the measured cables and components removed, and the step generator reference plane terminated in an ideal 50 ohms.

The wave-shape is the expected shape of the step generator. The major reflections on the acquired waveforms were removed.

The transfer functions are FIR filters that run in real-time on the oscilloscope. The plots of these filters illustrate the extreme nature of this particular de-embed example.

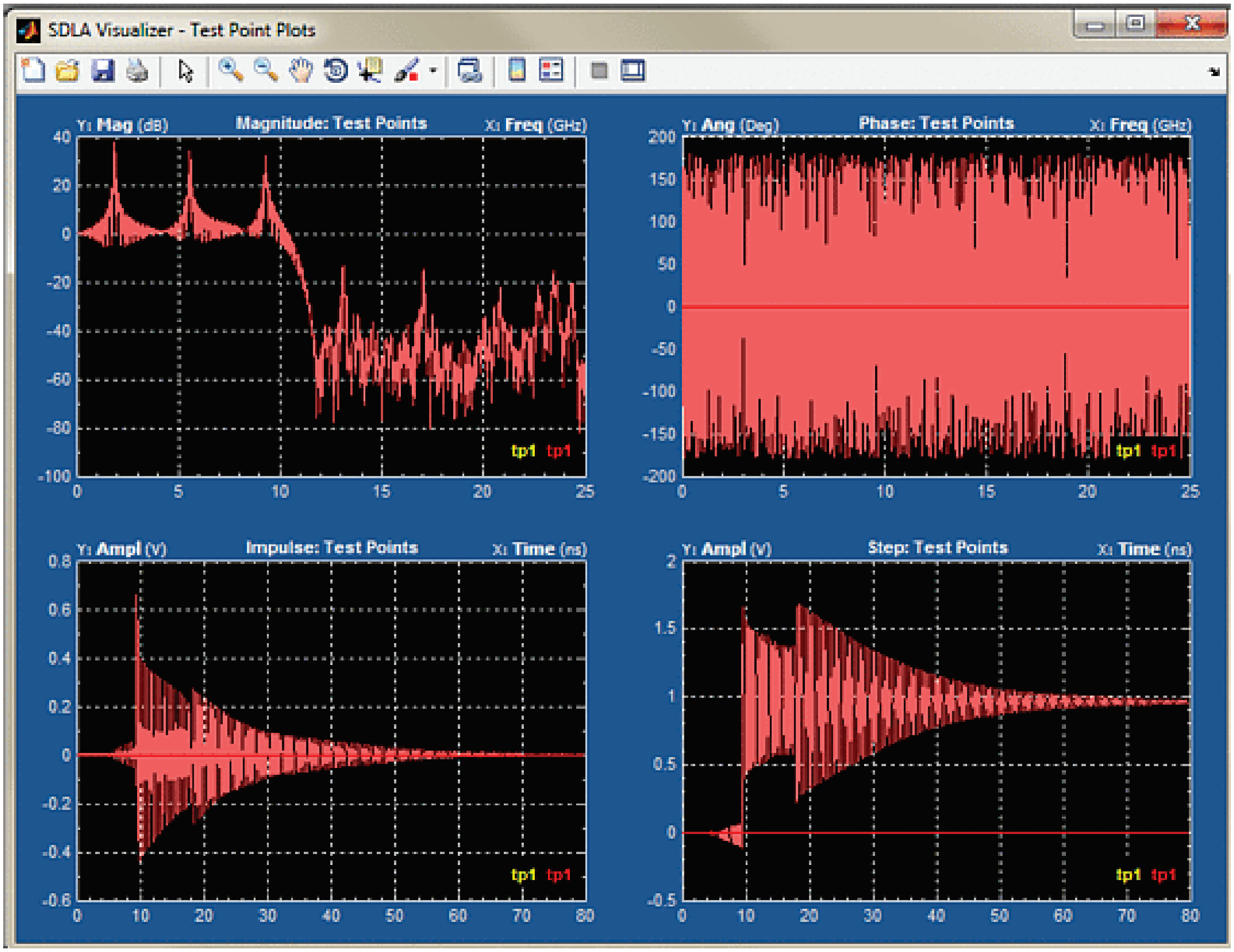

Figure 17. FIR filter transfer functions for the de-embedding example.

Conclusion

This paper has described the basis for a robust serial data link analysis system that updates simulated test point waveforms live on an oscilloscope display. The system takes in S-parameter models to create the transfer functions for obtaining these waveforms. A specific algorithm for preventing phase aliasing of cascaded S-parameters was presented. It was demonstrated that individual S-parameter blocks may be sufficient to cover the characteristics over the resulting time interval. However, it is possible that multiple S-parameter sets cascaded together may not cover a sufficient time interval for representing the cascaded results. This would result in phase aliasing of the final S-parameter set. A method, for which a patent application has been submitted, was presented for preventing aliasing during the S-parameter cascading procedure. An example of cascaded de-embedding and embedding was also provided.

References

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