

Keysight Technologies

Transforming Oscilloscope Acquisitions
for De-Embedding, Embedding and
Simulating Channel Effects

Application Note
S-parameter Series

Introduction to Signal Acquisition and Theory

Realizing accurate and reliable analysis of signal data on today's high-speed digital systems requires a thorough understanding of the theories of analysis of data acquisition. Armed with an understanding of the theory, and knowledge of the tools, the designer can accurately and efficiently achieve precise models of device behavior. This knowledge allows the engineer to develop optimum designs the first time, maximizing efficiency and the optimizing their value proposition.

This paper is the first of 6 papers whose intent is to guide designers and validation engineers of high-speed digital systems through the details of channel element measurement and modeling for the purpose of manipulating oscilloscope acquisitions to reveal the signals that the engineer wants to see and measure. This extra processing is required because the actual signal cannot be probed (for various reasons) or because the probed location is different than is desired, or because the measurement elements themselves (i.e. probes) affect the measurement result and need to be removed from the reported measurement.

About ten years ago, the electronics industry departed from the traditional parallel bus interface and embraced a serial topology. At first look this seemed a little strange. Not only did the bus clock rate have to be multiplied by at least a factor of 8 to get the same effective throughput, but it meant that digital designers would have to become expert at new blocks such as phase lock loops; traditionally an analog designers area. The issue at hand was that integrated circuit was becoming IO bound; it wasn't the internal capabilities but getting signals to and from the device. Additionally, the lowly printed circuit board made of FR-4 had become, in a sense, a precious commodity—in order to keep profit margins, the low cost material had to be used and running eight bit parallel buses was a waste of routing real estate. The result of this technological departure was a headlong rush into higher data rates and incumbent microwave principles applied in design. We now call this area of engineering, Signal Integrity.

The problem that Signal Integrity practitioners address is the myriad of issues that come into play in the conveyance of digital data from a digital transmitter through a channel to a receiver. At billions of bits per second (Gbs), everything in the transmission path affects the signal to some degree. Developers and designers must learn what the most significant contributors are and how to model and measure them. When these are understood they can be entered into simulators or other measurement equipment to assist in the understanding and optimization of system performance. The objective of an engineer working in the signal integrity space is correlation of simulations to measured results.

Engineers working in the high-speed digital area are necessarily concerned about signal integrity issues, but may not be signal integrity experts. The validation and design engineer, for instance, needs to understand how to solve the problem of specifying a signal characteristic at a remote location, but not necessarily be worried about the humidity dependence of the loss tangent of FR-4. They also would like to run some system scenarios using measured or simulated models to see the effects of varying one elements characteristics or even many elements simultaneously. These elements may be printed circuit transmission lines, vias on the boards, connectors, resistors, inductors, capacitors, and even the measurement probes themselves. At times, an element might even be another design whose sole purpose is allow access to measure the transmitted signal at some point. These are called 'fixtures' and though they may be of excellent quality they will have an effect and must be considered.

In the enterprise of evaluating these systems an oscilloscope is ultimately used to view the signals. Even if the signal location is not accessible or is understood to be affected by system elements at the time of acquisition, or is derived from added element; the system can be modeled and an accurate simulation of the real signal can be derived. Keysight Technologies, Inc. has developed a series of tools that can be effectively used to measure the elements, derive models from simulations, filter measured data for more accuracy, and ultimately accurately characterize the this signal of interest.

Hardware-based co-simulation comes of age

Whether measurements are made with probes or test fixtures, the task of validation leads inexorably to the process of co-simulation. Co-simulation, the combination of simulation and measurement, can show what a simple measurement alone cannot. It can show what a measured signal would look like if it were affected by additional circuitry that wasn't present in the physical measurement. It can also show the opposite - what a measured signal would have looked like if it were not affected by extraneous circuitry (parasitics) that are present in the physical measurement path. It can even show what a signal looks like at a different location than the physical location that was actually measured.

Co-simulation has been used for decades by extracting measured waveforms from oscilloscopes and importing them into EDA simulation tools. Although affective, it can be very cumbersome and time consuming. Modern high-performance oscilloscopes now have the ability to perform co-simulations directly inside the scope on live measured waveforms. These co-simulations are simply voltage transformations applied to the measured waveforms. A linear filter, which may or may not have gain, is applied to the measured waveform that renders a different view— that is, the measured waveform of an oscilloscope is converted to a filtered waveform that renders a simulation of what the signal would look like if the measurement circuit was changed. If the measurement circuit is to be changed by removing elements, it is commonly referred to as de-embedding. If it is changed by addition of elements, then term is embedding. In any event, the key to performing these measurement-to-simulation signal views is in the creation of a voltage transfer function that transforms the physical measurement to the desired measurement. This is the first step in ultimately understanding the measured results.

Not all oscilloscope de-embedding applications generate correction transfer functions from complex circuit models. Some simply extract the S21 component from S-parameter files and apply use it directly as the transfer function for embedding applications or use its inverse as the transfer function for de-embedding applications.

Transfer function derivation

Deriving the filter transfer function requires the definition of two circuits. The first circuit accurately reflects the existing measurement conditions on the bench, including the oscilloscope observation point (either scope's front-panel input connector, or a probe). The second circuit reflects the desired measurement conditions. As an example, assume a cable exists between the source device under test (DUT) and the oscilloscope. The objective is to remove (de-embed) the effects of the cable. In this case, the measurement circuit would manifest a single cable between the source and a scope channel input.

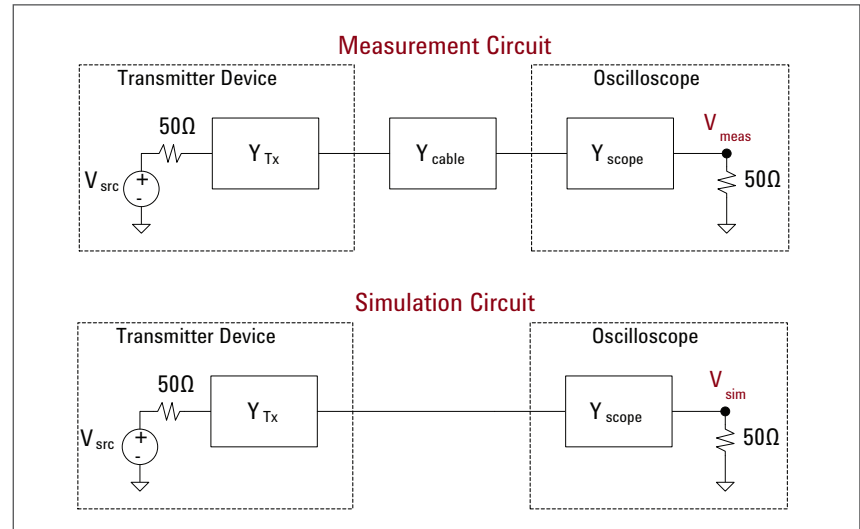


Figure 1. Measurement and simulation circuit models for observing waveform without cable

As shown in Figure 1, the simulation circuit would be identical to the measurement circuit except that its cable has been removed (i.e. a simulation of the scope directly connected to the source). By assuming that these two circuits are linear and time-invariant, the simulation can be performed by basic nodal analysis. The analysis of these circuits results in two transfer functions (in the frequency domain), from a common source to each circuit's observation node. Given:

$$H_m(f) = \frac{V_{meas}(f)}{V_{src}(f)}$$

$$H_s(f) = \frac{V_{sim}(f)}{V_{src}(f)}$$

Taking the ratio of these transfer functions produces the desired correction transfer function, $H(f)$, which is used to convert, or transform the measured waveform to the simulated waveform.

$$H(f) = \frac{H_s(f)}{H_m(f)} = \frac{V_{sim}(f)/V_{src}(f)}{V_{meas}(f)/V_{src}(f)} = \frac{V_{sim}(f)}{V_{meas}(f)}$$

$$V_{meas}(f) * H(f) = V_{meas}(f) * \frac{V_{sim}(f)}{V_{meas}(f)} = V_{sim}(f)$$

Which yields the filtered, or simulated, result desired.

Transfer function derivation

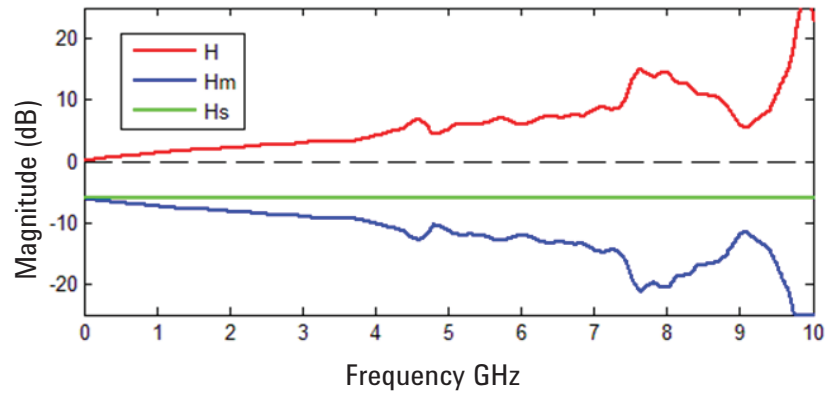


Figure 2. Transfer functions H_m , H_s , and H of the cable de-embedding example

Since the oscilloscope inherently operates in the time domain, it applies the transfer function to the measured waveform, $V_{meas}(t)$ by convolution with the impulse response, $h(t)$. This becomes the inverse Fourier transform of the frequency domain transfer function, $H(f)$, which is:

$$V_{sim}(t) = V_{meas}(t) * h(t)$$

The oscilloscope performs this convolution using a finite impulse response (FIR) digital filter that is implemented using either digital signal processing (DSP) hardware (as in Keysight Infiniium oscilloscopes), or using software. While both are accurate and effective, the obvious benefit of a hardware implementation is speed - the processing and updating the display is much faster. Figure 3 shows the impulse response, $h(t)$ and a filter that could be used to apply it to the measured signal, $V_{meas}(t)$.

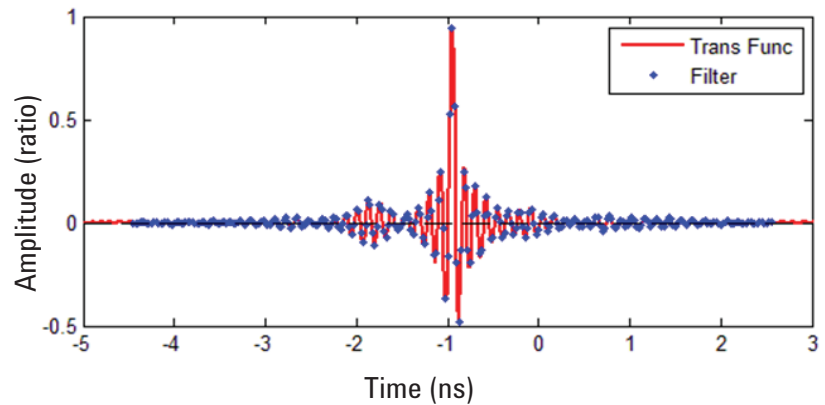


Figure 3. Correction filter (blue) and impulse response of de-embedding transfer function (red) from lossy cable example

Transfer function derivation

Figure 4 compares the correction filter's frequency response to that of the de-embedding transfer function to be applied to the measured waveform. In this example, the targeted transfer function is a band-limited version of the one calculated in Figure 2. The waveforms in Figure 5 represent the effects of applying the correction transfer function of Figure 3, to a measured waveform.

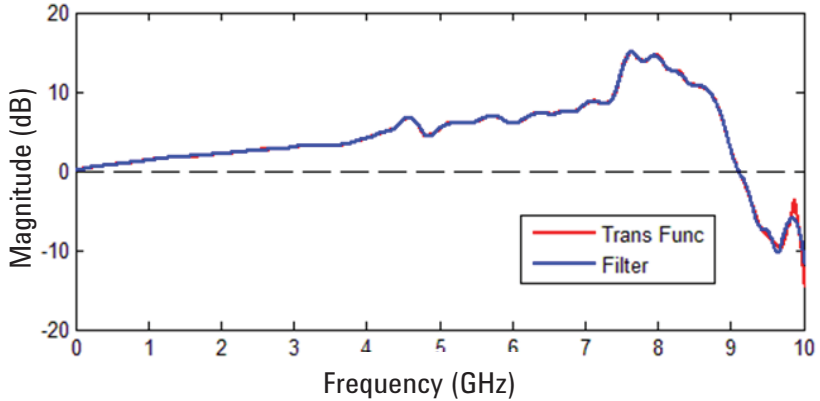


Figure 4. Comparison of correction filter's frequency response (blue) and the targeted de-embedding transfer function's frequency response (red) from the lossy cable example

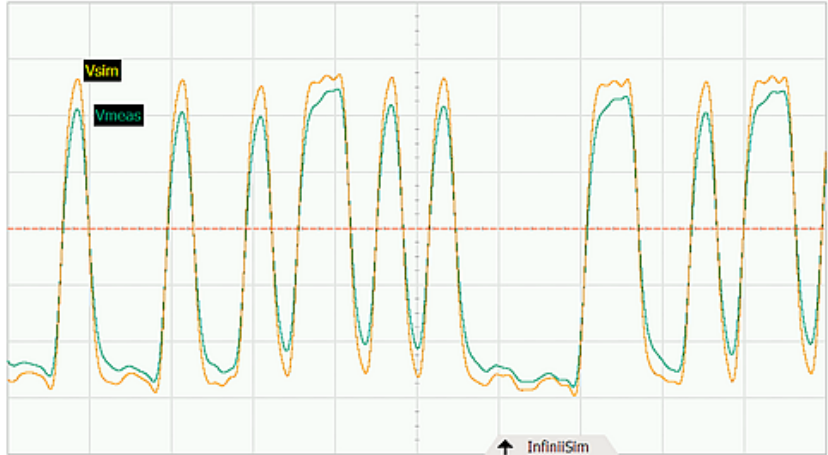


Figure 5. Waveforms V_{meas} and V_{sim} of lossy cable example

Creating transfer functions

Circuit modeling

The calculation of transfer functions requires complete and accurate descriptions of both the measurement circuit and the simulation circuit. The circuits shown above are good examples. These circuits are described using Y-parameter model elements. Y-parameter models are one form of N-port network models that describe port currents as a function of port voltages. They are convenient for performing nodal circuit analysis. However any N-port network model type could be used to describe these circuits because all N-port model types (Z, Y, S, H, etc.) can be converted into any other N-port model type.

S-parameters, for example, are commonly used to describe these circuit models because S-parameters are easy to measure directly. Also note that the models in the above example are single-ended 2-port models and although they are normally drawn with only two connections, they all have an implied connection to ground.

Observation nodes

Calculation of transfer functions also requires properly locating the observation voltage nodes of the two circuits. The previous example used the same observation node for both circuits, and removed the cable. Alternatively, the cable could have been left in place, but the simulation observation node would have to be relocated.

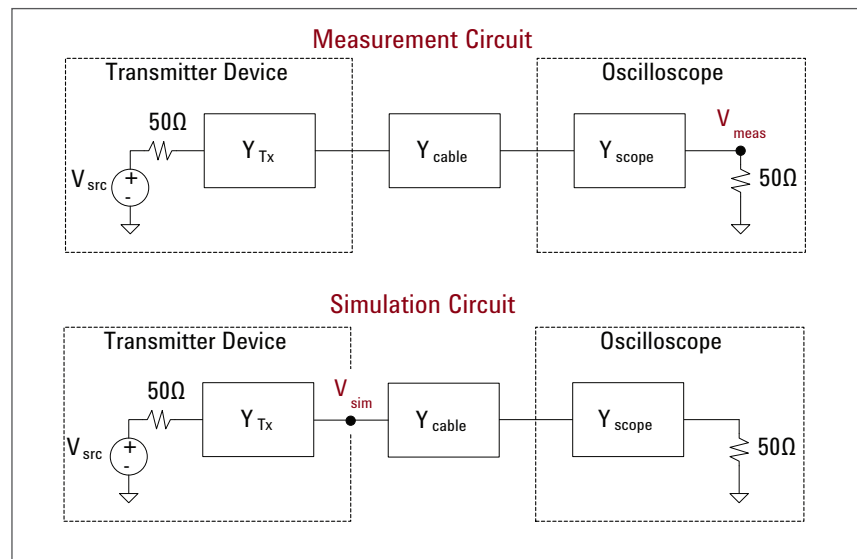


Figure 6. Measurement and Simulation circuit models for observing waveform at input of cable

Note that the examples locate the oscilloscope's measurement observation node behind the scope's model block instead of in front of it. That is because high bandwidth oscilloscopes with 50Ω inputs are calibrated to measure the incident voltage and not the node voltage at the input. If converted to an S-parameter model, the calibrated scope input model, V_{scope} would have a non-ideal return loss and an ideal insertion loss. This is not true however, for a calibrated probe. Probes are calibrated to measure the node voltage at the probe tip. Therefore it does not matter whether the measurement observation node is located before or after the probe input model block.

Creating transfer functions

Probe loading example

Oscilloscope probing of circuits is very common and universal. While modern probes are designed to minimize parasitic circuit loading, they generally may have a significant effect on measurement accuracy. Figure 7 depicts this diagrammatically, and Figure 8 shows this schematically, using S-parameter models.

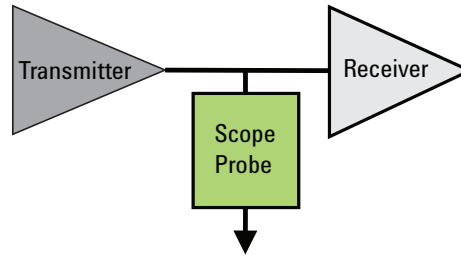


Figure 7. Oscilloscope Probe loading on a digital transmitter and receiver

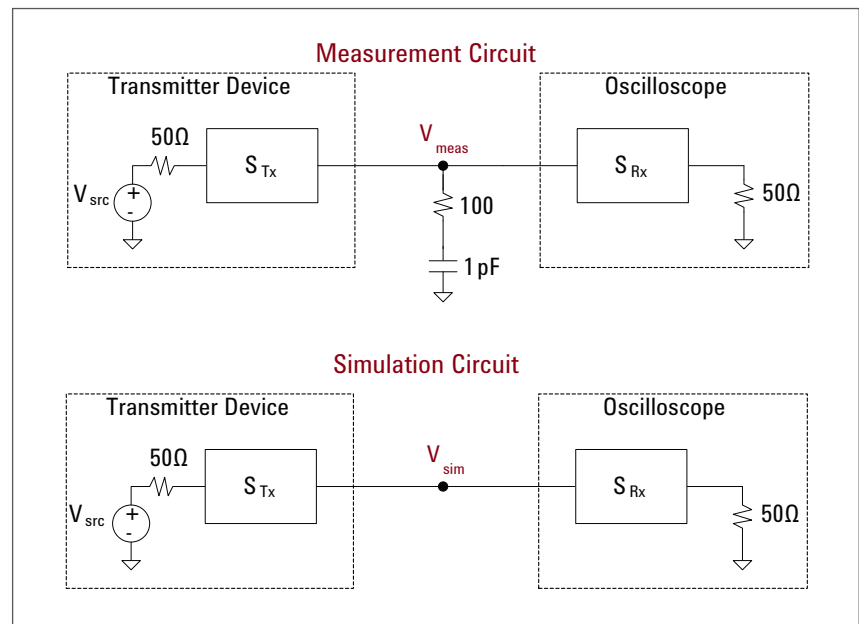


Figure 8. S-parameter modeling of probe loaded circuit and co-simulation of unloaded circuit

Creating transfer functions

Probe loading example

The probe loading model in this example is a simple series shunt RC comprised of a lead resistance, $R_{Probe} = 100$ ohms and capacitance, $C_{Probe} = 1$ pF. The insertion loss of the transmitter and receiver models won't affect the resultant corrected transfer function provided they are identical for both circuits. The transmitter's output return loss and the receiver's input return loss however, do affect the corrected transfer function. The intermediate transfer functions, $H_m(f)$ and $H_s(f)$ and the resulting corrected transfer function, $H(f)$, are shown in Figure 9.

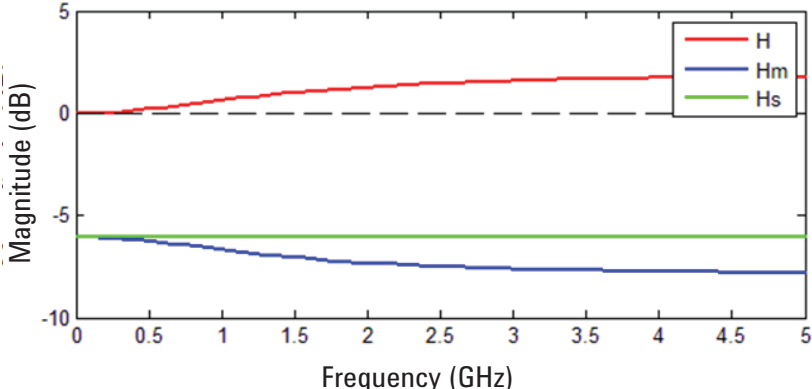


Figure 9. Transfer functions H_m , H_s , and H of probe loading example

Figure 10 shows the waveforms and the effects of correcting the probe loading in the example. In this case, the effect of the probe as modeled illustrates about a 10% degradation for 0-1-0 and 1-0-1 transitions. Removing the effect of the probe in this case will open the eye commensurately.



Figure 10. Waveforms V_{meas} and V_{sim} of probe loading example

The transfer function filter

In the foregoing discussion, the time domain FIR correction filter, $h(t)$ is derived from the frequency domain transfer function $H(f)$. This filter is convolved with the measured waveform to yield the co-simulated result desired. Since the correction filter is created from the transfer function, it could apply to the full bandwidth and frequency resolution represented by the transfer function, but that may not be best choice for a particular application. Therefore, it becomes prudent to analyze the characteristics of this filter and optimize it to meet specific needs.

Filter bandwidth

Consider the graphical representation of the transfer function of Figure 11. It was calculated to de-embed cable loss up to 9 GHz. Note that the frequency content of the measured signal (green trace) in Figure 11 only extends to about 5 GHz. Above that frequency is just noise. This is an example of why analyzing the characteristics of this filter becomes prudent. If the full 9 GHz of correction of this measurement is applied, it will simply increase, or boost the noise above 5 GHz without any appreciable benefit to the measured signal.

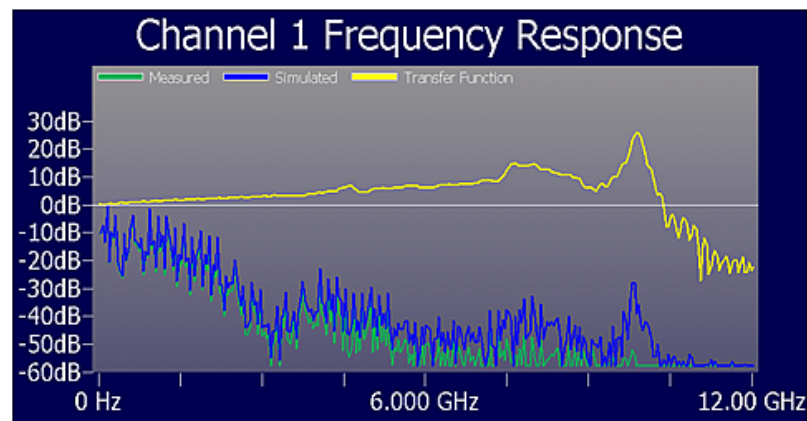


Figure 11. Correction transfer function for de-embedding a lossy cable (yellow), frequency spectrum of measured signal (green), and frequency spectrum of simulated signal (blue)

Filter effects on the eye diagram

Notice how limiting the bandwidth of the correction filter in Figure 11 improves the eye diagram measurements (see Figure 12). The top eye used no de-embedding. The middle eye portrays de-embedded the cable loss, reducing its inter-symbol interference (ISI), but also significantly increasing the noise. The bottom eye portrays de-embedded the cable loss only up to 5.5 GHz, also reducing its ISI, but without increasing its noise.

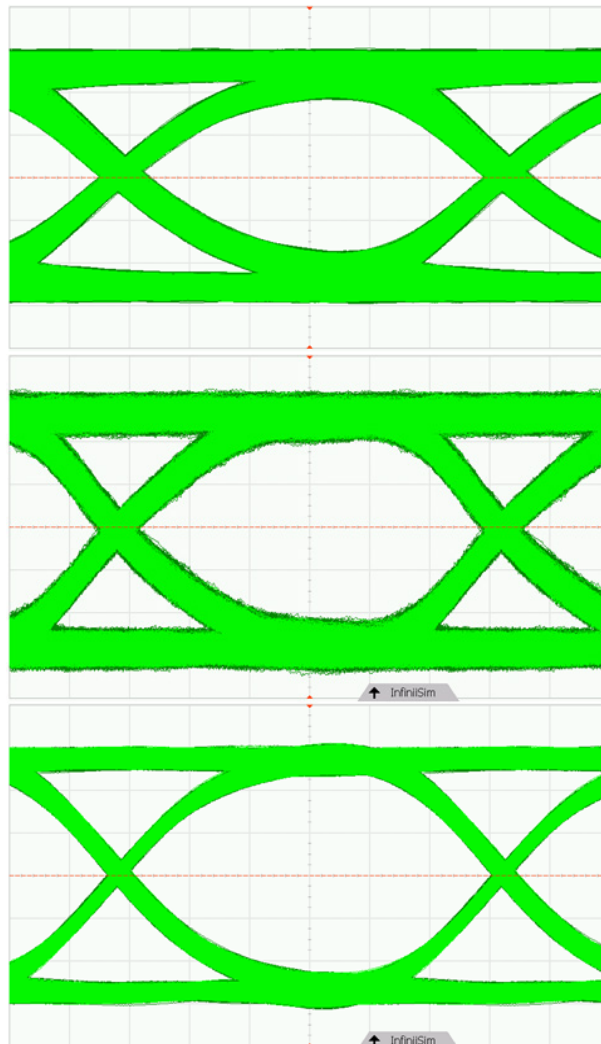


Figure 12. Eye diagram measurements using; no de-embedding, de-embedding to 9 GHz, and de-embedding

Understanding filter length

The length (number of coefficients or points) of the FIR correction filter determines its ability to apply long-time constant or slowly varying characteristics. That is, longer filters correspond to transfer functions with finer frequency resolution. However, the filter's length also affects waveform processing time. Longer filters slow down oscilloscope display and measurement update rate. So there is a trade off in choosing the filter length. Refer back to the filter shown in Figure 3. It was chosen to have a length of ~ 7 ns (280 points). Now observe the filter shown in Figure 13. This filter was designed to apply the same transfer function, but it is only ~ 2.5 ns long (100 points). Notice that this shorter version is not long enough to represent all of the bumps and wiggles in the target transfer function (see Figure 15).

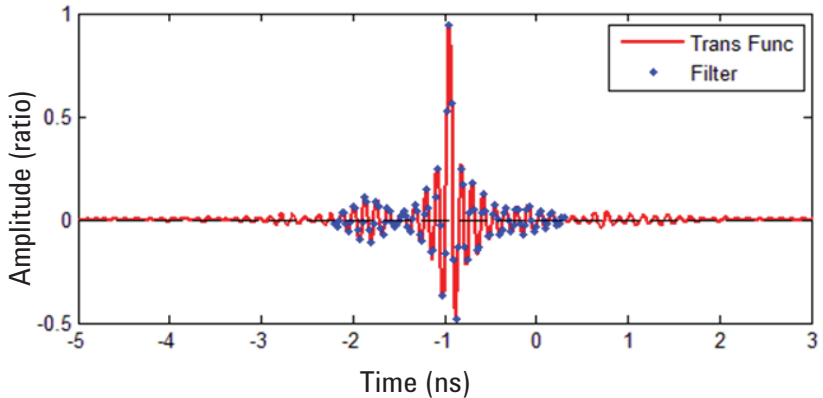


Figure 13. Step responses of filter (blue) and de-embedding transfer function (red) from lossy cable example

Although the filter's length can often be optimized solely by examining the filter itself, it is usually better to view the filter's step response. That is because a step response visually emphasizes the lower frequency components of the filter more than an impulse response does (see Figure 14).

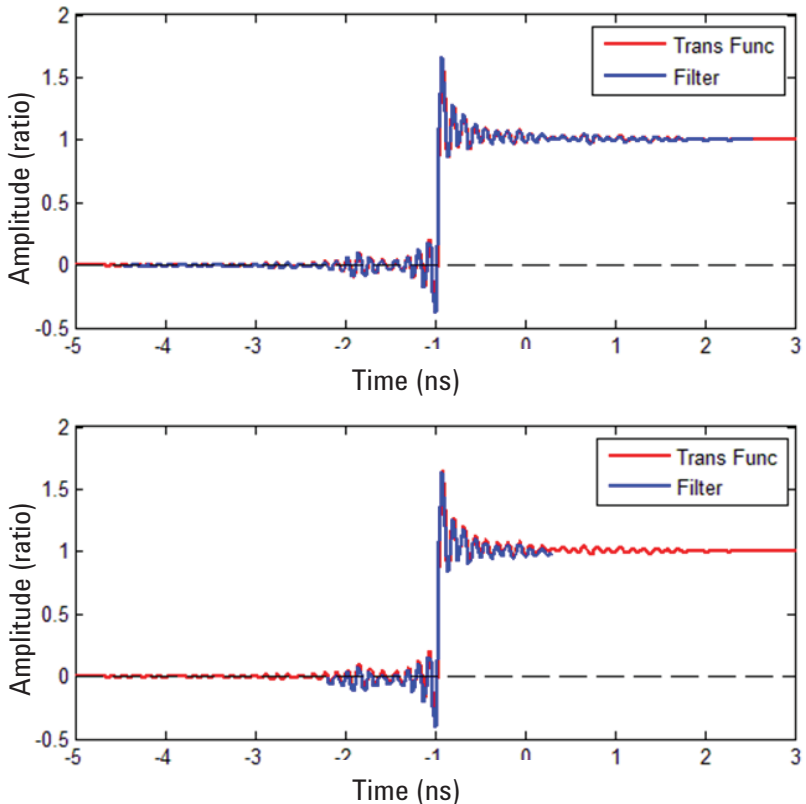


Figure 14. Step responses of filters (blue) and de-embedding transfer functions (red) from the lossy cable example using two different length filters

Understanding filter length

The step responses for both filters of Figure 14 are nearly identical over the reduced filter length. Shortening the transfer function, however, does alter the frequency response of the transfer function and serves to smooth the filter's effective frequency response (see Figure 15). Shortening the filter to produce a smoothed filter frequency response can be appropriate, but it is cautioned to make sure that doing this is appropriate for your application. In particular, the transfer function should be evaluated for quickly changing phase or magnitude responses.

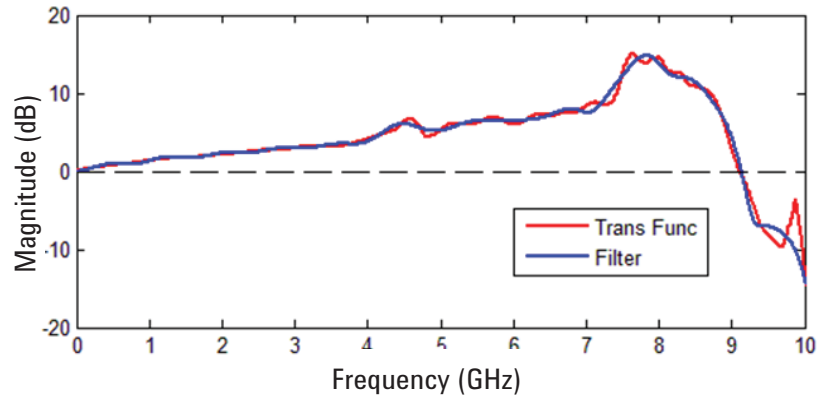


Figure 15. Frequency response of filter from the lossy cable example with reduced length

Two-port vs. four-port transfer functions

The discussion, up to this point, has described de-embedding using single-ended 2-port networks. It should be noted that de-embedding can be applied to any N-port network. However, in reality, many if not most de-embedding applications involve differential signals and differential de-embedding applications use either differential 2-port or 4-port network models.

Differential 2-port networks

Differential 2-port networks use simplified models of the actual physical circuits in which only the odd mode of the signals are modeled and the even mode is ignored. Using differential 2-port networks in de-embedding applications can be a very effective way to simplify and accelerate your measurements. However, they can only be used to model highly balanced differential circuits in which there is little to no coupling between the even and odd modes of the circuit.

Understanding filter length

4-port networks

When the ultimate accuracy is required or your differential circuits are not well balanced, you must use 4-port networks for your de-embedding applications. 4-port de-embedding circuits necessarily become more complicated than 2-port circuits because they must model twice as many signals (see Figure 16) As a result, the transfer functions derived from these circuits become matrix functions, similar to the 4-port network models themselves. Given:

$$H(f) = \begin{bmatrix} H_{11}(f) & H_{12}(f) \\ H_{21}(f) & H_{22}(f) \end{bmatrix}$$

$$\begin{aligned} V_{sim+}(f) &= H_{11}(f) \cdot V_{meas+}(f) + H_{12}(f) \cdot V_{meas-}(f) \\ V_{sim-}(f) &= H_{21}(f) \cdot V_{meas+}(f) + H_{22}(f) \cdot V_{meas-}(f) \end{aligned}$$

Or in matrix form

$$V_{sim}(f) = H(f) \cdot V_{meas}(f)$$

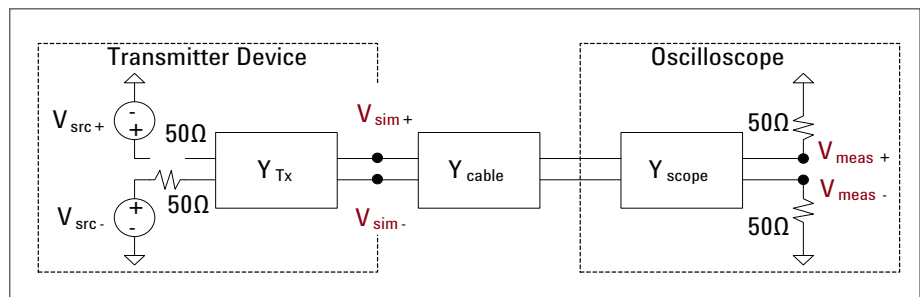


Figure 16. Circuit model of differential application using 4-port Y-parameters

Whether discussing 2- or 4-port networks, a convenient means to derive their models by measuring S-parameters or by generating them using a simulation tool has been developed. The measurement of S-parameters may be performed on vector network analyzers (VNAs) or Time Domain Reflectometers (TDRs). The characteristics of the S-parameters files themselves are critical however, the requirements for successful use of them for real time oscilloscope transfer function generation is addressed in the next paper.

Summary

Engineers need the ability to transform oscilloscope waveforms when a condition exists that differs from what is physically present when making the measurement. It is critical that the engineer can observe what the waveforms look like in different locations, or apply “what if” scenarios where circuit elements have changed from those taken from the original acquisition.

This paper has laid the groundwork and presented a generalized approach to addressing the wide variety of these co-simulations; from de-embedding specific elements, to embedding circuit blocks, to changing the location of the observed voltage node. The approach involves the definition of two circuits; the measurement circuit and simulation circuit which identify circuit element models and observation points. The circuits are pre-analyzed to produce a transfer function whose impulse response, when convolved with physically measured waveforms, answer the posed transformation question without physically changing the measurement setup.

The next paper in this series will discuss S-parameter requirements for oscilloscope de-embedding applications. Specifically it is a tutorial on achieving the big picture of interoperating oscilloscope data and how to understand its relationship to S-parameters.



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