APPLICATION NOTE

S-parameter Requirements for Oscilloscope De-Embedding Applications

Introduction

A tutorial in helping the reader achieve the big picture of interoperating oscilloscope data and how to understand its relationship to S-parameters

As our high-speed signal environment keeps getting faster, circuit elements that were generally benign at lower frequencies are taking on whole new characteristics. Generally, between the measurement point and the point of interest there can be any number of parasitic circuit elements that will affect the waveform. Circuit traces become RF antennas with all the parameters of a transmission line. Circuit boards become complex circuits with all the trimmings of a complex resistance/inductance/capacitive (RLC) network. Test points become impedance incongruences and probe tips and cables become reactive networks. Therefore, it is safe to say, in many cases, what is directly measured from the oscilloscope isn't really what we want. The challenge is to extend the oscilloscope's ability to render waveforms that represent different circuits and/or circuit locations from what is probed or directly measured.

The solution to this dilemma of measurement correctness is to develop transfer functions. Such functions are designed to transform the measured waveform to a "filtered" waveform, or simulated waveform of the observed condition vs. the real condition. In effect, these "filters" are used to factor out parasitics or other electrical artifacts and leave behind the accurate data. This paper will discuss the development and manipulation of S-parameter files for use in waveform transformation in oscilloscopes commonly referred to as de embedding or embedding.

The formulation of the transfer function depends on circuit definitions and element models that are evaluated against frequency (assuming linearity and time invariance). While not exclusive, the most common circuit element models are defined using S-parameters though RLC representations. Of course, other network parameters sets may be used as required.

S-parameters – Getting Started

S-parameters can be measured, directly, with vector Network Analyzers (VNAs) and Time Domain Reflectometers (TDRs). They can also be created from a simulation tool such as the Keysight Technologies, Inc. Advanced Design System (ADS).

There are two primary standard file formats used to store S-parameters: Touchstone and CITIfiles. Touchstone files are identified by the file extensions .s1p, .s2p, or .s4p. CITIfile files are identified by either .cti or .cit. Formatted as ASCII text, these files are easily viewed or edited using any text-based file editor. Both of these file formats have been revised over the years, so it's important to ensure that the particular version or format used is supported by the particular de-embedding application. Adherence to the format's documented requirements is also necessary.

The size of S-parameter files depends directly on the frequency resolution and maximum frequency of the data. Although the these standard formats do not limit the size of S-parameter files, Hardware I/O can significantly slow the transfer of large file function generation in de-embedding applications, especially for 4-port models.

Some de-embedding applications allow the designer to insert special keywords into the comment sections of S-parameter files. These keywords are read by the application and allow the user to control how the application interprets the file data. This is especially useful if the S-parameter measurements of one device will be used for multiple purposes. As well, this keyword technique is valuable for specifying other resolutions or maximum frequencies for different applications, or to limit file size used for de-embedding.

Best Practices for Obtaining Good S-parameter Measurements

The detailed use of a VNA to measure the S-parameter file for a circuit element is beyond the scope of this particular paper. However, there are certain general procedures and factors that should be observed to help ensure good VNA measurements.

Frequency sweep

Because de-embedding applications transform between the time and frequency domains using Fourier transforms, they must operate on uniformly sampled data that extends across the entire frequency range; f_{DC} to f_x. S-parameter data can be generated/modeled using either a linear or logarithmic frequency sweep. If a logarithmic sweep is used then that data necessarily must be linearly re-sampled or interpolated by the de-embedding application. This resampling will be valid only if the amplitude and phase characteristics are adequately sampled. Logarithmic swept data can sometimes be used, but linearly swept data is always preferred.

IF Bandwidth

It is recommended that 1 kHz or lower be used as the IF bandwidth. 1KHz IF bandwidth provides superior signal to noise (S/N) at the price of only slightly increased measurement time.

Minimum Frequency

Exercise caution in choosing the minimum measurement frequency. The accuracy of most microwave VNAs degrades considerably at low frequencies. It is often necessary to break VNA measurements into two separate ranges using a separate low-frequency VNA for the low frequency range and then combining the S-parameter data into a single file.

Frequency Resolution

Whether synthesizing S-parameters with a circuit simulator or measuring them directly with a vector network analyzer, it is important to select an appropriate frequency resolution for the S-parameter data. Obviously, using too fine of resolution will produce very large data files and increase measurement and processing times. Using too coarse a resolution reduces file size but can make the data too granular to analyze accurately.

Note that there are several important limitations to maximizing the frequency resolution. The first is interpolation. The S-parameter data must be “interpolatable” in the frequency domain. This will be achieved if the resolution used ensures the data contains all of the significant information needed for the application. Having too fine a resolution does not add any information to the frequency domain sampling and will merely cost more time in the measurement process.

Settling Time

Settling time presents a limitation as well. Resolution in the frequency domain corresponds to range in the time domain. The frequency resolution must be set be fine enough in the S-parameters to model the lowest time-constant elements of the circuits. The best method for determining how much frequency resolution the models require is by observing how much time range is required for the step response to settle in the time domain. Then the resolution can be determined by:

$$\text{FreqRes} = 1 / \text{TimeRange}$$

Also, the derived S-parameters need to have enough frequency resolution to accurately represent the full group delay of the circuits that they are modeling. The recommended maximum resolution to model coax cable for example is:

$$\text{FreqRes} = (1/4) / \text{PropDelay}$$

This may appear to be twice as fine as needed, but it is often required to extrapolate measured data down to DC or zero Hz. Extrapolating the phase down to DC with only half of this resolution is prone to error, therefore, the higher frequency resolution is warranted.

Maximum Frequency

As with frequency resolution, the maximum frequency of the S-parameters also needs to be chosen with care. The primary effect of choosing an insufficiently large maximum frequency is unwanted preshoot and ringing as described in the following section about causality. The models themselves may have preshoot and ringing as long as they are stimulated by the spectral content of the measured signal. In most cases some preshoot and ringing is acceptable in the simulated signal as long as it is insignificant relative to the random noise in the signal. Average-mode measurements (on the oscilloscope) have a much higher signal to noise ratio and, therefore, afford the use of models with higher maximum frequency.

The signal-to-noise ratio of the measured signal has a major effect on the maximum frequency to which lossy test fixtures and cables can be de-embedded. It is usually recommended to limit the bandwidth of de-embedding applications when applying the transfer function and allow the models themselves to have a higher bandwidth. This is so that the designer can, if desired, adjust the de-embedding bandwidth by observing the simulated signal and re-computing. New transfer functions take much longer to compute than using previously generated transfer functions with different bandwidths.

Instrument Calibration Pitfalls

Finally, instrument calibration is critical. If the instrument isn't calibrated, all the data acquired can be corrupt. Newer models of VNAs are easier and less complicated to calibrate than older models. However, close attention must be paid to the calibration process of all models, since even the slightest calibration error voids all subsequent data acquisitions. It is highly recommended that the VNA's calibration is verified by measuring the calibration standards after each calibration.

Common Issues in Measuring S-Parameters

If the case arises that the S-parameter file set must be evaluated and processed further in order to deliver optimal accuracy in the process of de-embedding or embedding, the following provides insights to the issues and guidance in addressing them.

Extrapolation To DC

As mentioned above, S-parameters for de-embedding require values that extend all the way down to and including zero Hz. If the S-parameters do not extend all the way down to DC and cannot be measured with a VNA, the de-embedding applications will be forced to extrapolate them to DC. Of the two common extrapolation technique one simply copies the first measured point to DC (see Figure 1) while the other extrapolates down to DC by linearly fitting the first two measured points (see Figure 2).

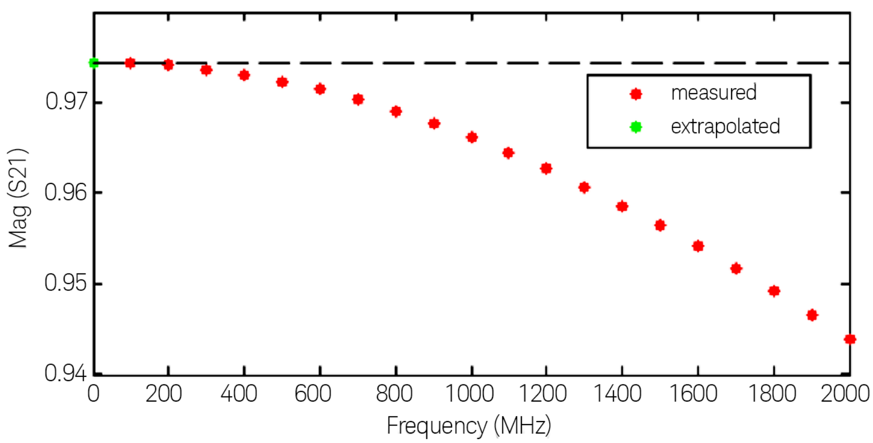

Figure 1. Extrapolated measurement data using copy method

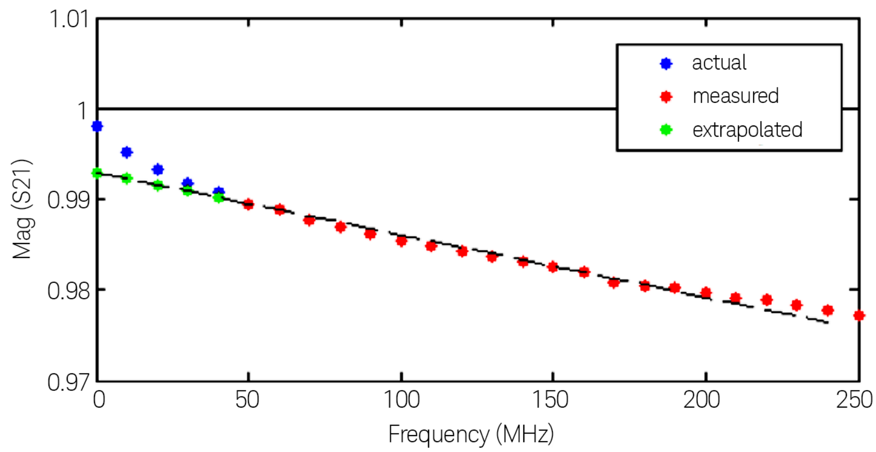

Figure 2. Measurement and Simulation circuit models for observing waveform without cable

This extrapolation method referenced in Figure 2 can sometimes provide a better match to the actual value, but is particularly susceptible to exaggerating the DC error either from measurement noise or from ripple in the model's response (see Figure 3). In either event, while extrapolating S-parameters data to DC will generally provide valid data, in some cases it can be problematic and the engineer should take care to insure the data is accurate.

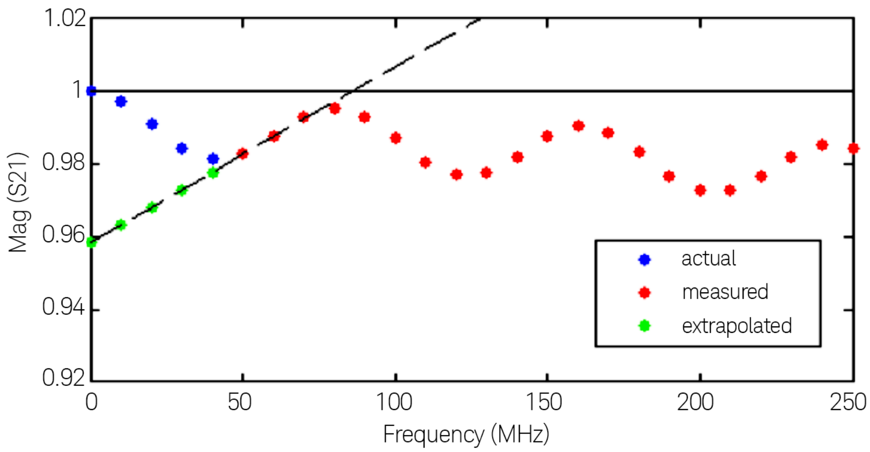

Figure 3. Measurement and Simulation circuit models for observing waveforms without cable

Both of these methods are valid extrapolation methods provided that the lowest measured frequency points are sufficiently close to DC. However high-frequency VNAs, the most common tool for measuring S-parameters, often cannot sweep low enough, or their accuracy degrades so much that their lowest measured values cannot be accurately extrapolated. In such cases the best procedure is to measure the S-parameters in two separate frequency bands using two different VNAs and then merge them together. In any event, it is prudent to always verify that the S-parameters contain valid DC values or that they can be extrapolated to DC without introducing significant error.

Modeling Noisy Measurement Data

Simulated S-parameters are generally superior to measured S-parameters for de-embedding applications for a variety of reasons. The obvious ones are that they are noiseless and they inherently include a zero Hz value. They also do not suffer from reduced accuracy at low frequencies. Measured S-parameters can include all characteristics of the measured device, but they also offer the option of correcting only selected characteristics. For example, multiple impedance discontinuities on a long transmission line can produce ripple in the insertion loss of the cable. As is often the case the correction should be applied to the overall loss of the cable, but not the ripple of that particular cable. This is because the ripple is highly sensitive to the exact delay between the discontinuities of that particular cable, but the loss is not and can be applied to a variety of similar cables. Simulating S-parameters using a lossy transmission line model that match the loss of the measurement allows modeling the loss only.

Another area where measured data can give improved results by optimization with a simulator is where VNA noise or bias error yields a non-passive result on a known passive device. In this case, the simulator tool performs an optimization of given circuit structures to the measured data.

Averaging S-parameters

There are several situations where averaging S-parameters is appropriate. One instance would be for creating a nominal model set of test fixtures or reducing the noise in a set of measured S-parameters. While it appears to be a straight-forward proposition, it turns out that averaging complex values is more problematic than initially assumed.

The reason for this is that there are two ways to average complex numbers - averaging the real and imaginary values or averaging the magnitude and phase values. And, the method chosen will depend on the specific application. The following discussion will detail the approaches to averaging.

Random Noise Measurement

This measurement most generally appears as a two-dimensional Gaussian error vector added to the actual device model data vector at each frequency in the data set. In other words, each real and imaginary component of noise is comprised of independent Gaussian distributions. So for reducing measurement noise, the approach is to average its real and imaginary components. Visualize, for example, averaging out the noise of an S11 measurement of a perfect 50 Ω termination. The real and imaginary components would average down to zero, but the magnitude and phase would not.

Assume that the objective is to determine the nominal model for a set of coax cables. Also assume that the insertion loss variation and time delay variation of the cables is much larger than the measurement noise. In this case, where the goal is to average the S21 data for a set of cables that all had the same loss, but different time delays, it is better to average magnitude and phase. The result is that the magnitude and phase would average to correct values, but real and imaginary components would not.

TIP– Be careful when de-embedding using nominal models. Correction transfer functions can be very sensitive to the absolute time delay of some circuit elements. De-embedding with a nominal delay model may actually make the measurement results worse.

It is usually better to average the real and imaginary components of insertion loss values, whether reducing measurement noise or generating nominal models. That is because the process variation of S11 for many devices is large relative to its nominal value, producing the effect described for measurement noise reduction. Also note that averaging magnitude, in dB, is not possible. The approach is to convert it to a simple gain value before averaging. Phase values typically need to be unwrapped prior to averaging.

Frequency Response Evaluation

It is imperative to examine the frequency response of the insertion loss of the circuit element being measured. One issue is interpolate-ability. This implies that the frequency resolution is fine enough to capture all the "bumps and wiggles" of the device. This is directly analogous to sampling in time domain. The directive is to always sample quickly enough to capture all trends of the response.

A second issue is quickly changing insertion loss responses. Because such device responses may change significantly over time and temperature, the magnitude and phase is affected, proportionally. Unless the designer is aware of this and compensates accordingly, it can make a de-embed correction worse than the non-de-embedded result. For accurately de-embedding and embedding, correct phase is just as important as correct magnitude.

Finally, when using this approach, consider limiting the bandwidth of the measurement when a device exceeds ~15 dB of gain range. In the case of de-embedding a lossy channel for example, the frequency bands with greatest loss will have the greatest de-embedded gain. If there is a section with 20 dB of loss, that band may have only a 6 dB of S/N ratio (function of signal spectrum) and amplifying it by 20 dB (for de-embedding) would result in a very noisy waveform. In the example in Figure 4, the reduction of signal to noise at around 4.5GHz because of the channel, gives rise to oscillatory behavior in the step function.

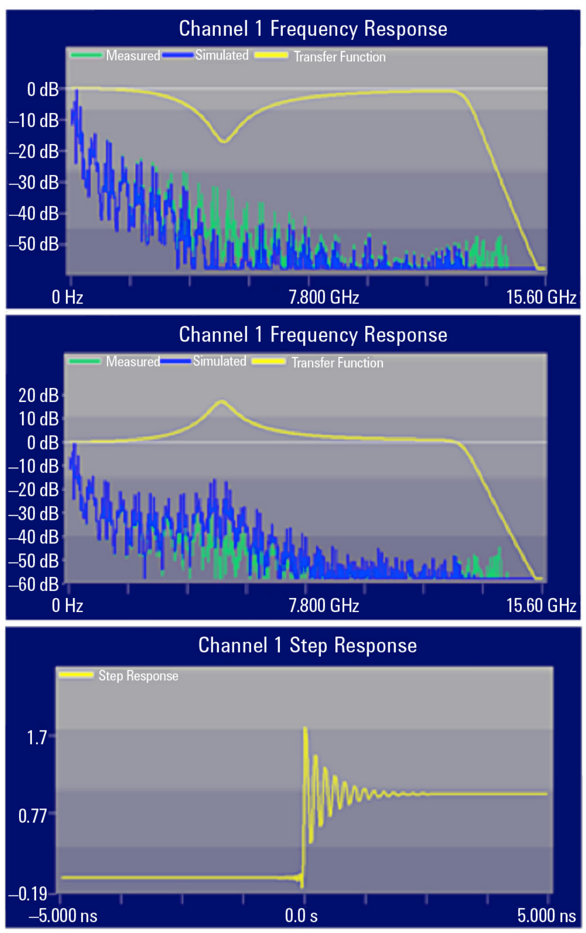

Figure 4. Result of de-embedding a section of lossy channel

Other Issues for Consideration

The preceding discussion has addressed the best practice approach for addressing the issues common to S-parameter comprehension, manipulation and pitfalls. It is hoped the reader now has a reasonable understanding of the global approach to obtaining reliable S-parameter readings. There can be a couple of peripheral effects that can skew otherwise seemingly valid measurements. These are addressed in the following discussion.

Passivity

Concern over the passivity of N-port network models arose from the possibility that some circuit simulators become unstable when ideally passive model elements possess a slight gain. This can happen, for example, when measurement noise causes the measured insertion loss of a passive connector to have a magnitude at some frequency that is greater than one.

While this is not a problem for de-embedding applications, it is a condition of the process and the engineer should be aware of it. It is mentioned here for completion and the engineer should be aware that forcing measured S-parameter data to be passive (say by truncation) actually creates a less tolerable error than it removes, and is not recommended. When possible, measured S-parameters should be replaced by simulated models that are fit to the measured data, as described below. This not only ensures passivity, it removes all noise from the S-parameters.

Causality

As with passivity, the concern over the causality of S-parameter models causes many engineers to corrupt their otherwise accurate circuit models in order to make them causal. It is known that the device is causal and therefore assume that the respective model must be causal as well. However, that is not always the case.

One source of the concern about causality originated from some over-simplified commercially available lossy transmission line models. These models do not model phase at all and are highly non-causal. They are inappropriate for any time-domain analysis and should not be used for oscilloscope de-embedding applications.

Another source of concern is the Gibbs phenomenon that occurs when converting a band-limited frequency domain model to the time-domain using Fourier transforms. Consider the RC high-pass filter model whose frequency response is shown in Figure 5. Notice that it is only modeled up to 2 GHz.

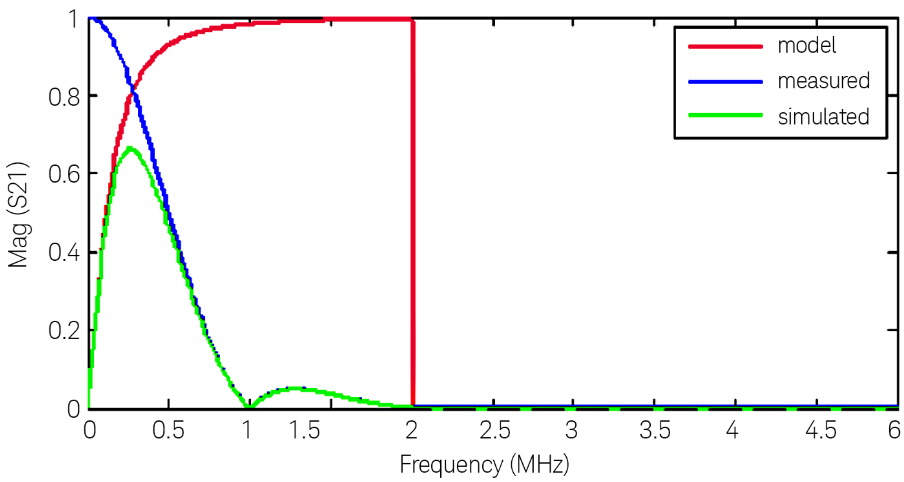

Figure 5. Measurement and Simulation circuit models for observing waveform without cable

Viewed in the time-domain, the model's impulse response appears to be non-causal as shown in Figure 6. But the pre-shoot seen on the impulse response of the model does not appear on the simulated signal as long as the measured signal's significant spectral content does not extend above 2 GHz.

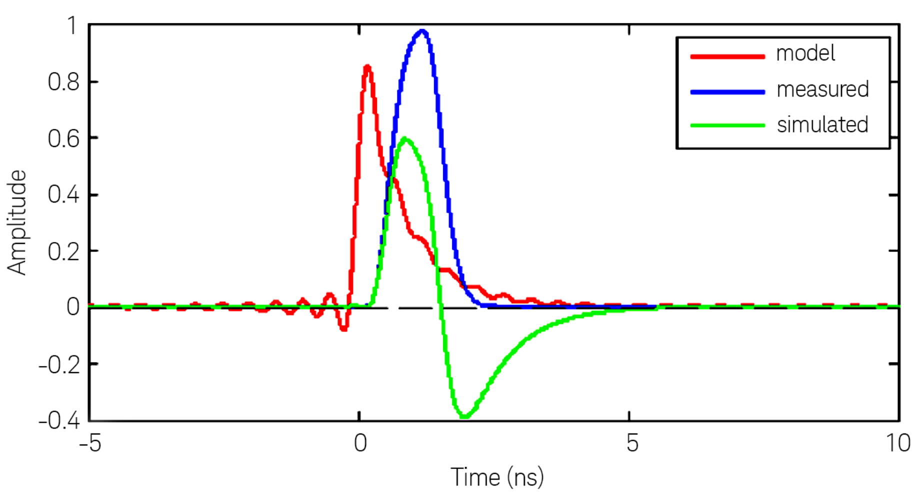

Figure 6. Measurement and Simulation circuit models for observing waveform without cable

It is worth noting that although most S-parameters used for oscilloscope de-embedding applications do not contain meaningful non-causal information, S-parameter data does support negative time information. The requirement that S-parameter data be "interpolate-able" in the frequency domain also ensures the data supports negative time.

Port Options – Viewing Network Elements

Network elements are represented as n-port, where n is usually two or four. The value of “n” could be as high as six, eight or even 16, where crosstalk between lanes is desired to be analyzed. But, realistically, such values are rarely seen for oscilloscope applications. Single ended systems usually consist of 2-port elements. Differential systems, as many of the high speed interfaces today are, require 4-port models.

In such network representations, the major issues revolve around frequency. Frequent anomalies arise in the inconsistent ordering of the ports between measurement and transfer function generation.

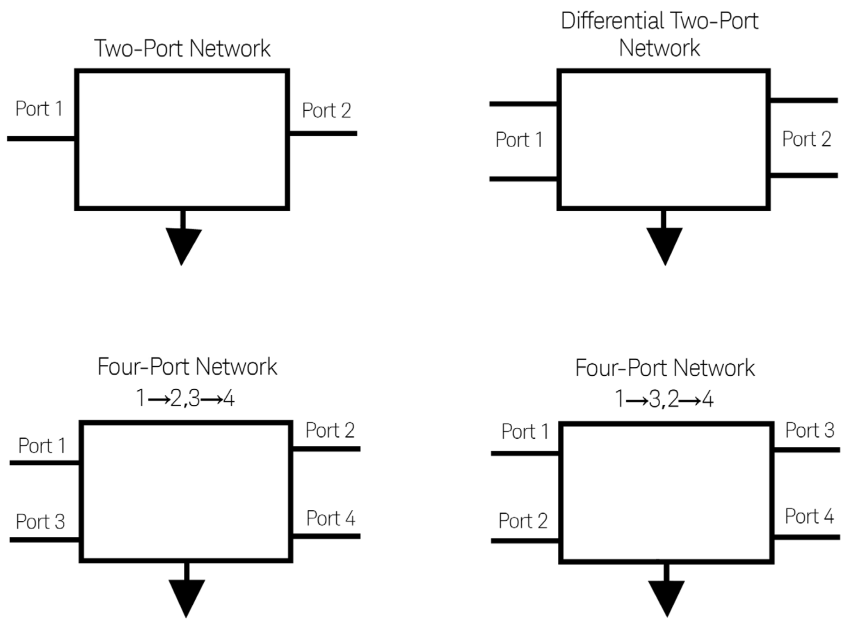

Figure 7. Generalized two- and four- Port models of circuit elements

For industry standard two-ports, port 1 is the input and port 2 is the output. (1→2). For four-ports, standard usage allows ports 1 and 3 or ports 1 and 2 as the inputs. (1→2, 3→4 or 1→2, 3→4 respectively). Port assignments such as 1→4, 3→2, while possible to re-order to standard configuration, are undesirable for many tools so should be avoided.

Doing N-Port Math

The signals input to the network are defined as having both differential and common components. To support this more intuitive treatment, the standard 4-port S-parameter set can be transformed to comprise four matrices. The first one relates differential responses to differential inputs. The second one relates common mode responses to common mode inputs. The remaining two relate conversions between differential and common mode inputs. In equation form this is represented as:

$$O_{CM} = I_{CM} * G_{CM} + I_{DM} * G_{Diff\_to\_Common}$$
$$O_{DM} = I_{Diff} * G_{DM} + I_{CM} * G_{Common\_to\_Diff}$$

The mixed mode description is more intuitive because the user can view the S-parameter data and comprehend where the problems are in both the frequency domain and the observe mode conversions.

To present this and close the discussion, a simplification on the mixed mode is a Differential 2-port. In this case, only a portion of the second equation above is used and takes into account only differential input and output:

$$O_{DM} = I_{Diff} * G_{DM}$$

This is effectively a 2-port analysis as the inputs are a pure differential signal. This assumes common mode input is small, that cross conversion terms and common mode gain terms are insignificant. With this simplification, the user needs to validate that the assumptions are true. In more complex circuits where a number of differential structures exist, conversion terms will not be zero and there is always some common mode component in an input signal.

Summary

Even the most accurate and precise data is useless unless the engineer understands how the data was acquired and what it represents. This paper has provided a look at manipulating data acquired from oscilloscope measurements of circuit elements – an adjunct to paper one of the series, elaborating on some of the critical parameters the engineer may not be intimately familiar with. It has discussed the elements and nuances of S-parameters so the reader may understand their functions in translating measured data into accurate, real-time data via modeling. The techniques of embedding and de-embedding have been discussed and the best practices for this process have been presented. A short discussion of port networks had been presented as well.

It is hoped that the information presented here will help the engineer understand what has been acquired and how the resultant manipulation of the data, via comprehension of S-parameters, will develop accurate representational models. By understanding what is being observed and what the process is to obtain the desired results, engineers have another valuable tool to add to their arsenal.