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Guidelines for multiport and mixed-mode S-parameter measurements in high-speed interconnection design

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Abstract

We present here fundamental issues in time-domain reflection and transmission (TDR/T) measurements that must be considered when characterizing mixed-mode and multiport scattering parameters of high-speed data interconnections. This paper shows that blindly applying mixed-mode methods can lead to significant measurement errors for certain classes of interconnections, mostly due to a lack of *a priori* knowledge about the test structures. From experience gained in signal integrity (SI) measurements, we have developed a set of guidelines to tell us when we may make mixed-mode, multiport, or only two-port scattering parameter measurements of high-speed transmission lines and interconnections.

Author(s) Biography

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Summary

There are many subtle features of a measurement set-up that can affect the accuracy of high-frequency scattering parameter measurements made with either TDR/T scopes or vector network analyzers (VNAs). Since some of the errors at the upper frequencies may be less significant than others when determining waveform distortion in interconnections, the overall accuracy requirements for *S*-parameter measurements is still an open debate in the high-speed signal integrity (SI) world.

This paper expands the measurement accuracy discussion even further to include the effects of misapplying differential-, common-, and mixed-mode *S*-parameter methods to the characterization of high-speed interconnection networks. We show that measurement errors made in mixed-mode *S* can be significant for SI purposes when we are not clear and specific in our understanding of:

- signal visualization *vs*. network identification,
- wave propagation mode *vs*. signaling mode, and
- multiport **S** *vs*. mixed-mode **S**.

With clarity in these subjects, we can avoid certain errors when applying multiport, differential-, common-, and mixed-mode measurements, ultimately improving our designs.

From our own experience and communication with SI engineers, we have developed a set of guidelines to help determine when and how we should be making multiport, differential-, common-, and mixed-mode measurements of high-speed transmission lines and interconnections. For the purposes of determining matrices of network parameters (**S**, **Z**, **Y**) with TDR/T or VNA equipment, as opposed to visualizing differential and common-mode signals, we look to the following guidelines.

Summary of Multiport and Mixed-Mode Measurement Guidelines

1. Identify the *true* electromagnetic ports for the interconnection network being characterized.
2. For *true* one- and two-port networks, do not use two TDR signal sources configured in differential or common-mode drive.
3. For *true* one-, two-, three-, and four-port networks single-ended multiport network analysis will most often work, using either VNAs or TDR scopes. Drive one port at a time and measure all port voltages. All ports must be terminated in the reference impedance (normally 50 Ω).
4. With TDR equipment, *true* four-port networks may often be characterized using four TDR source/samplers in differential and common-mode configurations. This is known as the mixed-mode TDR/T measurement set-up. Here the sources are turned on for two ports for the forward signal transmission, all ports are terminated in the reference impedance, and all port voltages measured. This is then repeated in the reverse signal transmission.
5. All VNA and TDR/T measurement systems must be fully calibrated. Ideally this calibration is made using a full kit of calibration standards, like Open, Short, Load, and Thru (OSLT) standards, or using an automated electronic calibration module with sufficient impedance states. Mixed-mode TDR/T set-ups require differential standards, which can sometimes be constructed from two sets of single-ended standards.
6. Ideally, all measurement set-ups should allow for calibration devices to be connected at the measurement reference plane, that is, the same points used when making connection to the network under test. This may require the construction and characterization of a custom calibration kit for the particular network being characterized.
7. When using a mixed-mode TDR/T set-up, the calibration must de-skew the two source signals so they are aligned at the entry point to the network's ports, the measurement reference plane.
8. When using mixed-mode TDR/T set-up, the delay for the combined differential drive signal (V^+-V^-) must be the same as the delay for the combined common-mode drive signal (V^++V^-).
9. For all measurement set-ups, great care must be taken to not disturb the cables connecting the sources and samplers to the network. Slight bending and motion of the test cables and connections may invalidate the calibration.
10. If the interconnection network under test is coupled to adjacent transmission lines and conductor systems beyond the ports being measured, the other conductor systems must be electrically terminated as they would be in the target application.

Introduction

For a large class of transmission lines and interconnections encountered in high-speed electronic design, we want to characterize frequency-domain behavior in terms of scattering and impedance parameters. The network descriptions in the frequency domain add to our visualization of our signals in the time domain and help predict limits to our signal quality. Many simulators and electronic design tools require files of frequency domain parameters and we want to supply our tools with accurate data from measurements, or from electromagnetic field modeling, in order to predict the signal integrity on our interconnection network.

When we work with multiple conductor interconnection networks, we now have a choice of using TDR/T or VNA instruments to measure *S*-parameters. Some of the TDR-equipped oscilloscopes provide calibration and transformations that deliver accurate scattering parameters to 20 GHz and beyond. We can also use commercially available software to perform TDR to *S*-parameter calibrations in our custom measurement set-ups or when using basic equipment.

One question we face in TDR network analysis is, “Do I characterize my interconnect structure by measuring with differential and common-mode drive, or by measuring the device as a multiport with single-ended drive applied to each port in sequence?”

The differential and common-mode drive and response combination allows the TDR/T to obtain the mixed-mode *S*-parameters [1-2], while at the same time providing direct visualization of how an interconnection network will affect differential and common-mode signals.

With multiport methods, the TDR/T equipment works much like a multiport VNA, requiring a full four-port calibration when using four TDR source/sampler units. Here too scopes and commercial software are available to make the transformation from TDR/T waveforms to calibrated four-port **S**.

For the most part, recent literature seems to show a favor towards mixed-mode TDR/T set-up for charactering transmission lines used in modern high-speed digital systems.

Since certain researchers have presented transformations between mixed-mode and multiport *S*-parameters representations [3-7], it’s been easy to assume we can always measure either way and then compute the other form as needed. We certainly did in our lab, and many others have gotten by this way for a certain class of interconnections.

Value in Matching Measurement Method to Network Topology

What we are finding instead is that the measurements we use—one-port, multiport, or mixed-mode—must be matched to the true electrical topology of the interconnection we need to characterize.

This simple and somewhat obvious statement becomes complex and possibly confusing even when we look at canonical circuits, like ideally balanced transmission lines and completely unbalanced and isolated transmission lines.

Since we want our methods to work equally well in both limits of idealized circuits plus all the stuff in between, we desire some guidelines to help us choose the best measurement method for the job. We now, with some apology, must add one more thing to pay attention to when making high-frequency *S*-parameter measurements.

To show what we mean, we first present a discussion of the fundamentals and definitions of measurement ports for multiconductor interconnections. We then make a number of key observations regarding the direct and general applicability of mixed mode scattering parameter $\mathbf{S}_{\text{mix}}$ measurements to differential signal integrity, showing and extreme example where problems arise when we don't match measurement method to network type.

This work presents additional guidance to engineers making high-frequency measurements of their circuits, interconnections, and packages using differential and common-mode signals. Its goal is to advocate the use the appropriate technique for the job and to encourage the use of multiport TDR/T or VNA measurements when there may be some ambiguity as to the true circuit nature.

Origins of Some Confusion

The main references that introduce and describe mixed-mode scattering parameters are found in Refs [1-7]. These authors and others show a mathematical relationship between conventional m-port scattering parameters $\mathbf{S}$ and the mixed-mode $\mathbf{S}_{\text{mix}}$. One particularly detailed demonstration is made by Pupalaikis [1], a clear description of things is found in Anritsu's product literature [6], and a sound theoretical description is made by Ferrero & Pirola [7]. This literature gives one the impression we can always work from one description to the next, which is true if the test structure maintains four measurement ports at all frequencies. If the number of ports is in reality less than four, the transformation between the two sets of observations is not possible.

What is a Port?

A *port* is a two-wire connection to a circuit. When current is driven into the network on one wire, the second wire returns exactly the same current when all other ports are terminated. Figure 1 shows examples of one-, two- and four-port networks.

It is possible for one terminal on all ports to be considered a common reference or *ground*. However, the ports do not have to share a common ground; port potentials are measured between the two wires at each port independently.

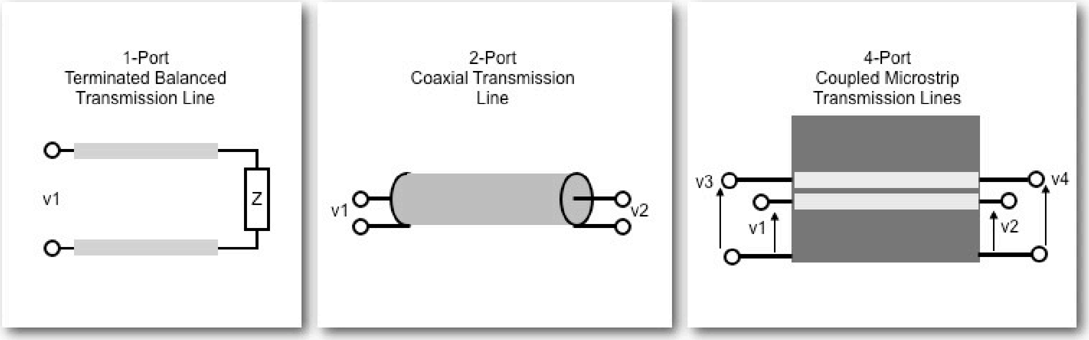

Figure 1. Basic 1- 2- and 4-port networks showing terminals

In frequency-domain network analysis, we like to define a reference impedance, say $Z_{ref} = 50\ \Omega$, and talk about the incident voltage wave at port j as a_j. The a_j wave variables are complex values representing the amplitude of the incident waves and their phase or timing relationships. This is more convenient in defining scattering parameters than using both current and voltages at each port. It's also the case our instruments more readily respond to potential differences than charge flow, giving us quantities more like wave amplitudes to start with.

The b_i wave variables represent the amplitude and phase of the waves flowing out of all ports in response to the a_j, including reflection waves that may be returned to the ports being driven by a source.

In the simplest manner, where only one port has an incident wave and we are reporting only one response wave, we think of scattering parameters as the ratio:

$$S_{ij} = \frac{b_i}{a_j} . \qquad (1)$$

A four-port network is described using a 16-term **S** matrix:

$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{bmatrix}. \tag{2}$$

Various books describe *S*-parameters and their applications in signal integrity [8-9].

The main point of this paper is to point out that if we use a TDR/T measurement system to make mixed-mode *S*-parameter characterizations, the network under test must be fully describable as a four-port network using Eq. (2).

This can be a source of confusion because it looks like we are making two-port measurements in mixed-mode TDR set-ups. We configure two TDR sources to provide a differential drive and use two samplers to receive the signals at the other side. We report the difference voltages at the source end and the receiver end, and think we have a two-port measurement.

We can do this for common-mode drive and response where we sum the two voltages at both ends, and we can do mixed measurements where we drive common-mode and measure difference potentials, or drive differentially and measure sum signals. All this is done with a two-port configuration, or so we think.

The reality is that we have connected our instrument to the four-ports of our network. We can then take advantage of the TDR/T equipment to visualize differential signals propagating through our interconnections in the time domain, and we can use the same TDR/T equipment to acquire *S*-parameters in the frequency domain.

We can get ourselves into trouble in both time and frequency domains when we use a mixed-mode TDR set-up to characterize networks with fewer than four ports.

What is a Mode?

Here is another potential area for confusion. We use the terms *common mode*, *differential mode*, *mixed mode*, *odd mode*, *even mode*, *stripline mode*, *coplanar strip mode*, and so on. We may even talk about things served *a la mode*. While it is certainly fashionable to talk about modes, we should be clear in our thinking when we use those terms.

Figure 2 shows a transmission line configuration used to ship high-speed digital signals. If we consider the conductors, we can visualize a potential difference between conductor pairs. If we apply a time-varying potential difference across a conductor pair, Maxwell's equations will tell us how the conductors will guide the energy from start to finish. The wave propagation is independent of the signal amplitude (for linear time-invariant interconnections, and we certainly hope our interconnections meet these criteria.)

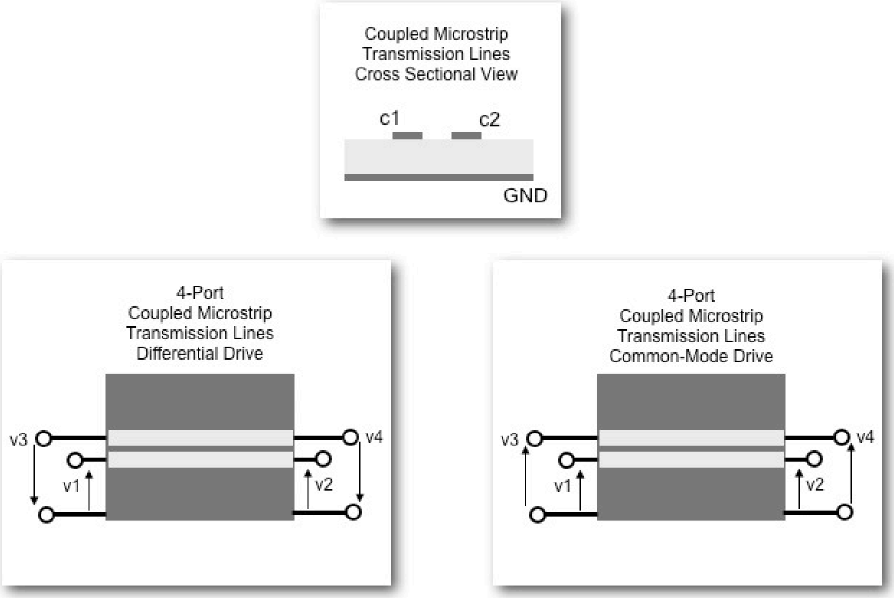

Figure 2. Four-port coupled microstrip transmission lines. In differential drive, two TDR sources are used. Initially v+ source connected to Port 1 and v- source connected to Port 3. The difference voltages are recorded at both the far and near ends. In common-mode drive, two TDR sources are initially connected to Port 1 and Port 3, both in positive polarity. The sum or average of the sum voltages are recorded at both ends.

Without even considering whether or not the structure in Fig. 2 is used to ship one differential signal or two single-ended signals, we could guess that C1-GND supports a microstrip wave propagation mode, C2-GND supports a microstrip wave propagation mode, C1-C2 supports a coplanar strip wave propagation mode, and C1-C2-GND may support some sort of a hybrid propagation mode.

How do we know which mode is supported? We need to know something about the characteristic impedance of each mode.

If we want to determine this from measurement, we could define the four port connection as shown and make VNA or TDR/T multiport measurements, driving one port at a time and terminating all others. Note that we terminate the ports as defined, we don't need to terminate the C1-C2 coplanar strip mode in addition for the purposes of multiport measurements.

In a real application, it's likely the impedance of the coplanar strip and microstrip modes are sufficiently close (let's say they fall between 40-120 Ω) that they can both carry significant power when being driven for the "differential" case. The application will call for the termination of both the microstrip and coplanar strip modes with the pi- or T-termination networks [8], but that type of termination is not required in order to characterize the network with multiport network analysis.

So what does the conversion from differential to common-mode mean?

While language is sometimes a limitation, it's the best we have to communicate with. In this paper, we prefer to think of the wave propagation modes separate form signal modes. *Differential* and *common* would then refer to signal modes instead of wave propagation modes. The conductor structure supports the three modes mentioned. The potentials on the conductors and mode impedances will determine which propagation mode will be carrying the most power.

The interconnection network will possibly transfer power from one wave propagation mode to another, whether we like it or not. Others describe the causes of this and the design rules to minimize mode conversion [8-9]. Most good techniques focus on reducing discontinuities since this is where impedance changes are taking place in the shortest distance. Even with well-designed transmission lines and terminations, the signal power won't stay in the intended mode.

With differential drive, where two signal sources share a common ground but drive signals of opposite polarity, the power being transmitted will be shared between the microstrip and coplanar strip modes in the Fig. 2 structure[1]. If we drive that same structure with two single-ended sources, the power will be in two microstrip modes. The two microstrip modes may be coupled, but there will be little power in the coplanar strip mode.

Any changes in impedance along the transmission line will work to redistribute the propagating wave into other modes. This conversion can change our desired signal (let's say differential), transferring coplanar strip power to microstrip power. The transfer shows up as an increase in the common mode signal received at both the near- (reflected) and far-ends (transmitted).

What's worse, the characteristic impedances of the propagation modes may be strong functions of frequency where certain frequency components are more susceptible to mode conversion. It's not uncommon see frequency dependence in the differential to common-mode signal conversion.

Since TDR/T oscilloscopes with fast rise time sources are great tools for observing differential and single-ended signals, it's natural to use them to measure the conversion of differential signals to common-mode signals and *vice versa*. It's from this that we realize we should be able to quantify the mixed-mode scattering parameters using differential and common mode measurements and work toward the conventional four-port **S** matrix, and the s4p files we need for our design analysis [1].

This requires that the circuit we are measuring is indeed a four-port network to start with.

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[1] Note this is different than driving a truly balanced circuit with a balun network, and not connection can be made between signal source ground and the network's virtual ground.

Observations

1. An Extreme Measurement Example to Make a Point

In order to make the point clear about matching number of ports to mixed-mode TDR set-ups, we measured a one-port interconnection with the conventional TDR differential connection.

The interconnection network was close to a terminated balanced circuit where the coplanar strip mode was terminated and the characteristic impedance of the microstrip modes was so high (> 1 kΩ) that we neglected the power. In this arrangement, there are only two terminals to make contact with (C1 and C2); there is no physical ground connection, only a virtual ground. It looks more like Fig. 1a.

However, to set up most TDR systems to make a differential measurement, the two sources share a common physical ground reference. We connected this reference to our interconnection ground, though it does not play a real role.

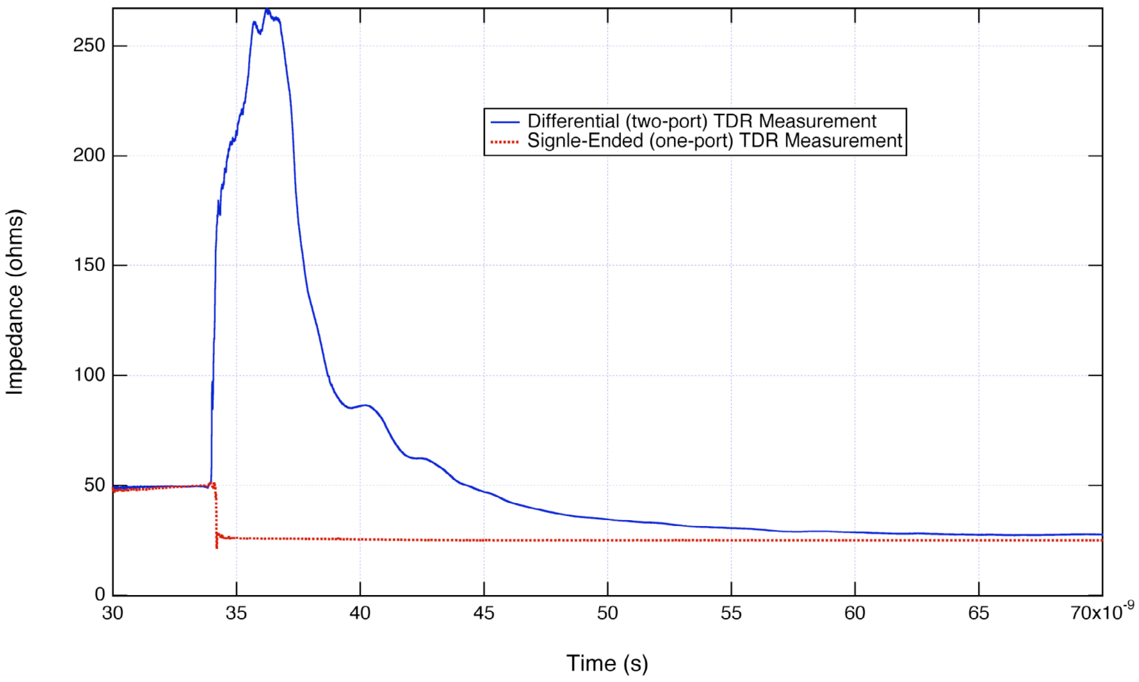

Figure 3. TDR measurements of terminated, nearly balanced transmission line using differential TDR sources and samples (attempting to connect to two ports), and true single-ended connection.

Figure 3 shows the differential reflection waveform recorded from this set up.

The problem is obvious and shows the extreme misapplication of differential TDR: the network is only a one-port device so making a two-port connection to it yields results that are not easily interpreted.

Figure 3 also shows the differential reflection when we make a true one-port connection to our terminated network.

For those working in high-speed data systems, the circuit of Fig. 2 and their stripline counterparts are more common, but this should not let us think that the characterization techniques we use for those networks would always apply to all others.

This simple example shows that we must use our knowledge of the circuit, designs, board layout drawings, and mechanical drawings to match the true number of electromagnetic ports to the measurement equipment.

If in doubt, it best to use conventional network analysis, driving one port at a time and letting the conventional **S** matrix inform us as to the number of ports in our network.

2. A Case Where the Common Mode Port Will Not Exist

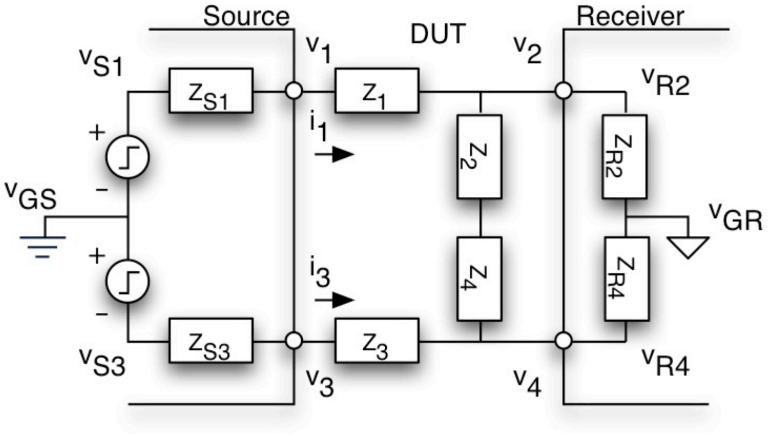

Figure 4. Balanced device under test, differential- or common-mode drive, differential or common receive, isolated Source and Receiver grounds.

In Fig. 4 we have a case where a common mode drive (both sources set to the same polarity) will not drive current into the DUT circuit. To see this, we do what we need to do and identify the port voltage (what may be considered at some point the true a wave amplitude). With a two-conductor system, the port voltage is the potential difference v_1-v_3. From electromagnetics, we know that the potential difference, as opposed to the absolute potential, is related to the electric fields established between metallic conductors. For common mode drive, v_1-$v_{GS} = v_3$-v_{GS} so v_1-v_3=0. With zero potential difference between the terminals, no current will be flowing into or out of the network even though the scope will be reporting a finite common mode waveform.

This should not surprise us; with only two terminals at each end of our network, the circuit in Fig. 4 represents a two-port device. That is, there can only be four *S*-parameters so the common- and mixed-mode *S*-parameters do not exist.

If we try here to define common-mode input wave amplitude (a_c) as v_1+v_3, we do not have a unique port voltage (we don't know v_{GS} absolutely). What would happen if we used a "measured" a_c to form $S_{cc21}=b_{c2}/a_{c1}$. If $|a_c|$ is taken as v_1+v_3, and $|b_c|$ is taken as v_2+v_4, we could report a non-zero and finite S_{cc21} even though there is no current flowing in the "common mode" at all.

By knowing that the topology of Fig. 4 leads to a condition where the common mode is not supported, we now know not to apply $\mathbf{S}_{mix}$ This we may not pick up with a thoughtless application of mixed-mode TDR/T measurement data alone.

Related observations for Fig. 4—

The circuit may be considered balanced since it does not share a common return path with the instrument (or driver and receiver), allowing us to find a virtual ground potential in the middle of the terminal voltage difference. If Z_1=Z_3 and Z_2=Z_4, the virtual ground is readily identified, as is a symmetry or balance in the DUT impedance, but the virtual ground is not a current return path to the instrument.

Here, we take the current directed towards the DUT circuit to be positive so that i_3 is negative in differential drive.

This is a two-port network for all Z and all V_S, regardless of balance; we only have two useful port voltages (v_1-v_3 and v_2-v_4).

3. Another Condition Where the Common Mode Will Not Exist

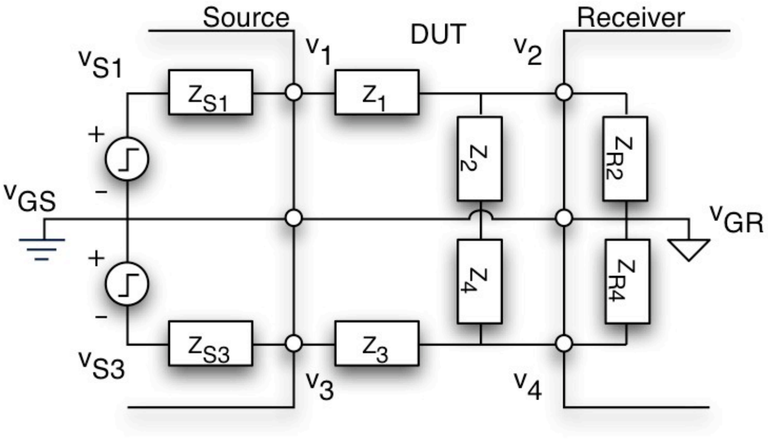

Figure 5. Balanced device under test, differential- or common-mode drive, differential or common receive, connected Source and Receiver grounds.

When this DUT network is balanced, we have at most two DUT ports, so common and mixed modes cannot be supported by the DUT.

The story for the overall network may be different. The Source and Receiver share a common reference that is not connected to the DUT. Even when the DUT is balanced, the overall measurement network may not be since Z_{R2} and Z_{R4} are in the current return path. If $Z_{R2} \neq Z_{R4}$ then the overall network is unbalanced regardless of the DUT Z.

When the overall measurement network is unbalanced, we can “see” four ports: v_1-v_{GS} would be the voltage at Port 1; v_3-v_{GS} would be the voltage at Port 3; i_1 and i_3 would be defined as before with the total return current on the common being equal and opposite to the sum i_1+i_3.

However, we must realize that an unbalanced condition induced by the Source and Receiver is not intrinsic to the DUT and measurement of $\mathbf{S}_{\mathrm{mix}}$ directly again requires a bit of thought and a priori knowledge, or the correct calibration.

One condition or definition of balance for the overall network could be when $Z_{R2}=Z_{R4}$ and the DUT’s virtual ground potential equals the common ground potential. We could also define balance when the net return current on the common connection is zero. However, we should identify overall measurement network balance when $Z_1=Z_3$ and $Z_{R2}=Z_{R4}$ regardless of V_S and Z_S. This is another way of concluding there is only two DUT ports.

4. The Differential DUT is Two, Two-Ports

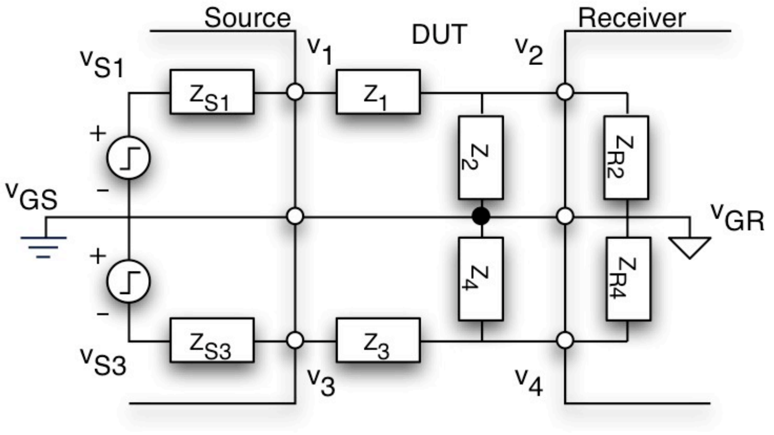

Figure 6. Symmetric, unbalanced device under test, differential- or common-mode drive, differential or common receive, connected Source, Receiver and DUT grounds

Now we have the picture that most people propose for the serial data channels. The circuit is generally and most often a four-port in practice, but under symmetry and weak-coupling conditions, or nearly so, this network smells, tastes, and looks like two two-port devices. It is fully characterized without the top half interacting with the lower half.

In this case it is likely we can observe this fact from either the mixed-mode TDR/T measurements or multiport measurements of this network. We are still left with a question as to the definition of $a_{c1}=a_1+a_3$ under common drive conditions. This seems to imply the ground is split and the Port 3 to Port 4 connection is somehow added on top of the Port 1 to Port 2 section (with v_{GS3} coming in common with v_1). We just don't see a true common mode port with this network, though here, and in the cases above, we can clearly see the conventional definition of the differential port.

It is true that full symmetry is difficult to realize in practice at high frequency, requiring $Z_2=Z_4$ in addition to $Z_1=Z_3$ for DUT balance, and $Z_1+(Z_2||Z_{R2}) = Z_3+(Z_4||Z_{R4})$ for overall network balance, This is the goal of many circuits and many circuits get close enough that we're proposing more care must be taking when forming $\mathbf{S}_{\text{mix}}$ from measurements, at least more care than many applications have demonstrated recently.

Guidelines

From a basic analysis, an extreme measurement example, and general observations on the true number of ports, we have come up with the following guidelines to help reduce errors when characterizing conventional high-speed digital interconnection networks. These are just the start, and there may be occasion to drill down even farther as speeds increase or accepted networks evolve.

1. Identify the *true* electromagnetic ports for the interconnection network being characterized.
2. For *true* one- and two-port networks, do not use two TDR signal sources configured in differential or common-mode drive.
3. For *true* one-, two-, three-, and four-port networks single-ended multiport network analysis will most often work, using either VNAs or TDR scopes. Drive one port at a time and measure all port voltages. All ports must be terminated in the reference impedance (normally 50 Ω).
4. With TDR equipment, *true* four-port networks may often be characterized using four TDR source/samplers in differential and common-mode configurations. This is known as the mixed-mode TDR/T measurement set-up. Here the sources are turned on for two ports for the forward signal transmission, all ports are terminated in the reference impedance, and all port voltages measured. This is then repeated in the reverse signal transmission.
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6. Ideally, all measurement set-ups should allow for calibration devices to be connected at the measurement reference plane, that is, the same points used when making connection to the network under test. This may require the construction and characterization of a custom calibration kit for the particular network being characterized.
7. When using a mixed-mode TDR/T set-up, the calibration must de-skew the two source signals so they are aligned at the entry point to the network's ports, the measurement reference plane.
8. When using mixed-mode TDR/T set-up, the delay for the combined differential drive signal (V^+-V^-) must be the same as the delay for the combined common-mode drive signal (V^++V^-).
9. For all measurement set-ups, great care must be taken to not disturb the cables connecting the sources and samplers to the network. Slight bending and motion of the test cables and connections may invalidate the calibration.
10. If the interconnection network under test is coupled to adjacent transmission lines and conductor systems beyond the ports being measured, the other conductor systems must be electrically terminated as they would be in the target application.

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