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Two Domains. Four Kinds of Ratios.

An Introduction to Characterizing the Electrical Properties of High Performance PCB Interconnects Using Time and Frequency Domain Based Ratios.

EXECUTIVE SUMMARY

High performance printed circuit board (PCB) interconnects are routinely used to route high speed digital, microwave, and RF/wireless signals from one location to another inside a variety of products ranging from small wearable products to large rack-mounted storage devices in cloud server farms.

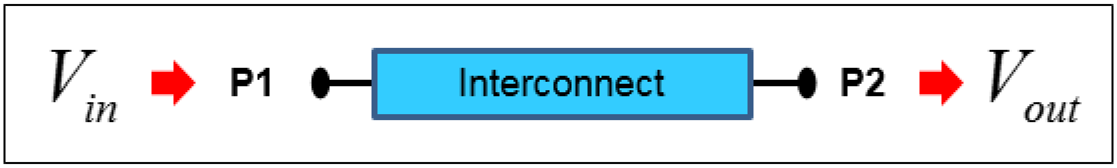
Unless they are designed properly, these interconnects modify the digital, microwave, and/or RF/wireless signals that propagate through them. The modifications are usually a combination of attenuation (the amplitude of the signal exiting the interconnect is lower than the amplitude of the signal entering the interconnect) and distortion (the shape of the signal exiting the interconnect is different than the shape of the signal entering the interconnect). Both of which are undesired and can, in a worst case situation, render the interconnect non-functional.

Quantifying the attenuation and distortion properties of an interconnect can be accomplished by four kinds of ratios in the time and frequency domains. These four ratios are THRU (through), REFL (reflection), NEXT (near end crosstalk) and FEXT (far end crosstalk).

This white paper describes the basis for why these two domains and four ratios are all that are needed to completely quantify the attenuation and distortion properties of a PCB interconnect.

Black Box Representation of a Simple Interconnect

Referring to Figure 1, we can conceptually envelop a simple PCB-based interconnect by a black box so that the only accessable electrical connections for measuring and characterizing the interconnect occur at each end. This is not as unrealistic as it sounds since most PCB-based interconnects are inaccessible from any direct probing anyway because the conductive traces used to direct where the interconnect is routed in the PCB are covered by solder mask and/or routed on inner layers.



Using this black box approach, we can completely encompass the entire physical construction of the interconnect including any connector and component mounting pads, via through/stubs and microstrip/stripline transmission lines structures. And by doing so we will also automatically capture all materials whose electrical properties impact how the signal propagates through the interconnect including anisotropic dielectric constant variations, conductor surface roughness variations, as well as frequency dependent variations in dielectric and conductor conductivities.

By their very nature, PCB interconnects are passive structures. They do not “broadcast” any information about their attenuation and distortion producing properties that we can sense, for example with some kind of antenna or probe. In order to quantify what is going on inside the interconnect, we need to inject some kind of signal into the interconnect and record the response of the interconnect to that injected signal. For the example shown in Figure 1, that means sending a predefined signal shape, V_{in}, into the interconnect at Port 1, and then measuring what comes out at the other end, V_{out}, at Port 2.

This poses a bit of a problem since we may not always know what the actual signals are. For example, a signal passing through a midplane or backplane can vary depending on what line cards or blades are plugged into it.

A more universal approach that works around this problem is to characterize the interconnect by the ratio of the output signal to the input signal, V_{out}/V_{in}. Using this approach, we can then multiply any shaped input signal - whether it’s high speed digital, microwave or RF/wireless - by this ratio to get the shape of the output signal. It is worth noting that in this ratio definition, everything that goes on inside the PCB interconnect that causes attenuation and distortion - dielectric losses, skin depth losses, surface roughness losses, oxide coating losses and impedance mismatch losses - is included in the ratio. Defining the ratio in this black box manner results in a comprehensive characterization that does not accidentally leave any detrimental phenomena out of the measurement. Nothing “falls through the cracks”, so to speak.

The Importance of Sufficient Characterization Bandwidth

This ratio concept works quite well as long as the input signal used to obtain the ratio has a bandwidth equal to or greater than the bandwidth of any signal that is propagated through the interconnect during actual or proposed use. This is relatively easy to accomplish in an electrical characterization laboratory equipped with modern interconnect characterization instruments such as the Vector Network Analyzer (VNA) and Time Domain Reflect/Time Domain Through (TDR/TDT).

A VNA characterizes interconnects by injecting a variable frequency sine wave into the interconnect and observing how the sine waves of varying frequency are attenuated and phase shifted by the interconnect. As long as the start and stop frequency of the variable frequency source in the VNA are lower and higher than the necessary bandwidth of the interconnect, accurate characterization is achieved. A measurement made using sine waves is classified as a frequency domain measurement. A frequency domain ratio is also called an S-parameter.

A TDR/TDT accomplishes the same goal by injecting a leading edge of a pulse into the interconnect. As long as the rise time of the leading edge of the TDR/TDT pulse is faster (shorter in time) than the fastest rise time of any signal propagated through the interconnect during actual use, accurate characterization is achieved. A measurement made using the leading edge of a pulse is classified as a time domain measurement. A time domain ratio is also called a T-parameter.

Note that in both VNA and TDR/TDT cases, two measurements need to be made before a ratio can be computed. One measurement that captures the amplitude and shape of the input signal, V_{in}, and one measurement that captures the amplitude and shape of the output signal, V_{out}.

Output/Input Ratios for a Single-Ended Interconnect

In Figure 1, we injected the signal into the left side Port 1, while we looked at what came out at the right side Port 2. We may then ask: Does the interconnect behave differently if we reverse the ports, and send the input signal, V_{in}, into Port 2 and monitor what comes out of Port 1? It is a valid question to ask since many PCB-based interconnects are not symmetrical about the center of the interconnect. Bends, twists and via locations on the input side of the interconnect's center are not "mirror images" of the bends, twists and via locations on the output side of the interconnect's center. Thus if we want to properly characterize the interconnect, we need to also characterize the interconnect with the signal propagating in the opposite direction.

To keep track of which direction the signal is propagating when we measure/calculate one of the S-parameter or T-parameter ratios, we use a subscripting notation where the first subscript is the port associated with the output port, while the second subscript is associated with the input port. For example, the S and T-parameters for the interconnect in Figure 1, where the input signal, V_{in}, is sent into Port 1 and the output signal is measured at Port 2 would be defined as S_{21} and T_{21} respectively. However, if the input signal is sent into Port 2, then the subscripts would be reversed to S_{12} and T_{12}

respectively. S and T-parameters associated with an output port that is “at the other end of the interconnect” from the input port are also called THRU (through) parameters.

One of the nice properties of these two THRU parameters is that for passive linear PCB interconnects, they are equal, meaning $S_{21} = S_{12}$ and $T_{21} = T_{12}$ If they are not, then it indicates a re-measurement is required.

If there are impedance mismatches inside the interconnect, then a portion of the signal that is sent into Port 1 comes back out of Port 1. Similarly, if we send a signal into Port 2, a portion of the signal comes back out of Port 2. This is obviously not a desirable situation, for if part of the input signal comes back out of the input port, it cannot also be part of the signal present at the output port. In many cases, impedance mismatches create structural resonances that introduce a significant amount of distortion.

Using the same subscript notation scheme defined above, we can then define four new ratios: S_{11} and T_{11} for the case where the signal is input in to Port 1; and S_{22} and T_{22} for the case where the signal is input into Port 2. Ideally, we would like the interconnect to be direction-agnostic, meaning $S_{11} = S_{22}$ and $T_{11} = T_{22}$. But unlike the THRU parameters, this is rarely the case. Ratios associated with an output port that is the same as the input port are also called REFL (reflection) parameters.

Note that in an ideal interconnect, the magnitude of the THRU parameters must equal 1 (the entire input signal appears at the output), while the magnitude of the REFL parameters must be equal to 0 (nothing from the input signal is reflected back out of the input port). From these two properties of an ideal interconnect one can easily gauge the overall quality of the interconnect by simply observing how far the magnitudes of the THRU parameters are from 1 and how far the magnitudes of the REFL parameters are from 0.

Referring to Figure 2, we can thus define the four VNA and four TDR/TDT measurement-based ratios tabulated in Table 1.

Figure 2: VNA and TDR/TDT Parameters for a Single-Ended (One Trace) Interconnect

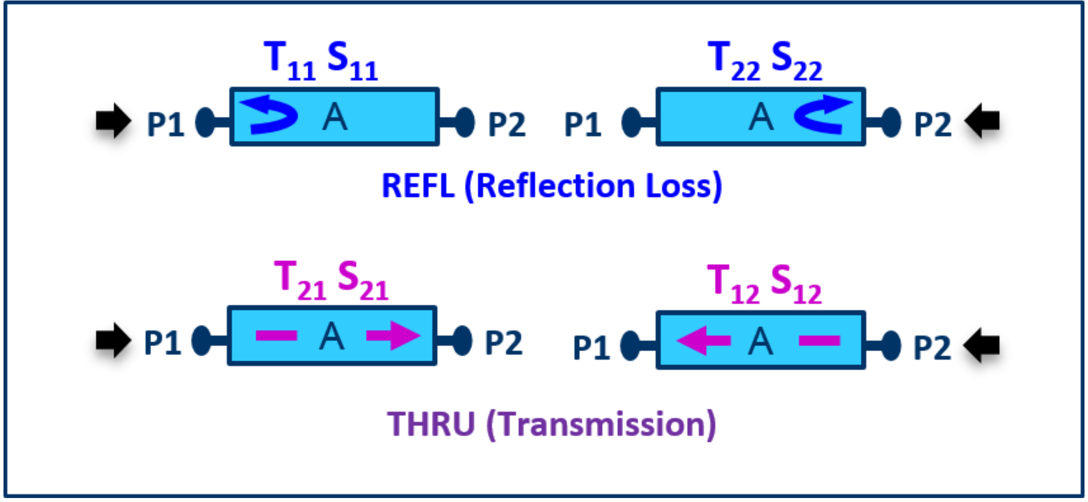


Table 1: VNA and TDR/TDT Parameters for a Single-Ended (One Trace) Interconnect

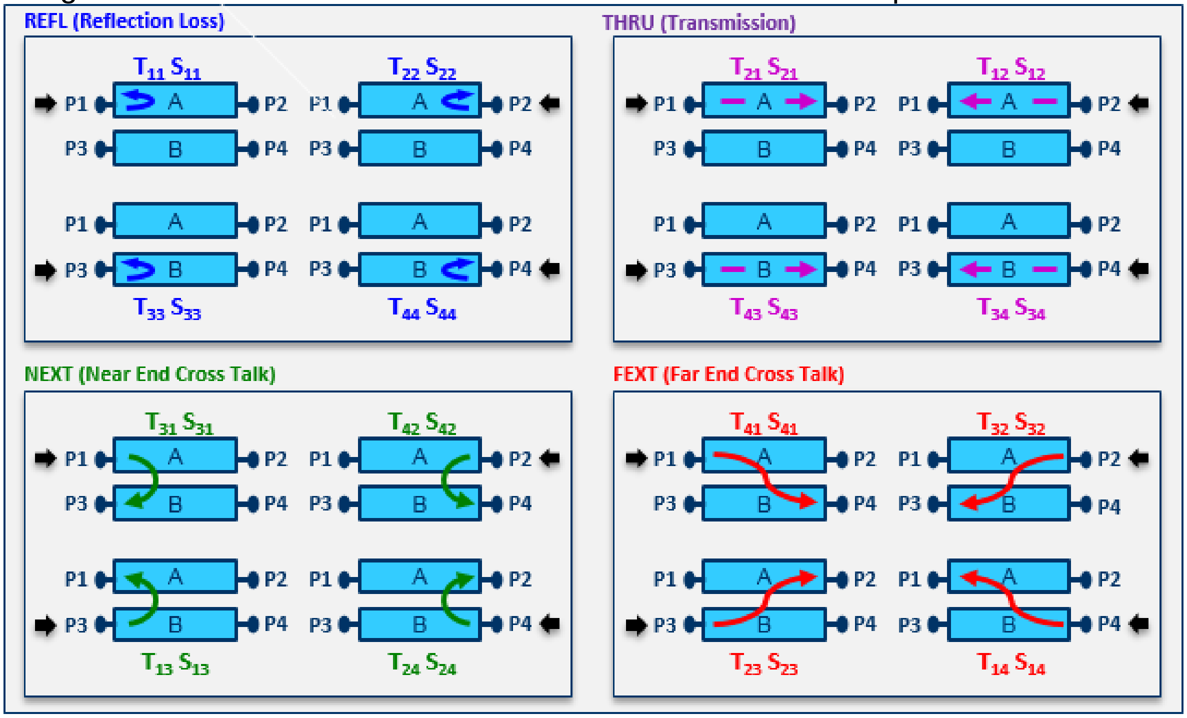
Freq Domain S-Parameter	**Time Domain T-Parameter**	**Type Parameter**	**Ratio Definition**
S_{21}	T_{21}	THRU	V_{out} (Port 2) / V_{in} (Port 1)
S_{21}	T_{21}	THRU	V_{out} (Port 1) / V_{in} (Port 2)
S_{11}	T_{11}	REFL	V_{out} (Port 1) / V_{in} (Port 1)
S_{22}	T_{22}	REFL	V_{out} (Port 2) / V_{in} (Port 2)

S-Parameter and T-Parameter Ratios for Two Electrically Coupled Interconnects

If we have two single-ended interconnects that are routed close to each other, energy can flow between the two interconnects. One example of such an interconnect is shown in Figure 3, where two coupled traces are designed to carry a differential pair set of signals. In this case, we have two additional kinds of ratios called NEXT (near end crosstalk) and FEXT (far end crosstalk) that get added to the THRU and REFL parameters defined above.

Referring to Figure 3, we can thus define sixteen VNA and sixteen TDR/TDT measurement-based ratios for two electrically coupled interconnects.

Figure 3: S-Parameter and T-Parameter Ratios for Two Coupled Interconnects



It is also worth noting that this ratio scheme is scalable to multiple (more than two) coupled interconnects. One example where this is commonly done is in the characterization of parallel data bus architectures where the individual traces are routed close to each other.

The Importance of Complementary S and T-Parameter Ratios

One of the major sources of a PCB interconnect's undesired attenuation and distortion properties is conversion of electromagnetic energy (associated with the signal that is propagating through the interconnect) into thermal energy. This conversion is frequency dependent – with more conversion occurring at higher frequencies than at lower frequencies. Conversion mechanisms that fall into this category include dielectric loss tangent and conductor skin depth, surface roughness and oxide coating related losses. Structures such as via stubs are also prone to resonate, introducing additional signal distortions. These sources of attenuation and distortion are best characterized in the frequency domain using the S-parameter ratios.

However, discrete changes in the characteristic impedance of the interconnect, usually occurring at via locations or along the interconnect at locations where the cross section of the conductors and/or the dielectric construction that comprise the interconnect are not physically or electrically uniform, are usually best charactersized in the the time domain using the T-parameters.

Conclusion

High performance printed circuit board (PCB) interconnects are routinely used to route high speed digital, microwave, and RF/wireless signals from one location to another inside a variety of products ranging from small wearable products to large rack-mounted storage devices in cloud server farms. Unless they are designed properly, these interconnects can attenuate and distort the digital, microwave, and/or RF/wireless signals that propagate through them.

Complete characterization of these PCB interconnects can be accomplished by four kinds of ratios in the time and frequency domains. These four ratios are THRU (through), REFL (reflection), NEXT (near end crosstalk) and FEXT (far end crosstalk).

For a singled-ended interconnect, a total of eight ratios are required: four in the frequency domain and four in the time domain. For a coupled pair interconnect, a total of thirty two ratios are required: sixteen in the frequency domain and sixteen in the time domain.

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Franz Gisin is Director of Signal Integrity at Multek's Interconnect Technologhy Center in Milpitas, California. Franz Gisin's core focus is the electrical characterization of PCB-based high performance digital, RF and microwave interconnects.

Prior to Multek, Franz Gisin has worked for over 40 years in electromagnetics including EMC (Electromagnetic Compatibility), signal integrity and the characterization and modeling of high performance interconnects.

Franz Gisin has a BS in Electrical Engineering and an MS in Applied Mathematics.

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