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Broadband Measurements in the Differential Mode: Accurate Determination of Dispersive Attenuation

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Abstract

Two new methods for measuring dispersive attenuation (S_{21}) in the differential mode are presented and compared. While conventional vector network analyzers can obtain S_{21} in the single-ended mode over wide frequency ranges, differential mode measurements require special methods, such as the use of baluns, which limit the frequency range over which data is obtainable. New methods are being developed that allow existing instruments to obtain data in the differential mode over wide frequency ranges. Two approaches are discussed and examples of data obtained using them are presented and compared over a 6 GHz frequency range.

Introduction

Characterization in the frequency domain for single ended excitation has developed over the years to a very high level of sophistication and refinement. In fact, instruments for automated measurements for single ended mode excitation are available commercially in a number of frequency ranges up to ultrahigh frequencies, well above the range currently needed for high-performance digital electronics. In contrast, excitation and characterization in the differential mode does not enjoy the same multiplicity of options, especially in the frequency domain. Since materials are generally more absorptive at high frequencies and metals more readily expel high frequency currents to their surface, accurate determination of loss in all the design modes is becoming increasingly important to designers. A brief review of the trends helps understand the present situation and the urgent needs.

Frequency domain and time domain characterization of electronic transmission lines has been a necessary endeavor since the first Morse code telegraph line was laid. However, the development of RADAR caused the industry to concentrate on the types of transmission lines and test methods best suited for that technology. Therefore, during the largely “analog” era, the most successful style of high frequency transmission line was single ended, usually in the form of coaxial cables and connectors. This naturally led to today’s high-end test equipment being predominantly oriented towards single-ended, two-port measurements. Interestingly, the measurement needs of the telecommunication industry, where the differential mode is the preferred design configuration, were largely satisfied by compromise and tradeoff approaches. That included assumptions of lossless cables, extrapolation of the differential characteristics from single ended measurements and, as is described later, the use of baluns.

In the present day atmosphere, the interplay between communication and computer technologies, in addition to blurring their boundaries, is creating two effects. Increasingly differential mode routing is appearing on circuit boards and in computer cables. In addition, the advances in the performance of computers (and digital electronics, in general) are driving the need for higher speed communication and data throughput. Both of these trends are accelerating the need for broadband measurements in the differential mode. What’s more, it is well known that losses increase at high frequencies and contribute to signal dispersion. For these reasons, accurate determination of loss and dispersion in the differential mode is now a requirement for high-speed digital design. Design issues are addressed in companion paper in this conference [1].

Currently, testing of differential transmission lines relies on four basic test methods:

1. Evaluation of signal degradation by making transmission measurements of clock-like digital data (logic transitions at fixed time intervals). The source for such testing is typically a pulse generator or data pattern generator. The tests are used for risetime degradation and nearend cross talk (NEXT) estimation.

2. Evaluation of signal degradation by making transmission measurements of bit trains: logic transitions at fixed time intervals that are multiples of the unit interval, with the duration of logic states representing data like spectral content. The source during testing is typically a data pattern generator. These are used for bit error rate testing (BERT),

simplex and duplex eye pattern testing, NEXT and balance degradation, etc.

3. Time domain reflectometry (TDR) and time domain transmission (TDT) testing. The source during testing is typically a pulse generator that mimics a single logic transition. These measurements are made on the assumption that the time interval to the next logic state transition is many multiples of the electrical length of the transmission line under test. This method is used for the measurement of risetime degradation, characteristic impedance, propagation delay, skew, etc, and is the preferred method for measuring NEXT.

The above three test methods are entirely in the time domain. The available modes of excitation are differential, unbalanced differential and even mode (sometimes referred to as common mode). Four or more ports are generally available for measuring differential devices.

4. Vector or Scalar Network Analyzer (VNA or NA) frequency domain measurements. The source during testing is a sinusoidal frequency synthesizer. These are used for single ended insertion loss (S_{21}) and return loss (S_{11}) measurements. Some four port network analyzers have been developed with the use of baluns and other phase shifting power splitters in attempts to turn two port systems into four port systems. Systems that use baluns, in fact, achieve differential excitation. Baluns have been used very successfully to date. However, digital data rates are reaching speeds such that today's baluns have neither the needed bandwidth nor performance.

Baluns and other phase shifting power dividers have internal reflections. Due to the nature of the components that are used to build these devices, the internal reflections change depending on the impedance and phase relationships of the loads terminating the balun or power divider. These internal balun reflections interact with the VNA during calibration. The calibration becomes inaccurate when the device under test is mated to the balun if the device under test has a different load impedance and phase relationship than the calibration standard that was used for calibration.

All four of the above listed test methods have limitations causing them to be less than ideal for characterizing differential transmission lines intended for use at data rates exceeding 2.0 Gb/s. This leads to the need to evaluate new test methods for characterizing differential transmission lines intended for transmitting digital data at rates higher than 2.0 Gb/s. This report evaluates two new test methods suitable for broadband characterization of loss and dispersion in the differential mode.

One of the new test methods builds on the strengths of existing high-speed time domain equipment by adding computational software that utilizes existing equipment capabilities to obtain vector characterization of the differential device under test. The most useful test equipment for this purpose is a TDR/TDT system operated in the TDT mode. This is probably the most prevalent measurement apparatus in any typical high-speed digital electronics laboratory.

This method is compared to the second new test method that builds on the strengths of existing two port VNA by adding hardware that duplicates the original two ports both physically and electronically. Software is added such as to combine individual single ended measurements so as to determine differential S-parameters.

The purpose of this report is to evaluate the two new test methods and equipment. Sets of coaxial cable test specimens are measured and the results compared. The coaxial cable specimens are grouped into differential pairs. Each pair has predetermined differential characteristics: balanced, unbalanced impedance, unbalanced losses, unbalanced skew. Differential transmission lines made from pairs of coaxial cables have the following features: no coupling between halves of a differential pair; homogeneous dielectric; isotropic dielectric. The choice of coaxial cables for the differential transmission lines used to compare these test methods is made deliberately such as to test the main features of the test methods. A follow up, second round of tests is aimed at characterizing some more complex properties of differential channels that are typically used in high speed digital design.

S_{21} Measurements

S-parameters have long been used to characterize microwave devices. As the speed of digital systems has increased, S-parameters are increasingly also being used in their characterization. The S-matrix of an N-port device is a frequency dependent N×N matrix that relates the input and output at each port. Thus, if the signals incident on the various ports of the device are represented by the vector ***a***, the response is given by the vector ***b***=***Sa***. Consider a two-port device such as a cable:

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

S_{11} and S_{22} are the reflection coefficients from either end of the device while S_{21} and S_{12} are the transmission coefficients in either direction through the device. For simple structures such as cables, S_{21} and S_{12} are essentially equivalent. (Note that if the impedances of the ports are not matched, ***a*** and ***b*** are the so-called normalized voltages). See, for example, [2] for more information.

Although differential transmission lines are four-port systems, so-called mixed-mode S-parameters are used rather than four-port S-parameters. Mixed-mode S-parameters relate the input and output of the even and odd modes. They have two additional subscripts that indicate even or odd mode. These two subscripts can take on the value ‘C’ for common (even) mode or ‘D’ for differential (odd) mode. For example, S_{CD21} refers to the fraction of the signal that leaves the circuit on the far end as even mode when the circuit is stimulated on the near end in odd mode. For simplicity, in this paper S_{21} is used to refer to S_{DD21}.

The S_{21} parameter is particularly useful for characterizing structures such as cables and backplanes. Since these structures are essentially invariant along their length, characterizing them at one length generally allows accurate computation of the S_{21} parameters at other lengths.

In cables, the loss component of S_{21} is frequently modeled by the simple two-term expression:

$$loss = a\sqrt{f} + bf$$

where *loss* is measured in dB. The first term represents skin effect loss while the second term represents dielectric loss. Phase effects are usually not included. For accurate determination of cable behavior at high frequency, this model is often not sufficient. Cables in particular are prone to peaks in loss due to periodic impedance variations. In these cases, the measured values of S_{21}, including phase, are essential.

In this paper two new ways of obtaining S_{21} in differential mode are discussed. The first is the four-port VNA system produced by ATN Microwave. This system can provide full mixed-mode S-matrices at frequencies of up to 20 GHz. The second is a method for extracting S_{21} from time-domain transmission (TDT) data in software. This method can provide S_{21} at frequencies up to the bandwidth of the time domain instrument, typically 10–12 GHz.

ATN Microwave VNA

The ATN microwave VNA system is effectively a four-port VNA. Among other things, this allows differential structures such as cables to be characterized without the use of baluns. These systems can take data up to either 6 or 20 GHz depending on the model.

The system consists of a combination of a two-port VNA with hardware that multiplexes the ports of the VNA onto four system ports and software to drive the system. The four channels are connected to the DUT after they are all calibrated with shorts, opens, matched loads and fixture transmission measurements: a total of sixteen measurements. The software combines a series of two-port measurements taken at different combinations of the four system ports to arrive at a composite four port measurement and determines the differential scattering parameters. Plots and the actual data may be manipulated and saved for later analysis. More detail on the system is available from ATN Microwave’s web page [1].

Extraction of S_{21} from TDT Data

Extraction Principle

Since TDT systems have a bandwidth of about 12 GHz, in principle S_{21} data should be obtainable from TDT data up to 12 GHz. In practice, data can be obtained up to and sometimes slightly above 10 GHz if the measurements are made carefully.

Mathematically, the procedure can be thought of in the following idealized fashion. The TDT instrument generates an unknown signal *s(t)*. This signal is measured after it has propagated through the fixturing alone. The resulting signal is $m_{fix}=f(t)*s(t)$, where $f(t)$ is the impulse response of the fixture and * represents convolution. A second measurement is made through both the fixture and the DUT. The resulting signal is $m_{DUT}=f(t)*g(t)*s(t)$, where $g(t)$ is the impulse response of the DUT.

The Fourier transform is then applied to these two signals to obtain $M_{fix}(\omega)=F(\omega)S(\omega)$ and $M_{DUT}(\omega)=F(\omega)G(\omega)S(\omega)$. Note that the convolution becomes a multiplication when the measurements are transformed. Identifying the transform of the DUT impulse response (G) as S_{21}, one obtains:

$$S_{21}(\omega)=M_{DUT}(\omega)/M_{fix}(\omega)$$

In practice, the algorithm is more complicated. Discrete transforms such as the FFT assume that the signal is periodic and its value is known for one period. While the TDT signal is indeed periodic, its period is around 4 µs. Since only about 100 ns of TDT data is typically measured, these assumptions are violated. It is possible to overcome this issue as the examples that follow show. However, the methods used to do so are beyond the scope of this paper.

Issues

There are several issues to consider when using TDT extraction to obtain S_{21} data. The first issue involves the limited dynamic range of TDT measurements relative to VNA measurements. The peak loss that can be measured reliably is roughly 40 dB for TDT extraction versus 100 dB for a VNA. This limits the length of cables that can be measured using TDT to roughly half the length that can be measured using a VNA.

A second issue involves measurement of cables that are not 50 Ω. For long cables, the reflection due to the mismatch can be excluded by time-windowing the data. That is, the sample duration is chosen such that it is less than twice the propagation time down the length of the cable. This eliminates all multiple reflection effects and the only special treatment necessary is to adjust the S_{21} amplitude by the amount of amplitude loss at the interfaces between the cable and the measurement system.

For short cables, there are two options. The data can be time-windowed, in which case the short sample duration results in coarse frequency resolution. Alternatively, the multiple reflections can be factored out of the results mathematically. Although this procedure is not perfect, it substantially reduces the oscillations that would otherwise occur in the measured S_{21} at low frequencies. Note that factoring out the effects of impedance mismatch is necessary in VNA measurements as well. Figure 1 shows an example of impedance mismatch. Reflection from the impedance mismatch at the near end of the cable is visible near 110 ns. This data could be windowed at 100 ns if desired.

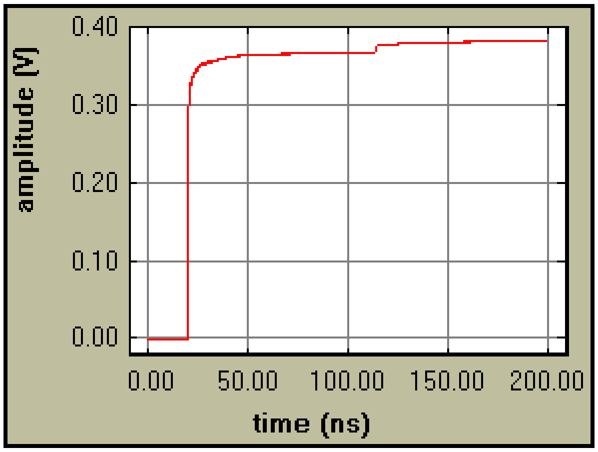

Figure 1: TDT data for an 11.7 m, 75 Ω cable that has not been time-windowed.

Procedure

The procedure for extracting the S_{21} of a DUT consists of four steps. First, the conductors of the DUT are soldered to SMA connectors as shown in Figure 2. The length of wire between the DUT and the connector is kept as short as possible to minimize the possibility of resonances in the frequency range of interest. If the DUT is already fixtured, this step can be omitted.

The second step consists of attaching the fixtured DUT to the TDT equipment through short, low-loss cables as shown in Figure 3 and measuring the resulting TDT waveform. The DUT is then replaced with barrels as shown in Figure 4 and the measurement is repeated. These two measurements are what the extraction software uses to determine the S_{21} of the cable. An example of TDT data is show in Figure 5.

Finally, the software extractor is used to load the two measured waveforms. The extractor then computes S_{21} in a process that takes a few seconds to a minute depending on the amount of points in the waveforms and various settings of the extraction program. Example results are shown in the next section.

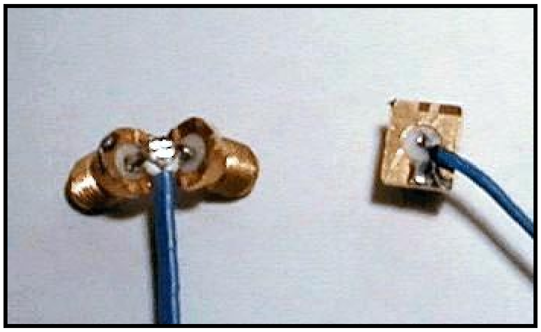

Figure 2: TDT fixturing for differential (left) and single-ended cable (right).

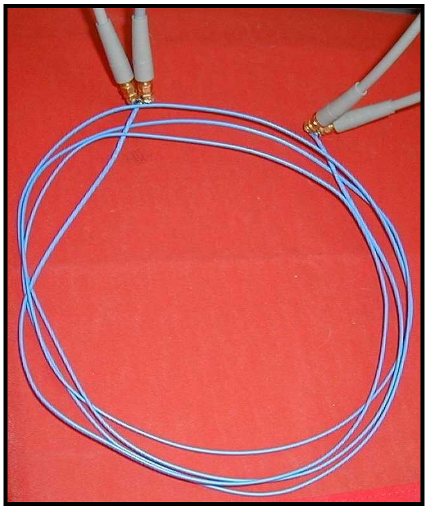

Figure 3: DUT measurement.

Figure 4: Fixturing measurement.

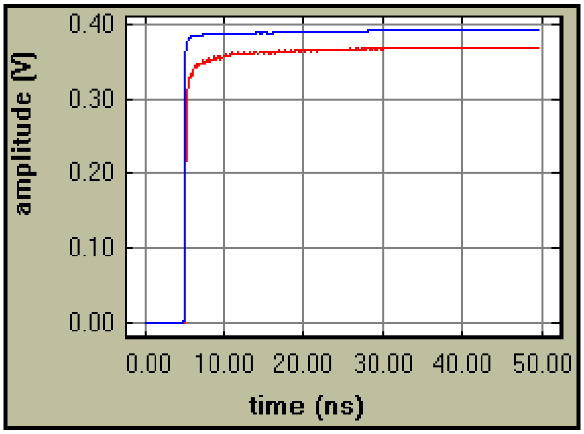

Figure 5: TDT data for 22 AWG quad cable (red) and SMA barrel (blue).

Comparison

The results of measuring the S_{21} of a set of cables using both the ATN microwave VNA and TDT extraction are shown in this section. Four types of cables are measured as shown in Table 1. The first three types of cable (RG-58, RG-59, and RG-316) are fixtured with SMA connectors and no additional fixturing is required for measurement. These cables are measured in pairs to test the ability of the methods to make differential measurements. They are measured in both short and long lengths and both with and without added skew. These measurements are meant to test the ability of the two measurement methods to deal with skew, impedance mismatch, and both long and short cables. The final cable type (22 AWG quad) is fixtured separately for the TDT and ATN measurements.

Note that in the phase comparisons the ATN data is shifted by a linear term. This linear term relates to the propagation delay of the cable. By removing the phase shift associated with propagation delay, the fine structure is more apparent and comparisons are more easily made. Because of the way in which TDT data is taken, the propagation delay does not affect the TDT results.

The agreement of the measurements made by the two methods is quite good. The agreement of the measurements made on the 22 AWG quad cable is particularly striking due to the sharp peaks as shown in Figure 12 and Figure 13. The agreement of these two, unrelated, methods is a good indication of their accuracy.

There are two measurements where the differences between the two measurement methods appear significant. The first is in the measurement of the 18” RG-58 cable shown in Figure 6. These measurements are rather close, falling within 0.2 dB or 2%, but the difference appears magnified because the measured loss is small.

The second measurement is that of the 30’ of RG-316 shown in Figure 11. In this case, two effects cause the difference. The first is that the loss of the cable exceeds 40 dB near the loss peak that falls near 5 GHz. This exceeds the dynamic range of TDT extraction so the data becomes unreliable in this region. The second effect is that the skew resonance has shifted slightly between the two measurements. This is confirmed by examining the phase plot, where the 180º phase shift associated with the loss peak falls at 4.9 GHz and 5.3 GHz for the TDT and ATN measurements respectively. This explains the lower magnitude of the TDT data above the loss peak. The cause of the shift in skew frequency is unknown, but is likely due to some skew present in one of the measurement setups.

Table 1: List of compared cables

Type	Length	Skew	Figure
RG-58 (100 Ω)	18 in	—	6
``	18 in	77 ps	7
``	35 ft	60 ps	8
RG-59 (150 Ω)	50 ft	4.5 ns	9
RG-316 (100 Ω)	18 in	—	10
``	30 ft	105 ps	11
22-AWG quad	11.7 m	—	12,13

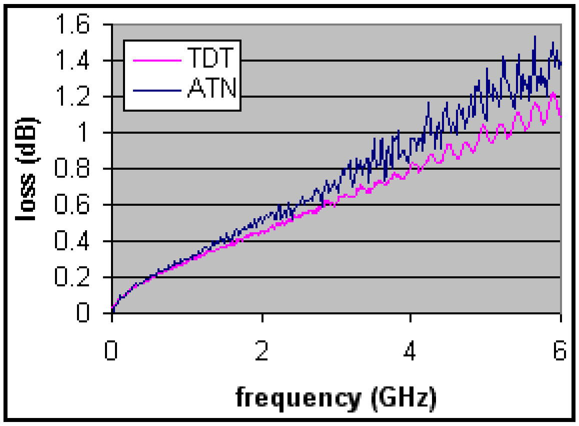

Figure 6: S_{21} loss for 18” of RG-58 without added skew, measured using TDT extraction.

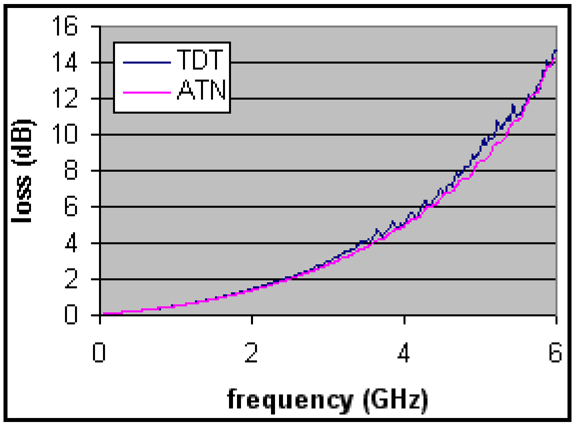

Figure 7: S_{21} loss for 18” of RG-58 with 77 ps added skew, measured using TDT extraction. Note that the upward curve of the data at high frequency is due to skew.

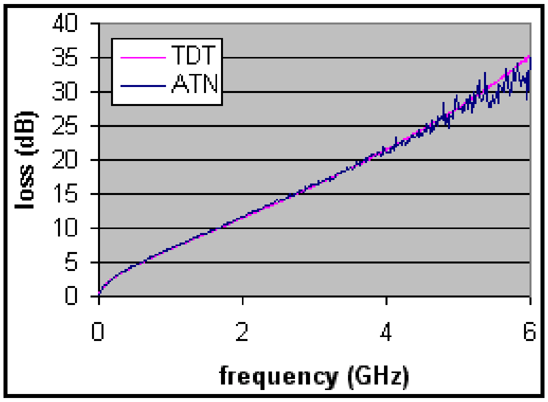

Figure 8: S_{21} loss for 35’ of RG-58, measured using TDT extraction.

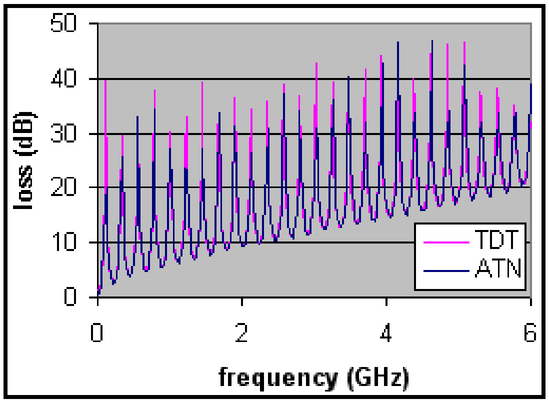

Figure 9: S_{21} loss for 50’ of RG-59, measured using TDT extraction. Note the many peaks due to the significant skew.

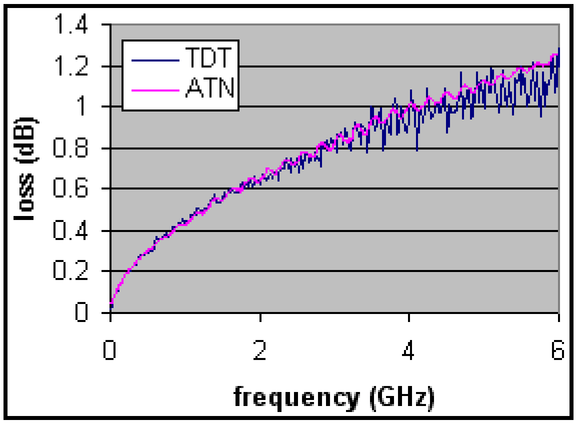

Figure 10: S_{21} loss for 18” of RG-316, measured using TDT extraction.

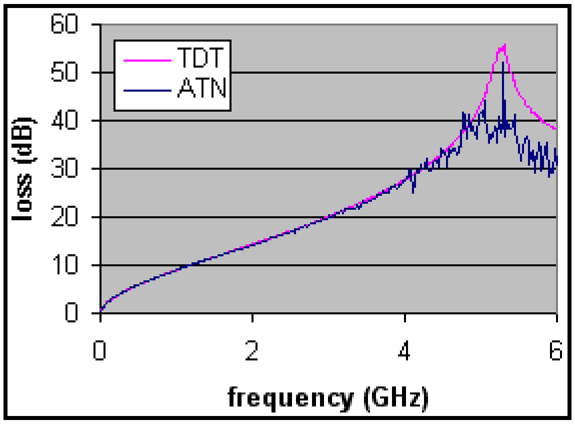

Figure 11: S_{21} loss for 30’ of RG-316, measured using TDT extraction. Note the peak at 5 GHz due to skew.

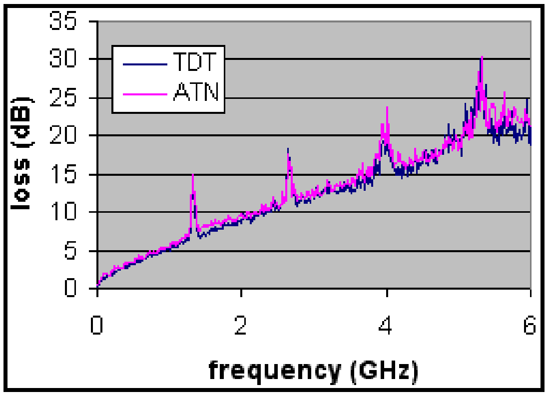

Figure 12: S_{21} loss comparison of 11.7 m, 22 AWG quad cable data obtained using TDT extraction and the ATN VNA.

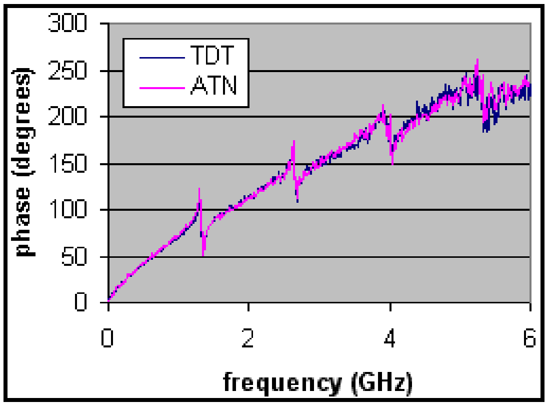

Figure 13: S_{21} phase comparison of 11.7 m, 22 AWG quad cable data obtained using TDT extraction and the ATN VNA.

Skew and S_{21}

Skew has a dramatic effect on the measured S_{21} as is seen in the results presented in this paper. How one deals with skew during measurement depends on whether one wants to measure a particular cable, including skew, or whether one wants to determine the characteristics of a type of cable, without skew. In the first case, no special treatment is needed. In the second case, the skew must be removed from the measurement.

This can be done simply when performing TDT extraction by adjusting the skew control on one of the TDT channels. It is also possible to remove skew mathematically if the amount of skew is known. However, this requires knowledge of both S_{21} and S_{CD21} in order to get amplitude correct near the nulls in S_{21}.

Summary

Methods for determining the characteristics of cables and transmission lines operating in the differential mode will be critical in designing upcoming generations of electronic systems. Both the ATN Multiport VNA and TDT extraction provide viable ways of obtaining this S_{21} data. The choice of one or the other depends on many factors including availability and familiarity with TDT or VNA systems. In addition, whether one would use the other functionality of either system is an important consideration.

References

1. "The ATN-4000 Series Multiport and Differential S-Parameter Systems," http://www.atnmicrowave.com/multi/multi.html
2. V.Valkenburg, ed. *Reference Data for Engineers: Radio, Electronics, Computer and Communications,* 8th edition. Boston: Newnes, 1998, pp 31-1–31-31.