Traditionally, RF and digital engineers have had little in common. However, as the state-of-the-art on each side advances, the technologies are overlapping. In particular, high-speed digital data (≈1 Gb/second or faster) clearly exhibit phenomena associated with RF signals. Understanding these phenomena — the analog effects described by Maxwell’s Equations — and their effect on system performance is critically important in high-speed physical layer design and validation.

Generally, rise times decrease (shorten) as data rates increase, and the harmonic content of these high-speed signals can be many times that of the fundamental. Consequently, signal integrity analysis now commonly involves frequency domain tools. The precision, accuracy, and high dynamic range of vector network analyzers (VNAs) make them well suited to the task.

However, time domain issues do not usually involve VNAs. For several reasons, the differential Time Domain Reflectometer (TDR) has been the tool of choice. First, time domain analysis of digital signals seems to make the most sense for preserving state-to-state transitions, and understanding their consequent signal levels versus time. Also, most systems transmitting high-speed data use differential signaling, while most network analyzers are designed for single-ended, two-port devices.
As higher data rates push the state-of-the-art for backplanes and interconnects, they also push the limits of the equipment used in their design. The dynamic range of a very high-speed TDR system is often inadequate for analyzing low-level signals such as crosstalk, or the signal components responsible for generating electromagnetic interference (EMI). Parasitic elements that are often ignored or compensated for at lower data rates can become quite significant at higher data rates. TDR systems do not correct the systematic sources of error in the measurement equipment, nor do they support de-embedding of fixtures or interconnects used with the device-under-test (DUT).

Frequency domain measurements with a VNA can address some of these TDR shortcomings, and provide some additional benefits. In addition to their exceptional accuracy and dynamic range, VNA systems can provide forward and reverse transmission and reflection data without changing the measurement setup. VNA systems also can easily translate performance to alternate reference impedances, and simulate the effects of compensation networks.

The disadvantage of a VNA is that traditional two-port systems are not designed for measuring balanced devices, and they do not provide data in a format that is meaningful to the signal integrity engineer. For the VNA system to be viable for signal integrity analysis, it must be able to characterize balanced devices and present the data in a useable format.

New four-port (two-channel) VNA-based systems designed specifically for signal integrity provide the best of both worlds. They perform the measurements in the frequency domain, but allow the data to be presented in a number of different ways. The user can choose how to view the data, depending on what is most appropriate for the type of device being measured and its intended application.
In an ideal digital system, signals are at a level defined to represent a logical “0” or a logical “1,” and there is no skew on the data or address lines of a parallel path. Unfortunately, describing the behavior of a device in terms of logic levels is an abstraction and is often an over simplification.

In reality, the behavior of electrical signals is more complex. As with signals that propagate in any material, the behavior of digital signals can be accurately described by Maxwell’s equations, which relate electric and magnetic fields. From this representation, phenomena such as loss, dispersion, delay, transient behavior, crosstalk, radiation, and reflections can be described. These analog effects manifest themselves in maladies such as overshoot, undershoot, ringing, rise-time degradation, pulse droop, dropouts, ground bounce, and eye closure.

Signal integrity, therefore, may be defined as the validity of the digital abstraction of a signal. Conversely, signal integrity problems can be attributed to the analog effects that Maxwell’s equations define.

The validity of the abstraction becomes more questionable as edge rates get faster. For the leading edge systems of today, and the systems of tomorrow, better characterization techniques are essential. Just as the task of characterizing these phenomena becomes more difficult, it also becomes increasingly important.
Advantages of a VNA-Based System

If the ideal instrument for assessing the physical layer characteristics of devices used for high-speed applications such as InfiniBand, 3GIO, OC-192, and OC-768 were defined, it would combine the best features of several current tools.

Like a VNA, it would offer high accuracy and high dynamic range. It would have the headroom for tomorrow’s increasingly faster data rates. It would support probing and fixture removal, and would provide a comprehensive analysis of the device-under-test with the least amount of connection. Like a TDR or high-speed oscilloscope, the instrument would provide step and impulse response information, and eye diagrams. It would be easy-to-use, straightforward, and familiar. It also would enable fast and easy calibration, linkage to design software, and drastically reduced design cycle times.

A VNA-based physical layer test system combines these features and completely characterizes the DUT in all modes of operation, which is particularly meaningful for such tasks as device modeling, debugging, or product design. Also, the format of the data can be changed depending on what is most meaningful for a given type of device, or for the type of information that is needed.

Several capabilities are increasingly important as speed increases. These include such things as de-embedding the effects of test fixtures and probes, simulating the effects of compensation networks on a DUT, translating the performance to an alternative reference impedance, and examining the effects of phase skew. These types of analysis are done most conveniently in the frequency domain; so working with frequency parameters is more common.

The completeness of the characterization is central to the way measurements are made. Initially, characterization completeness is necessary to perform error correction and realize the accuracy described above. Furthermore, it is a significant convenience. By connecting the DUT to the system with a one-time connection, the device can be characterized fully without the need to disconnect and reconnect the DUT, or re-configure and re-calibrate the system. It provides both types of response (transmission and reflection), in all directions (forward and reverse), and in all modes of operation (single-ended, differential-mode, common-mode, and mode-conversion).

Accuracy

A VNA-based system has exceptional accuracy. To achieve this accuracy, a systematic error model is applied to raw measured data. The error terms for the model are derived from the calibration procedure (which involves connecting known standards to the instrument). The result is a measurement technique with bounded measurement uncertainties and traceability to a national standards laboratory (such as the National Institute of Standards and Technology, NIST).
Advantages of a VNA-Based System (continued)

Dynamic Range

Frequency domain instruments also are capable of providing measurements with very high dynamic range. For example, dynamic range in the time domain of better than 100 dB is readily available in a system having an effective 10/90 transition time of 35 pS.

This high dynamic range enhances the capability to measure difficult crosstalk parameters and, often more importantly, mode-conversion parameters. In an ideal balanced device that is perfectly symmetrical, these mode-conversion terms are equal to zero. In a non-ideal (but very good) device, the terms are very small. High dynamic range provides the ability to distinguish these very small terms, and pinpoint elusive EMI issues.

Another consideration driving the need for high dynamic range is masking. Time domain responses are most accurate closest to the location of the source. A discontinuity in the DUT will reflect some power back to the source, meaning less power transmits to the rest of the DUT. This loss of power going away from the source is referred to as masking.

Masking effects can be seen in figure 1. The plot on the left shows the differential-mode input reflection of a device ($S_{DD11}$). The first large discontinuity is the input connector; the second is the output connector. Because these connectors are physically identical, the apparent impedance difference between the two can be attributed to masking. The input connector has decreased or masked the power level at the output connector. The plot on the right of the output reflection ($S_{DD22}$) proves this. Looking backwards into the device, the output connector now exhibits the greater apparent impedance. Were it not for masking, these two plots, and the measured impedance of the input and output connectors, would be identical.

Greater dynamic range extends the ability of the system to accurately characterize devices that have several discontinuities or high loss.

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Figure 1. High dynamic range defeats the masking effects of large discontinuities.
Error Correction

As with all instruments, hardware imperfections in a VNA contribute to measurement errors. Unlike some instruments, however, a VNA-based system can combat the problem in several ways.

Systematic errors are related to signal leakage, signal reflection, and frequency response. These errors are repeatable and predictable over time and temperature, and therefore can be characterized through calibration and mathematically removed from the measurement. Known calibration standards are measured, an error model is calculated, and the model is used to remove the effects of the systematic error from the DUT measurement. These standards may include precision short circuits, open circuits, 50 Ω terminations (loads), and through connections (typically referred to as S/O/L/T).

Factors contributing to random errors – which are generally of smaller magnitude than systematic errors – include instrument noise, switch repeatability, and connector repeatability. Instrument settings such as source power, averaging, and IF bandwidth often can reduce instrument noise and switch repeatability errors. Proper care and technique can lessen significantly connector repeatability errors.

Using an available four-port electronic calibration module further improves the accuracy and repeatability of these error corrections. This solid-state module replaces the mechanical S/O/L/T standards, and reduces the number of physical connections required for complete calibration.
The behavior of linear devices can be defined by one of two fundamental models, the state-variable model, or the wave model. There are various forms of the state-variable model, including $Z$-, $Y$-, and $H$-parameters. This model provides limited insight into the analog effects responsible for increasing bit-error-rate, EMI generation or susceptibility, and signal degradation.

At higher data rates, requiring the propagation of a fast leading edge, a transmitted/reflected wave model is more appropriate, and this is what the VNA-based system uses. The wave model (figure 2) relates the signal (incident) at any one terminal, to the signal transmitted to any other terminal, or reflected back onto itself.

When these signals are viewed in the time domain, we refer to this technique as TDR/TDT (time domain reflection/transmission) characterization. When the signals are viewed in the frequency domain, we refer to this approach as S-parameter characterization.

**Single-Ended S-Parameters**

S-parameters are typically organized in matrix form, where the columns represent the stimulus applied to a terminal, and the rows represent the response at the other terminals (transmission) or back into itself (reflection). Figure 3 shows an $S$-matrix for a four-port, single-ended device. The elements along the diagonal ($S_{11}$ through $S_{44}$) represent reflection terms, the elements below the diagonal are forward transmission terms, and the elements above the diagonal are reverse transmission terms.

These sixteen parameters fully characterize the frequency domain performance of the device, and are directly related to the time domain by linear transformation. An inverse Fast Fourier Transform (FFT) makes the conversion from the frequency-to-time domain. In the opposite direction, time-to-frequency domain, the standard FFT is used.
Differential S-Parameters

Balanced (differential) devices are commonly used for high-speed applications because of their many favorable performance characteristics. In general, a balanced pair can support two modes. In the intended (differential) mode of operation, the signals of each side of the pair are equal amplitude and opposite phase. In the unintended (common) mode of operation, signals are equal amplitude and in-phase. Any signal can be decomposed into a differential-mode component and a common-mode component.

A balanced two-port (four-terminal) device also is fully characterized with sixteen parameters, but the parameters include the operating mode in addition to the terminal of interest. The modes are organized in quadrants (DD, CD, DC, and CC, defined below). Each quadrant includes four parameters (reflection from port 1, reflection from port 2, transmission from port 1 to port 2, and transmission from port 2 to port 1).

- The DD Mode: Differential-mode stimulus, differential-mode response (shown in the upper-left quadrant of the balanced matrix, figure 4).
- The CC Mode: Common-mode stimulus, common-mode response (lower-right quadrant).
- The CD Mode: Differential-mode stimulus, common-mode response (lower-left quadrant). Provides insight into the potential for the device to generate EMI.
- The DC Mode: Common-mode stimulus, differential-mode response (upper-right quadrant). Provides insight into the potential for the device to be susceptible to EMI.

Again, these sixteen parameters comprehensively characterize a linear device with two balanced ports. It is important to note that this discussion is independent of the domain. These terms can be observed in both the time domain and the frequency domain.
DUT Fixturing Considerations

Instrumentation used for physical layer validation typically has some type of coaxial interface, an SMA connector for example. A high-speed DUT, however, likely will have any number of different connectors designed for a specific application. Interfacing the instrument to the DUT, therefore, requires a test fixture or other type of vehicle to achieve connectivity.

The ideal fixture would provide a transparent connection between the instrument and the DUT. It would allow direct measurement of the device without distorting the data. In terms of performance characteristics, this means it would be lossless, have a linear phase shift with frequency, have no impedance mismatch, and provide infinite isolation between terminals.

A fixture for high-speed component characterization (<200 pS transition time) must be carefully designed. The components and medium that are used, how transitions are done, and the interface type all need to be characterized over the operating bandwidth. A vector network analyzer readily assesses these factors.

Since it is impossible to make an ideal fixture, a practical approach is to develop the best possible fixture, and then account for its effects. Good fixture design, combined with de-embedding or direct calibration techniques, can provide very accurate results.

Removal of Fixture Effects

There are three fundamental techniques for removing errors introduced by a fixture: modeling, de-embedding, and direct measurement. They vary in their relative accuracy, and also in their complexity. The best choice will depend on the specifications of the DUT being measured and the required degree of accuracy.

- **Modeling** uses mathematical corrections derived from an accurate model of the fixture, and therefore requires some knowledge of the fixture characteristics. The simplest example of this is a port reference plane extension (or rotation) feature. The instrument calibration establishes the reference plane at the junction of the test port cables. The fixture then is connected to the test port cables and the reference plane is adjusted mathematically to a point at the other side of the test fixture. The only knowledge required of the fixture is its delay. If the fixture has low insertion loss and good impedance matches, this technique may be sufficient. Of course, the overall measurement accuracy will depend on the accuracy of the model. Often developing a precise model is more difficult than using the other methods.

- **De-embedding** is the process of mathematically removing all of the linear effects of a test fixture from a measurement. It requires either an accurate linear model or measured S-parameter data of the fixture. In contrast to normalization, which adjusts only the magnitude of the transmission, this technique considers eight parameters, including magnitude and phase responses in transmission and reflection. Agilent Application Note 1364-1, “De-embedding and Embedding S-Parameter Networks Using a Vector Network Analyzer,” describes this technique more thoroughly.

- **Direct measurement** involves measuring physical calibration standards and calculating error terms. This places the reference plane directly at the DUT, eliminating the effects of the test fixture. An example of this approach is using controlled impedance (RF) probes with printed short-open-load-through calibration standards.
Example of Undesired Fixture Effects

Figure 5 shows an example of a typical PCB fixture provided by manufacturers of high-speed components. Specifically, this fixture is used to connect an InfiniBand 1x cable to measurement instrumentation. The fixture construction consists of microstrip transmission lines printed on FR4 board material, with signals launched using through-hole SMA and InfiniBand connectors.

The plot above the test fixture in figure 5 shows the TDR response of the device. The data shows a large impedance mismatch at the test fixture input. The time delay indicates that the physical connection of the SMA connector to the printed circuit board is causing the mismatch. This induces a serious discontinuity and masks the true performance of the remaining circuit (see “Dynamic Range” above for more information about masking). In other words, the fixturing required to make the measurement diminishes the ability to characterize the DUT accurately. This fixture-induced mismatch error has real implications on the characterization of the DUT, and can be further illustrated. Using the same fixture, a 100 pS transition time is applied to the device (as required by the InfiniBand specification).

Figure 5. A poorly designed test fixture can induce mismatch errors and significantly degrade the quality of the measurement.
Shown in figure 6 is the step response of the fixture with the 100 pS transition time applied. The response includes the SMA connector and transmission line of the fixture, leading up to but not including the DUT (the high-speed 1x connector). Due to the test fixture problems, the step response has been degraded from 100 to 160 pS, and ringing has been introduced, before ever reaching the DUT.

Proper fixture design can improve or eliminate these problem areas. Figure 7 shows the same step response for a fixture that has been carefully designed for high-speed applications. Note the sharpness of the transitions, the elimination of the SMA connector discontinuities, the lack of overshoot and ringing, and the improvement of the transition time (120 pS vs. 160 pS). These improvements reduce masking effects, and provide a more accurate signal to the DUT.

Fixture design plays an important role in accurate characterization of high-speed devices. In design and layout of the fixture, careful consideration has to be taken with the connector type, connector launch, transitions, and the medium used to transition into the high-speed connector.

![Figure 6](image1.png)  ![Figure 7](image2.png)

Figure 6. A poorly designed test fixture hides the true performance of the DUT.  
Figure 7. An improved test fixture design eliminates fixture-induced errors.
Measurement Examples

VNA-based systems, operating in the frequency domain and seamlessly transforming data into the time domain, can provide tremendous insight into device performance. The InfiniBand specification demonstrates this point, since it requires both types of measurement.

Frequency domain parameters can be divided into one of two types: transmission or reflection. Loss and crosstalk are examples of transmission measurements. These measurements are similar, except that “loss” is measured on a DUT path that is supposed to be a through connection, and “crosstalk” is made on a path that is supposed to be isolated. Both measurements are equal to the $S_{21}$ parameter (or $S_{DD21}$ in the case of a differential signal) and typically are expressed in logarithmic terms (dB).

An example is shown here. The differential-mode forward transmission ($S_{DD21}$) of a balanced line is measured as insertion loss (figure 8). If the receiver is connected to an adjacent balanced line, the amount of coupled energy present can be measured as crosstalk (figure 9).

Figure 8. Differential-mode forward transmission is seen as insertion loss.

Figure 9. Crosstalk is the energy present on an adjacent (non-selected) line.
Measurement Examples (continued)

Return loss, VSWR, and impedance are all derived from the reflection data. In figure 10, reflection at the device input is measured as return loss expressed in dB.

VSWR, the ratio of transmitted power to reflected power, is calculated as shown in the equation above the plot in figure 11.

\[
\text{VSWR}_{\text{differential, port}} = \frac{1 + |\theta_{DD1}|}{1 - |\theta_{DD1}|}
\]

Figure 10. Differential input reflection measured as return loss.

Figure 11. Differential input reflection expressed as VSWR.
Similarly, impedance is related to the reflection parameter according to the relationship shown in the equation above the plot in figure 12. Note that the impedance is a complex number, so it can be examined in terms of its real, imaginary, magnitude, or phase components.

The time-domain impulse response is determined from the frequency domain data by performing an inverse Fast Fourier Transform. A chirp-z algorithm accomplishes a numerically efficient implementation of a discrete transform. This can be applied to both transmission and reflection parameters.

There are several methods of determining the step response from the impulse response, such as integrating the impulse response, or convolving the impulse response with a step function. The step response of a reflection parameter provides the impedance profile as seen in figure 13 (provided the vertical axis is converted from a reflection parameter to an impedance).

$$Z_{\text{differential\ input}} = 20 \log_{10} \frac{1 + |S_{\text{DD1}}|}{1 - |S_{\text{DD1}}|}$$

Figure 12. Differential input impedance.

Figure 13. Differential impedance profile.
Measurement Examples (continued)

The impulse response of a transmission parameter can be convolved with any arbitrary input waveform to determine its corresponding output waveform (bottom of figure 14). From this, an eye diagram can be constructed, and the resulting deterministic jitter can be measured (top of figure 14). This method clearly shows the difference between the jitter of an uncompensated cable (figure 14) and that of a compensated cable (figure 15). The compensation network acts by filtering the response of the DUT so that the frequency spectral content is in the correct proportions. Typically, an uncompensated device will attenuate the high frequency components more than the lower frequency components. In this case, the compensation network will attenuate the lower frequency components and pass the high frequencies, thereby restoring the original relationship of the low frequency to the high frequency components. The net result will be an eye diagram with less jitter and a better-defined opening, but lower overall amplitude.

**Figure 14. Input and output waveforms and eye diagram.**

**Figure 15. Compensated input and output waveforms and eye diagram.**

**Conclusion**

The VNA-based system performs a complete characterization in a single set of connections, and provides the user with a number of data formatting options. Error correction provides enhanced accuracy, and high dynamic range helps identify and correct EMI and BER problems. The system also can analyze the effects of phase skew, de-embed fixtures and probes, and allow for alternate reference impedances.

The comprehensiveness and flexibility of this system combine the best capabilities of existing solutions, and provide new insight for high-speed physical layer test.
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