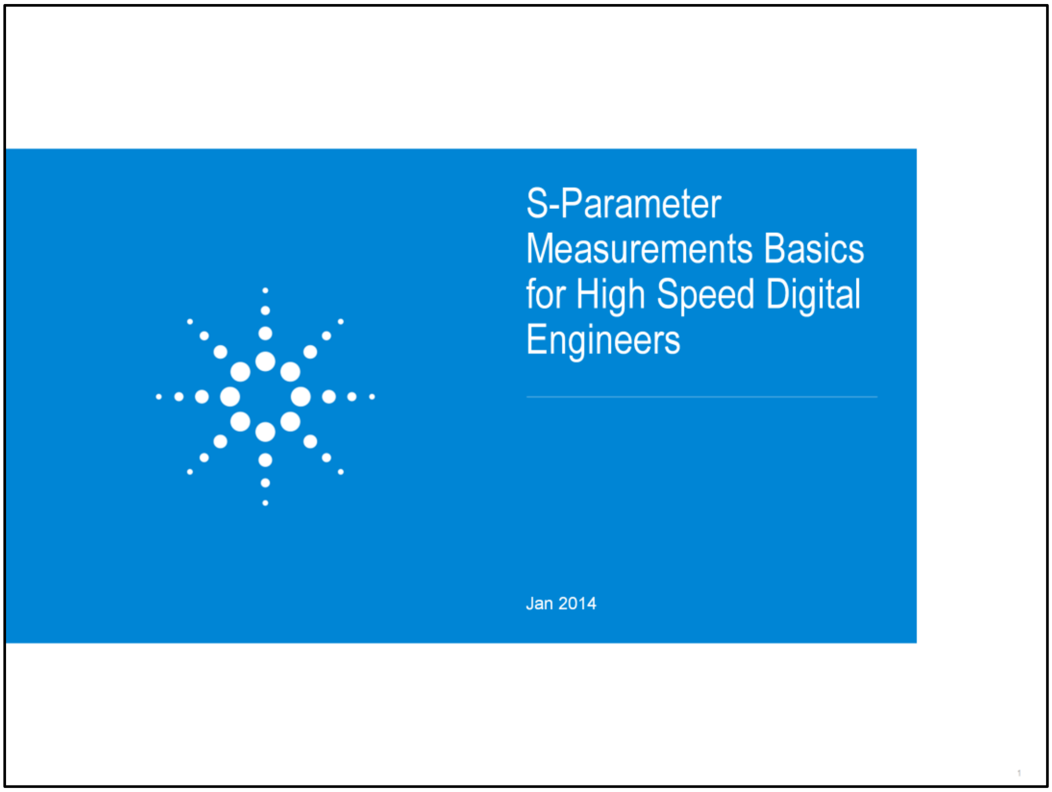
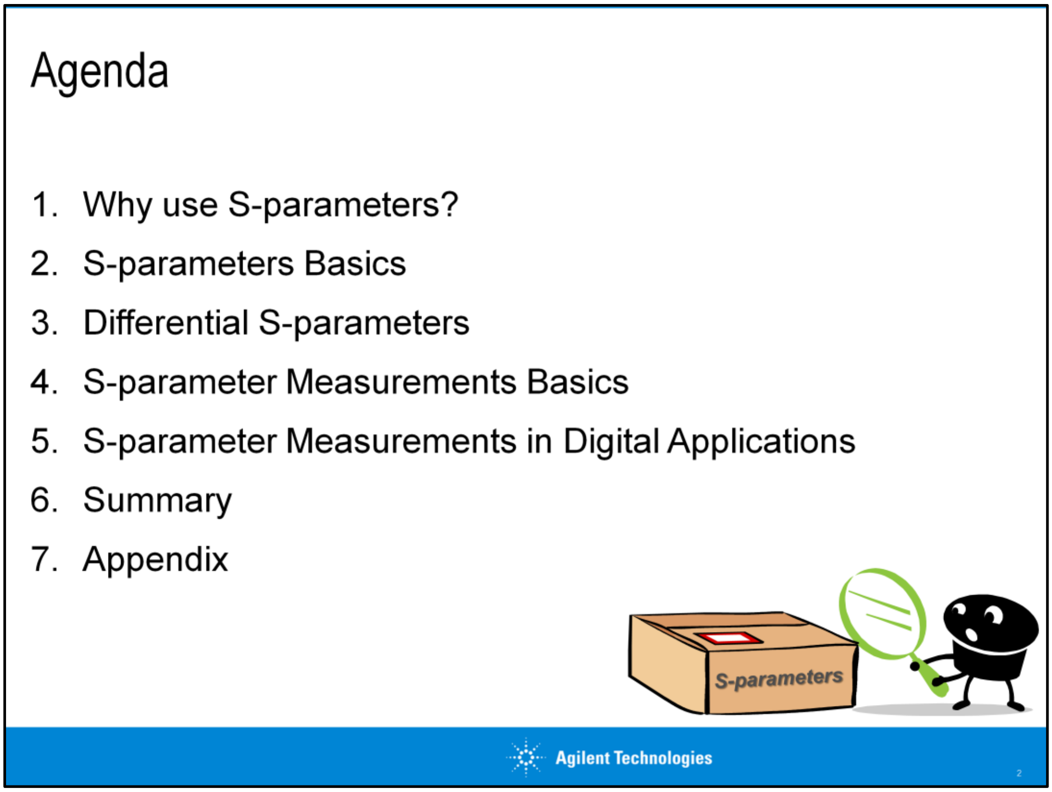
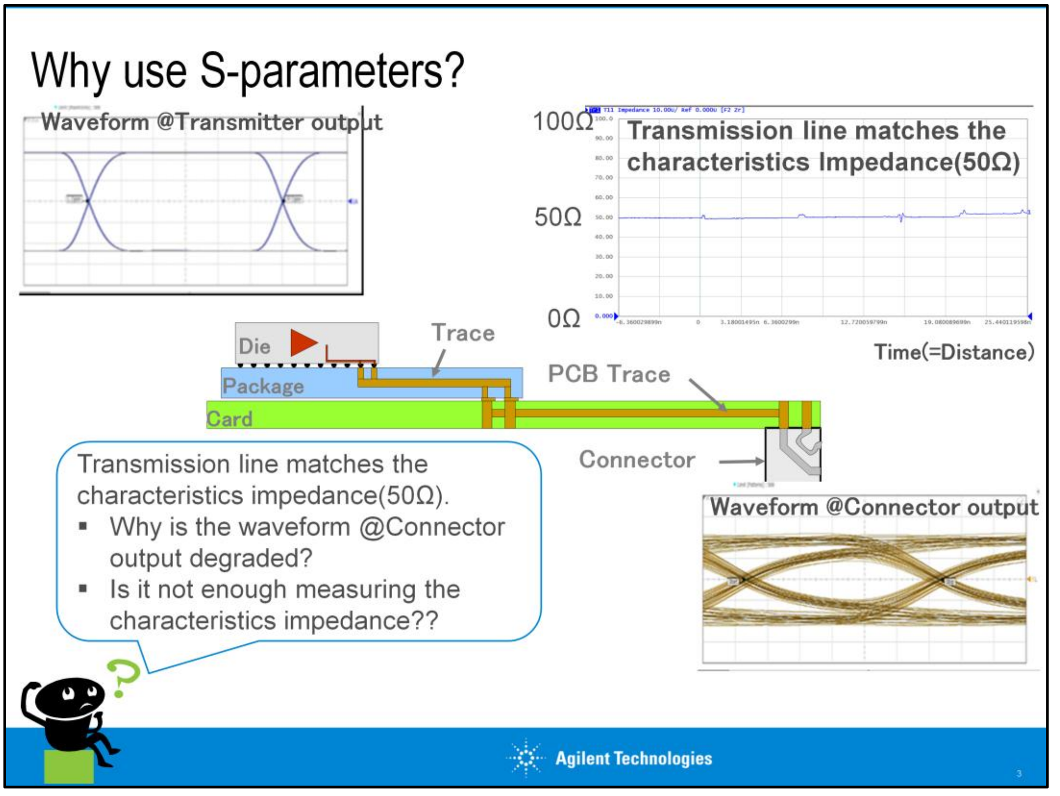


S-Parameter Measurements Basics for High Speed Digital Engineers

Frequency dependent effects are becoming more prominent with the increasing data rates of digital systems. Differential circuit topology is commonly-used implementation method with the goal of enhancing the data carrying capable of the physical layer. Simple impedance and delay measurements of copper transmission lines are not sufficient to ensure accurate analysis of gigabit interconnects. The challenge to push design rules to the limit now requires the use of concurrent time and frequency domain measurements.

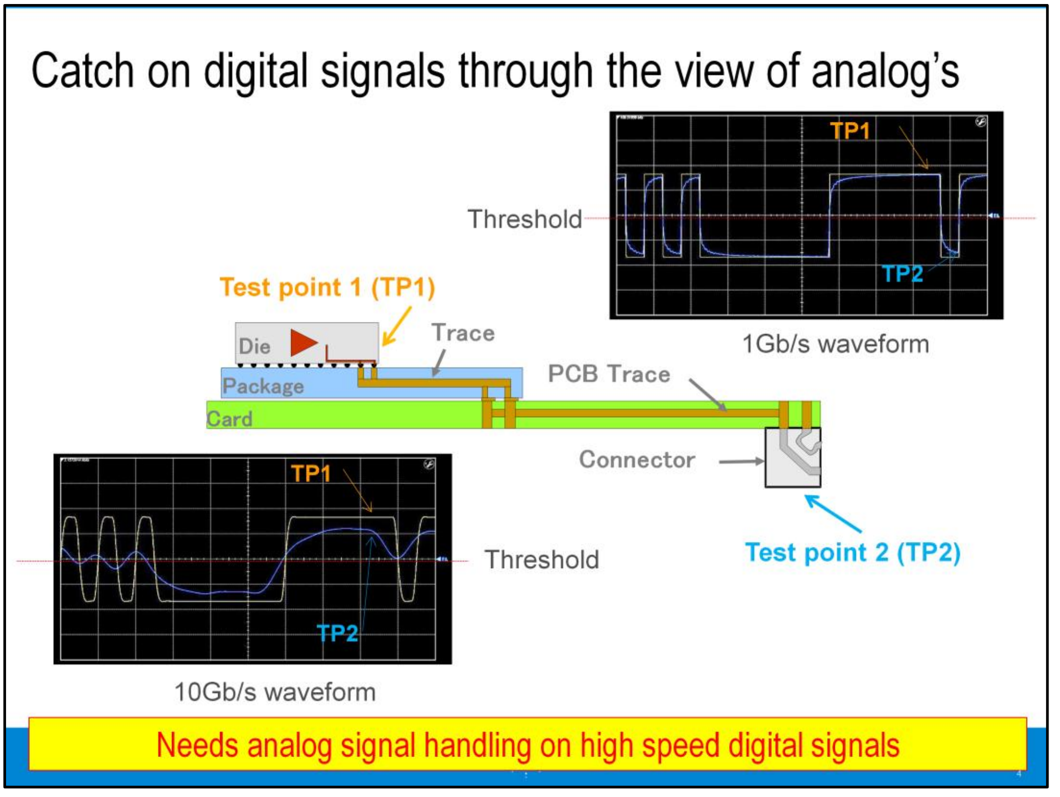


This presentation covers the basics of S-parameters and their measurements for high speed digital engineers. Readers will learn why use, and how to use and handle S-parameters. The session starts with S-parameter fundamentals and takes you through the concepts of reflection, transmission and S-parameters with typical nomenclature. This presentation will cover Differential S-parameters (e.g., Differential insertion loss) which represents characteristics of differential circuit topology used in high speed digital applications.
An appendix is also included with information on ENA Option TDR, VNA based TDR measurement instrument, broadly recognized and used in high speed digital industry and standards (e.g., USB, HDMI, SATA, DisplayPort, MIPI D-PHY/M-PHY, Ethernet, MHL, PCIe, Thunderbolt, BroadRReach, …).

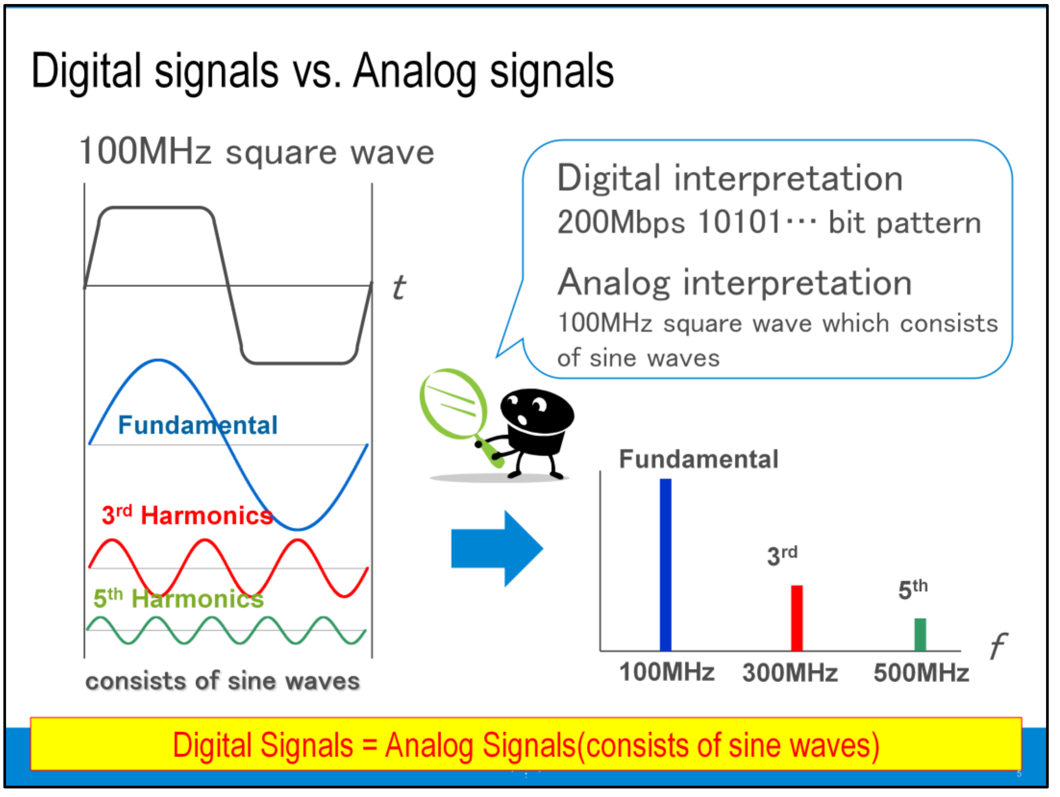


Why use S-parameters?

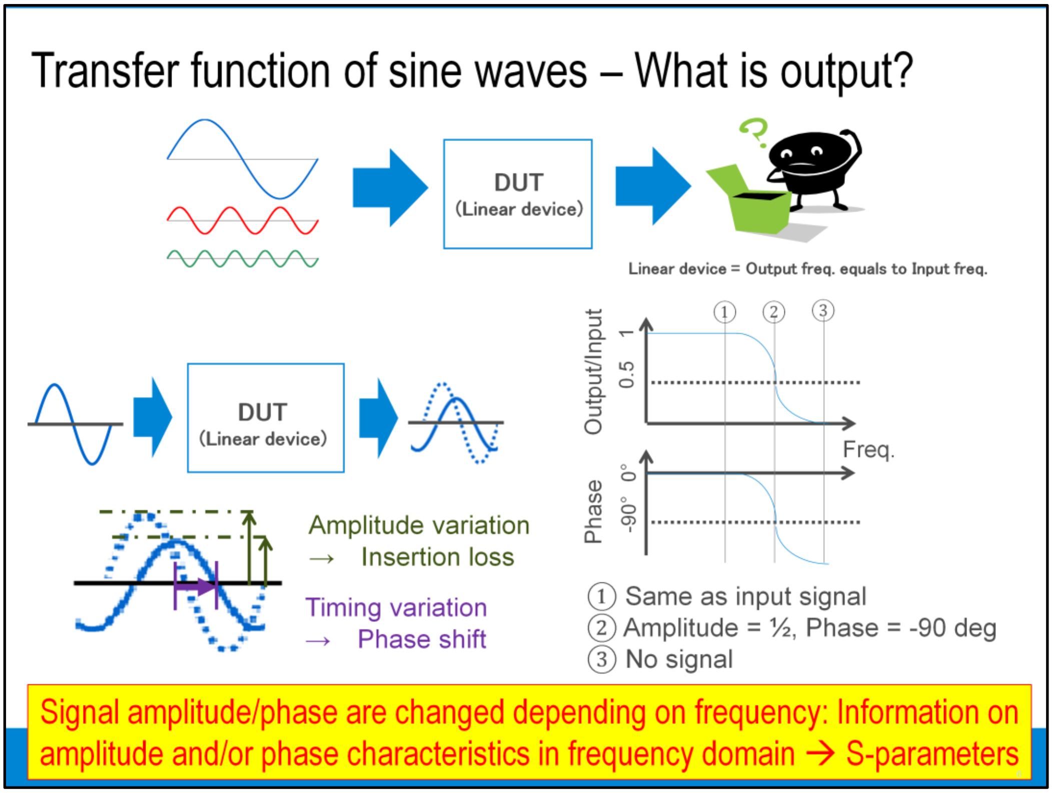
This is a sample of typical transmitter device consists of chip, package, and card. A channel (transmission lines/traces) match the characteristics impedance(50Ω as shown in the top-right figure). However, the output signal/waveform at the output connector (bottom-right eye diagram) is degraded/distorted compared to the input signal/waveform (top-left eye diagram). Why is the waveform @Connector output degraded? Is it not enough measuring the characteristics impedance?



Catch on digital signals through the view of analog's
Comparing waveforms before and after transmitting the channel for 1Gbps and 10Gbps, the 10Gbps waveform is dramatically distorted. It's far from an ideal digital signal. The higher the bitrate, the more we need to observe/manage the digital signal same as analog signal.



Digital signals vs. Analog signals
Let's see 100MHz square wave for instance. With digital interpretation, it's a 10101… 200Mbps bit pattern. On the other hand, with analog interpretation, it's a composite(synthesized) waveform consisting of sine waves, 100MHz fundamental and harmonics.

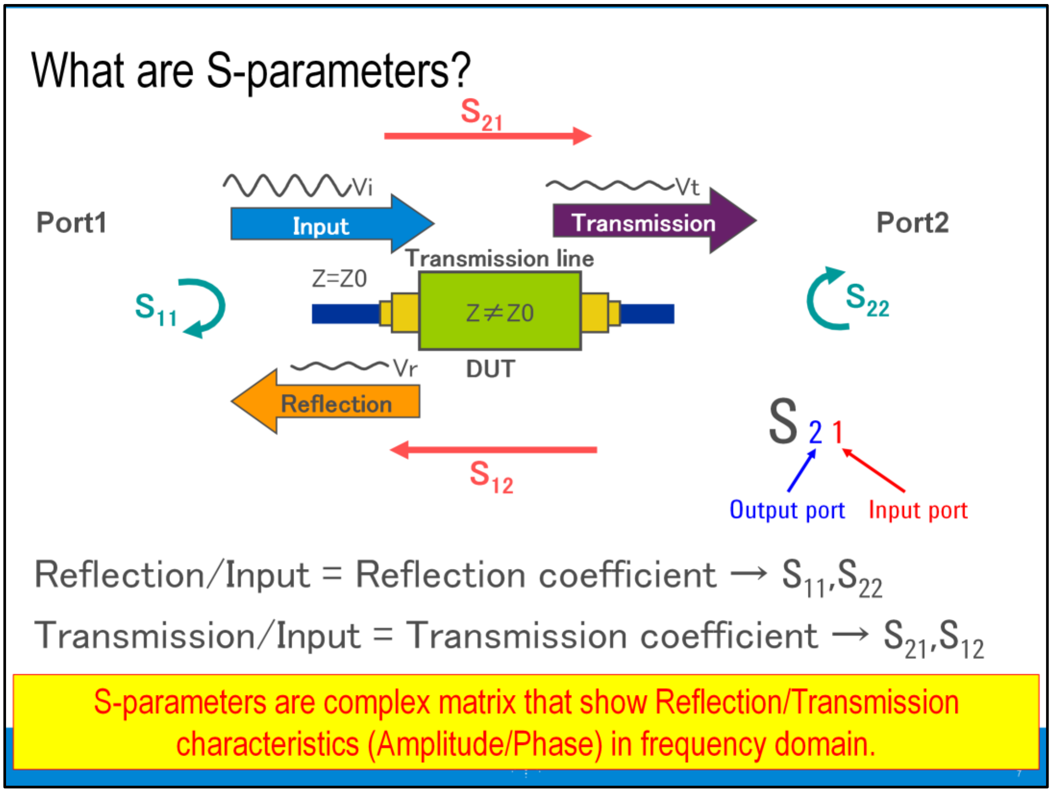


Transfer function of sine waves – What is output?

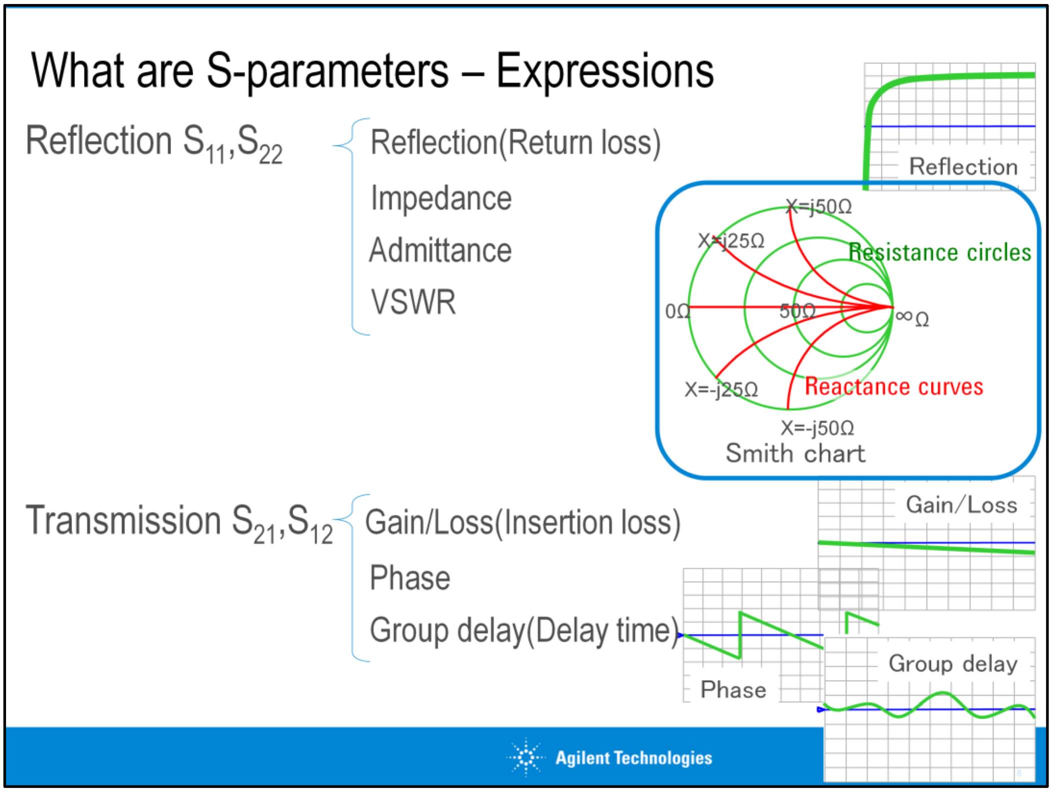
Devices that behave linearly only impose magnitude and phase changes on input signals. Any sinusoid appearing at the input will also appear at the output at the same frequency. No new signals are created.

This is an example of a sine wave applied to a linear device which has a characteristics shown in mid-right figures, Output/Input and Phase. The device imposes a non-uniform amplitude and phase change to each frequency component. At the frequency point 1, we can see the output signal same as the input signal (dotted line in the bottom-left figure). At 2, amplitude is decreased as half and phase is delayed as -90 degree (solid line in the bottom-left figure). At 3, no signal can be detected from output.

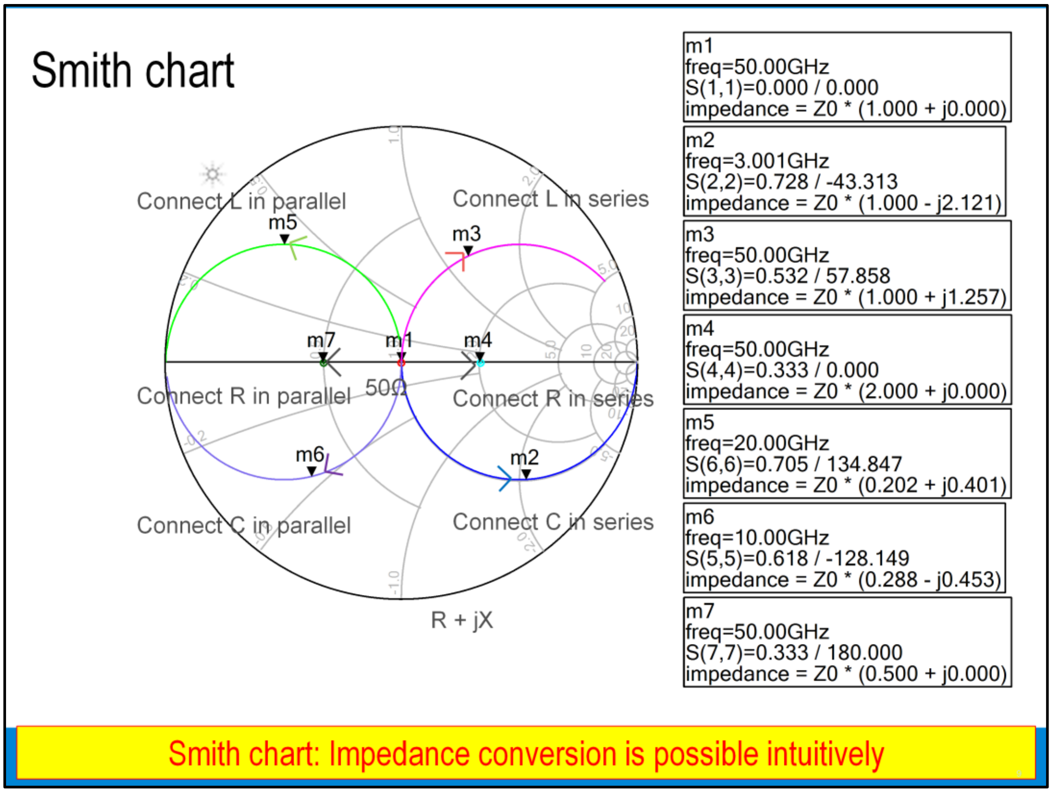
When a single sinusoid is passed through a linear network, we don’t consider amplitude and phase changes as distortion. However, when a complex, time-varying signal is passed through a linear network, the amplitude and phase shifts can dramatically distort the time-domain waveform. Therefore both amplitude and phase information in frequency domain are important. Then, S-parameters is the parameter which supports both information and has many advantages for high frequency device characterization.



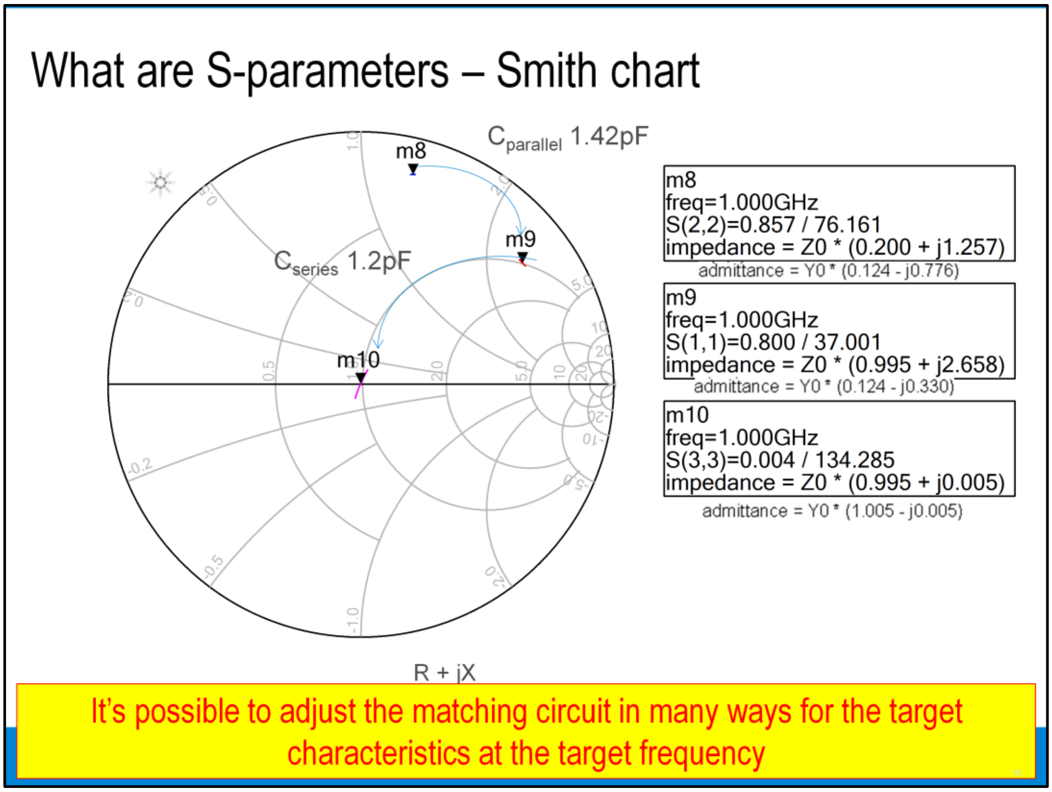
What are S-parameters?
S-parameters are complex matrix that show Reflection/Transmission characteristics(Amplitude/Phase) in frequency domain.
Two-port device has four S-parameters. The numbering convention for S-parameters is that the first number following the “S” is the port where the signal emerges, and the second number is the port where the signal is applied. So S21 is a measure of the signal coming out port 2 relative to the RF stimulus entering port 1. When the numbers are the same (e.g., S11), in indicates a reflection measurement, as the input and output ports are the same.



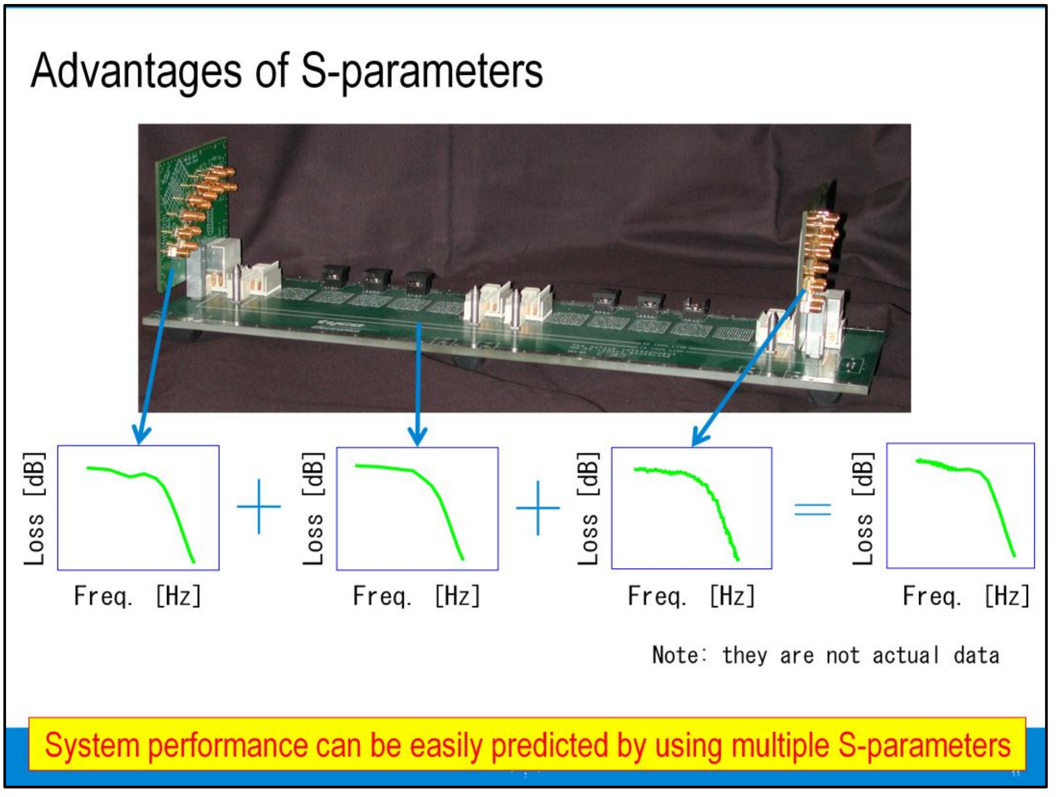
What are S-parameters – Expressions
With amplitude and phase information, we can quantify the reflection and transmission characteristics of devices. Some of the common measured terms are scalar in nature (the phase part is ignored or not measured), while others are vector (both magnitude and phase are measured). For example, return loss is a scalar measurement of reflection, while impedance results from a vector reflection measurement. Some, like group delay, are purely phase-related measurements.
Reflection, S11/S22: Reflections(Return loss), Impedance, Admittance, VSWR. Smith chart is one of display methods for complex reflection coefficient.
Transmission, S21/S12: Gain/Loss(Insertion loss), Phase, Group delay(Delay time).



What are S-parameters – Smith chart.
Smith chart maps rectilinear impedance plane onto polar plane. On the Smith chart, the vertical lines on the rectilinear plane that indicate values of constant resistance map to circles, and the horizontal lines that indicate values of constant reactance map to arcs. Zo maps to the exact center of the chart. It's useful for evaluation of impedance matching network.

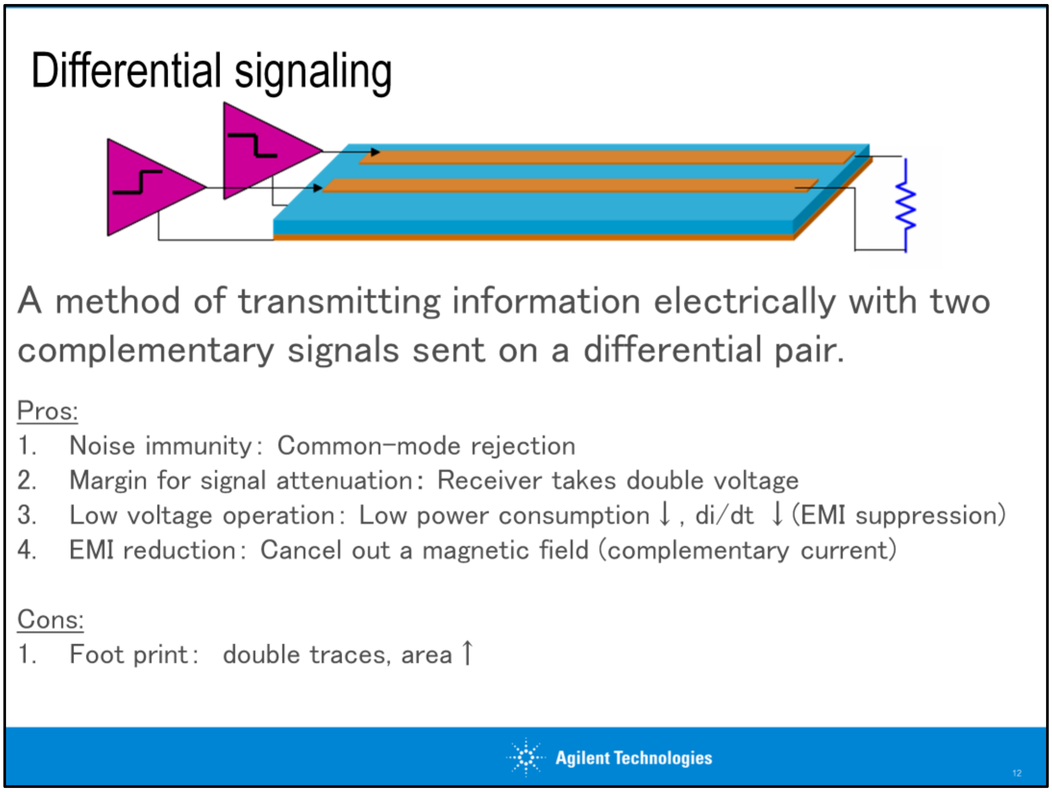


Let's see an example of matching circuit design. Marker 8 (m8) shows the reflection (impedance) of a device without a matching circuit and the place of marker 10 (m10) is the target (system impedance: Z0). If the matching circuit consists of 1.42 pF in parallel, and 1.2 pF in series, then reflection characteristic matches Z0. It's not a sole way to meet the target characteristic at the target frequency.



Advantages of S-parameters

The measured S-parameters of multiple devices can be cascaded to predict overall system performance.



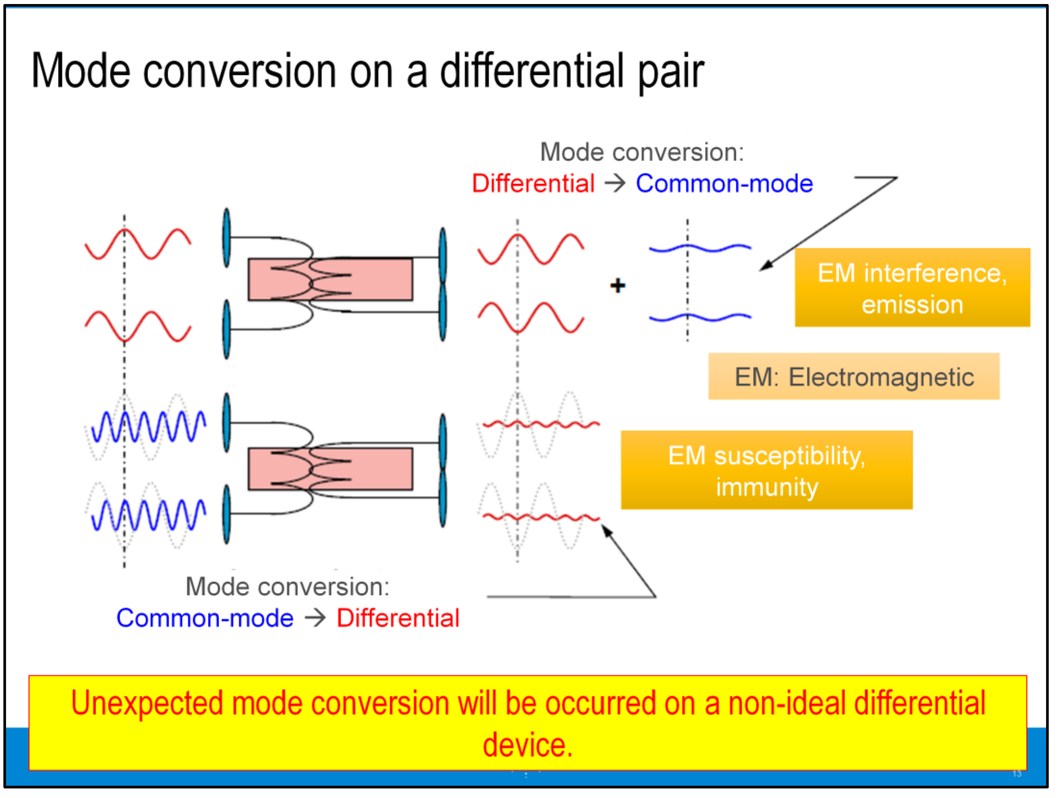
In today's high speed digital applications, differential signaling (differential circuit topology) is widely and commonly used. Let's review pros and cons of differential signaling.

Pros:

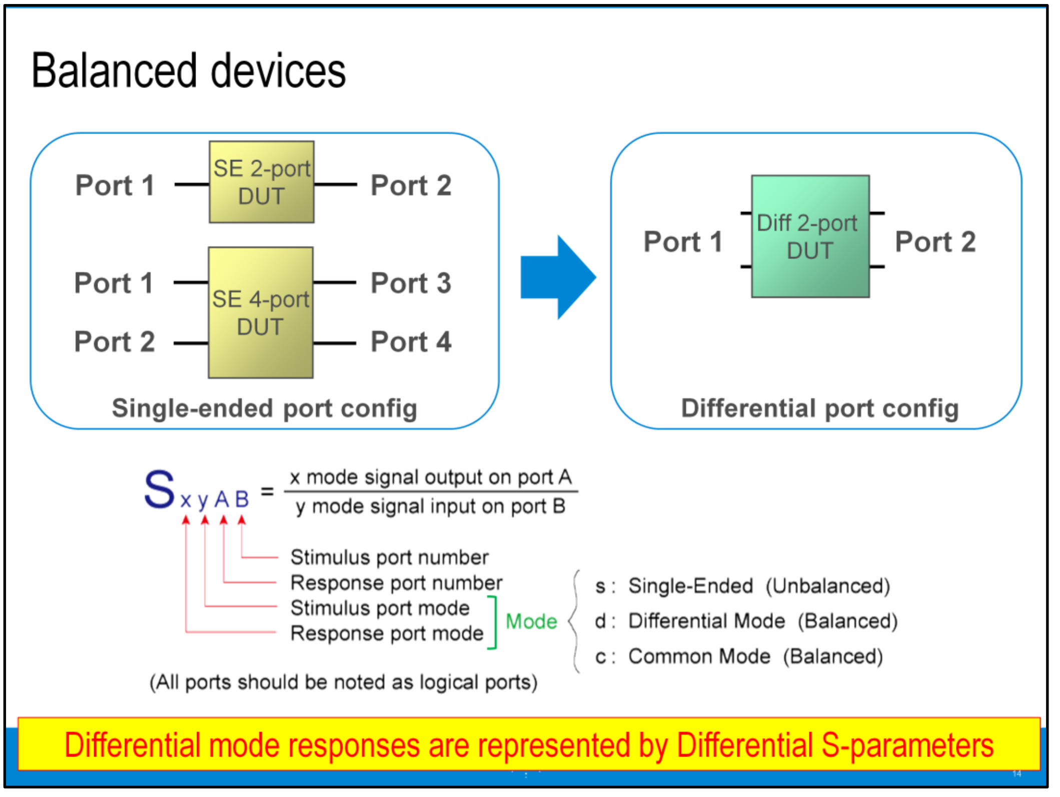
1. High noise immunity : Common-mode rejection
2. High margin for signal attenuation : Receiver takes double voltage
3. Low voltage operation : Low power consumption, low di/dt (EMI suppression)
4. Low EMI : Cancel out a magnetic field (complementary current)

Cons:

1. Large foot print : double traces, more area needed

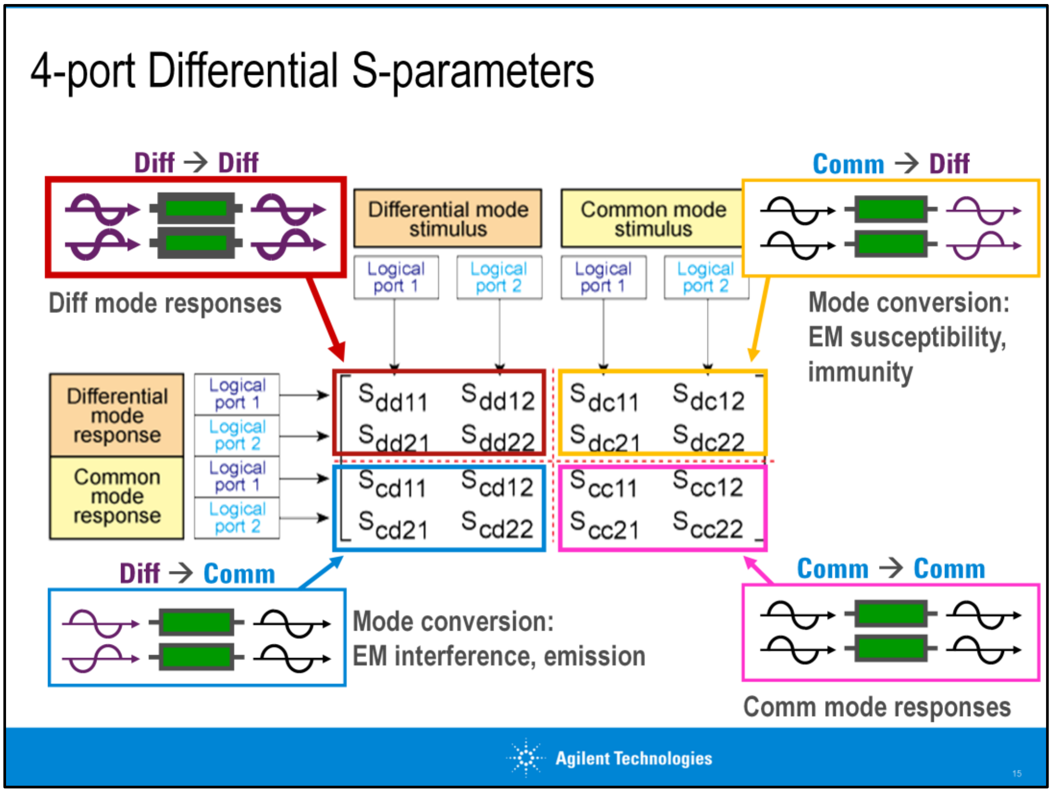


Mode conversion on a differential pair
Non-ideal differential transmission lines, however, do not exhibit benefits(pros) described in the previous slide. A differential transmission line with even a small amount of asymmetry will produce a common signal that propagates through the device. This asymmetry can be caused by any physical feature that is on one line of the differential pair and not the other line, including solder pads, jags, bends and digs. This mode conversion is a source of EM interference (emission/radiation). Most new product development must pass the EMC compliance testing near the end of the design cycle. Very often the test results show that the design exhibits EM interference or susceptibility (immunity). However, there is usually very little insight as to what physical characteristic is causing the problem. Mode conversion analysis provides the designer with that insight so that EM problems can be resolved earlier in the design stage.

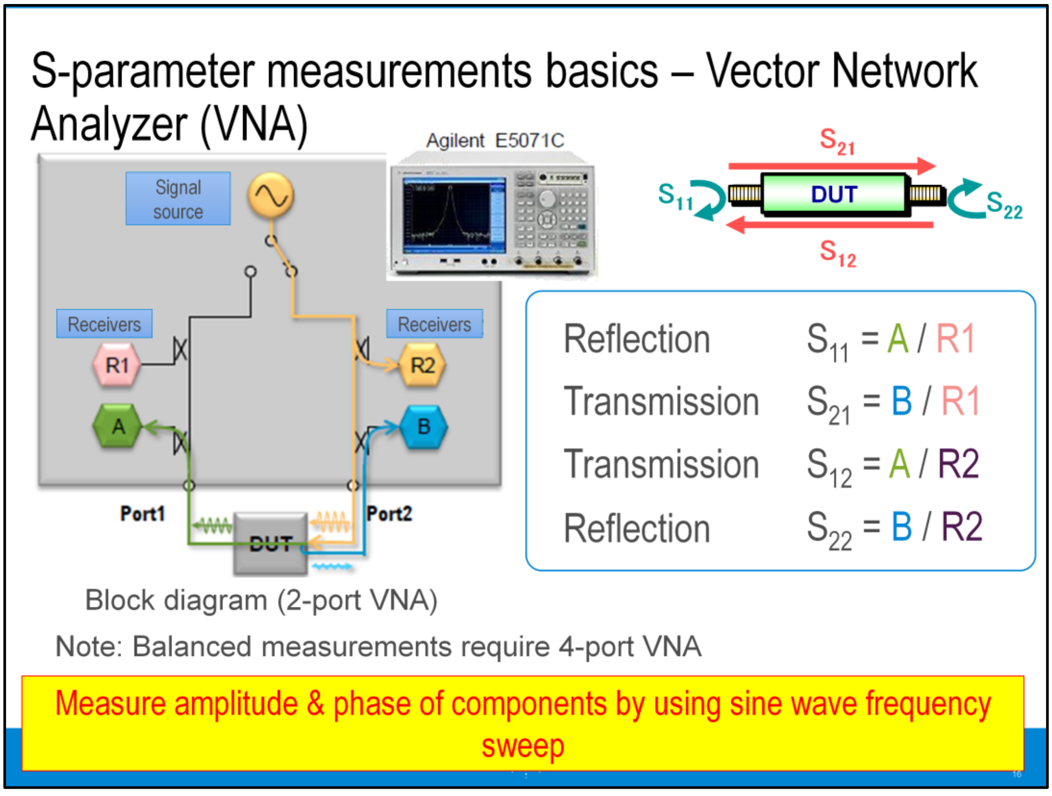


Standard Single-ended devices generally have one input port and one output port. Signals on the input and output ports are referenced to ground. On the other hand, balanced devices have two pins on either the input, the output, or both. The signal of interest is the difference and average of the two input or output lines, not referenced to ground.

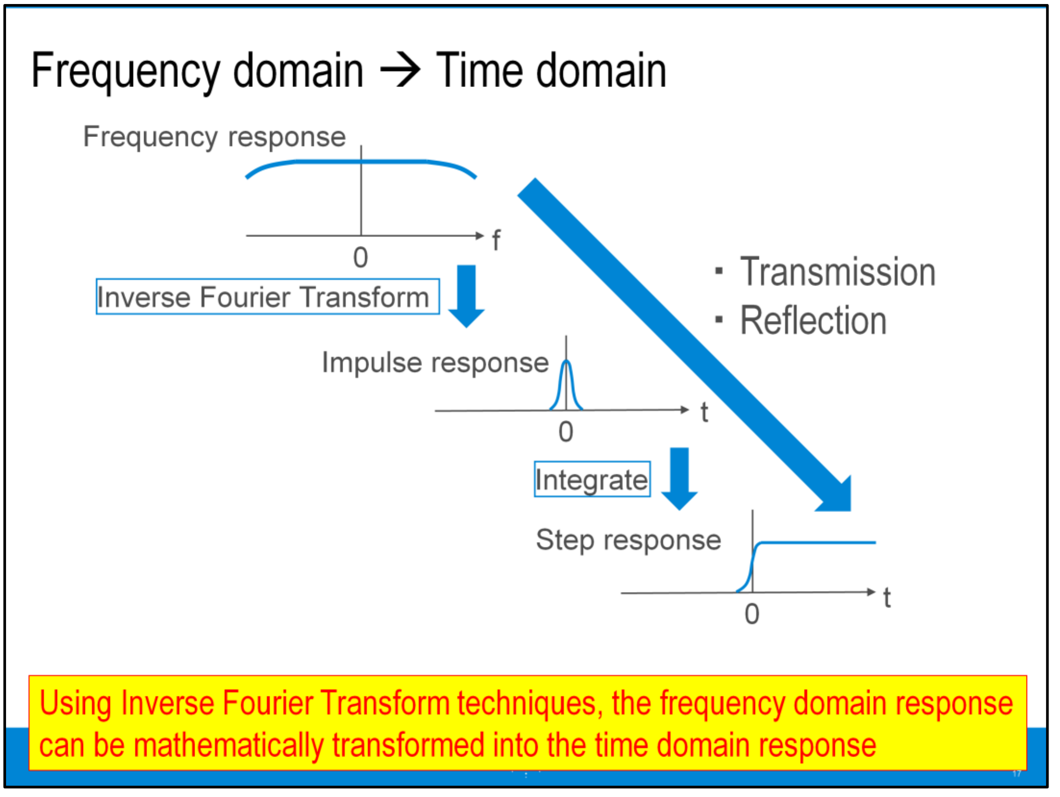
Differential mode responses can be obtained by balanced measurements, and are represented by Differential S-parameters. The format of the parameter notation "Sxyab", where "S" stands for S-parameter, "x" is the response mode (differential or common), "y" is the stimulus mode (differential or common), "a" is the response port number and "b" is the stimulus port number. This is typical nomenclature for frequency domain S-parameters.



The sixteen S-parameters that are obtained by fully characterizing a differential interconnect can be categorized into 4 stimulus/response quadrants.
In order to interpret the large amount of data in the differential parameter matrix, it is helpful to analyze one quadrant at a time. The first quadrant is defined as the upper left 4 parameters describing the differential stimulus and differential response characteristics of the device under test. This is the actual mode of operation for most high-speed differential interconnects, so it is typically the most useful quadrant that is analyzed first. It includes input differential return loss (Sdd11), input differential insertion loss (Sdd21), output differential return loss (Sdd22) and output differential insertion loss (Sdd12).
The second and third quadrants are the upper right and lower left 4 parameters, respectively. These are also referred to as the Differential quadrants. This is because they fully characterize any mode conversion occurring in the device under test, whether it is common-to-differential conversion (EMI susceptibility, immunity) or differential-to-common conversion (EMI interference, emission/radiation). Understanding the magnitude and location of mode conversion is very helpful when trying to optimize the design of interconnects for gigabit data throughput.
The fourth quadrant is the lower right 4 parameters and describes the performance characteristics of the common signal propagating through the device under test. If the device is design properly, there should be minimal mode conversion and the fourth quadrant data is of little concern. However, if any mode conversion is present due to design flaws, then the fourth quadrant will describe how this common signal behaves.

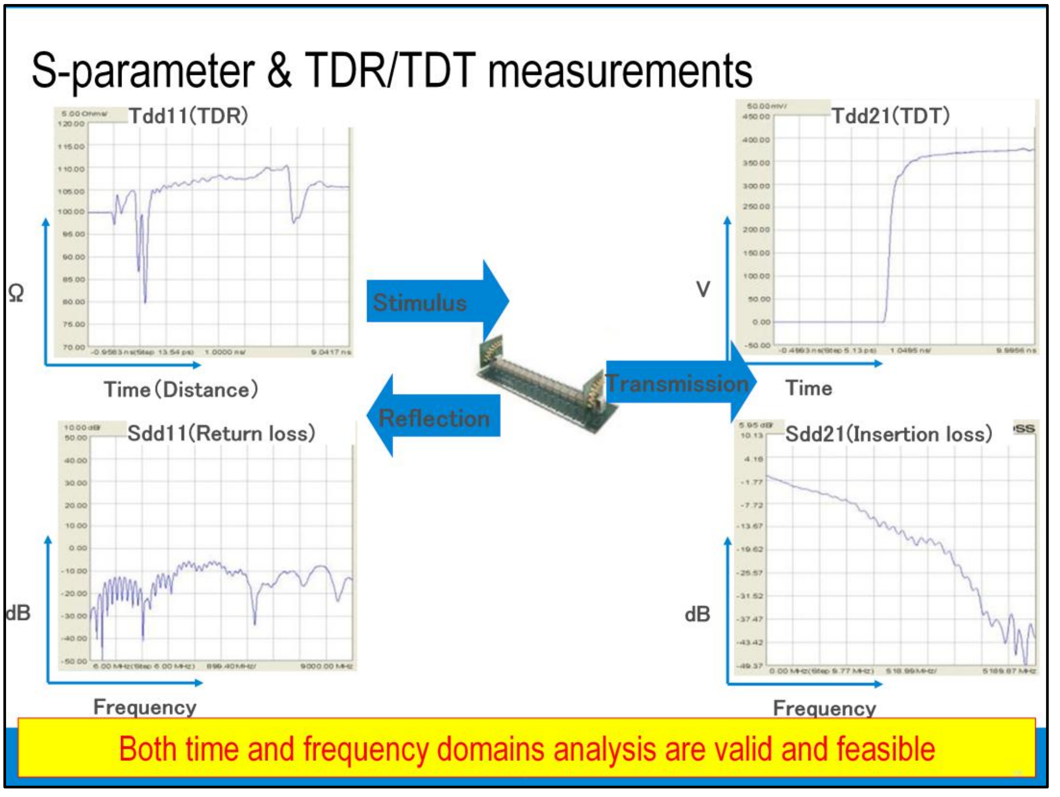


For two-port VNA (e.g., Agilent E5071C ENA Series Network Analyzer), S-parameters can be obtained with four receivers: R1, R2, A, and B.
S11 (=A/R1) and S21 (=B/R1) are determined by measuring the magnitude and phase of the incident (R1), reflected (A) and transmitted (B) voltage signals when the output is terminated in a perfect Zo (a load that equals the characteristic impedance of the test system). This condition guarantees that R2 is zero, since there is no reflection from an ideal load. S11 is equivalent to the input complex reflection coefficient or impedance of the DUT, and S21 is the forward complex transmission coefficient. Likewise, by placing the source at port 2 and terminating port 1 in a perfect load (making R1 zero), S22 (=B/R2) and S12 (=A/R2) measurements can be made. S22 is equivalent to the output complex reflection coefficient or output impedance of the DUT, and S12 is the reverse complex transmission coefficient.
Note that 4-port VNA is required for fully characterizing a 2-port differential device.

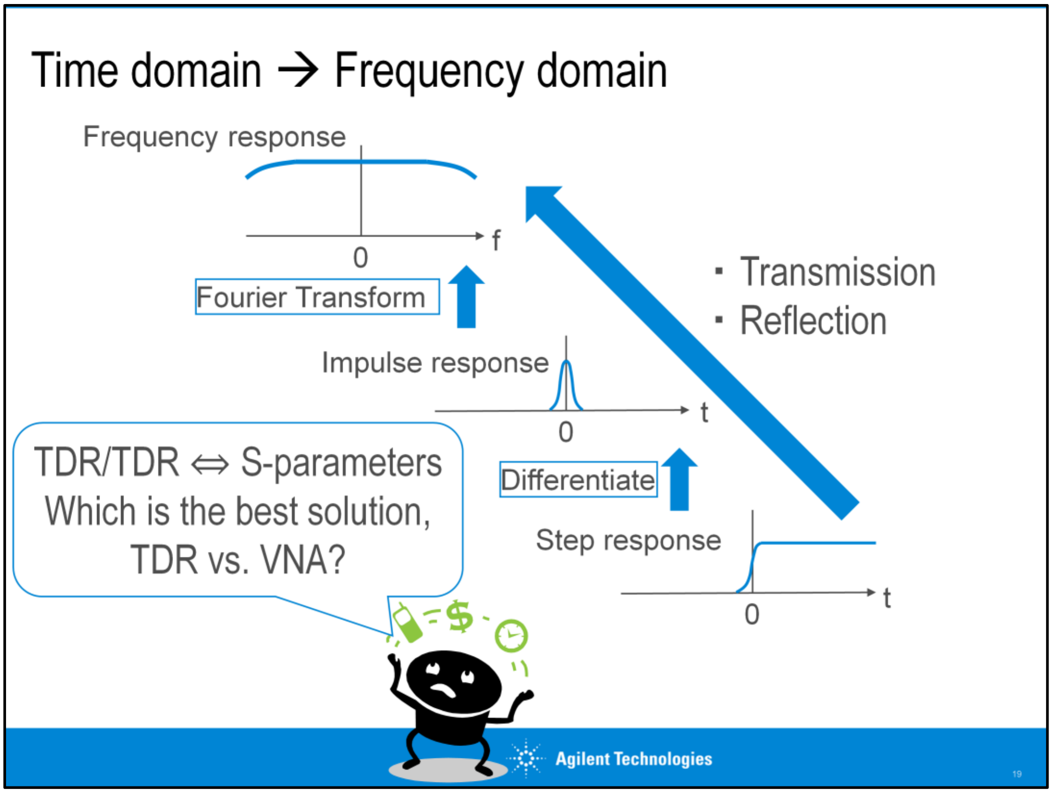


S-parameters (frequency response) can be transformed into the time domain parameters (impulse response → step response) by performing an inverse fourier transform (IFT).

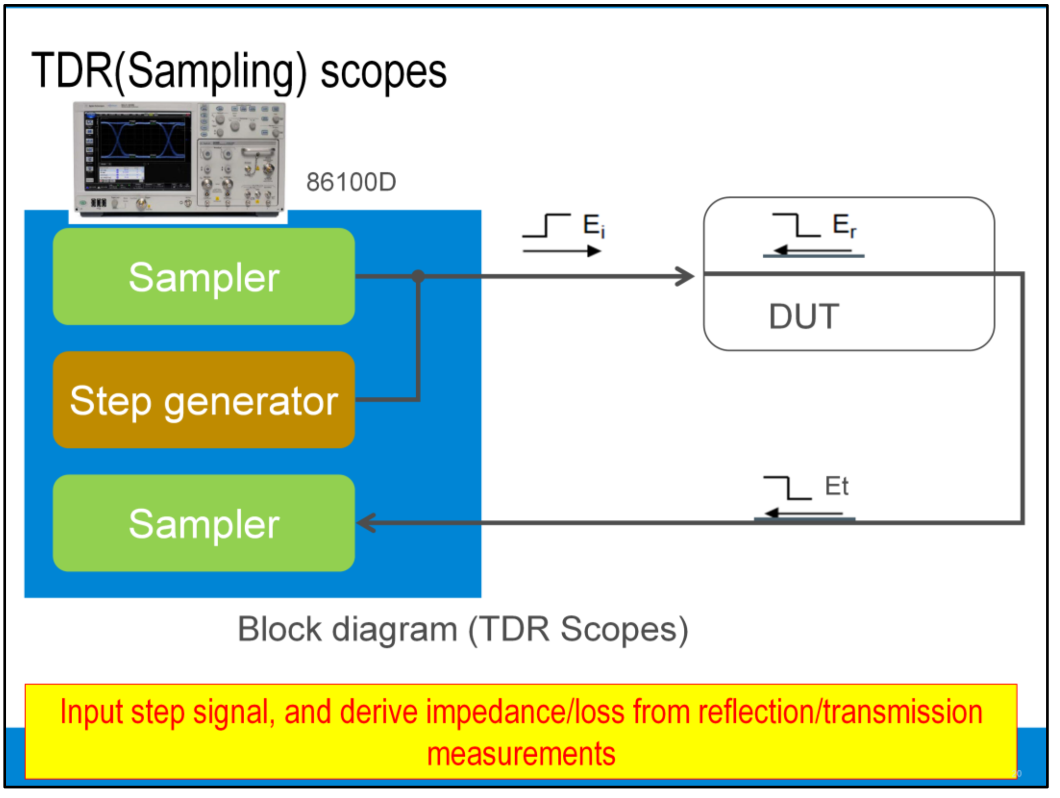
The matrix representing the time domain will have similar notation, except the "S" is replaced by a "T" (i.e. Tdd11).



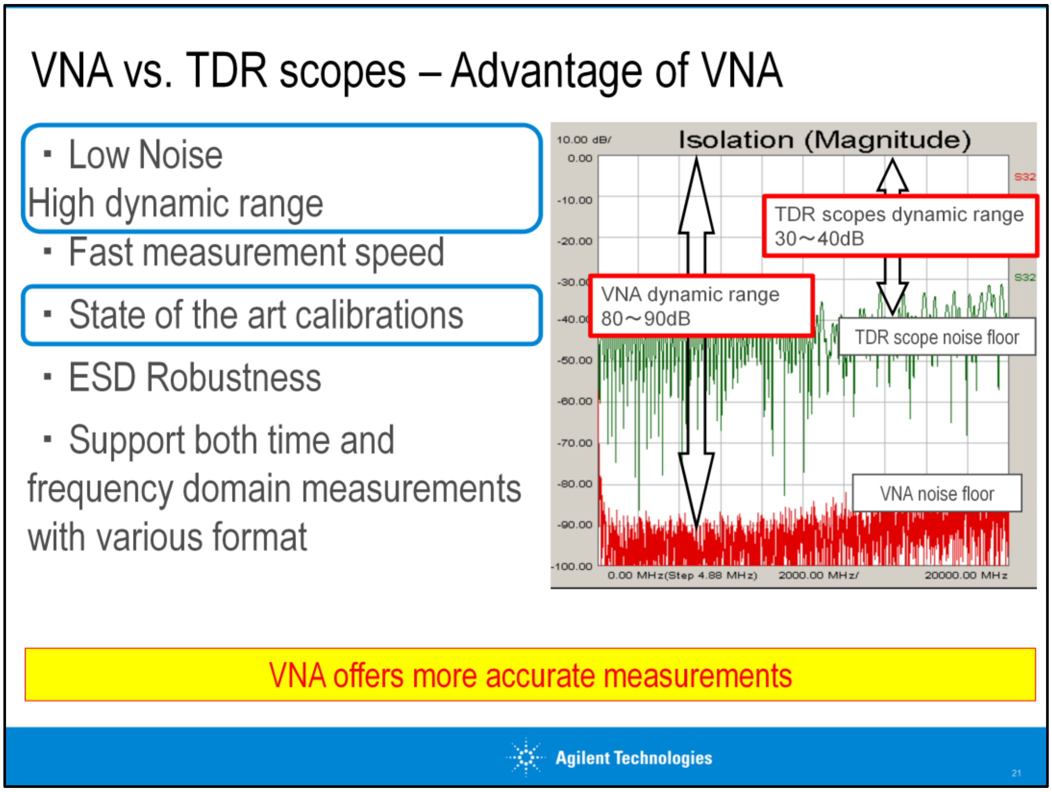
Both time and frequency domain data help us understand device characteristics. Just four differential parameters are shown in this slide, but other parameters like mode conversions are often required to evaluate a device thoroughly.



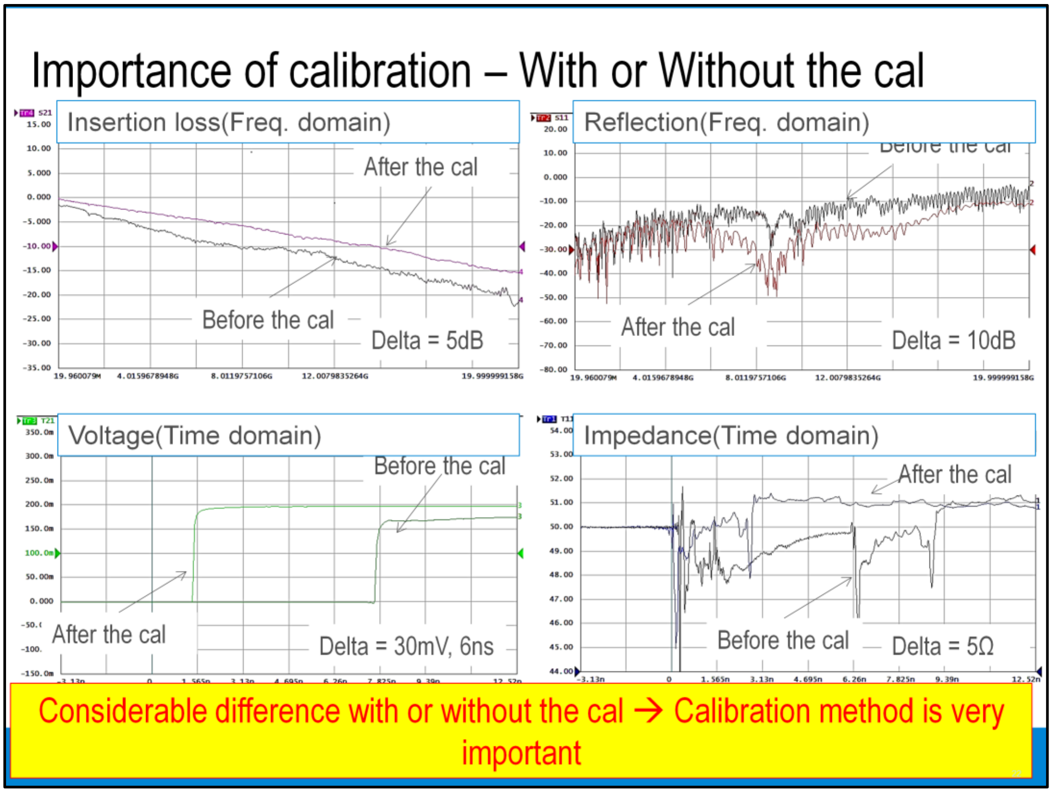
It's also possible that the time domain parameters (step response → impulse response) can be transformed into S-parameters (frequency response) by performing an fourier transform (FT).
Which is the best solution?



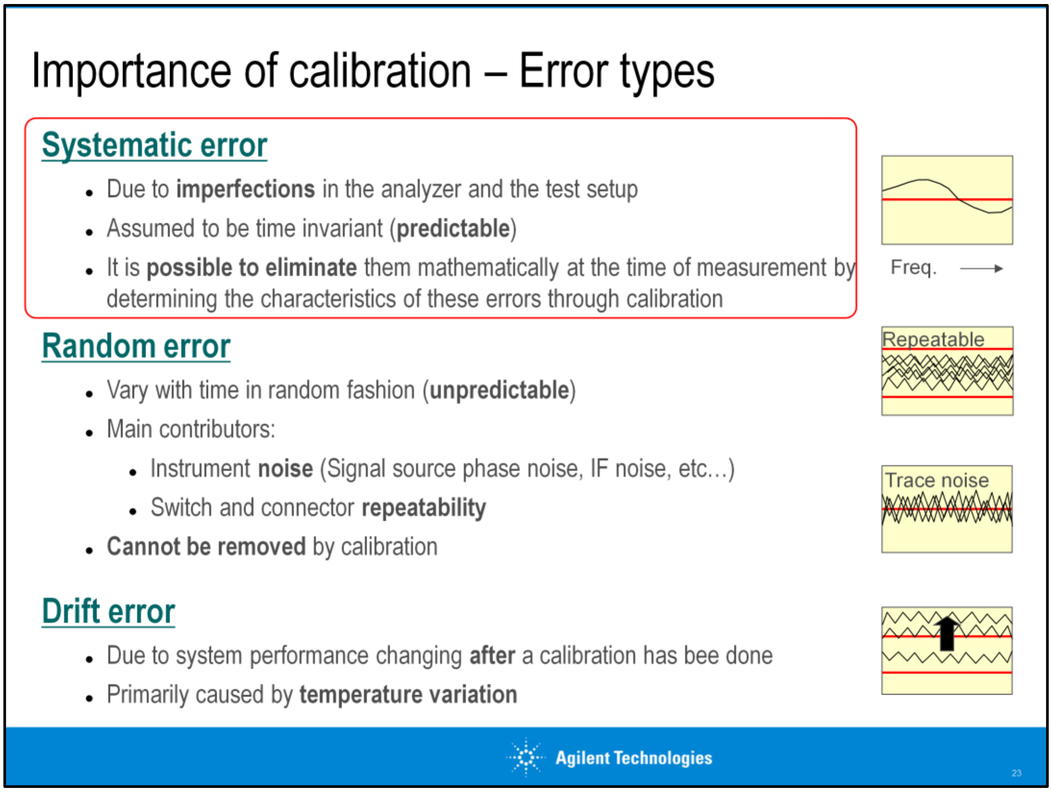
Let's review the measurement principle of TDR scopes. The TDR instrument accomplishes this task with a fast step (step generator) with little overshoot in concert with a wideband receiver (sampler) to measure step response.



The VNA uses a precise sine wave and sweeps frequency as a narrow band receiver tracks the swept input response. This narrow band receiver achieves low noise and high dynamic range of the VNA. Whether the data acquisition hardware is time domain based or frequency domain based, Differential data is also compiled in a 4-port measurement system. In this regard, however, VNA offers more accurate measurements with state of the art calibration techniques. Furthermore, VNA offers faster measurement speed thanks to high dynamic range, and higher robustness against ESD with protection circuits implemented inside the instrument for all ports while maintaining excellent RF performance.

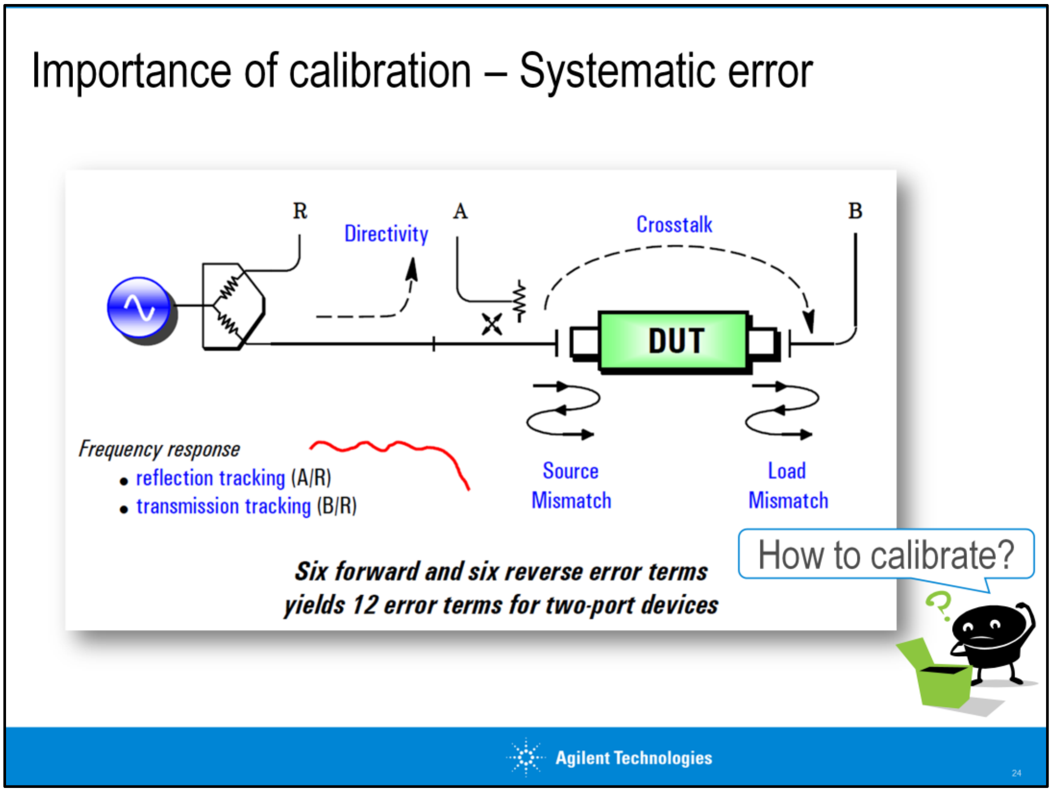


Without a calibration, we cannot see the actual device characteristics hidden behind the incorrect results due to measurement errors. Therefore, calibration, in other words error correction, is important to obtain accurate data.



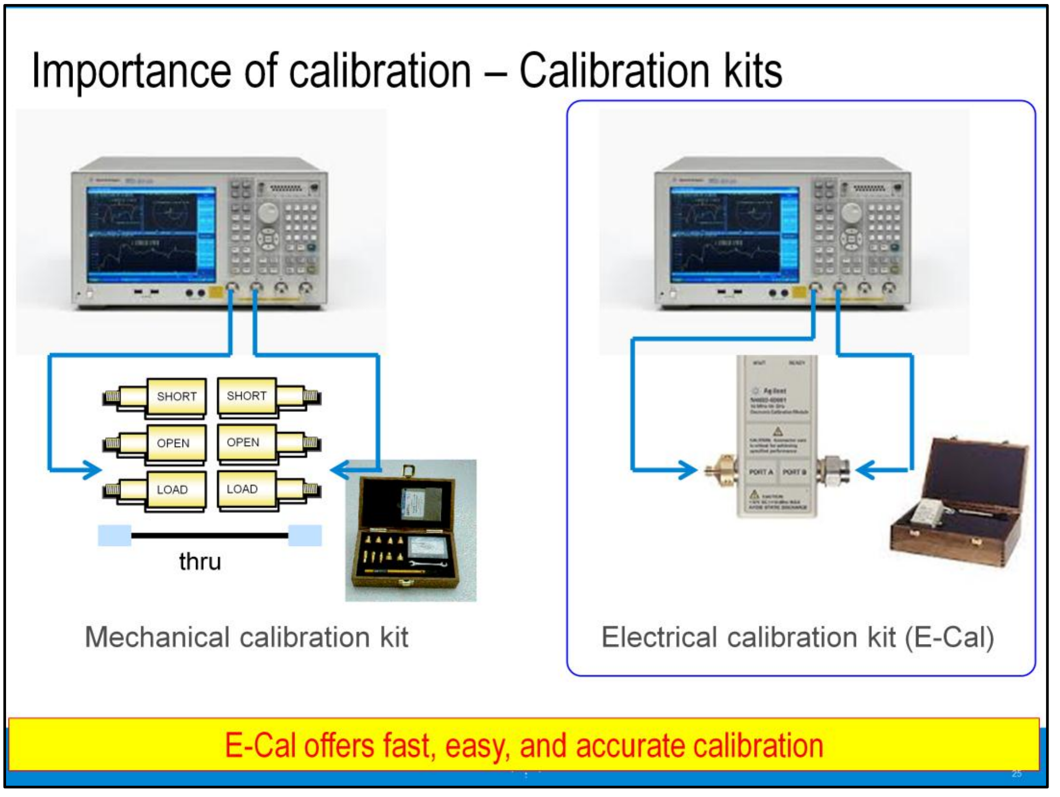
Importance of calibration – Error types

There are three basic sources of measurement error: systematic, random and drift.
Systematic errors are due to imperfections in the analyzer and test setup. They are repeatable (and therefore predictable), and are assumed to be time invariant. Systematic errors are characterized during the calibration process and mathematically removed during measurements.
Random errors are unpredictable since they vary with time in a random fashion. Therefore, they cannot be removed by calibration. The main contributors to random error are instrument noise (source phase noise, sampler noise, IF noise).
Drift error are due to the instrument or test-system performance changing after a calibration has been done. Drift is primarily caused by temperature variation and it can be removed by further calibration(s). The timeframe over which a calibration remains accurate is dependent on the rate of drift that the test system undergoes in the user’s test environment. Providing a stable ambient temperature usually goes a long way towards minimizing drift.

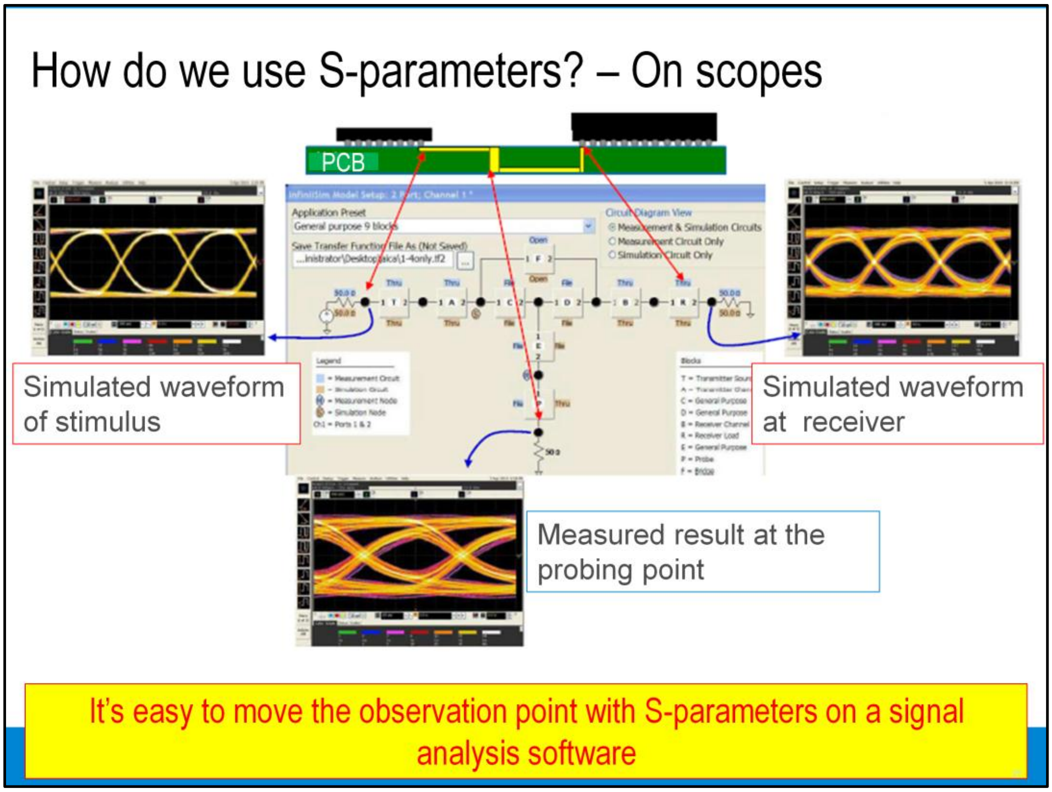


Importance of calibration – Systematic error

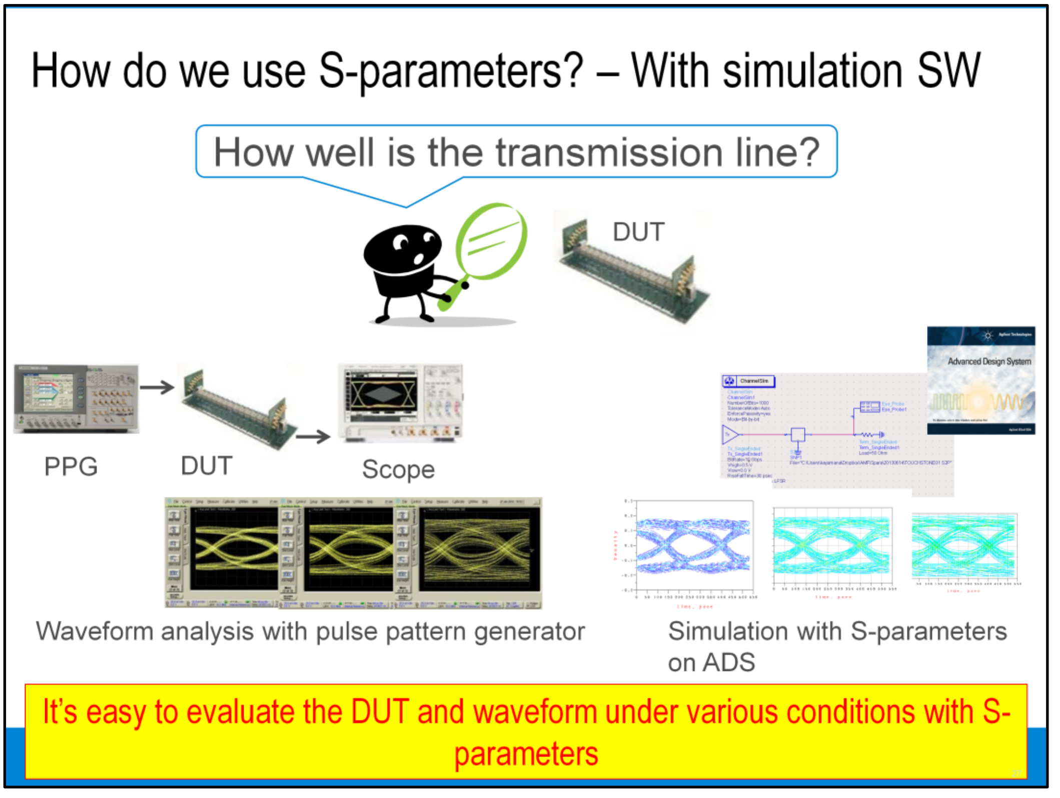
There are the major systematic errors associated with network measurements. The errors relating to signal leakage are directivity and crosstalk. Errors related to signal reflections are source and load match. The final class of errors are related to frequency response of the receivers, and are called reflection and transmission tracking. The full two-port error model includes all six of these terms for the forward direction and the same six (with different data) in the reverse direction, for a total of twelve error terms. This is why we often refer to two-port calibration as twelve-term error correction.



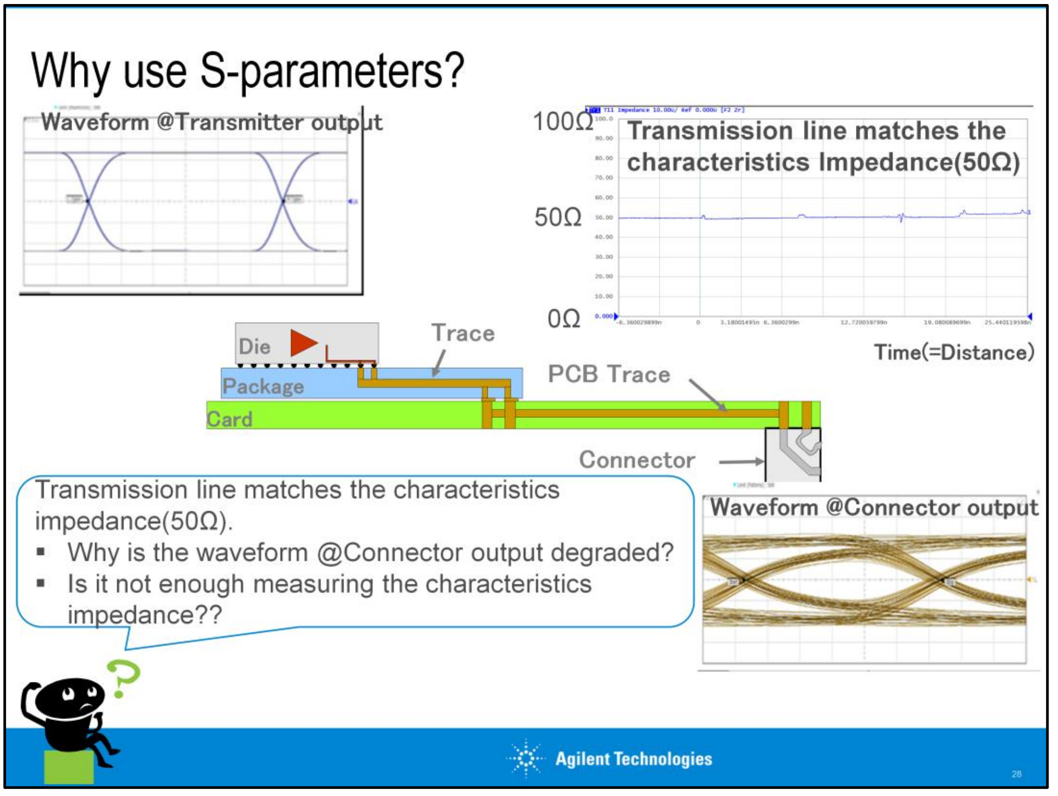
Importance of calibration – Calibration kits
Vector-error correction is the process of characterizing systematic error terms by measuring known calibration standards, and then removing the effects of these errors from subsequent measurement.
Traditional two-port calibration usually requires twelve measurements on four known standards (short-open-load-through or SOLT). Some standards are measured multiple times (e.g., the through standard is usually measured four times). The standards themselves are defined in a cal-kit definition file, which is stored in the network analyzer.
Electronic calibration (ECal) replaces the traditional calibration technique, which uses mechanical standards. Mechanical standards require numerous connections to the test ports for a single calibration. These traditional calibrations require intensive operator interaction, which is prone to error. With ECal, a full one- to four-port calibration can be accomplished with a single connection to the ECal module and minimal operator interaction. This results in faster and more repeatable calibrations.
By reducing the number of connections required for a calibration, it can: Calibrate faster, save time and make measurement sooner / Reduce the chance of operator error, for greater confidence in the calibration / Reduce the wear on connectors, for lower repair cost on both the test port connectors and calibration standards.



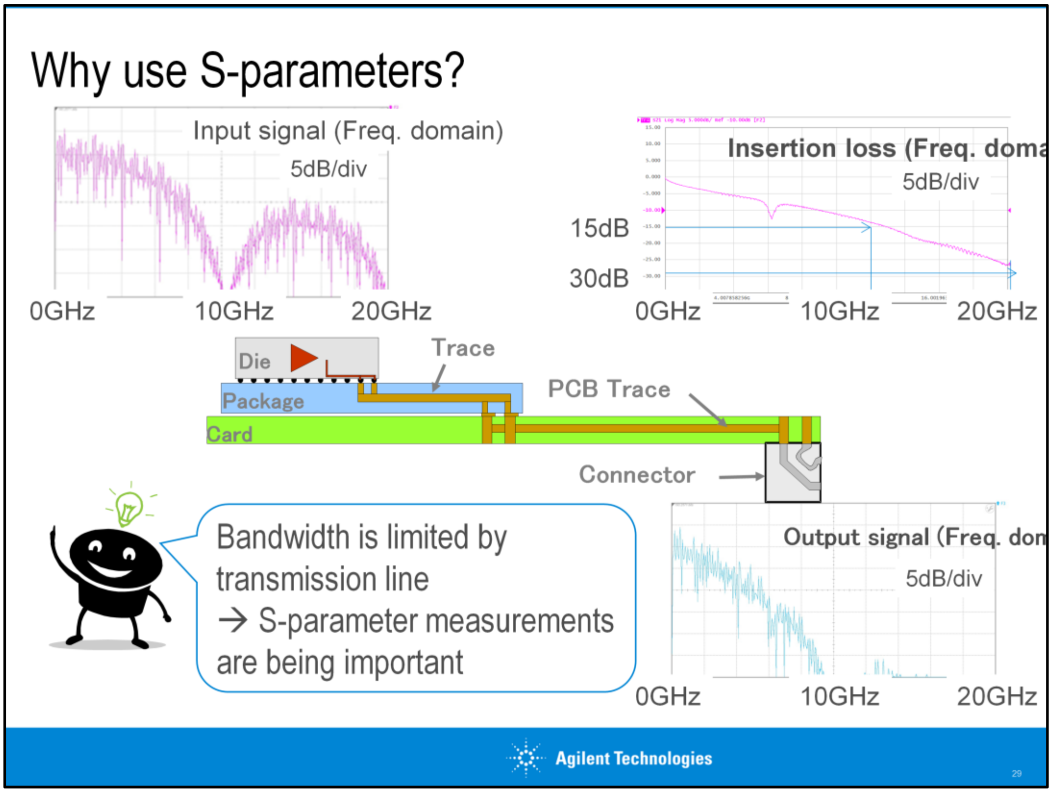
Sometimes it's difficult to probe a transmitter output on a die, but it's possible to move the observation point (simulate a waveform at the target point) from the actual probing point with S-parameters on an oscilloscope (Agilent InfiniiSim Transformation Toolset).



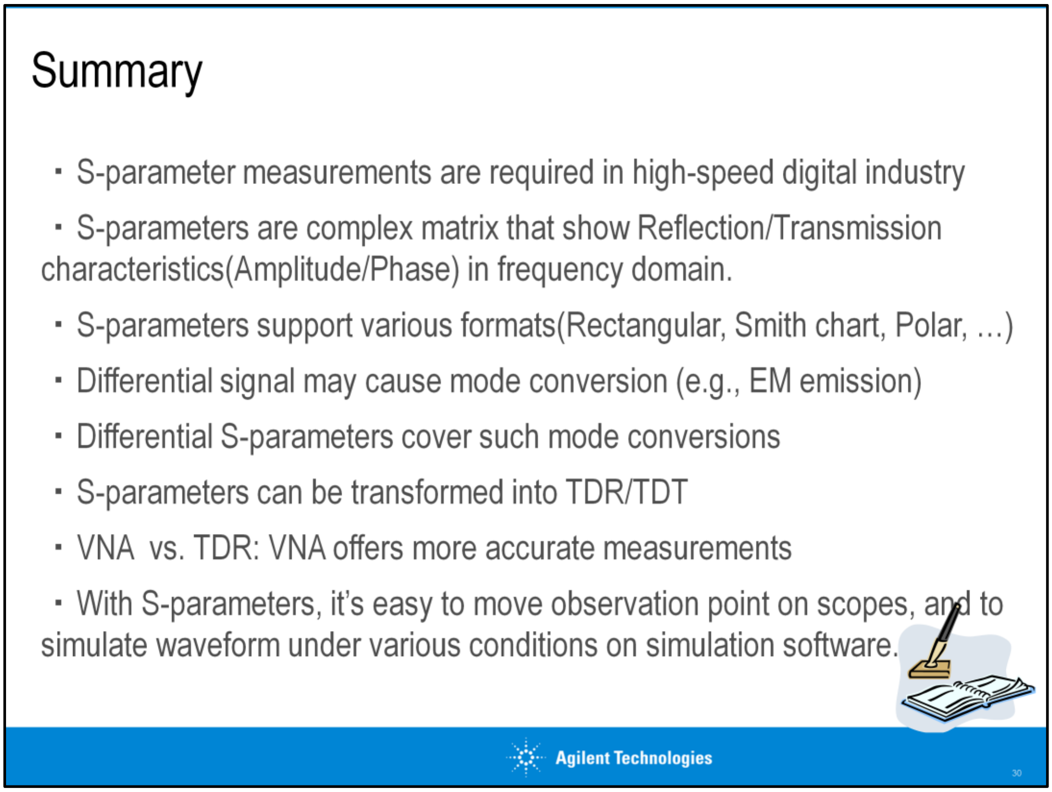
S-parameters are easily imported and used for circuit simulations in electronic-design automation (EDA) tools like Agilent's Advanced Design System (ADS). S-parameters are the shared language between simulation and measurement.



Now, let’s go back to the start point.
Why is the waveform @Connector output degraded? Is it not enough measuring the characteristics impedance?



Bandwidth is limited by transmission line (insertion loss = -15 dB @10GHz) → S-parameter measurements are being important in high speed digital applications.



S-parameter measurements are required in high-speed digital industry

・S-parameters are complex matrix that show Reflection/Transmission characteristics(Amplitude/Phase) in frequency domain.

・S-parameters support various formats(Rectangular, Smith chart, Polar, …)

・Differential signal may cause mode conversion (e.g., EM emission)

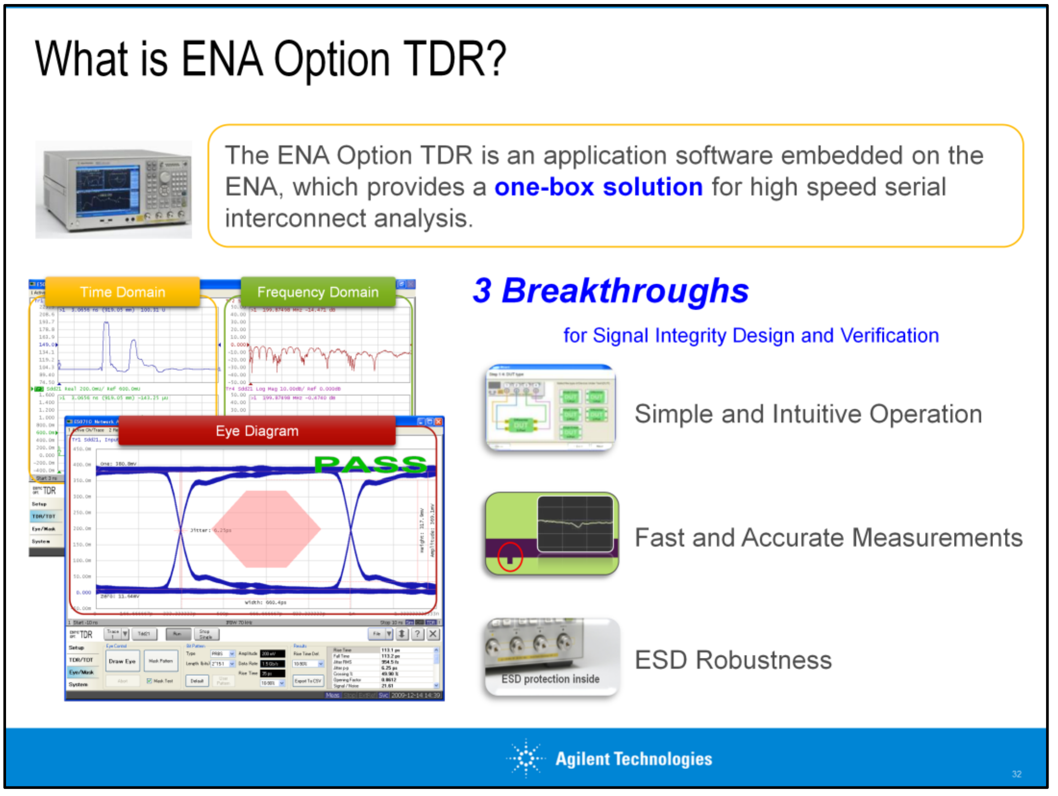
・Differential S-parameters cover such mode conversions

・S-parameters can be transformed into TDR/TDT

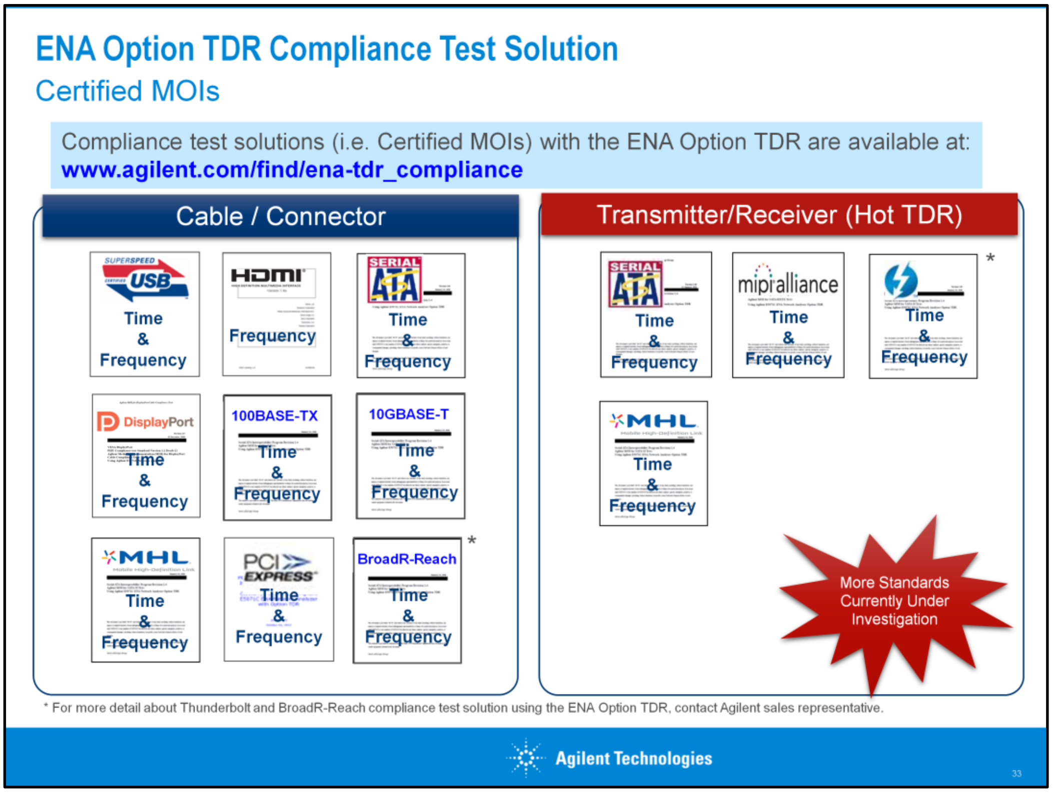
・VNA vs. TDR: VNA offers more accurate measurements

・With S-parameters, it's easy to move observation point on scopes, and to simulate waveform under various conditions on simulation software.

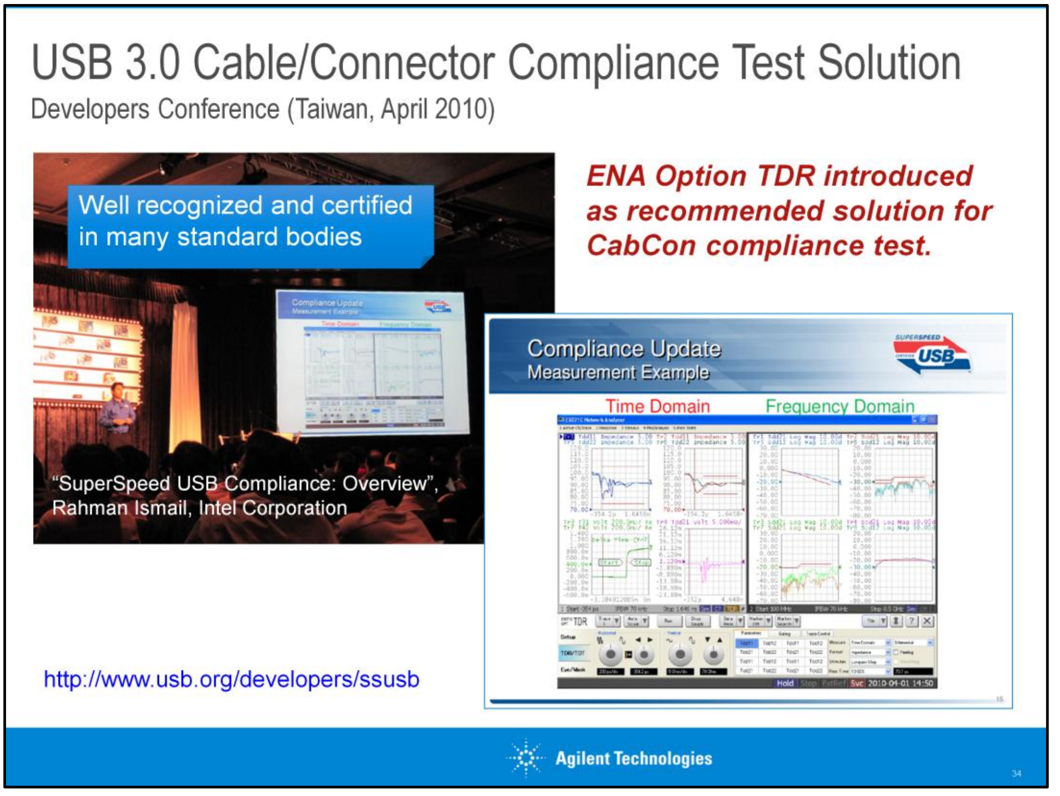
Agilent offers high speed digital and signal integrity solutions from design and simulation to compliance test.



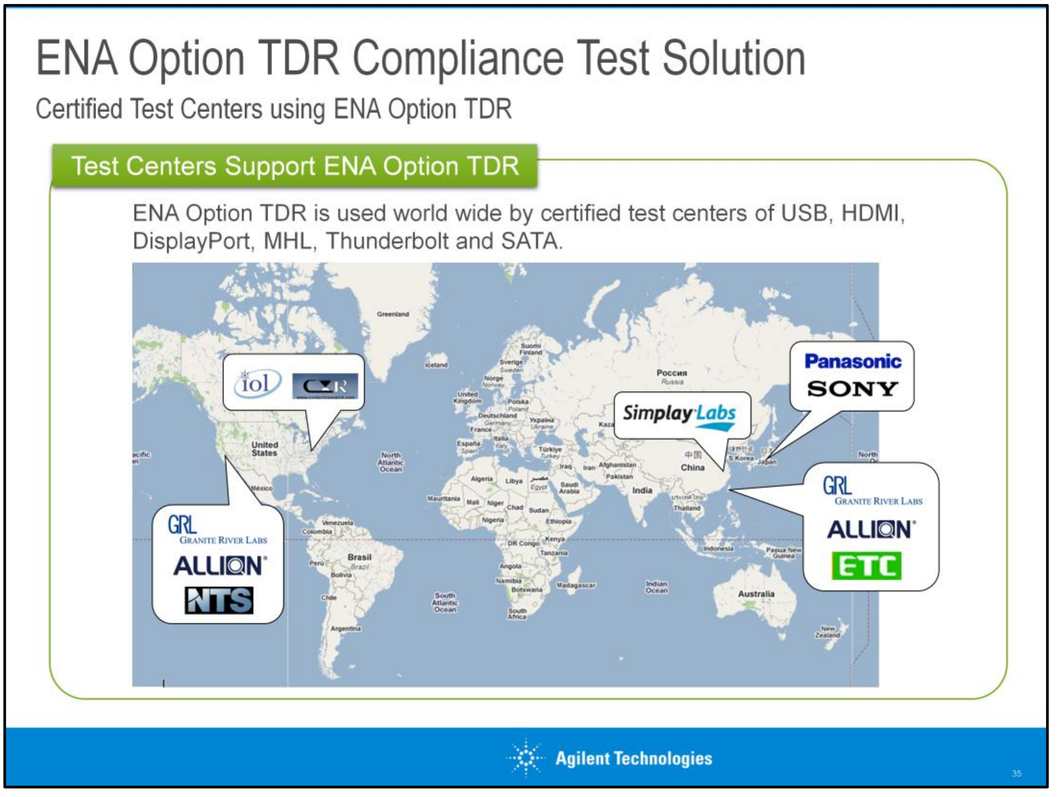
The ENA Option TDR is an application software which provides a one-box solution: We can measure both time domain and frequency domain measurements, and additionally eye diagram analysis on this product. It offers three breakthroughs, advantages against competitive solutions: Simple and Intuitive Operation / Fast and Accurate Measurements / ESD Robustness.



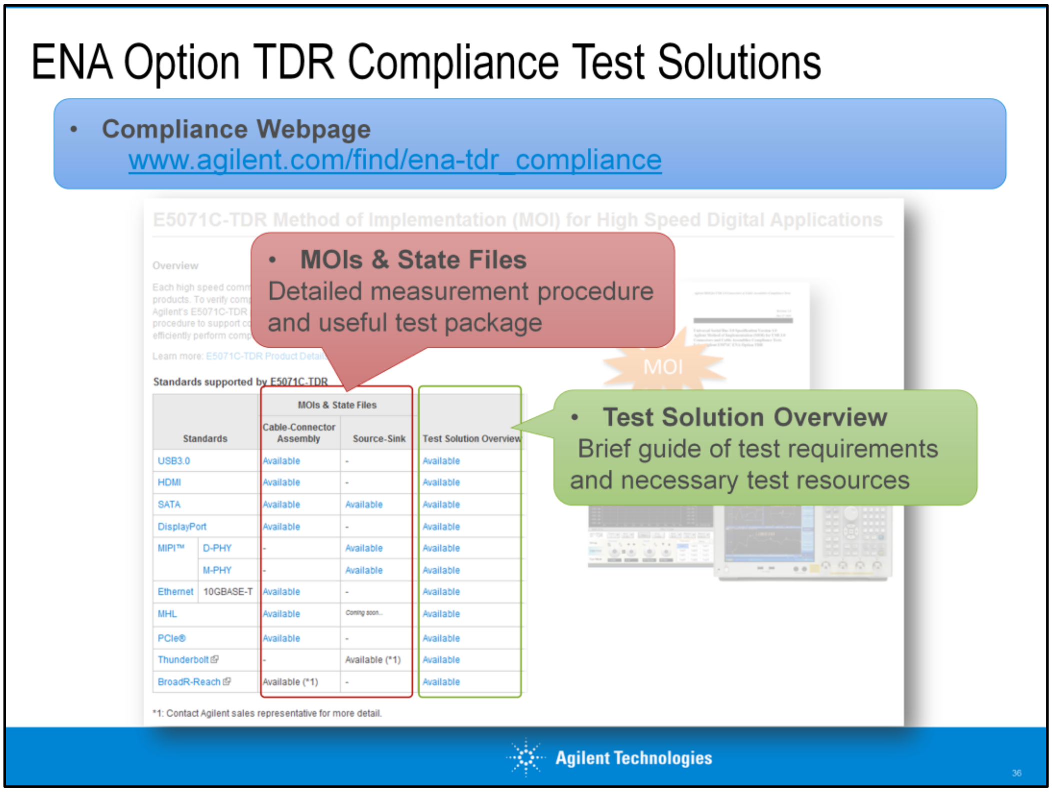
ENA Option TDR is certified for a variety of high speed serial standards.
For cable/connector compliance testing, certification is available for USB3, HDMI, SATA, DisplayPort, 100BASE-TX, 10GBASE-T Ethernet, MHL and PCI Express.
For transmitter/receiver Hot TDR testing, certification is available for SATA, MIPI (D-PHY, M-PHY) and Thunderbolt.
MOI (or method of implementation) documents, and state files are currently available from the Agilent web site. State files contain pre-configured setups in accordance with the standard requirements and allows for quick and easy measurements.



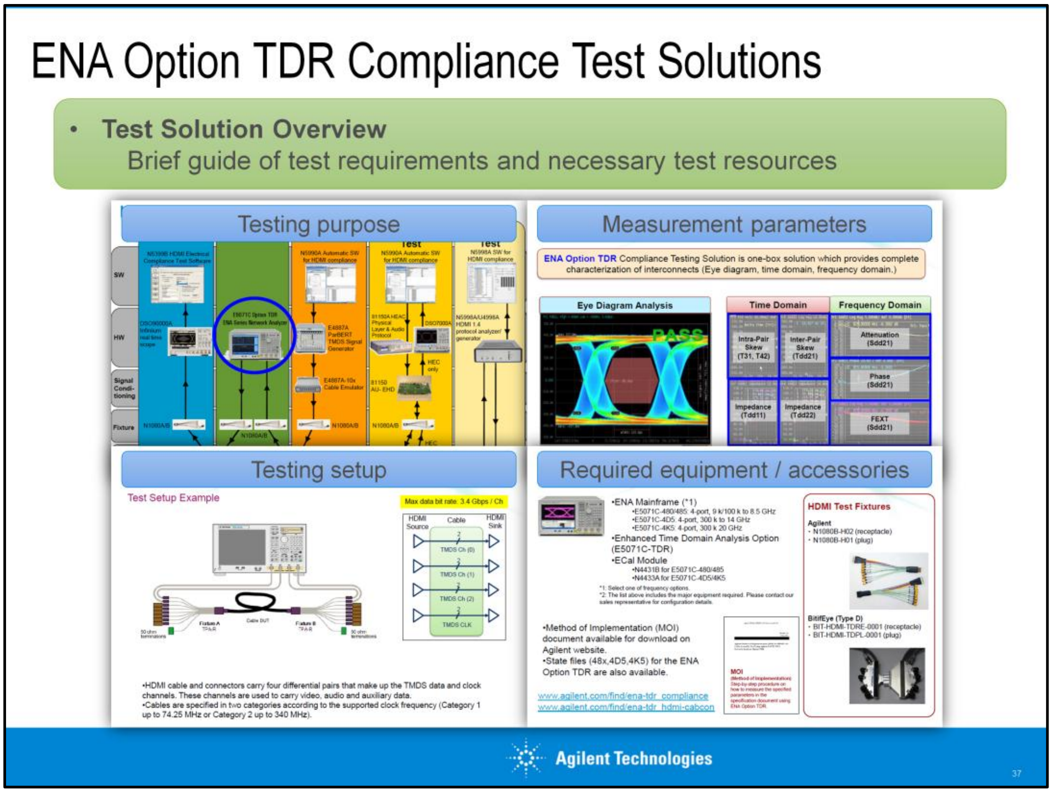
In the USB3 developers conference, ENA Option TDR introduced as recommended solution for cable assembly compliance test with its advantage: one-box solution, both time and frequency domain measurements
can be done much easier and faster than competitor's product. As a result, now, our solution is well recognized and certified in many standard bodies.



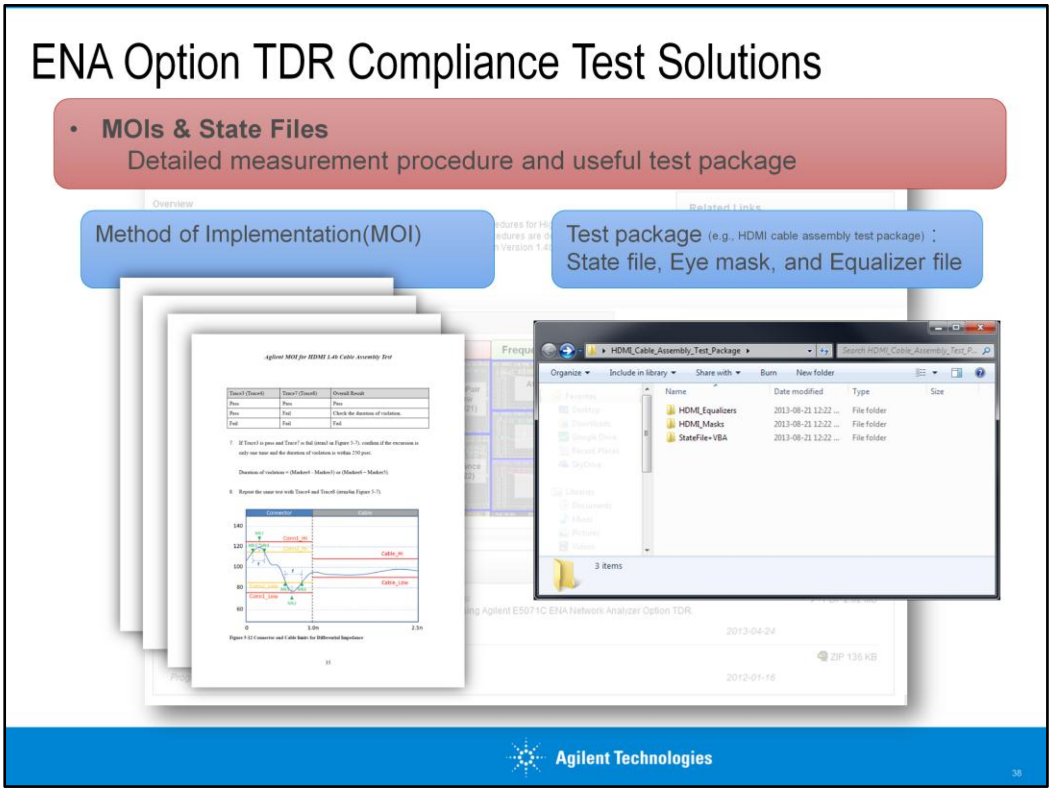
Many of the test centers for high speed serial compliance testing have already adopted ENA Option TDR. When looking for an instrument for pre-compliance testing, it is always preferable to use instrumentation used at the test centers to ensure measurement correlation.



Both materials are available in this compliance webpage on A.com. As you can see, ENA Option TDR supports a variety of high speed digital standards. In the next two slides, I'm going to show those contents briefly.



Test solution overview helps you understand what kind of measurements are required. For example, let's see the HDMI compliance test overview. Start from testing purpose, compliance test setup, measurement parameters, and required equipment with accessories. You can grab the information quickly.



MOI, method of implementation shows the detailed measurement procedure. Besides that, state file included in the test package is also available, which contains pre-configured setups in accordance with the standard requirements, and allow for quick and easy measurements. Using MOI and state file, you can efficiently perform compliance test.

Additional Resources

•ENA Option TDR Reference Material

www.agilent.com/find/ena-tdr

- •Technical Overview (5990-5237EN)
- •Application Notes
  - •Correlation between TDR oscilloscope and VNA generated time domain waveform (5990-5238EN)
  - •Comparison of Measurement Performance between Vector Network Analyzer and TDR Oscilloscope (5990-5446EN)
  - •Effective Hot TDR Measurements of Active Devices Using ENA Option TDR (5990-9676EN)
  - •Measurement Uncertainty of VNA Based TDR/TDT Measurement (5990-8406EN)
  - •Accuracy Verification of Agilent's ENA Option TDR Time Domain Measurement using a NIST Traceable Standard (5990-5728EN)

•Method of Implementation (MOI) for High Speed Digital Standards

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