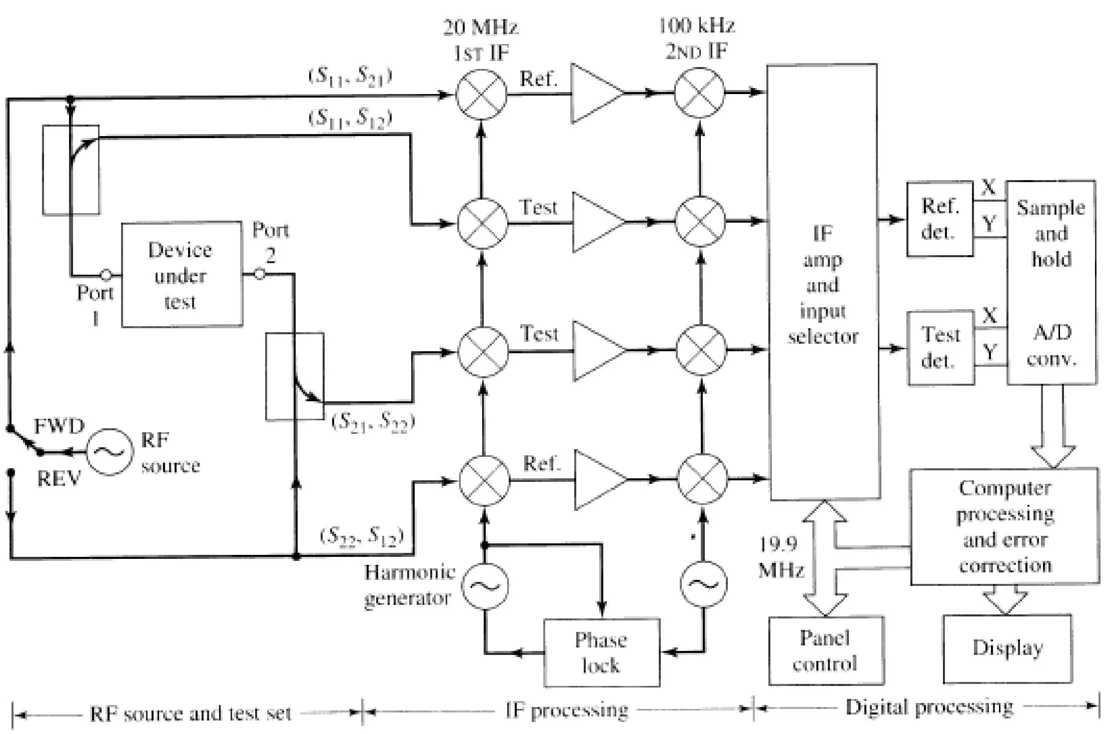
Lecture 18: Vector Network Analyzer.

A network analyzer is a device that can measure *S* parameters over a range of frequencies. There are two types:

1. Scalar network analyzer. Measures only the magnitude of the *S* parameters.
2. Vector network analyzer (VNA). Measures both the magnitude and phase of the *S* parameters.

The latter is generally a much more expensive piece of equipment.

The VNA is basically a sophisticated transmitter and receiver pair with vast signal processing capabilities. Here is a block diagram of a typical vector network analyzer (text p. 188):



We will examine the basic subsystems of a VNA in this lecture and some important topics concerning the sources of error and calibration of the VNA.

The following pages are from "Network Analyzer Basics," Agilent Product Note E206. (Agilent Technologies is the company that was formed when Hewlett Packard Corporation spun-off its test and measurement business.)

Network Analyzer Basics

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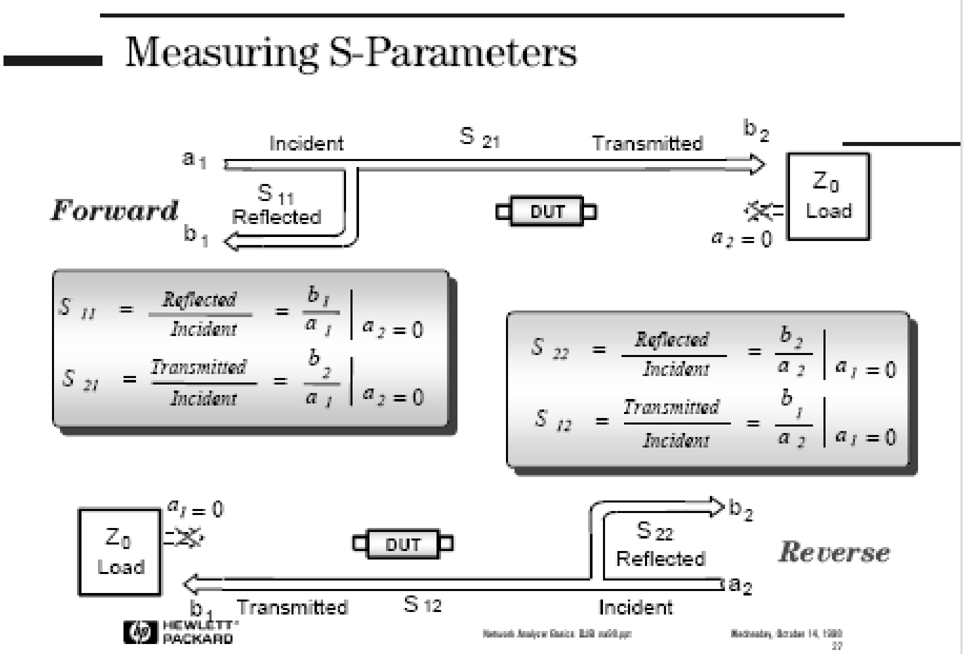

S_{11} and S_{21} are determined by measuring the magnitude and phase of the incident, reflected and transmitted voltage signals when the output is terminated in a perfect Zo (a load that equals the characteristic impedance of the test system). This condition guarantees that a_2 is zero, since there is no reflection from an ideal load. S_{11} is equivalent to the input complex reflection coefficient or impedance of the DUT, and S_{21} is the forward complex transmission coefficient. Likewise, by placing the source at port 2 and terminating port 1 in a perfect load (making a_1 zero), S_{22} and S_{12} measurements can be made. S_{22} is equivalent to the output complex reflection coefficient or output impedance of the DUT, and S_{12} is the reverse complex transmission coefficient.

The accuracy of S-parameter measurements depends greatly on how good a termination we apply to the port not being stimulated. Anything other than a perfect load will result in a_1 or a_2 not being zero (which violates the definition for S-parameters). When the DUT is connected to the test ports of a network analyzer and we don't account for imperfect test port match, we have not done a very good job satisfying the condition of a perfect termination. For this reason, two-port error correction, which corrects for source and load match, is very important for accurate S-parameter measurements (two-port correction is covered in the calibration section).

Network Analyzer Basics

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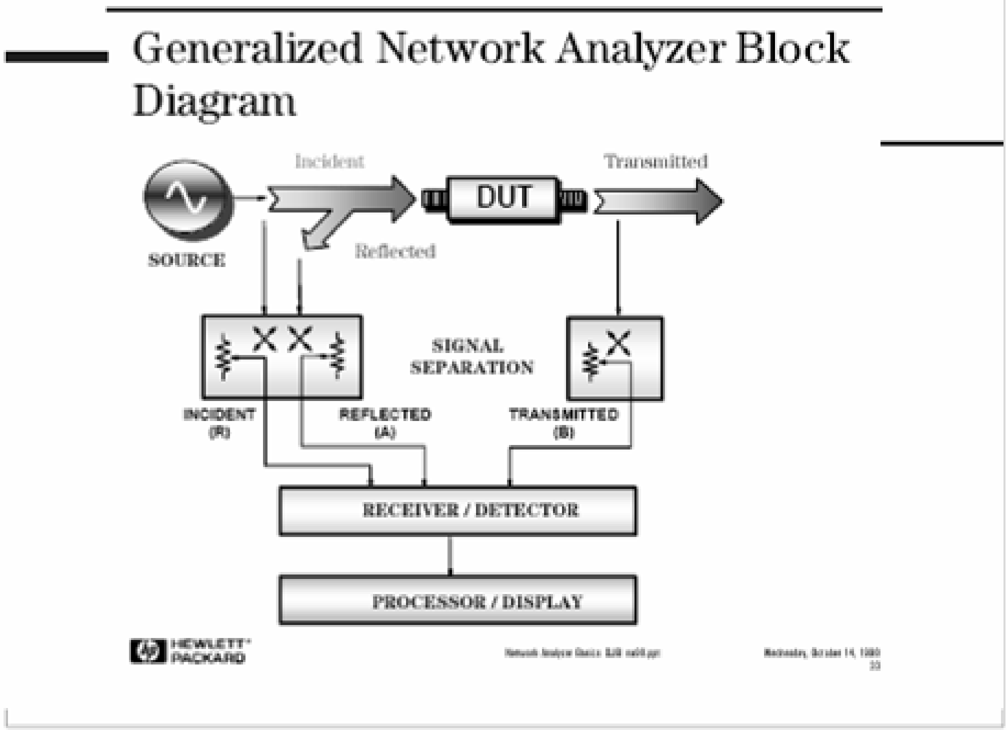

Here is a generalized block diagram of a network analyzer, showing the major signal processing sections. In order to measure the incident, reflected and transmitted signal, four sections are required:

1. Source for stimulus
2. Signal-separation devices
3. Receiver that provides detection
4. Processor/display for calculating and reviewing the results

We will briefly examine the source, receiver, and processor sections. More detailed information about the signal separation devices and receiver section are in the Appendix.

Network Analyzer Basics

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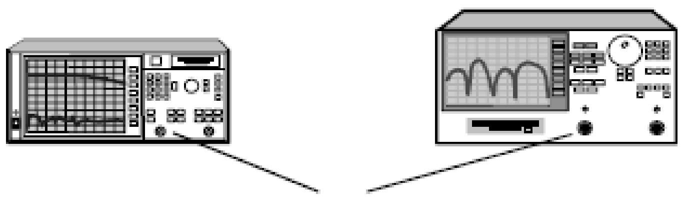
Source

- Supplies stimulus for system
- Swept frequency or power
- Traditionally NAs used separate source
  - Open-loop VCOs
  - Synthesized sweepers
- Most HP analyzers sold today have integrated, synthesized sources



Integrated, synthesized sources

The signal source supplies the stimulus for our stimulus-response test system. We can either sweep the frequency of the source or sweep its power level. Traditionally, network analyzers used a separate source. These sources were either based on open-loop voltage-controlled oscillators (VCOs) which were cheaper, or more expensive synthesized sweepers which provided higher performance, especially for measuring narrowband devices. Excessive phase noise on open-loop VCOs degrades measurement accuracy considerably when measuring narrowband components over small frequency spans. Most network analyzers that HP sells today have integrated, synthesized sources.

Network Analyzer Basics

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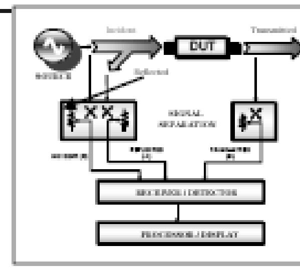
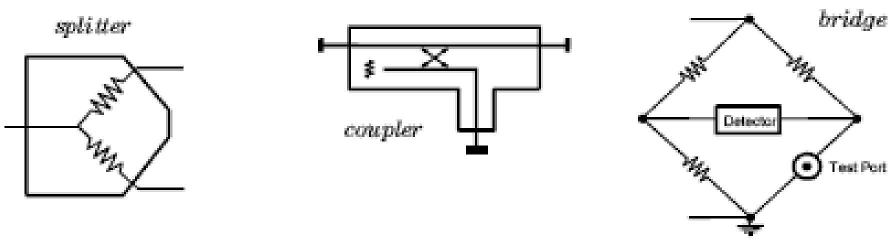
Signal Separation



Serves two purposes:

- ***Measures incident signal for reference***
- ***Separates incident and reflected signals***



There are two functions that our signal-separation hardware must provide. The first is to measure a portion of the incident signal to provide a reference for ratioing. This can be done with splitters or directional couplers. Splitters are usually resistive. They are non-directional devices (more on directionality later) and can be very broadband. The trade-off is that they usually have 6 dB or more of loss in each arm. Directional couplers have very low insertion loss (through the main arm) and good isolation and directivity.

The second function of the signal-splitting hardware is to separate the incident (forward) and reflected (reverse) traveling waves at the input of our DUT. Again, couplers are ideal in that they are directional, have low loss, and high reverse isolation. However, due to the difficulty of making truly broadband couplers, bridges are often used.

More detailed information about these signal separation devices are provided in the Appendix Section.

Network Analyzer Basics

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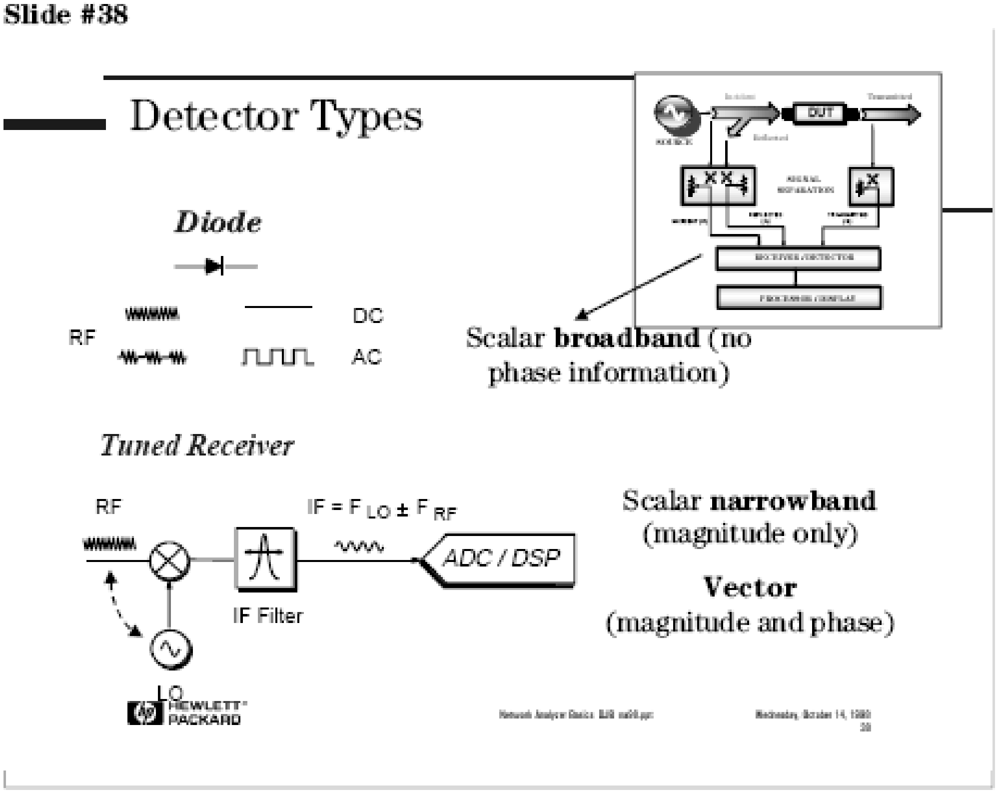

There are two basic ways of providing signal detection in network analyzers. Diode detectors convert the RF signal level to a proportional DC level. If the signal is amplitude modulated (AC detection), the diode strips the RF carrier from the modulation. Diode detection is inherently scalar, as phase information of the RF carrier is lost.

The tuned receiver uses a local oscillator (LO) to mix the RF down to a lower "intermediate" frequency (IF). The LO is either locked to the RF or the IF signal so that the receivers in the network analyzer are always tuned to the RF signal present at the input. The IF signal is bandpass filtered, which narrows the receiver bandwidth and greatly improves sensitivity and dynamic range. Modern analyzers use an analog-to-digital converter (ADC) and digital-signal processing (DSP) to extract magnitude and phase information from the IF signal. The tuned-receiver approach can be used in scalar or vector network analyzers.

Network Analyzer Basics

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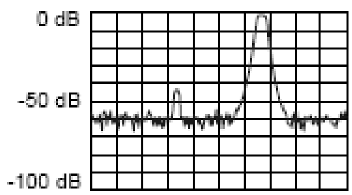
Comparison of Receiver Techniques

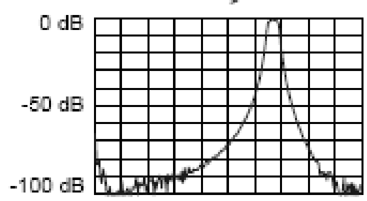
Broadband (diode) detection



-60 dBm Sensitivity

- higher noise floor
- false responses

Narrowband (tuned-receiver) detection



< -100 dBm Sensitivity

- high dynamic range
- harmonic immunity

Dynamic range = maximum receiver power - receiver noise floor

Dynamic range is generally defined as the maximum power the receiver can accurately measure minus the receiver noise floor. There are many applications requiring large dynamic range. One of the most common are filter applications. As you can see here, at least 80 dB dynamic range is needed to properly characterize the rejection characteristics of this filter. The plots show a typical narrowband filter measured on an HP 8757 scalar network analyzer and on the HP 8510 vector network analyzer. Notice that the filter exhibits 90 dB of rejection but the scalar analyzer is unable to measure it because of its higher noise floor.

In the case where the scalar network analyzer was used with broadband diode detection, a harmonic or subharmonic from the source created a "false" response. For example, at some point on a broadband sweep, the second harmonic of the source might fall within the passband of the filter. If this occurs, the detector will register a response, even though the stopband of the filter is severely attenuating the frequency of the fundamental. This response from the second harmonic would show on the display at the frequency of the fundamental. On the tuned receiver, a spurious response such as this would be filtered away and would not appear on the display.

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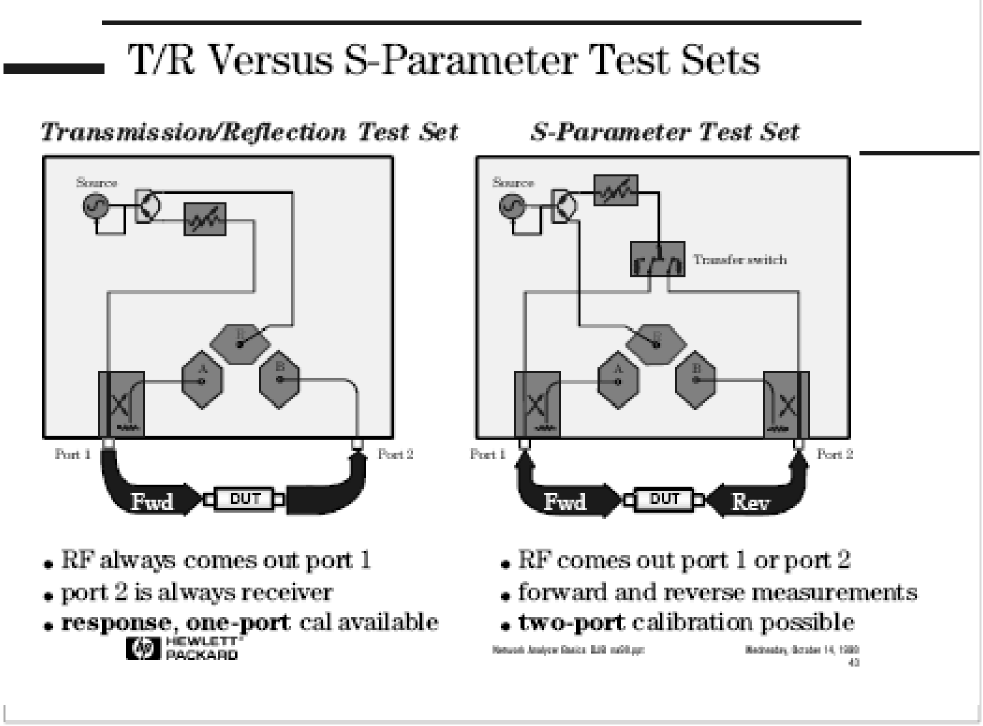

There are two basic types of test sets that are used with network analyzers. For transmission/reflection (T/R) test sets, the RF power always comes out of test port one and test port two is always connected to a receiver in the analyzer. To measure reverse transmission or output reflection of the DUT, we must disconnect it, turn it around, and re-connect it to the analyzer. T/R-based network analyzers offer only response and one-port calibrations, so measurement accuracy is not as good as that which can be achieved with S-parameter test sets. However, T/R-based analyzers are more economical.

S-parameter test sets allow both forward and reverse measurements on the DUT, which are needed to characterize all four S-parameters. RF power can come out of either test port one or two, and either test port can be connected to a receiver. S-parameter test sets also allow full two-port (12-term) error correction, which is the most accurate form available. S-parameter network analyzers provide more performance than T/R-based analyzers, but cost more due to extra RF components in the test set.

There are two different types of transfer switches that can be used in an S-parameter test set: solid-state and mechanical. Solid-state switches have the advantage of infinite lifetimes (assuming they are not damaged by too much power from the DUT). However, they are more lossy so they reduce the maximum output power of the network analyzer. Mechanical switches have very low loss and therefore allow higher output powers. Their main disadvantage is that eventually they wear out (after 5 million cycles or so). When using a network analyzer with mechanical switches, measurements are generally done in single-sweep mode, so the transfer switch is not continuously switching.

S-parameter test sets have two types of archectitures, 3-samplers and 4-samplers. More detailed information of the two archectitures is available in the Appendix section.

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Network Analyzer Basics

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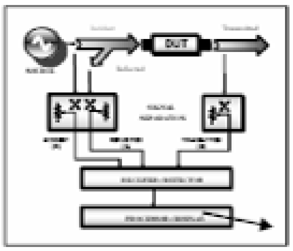
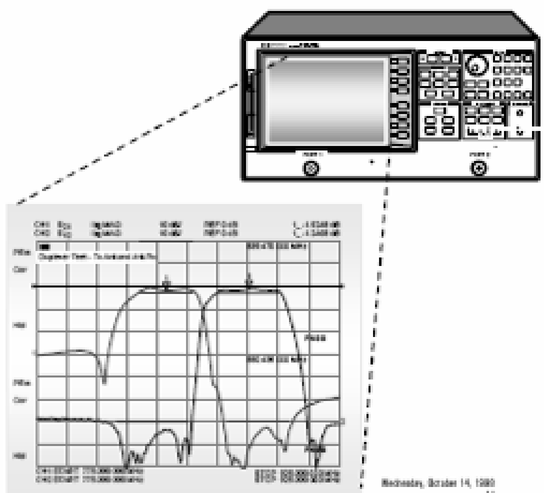
Processor / Display





- markers
- limit lines
- pass/fail indicators
- linear/log formats
- grid/polar/Smith charts

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The last major block of hardware in the network analyzer is the display/processor section. This is where the reflection and transmission data is formatted in ways that make it easy to interpret the measurement results. Most network analyzers have similar features such as linear and logarithmic sweeps, linear and log formats, polar plots, Smith charts, etc. Other common features are trace markers, limit lines, and pass/fail testing. Many of HP's network analyzers have specialized measurement features tailored to a particular market or application. One example is the HP 8730A tuner analyzer

Network Analyzer Basics

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Measurement Error Modeling

Systematic errors

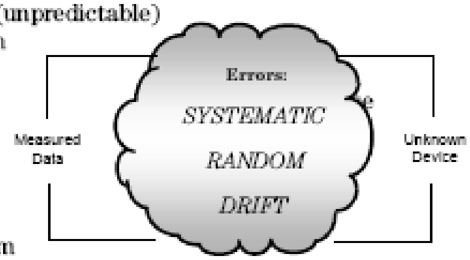
- due to **imperfections** in the analyzer and test setup
- are assumed to be **time invariant** (predictable)
- can be characterized (during calibration process) and **mathematically removed** during measurements

Random errors

- **vary** with time in random fashion (unpredictable)
- **cannot be removed** by calibration
- main contributors:
  - **instrument noise** (source noise, IF noise floor, etc.)
  - **switch** repeatability
  - **connector** repeatability

Drift errors

- are due to instrument or test-system performance changing ***after*** a calibration has been done
- are primarily caused by **temperature variation**
- **can be removed** by further calibration(s)



Let us look at the 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 (therefore predictable), and 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

Drift errors 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.

Network Analyzer Basics

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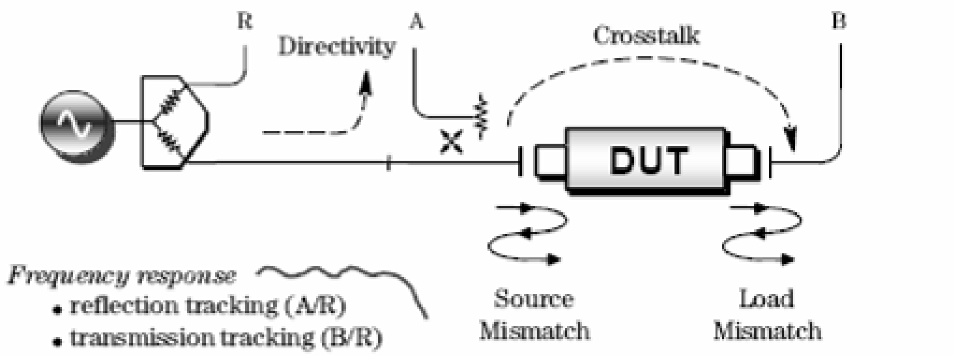
Systematic Measurement Errors



Six forward and six reverse error terms yields 12 error terms for two-port devices

Shown here 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.

Network Analyzer Basics

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What is Vector-Error Correction?

- Process of characterizing systematic error terms
  - measure **known standards**
  - remove effects from subsequent measurements.
- **1-port calibration** *(reflection measurements)*
  - only 3 systematic error terms measured
  - directivity, source match, and reflection tracking
- **Full 2-port calibration** *(reflection and transmission measurements)*
  - 12 systematic error terms measured
  - usually requires 12 measurements on four known standards (SOLT)
- Some standards can be measured **multiple** times (e.g., THRU is usually measured four times)
- Standards defined in **cal kit definition** file
  - network analyzer contains standard cal kit definitions
  - **CAL KIT DEFINITION MUST MATCH ACTUAL CAL KIT USED!**

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 measurements.

One-port calibration is used for reflection measurements and can measure and remove three systematic error terms (directivity, source match, and reflection tracking). Full two-port calibration can be used for both reflection and transmission measurements, and all twelve systematic error terms are measured and removed. Two-port calibration usually requires twelve measurements on four known standards (short-open-load-thru or SOLT). Some standards are measured multiple times (e.g., the thru standard is usually measured four times). The standards themselves are defined in a cal-kit definition file, which is stored in the network analyzer. HP network analyzers contain all of the cal-kit definitions for our standard calibration kits. In order to make accurate measurements, the cal-kit definition MUST MATCH THE ACTUAL CALIBRATION KIT USED!

Network Analyzer Basics

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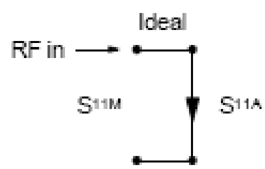
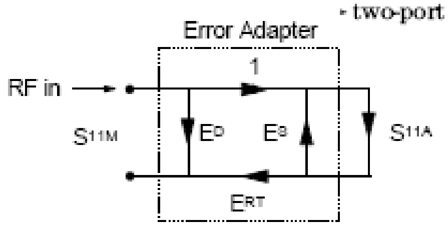
Reflection: One-Port Model



- If you know the systematic error terms, you can solve for the actual S-parameter
- Assumes good termination at port two if testing two-port devices
- If port 2 is connected to the network analyzer *and* DUT reverse isolation is low (e.g., filter passband):
  - assumption of good termination is not valid
  - two-port error correction yields better results



E_D = Directivity
E_{RT} = Reflection tracking
E_S = Source Match
S_{11M} = Measured
S_{11A} = Actual

$$S_{11M} = E_D + E_{RT}\frac{S_{11A}}{1 - E_S S_{11A}}$$

To solve for S_{11A}, we have 3 equations and 3 unknowns

Taking the simplest case of a one-port reflection measurement, we have three systematic errors and one equation to solve. In order to do this, we must create three equations with three unknowns and solve them simultaneously. To do this, we measure three known standards, for example, a short, an open, and a Zo load. Solving the equations will yield the systematic error terms and allow us to derive the actual reflection S-parameters of the device from our measurements.

When measuring two-port devices, a one-port calibration assumes a good termination at port two of the device. If this condition is met (by connecting a load calibration standard for example), the one-port calibration is quite accurate. If port two of the device is connected to the network analyzer and the reverse isolation of the DUT is low (for example, filter passbands or cables), the assumption of a good load termination is not valid. In these cases, two-port error correction provides more accurate measurements. An example of a two-port device where load match is not important is an amplifier. The reverse isolation of the amplifier allows one-port calibration to be used effectively. An example of the measurement error that can occur when measuring a two-port filter using a one-port calibration will be shown shortly.

Network Analyzer Basics

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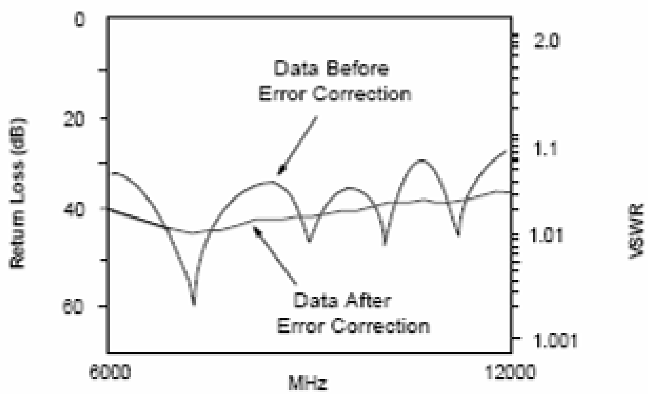
Before and After One-Port Calibration



Shown here is a plot of reflection with and without one-port calibration. Without error correction, we see the classic ripple pattern caused by the systematic errors interfering with the measured signal. The error-corrected trace is much smoother and better represents the device's actual reflection performance.

Network Analyzer Basics

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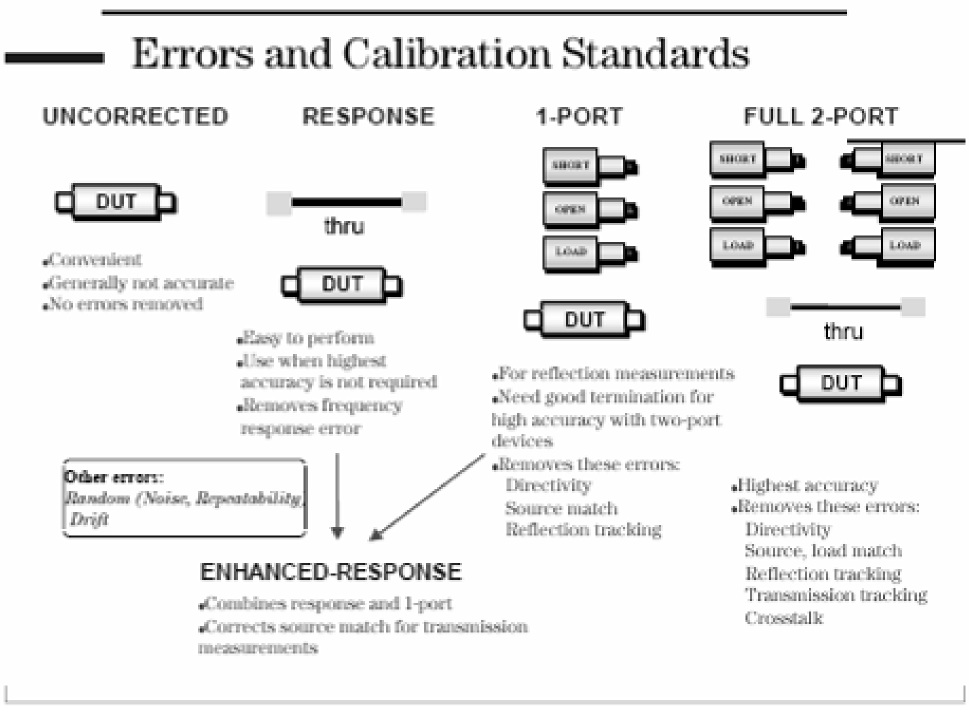

A network analyzer can be used for uncorrected measurements, or with any one of a number of calibration options, including response calibrations and one- or two-port vector calibrations. A summary of these calibrations is shown above. We will explore the measurement uncertainties associated with the various calibration schemes in this section.

Network Analyzer Basics

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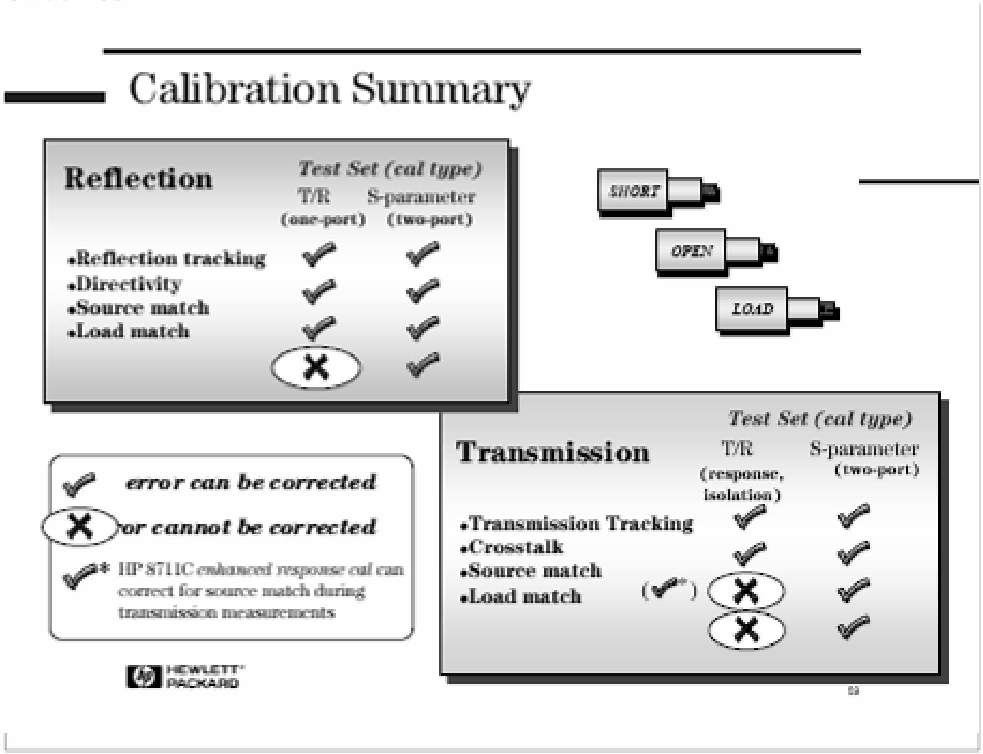

This summary shows which error terms are accounted for when using analyzers with T/R test sets (such as the HP 8711C family) and S-parameter test sets (such as the HP 8753/8720 families).

The following examples show how measurement uncertainty can be estimated when measuring two-port devices with a T/R-based network analyzer.