Vector Network Analyzer

Application note

Version 1.0
Introduction
A vector network analyzer is used to measure the performance of circuits or networks such as amplifiers, filters, attenuators, cables and antennas. It does this by applying a test signal to the network to be tested, measuring the reflected and transmitted signals and comparing them to the test signal. The vector network analyzer measures both the magnitude and phase of these signals.

Basic Need to Test RF Components
R&D engineers need to measure these components to verify their simulation models and their actual hardware prototypes. For component production a manufacturer must measure the performance of their products so they can provide accurate specifications. This is essential so prospective customers will know how a particular component will behave in their application.

Types of Devices which needs to be tested
The devices which can be tested by Transcom Network Analyzer include both passive and active devices. Network analyzers can measure both linear and nonlinear behaviour of devices. Some of the devices which are being tested by our network analyzer are:
**Passive Devices**: Duplexers, Diplexers, Filters, Couplers, Splitters, combiners, Isolators, Circulators, Attenuators, Adaptors, Loads, Cables, Transmission Lines, Antennas and Multiplexers etc.

**Active Devices**: RFICs, Transceivers, Tuners, Convertors, Amplifiers, Modulators and Oscillators etc.

**Basic Concept: Light wave Analogy to RF Energy**

One of the most fundamental concepts of RF network analysis involves incident, reflected and transmitted waves traveling along transmission lines. It is helpful to think of traveling waves along a transmission line in terms of a light wave analogy. We can imagine incident light striking some optical component like a clear lens. Some of the light is reflected off the surface of the lens, but most of the light continues on through the lens. If the lens were made of some lossy material, then a portion of the light could be absorbed within the lens. If the lens had mirrored surfaces, then most of the light would be reflected and little or none would be transmitted through the lens.

![Lightwave Analogy Diagram](image-url)

This concept is valid for RF signals as well, except the electromagnetic energy is in the RF range instead of the optical range, and our components and circuits are electrical devices and networks instead of lenses and mirrors.

**Structure of Vector Network Analyzer**

A typical vector network analyzer contains a signal source, signal separation devices and a set of receivers. The signal source is used for generating incident signal. Signal separation devices are used for separating reference and incident signals. The incident signal stimulates Device-Under-Test (DUT), then receivers is used for receiving transmitted signal and reflect signal. With processor unit, S parameters could be obtained by calculation.
Transmission / Reflection and S-Parameter Test Sets for Measurement

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.

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 lossier 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.
Measurement by Vector Network Analyzers

Vector network analyzers have the capability to measure phase as well as magnitude. This is important for fully characterizing a device or network either for verifying performance or for generating models for design and simulation. Knowledge of the phase of the reflection coefficient is particularly important for matching systems for maximum power transfer.

Basic measurement which are performed by a Network Analyzer are Reflection & Transmission Parameters and S-Parameters. Reflection Parameters like VSWR and Return loss and Transmission Parameters like Insertion Loss and Attenuation can be measure with a log magnitude and VSWR format. We often want to know the impedance of the DUT. Our network analyzer can display the Smith chart, plot measured data on it, and provide adjustable markers that show the calculated impedance at the marked point in a several marker formats. We can analyse Phase and Magnitude Variation with Frequency, Deviation from Linear Phase & Group Delay for a DUT and characters unknown devices using S – Parameters.

Measuring S - Parameters
S11 and S21 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. 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 $a_1$ zero), S22 and S12 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.

<table>
<thead>
<tr>
<th>$S_{11}$</th>
<th>Forward reflection Coefficient (Input Match)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{12}$</td>
<td>Reverse Transmission Coefficient (Isolation)</td>
</tr>
<tr>
<td>$S_{21}$</td>
<td>Forward Transmission Coefficient (Gain or Loss)</td>
</tr>
<tr>
<td>$S_{22}$</td>
<td>Reverse Reflection Coefficient (Output Match)</td>
</tr>
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The accuracy of S-parameter measurements depends greatly on how good a termination we apply to the load port (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.

**Displaying measurements**

S-parameters are essentially the same parameters as some of the terms we have mentioned before, such as input match and insertion loss. It is important to separate the fundamental definition of S-parameters and the format in which they are often displayed. S-parameters are inherently complex, linear quantities. They are expressed as real-and-imaginary or magnitude-and-phase pairs. However, it isn’t always very useful to view them as linear pairs. Often we want to look only at the magnitude of the S-parameter (for example, when looking at insertion loss or input match), and often, a logarithmic display is most useful. A log-magnitude format lets us see far more dynamic range than a linear format.

**Measuring Reflection parameters**
The input reflection coefficient $\Gamma$ can be obtained directly from $S_{11}$:

$$\Gamma = \frac{V_{\text{reflected}}}{V_{\text{incident}}} = S_{11} = \rho \angle \phi$$

$\rho$ is the magnitude of the reflection coefficient i.e. the magnitude of $S_{11}$: $\rho = |S_{11}|$

Sometimes $\rho$ is expressed in logarithmic terms as return loss: return loss = $-20 \log (\rho)$

VSWR can also be derived:

$$VSWR = \frac{E_{\text{max}}}{E_{\text{min}}} = \frac{1 + \rho}{1 - \rho}$$

Measuring Transmission parameters

Transmission coefficient $T$ is defined as the transmitted voltage divided by the incident voltage. This is the same as $S_{21}$.

$$T = \frac{V_{\text{transmitted}}}{V_{\text{incident}}} = S_{21} = \tau \angle \phi$$

Transmission coefficient $\tau$ is defined as the transmitted voltage divided by the incident voltage. If $|V_{\text{trans}}| > |V_{\text{inc}}|$, the DUT has gain, and if $|V_{\text{trans}}| < |V_{\text{inc}}|$, the DUT exhibits attenuation or insertion loss. When insertion loss is expressed in dB, a negative sign is added in the definition so that the loss value is expressed as a positive number.

$$\text{insertion_loss(dB)} = -20 \log \left| \frac{V_{\text{trans}}}{V_{\text{incident}}} \right| = -20 \log \tau$$

If $T$ is greater than 1, the DUT has gain, which is also normally expressed in decibels:

$$\text{insertion_gain(dB)} = 20 \log \left| \frac{V_{\text{trans}}}{V_{\text{incident}}} \right| = 20 \log \tau$$

Measuring Phase

We know insertion phase versus frequency is a very important characteristic of a component, let’s see how we would measure it. Looking at insertion phase directly is usually not very useful. This is because
the phase has a negative slope with respect to frequency due to the electrical length of the device (the longer the device, the greater the slope). Since it is only the deviation from linear phase which causes distortion, it is desirable to remove the linear portion of the phase response. This can be accomplished by using the electrical delay feature of the network analyzer to cancel the electrical length of the DUT. This results in a high-resolution display of phase distortion (deviation from linear phase).

**Measuring group Delay**

Another useful measurement of phase is group delay. Group delay is a measure of the time it takes a signal to pass through a network versus frequency. It is calculated by differentiating the phase response of the device with respect to frequency, i.e. the rate of change of phase with frequency:

\[
\text{group delay} = \frac{d\phi}{d\omega}
\]

The linear portion of phase is converted to a constant value typically, though not always, representing the average time for a signal to transit the device. Differences from the constant value represent deviations from linear phase. Variations in group delay will cause phase distortion as a signal passes through the circuit. When measuring group delay the aperture must be specified. Aperture is the frequency step size used in the differentiation. A small aperture will give more resolution but the displayed trace will be noisy. A larger aperture effectively averages the noise but reduces the resolution.

**Measuring Gain Compression using Power Sweep**

The most common measurement of amplifier compression is the 1-dB compression point, defined here as the input power which results in a 1-dB decrease in amplifier gain (referenced to the amplifier’s small signal gain). The easiest way to measure the 1-dB-compression point is to directly display normalized gain (B/R) from a power sweep. The flat part of the trace is the linear, small-signal region, and the curved part on the right side corresponds to compression caused by higher input power.

**Vector-Error Correction or Calibration**

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.

1. One-port calibration is used for reflection measurements and can measure and remove three systematic error terms (directivity, source match, and reflection tracking).

2. 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-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 calibration-kit definition file, which is stored in the network analyzer.
Transcom network analyzers contain all of the calibration-kit definitions for our standard calibration kits. In order to make accurate measurements, the calibration-kit definition MUST MATCH THE ACTUAL CALIBRATION KIT USED! If user built calibration standards are used (during fixture measurements for example), then the user must characterize the calibration standards and enter the information into a user calibration-kit file.

**Calibration Methods**

- **Response**
  - $S_{11}$, $S_{21}$, $S_{12}$, $S_{22}$

- **2-port One Path**
  - $S_{11}$, $S_{21}$

- **2-port Two Path**
  - $S_{11}$, $S_{21}$, $S_{12}$, $S_{22}$

- **Electronic**
  - $S_{11}$, $S_{21}$, $S_{12}$, $S_{22}$
Transcom Vector Network Analyzers

**T4 USB VNA** offers wide dynamic range, low noise level, high resolution scanning with laboratory and research grade performance. T4 covers frequency range of 1MHz to 4GHz with 2-port and 2-pass that competitive with most of the bench-top VNAs on the market. T4 is suitable for laboratory, manufacturing and many other safety testing environment.

**T5000 Series bench-top vector network** analyzer offers the high RF performance, wide frequency range and versatile functions. The T5000 series is the economic solution for manufacturing and R&D engineers evaluating RF components and circuits for frequency range up to 8GHz.

**T5845A** is a built-in multiport test set new generation of multiport matrix vector network analyzer developed by Transcom Instrument Co.Ltd. It can be widely applied to the research, development and test of RF devices in the fields of communication, medical care, scientific research and electronics. The instrument has made a breakthrough in conventional multiport test scheme of 2/4 port VNA+matrix switch. It can carry out parallel test on DUT with 10 ports under standalone operation, thereby greatly improving test efficiency and reducing test cost and time.

More information about our Test & Measurement devices can be obtained from our website www.transcomwireless.com
About Transcom
Shanghai Transcom Instrument Co., Ltd. (NEEQ: 831961), established in 2005, independently research and develop high-end radio frequency communication testing instruments and is a professional provider of overall testing solutions. Starting from 2009, Transcom, titled as National High-Tech Enterprise and the fostered enterprise by Shanghai Little Giant Project, has undertaken the tasks of development for National “New-Generation Broadband Wireless Mobile Communication Network” and the construction of Shanghai Engineering Research Center for Wireless Communication Testing Instruments.

In 2015, Transcom officially announced its new five-year development strategy “1+3”. In detail, Transcom will continue to enhance its potential to be the national team for domestic wireless communication instruments, and develop security software for mobile communication network (network communication/data mining), wireless signal (spectrum monitoring/situation analysis) and Beidou navigation (signal monitoring for satellite navigation/mobile anti-jam verification platform). The strategy has now been implemented systematically with progressive achievements in Shanghai, Guangdong and other cities.

Keep innovating for excellence!