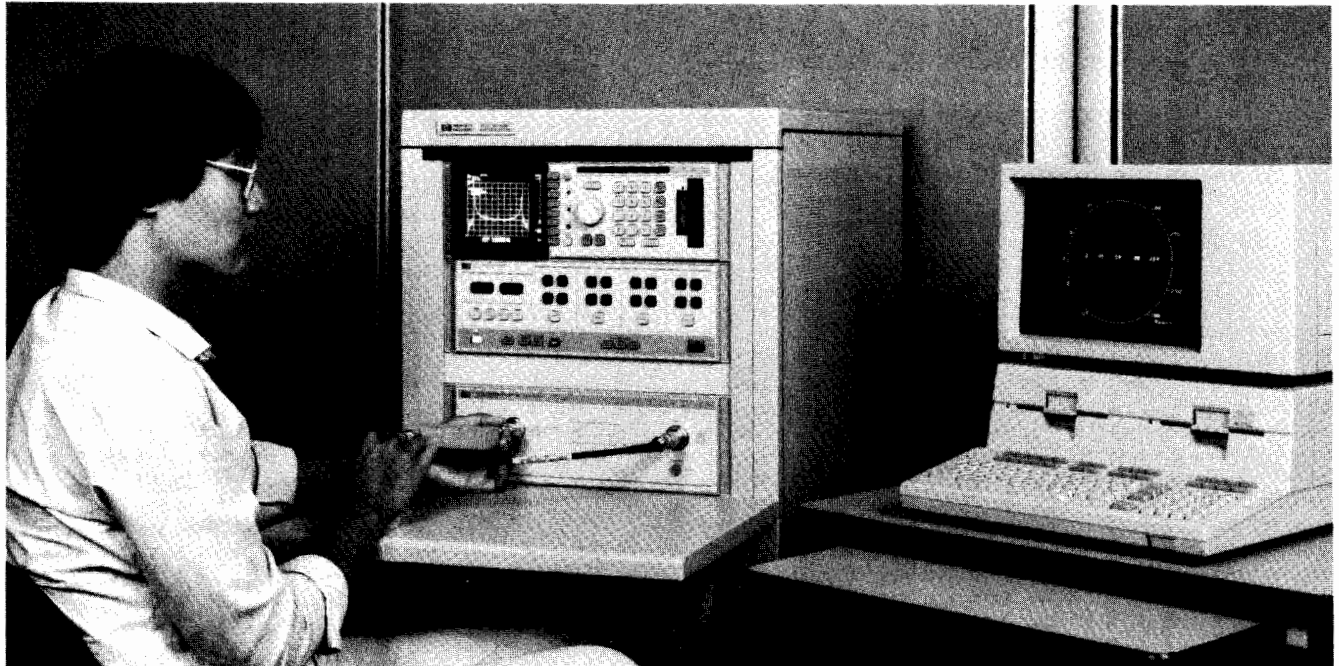


NETWORK ANALYZERS

Complete Characterization of Linear Networks



Why Network Analysis?

Characterizing the behavior of linear networks that will be stimulated by arbitrary signals and interfaced with a variety of other networks is a fundamental problem in both synthesis and test processes. For example, the engineer designing a multi-component network must predict with some certainty the final network performances from knowledge of the individual components. Similarly, a production manager must know allowable tolerances on the products manufactured and whether the final products meet the specified tolerances. Network analysis offers a solution to these problems through complete description of linear network behavior in the frequency domain. Additionally, some network analyzers offer the capability to transform measurement data, taken in the frequency domain, to the time domain providing further insight into the behavior of linear networks.

Network analysis accomplishes the description of both active and passive networks by creating a data model of such component parameters as impedances and transfer functions. However, these parameters not only vary as a function of frequency but are also complex variables in that they have both magnitude and phase. Until the advent of the modern network analyzer, phase was difficult to measure at CW frequencies and often involved laborious calculations; these measurements were accomplished by conventional oscilloscopes at lower frequencies and slotted lines at microwave frequencies. However, swept network analyzers now measure magnitude and phase (the total complex quantity) as a function of frequency with less difficulty than conventional CW measurements. Impedance and transfer functions can then be conveniently displayed on a swept CRT, as in Figure 1, X-Y recorder, or computer controlled peripherals such as a printer and/or a plotter. HP computers also combine with network analyzers to give new levels of speed and accuracy in swept measurements that could only be attained previously by long calculations at CW frequencies.

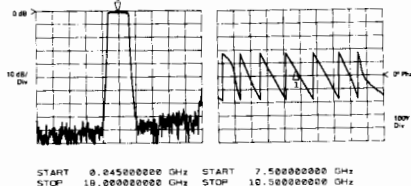


Figure 1. 45 MHz to 18 GHz measurement of magnitude and phase in a single sweep.

Thus, network analysis satisfies the engineering need to characterize the behavior of linear networks quickly, accurately, and completely over broad frequency ranges. In design situations, this minimizes the time required to test new designs and components, allowing more time to be spent on the design itself. Likewise, production test times may be minimized while reducing the uncertainties surrounding the test. Hewlett-Packard manufactures a full line of scalar network analyzers (magnitude only) and vector network analyzers (both magnitude and phase).

What Is Network Analysis?

Network analysis is the process of creating a data model of the transfer and/or impedance characteristics of a linear network through stimulus-response testing over the frequency range of interest. All network analyzers in the HP product line operate according to this definition.

Creating a data model is important in that actual circuit performance often varies considerably from the performance predicted by calculations. This occurs because the perfect circuit element doesn't exist and because some of the electrical characteristics of a circuit may vary with frequency.

At frequencies above 1 MHz lumped elements actually become "circuits" consisting of the basic elements plus parasitics like stray capacitance, lead inductance, and unknown absorptive losses. Since parasitics depend on the individual device and its construction they are almost impossible to predict. Above

1 GHz component geometries are comparable to a signal wavelength, intensifying the variance in circuit behavior due to device construction. Further, lumped-element circuit theory is useless at these frequencies and distributed-element (or transmission-line) parameters are required to completely characterize a circuit.

Data models of both transfer and impedance functions must be obtained to completely describe the linear behavior of a circuit under test. At lower frequencies, h , y , and z -parameters are examples of transfer and/or impedance functions used in network description; at higher frequencies, S -parameters are used to characterize input-output impedances and transfer functions. Therefore, a network analyzer must measure some form of a circuit's transfer and impedance functions to achieve its objective of complete network characterization. Figure 2 shows an example of a swept impedance measurement.

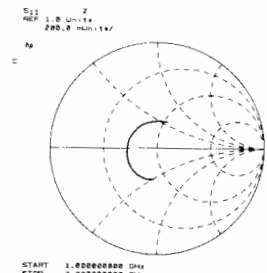


Figure 2. Input impedance of microcircuit amplifier is read directly with Smith Chart overlay for Polar Display.

Network analysis is generally limited to the definition of linear networks. Since linearity constrains networks stimulated by a

sine wave to produce a sine wave output, sine wave testing is an ideal method for characterizing magnitude and phase response as a function of frequency. In non-linear measurements phase is often meaningless and amplitude has to be defined with respect to individual frequency components. For non-linear measurements, refer to the sections on spectrum analyzers, wave analyzers (signal analyzers) and vector modulation products in this catalog.

Network Analyzers

Hewlett-Packard network analyzers are instruments that measure transfer and/or impedance functions of linear networks through sine wave testing. A network analyzer system accomplishes these measurements by configuring its various components around the device under test. The first requirement of the measurement system is a sine wave signal source to stimulate the device under test. Since transfer and impedance functions are ratios of various voltages and currents, a means of separating the appropriate signals from the measurement ports of the device under test is required. Finally, the network analyzer itself must detect the separated signals, form the desired signal ratios, and display the results.

Signal Sources and Signal Separation

In the general case, any sine wave source meeting the network analyzer's specifications can be used to stimulate the device under test. For CW measurements a simple oscillator may suffice; for greater CW frequency accuracy a signal generator or synthesizer may also be desirable. If the analyzer is capable of swept measurements, great economies in time can be achieved by stimulating the device under test with a sweep oscillator or sweeping synthesizer. This allows quick and easy characterization of devices over broad frequency ranges. Some network analyzers will operate only with a companion source that both stimulates the device under test and acts as the analyzer's local oscillator.

At low frequencies it is not particularly difficult to separate the appropriate voltages and currents required for transfer and impedance function measurements. Signal separation is merely the process of establishing the proper shorts, opens, and connections at the measurement ports of the device under test. As frequencies increase, the problem of signal separation usually involves traveling waves on transmission lines and becomes correspondingly more difficult. Hewlett-Packard manufactures test sets (often called "transducers") applicable for separating the appropriate traveling waves in a variety of high frequency measurements.

Broadband and Narrowband Detection

After the desired signals have been obtained from the test set (or transducer) they must be detected by the network analyzer; HP network analyzers can use one of two detection methods. Broadband detection accepts the full frequency spectrum of the input signal while narrowband detection involves

tuned receivers that convert CW or swept RF signals to a constant IF signal. There are certain advantages to each detection scheme.

Scalar network analyzers usually employ broadband detection techniques. Broadband detection reduces instrument cost by eliminating the IF section required by narrowband analyzers but sacrifices noise and harmonic rejection. However, noise is not a factor in many applications, and careful measurement techniques, using filters, can eliminate harmonic signals that would otherwise preclude accurate measurements. Broadband systems are generally source independent while some narrowband systems require companion tracking sources. Finally, broadband systems can make measurements where the input and output signals are not of the same frequency, as in the measurement of the insertion loss of mixers and frequency doublers. Narrowband systems cannot make these measurements.

Vector network analyzers normally employ narrowband detection techniques. Narrowband detection makes a more sensitive low noise detection of the constant IF possible. This allows increased accuracy and dynamic range for frequency selective measurements (as compared to broadband systems) and high resolution through IF substitution using precision IF attenuators. Source dependent narrowband systems utilize a companion tracking source not only to stimulate the device under test, but also to produce a signal offset from the RF by a fixed frequency for tuning the analyzer's constant IF.

Signal Processing and Display

Once the RF has been detected, the network analyzer must process the detected signals and display the measured quantities. All HP network analyzers are multi-channel receivers utilizing a reference channel and at least one test channel; absolute signal levels in the channels, relative signal levels (ratios) between the channels, or relative phase difference between channels can be measured depending on the analyzer. Using these measured quantities, it is possible to either display directly as shown in Figure 2, or compute the magnitude and phase of transfer or impedance functions.

Magnitude measurements fall into two categories, relative and absolute; absolute measurements involve the exact signal level in each channel while relative measurements involve the ratios of the two signal channels. Absolute measurements are usually expressed in voltage (dBV) or in power (dBm). The units dBV are derived by taking the log ratio of an unknown signal in volts to a one volt reference. Similarly, dBm is the log ratio of unknown signal power to a one milliwatt reference.

Relative ratio measurements are usually made in dB, which is the log ratio of an unknown signal (Test Channel) with a chosen reference signal (Reference Channel). This allows the full dynamic range of the instrumentation to be used in measuring variations of both high and low level circuit responses. For example, 0 dB implies the two signal levels have a ratio of unity while ± 20 dB im-

plies a 10:1 voltage ratio between two signals.

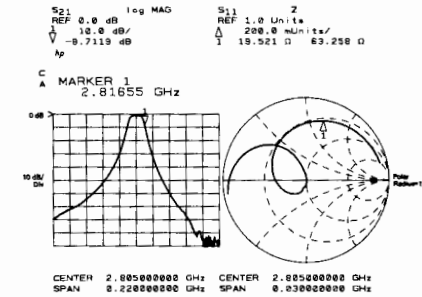


Figure 3. Simultaneous measurement of transmission response and passband reflection coefficient.

All network analyzer phase measurements are relative measurements with the reference channel signal considered to have zero phase. The analyzer then measures the phase difference of the test channel with respect to the reference channel.

Measurement results at CW frequencies may be displayed on analog meters, LEDs or computer controlled printers. Swept frequency measurements of amplitude and phase may be displayed versus frequency on CRTs, digital plotters or X-Y recorders. Insertion Loss is displayed in two different ways in Figure 4. The addition of digital storage and normalization to network analyzer CRTs ensures flicker-free traces and removal of frequency response errors for fast, real-time displays of test device responses versus frequency.

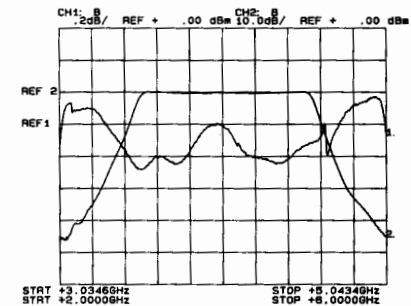


Figure 4. Simultaneous measurement of filter passband and skirts using alternate sweep.

Low Frequency Network Analysis

Networks operating at frequencies below 10 MHz are generally characterized by measuring the gain and phase changes through the network and the associated input and output impedances; h, y, and z-parameters as well as other lumped-component models are typical analytical and computational tools used to represent these measurements. The first derivative of phase with respect to frequency, group delay, is an important measurement of distortion in communication systems. Hewlett-Packard produces a broad line of instrumentation capable of measuring all of these parameters.

Phase information complements amplitude data in the measurement of low frequency parameters. Phase is more sensitive to

NETWORK ANALYZERS

Complete Characterization of Linear Networks (cont.)

network behavior and it is a required component of complex impedance and transfer functions. For instance, phase is required to determine the frequency of network resonances (poles) and anti-resonances (zeros). This is because the phase shift of a network transfer function is exactly zero at the frequency of resonance. Phase information is also vital in circuit design, particularly loop design, where phase margins are critical.

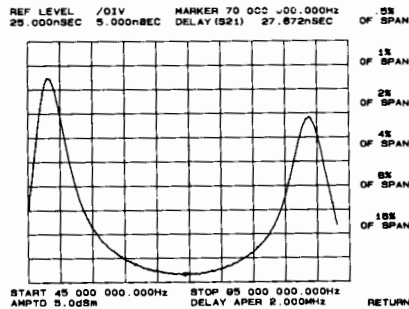


Figure 5. Direct measurement of group delay with digital readout at marker.

Phase data is also required to measure delay distortion or group delay of networks. Delay distortion occurs when different frequency components of a complex waveform experience nonlinear phase shifts as they are transmitted through a network. Group delay is a measure of this distortion and is defined as:

$$T_g = - \frac{d\theta}{d\omega}$$

There are several techniques for measuring group delay; the most common techniques are phase slope, amplitude modulation, frequency modulation, and frequency deviation. Most HP network analyzers can make measurements with at least one of these techniques while several analyzers measure and display group delay directly. Choice of a group delay measurement technique is dependent on the particular device under test and the resolution required.

An alternative method for measuring phase distortion is deviation from linear phase or differential phase. Deviations from linear phase can be measured by introducing enough electrical length in the network analyzer's reference channel to linearize a device's phase shift. Once this has been accomplished it is possible to observe any variations in phase shift linearity at high resolution. Since group delay is the derivative of phase ($d\theta/d\omega$), nonlinearities in phase shift correspond directly to changes in a device's group delay. Figure 6 shows deviation from linear phase and group delay. Introduction of electrical length in the measurement channel may be accomplished by physically adding cable, or it may be accomplished electronically on some network analyzers.

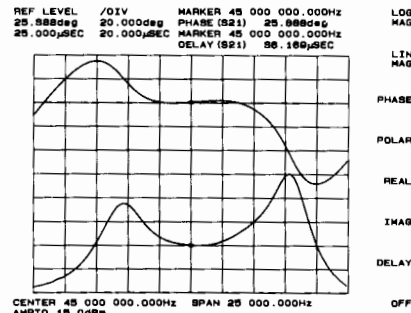


Figure 6. Two independent techniques for measuring filter phase distortion.

At lower frequency (typically ≤ 50 kHz) digital signal analysis using Fast Fourier Transformations (FFT) can also be used to determine the magnitude and phase of transfer characteristics. This subject is treated in the signal analyzers section of this catalog.

High Frequency Network Analysis

Measurements of voltages and currents become more and more difficult as frequency increases. Consequently, h , y , and z parameters lose their usefulness at high frequencies. High frequency network behavior can be better described using transmission line theory in terms of forward and reverse travelling waves. Thus, travelling waves make a logical replacement for voltages and currents in high frequency measurements.

Scattering parameters or S-parameters were developed to characterize linear networks at high frequencies. S-parameters define the ratios of reflected and transmitted traveling waves measured at the network ports. A two-port device is modeled with S-parameters in Figure 7. S_{11} is the complex re-

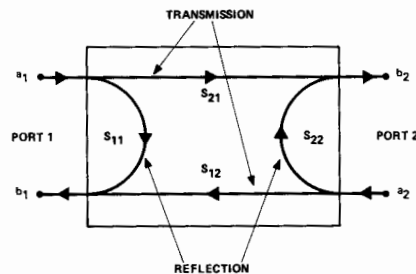


Figure 7. S-parameter model for a two-port linear network.

flection coefficient at port 1 and is the ratio of b_1/a_1 , if $a_2 = 0$ (port 2 terminated in its characteristic impedance). S_{21} is the complex transmission coefficient from port 1 to port 2, b_2/a_1 , if $a_2 = 0$. The "a" and "b" signals represent the amplitude and phase of the incident and emerging or reflected traveling waves. By reversing the ports and terminating port 1 in its characteristic impedance, S_{22} and S_{12} can be similarly defined. From these definitions, the following equations can be derived:

$$\begin{aligned} E r_1 &= S_{11} E i_1 + S_{12} E i_2 \\ E r_2 &= S_{21} E i_1 + S_{22} E i_2 \end{aligned}$$

where incident signals act as independent variables determining the signals leaving the network. The definition of an S-parameter can be easily extended to multiport networks; measurement is also easily accomplished by terminating additional ports in their charac-

teristic impedances. Thus, S-parameters completely describe linear network behavior in the same manner as low frequency parameters.

S-parameters offer numerous advantages to the microwave engineer because they are both easy to use and easy to measure. They are easy to measure because the device is terminated in its characteristic impedance, allowing swept broadband frequency measurement without tuning, enhancing the stability of active devices, and permitting a test set up to be used for different devices. The design process is simplified because S-parameters are directly applicable to flow graph analysis. HP network analyzers and the appropriate test sets will measure and directly display S_{21} or S_{12} as gain or attenuation and S_{11} or S_{22} as reflection coefficient, return loss or impedance. Figure 8 shows measurements of both S_{21} and S_{11} . Also, S-parameters may be directly related to h , y , and z -parameters through algebraic transformations.

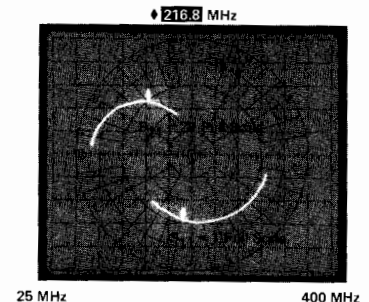


Figure 8. Simultaneous measurement of transistor S-parameters.

Additional Capabilities

Precision design work and manufacturing tolerances demand highly accurate measurements, but most errors in network measurements are complex quantities that vary as a function of frequency. By characterizing and virtually removing these systematic errors, measurement accuracies are improved by several orders of magnitude. Hewlett-Packard now offers network analyzers with built-in, high-speed computational hardware that can perform the complex mathematics required for sophisticated error correction. In many cases, this improvement in accuracy is provided in real time, permitting operator adjustment to the network being characterized while maintaining a high level of measurement accuracy. Other network analyzers, when combined with HP desktop computers into measurement systems, also offer accuracy enhancement through error correction.

Adding the computational capabilities of a digital computer can complement the network analyzer's versatility through simplifying and speeding measurements, data processing, and accuracy enhancement. Hewlett-Packard has combined network analyzers and computers into measurement systems and now offers some analyzers that may be easily interfaced with HP desktop computers through the Hewlett-Packard Interface Bus.

Computer controlled network analyzers can be programmed to set up and make many measurements automatically. The measurement process is further accelerated by the computer's ability to store, transform, sum-

marize, and output data in a variety of formats to a number of peripherals. These capabilities make the computer controlled network analyzer ideal for both computer aided design or automatic production testing.