APPLICATION NOTE

The Bird BNA Series
Vector Network Analyzer Basics

Vector Network Analyzer Basics

A vector network analyzer (VNA) is an extremely sophisticated instrument capable of characterizing impedance of electrical networks with measurements offering magnitude and phase details that enable thorough behavioral insights. The device under test (DUT) often tends to be used in radio frequency (RF) applications that involve understanding the response of things such as individual components, cables, antennas, filters, amplifiers, and much more. In all cases, it is the job of the VNA to compare its source signal to measurements of reflected and transmitted signals, yielding impedance and scattering parameter (S-parameter) data to inform the user of a device's power-handling capabilities.

This application note will provide cursory insight on topics necessary to get you started in understanding the vector network analyzer. We will start with a review of the foundational terminology applied during the use of a VNA and other RF-related topics. We then offer an overview of the hardware ecosystem that makes up the VNA architecture. Finally, we provide an understanding of S-parameters.

VNA Measurement Concepts and Common Terminology

The operation of a VNA is regularly analogized with how light responds when sent through a lens. The ***incident*** light (shown in **Figure 1**) is the source or reference which starts off at its full potential. While it may be desired to have the entirety of the source pass through the lens, we understand that there may be attributes of the lens that cause it to increase or diminish the intensity of the incident as well as imperfections that may distort or skew the signal. We refer to the resultant signal after its pass through the lens as the **transmitted** signal.

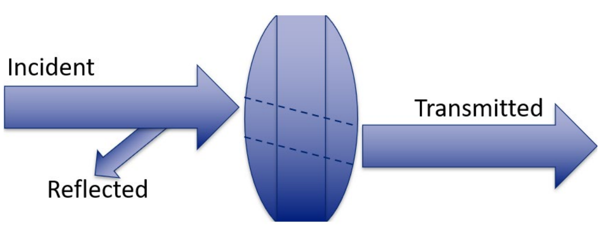

Figure 1: General concept of light response as it passes through a lens.

Additionally, we can understand that when the incident strikes the lens there will inevitably be some of it which does not pass but bounces back in the direction of the origin. This is referred to as the reflected signal.

The goal of an RF system is to achieve transferring the maximum amount of power. To quantify this, measurements of the incident, reflected and transmitted signals are necessary. Further, once these values are known, different ratio-based measurements can be quantified for the device or system, examples of which are illustrated in **Figure 2**, with definitions for each provided in the text that follows.

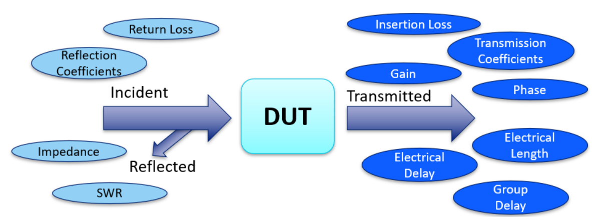

Figure 2: VNA measurement summary with respect to the device under test using measurement information from incident, reflected, and transmitted signals.

- **Return Loss** – "Also known as reflection loss; a measure of the fraction of available power that is not delivered by a source to a load." [1]
- **Reflection Coefficients** – "A parameter that describes how much of an electromagnetic wave is reflected by an impedance discontinuity in the transmission medium." [2]

- **Impedance** – "The effective resistance of an electric circuit or component to alternating current, arising from the combined effects of ohmic resistance and reactance." [3]
- **Standing Wave Ratio (SWR)** – "The ratio of the maximum amplitude of the total voltage to the minimum amplitude of that voltage." [4] Also referred to as voltage standing wave ratio or VSWR and often referred to as "match".
- **Insertion Loss** – "A measure of the amount of loss in power or signal strength that occurs when a device, such as a filter or an amplifier, is inserted into a transmission line or circuit." [5]
- **Gain** – In general, similar to the definition of insertion loss with the exception that the amount of power increases through the device in the circuit.
- **Transmission Coefficients** – "The ratio of the transmitted particle current and the incident particle current, and will depend on the incident energy." [6]
- **Phase** – "The position of a wave at a point in time on a waveform cycle and lies somewhere between 0 and 360 degrees." [7]
- **Electrical Length** – "A dimensionless parameter equal to the physical length of an electrical conductor such as a cable or wire, divided by the wavelength of alternating current at a given frequency traveling through the conductor." [8]
- **Electrical Delay** – The time it takes for an electrical signal to pass through a DUT.
- **Group Delay** – "The negative derivative of the phase response, so a distortion [-]less system has a constant, positive group delay." [9]

These types of system observations are achieved by the hardware elements that compose the VNA as highlighted in the next section.

VNA Building Blocks and Architectures

Before looking at the vector network analyzer architecture as a whole, it is important to understand the fundamental components and the role that each play.

Because we want to observe how our device responds to a known stimulus, the network analyzer relies upon a signal source (**Figure 3**) to perform repetitive frequency sweeps over the range of interest using a controlled power level.

Figure 3: Symbol for an RF signal source.

The source can also be configured for power sweeps using a known frequency or set of frequencies when performing gain compression point testing of an amplifier.

Some multi-port network analyzer topologies may use a single source to drive all ports. In such cases, switches help simplify the design and limit cost. **Figure 4** provides examples of different switches you might encounter in any type of circuit.

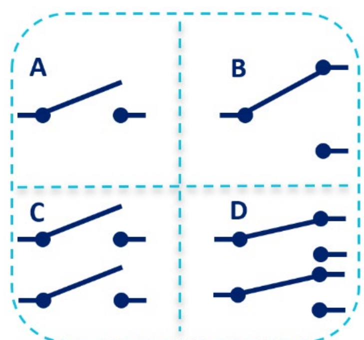

Figure 4: Different switch form factors – A) single pole, single throw (SPST), B) single pole, double throw (SPDT), C) double pole, single throw (DPST, and D) double pole, double throw (DPDT).

Measurements are made by way of signal separation hardware to help minimize the invasiveness of placing sensors in the immediate path of the incident, reflected, or transmitted signals. This can be achieved by using directional couplers or directional bridges, the latter of which is not a focus for this writing. From **Figure 5A**, we can see how the incident signal might enter port 1 of a directional coupler then exit port 2. Port 3 yields a resultant signal that is typically on the order of 10 to 20 dB less than that of the incident and used by the VNA for its measurements.

In many cases, the output on port 3 of the directional coupler is buffered by some resistance or attenuation.

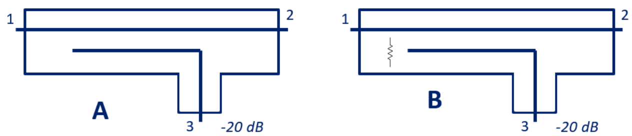

Figure 5: A) Symbol for directional coupler with the coupled signal being -20 dB relative to the incoming signal. B) Symbol for directional coupler with the addition of attenuation per the resistance symbol.

In these cases, the symbol for the device will be modified to appear as in **Figure 5B**.

Since even a single port network analyzer will need to be able to measure the incident in reflected signals, it is common to find multiple coupling devices within a network analyzer topology. While coupling devices are optimal choices for sampling signals, they will carry some level of insertion loss and have an effect on the overall directivity of the system. Similar can be said of any switches or mixers. Much of this though, can eventually be compensated for by factory and measurement calibrations.

As alluded to in the previous paragraph, a portion of the network analyzer circuitry is dedicated to mixers and a tunable local oscillator (LO) – see **Figure 6** – that helps resolve higher frequencies to a lower intermediate frequency (IF), then used to define a signal passband through a downconverter. Some diagrams may opt to bypass showing the passband in favor of implying that the functionality gets addressed by the analog-to-digital conversion (ADC) and digital signal processing (DSP) stages.

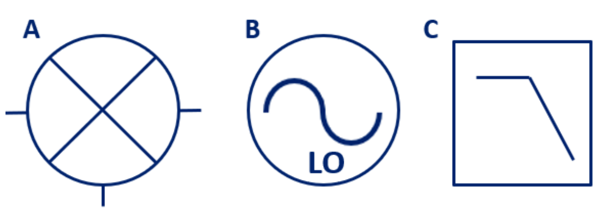

Figure 6: Symbols for A) mixer, B) local (IF) oscillator, and C) passband or low pass filter.

Figure 7 shows all the components assembled representing a typical 2-port vector network analyzer construction. The ADC and DSP blocks handle tasks such as down-conversion and filtering then passing along the outcomes for analysis. Results and calculations (either from standard S-parameters or data comparison) can be evaluated through an integrated display or accessed using an available input/output (IO) or communications protocol, popular choices being USB and LAN.

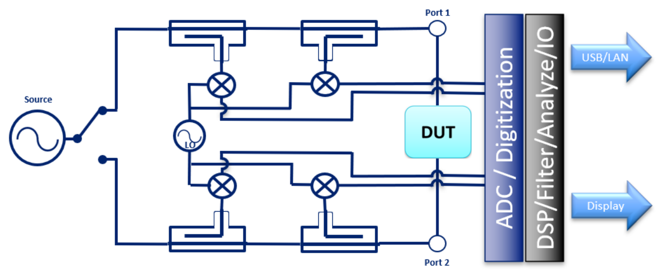

Figure 7: Example of a 2-port network analyzer architecture.

While the diagram captures the basic working principles of either a scalar or vector network analyzer, it is important to understand the distinction between the two. The function of a scalar network analyzer is to provide magnitude information only, ignoring any information about phase. This may make for a good choice where simple gain/loss, return loss, and VSWR measurements are of primary interest, for instance, in manufacturing. However, the vector network analyzer is the optimal choice in a research and development setting where phase information is critical for not just some of the more informative measurements (i.e. impedance or group delay) but also used for system corrections applied through the process of calibration.

The evolution of network analyzers has seen a shift from standalone units with embedded operating systems and integrated displays to more disaggregate solutions that leverage the power and flexibility of personal computers. Modern VNAs, particularly those with a modular USB or PXI form factor, are designed to integrate seamlessly with PCs, becoming an extension of the computer itself. This arrangement aids the user in the possible transition from the design phase in their lab to creating automated setups that can be deployed in production. Furthermore, with no residual data retained post-power down, these VNAs ensure that sensitive setup and measurement information remains with the user's PC. This translates to the ease of sharing VNA hardware with the confidence that each user can retain their unique configurations without much concern for loss or over-writing.

S-parameters

Simply put, the job of the VNA hardware is to capture scattering parameter, or S-parameter, data – by measuring magnitude and phase of incident, reflected, and transmitted signals – then use it to inform the operator on the device performance through measurements such as those referenced in Figure 2. To get full appreciation of all S-parameter measurements, it is important to understand that, while we see the incident passing in one direction in Figure 2, the incident could also originate on the opposing side of the lens and provide information from another perspective. Figure 8 shows the full set of S-parameters that can be gained from a 2-port test configuration.

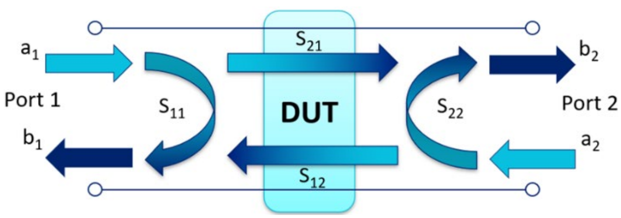

Figure 8: Visual concept of how S-parameters are defined through source and measurement signals.

S11 and S22 are all about reflections. S11 tells you how much of the signal that you send into your device bounces back, which is crucial because too much bounce-back means the device is not absorbing the signal properly, affecting performance. S22 does the same, but it looks at the signal coming out of the device. Either case is in reference to a characteristic impedance, Z0, to which the input and/or output is intended to match at certain frequencies for maximum power transfer conditions. Measuring S11 and S22 is like checking both the front door and back door of a house to make sure they are properly sealed against poor weather conditions.

S21 and S12 deal with transmission - how much signal goes through the device from one port to the other. S21 measures the signal that goes from the input to the output, giving you an idea of the efficiency of the signal transfer. On the flip side, S12 measures the signal that makes it through the device the opposite way, from the output back to the input. While S21 is usually the star of the show, as it tells us about signal gain or loss, S12 can be just as important, especially when isolating signals is a key concern.

Conclusion

In summary, VNAs are more than just test equipment; they are the gatekeepers of quality and performance in the RF domain. Their importance extends through every stage of the product lifecycle, from conception and design to manufacturing and field deployment. Understanding how to leverage the capabilities of a VNA can unlock new possibilities in engineering, leading to innovations that continue to push the boundaries of what is possible in electronics and communications technology.

S-parameters are the key metrics VNAs use to gauge a device's performance. S11 and S22 are reflective parameters, telling us how much signal is reflected back from the input and output, respectively—critical for understanding how well the device absorbs and transfers power. On the other hand, S21 and S12 are transmission parameters, revealing the efficiency of signal transfer through the device from one port to another. S21 usually takes center stage by indicating signal gain or loss, while S12 provides insight into signal isolation, particularly important in complex RF systems.

These measurements are made possible by a network analyzer's internal hardware, which includes signal sources for frequency sweeps, directional couplers for signal separation, and mixers for frequency resolution. Calibration plays a vital role in offsetting any insertion loss from these internal components, ensuring accuracy in measurements. Today's VNAs often interface with PCs, enhancing the transferability of data and settings across different development and production stages. This setup also heightens security as all sensitive information resides on the PC, adhering to existing security protocols. Whether it's for reflection, transmission, impedance, or delay measurements, VNAs serve as critical tools in assessing and ensuring device and system efficacy.

For more information about Vector Network Analyzers, please visit https://birdrf.com.

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