Estimated reading time: 16 minutes.

RF performance evaluation using test equipment

To measure a Radio Frequency (RF) signal is a task that requires a reasonable knowledge in test equipment usage. Depending on the test equipment configuration, one could read completely wrong results, which do not represent the true performance of the device being tested.

In order to analyze an RF signal, one can choose between two types of measurements:

1. Radiated (antennas)
2. Conducted (cables)

The very first measurement to evaluate the performance of an RF signal is a conducted measurement. This measurement is usually made by connecting a coaxial cable to the Device-Under-Test (DUT), so that the signal propagation is confined inside this cable to avoid interference.

Once the DUT passes on conducted measurements, the radiated measurements are performed. In this tutorial, only conducted measurements are discussed.

Introduction on spectrum analyzer usage

One of the most important instruments to operate when measuring an RF signal is the spectrum analyzer, since it is capable of showing signals in the frequency domain.

Before getting started with the usage of the spectrum analyzer, a basic review of frequency domain and time domain signals are discussed in the following sections.

Time Domain Signals

Time Domain analysis is the study of mathematical functions, physical signals, or series of data in the context of time. In the time domain, the value of the signal or function is known for all real numbers in continuous time, or at several distinct instants in discrete time. [1]

The parameter's behavior in the time domain is usually periodic, which means that it repeats itself in a distance equal to T. T being the period of time that contains a cycle of the frequency “f”. This establishes the basic rule of mapping between the two domains: $f = 1/T$. An important point is to identify conditions where it is more convenient to analyze a signal in the frequency domain. We know that in the time domain we need to clearly define the function and the parameters that describe it, for example:

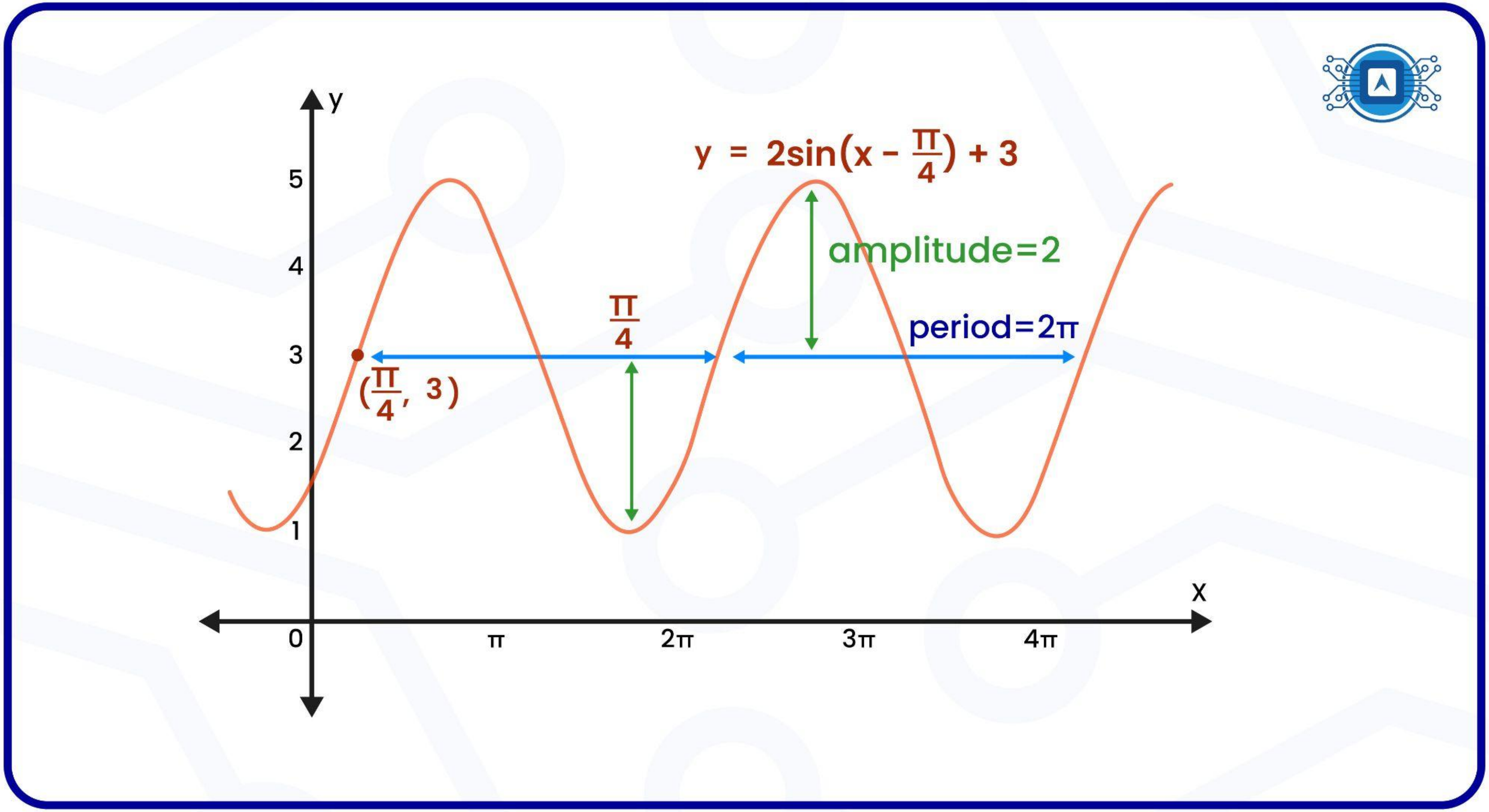

Image 01: A sinusoid representation in the time domain. Source: *Math.net <https://www.math.net/sinusoidal>*.

The image shows the signal in the time domain, where:

A = Amplitude

$f = 1/T = \omega/2\boldsymbol{\pi} =$ frequency

$\boldsymbol{\varphi} = 2\boldsymbol{\pi}.\boldsymbol{\Delta}T/T =$ the initial delay's angle ΔT

Oscilloscope

The oscilloscope is a commonly used instrument to see real-world signals in the time domain. The time domain graph shows how a signal changes over time, whereas the frequency domain graph shows how much of the signal is within each frequency band in a specific frequency range.

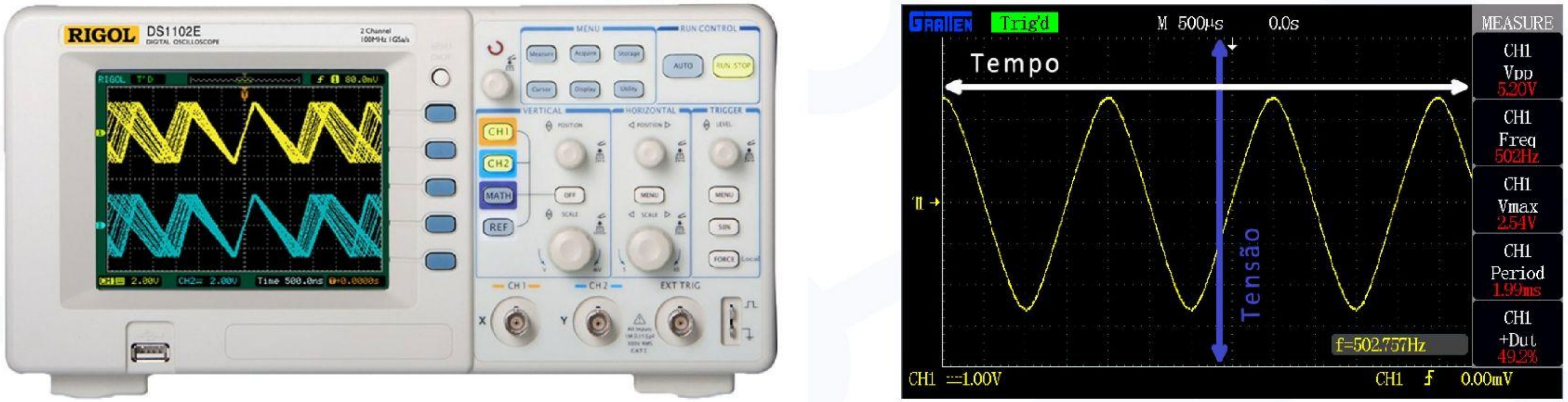

Image 02: Digital Oscilloscope (left), Screenshot of an oscilloscope with a sinusoidal signal (right).
Source: *Rigol UK <https://www.rigol-uk.co.uk/products/digital-oscilloscopes/rigol-ds1000e-series/>*.

Frequency Domain Signals

In physics, electronics, control systems engineering, and statistics, the frequency domain refers to the analysis of mathematical functions or signals regarding frequency, instead of time. To clarify, a graph in the time domain shows how a signal changes over time, whereas a graph in the frequency domain shows how much of the signal is within each frequency band in a specific frequency range. A frequency domain plot can also include information about the phase shift that must be applied to each sinusoid in order to recombine the frequency components to recover the original signal in time.

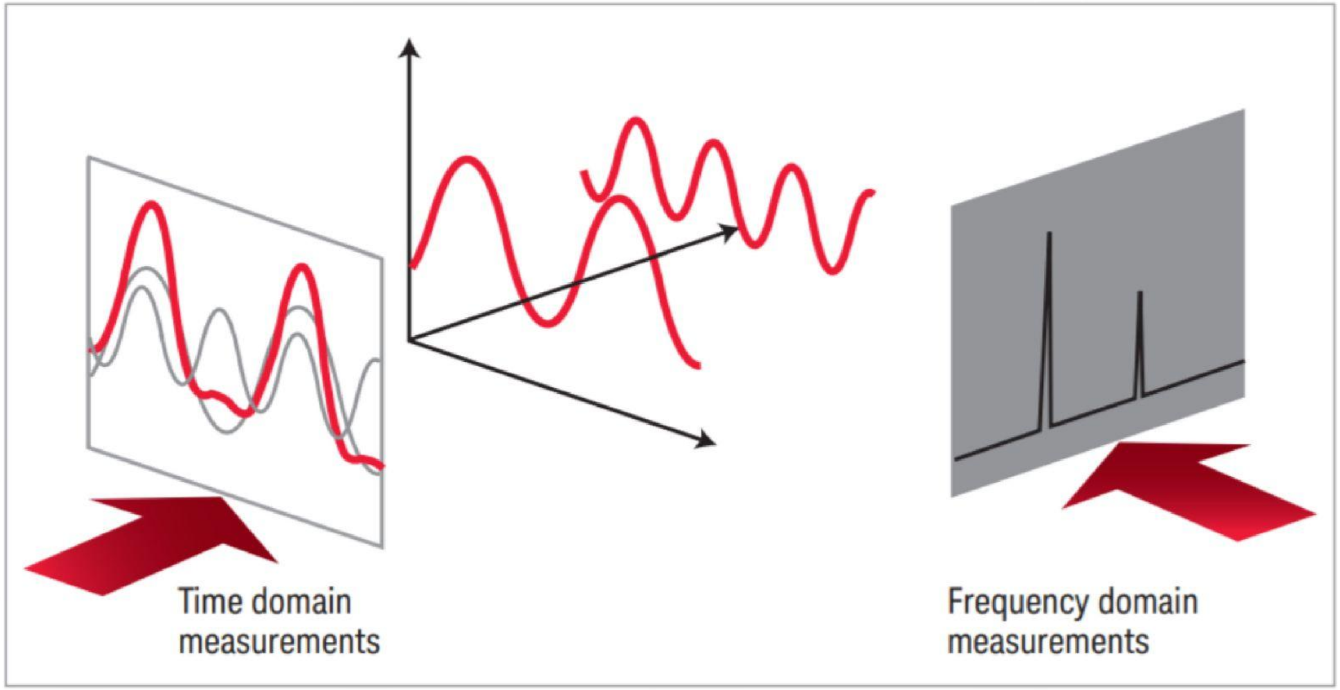

Image 03: The time domain of a signal on the left, and the frequency domain of the same signal on the right. The time domain displays a signal in respect to amplitude vs. time whereas the frequency domain displays amplitude vs. frequency. Source: Keysight <https://edadocs.software.keysight.com/kkbopen/why-measuring-in-the-time-domain-and-frequency-domain-is-the-same-but-not-603167255.html>.

Fourier Transform

The Fourier transform converts a time domain function into a complex sum of values or the integral of sinusoidal waves of different frequencies, with amplitudes and phases. Each of these elements represents a frequency component. The “spectrum” composed by the frequency components is the signal representation in the frequency domain. The inverse Fourier Transform converts the function in the frequency domain back to the function in the time domain. The spectrum analyzer is a commonly used tool for visualizing electronic signals in the frequency domain.[1]

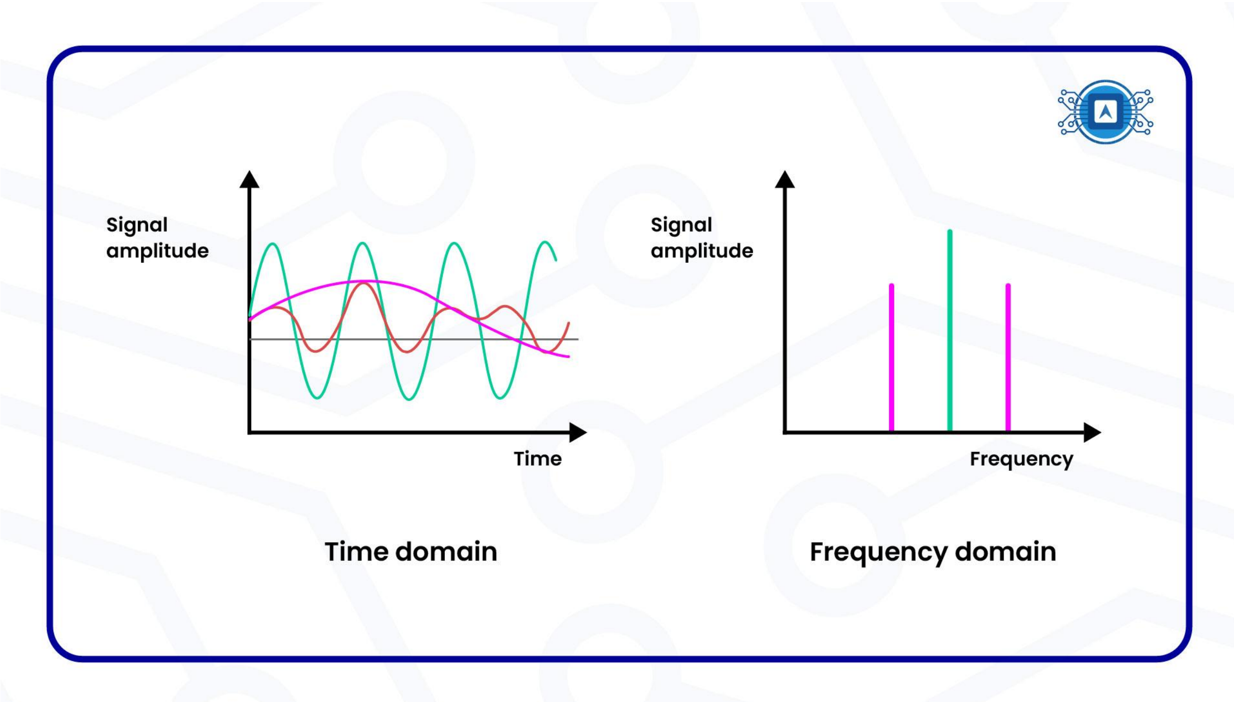

Image 04: Signals in the time and frequency domain. Source: Adapted from *Deep AI* *<https://deepai.org/machine-learning-glossary-and-terms/frequency-domain>.*

Spectrum Analyzer

The spectrum analyzer is a test equipment that allows one to perform frequency domain analysis as seen in the Fourier transform. Therefore, it presents a graph of amplitude versus frequency. The spectrum analyzer can be used to perform the following analysis on RF signals:

- Power;
- frequency tuning;
- modulation;
- intermodulation;
- noise and harmonic distortion.

To obtain the analysis of these signals we set up:

- The center Frequency
- The frequency range around the center frequency, which is also known as the SPAN
- Signal power amplitude
- The Resolution BandWidth filter
- The reference power level

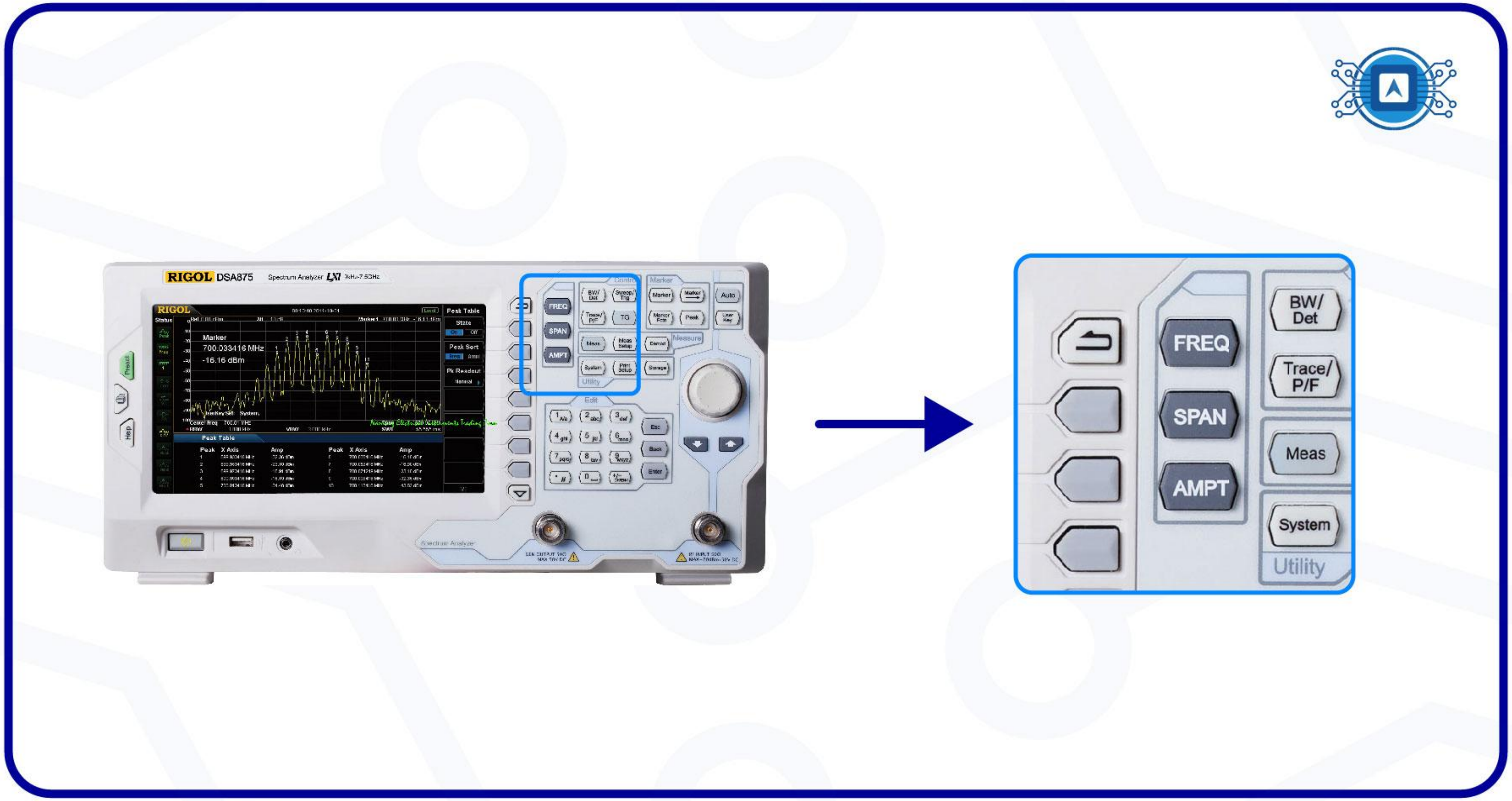

Image 05: Rigol DSA815-TG 9kHz to 1.5GHz with Pre-Amplifier and Tracking Generator Spectrum Analyzer with detail on FREQ, SPAN and AMPT buttons. Source: *Rigol <https://www.rigolna.com/products/spectrum-analyzers/dsa800/>.*

The amplitude is usually given in decibel milliwatt (dBm) and the frequency in Hertz (Hz). The RBW is usually chosen as 1/10 or 1/20 of the desired frequency span, depending on how close the frequency components of the signal are. The lower the RBW value, the higher the frequency resolution. However, using an RBW that is too narrow could make it difficult to measure the signal power with precision.

The reference power level must be above the input signal being fed to the spectrum analyzer, so as not to overload the instrument front-end. Most of them have internal protection, but a good margin should always be considered when testing an unknown signal for the first time.

The dBm unit

A dBm or dBmW (decibel milliwatt) is a unit of measurement used mainly for telecommunications to indicate absolute power by means of a logarithmic expression. It is defined as the power level in decibels relative to the reference level of a 1 mW and can be expressed using the equation:

$$P_{\mathrm{dBm}} = 10 \log_{10}\left(\frac{P}{1mW}\right)$$

,

where:

- PdBm is the power in dBm
- P is the power in milliwatt

One can notice that spectrum analyzers use the Fourier Transform (usually the FFT - Fast Fourier Transform) which displays the frequency domain signal on the screen.

A practical example of using a spectrum analyzer is to place an antenna (UHF) on the instrument's input and pick up the signals from TV antennas and check the signal power reaching the antenna.

Image 06: Spectrum analyzer collecting signal from TV transmitters. Source: *Shutterstock*.

Introduction and Use of the Vector Network Analyzer

Vector network analyzers, VNAs for short, measure the transmission and reflection properties of RF devices. They examine all the ports of the device and provide information about the impedance of the ports and the transmission gain/loss through the device.

How a Vector Network Analyzer works (VNA)

A vector network analyzer (VNA) includes both source signals and receivers. Receivers detect changes in the output signal from a device (or network) compared to the input of the source signals in the device. By comparing the ways in which current and voltage are affected by the device, a VNA measures the amplitude and phase of the desired device parameter. The device parameters in transmission measurements can be the transmission coefficient, insertion loss and gain. On the other hand, reflection measurements can be the reflection coefficient, VSWR and return loss, impedance. The most well known measurements that the VNA performs are the S-parameters (scattering parameters).

S-parameters (Scattering parameters)

The S-parameters are members of a family of network parameters, such as Y, Z, H, T and even ABCD-parameters.

S-parameters differ from these other parameters in the way each of its terms are obtained. For example, Y and Z parameters require open and short circuits to zero out some terms to obtain others. In signals that propagate as electromagnetic waves, one has to use impedance matching/mismatching to zero out some terms to obtain the others. Thus, one has to use a combination of different loads to calibrate the VNA, including open and short circuits.

Despite popular belief, the values are not measured in terms of power (except in now obsolete six-port network analyzers). Modern vector network analyzers measure voltage traveling wave's amplitude and phase factors, using essentially the same circuit used for digital demodulation of wireless signals.

Many electrical properties of component networks (inductors, capacitors and resistors) can be expressed using S-parameters, such as gain, return loss, voltage standing wave ratio (VSWR), reflection coefficient and amplifier stability.

The term 'scattering' is more common to optical engineering than RF engineering, referring to the effect observed when a plane electromagnetic wave meets an obstruction or passes through different dielectric material. In the context of S-parameters, scattering refers to the way in which currents and voltages in a transmission line are affected when they encounter a discontinuity caused by the insertion of a network into the transmission line. This is equivalent to the wave encountering an impedance that is different from the typical impedance of the line.

Although generally used at any frequency, S-parameters are mainly used for networks operating at radio (RF) and microwave frequencies, where signal power and energy considerations are more easily quantified than currents and voltages. S-parameters change with the measurement frequency, so the frequency must be specified for any indicated S-parameter measurements in addition to the typical or system impedance.

The S-parameters are represented in matrix form and obey the rules of matrix algebra. The 2-port S-parameters have the following general descriptions:[4]

S(11) - Is the input voltage reflection coefficient.

S(12) - Is the reverse voltage gain.

S(21) - Is the direct voltage gain.

S(22) - Is the output voltage reflection coefficient.

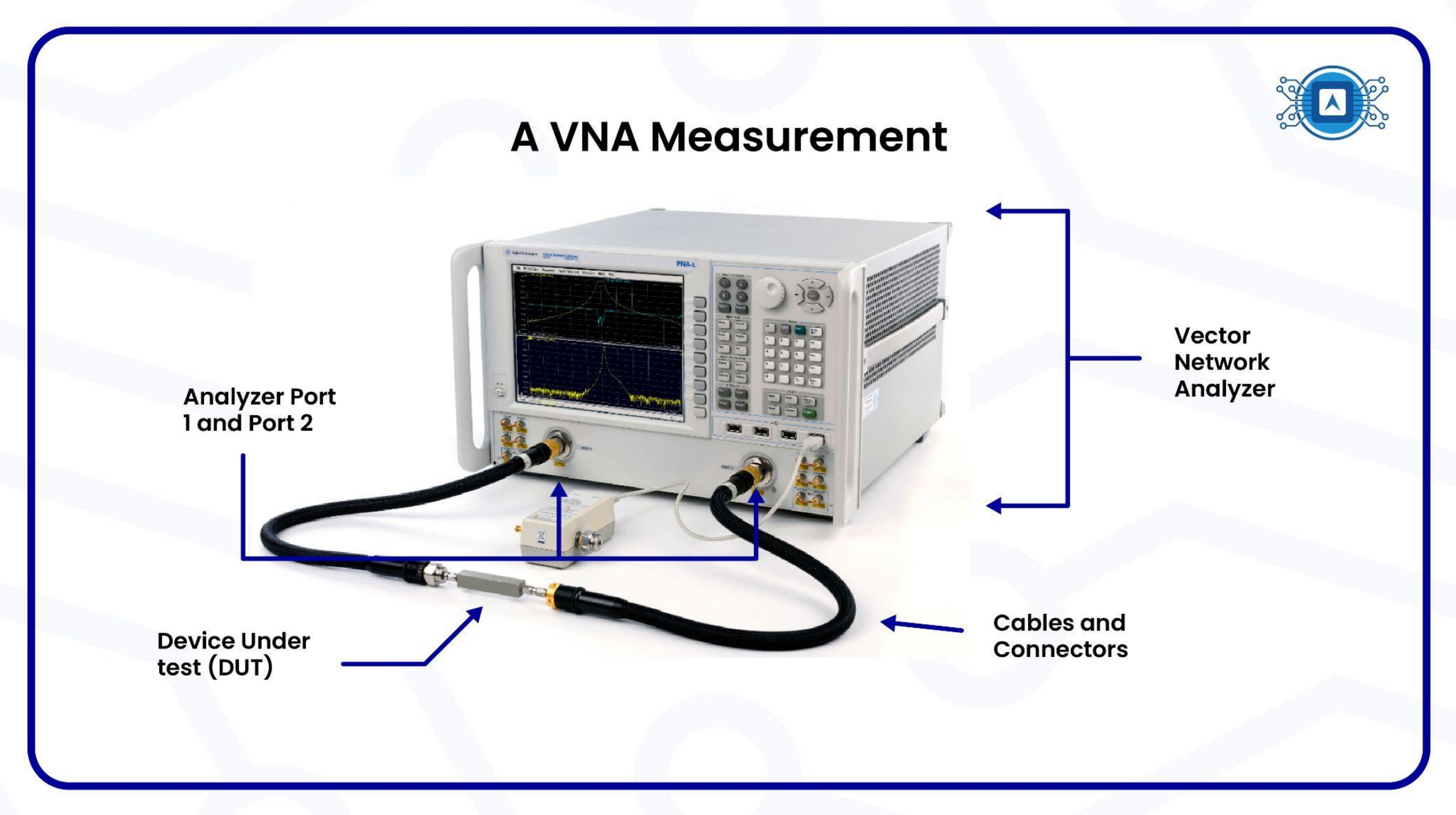

Image 07: A typical VNA measurement of a DUT. Source: *Keysight*
<https://about.keysight.com/en/newsroom/imagelibrary/library/PNA-L_images/image001_high.jpg>.

Calibration kit

Standard elements for OSLT calibration

- Load of 50 Ohm (or 75 Ohm)
- Short circuit
- Open circuit
- Through adapter
- Sliding load (optional)

Image 08: Box with coaxial calibration kit. Source: *Omlink <https://www.omlinc.com/22-products/vna-calibration-kit/7-vna-calibration-kit>.*

VNA calibration

The VNA must be calibrated before doing any measurement with it. The reason is that the S-parameters are obtained by reference to a calibration plane. This plane is defined as the test point to be connected to the Device-under-test (DUT), which is usually the end of a cable. The calibration compensates the cables losses and corrects several errors, among which are crosstalk, return losses, transmission losses of the cables and/or test fixtures. The objective is to eliminate any influence of the cables and/or fixtures on the measurements results.

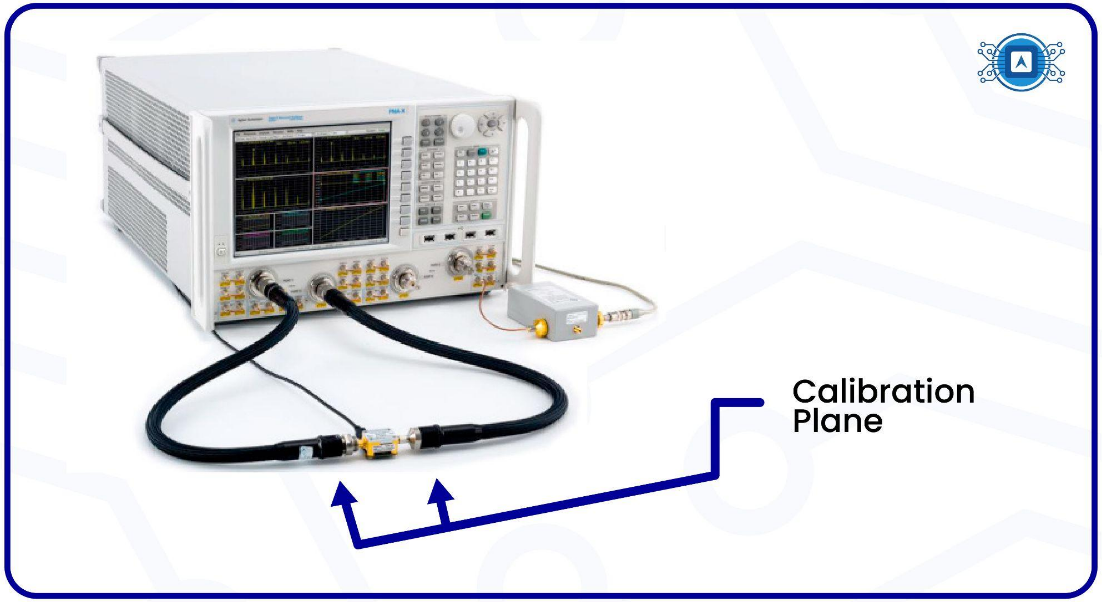

Image 09: VNA calibration plane at the end of each cable. Source: *Science Direct* *<https://www.sciencedirect.com/topics/computer-science/vector-network-analyzer>.*

The VNA calibration procedure depends on the number of ports used. Each port has to be calibrated for an OPEN, SHORT and LOAD, besides the THRU to other ports if more than one port is used. For the sake of simplicity, it is considered here a bi-directional 2-port VNA (some VNAs have 2 ports but they are unidirectional) and a regular SOLT calibration kit. Thus, proceed as follows:

1. Set the VNA for calibration using the menu options according to its manual.
2. Calibrate port 1 and port 2 for OPEN, SHORT and LOAD.

    a. Assuming two cables are connected to each of the 2 ports of the VNA:
        i. Connect the OPEN standard from your calibration kit to the end of the cable that is to be connected directly to the DUT.
        ii. Repeat for the SHORT and LOAD standards.
        iii. Do that for both ports of the VNA.
3. Calibrate port 1 and port 2 with the THRU standard by connecting one end to port 1 cable to the end of port 2 cable (basically shorting out ports 1 and 2 through their cables).

Once the calibration procedure is done, check the manual of your equipment to see how to activate the calibration and perform the measurements.

It is also important to ask for assistance from the VNA manufacturer’s, if the reader is dealing with very expensive equipment or if the manual is not clear on how to operate the menu to get to the calibration state.

References

[1] TIME/FREQUENCY Domain Representation of Signals. Available at: https://learnemc.com/time-frequency-domain . Accessed June 13, 2022.

[2] TIME Domain Analysis vs Frequency Domain Analysis: A Guide and Comparison. Available at: https://resources.pcb.cadence.com/blog/2020-time-domain-analysis-vs-frequency-domain-analysis-a-guide-and-comparison . Accessed June 13, 2022.

[3] PRACTICAL Introduction to Frequency-Domain Analysis. Available at: https://www.mathworks.com/help/signal/ug/practical-introduction-to-frequency-domain-analysis.html;jsessionid=3ba495270d06f2489720028c43b5 . Accessed June 13, 2022.

[4] SCATTERING parameters. *In*: Wikipédia. [*S. l.*], 2005. Available at: https://en.wikipedia.org/wiki/Scattering_parameters . Accessed June 13, 2022.

[5] CHOMA, Dr. John. Scattering Parameters: Concept, Theory, and Applications. Available at: https://www.ieee.li/pdf/essay/scattering_parameters_concept_theory_applications.pdf . Accessed June 13, 2022.

Additional Reading

Glossary

Decibel

The bel (symbol: B) is a dimensionless unit of measurement, which compares the intensity of a signal to a reference level. It is named after the physicist Alexander Graham Bell.

NYQUIST

It is a graphical technique to determine the stability of a dynamic system. It was developed by the Swedish-American electrical engineer Harry Nyquist at Bell Telephone Laboratories in 1932.

ALIASING

In digital signal processing and similar subjects, aliasing is an effect that causes different signals to become indistinguishable (or aliases of each other) when sampled. It also refers to the distortion or artifact that results when a signal reconstructed from samples is different from the original continuous signal.