

Experiment 12 - Measuring X-Parameters Using Nonlinear Vector Network Analyzer

1 Introduction

In this experiment, firstly, we will be measuring X-parameters for our power amplifier of interest. X-parameters are measured on a nonlinear vector network analyzer (NVNA). We will then be using these X-parameters in simulation to extract 1-dB compression point, and third-order intercept point (TOI). Finally, we will perform a comparison between NVNA X-parameters and VNA power sweep measurement.

2 Background

The single large-tone X-parameters formalism is

$$\begin{aligned}
 B_{p,k} = & X_{p,k}^{(FB)}(|A_{1,1}|, DC, f) * P^k + \\
 & \sum_{\substack{q=1, l=1 \\ (q,l) \neq (1,1)}}^{q=N, l=K} X_{p,k;q,l}^{(S)}(|A_{1,1}|, DC, f) * A_{q,l} * P^{k-l} + \\
 & \sum_{\substack{q=1, l=1 \\ (q,l) \neq (1,1)}}^{q=N, l=K} X_{p,k;q,l}^{(T)}(|A_{1,1}|, DC, f) * A_{q,l}^* * P^{k+l}
 \end{aligned} \tag{1}$$

where $A_{q,l}$ is the contribution from the incident wave of the l th harmonic at port q , $A_{q,l}^*$ is its complex conjugate, and $B_{p,k}$ is the contribution from the scattered wave of the k th harmonic at port p . These frequency components of the incident and scattered waves are called pseudowaves. $X_{p,k}^{(FB)}$ is a scattering parameter of type FB that accounts for the contribution from the large-amplitude input tone at the fundamental frequency, $A_{1,1}$, to the k th harmonic of port p for a system in which all the other incident pseudowaves are zero. All the other incident pseudowaves being equal to zero is equivalent to the system being perfectly matched at each harmonic at each point. The X-parameter of type FB has the same units as the scattered and incident waves. $X_{p,k;q,l}^{(S)}$ is a scattering parameter of type S that accounts for the contribution to the k th harmonic of the scattered wave at port p from the l th harmonic of the incident wave at port q . $X_{p,k;q,l}^{(T)}$ is a scattering parameter of type T that accounts for the contribution to the k th harmonic of the scattered wave at port p from the l th harmonic of the conjugate of the incident wave at port q . Intuitively, these parameters determine the circuit's sensitivity to mismatch to the system impedance at the k th harmonic of port p . The X-parameters of types S and T are ratios of power waves and thus,

like traditional scattering parameters, unitless. DC is the DC voltage or current biasing and f is the fundamental frequency. We include them here to clarify that all of these parameters depend on the fundamental frequency and any DC biases in addition to the magnitude of the input at the fundamental frequency. P^{k-l} is a pure phase term that compensates for the magnitude-only dependence of $A_{1,1}$ on the X-parameters to ensure the time-invariance of the model. N is the total number of ports and K is the total number of harmonics. These X-parameters together characterize the nonlinear dynamics of the network of interest with a large-signal operating point at a particular input fundamental frequency and power.

X-parameters can be measured in the laboratory with a nonlinear vector network analyzer (NVNA). An NVNA is based on the same form factor as a PNA-X, a Vector Network Analyzer (VNA) that has two filtered microwave sources and an internal combiner, pictured in Figure 1.

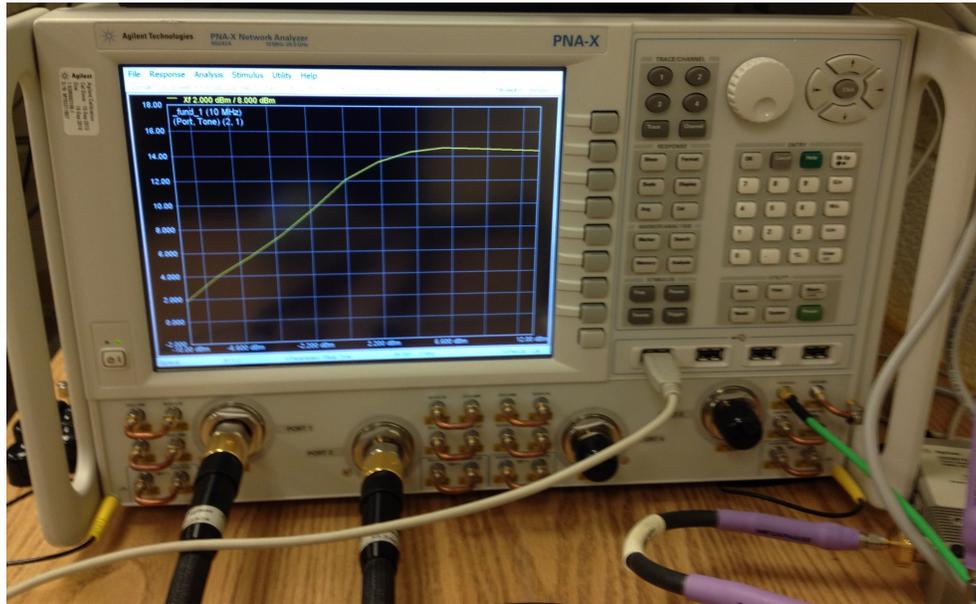


Figure 1: An Agilent PNA-X Series Network Analyzer

The PNA-X on its own can use these two microwave sources to measure some nonlinear device figures of merit such as inter-modulation distortion (IMD) or mixer conversion gain. Because a nonlinear system can no longer rely on the linear properties of homogeneity and superposition, any accurate measurement of a nonlinear figure of merit requires absolute power measurements. These absolute power measurements are calibrated with the use of an external power meter, pictured in Figure 2. All of the nonlinear measurements made with the PNA-X are scalar because it is unable to capture cross-frequency phase information.



Figure 2: An Agilent Power Meter Used for Amplitude Calibration

The additions to a PNA-X that turn it into an NVNA are designed to solve this problem and allow the device to capture cross-frequency phase relationships between incident and scattered waves. The key addition is a phase reference repetitive-pulse generator, as pictured in Figure 3.



Figure 3: Repeated Pulse Generator Serves as a Phase Reference for NVNA Measurement System

This repetitive-pulse generator takes in a sinusoid at frequency f and generates an impulse repeating at that frequency, as shown Figure 4.

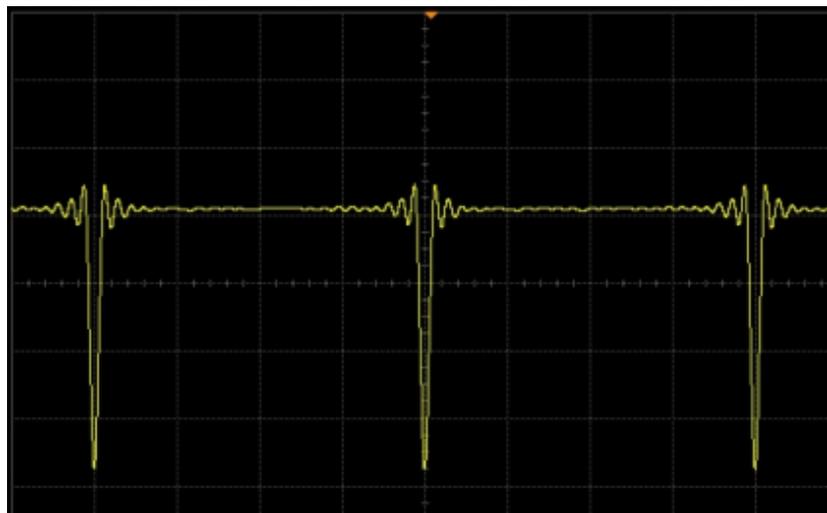


Figure 4: Time-Domain Plot of the Impulse Produced from the Repetitive-Pulse Generator

In the frequency domain, this time-domain impulse train is an impulse train with its impulses at $n * f$ for all integer values of n , having an appearance similar to the bristles of a comb, as shown in Figure 5.

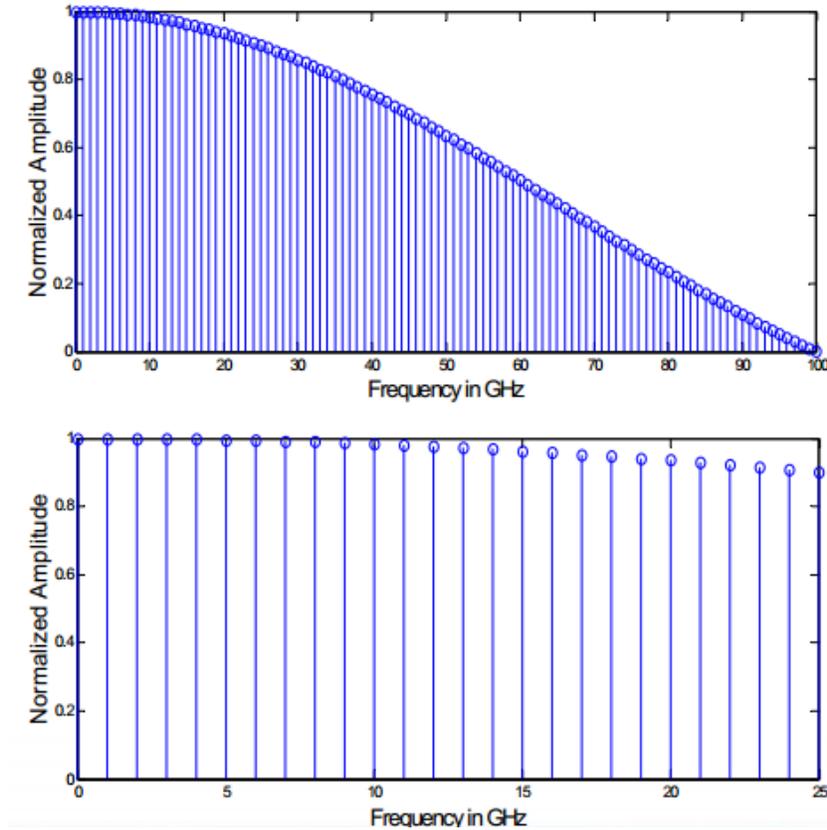


Figure 5: Frequency-Domain Plot of the Impulse Produced from the Repetitive-Pulse Generator

Most importantly, the phase relationship between the different harmonics at the output of the repetitive-pulse generator is constant versus input drive frequency and power. Thus, the repetitive-pulse generator can provide a static cross-frequency phase reference for a variety of measurement scenarios. Other examples of potential phase references would be devices that take in a sinusoid and output a square wave, a triangle wave, or a sawtooth wave. The repetitive-pulse generator is preferred to these other potential phase references because its frequency output spectrum decreases more slowly in magnitude with respect to increasing output frequency and includes both even and odd harmonics.

In the NVNA, a separate signal generator sources two phase reference repetitive-pulse generators. The input frequency to these repetitive-pulse generators is planned carefully so that every frequency seen at the output of the DUT – harmonics, intermods, mixing products, etc. – will have a corresponding harmonic component at the same frequency in the output of the repetitive-pulse generators. The output of the first repetitive-pulse generator is connected to a receiver in the NVNA, where it is used as an absolute phase reference for all of the incident and scattered test signals. During phase calibration, the second repetitive-pulse generator is connected to the NVNA test port that will provide the large-signal stimulus to the input of the DUT. This is used to calibrate the cross-frequency phase relationships at the device plane.

Therefore, each frequency component in the scattered and incident waves can be compared to the corresponding frequency component in the phase reference. The phase calibration process gives the NVNA the information it needs to relate the phases of the different frequency components in the phase reference to each other. Hence, two measured frequency components at different frequencies can first be compared to their corresponding frequency components in the phase reference.

Since the frequency references can be compared to each other, the different measured frequency components can be compared to each other.

Maintaining an accurate, static, cross-frequency phase relationship allows the NVNA to make vector measurements across different frequencies. This allows for the conversion of the nonlinear frequency-domain measurements to the time domain as well as the generation of accurate distortion models for a device. The calibration of an NVNA is a three-step process. The first step is the aforementioned phase calibration to measure cross-frequency phase. The second is an amplitude calibration using a power meter to calibrate the microwave sources and receivers of the NVNA. Last, the NVNA performs a vector error correction, usually made using an Electronic Calibration (ECal) Module like the one pictured in Figure 6, to move the reference planes of the measurement to the ports of the device under test (DUT) (see Dunsmore for in-depth description of ECal).



Figure 6: Electronic Calibration Module Used for Vector Error Correction

This vector error correction in NVNA measurements is different from that of a typical VNA. A typical VNA uses the error model in Figure 7. Because of the superposition property of linear devices and the fact that the stimuli needed for S-parameter extraction are only applied at one port at a time, the forward and reverse error models can be separated to form the ten-term error model, each direction being comprised of five error terms. This error model compensates for errors caused by imperfections in the VNA measurement components, imperfect directivity, reflectivity, and transmission tracking, and source and load mismatch. To minimize the number of terms in the model, the error model combines the e_{1f}^{10} and e_{1f}^{01} terms and the e_{2r}^{10} and e_{2r}^{01} by normalizing one parameter to unity. This is possible because a VNA only makes ratios of power waves so no absolute measurements are needed.

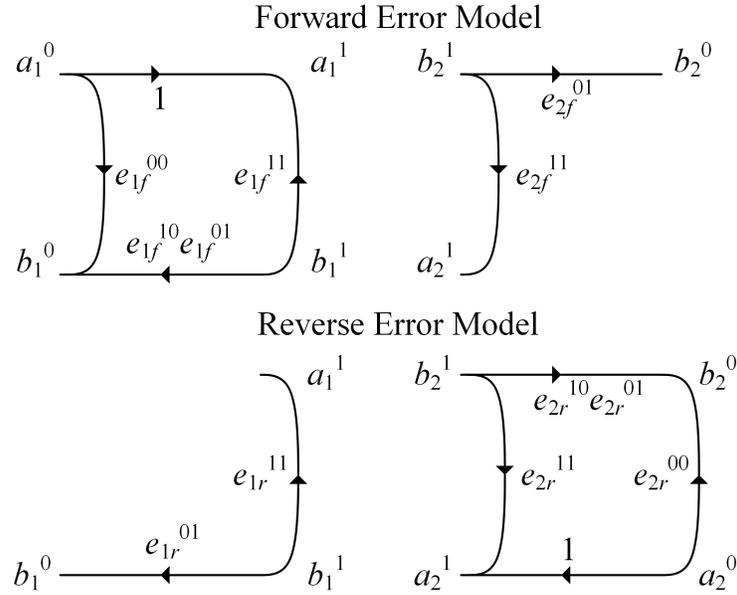


Figure 7: Linear Ten-Term Error Model

The NVNA needs to be able to measure absolute power and cross-frequency phase and it does not assume that the DUT has linear behavior. Thus, no error terms can be normalized or combined. Since stimuli in X-parameter measurements are often simultaneously applied to both input and output ports, the error model can no longer be separated into forward and reverse portions. Because of all of this, the NVNA uses a single eight-term error model, as shown in Figure 8. After calibration is completed, X-parameters can be measured.

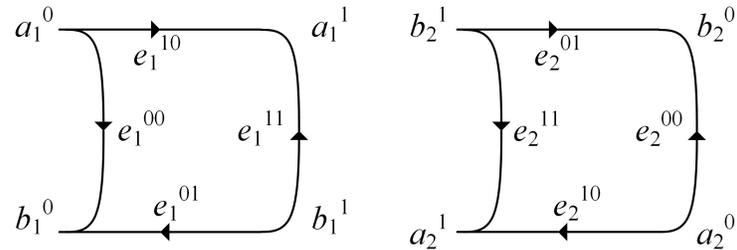


Figure 8: Nonlinear Error Model for Vector Error Correction

The X-parameter measurement uses both microwave sources. The first source provides the large-signal fundamental $A_{1,1}$ to bias the nonlinear circuit. When only this source is provided, the $X^{(FB)}$ terms can be recovered. The second source provides one other incident pseudowave, such as $A_{1,3}$, from which $X_{x,y;1,3}^S$ and $X_{x,y;1,3}^T$ can be extracted, where x can be any of the ports and y can be any of the harmonics. This second, smaller tone is called the extraction tone. This tone must be small enough not to violate the assumption that $A_{1,1}$ is the only large tone, but large enough that it can be measured. The Procedure discusses some of the methods for determining the proper magnitudes for the extraction tone level.

3 Pre-lab

1. What does it mean for a system to be linear? How could you test for linearity?
2. What is an intuitive interpretation of the X-parameter of type FB?
3. What are the intuitive interpretations of the X-parameters of types S and T?
4. Why does the X-parameter of type T exist? In other words, why is it necessary to include the response of the conjugate term in the X-parameter formalism?

4 Equipment

- Agilent PNA-X Network Analyzer N5242A
- Agilent Comb Generator U9391C FFM (measurement phase reference)
- Agilent Comb Generator U9391C FFF (calibration phase reference)
- Agilent MXC Analog Signal Generator N5181B
- EPM Series Power Meter E4419B
- Electronic Calibration Module (ECal) N4691-60004
- Three DC Power Supplies
- Assorted Measurement Cables
- Device Under Test – Gali-1+ Amplifier Evaluation Test Board
- Assembling the Test Setup
- X-Parameters Test Setup

5 Lab Procedure

Prepare the PNA for an X-Parameters Measurement:

1. Ensure that the X-Parameter Measurement Test Setup is aligned as shown in Figure 9.

Setup the Amplifier:

- You will now set up the amplifier to be tested. Bias the amp with a 12VDC source. Set the current limit to 60mA.
- Connect port 1 of the PNA to RFin of the amp and port 2 of the PNA to RFout. Now turn on the power to your amplifier.

Run Pretest:

- Now you will run a pretest to make sure that your system is set up correctly before you calibrate the PNA. As mentioned before in the course, a pretest is a measurement made before the calibration is performed. The idea of a pretest is that it can quickly determine.
- At the top of the screen make sure the domain is “Src1Power.” The format should be “LogMag.” We want to see the transmitted power so change (Port, Tone) to (2,1), which is $X_{2,1}^{(FB)}$. Now press Measure: “Single” and verify that your system is set up correctly. We are viewing Pout vs. Pin not Gain vs. Pin as was viewed in the last lab. Your system should look similar to the diagram shown in Figure 10.

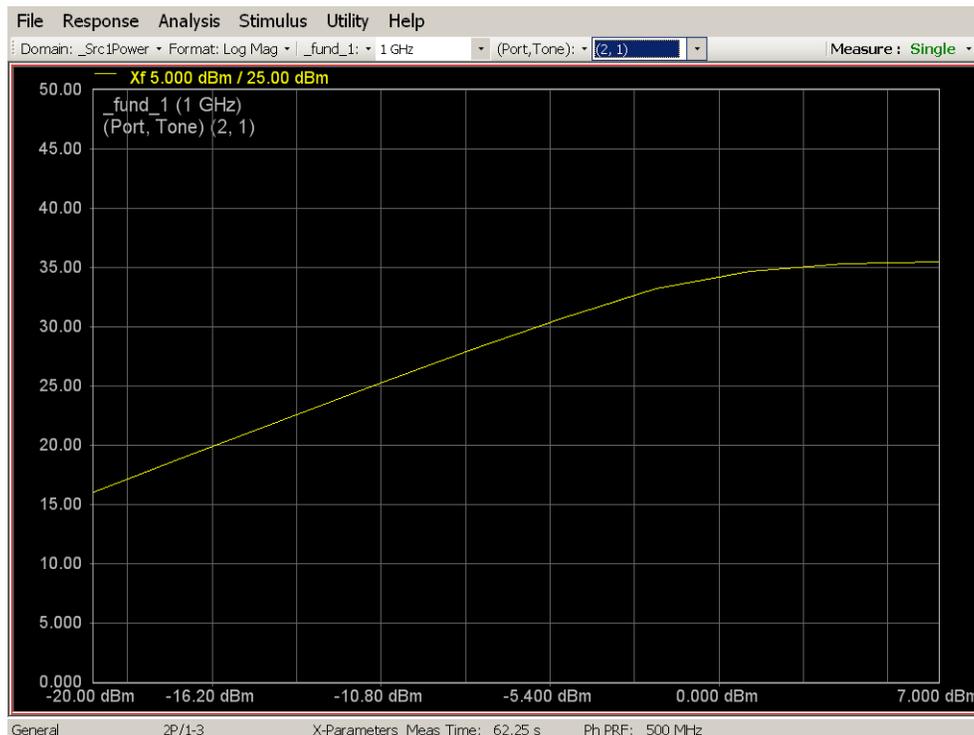


Figure 10: Sample Test Measurement for Correct Test Setup

- After a successful pretest you will begin calibrating the PNA. Turn off power to your amplifier and disconnect it from the PNA.

Calibrate the PNA:

13. Open the calibration wizard by selecting Response>Calibration Wizard.
14. Follow steps to complete phase calibration on Port 1. There is no need for receiver attenuation or averaging so click next. Choose U9391C-FFF as the phase reference module. There are two different ones, but we are calibrating the FFF one using the other FFM device. Click “Next.” You should get a pop-up window telling you to connect the phase reference (FFM comb generator) to Port 1 of the PNA. Do so now and click “OK” when done. Phase calibration is now complete.
15. You will now calibrate the Receiver Amplitude. Connect the power meter to Port 1. Click “Next” on the calibration wizard. On the next page use the default settings and click “Next.” A pop up window will tell you to connect Device0 (power meter) to Port 1. Click “OK.” This will complete the receiver Amplitude calibration.
16. (**Read this section in its entirety before proceeding!**) Now you will do a vector (SOLT) calibration on the PNA using the ECal. Click “Next” and the familiar calibration window will pop up. Select “Use Electronic Calibration (ECal)” then click “next”. Select “2 Port ECal” for ports 1 and 3 then click “next”. Make sure Port 1 AND Port 3 says “APC 3.5 female” because there is an adapter on this ECal. This should give you an “Unknown Thru” ECal Method. If this is not the case go back a step and make sure you correct this. Now click “Next.” Follow instructions to finish calibration. Use the (SOLT) Thru when it tells you to connect Port 1 to Port 3. This provides a thru reference to compensate for the adapter that was added on to the ECal to make the genders connect correctly. Hit “Finish” when the calibration is finished and hit “OK” to exit the calibration wizard.

Make Measurement for Analysis:

17. Select Analysis > Configure X-parameter extraction: this tells the NVNA the proper power levels for the extraction tone. There is a tradeoff between having the tones be large enough that they are above the noise floor level, but small enough that they don't violate the assumption that they are small signal. Using Automatic ET Level – Power Based. Port 1 will be the Max power of the b1 wave. Port 2 will be the max power of the b2 wave. To determine the value needed for “Port 1 Maximum Output Power” use the maximum input power and the return loss given in the datasheet for the amplifier. To determine the value needed for “Port 2 Maximum Output Power” use the maximum output power of the amplifier. Make sure you understand why you are using those parameters to determine these values. Click “OK” to close.
18. Now click “Measure: Single” to perform your actual measurement. Save the data in the .xnp format so you can analyze it in ADS later.

ADS Simulation

19. We start by importing the .xnp measurement file you saved from the NVNA. In ADS click on Data Items > X-Port (Or type component name **X2P** in the upper left search panel).

20. Double click on the X2P box and click *browse* to import your xnp file. Before you close the window, change the *file type* to GMDIF.
21. Build the circuit as in Lab 10 Part II and replace the S2P block with X2P block you just created.
22. Simulate the circuit and plot Gain vs. Pin, Pout vs. Pin, and PAE vs. Pin.
23. Compare these three plots with your power sweep data from Lab 10 Part IV and check if there is an agreement between those two large signal measurements.
24. So far, you have four sets of data:
 - (a) VNA power sweep data from Lab 10 Part III.
 - (b) Circuit model single-tone HB simulation data from Lab 11.
 - (c) Dataset model single-tone HB simulation data from Lab 11.
 - (d) X-parameters NVNA measurement data from this lab.

Plot Gain vs. Pin, Pout vs. Pin, and PAE vs. Pin of the above four datasets together in three separate plots and compare them.

6 Conclusion

1. What do you see in your comparison among the four datasets? Are they lined up with each other?
2. What microwave devices can we model with the single large-tone X-parameter formalism?
3. Describe some limitations to the X-parameter formalism and some possible extensions.