Keysight Technologies
PNA-X Application:
Power-Added Efficiency (PAE)

Application Note

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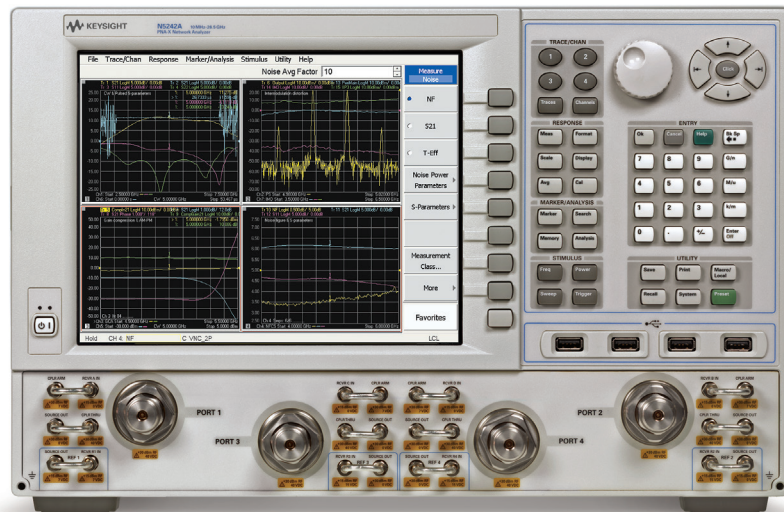
Introduction

Power-Added Efficiency (PAE) is a measure of the power conversion efficiency of power amplifiers. Ideally, all supplied power to the amplifier is converted into output power. However, that is not the case in reality. As such, PAE is an important performance parameter for power amplifiers, and is commonly defined as

$$\text{PAE (in percentage)} = \frac{\text{Power (RF\_out)} - \text{Power (RF\_in)}}{\text{Power\_dc}} * 100\%$$

Between linear and saturation regions of operation, there is a point where the power amplifier is most efficient. Up to a certain point, output power is improved while input power is increased. Beyond that point, increased input power will only generate more heat for the device. The objective of PAE measurement is to find this optimal point, the point where the power amplifier is most efficient in transferring input power into output power. Until recently, measuring this conversion rate was not possible with the PNA network analyzer because it was not possible for the network analyzer to perform DC measurements on the amplifier.

With the N5242A PNA-X, it is now possible to perform PAE measurements along with other power amplifier measurements. With one setup and connection, the following measurements (and more) can now be performed:

- S21: gain versus frequency
- S21: gain versus power (gain compression)
- AM-PM: phase versus power
- IMD: intermodulation distortion
- PAE: power-added efficiency ← **New!**

Making PAE Measurements

This application note provides a measurement example of a power amplifier.

Step 1. Measurement setup

Set the frequency range, number of points, IF bandwidth (IF BW), power level and so on.

Step 2. Calibration

Because measurements of both absolute power (B and R1 receivers, for example) as well as ratioed power (S21 and S11, for example) will be made, it is necessary to perform power calibrations as well as error corrections. For this application, both source and receiver power calibrations are needed. Source power calibration is needed for R1 receiver measurements, and receiver power calibration is needed for B receiver measurements. As for error correction, the most convenient approach is to use an Electronic Calibration (ECal) module.

a) Perform a full 2-port calibration using an ECal module
b) Perform a source power calibration on port 1 using a power meter and a power sensor
c) Perform receiver power calibrations on R1 and B receivers using the active source power calibration, and then append the calibration to the active CalSet

Step 3. Connect device-under-test (DUT)

With the amplifier-under-test (AUT) connected to ports 1 and 2 for RF measurements, and to the sensing circuit and the *Power I/O* connector for DC measurements, voltages can be displayed on the PNA-X as AI1 and AI2 traces. Figure 1 shows an example of a test setup.
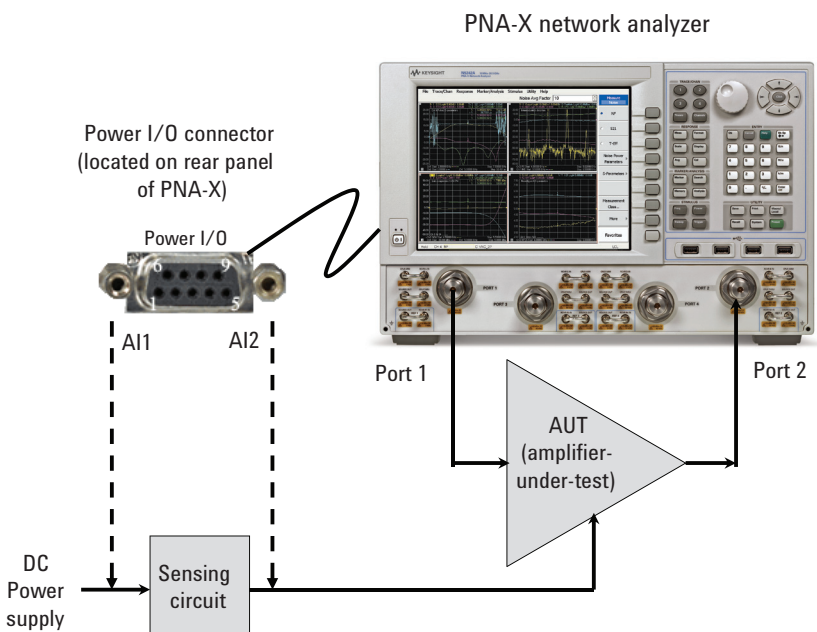

Figure 1. An example of a test setup for PAE measurements. (See Figure 5 for details on the power I/O connector and its pins.)

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Step 4. Add traces to display measurements

Figure 2 shows measurements made over frequency and Figure 3 shows measurements made over power, with Figure 4 showing the equation used via the *Equation Editor* to display the value of PAE. In Figure 2, the top window shows:

- **B** receiver measuring power out (trace 1). (Note: Receiver attenuation was applied to avoid compressing the receiver.)
- **R1** receiver measuring power in (trace 2).
- **S21** measuring gain (trace 3).
- **S11** measuring input match (trace 4).

In the bottom window, we display:

- **AI1** receiver measuring voltage at pin 7 (trace 5). Looking at Figure 1, AI1 provides the DC power supply reading. See Figure 5 for details on AI1 and pin 7.
- **AI2** receiver measuring voltage at pin 8 (trace 6). Looking at Figure 1, this provides the reading of the DC power being supplied to the amplifier. Using AI1 and AI2 readings, voltage drop across the sensing circuit can be calculated. See Figure 5 for details on AI2 and pin 8.
- **Vsupp**, voltage being supplied to the test setup (trace 7). A factor of 2 was applied to all voltage readings using the *Equation Editor*. Scaling was necessary here because AI1 and AI2 have a range of ±10 V. Since the DC power needed to drive this amplifier was 15 V, we built in a voltage divider as part of the sensing circuit so that the AI1 and AI2 readings are less than 10 V. Subsequently, we need to scale up the voltage readings in order to reflect the true voltage values.
- **Isupp**, current being supplied to the amplifier (trace 8). This value was calculated using the *Equation Editor* and the readings of AI1, AI2, and the precision resistor in the sensing circuit. Using AI1 and AI2 values, voltage drop across the sensing circuit can be determined. Dividing this voltage drop by the value of the precision resistor provides the current being delivered to the amplifier.
- **PAE**, value of power added efficiency being displayed in percentage using *Equation Editor* (trace 9). Details of equation can be seen in Figure 4.

Using frequency sweep, one can locate the optimal frequency point of operation, such as maximum PAE. For this particular AUT, Figure 2 shows that the best frequency for operation is around 900 MHz, with 16% PAE. With this information, one can then switch over to power sweep to find the optimal operating point. As shown in Figure 3, the efficiency of this AUT increases significantly up to 4 dBm, after which point, the increase is rather small. The traces shown in Figure 3 are a subset of those in Figure 2. Nonetheless, as illustrated in these two figures, the PNA-X can help to reveal a lot of information during the design and test phases of power amplifiers.
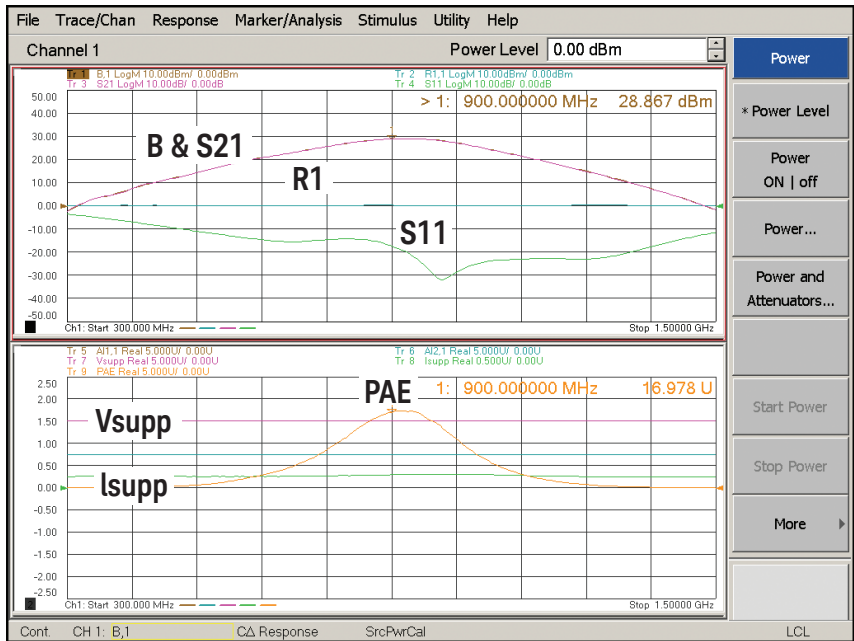
Figure 2. Measurements made over frequency sweep, including PAE. (Note, in the top window traces B and S21 overlap each other. Since S21 equals B/R1, when R1 equals 0 dB, S21 equals B. All parameters in unit of dB.)
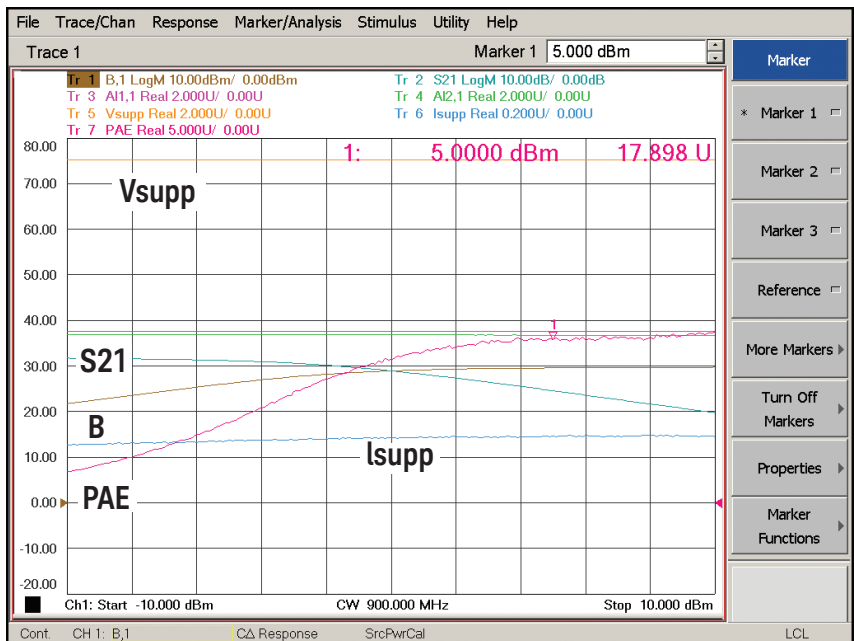

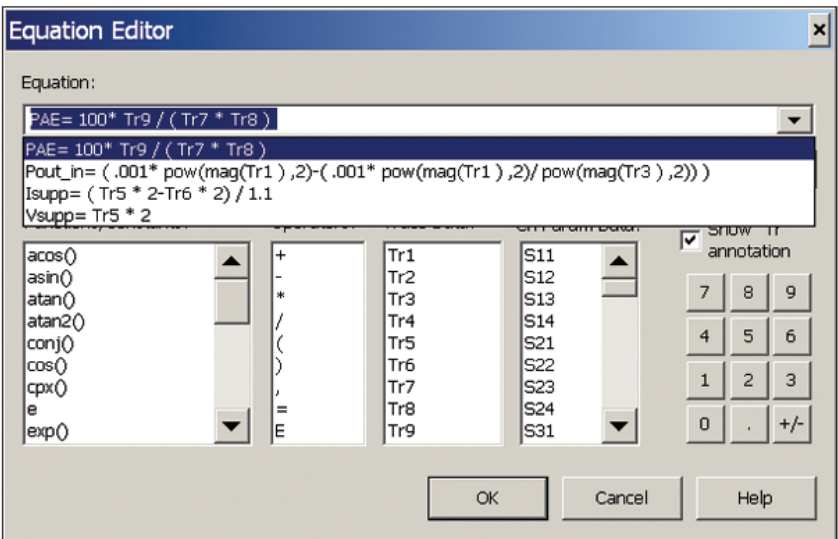**Figure 3. Measurements made over power sweep, including PAE.**

Figure 4. *Equation Editor* can be used to display traces on the PNA-X, such as PAE, by using other traces already on the screen.

PAE Calculations Using Equation Editor

$$\text{PAE (in \%)} = \frac{\text{Power\_out} - \text{Power\_in}}{\text{Power\_dc}} * 100\%$$

With AUT connected as shown in Figure 1,
    Power_out = B (in watts)
    Power_in = Power_out / gain = B / S21 (in watts)
    Power_dc = V_supplied * I_supplied (in watts)
    V_supplied = AI1
    I_supplied = (AI1 – AI2) / R, where R = precision_resistor (in ohms)

Using the above definitions,
    Power_out – Power_in =
        0.001*pow(mag(B),2) – (0.001* pow(mag(B),2) / pow(mag(S21),2))
    Power_dc = AI1 * (AI1 – AI2) / R

Notes:
1. The underlying trace (called the equation trace in the Help System) must be an unratioed parameter, such as A. This is the trace to which the *Equation Editor* will apply. For PAE measurements, the easiest approach is to add an AI1 trace before applying *Equation Editor*.
2. Results of the "Power_out – Power_in" equation must be displayed in REAL format. Data in other formats is not meaningful. The same applies for the individual Power_ out or Power_in. Units are in Watts.
3. In the "Power_out – Power_in" equation, all the terms are squared because parameters (such as B and S21) are measured voltage waves. As such, they must be squared in order to convert to power waves. Note: "pow(mag(B), 2)"=|B|^2.
4. When using *Equation Editor*, it is always best to use trace annotation (such as Tr1, Tr2, Tr3, and so on) instead of using the absolute terms (such as B_1, S21, etc). The reason is because error correction does not always apply when you use the absolute terms; sometimes it does and sometimes it doesn't. Using trace data always includes calibration.
5. dBm and power (in Watts) conversion: dBm = 10*log(power/1mW)
6. When calculating PAE manually for comparison, remember to convert all parameters ack to linear format before applying the equation
    (Power_out –Power_in)/Power_dc

Equipment Requirements

With the N5242A PNA-X, firmware A.07.22.00 or later, analog inputs have been enabled to allow sensing of voltages from the amplifier under test. With voltages sensed, current can be determined by using the *Equation Editor* and then efficiency calculated.

Analog inputs are accessible through the **Power I/O** (9-pin D-sub) connector located on the rear panel of the PNA-X, see Figure 5 for details. Pin 7 is Analog-In1 (AI1) and pin 8 is AnalogIn2 (AI2). Using these two pins, the PNA-X is able to make DC measurements by reading in voltages and displaying them as unitless traces of AI1 and AI2.

Figure 5. Power I/O connector on rear panel of PNA-X.

Power I/O Connector[1]

Pin	Name	Description
1	+15V	+15V @ 400 mA
2	−15V	−15V @ 400 mA
3	AnalogOut1 (AOS1)	Analog Output Voltage: programmable ±10V
4	AnalogOut2 (AOS2)	Analog Output Voltage: programmable ±10V
5	ACOM	System ground
6	GndSense	Ground sense for Analog In & Out
7	AnalogIn1 (AI1)	Analog input: ±10V @ 1.22mV typical resolution
8	AnalogIn2 (AI2)	Analog input: ±10V @ 1.22mV typical resolution
9	Power Button	Active low replicates power button key press

1. For more details, please see PNA Help.

In order for the PNA-X to sense voltage, the user must supply a circuit that would provide the voltage signal of the power amplifier to the PNA-X. Figure 6 shows an example of a resistive circuit that can be used in this application.
Depending on the voltage level being sensed, this circuit allows scale readings of 1, 2 or 10. Figure 7 shows the actual realization of the circuit. Using a single-pull double-throw (SPDT) switch, two readings are available in this implementation, either a scale of 2 or 10.
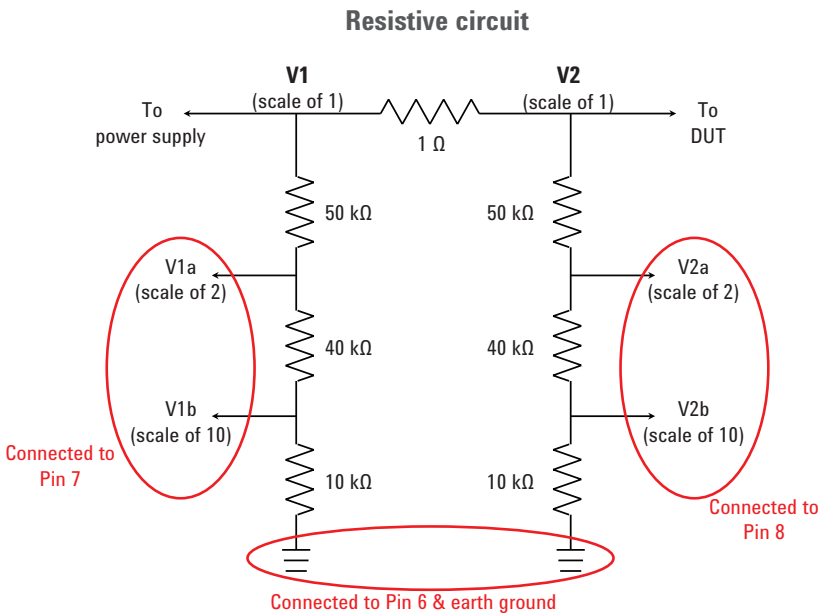
Resistive circuit

Figure 6. Example of a resistive circuit that can be used for sensing power amplifiers.
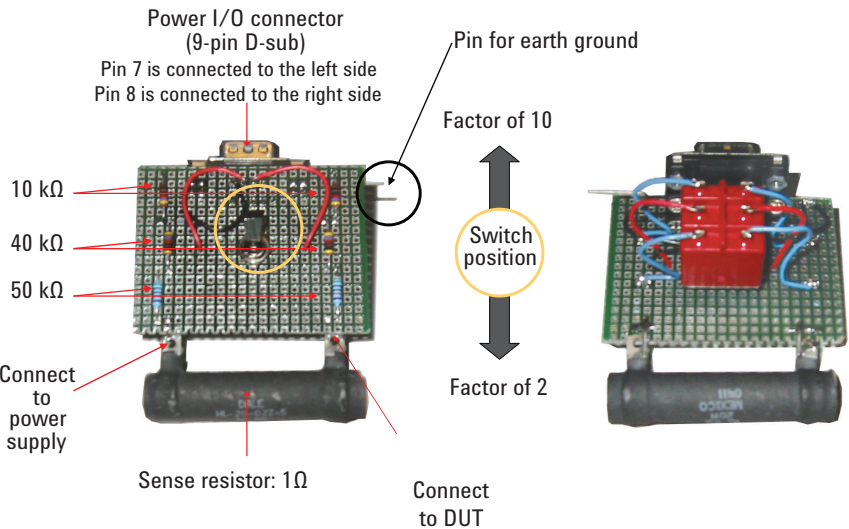

Figure 7. Actual realization of the sensing circuit shown in Figure 6. Left: top view, right: bottom view.

Because the range for AI1 and AI2 is ±10V, a voltage divider circuit (such as the one shown in Figure 6) comes in handy for measuring voltages outside that range. For example, using this circuit and with the scale of 2, a 15V signal would be measured as 7.5V. This scaled value of 7.5V fits nicely with the range of the AI1 and AI2, as opposed to the original voltage of 15V which is not measurable because it would be out-of-range. Once the data is acquired into the PNA, we can use the *Equation Editor* to scale the data back to its original values. For measurements within the range of ±10V, using a simple high power resistor (such as a 1 ohm precision high power resistor) would be sufficient.

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Reading Analog (DC) Signals

Analog (DC) input (and output) signals can be measured and displayed on the PNA-X by simply adding the AI1 and AI2 traces. To add these traces, select **Traces > New Traces** > Receiver tab, and then use the dropdown menu to select **AI1** and **AI2**, then click OK. Figure 8 shows an example of the screen.

When the analog input measurements are created, *Source Port* must also be selected to indicate which sweep will be utilized when collecting these data. This allows different measurements for the same analog input based upon source port selection. Figure 9 shows the traces as they appear on the display and with a different source port.
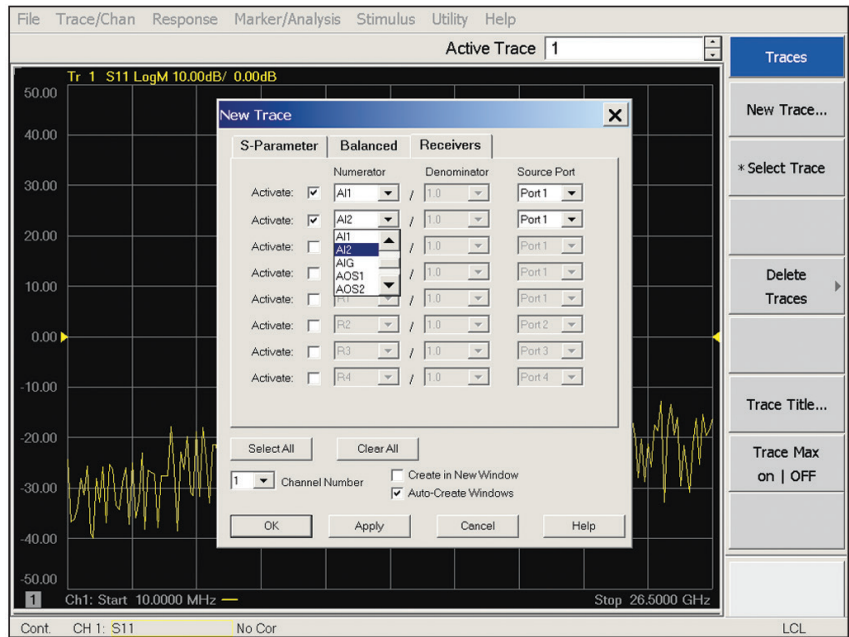

Figure 8. Simple steps to add AI1 and AI2 traces onto the PNA-X display. Other analog measurements available include AIG (analog input ground), AOS1 and AOS2 (analog output sense 1 and 2, respectively).

Figure 9. AI1 and AI2 traces displayed on the PNA-X, and with different source ports.

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Calibrating Analog Inputs (AI1 and AI2)

Currently, the analog readings from the PNA-X are not calibrated and their accuracy is unknown. However, users can perform some simple measurements to determine their correction factors. With the correction factors applied via the *Equation Editor*, measurements will be accurate to 1.22 mV (typical resolution of the PNA) or to the accuracy of the multimeter used, whichever is larger.

To calibrate these inputs, in addition to the PNA-X, you need two more instruments:

– A power supply to provide the DC drives for AI1 and AI2 (pins 7 and 8 of the *Power I/O* connector on the rear panel of the PNA-X)

– A digital multimeter for data acquisition

An example of the setup is shown in Figure 10. The setup can also be automated with a simple program to make data gathering easier and faster.
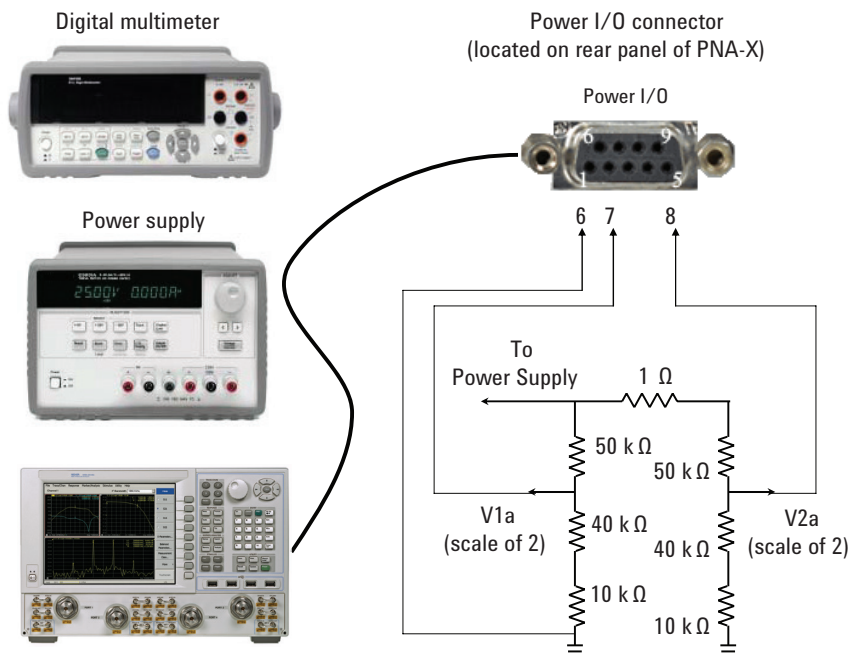

Figure 10. An example of the setup used to calibrate the analog inputs of the PNA-X. In this example, connections made to pins 7 (AI1) and 8 (AI2) are also made to the digital multimeter for readings comparison. Pin 6 is ground. Resistive circuit shown is the same as that of Figure 6, and output with a scale of 2 is used in this example.

Because the PNA-X analog readings are not calibrated, there will be discrepancies between the PNA-X readings and the multimeter readings. Fortunately, the differences can be fitted into a straight line with a constant slope, and the value of the slope is the correction factor. Because the characteristic is a straight line, a minimum of two data points (located far apart) is usually sufficient to determine the correction factor. However, more data points can also be used. The calibration process is very simple: (1) set the voltage on the power supply, (2) read the values on the PNA-X and the multimeter, (3) repeat steps until all data points have been acquired.

Using the resistive circuit shown in Figures 6 and 7 (with a scale of 2), Figures 11 and 12 show examples of data gathered for AI1 and AI2, respectively. Plus, the value of each slope is also shown below each graph. These values can then be applied onto the measurement traces using Equation Editor, such as those of Figure 2.
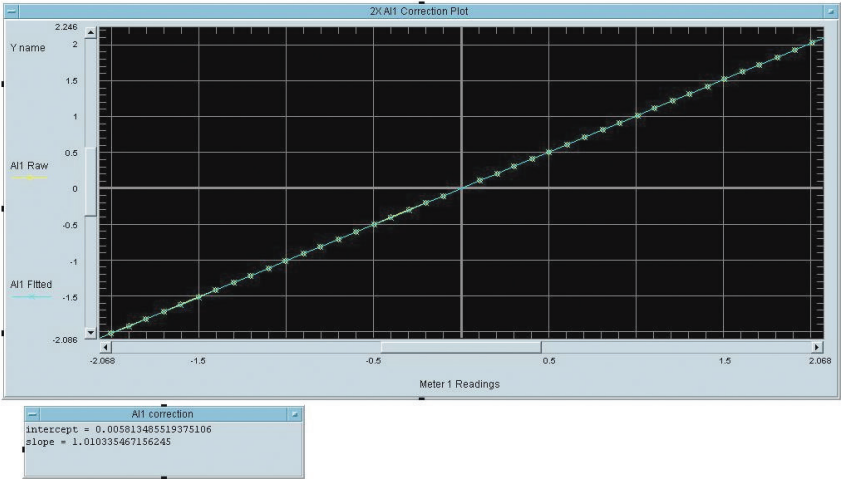

Figure 11. Example of data gathered for AI1 using resistive circuit shown in Figures 6 and 7 (with a scale of 2).
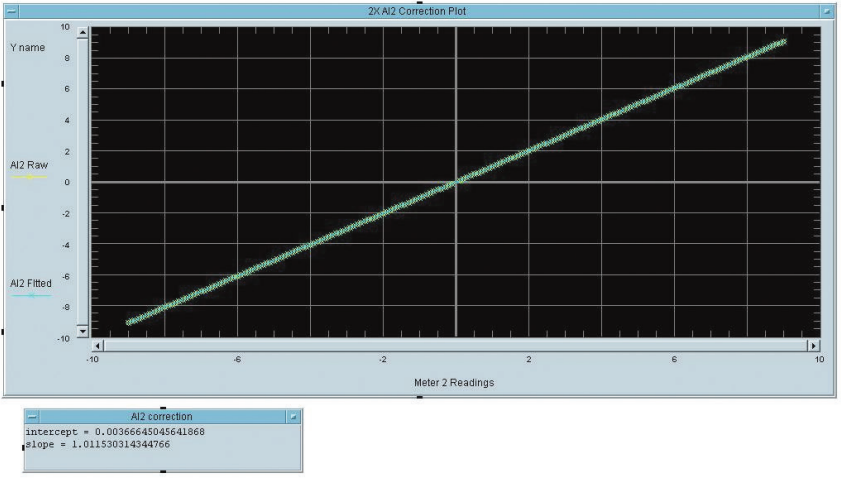

Figure 12. Example of data gathered for AI2 using resistive circuit shown in Figures 6 and 7 (with a scale of 2).

Summary

As shown in this application note, with DC inputs enabled (AI1 and AI2), the PNA-X can perform a comprehensive suite of measurements when it comes to testing amplifiers. When combined with the *Equation Editor*, PNA-X capabilities are boundless.

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