Edited by **David Newkirk, WJ1Z** • Electronic Publications Editor

An *ARRL Radio Designer* Voltage Probe Mystery: The 3-dB Pad that Loses 9 dB

One of the many features that gets us so revved up about bringing *ARRL Radio Designer*[1] to experimentally minded hams is Voltage Probe—*ARD*'s feature for reporting the voltage between any two points in a simulated circuit. *ARD* users' enthusiasm for Voltage Probe has tended to grow slowly, though, because time and space didn't allow us to work a Voltage Probe example into *The ARRL Radio Designer Manual*—and what documentation the *Manual* contains makes Voltage Probe look like a bear to use.

This month, we explore how *easy* using Voltage Probe can be by simulating a simple circuit—the 3-dB pi attenuator shown in Figure 1—and confirming its operation with Voltage Probe. Along the way, we'll run into a situation that may or may not seem mysterious, depending on what you already know about how radio transmitters interact with their antenna-system loads.

The Circuit

The attenuator circuit file is so simple that I won't call it out in a separate table. Instead, here's the whole thing:

```
* Be sure to turn on Voltage Probe
* before analyzing this file!
BLK
 RES 1 0 R=292
 RES 1 2 R=17.6
 RES 2 0 R=292
PUREPAD:2POR 1 2
END
FREQ
 ESTP 0.5MHZ 500MHZ 300
END
```

I like to put in that "Be sure to turn on Voltage Probe…!" reminder because I'll otherwise probably forget to turn on Voltage Probe when revisiting this file weeks or months later. (Sure, *ARD* lets you know if you forget and then try to load reports that contain Voltage Probe traces, but I just don't want my computer to get the idea that it's smarter than me.) Notice that the netlist doesn't set any Voltage Probe specs. This should come as a great relief to those who read *The ARRL Radio Designer Manual*'s definitive-but-undemonstrative Voltage Probe documentation and come away convinced that we must specify *circuit instances* and *circuit hierarchies* right in our netlists or Voltage Probe won't play.

Nope, all you *really* need to get started with Voltage Probe is an analyzable, ready-to-run netlist. Then all you do is:

1. Turn on Voltage Probe by clicking on *ARD*'s **Vprobe** button.
2. Analyze the circuit (click **Ana** or press **F10**).
3. Open Report Editor (press **F2** or do it via the **Report** menu) and, via the drop-down **Function** menu, select one of the four Voltage Probe response types: MV (magnitude of voltage), PV (phase of voltage), RV (real component of voltage), or IV (imaginary component of voltage). (We'll use MV for this example.)
4. Click **Add Trace**. This pops the **Set Voltage Probe Options** dialog (Figure 2).
5. Click **Select**. This selects the only possible circuit to probe—PUREPAD—and end-runs questions the *ARRL Radio Designer Manual* may have made you think you'd have to answer about circuit hierarchies and subcircuits.
6. Click the **Excitations** button. The **Excitations** dialog (Figure 3) pops with Port 1 preselected and configured for 1 V of excitation and a 50.000-Ω termination.
7. Let's assume that we're interested in seeing what the voltages in our 3-dB pad would be if we connected it at the output of a 100-W transmitter designed for a 50-Ω load. Working from the formula

$$P = \frac{E^2}{R}$$

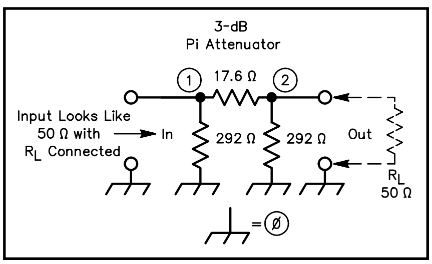

Figure 1—A simple 3-dB pi attenuator is a great way to start learning about how to use *ARRL Radio Designer*'s Voltage Probe feature because we know exactly what it's supposed to do: deliver an output voltage (measured across Nodes 2 and 0) that's 0.707 times that supplied across its input terminals (Nodes 1 and 0). As basic as this example is, though, it can easily mislead us if we let a very common misconception about radio transmitters trick us into misspecifiying the pad's input excitation.

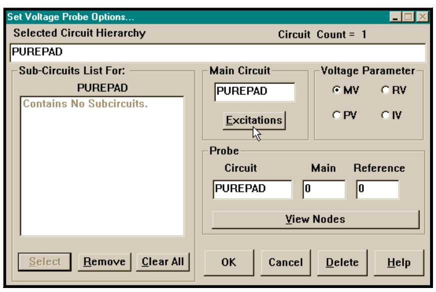

Figure 2—Clicking **Add Trace** after selecting a Voltage Probe trace in Report Editor pops *ARD*'s Set Voltage Probe Options dialog, the **Selected Circuit Hierarchy, Sub-Circuits List For:** and **Main Circuit** fields of which you can stop worrying about merely by clicking **Select** to choose the only option possible in **Sub-Circuits List For:** box. Next, click on **Excitations** to pop the dialog shown in Figure 3.

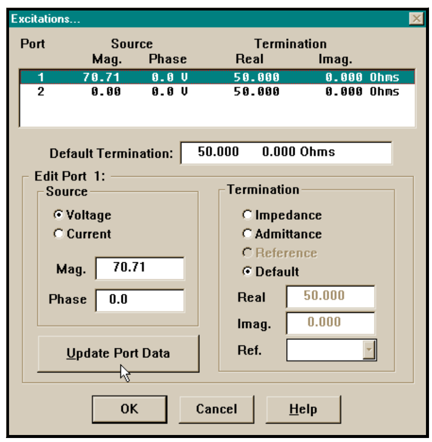

Figure 3—It's easy to set a passive load in Excitations: Just specify a source with a magnitude (**Mag.**) of 0.00 V and a **Phase** of 0.0°.

where *P* is power in watts, *E* is voltage in volts and *R* is resistance in ohms, we calculate that *E* would be 70.71 V RMS at 100 W. So we type 70.71 into the **Mag.** (magnitude) field of the **Edit Port 1** box, click **Update Port Data**, and then click **OK**. (To prove a point, we won't change Port 1's termination, already set to 50.000 Ω. We also won't have to change Port 2's settings because they [0.00 magnitude, 0.0 degrees phase, 50.000 Ω real, 0.000 Ω imaginary] already constitute the passive, purely resistive 50-Ω load we want as our pad's output termination.) **OK**ing our way out of **Excitations** brings us back to the **Set Voltage Probe Options** dialog.

8. Click **View Nodes**. A **PUREPAD:** dialog box pops to show our pad netlist. Since we're interested in probing the voltage across the pad's output terminals (Nodes 2 and 0), we'll type *2* into the dialog's **Main** field and click **OK**.

9. Next, we **OK** our way out of **Set Voltage Probe Options** and click **Display** once we get back to **Linear Reports**. Figure 4 shows the results of our **MV [volts] PUREPAD(2,0)** probe (and includes an **MV [volts] PUREPAD(1,0)** probe trace we'll need in a minute).

Hmm. Exciting our 3-dB pad with the 70.71-V, 50-Ω "signal generator" simulated by Voltage Probe produces 25 V across the pad's output terminals, which we bridged (with the Port 2 default values in **Excitations**) with a passive 50-Ω load. We poke a calculator to confirm that 25 V is 3 dB less than 70.71 V—

$$\text{Gain (dB)} = 20 \times \log\left(\frac{25}{70.71}\right)$$

and something's immediately amiss: The pad's output isn't *3* dB below 70.71 V; it's *9* dB lower!

What's Wrong with This Picture?

What's wrong is that the pad's true input voltage is not the 70.71 V we set in the Port 1 parameters in Voltage Probe's **Excitations** dialog. The signal generator's internal impedance (Port 1's default source resistance, 50.000 Ω) and the input resistance of the loaded pad (50 Ω) form a voltage divider (Figure 5) that *halves* the generator voltage. The pad's input actually sees 36.355 V instead of 70.71 V.

I intentionally steered us through leaving Port 1's termination resistance set 50 Ω to make the following point. Many of us quite naturally think of our transmitters as having "50-Ω" outputs. After all, doesn't classical signal-generator theory say that maximum power transfer occurs when a generator's load impedance is the same as its internal impedance? And don't our radio's specs generally say that our radios want to "see" 50-Ω loads for optimum performance? And—to mercilessly drive the point home—don't many of us use *matching networks* (aka *antenna tuners*) to "match" the impedances of our antenna systems to our transmitters? The answer to all of these questions is *yes*, but they all still add up to a *no*: A transmitter's output impedance is, in most cases, *not* 50 Ω. (It's usually much less; otherwise, as much as half of the transmitter's output power would be dissipated as heat in the final amplifier's internal resistance.[2]) And *impedance matching* turns out to be a pretty misleading euphemism for what's usually *really* going on: *impedance transformation.*

So now we can understand why Voltage Probe reports our pad's loss as 9 dB. Yes, a 50-Ω system operating at 100 W has 70.71 V across it. But specifying 70.71 V and a generator impedance of 50 Ω in this case results in an immediate halving of that excitation voltage—a 6-dB loss—in the two equal resistances of the generator and the terminated pad. Expressing in decibels the difference between the pad's actual input voltage (35.355 V), shown in Figure 4's **MV [volts] PUREPAD(1,0)** trace), and output voltage (25 V) in does indeed confirm that we've built a 3-dB pad. (I hope you weren't *really* wondering!) Asking *ARD* to show you the S-parameter MS_{21} (the magnitude of forward transmission gain) for the pad would give the correct number right off the bat.

We can do one of several things if we want to see the correct *absolute* value of voltages as probed across various points in the pad. We can leave Port 1 terminated in 50 Ω and double the excitation voltage (to 141.42 V); we can set the generator's impedance (the **Real** part of Port 1's termination) to 0 and leave the excitation voltage at 70.71;[3] or we can experiment in **Excitations** with driving the pad with a *current* source *paralleled* by a resistance. Which method we choose depends on how closely we want our modeling to simulate how the pad will be used, and to what degree the numbers we'll enter in **Excitations** may be correct, guesses (do we really know our transmitter's *actual* internal resistance?) or rules of thumb. If we were characterizing our 3-dB pad in a radio lab, we'd very likely drive it from a 50-Ω generator as we've done here, and setting the Port 1's termination to 50 Ω would be quite true-to-life. If, however, we wanted to model the frequency response of, say, a low-pass filter output-terminated in 50 + *j*0 Ω and input-terminated with the very low impedance of a high-power transmitter, specifying a 50-Ω source impedance would give unrealistic results.

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You can download the circuit (ex9601-1.ckt) and report (ex9601-1.rp2) files for this month's Voltage Probe example via the *ARRL Radio Designer* home page (**http://www.arrl.org/ard/ardpage.html**), available as a subpage of *ARRLWeb* (**http://www.arrl.org/**), the League's World Wide Web service.

[1]Available from ARRL for $150 plus shipping as publication #4882. Contact HQ Publications Sales at (voice) 860-594-0250, (fax) 860-594-0303 or (e-mail) *pubsales@arrl.org*.

[2]I like the businesslike treatment of this topic in Donald K. Belcher, WA4JVE, "RF Matching Techniques, Design and Example," *QST*, Oct 1972, pp 24-30, but we can find an analogous situation closer to home. When you plug, say, a 1.5-kW space heater into a wall outlet and turn it on, the power grid does *not* respond by dissipating 1.5 kW—assuming that that the internal impedances of the power grid and heater are equal so as to achieve the oft-misinvoked "optimum power transfer"—in return. Quite the contrary: Our homes' electrical distribution panels include fuses or circuit breakers precisely because the impedance of our homes' connections to the power grid is *extremely low*—much, even dangerously, lower than that of any safe load we're likely to plug in.

[3]Whether we can set a termination of 0 Ω depends on whether our modeling software will work right if we specify it. *ARD* handles a Port 1 impedance of 0 Ω well in this particular example, but in other contexts it—and other circuit simulators—may not like a 0-Ω termination. Our computer's math processing ability tends to choke when asked to divide by zero or infinity.

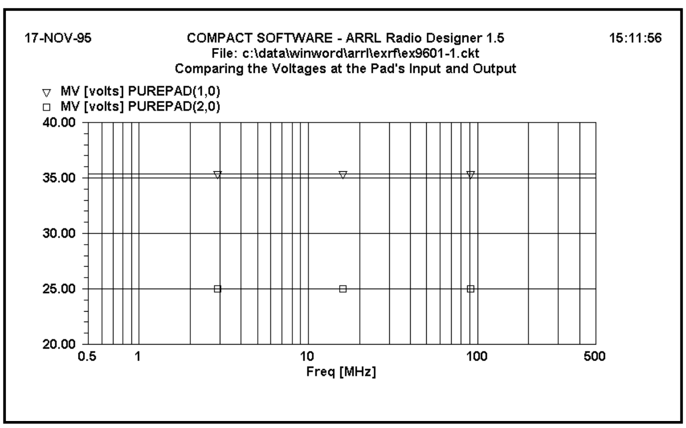

Figure 4—With Voltage Probe driving the 3-dB pad with a 70.71-V 50-Ω source, *ARRL Radio Designer* reports the pad's output voltage as 25 V (the **MV [volts] PUREPAD(2,0)** trace). That this is 9 dB, not 3 dB, lower than 70.71 V has to do with what the **MV [volts] PUREPAD(1,0)** trace reveals.

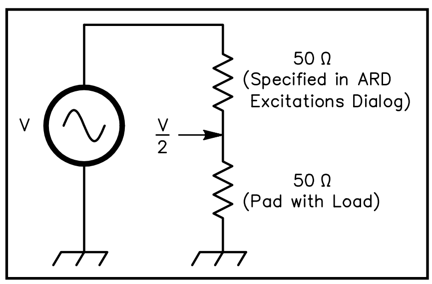

Figure 5—The generator and pad input resistances act as a voltage divider, knocking our 70.71 V down by a factor of 2—6 dB—to 35.355 V at the pad's input.