Chapter 20: Radio Frequency Measurements

Chapter 20 Objectives

At the conclusion of this chapter, the reader will be able to:

- Describe the instrumentation needed for general RF measurements
- Use appropriate set up precautions to avoid damage to instruments such as spectrum analyzers
- Set up a tracking generator as part of a spectrum analyzer system
- Calibrate a spectrum analyzer to accommodate cable and test fixture losses
- Measure the frequency response of a system or component using a spectrum analyzer
- Utilize a communications analyzer to assess receiver MDS and SINAD performance
- Measure two-port system S-parameters using a vector network analyzer (VNA)

What do you want to measure today?

Often we must use specialized test equipment to complete measurements on radio frequency systems. What might you be measuring? It depends very much on what sector of the communications industry you're working in. For commercial voice communications, you may need to check receiver operation using a communications analyzer. Such analyzers can also check transmit power, modulation and spectral cleanliness. In avionics (electronics used in aviation), you may be testing anything from cables, direction finders, radar transceivers, and of course, voice communication systems. This chapter is intended as a starting point in this fascinating area of communications electronics.

20-1 RF Test Equipment

The instruments we use to measure RF system characteristics come in two major categories - *signal sources* and *signal analyzers*. The most common signal source instrument is the RF signal generator; these come in many forms. A basic generator, the Fluke 6080A, is shown in Figure 20-1. This unit can provide RF signals from 500 kHz to 1024 MHz with 1 Hz resolution ("frequency step"). It's an older model that's still in common use in many shops; it can apply any combination of AM, FM, and PM to the generated signal.

Figure 20-1: The Fluke 6080A Signal Generator

The Siglent SSG5060X-V of Figure 20-2 is a typical modern generator. It is a specialized tool called a vector signal generator, or VSG. A VSG provides an accurate carrier frequency and conventional AM, FM, and PM modulation, but also gives control over the in-phase and quadrature phase (I and Q) components of its RF output. By manipulating both I and Q components, a VSG can be used to generate complex test signals for digital data transmission systems. Digital data transmission is used in a wide variety of applications including cellular telephony, wireless Internet, medical telemetry, as well as military and avionics systems.

Figure 20-2: The Siglent SSG5060X-V Vector Signal Generator

Signal Analyzers

Signal analyzers provide a way of measuring and visualizing the RF signals generated in an electronic communications system. These instruments come in many forms, but by far the most common type of analyzer is the *spectrum analyzer*. A spectrum analyzer is a calibrated radio receiver that displays signals in the frequency domain. The Agilent E4411B analyzer of Figure 20-3 is a typical entry-level model; it can display signals from 1 MHz to 1.5 GHz (1500 MHz). This particular model is configured with a 75 Ω input; it's designed for use in cable Internet and TV (CATV) applications.

Figure 20-3: The Agilent E4411B Spectrum Analyzer

The Rigol DSA-832E spectrum analyzer of Figure 20-4 is a modern example of a general-purpose signal analyzer; it covers 9 kHz to 3.2 GHz. (Increasing the upper limit frequency of an analyzer makes it useful for many more purposes - - but also greatly increases its cost.) An option included with this analyzer is a *tracking generator* (TG). A tracking generator is an RF generator that follows or "tracks" the frequency being swept by a spectrum analyzer. It's extremely handy for measuring the frequency response of amplifiers, filters, and other components. It's also very handy for testing cables and connectors over a wide frequency range. The analyzer of Figure 20-4 can be considered to contain both a signal source (the tracking generator) and a signal analyzer (the spectrum analyzer).

Figure 20-4: The Rigol DSA-832E Spectrum Analyzer

In Figure 20-4 you can see that *RF terminations* are in place at the GEN OUTPUT and RF INPUT connectors of the instrument; detail of this is shown in Figure 20-5. An RF termination is simply a precision, pure resistance (no inductance or capacitance) that can be connected to the input or output terminals of equipment. Such a termination ensures that a signal generator or other signal source sees a proper load (50 T in this case - - you can see this value stamped on the termination of Figure 20-5(a)), and also can be used for protecting inputs from electrostatic discharge (ESD) when they're not in use. The terminations in the figure are designed to handle about 500 mW (+27 dBm) maximum; this is well beyond the output power capabilities of most signal sources.

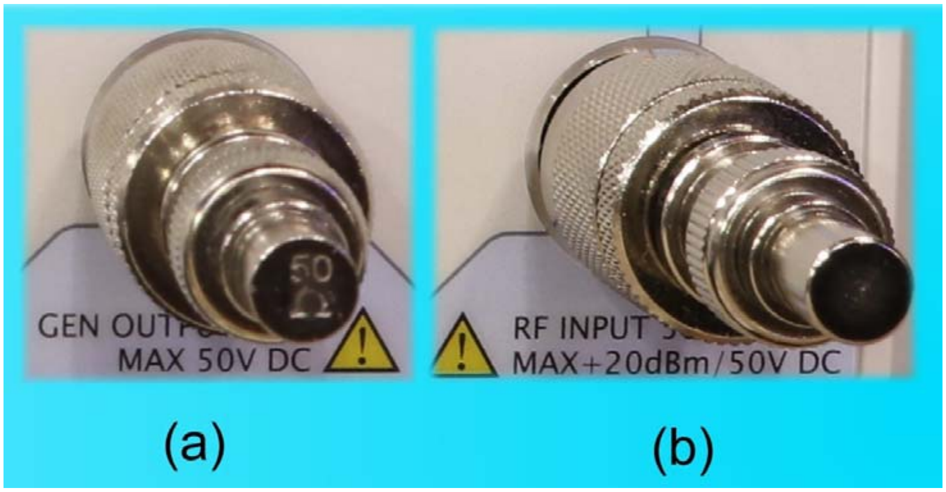


Figure 20-5: RF Termination at an Analyzer Terminal

A special type of analyzer, the vector network analyzer (VNA), is shown in Figure 20-6. A VNA is designed to accurately measure both amplitude and phase of an RF signal and typically contains a calibrated RF signal source. VNAs allow us to directly measure the scattering parameters, or S-parameters, of an RF device or system. We'll be examining this capability later in this chapter; it's quite handy for characterizing transmission lines, antennas, and quite a few other components.

Figure 20-6: The Siglent SNA5012 Vector Network Analyzer

You'll notice a couple of interesting things about the VNA of Figure 20-6. First, the connectors are simply labeled "Port 1" and "Port 2." This is because each "port" of a VNA can act as an input or an output. That's a bit strange if you're used to thinking of connections as being only an input, or only an output. The function of the ports is programmed when we set up the instrument.

Notice the large blank space between the Port 1 and Port 2 connections? Yes, this is an area where additional port connectors may be located on the instrument. Many VNAs feature four ports; such instruments can characterize the operation of an RF circuit from four different measurement vantage points *at the same time*.

Finally, notice that the display area of a VNA holds much more information than most other test equipment screens. This can be quite intimidating, but is not difficult to understand. The VNA can display the parameters of a circuit in many ways; this is often very informative.

In Figure 20-6, starting at the upper left, we see a Smith chart representation of a transmission parameter. (A Smith chart is merely a modified polar coordinate graph showing amplitude and phase). At right, we see a reflectance graph with frequency on the horizontal axis, and dB reflectance on the vertical axis; at bottom the same information as shown at top left is shown as a frequency-phase diagram.

If you are new to VNAs on the job, you'll probably be given very explicit information about the setups to be used and standards for results to be obtained.

The Care and Feeding of RF Test Equipment

Make no mistake: The equipment we've just shown you is very expensive. Many of these signal sources and analyzers can easily cost $50,000 or more to purchase. *The circuitry required to measure pico- and femto-watt level signals accurately over many GHz of frequency range is quite fragile*. Unlike a common benchtop multimeter, even a momentary signal overload can destroy the active devices on signal analyzer inputs. <u>We must always anticipate signal levels before connecting any RF test equipment</u>.

Damage to RF instrumentation not only means expensive repairs, but also can lead to downtime in the production environment. Downtime can cost your company many times the price of an instrument, depending on the nature of the product being produced or tested.

Instrument inputs can be damaged in many ways:

- Excess DC voltage. Normally, we do not want to introduce a DC voltage into a device input. Doing so, even within the limits shown on the equipment, can reduce the performance of the instrument. To prevent this from happening, use a DC blocking adapter on the input whenever a DC voltage might be present. (Of course, if you're in doubt, consult with a team member knowledgeable about the product being tested as well as the test equipment.)
- Excessive input power. Each input on an instrument is rated with a maximum allowable input power. Exceeding this power level will either degrade the long-term reliability and performance of the unit or cause an outright failure. Spectrum and vector spectrum analyzer inputs are always marked with this value. Know what you're measuring (and know what power values can be expected) before connecting the test equipment!
- Electrostatic Discharge (ESD). Both input and output ports on instruments can be damaged by static discharges. Semiconductors on inputs can be degraded or destroyed by ESD, even in cases where there's no visible spark. As in other areas of electronics, ESD is mitigated by the use of preventive measures such as anti-static mats, wrist / ankle bands, and the like. ESD can blow out input circuitry even when equipment is turned off; that's why it's common practice to connect RF terminators such as those shown in Figure 20-5 to unused inputs.

RTFM - Read the Full Manual!

Nearly every piece of test equipment comes with a printed or PDF operator's manual. The reasoning behind this is simple - - manufacturers want you to understand their equipment and be able to use it safely. This makes it much less likely that you'll run into trouble. Confusion and outright disaster can often be prevented by reviewing the information contained in these manuals.

Example 20-1

Alice wishes to measure the RF output of an aviation IFF (Identify Friend or Foe) unit using the DSA-832E analyzer of Figure 20-4. The IFF unit receives interrogation pulses on 1030 MHz and replies on 1090 MHz; it's rated at 316.2 watts peak power output during the response cycle. Can she safely connect the IFF unit's output to the input of the analyzer?

Solution
To make a determination in this case, look at the rating label on the instrument's RF INPUT terminal. As shown in Figure 20-5(b), the maximum allowed input is **+20 dBm** (100 mW). This is a miniscule amount of power compared to the output of the IFF unit (316.2 W).

Using Equation 4-5, we can convert the power output of the IFF unit into dBm:

$$\text{(4-5)}\quad dBm = 10\log\left(\frac{P}{mW}\right)$$

The dBm power level of the IFF unit is therefore:

$$dBm = 10\log\left(\frac{P}{mW}\right) = 10\log\left(\frac{316.2\,W}{1\,mW}\right) \approx \underline{\underline{55\,dBm}}$$

A power level of 55 dBm is 35 dB more than the instrument can handle. **The spectrum analyzer cannot be directly coupled to the IFF unit!**

To safely measure the RF output of the IFF unit, Alice should insert at least 40 dB of attenuation between the IFF output terminal and the spectrum analyzer. This will take the form of an *RF power attenuator* that is able to safely handle the 316.2 watt peak input from the transmitter and reduce it by precisely 40 dB (a 10,000-fold reduction in power). Several power attenuators are shown in Figure 20-7. After passing through the attenuator, the transmitted signal will be reduced by 40 dB to +15 dBm (31.6 mW), which can be safely measured by the spectrum analyzer.

RF Power Attenuators

There are several important specifications for RF power attenuators. These are the impedance (normally 50 or 75 ohms), the input power rating in watts, the amount of attenuation in dB, and the operating frequency range. Attenuators are generally symmetric in design. This means that there is no polarity to the signal flow; either connector can be used as the input or output. (For very high power attenuators, this may not be true. One port may be specifically designed to handle the high input power. This is usually marked clearly on the device.)

Several fixed RF power attenuators are shown in Figure 20-7. The attenuators pictured at left can handle 100 and 50 watts continuous input power, respectively. The Fairview Microwave SA3N1007-10 attenuator (far left) can handle peak powers of up to 10 kW for a very short duration (5 σs), and would be suitable for attenuation of the 316.2 watt burst output of the IFF unit in Example 20-1. This particular unit provides 10 dB attenuation, which is insufficient by itself for Alice's test procedure.

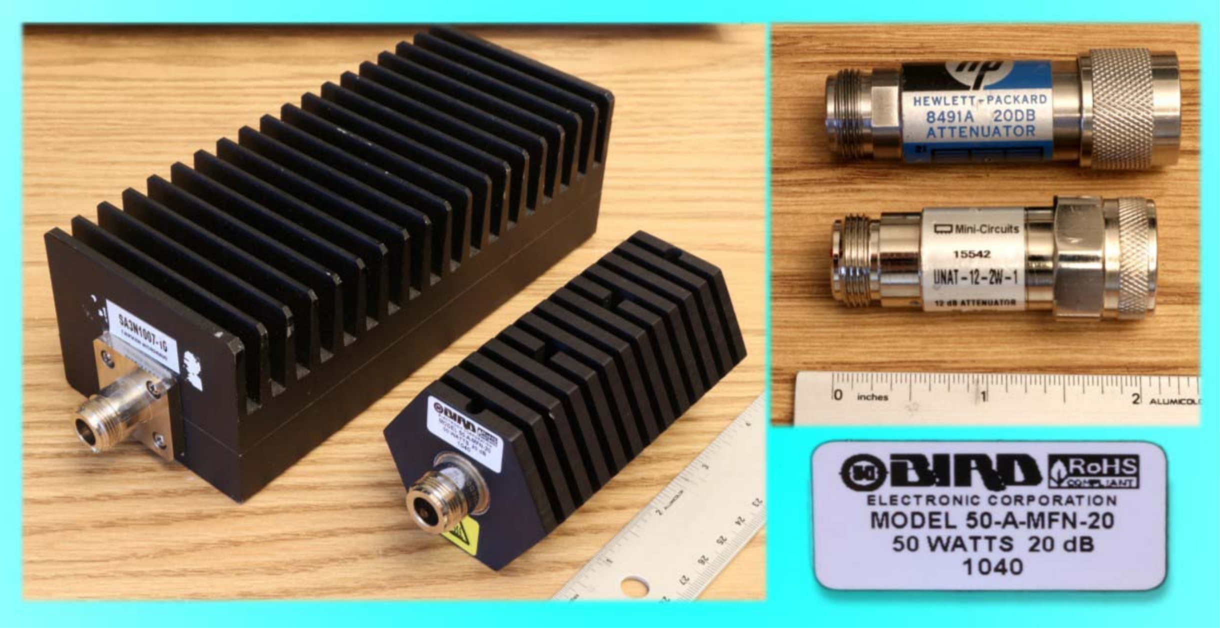


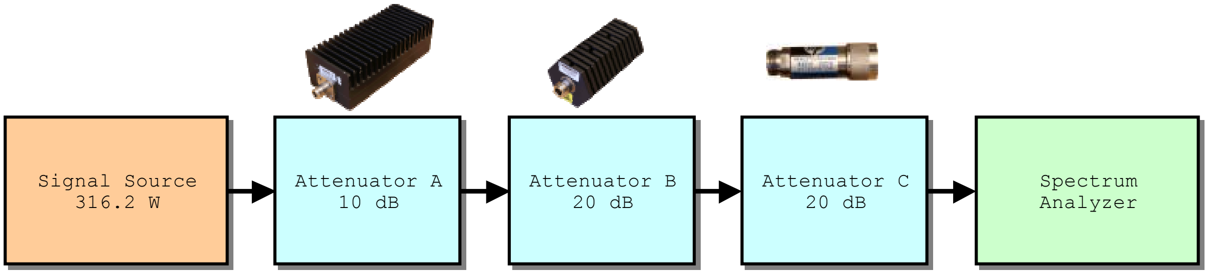
Figure 20-7: RF Power Attenuators

The smaller Bird 50A-MFN20 attenuator provides 20 dB attenuation. It can be cascaded with the 10 dB unit to provide a total of 30 dB attenuation. Finally, low-power coaxial "barrel" attenuators are available as shown at right. These are generally safe for input power levels up to 2 watts.

Example 20-2

Alice has decided to add 50 dB of attenuation by cascading 10 dB and 20 dB power attenuators, followed by a 20 dB HP 8491A barrel attenuator. What power level will result at the output of each attenuator - - and will this power level be safe for the succeeding attenuator and the spectrum analyzer? The input power is 316.2 watts peak.

Solution
To solve this problem, visualize the connection of the signal source and attenuator blocks.



We know that decibels are an efficient way of relating power levels at the input and output ports of each attenuator:

$$dB = 10\log\left(\frac{P_{OUT}}{P_{IN}}\right)$$

For attenuator A, the P_{OUT}/P_{IN} relationship can be easily determined by re-arranging the decibel formula:

$$\frac{P_{OUT}}{P_{IN}} = 10^{(dB/10)} = 10^{(10dB/10)} = 10^{1} = 10:1$$

Every 10 dB of attenuation divides the input power by a factor of 10. The power at the output of attenuator A is therefore:

$$P_{OUT}(A) = \frac{316.2\,W}{10} = \underline{\underline{31.62\,W}}$$

This power level is safe for attenuator B (rated for 50 W), which has the following P_{OUT}/P_{IN} relationship:

$$\frac{P_{OUT}}{P_{IN}} = 10^{(dB/10)} = 10^{(20dB/10)} = 10^{2} = 100:1$$

The power output from attenuator B is:

$$P_{OUT}(B) = \frac{31.62\,W}{100} = \underline{\underline{316.2\,mW}}$$

Finally, attenuator C (rated for 2 W) is also rated for 20 dB attenuation, so the final power output to the spectrum analyzer is:

$$P_{OUT}(C) = \frac{316.2\,mW}{100} = \underline{\underline{3.162\,mW}}$$

The final output power level from the attenuators is equal to 55 dBm (the output of the IFF unit) minus 50 dB (the total attenuation), or **+5 dBm**. This can readily be confirmed using Equation 4-5:

$$dBm = 10\log\left(\frac{P}{1\,mW}\right) = 10\log\left(\frac{3.162\,mW}{1\,mW}\right) = \underline{\underline{+5\,dBm}}$$

Note that any errors in the decibel values of the individual attenuators will accrue; this could impact the accuracy of Alice's measurements. We'll see how to account for this very soon.

Section Checkpoint

20-1 What are the two major classes of RF test equipment?
20-2 What is the difference between a signal generator and signal analyzer?
20-3 What kinds of modulation can be provided by most signal generators?
20-4 Give two reasons for using an RF terminating resistor on a test equipment input or output point.
20-5 Explain the differences between a spectrum analyzer and a VNA.
20-6 What precautions must be employed to avoid damage to RF test equipment?
20-7 What are the four important specifications given for any RF power attenuator?

20-2 Circuit Effects Impacting RF Measurements

The U.S. Federal Communications Commission (FCC) arbitrarily defines radio frequencies as those above 20 kHz. A good way to think about RF measurements is to compare the differences between working with DC and low-frequency circuits with the realities of working at radio frequencies.

In your early studies of DC circuits, you probably utilized a digital multimeter (DMM) to perform measurements of voltages and currents. The component layout of DC circuits is very much non-critical, as long as the wiring agrees with the schematic. The length and placement of the meter leads has no real effect on the readings. The only real consideration is to minimize unwanted DC resistance by keeping wires to a minimum length.

As you progressed to AC circuits you learned how to use the oscilloscope. *Your circuits now depended on frequency*. Most of the circuits you built in lab probably operated in the audio frequency range below 20 kHz. You were probably encouraged to keep component leads short and to consolidate grounds on breadboards. You might have even noticed the effects of noise - - because all AC circuits can be influenced by radiated energy.

But still, even with sloppy layout, low-frequency AC circuitry will generally work correctly (though not optimally). This is because low frequencies (such as audio) have long wavelengths. This means that a moderate length of exposed wire (such as 12 inches) doesn't radiate effectively. It's too short to be a good antenna. This wire also does not significantly impact the *impedance* of a low-frequency circuit. We know this to be true because its length as a transmission line[20] is a very small fraction of a wavelength.

Example 20-3

What is the wavelength of a 1 kHz signal in free space, and what is the electrical length of a 12" piece of wire at this frequency? Will this wire have a significant effect on an audio frequency circuit's total impedance?

Solution:
The wavelength can be calculated as follows:

(20-1) $\varsigma \,|\, \frac{v}{f}$

Therefore, the wavelength of our 1 kHz signal is:

$$\varsigma \,|\, \frac{v}{f} \,|\, \frac{3\Delta10^{8}\,m/s}{1\,kHz} \,|\, \underline{\underline{300\,km}}$$

The electrical wavelength of the wire is simply the physical length of the wire divided by the wavelength of the signal being conducted:[21]

(20-2) $EL \,|\, \frac{L}{\varsigma}$

Of course, we must convert our 12" wire length into units of meters before computing the electrical length:

$$L_m \,|\, 12\text{ inches }\Delta\frac{1\text{ meter}}{39.37\text{ inches}} \,|\, 0.305\,m$$

So,

$$EL \,|\, \frac{L}{\varsigma} \,|\, \frac{0.305\,m}{300\,km} \,|\, \underline{\underline{1.02\Delta10^{46}\,\varsigma}}$$

---

[20] As you read through this chapter, you may find it handy to review Chapters 11 and 12, which discuss transmission lines and antennas.

[21] Here we assume the velocity factor of the signal on the wire to be 100%.

Recall that we specify electrical length in fractions of a wavelength. Our 12 inch conductor is about one millionth of a wavelength at 1 kHz.

This is an extremely short electrical length, so there is practically no impact on the circuit's total impedance or operation. Life is simple at low frequencies!

Now let's consider how RF circuitry behaves. You've probably built a few RF circuits, possibly on breadboards or regular circuit boards. Very quickly we learn that conventional solderless breadboards become useless at frequencies above a few MHz. Why is this so?

There are many factors working against us in building RF circuits on breadboards. These factors include inter-column capacitances (often as much as 15 pF between adjacent columns), hidden inductances (introduced by the long column and ground bars within the breadboard), and poor shielding in general.

When you build any circuit on a solderless breadboard, you are adding many small but hidden capacitances and inductances. At low frequencies, these hidden reactances generally have limited impact on circuit operation. However, at radio frequencies the problems multiply.

Example 20-4

What is the wavelength of a 100 MHz signal in free space, and what is the electrical length of a 12" piece of wire at this frequency? Will this wire have a significant effect on a circuit's total impedance?

Solution:
The wavelength can be calculated as we did before:

$$\varsigma \mid \frac{v}{f} \mid \frac{3\Delta 10^{8}\,m/s}{100\ MHz} \mid \underline{\underline{3\ m}}$$

The electrical wavelength of the wire is simply the physical length of the wire divided by the wavelength of the signal being conducted. First, our wire's physical length must be converted into meters:

$$L_{m} \mid 12\text{ inches }\Delta\frac{1\text{ meter}}{39.37\text{ inches}} \mid 0.305\ m$$

So,

$$EL \mid \frac{L}{\varsigma} \mid \frac{0.305\ m}{3\ m} \mid \underline{\underline{0.102\ \varsigma}}$$

This is about 36.6 electrical degrees as there are 360 degrees in one wavelength.

A 12" inch section of wire is a very significant fraction of a wavelength at 100 MHz. <u>Such a length of wire will significantly change the impedance of any circuit operating at this frequency</u>.

You might wonder how we can know that this wire length can have such an effect. We can answer this in two ways.

First, from our early studies (Chapter 1), we know that the minimum length of an effective antenna is around 1/4 of a wavelength (0.25 #ς or 90 electrical degrees). The electrical length of the 12" wire (36.6°) is beginning to approach this value. *This wire will be radiating some of the signal passing through it*. This is an effect we might not have anticipated.

Second, we can use Equation 11-21 (or a Smith chart) to solve for the wire's added impedance by considering it as a section of transmission line with a characteristic impedance, Z_0, equal to that of free space (#377 Ω), and terminated on one end with an open circuit (Z_R=↔). Ignoring radiation losses in the wire, we get:

$$(11\,4\,21)\quad Z_{IN} \mid Z_0\left[\frac{jZ_0\sin\eta\,2\,Z_R\cos\eta}{jZ_R\sin\eta\,2\,Z_0\cos\eta}\right]$$

$$\mathrm{Re}\{Z_{IN}\} \mid Z_0\left[\frac{Z_0Z_R}{Z_0^{\,2}\cos^2\eta\,2\,Z_R^{\,2}\sin^2\eta}\right]$$

$$\lim_{Z_R \Downarrow \leftarrow}\mathrm{Re}\{Z_{IN}\} \mid 0\,\mathrm{T}$$

$$\mathrm{Im}\{Z_{IN}\} \mid Z_0/Z_0^{\,2}\;4\;Z_R^{\,2}\left(\left[\frac{j\sin\eta\cos\eta}{Z_0^{\,2}\cos^2\eta\,2\,Z_R^{\,2}\sin^2\eta}\right]\right)$$

$$\lim_{Z_R \Downarrow \leftarrow}\mathrm{Im}\{Z_{IN}\} \mid j\,377\mathrm{T}\cot\eta \mid j\,377\mathrm{T}\cot 36.6^\circ \mid \underline{\underline{507.6\,\mathrm{T}\not\subset 4\,90^\circ}}$$

In evaluating Equation 11-21, we rationalized the denominator, which allowed us to express the total impedance in terms of the resistive, real component *Re{Z$_{IN}$}* and the reactive, imaginary component *Im{Z$_{IN}$}*.

We then evaluated the limit Z_R→←of the real and imaginary component formulas to represent the open-circuited end of the wire. (An open circuit is an infinite resistance.) This is a bit beyond the scope of this text, but shows that we can use formulas like Equation 11-21 to gain useful circuit insights.

The results we obtained here are quite surprising. There's no resistance - - we know this because the real term is zero. The connected end of the open-circuited wire looks like a capacitive reactance of 507.6 Ω, corresponding to about 3.1 pF of *stray capacitance* at the 100 MHz operating frequency of our circuit. <u>The result is a pure capacitive reactance loading our circuit</u>.

Remember that the input and output terminations of RF circuits are normally designed to be either 50 or 75 ohms. *Inserting 507.6 Ω of stray capacitive reactance will significantly change the circuit impedance and operation.*

For comparison, we leave it to the reader to apply Equation 11-21 to Example 20-3. This result will quantitatively verify the conclusions of that example.[22]

TIP: With many calculators such as the TI-85/86 and TI-84 CE (among many others), you can directly enter Equation 11-21 (even with its imaginary numbers) and obtain results immediately with little or no algebraic work. It pays to read the manual!

Rule of Thumb for Wire Lengths

Often a rule of thumb is used to judge the maximum length of wiring in RF circuits. Any connecting wires in an RF circuit should be less than 1% of the wavelength (EL < 0.01 ς) at the desired operating frequency to minimize impact on the circuit's operation. Some circuits (such as those used in radar and aerospace) may require even stricter interpretation of this guideline.

It's important to remember that we must consider all circuit wiring when connecting test gear, as the following example shows.

---

[22] Plot spoiler: You'll observe 0 Ω resistance again with a very large capacitive reactance (around 21 GΩ). Compared to the impedances found in audio (600 Ω to 50 kΩ), this value of X$_C$ appears as an open circuit.

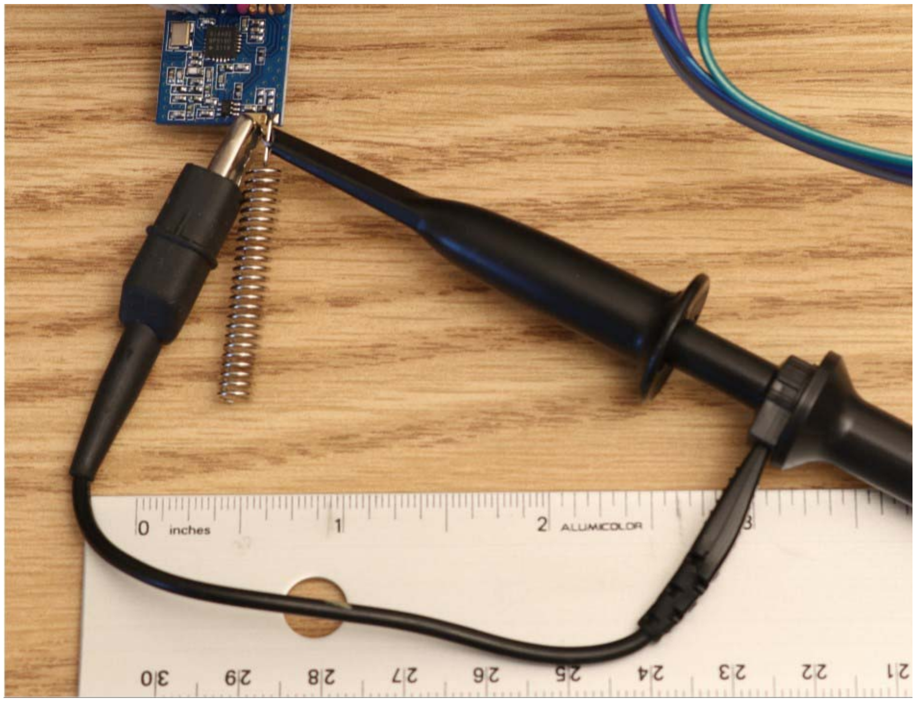


Figure 20-8: Consider all Leads when Measuring RF!

Example 20-5

Scope Probes not Always a Good Idea

Ian was having a very bad day. He'd been asked by his group leader, Susan, to measure the 416 MHz RF output of the telemetry module pictured in Figure 20-8, which uses a single-chip RF transceiver. Susan wanted to know the RF voltage present at the helical (spring) antenna terminal. Ian used a 10:1 scope probe rated for 500 MHz operation, and carefully connected the ground lead of the probe to a circuit pad immediately adjacent to the ANT (antenna) terminal. Susan said he should observe about 2.8 volts p-p at this terminal, indicating about 20 mW of output power into the 50 ohm antenna.

However, Ian couldn't get consistent readings at all - they varied between 1 and 4 volts p-p. Even moving his hand near the circuit changed the readings. In fact, Ian thought that he'd check the probe itself by temporarily connecting the tip to the circuit ground. "That should cause the scope to read zero voltage," he thought. But when he grounded the probe tip, the scope voltage jumped to 6 volts p-p! Ian even swapped scope probes, thinking his probe might be defective. But similar strangeness resulted. What could be wrong?

Solution:
We placed a ruler next to the setup of Figure 20-8 for reference. The probe tip may be correctly coupled to the circuit (the tip length is probably less than 0.01 ς), but the probe itself is essentially ungrounded at 416 MHz because the ground wire is about 4" in length. The ground lead is about 0.14 ς, long enough to cause serious trouble. A shorter ground lead is required (see Figure 20-9).

Additionally, because of the proximity of the ground lead to the helical antenna, it's very likely that RF energy is being directly induced into the ground lead from the antenna. This will produce invalid measurement results. To correct this problem, either a proper 50 T termination must be connected to the board in place of the antenna during the test, or the antenna must be remoted from the board with a length of coaxial cable.

Ultimately, the scope may not be the best tool to use for this type of measurement. Instead, the circuit might instead be connected to the input of a spectrum analyzer or RF power meter for direct measurement of the output.