Keysight Technologies
Oscilloscope Probe Loading Experiment

A hands-on lab experiment and probing tutorial
for EE students

Demo Guide

When you connect an oscilloscope probe to a test point in a circuit, the probe itself becomes a part of the circuit under test and can affect measured results. This is commonly referred to as "probe loading". Using a simple 2-resistor voltage-divider network, this experiment will empirically show how the frequency-dependent impedance of the probe can significantly impact measurement accuracy.

Required Equipment and Components

- 2-channel oscilloscope (≥ 50 MHz bandwidth)
- Function generator (≥ 10 MHz)
- Two standard 10:1 passive oscilloscope probes
- Breadboard
- Two 10 kΩ resistors

Compensating your Probes

It is important that you properly compensate your oscilloscope probes prior to building your circuit and performing this experiment, otherwise measurements will be inaccurate. To compensate your probes, connect one probe between the scope's channel-1 input and the probe compensation test terminal located somewhere on the front panel of your scope. Connect the second probe between the scope's channel-2 input and the same probe compensation test terminal. Don't forget to connect both probes' ground leads to a ground terminal on the front panel of the scope. Next, set the probe attenuation factors for both input channels to 10:1 (10-to-1). Note that some higher-end scopes will detect that 10:1 probes are connected and will then automatically set the probe attenuation factor for you.

Next, set up each channel's V/div setting, as well as the sec/div setting to show one or two periods of the probe compensation signal on the scope's display. The probe compensation signal is typically a 1 kHz square wave, so the appropriate sec/div setting should be 200 µsec/div.

Using a small flat-blade screw driver, adjust each probe's adjustable compensation capacitor as shown in Figure 1 such that both waveforms have a "flat" response. You should find this adjustable capacitor either near the probe tip, or on the part of probe closer to where it plugs into the scopes' BNC inputs.

Figure 1: Adjusting the probe compensation of each passive probe.

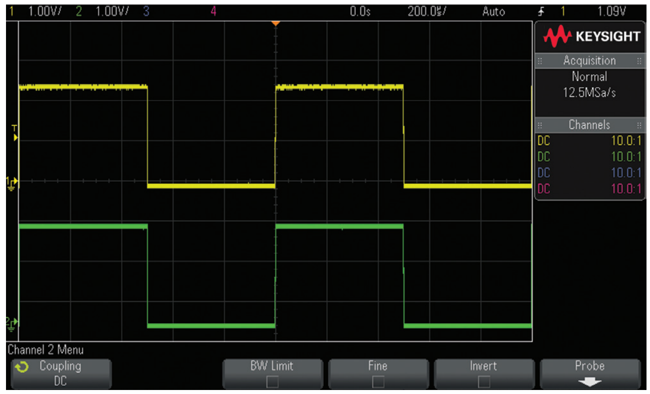

Figure 2: Using the scope's 1 kHz probe compensation signal to compensate 10:1 passive probes.

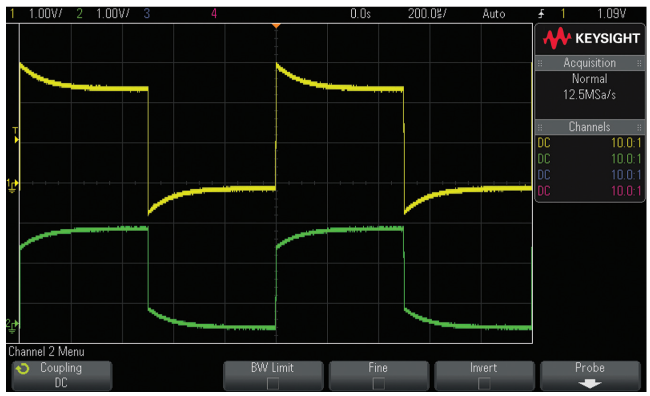

Figure 3: Improperly compensated probes.

Figure 2 shows what your channel-1 and channel-2 waveforms should look like if the probe compensation of each probe is properly adjusted. Figure 3 shows an example of the channel-1 probe (yellow waveform) over-compensated, and an example of the channel-2 probe (green waveform) under-compensated. So what is probe compensation all about? We'll find out later.

Building the experiment, predicting results, and measuring results

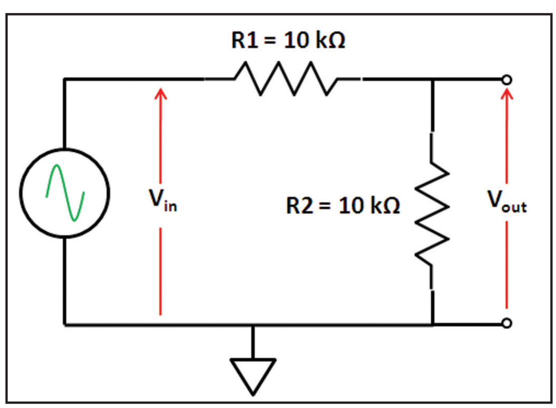

Figure 4: 2-resistor voltage-divider network.

Using your breadboard and two 10-kΩ resistors, build your 2-resistor voltage-divider network as shown in the schematic of Figure 4. Note that if you do not have a breadboard, then solder your two resistors together as opposed to simply connecting them together with long wires and clips. Long wires will introduce inductance into this experiment, which we want to avoid. Before turning on the function generator and making any measurements with your scope, answer the following questions:

V_{out}/V_{in} = ________________
If V_{in} = 5 V_{pp}, then V_{out} = ______________

Let's now test this circuit against these predicted results.

Function Generator Settings and Connections:

1. Set output load impedance to **High Z** (not 50-Ω)
2. Set waveshape to **Sine Wave**
3. Set amplitude to **5 Vpp**
4. Set offset to **0.0 V**
5. Set frequency to **10 kHz**
6. Connect output of generator to R1.
7. Connect ground of generator to circuit ground.

Oscilloscope Settings and Connections:

1. Connect channel-1 probe between V_{in} and ground.
2. Connect channel-2 probe between V_{out} and ground.
3. Begin with a **Default Setup** condition. Most scopes have a **Default Setup** selection on the front panel, or perhaps within the **Save/Recall** menu.
4. Insure that probe attenuation factors are still set to **10:1** for both channels of the scope.
5. Set channel-1 and channel-2 vertical scaling to **1.0 V/div**.
6. Center the channel-1 and channel-2 waveforms on-screen using the vertical position/offset controls.
7. Set the horizontal scaling (timebase) to **20.0 µs/div**.
8. Set triggering on a rising edge of channel-1 at approximately **0.0 Volts** (typical default setting).
9. Measure V_{in} and V_{out} (peak-to-peak) using either manually-placed cursors, automatic measurements, or simply count divisions and multiply by the vertical scaling factor (1.0 V/div).

Your scope's display should now look similar to Figure 5.

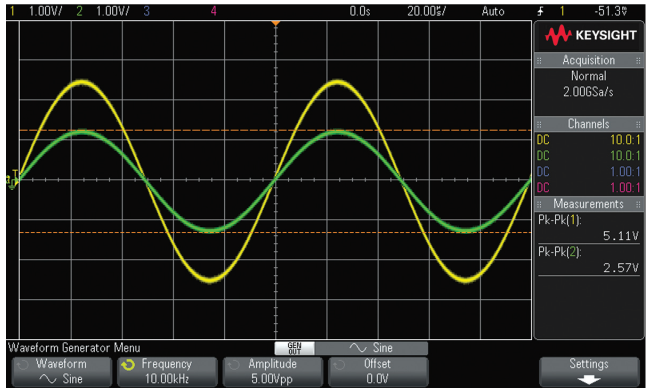

Figure 5: Measuring V_{in} and V_{out} at 10 kHz using two channels of the oscilloscope.

Record your measurements:

V_{in} @ 10 kHz= ___________

V_{out} @ 10 kHz= __________

V_{out}/V_{in} @ 10 kHz= ______

Is this pretty close to what you originally predicted? ____________

Now change the frequency setting of the function generator to **10 MHz**. Also change the scope's horizontal timebase setting to **20.0 ns/div** in order to view this faster input signal. Measure V_{in} and V_{out} once again. At this point, your scope's display may look similar to Figure 6.

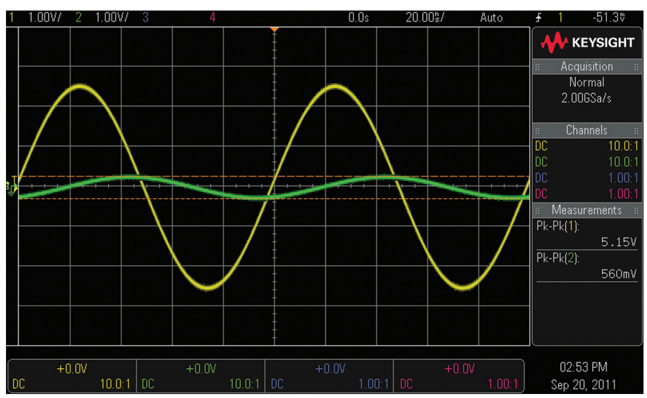

Figure 6: Measuring V_{in} and V_{out} at 10 MHz using two channels of the oscilloscope.

Record your measurements:

V_{in} @ 10 MHz = ___________

V_{out} @ 10 MHz = ___________

V_{out}/V_{in} @ 10 MHz = ________

Is this close to what you predicted? ________________

If not, why not? ____

____

____

____

Understanding Probe Loading

The reason the amplitude of the signal across R2 decreased at 10 MHz was due to capacitive probe and scope loading. In a perfect world, probes would have infinite impedance and would have no affect on your measurements. But any time you connect a probe to a device under test, whether you are using a spectrum analyzer, power meter, multimeter, power meter, network analyzer, or an oscilloscope, the probe and instrument become a part of your circuit under test and can affect the accuracy of measurements. This is especially true when testing higher frequency signals.

Now take a close look at the probes that you just used for this experiment — near the BNC connection end at the scope's input. You should see a vendor's name and model number associated with these particular probes. You should also see an input impedance specification/characteristc. It probably says something like, "10MΩ/15pF" as shown in Figure 7.

Figure 7: Oscilloscope probe model number and input impedance characteristics.

This means that when the probe is connected to the scope, it has an equivalent input resistance of 10 MΩ in parallel with 15 pF. Figure 8 shows an equivalent probe/scope loading model. This is what is hanging in parallel with R2 (refer to Figure 4). You can assume that the 10 MΩ resistor is so large compared to your 10 kΩ resistor (R2) that it's not even there. You can also assume that at low frequencies, the 15 pF capacitor will not affect your circuit. But what is the reactance of this capacitance at 10 MHz.

$X_c = 1/(2\pi fC) =$ ________________

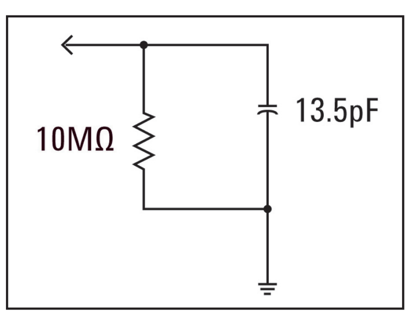

Figure 8: 10:1 passive probe loading model.

Now compute the load impedance that consists of R2 in parallel with Xc. Remember, you can ignore the 10 MΩ resistor.

Z_{Load} = *(R2)(Xc)/(√(R2²+Xc²)*) = ____________

Determine the approximate output voltage when the input frequency is set to 10 MHz — now based on the voltage-divider network consisting of R1 in series with Z_{Load}.

V_{out} = _______________

V_{out}/V_{in} = ____________

Is this closer to what you measured when the input signal was set at 10 MHz?

____

So we appear to have a dilemma here. We need to measure the output voltage of a circuit, but as soon as we connect an oscilloscope probe to the circuit, it changes the output characteristics. How do we handle this situation?

First of all, we ~~used 10 kΩ~~ resistors in this experiment to illustrate a point. The point was that the capacitive reactance of the probe at higher frequencies can "swamp out" the impedance of our load resistor (R2). But in reality, most higher frequency designs consists of lower impedance devices/components. But even in low impedance designs, probes can affect the circuit under test when frequencies get high enough, such as hundreds of Mega Hertz, or perhaps Giga Hertz signals. After all, most of today's PCs run on clock rates in the multi-Giga Hertz range.

Applications such as these typically require special high-frequency "active" probes. Passive probes, such as the ones you used in this experiment, consists of "passive" components only; resistors and capacitors. Higher frequency probes usually include "active" components, such as transistors and amplifiers. And these probes require power in order to operate. The input capacitance of active probes can be in the sub-pico Farads range. This means that they will have less affect — but theoretically never zero affect — on your circuit at higher frequencies. However, these probes also cost significantly more than standard passive probes, which are usually supplied with the scope. Active probes are almost always a "pay for" option.

If you would like to learn more about oscilloscope probes, download the Keysight Technologies, Inc. Application Note titled, "Eight Hints for Better Scope Probing" listed at the end of this document.

Understanding Probe Loading

Figure 9 shows a more detailed — but still simplified — electrical model of a typical 10:1 passive probe when connected to an oscilloscope using the scope's default
1 MΩ input selection. Although the electrical model of the passive probe and scope includes both inherent/parasitic capacitance (not designed-in) as well as an intentionally designed-in compensation capacitance network, let's ignore these capacitive elements for now and analyze the ideal signal behavior of this probe and scope system under low-frequency conditions.

After we remove all of the capacitive components from our electrical model, what remains is just a 9 MΩ probe tip resistor in series with the scope's 1 MΩ input impedance. The net input resistance at the probe tip is then 10 MΩ, which agrees with the probe loading model shown earlier (Figure 8). Using Ohm's law, you can see that the voltage level received at the scope's BNC input is then 1/10th the voltage level that is at the probe tip:

$V_{scope} = V_{probe}$ x (1 MΩ/10 MΩ)

This is why this type of probe is called a 10:1 (pronounced "10-to-1") probe. Once the scope knows that it has a
10:1 probe attached to its input, all measurements and vertical scaling factors are multiplied by 10 in order to reference measurements to the probe tip. The way a scope "knows" that it has a 10:1 probe attached is either by you manually entering the probe attenuation factor or through automatic detection. If you are using an older analog oscilloscope that does not have probe attenuation factors, then you've got to do the math yourself in order to reference measurements to the probe tip.

For low-frequency or dc applications, ignoring the capacitive elements is appropriate. But if you need to measure dynamic signals, which is the primary measurement application for oscilloscopes, the capacitive elements of this electrical model can't be ignored. So let's now take a closer look at the probe and scope model under dynamic/AC input signal conditions.

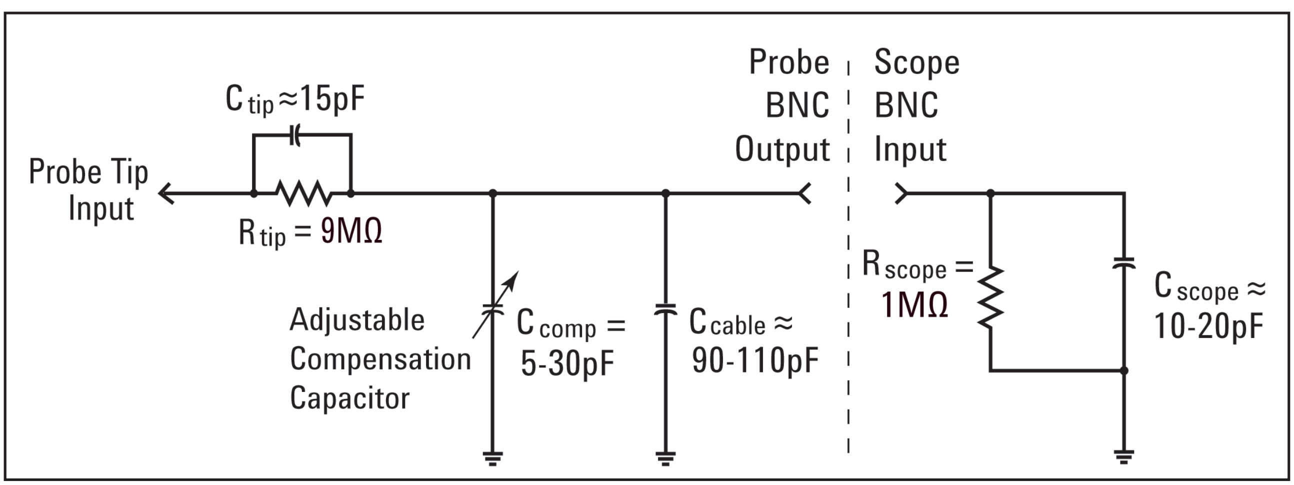

Figure 9: Simplified model of a typical passive 10:1 probe connected to the scope's 1 MΩ input impedance.

Inherent in all oscilloscope probes and scope inputs are parasitic capacitances. These include the probe cable capacitance (C_{cable}), as well as the scope's input capacitance (C_{scope}). "Inherent/parasitic" simply means that these elements of the electrical model are not intentionally designed-in; but are just an unfortunate fact of life in the real world of electronics. And the amount of inherent/parasitic capacitance will vary from scope-to-scope and probe-to-probe. But without additional designed-in capacitive components to compensate for the inherent capacitive elements in the system, the reactance of the system under dynamic signal conditions (non-dc) can change the overall dynamic attenuation of the probing system to something different than the desired 10:1 ratio.

The purpose of the additional/designed-in probe tip capacitor (C_{tip}) along with the adjustable compensation capacitor (C_{comp}) is to establish a capacitive reactance attenuation network that exactly matches the resistive attenuation of 10:1. In other words, the reactance of C_{tip} must be exactly 9X the reactance of the parallel combination of C_{comp} + C_{cable} + C_{scope}. If this is true, then not only will low-frequency signals be attenuated by a factor of 10 based upon the 9 MΩ probe tip resistance (R_{tip}) in series with the 1 MΩ scope input resistance (R_{scope}), but higher frequency signals will also be attenuated by a factor of 10 based upon a similar 10:1 capacitive reactance voltage-divider network.

Let's now compute the required amount of compensation capacitance (C_{comp}) using the following assumptions:

$C_{tip} = 15$ pF
$C_{scope} = 15$ pF
$C_{cable} = 100$ pF
$C_{parallel} = C_{scope} + C_{cable} + C_{comp}$
$C_{comp} = ?$

Remember, the reactance of C_{tip} must be 9X the reactance of $C_{parallel}$. Therefore we can use the following formula to compute C_{comp}:

$$\frac{1}{2\pi f C_{tip}} = 9 \times \frac{1}{2\pi f C_{parallel}}$$

where $C_{comp} = C_{parallel} - C_{scope} - C_{cable}$

What is the appropriate adjusted value of C_{comp}? __________

Once we know the value of the C_{comp}, we can then compute the overall capacitive loading, which is C_{tip} in series with $C_{parallel}$.

$$C_{Load} = \frac{(C_{tip})(C_{parallel})}{(C_{tip}+C_{parallel})} = \_\_\_\_\_\_\_\_\_\_$$

Is this the same value of loading capacitance shown in the probe loading model of Figure 8? ____________________

Summary

During this hands-on oscilloscope probe loading lab experiment, hopefully you learned that when you connect an oscilloscope probe to a device-under-test, the probe and scope become a part of circuit and can negatively affect the accuracy of measurements — especially when probing higher frequency signals. In many of your entry-level teaching labs, this may not be issue that you will need to be concerned about. But in some of your upper-level and graduate-level EE classes and labs that may focus on higher frequency RF applications, or perhaps high-speed digital applications, probe loading is something that you should watch for. And remember that digital signals have higher frequency harmonics far beyond the clock rate of the signal. As a "rule-of-thumb", the capacitive reactance of your probing system (including the scope) should be ≥ 10X the Thévenin-equivalent source impedance of your system under test. For the experiment outlined in this document (Figure 4), the Thévenin-equivalent source impedance would be 5 kΩ.

You also learned about the theory of operation of a passive 10:1 oscilloscope probe and how probe compensation works. Although understanding the theory of probe compensation may not be that important, properly compensating your probes is very important — even for many of your lower frequency entry-level lab experiments. It is always good practice before making any measurements with a scope to connect your probes to the probe compensation signal on the front panel of the scope and insure that they are properly adjusted.

If you would like to learn more about oscilloscopes, you can download a PowerPoint presentation titled, "Oscilloscope Fundamentals" at www.keysight.com/find/EDK. Just click on the "Software & Trials" tab to download this file. Note that this PowerPoint presentation also includes a complete set of speaker notes.

Also available are some application notes on oscilloscopes and probes listed at the end of document in the "Related Literature" section.

Related Literature

Publication Title	Publication Type	Publication Number
Eight Hints for Better Scope Probing	Application Note	5989-7894EN
Evaluating Oscilloscope Fundamentals	Application Note	5989-8064EN
Evaluating Oscilloscope Bandwidths for your Applications	Application Note	5989-5733EN
Oscilloscopes in Education	Application Note	5989-9166EN

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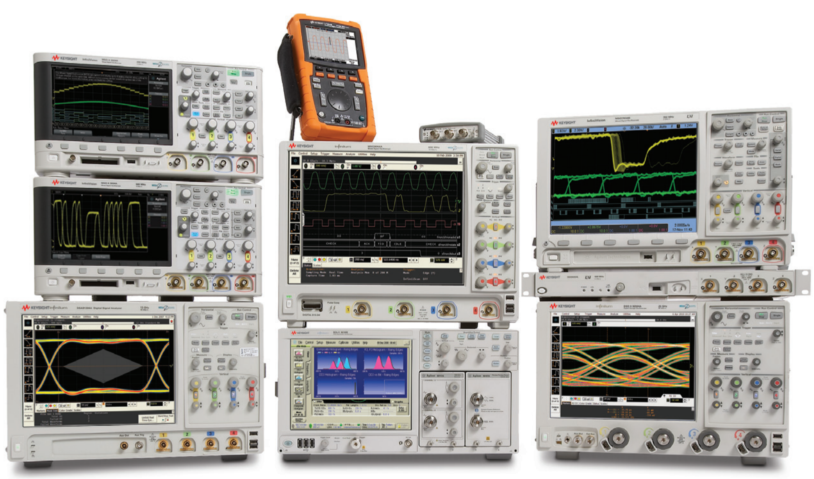

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