APPLICATION NOTE

Demystifying RCRC and RC Probes

An ideal oscilloscope probe would simply provide an exact replica of the signal being probed. However, in the real world, the probe becomes a part of the circuit under test because the probe or probing accessories attached to the device under test (DUT) introduce probe loading to the circuit. Depending on the probe and the circuit, the probe loading may cause unwanted side effects such as overshooting, ringing, and DC offset problems in the time domain. Learn more about the difference between RC and RCRC probe architecture, what this means for probe loading, and how to get the most accurate measurements.

Probe Loading Basics

When making measurements with an oscilloscope probe, you want a probe with minimal impact to the circuit. Since the probe is connected to the circuit it acts as a load when it draws signal current from the circuit. Figure 1 illustrates this with a simple circuit diagram. An ideal probe would draw zero current or have zero load on the circuit. In practice, all probes will draw some load; and you want a probe that draws as little load as possible. This means you want a probe with low probe loading.

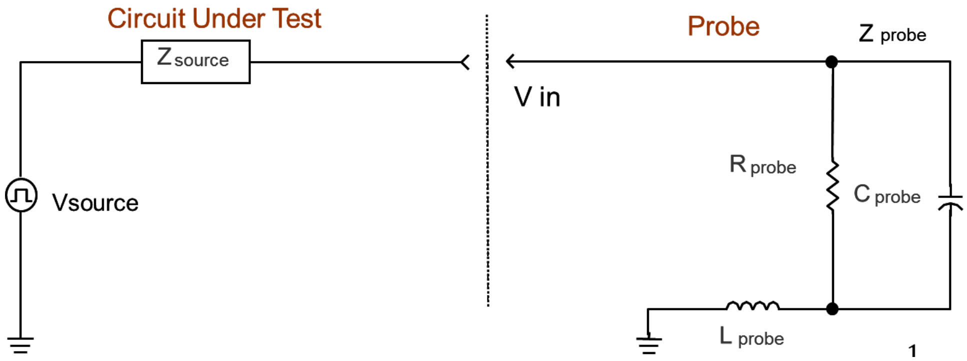


Figure 1. Circuit diagram showing how a probe becomes an additional load on the circuit under test

KEYSIGHT TECHNOLOGIES

Across the range of frequencies, the probe loading is different based on the resistive, capacitive, and inductive loading effects. Understanding the following 4 types of loading effects shown in Figure 2 will set the stage for understanding the difference between an RC vs. RCRC probe.

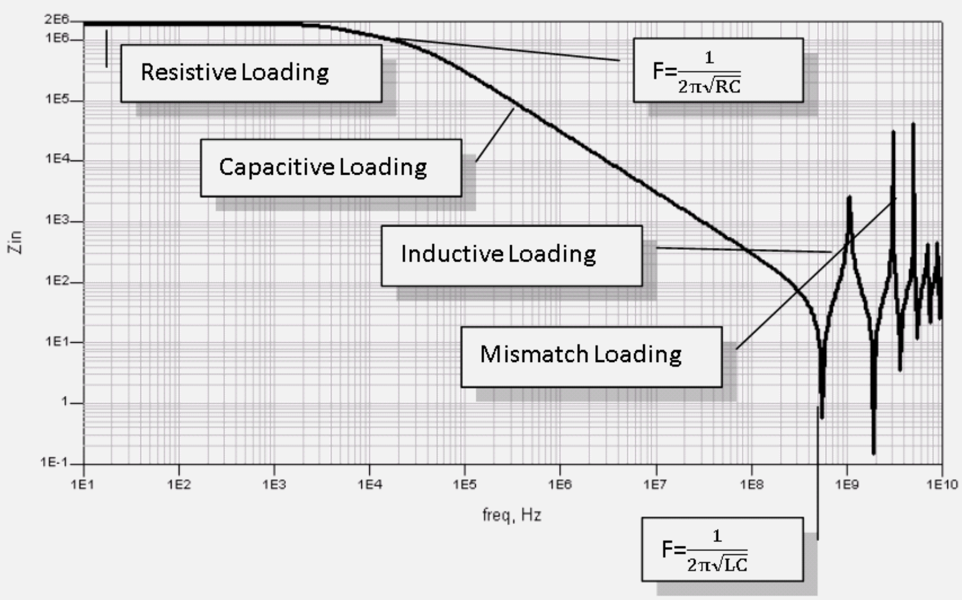


Figure 2. Typical probe loading profile of an oscilloscope probe

Resistive Loading

At DC or low frequency ranges, the primary loading is the probe's input resistance. Resistive loading mainly affects the DC parameters like DC amplitude accuracy, DC offset, and bias voltage change. This loading can be significant for low-impedance resistive divider type probes like a simple passive probe. When a low-impedance probe is used for probing a circuit with a similar or higher impedance magnitude, a large portion of the current that is flowing through the circuit will now flow into the probe, reducing the voltage at the point being probed. To avoid resistive loading, a larger input impedance is required.

Capacitive Loading

From the RC corner frequency to the first LC resonance frequency, the signal's load is mainly driven by the capacitive loading, as shown in Figure 2. Capacitive loading increases as the frequency increases. This is because as frequency goes up, the impedance of the probe's capacitance goes down. The probe's capacitance shunts the high-frequency signals to ground and significantly reduces the probe's input impedance as frequency increases. This loading is significant for high-impedance passive probes. It significantly limits the probe's bandwidth and slows down the edge speed of the signal. Higher-bandwidth probes require extremely low input capacitance, usually achieved by special geometries, lower K material/component selection, and good assembly processes.

Inductive Loading

Above the first resonance and below the second resonance frequency, the signal's load is mainly inductive. Inductive loading distorts the signal being measured if the LC resonance is below the probe's bandwidth. The loading comes from the inductance of the loop created from the probe signal tip to the probe grounding tip. The magnetic flux creates induced voltage in this loop. This parasitic inductor, together with the resistance and capacitance from the overall circuit, create a typical resonance frequency at: $f = 1/(2\pi\sqrt{LC})$.

If this self-resonance is not damped, it can cause a significant overshoot in the frequency response of the probing system and therefore distorts the measured signal. The effect of inductive loading typically appears as ringing in the observed waveform on the scope screen. The source of the ringing is the LC circuit, which comprises the probe's internal capacitance and the ground lead, and the probe tip inductance. The ground inductance includes the inductance of any jumper wires you have soldered onto the board or any alligator ground clips you've connected to facilitate probing. In order to minimize the inductive loading effect on your probing, our recommendation is to use as short a ground lead as possible.

Mismatch Loading

Mismatch loading is more significant when the frequency is at the range where the wavelength is equal to or less than the cable length (usually above the second resonance frequency). The probing system should be viewed as a transmission line instead of a first-order RLC model. The probe impedance therefore changes over frequency, which is seen as resonances in the frequency response, as shown in Figure 2. The mismatch can occur anywhere from the probe tip to the scopes' ADC input and causes multiple reflected waves. The longer the cable, the lower the resonance frequency is. To push the resonance frequency out to a higher frequency range, the amplifier at the probe tip is designed to drive the cable so that the mismatched signal path from the probe tip to the high-input-impedance amplifier is minimized. This is in part why active probes can have higher bandwidth than passive probes.

The Two Dominant Loading Effects for High-Bandwidth, Active Probes

Most high-bandwidth active probes for probing high-speed signals are dominated by two of the probe loading effects in the range specified by the max bandwidth: capacitive and resistive loading. This is a conscious design in probe architecture because high-speed digital designers require high accuracy probing solutions. When talking about the probe loading effects of these high-bandwidth, differential, active probes, we can summarize their probe loading by describing the two common probe architectures: RC and RCRC input impedance (see Figure 3).

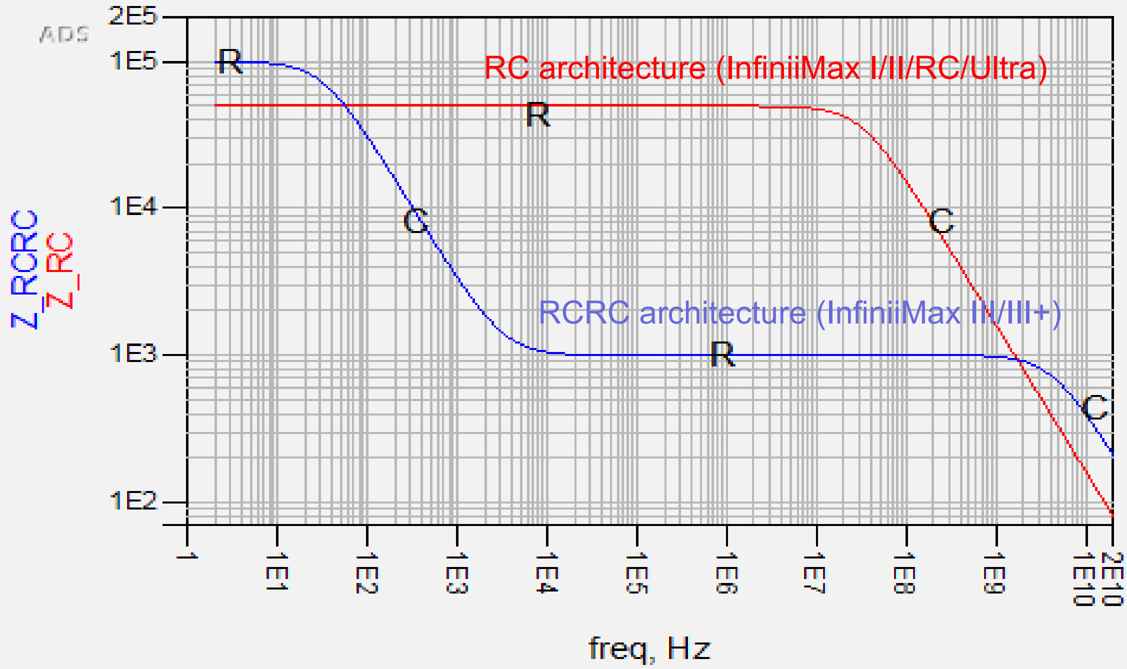


Figure 3. Input impedance profile of two common probe architectures: RC and RCRC

Take a look at the red trace in Figure 3. At frequencies as low as ~10 MHz, you see the input impedance is 50 kΩ driven by input R of the probe. It then intersects the 210 fF capacitance of the probe. That is what we call an RC input impedance profile since it is first dominated by the resistance, then the capacitance of the probe. This is a common input impedance profile for many oscilloscope probes including Keysight's InfiniiMax I/II/RC/Ultra probes.

Take a look at the blue trace in Figure 3. First, it has a 100 kΩ differential impedance at DC and at very low frequencies, then it intersects with the 50 nF capacitance of the probe, where it hits the mid-band impedance. Then over six decades of frequency, it maintains a 1 kΩ differential input impedance until it finally intersects the 32 fF capacitance. We call this profile an RCRC architecture since from low frequencies to high frequencies it's dominated by the probes' resistance, then capacitance, then resistance again, then capacitance again. This is very typical of high bandwidth such as the Keysight InfiniiMax III/III+ probes.

Comparing RC and RCRC Probes

Knowing the maximum bandwidth of your probe and the bandwidth of the signals you are trying to measure is the first step in understanding which probe will do the best job of accurately capturing your signal. An RC probe has the highest impedance (lowest loading and least signal distortion) across the widest frequency range. But an RCRC probe usually has a higher impedance than the RC probe at both the very low frequencies and very high frequencies, but it's midband impedance is usually much lower than RC probes.

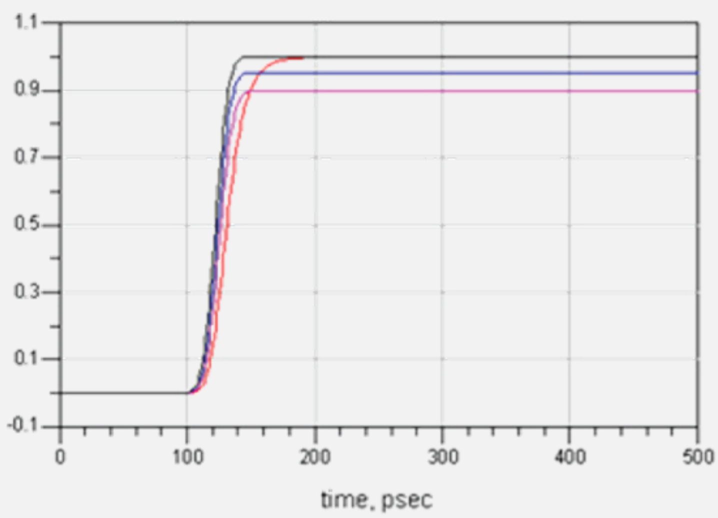
Another consideration when selecting a probe is to consider the source impedance. If you have a signal that transitions to high impedance modes, such as those signals found in the latest DDR and MIPI standards, then an RC architecture is best so that the probe loading does not affect the circuit under test. Generally, RCRC probes do an excellent job of reproducing wave-shapes with fast edge speeds, but may produce effects when trying to measure absolute voltage levels, especially when the source impedance of the target signal is high or if there are long time constants in the signal being probed.

RC vs. RCRC In The Time Domain

Below in Figure 4 is a simulated plot of three different probes measuring a step with a 20 psec risetime in the time domain. The black trace is the Vsource signal before the probe is attached. The red trace shows how the probe loading can affect the waveform when a Keysight InfiniiMax probe with RC architecture is connected. You can see that the edge has slowed down a bit with a rounded top, which is reducing the rise time and knocking the bandwidth down of the probe point.

The blue trace indicates the signal as loaded by a Keysight InfiniiMax probe with RCRC architecture. The magenta trace is another vendor's probe, but also with RCRC architecture. The blue trace doesn't nearly have the rise time degradation, but it does have amplitude degradation. What happened is the midband loading of 1 kΩ or 500 Ω per each side of the probe caused the amplitude to reduce by ~5%.

Note that the other vendor's trace may not be exactly comparable because it may have a different transfer function and the way the probe is calibrated may be different. But the point here is to note the general trend of the traces for RC vs. RCRC. RC probes generally have less impact on the signal amplitude due to lower input loading at midband ranges but may change the rise time of a fast step due to a probe loading effect with higher capacitance. RCRC probes generally have broadband attenuation, but they preserve the wave shape very well due to high bandwidth and low loading at high frequency. Note, for all these measurements, we assumed 25 Ω source impedance.



Black: a 20 pS 10-90% step with no probe attached (Vsource)

Red: tr=31.1 pS, Keysight InfiniiMax probe with RC architecture

Blue: tr=20.4 pS, Keysight InfiniiMax probe with RCRC architecture

Magenta: tr=21.4 pS, other vendor's probe with RCRC architecture

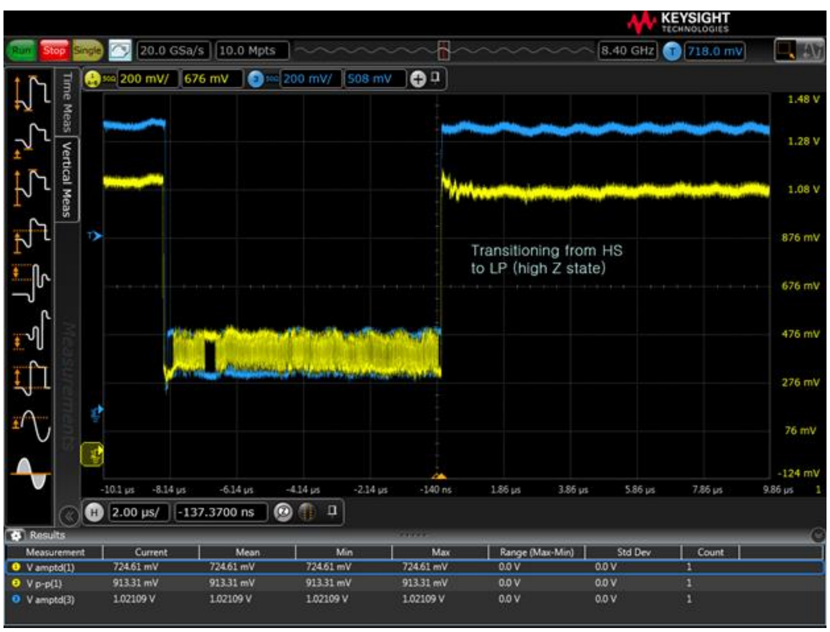
Figure 4. RCRC vs RC probe comparison in time domain

Selecting the Right Probe Gives You the Right Results

There are advantages and disadvantages to RC and RCRC probes, so there is not always one correct choice. Below are a few examples where we compare the two probe types for specific applications. You need to consider what would be best for your own device and application. To assist you, Keysight offers it's InfiniiMax Probing System with both RC and RCRC probes. The InfiniiMax I/II/RC/Ultra probes range from 1.5 GHz to 25 GHz. The InfiniiMax III/III+ probes range from 4 GHz to 30 GHz. Check out the InfiniiMax probes and more high-performance probes from Keysight at Infiniium Oscilloscope Probes and Accessories Data Sheet.

Example #1: MIPI D-Phy

The MIPI D-phy signal standard provides a flexible high-speed, differential and low-speed, low-power single-ended serial interface solution for interconnection between components within mobile and embedded devices. Depending on the application, the D-Phy can transition from 50 Ω HS (high speed) mode to high impedance LP (low power) mode to save power usage (Figure 5). In LP mode, the signaling is single-ended with a 1.2 V swing operating at a max data rate of 10 Mb/sec. The impedance driving the bus is typically pulled up or pulled down with a high value resistor, and this interacts with the RCRC input impedance of the probe, which causes very long time constant effects and a noticeable change in signal amplitude (yellow trace in Figure 5). In this case, the 1 KΩ differential input impedance of the RCRC probe introduces probe loading effects, resulting in amplitude change, while the higher impedance RC probe does not. Therefore, it is generally not recommended to use an RCRC type probe for this type of bus. An RC type of probe with high input impedance across the wide bandwidth range, such as a Keysight InfiniiMax I/II/RC/Ultra probe, is recommended for this application (blue trace in Figure 5). An RCRC probe would do a better job in measuring high speed signals with low source impedance, such as a 50 Ω transmission line.



Yellow: Keysight InfiniiMax probe with RCRC architecture

Blue: Keysight InfiniiMax probe with RC architecture

Figure 5. An RC probe is a better choice when probing buses that transition to a "high Z" state, such as this MIPI D-phy signal

Besides MIPI D-phy there are also more signal standards that use buses that transition to a “high Z” state including the latest DDR and LPDDR standards. When signals have a high impedance, an RC probe is recommended for the most accurate results.

Example #2: Embedded Multi-Media Controller (eMMC)

Let’s look at another example – the eMMC (Embedded Multi-Media Controller). The eMMC is a memory card standard used for solid state storage. It puts the MMC components (flash memory plus controller) into a small BGA IC package for use with portable consumer products such as mobile and tablet devices.

Here in the eMMC circuitry, we are about to measure the Data Strobe line. The driver circuit is driving the eMMC circuit load pulled down to ground through a 10 kΩ resistor (Figure 6). The data rate of the signal is 400 Mbps, which is a slow speed signal for an RCRC probe. The source impedance is indeed very heavy for any probe to deal with. When the Keysight InfiniiMax probe with RCRC architecture is used notice that the idle state voltage gets loaded by the probe and the signal level is shifted (Figure 7). However, when the Keysight InfiniiMax probe with RC architecture is used, the idle state gets down close to zero voltage as was expected (Figure 8). So, in this case, the RC probe is the better choice for more accurate measurement results.

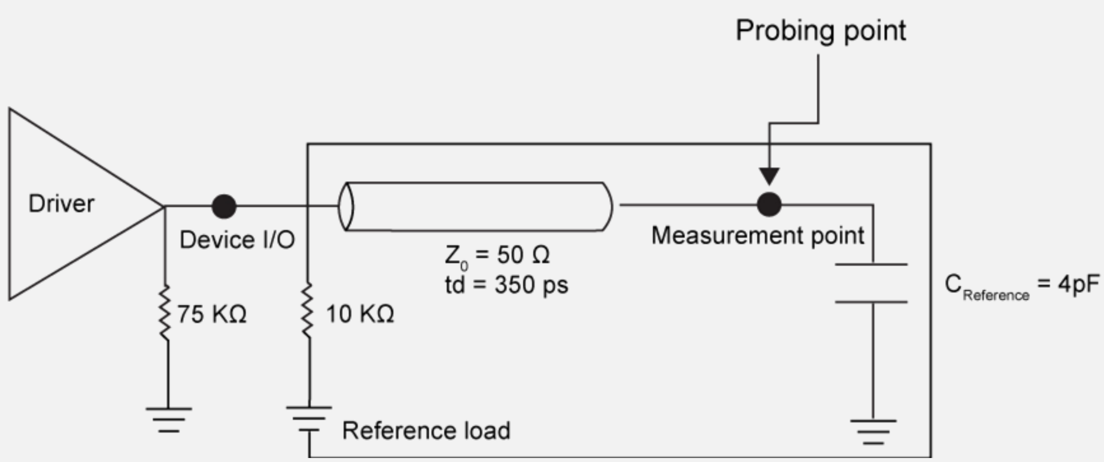


Figure 6. The driver circuit is driving the eMMC circuit load pulled down to ground through a 10 kΩ resistor

Figure 7. The eMMC data strobe line measured with a Keysight InfiniiMax probe with RCRC architecture

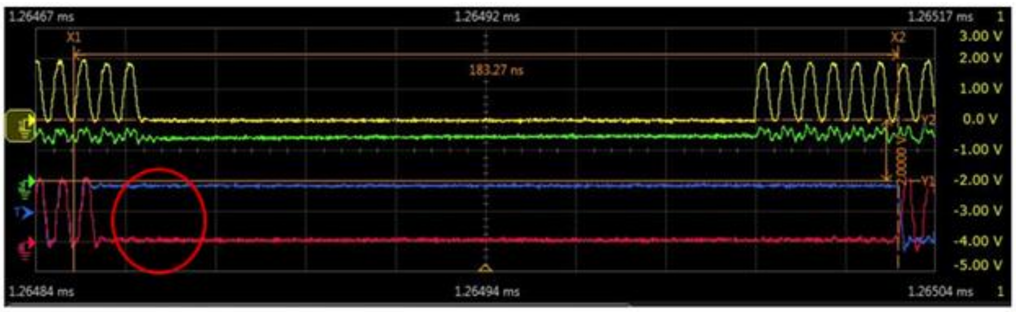


Figure 8. The eMMC data strobe line measured with a Keysight InfiniiMax probe with RC architecture

Conclusion

Most oscilloscope probes have either an RC or RCRC input impedance architecture, and it's important to know what your probe has to anticipate its measurement strengths and weaknesses. Be sure to consider probe loading effects to get the best accuracy possible. Most probe manufacturers provide input loading models so you can understand the probe loading characteristics before you choose a probe. Keysight has many different probes optimized for different jobs, check them out in the links below.

More Information

For more information on Keysight's probing solutions, check out the following:

- Keysight Probe Resource Center
- Infiniium Oscilloscope Probes and Accessories Data Sheet
- InfiniiVision Oscilloscope Probes and Accessories Data Sheet
- InfiniiMax Ultra Series Probes with RC Architecture Data Sheet
- InfiniiMax III/III+ Probes with RCRC Architecture Data Sheet

Learn more at: www.keysight.com

For more information on Keysight Technologies' products, applications, or services, please contact your local Keysight office. The complete list is available at:
www.keysight.com/find/contactus