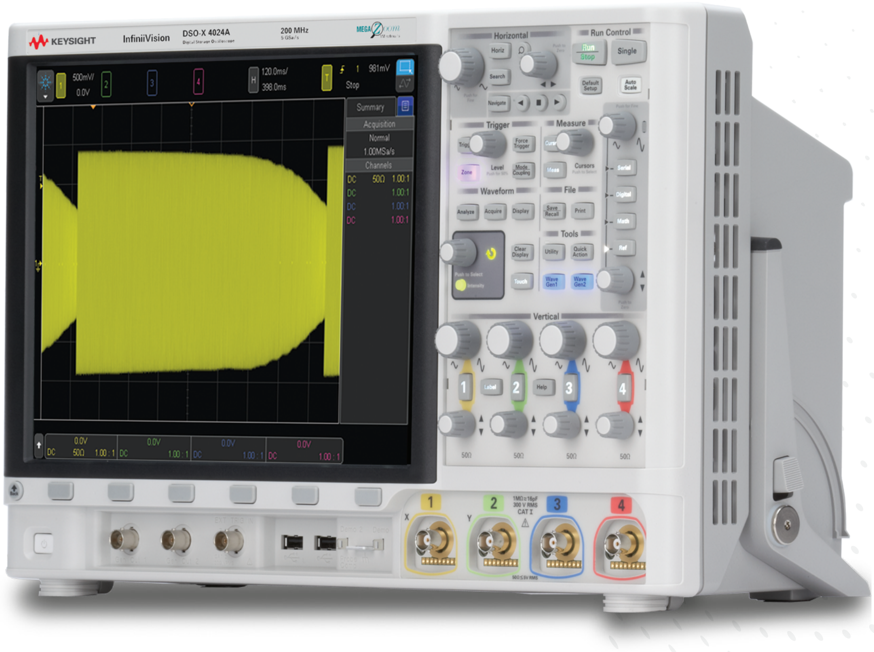
APPLICATION NOTE

Evaluating Oscilloscope Bandwidths for Your Application



KEYSIGHT TECHNOLOGIES

Introduction

Bandwidth is the specification that most engineers consider first when they select an oscilloscope. In this application note we will provide you with some helpful hints on how to select an oscilloscope with the appropriate bandwidth for both your digital and analog applications. But first, let's define oscilloscope bandwidth.

Defining Oscilloscope Bandwidth

All oscilloscopes exhibit a low-pass frequency response that rolls-off at higher frequencies, as shown in Figure 1. Most scopes with bandwidth specifications of 1 GHz and below typically have what is called a Gaussian response, which exhibits a slow roll-off characteristic beginning at approximately one-third the –3 dB frequency. Oscilloscopes with bandwidth specifications greater than 1 GHz typically have a maximally–flat frequency response, as shown in Figure 2. This type of response usually exhibits a flatter in-band response with a sharper roll-off characteristic near the –3 dB frequency.

There are advantages and disadvantages to each of these types of oscilloscope frequency responses. Oscilloscopes with a maximally-flat response attenuate in-band signals less than scopes with Gaussian response, meaning that scopes with maximally-flat responses are able to make more accurate measurements on in-band signals. But a scope with Gaussian response attenuates out-of-band signals less than a scope with a maximally-flat response, meaning that scopes with Gaussian responses typically have a faster rise time than scopes with a maximally-flat response, given the same bandwidth specification. But sometimes it is advantageous to attenuate out-of-band signals to a higher degree in order to help eliminate higher-frequency components that can contribute to aliasing in order to satisfy Nyquist criteria (fS > 2 x fMAX). For a deeper understanding of Nyquist's sampling theory, refer to the Keysight Technologies, Inc application note, "Evaluating Oscilloscope Sample Rates vs. Sampling Fidelity" listed at the end of this document.

Whether your scope has a Gaussian response, maximally-flat response, or somewhere in between, the lowest frequency at which the input signal is attenuated by 3 dB is considered the scope's bandwidth. Oscilloscope bandwidth and frequency response can be tested with a swept frequency using a sine wave signal generator. Signal attenuation at the –3 db frequency translates into approximately –30% amplitude error. So you can't expect to make accurate measurements on signals that have significant frequencies near your scope's bandwidth.

Closely related to an oscilloscope's bandwidth specification is its rise time specification. Scopes with a Gaussian-type response will have an approximate rise time of $0.35/f_{BW}$ based on a 10% to 90% criterion. Scopes with a maximally-flat response typically have rise time specifications in the range of $0.4/f_{BW}$, depending on the sharpness of the frequency roll-off characteristic. But you need to remember that a scope's rise time is not the fastest edge speed that the oscilloscope can accurately measure. It is the fastest edge speed the scope can possibly produce if the input signal has a theoretical infinitely fast rise time (0 ps). Although this theoretical specification is impossible to test–since pulse generators don't have infinitely fast edges–from a practical perspective, you can test your oscilloscope's rise time by inputting a pulse that has edge speeds that are 3 to 5 times faster than the scope's rise time specification.

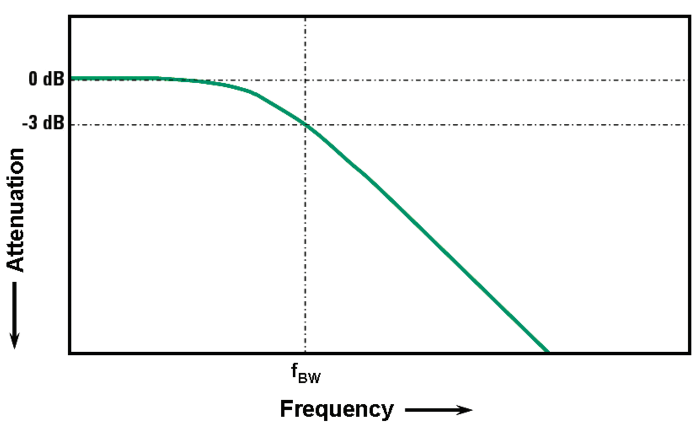


Figure 1: Oscilloscope Gaussian frequency response

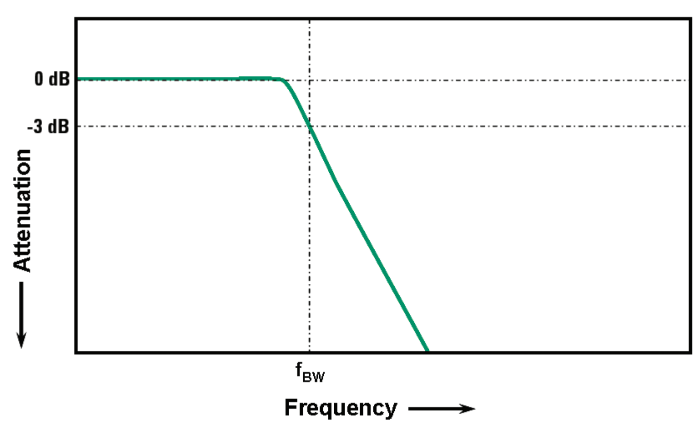


Figure 2: Oscilloscope maximally-flat frequency response

Required Bandwidth for Digital Applications

As a rule of thumb, your scope's bandwidth should be at least five times higher than the fastest digital clock rate in your system under test. If your scope meets this criterion, it will capture up to the fifth harmonic with minimum signal attenuation. This component of the signal is very important in determining the overall shape of your digital signals. But if you need to make accurate measurements on high-speed edges, this simple formula does not take into account the actual highest-frequency components embedded in fast rising and falling edges.

Rule of thumb

$f_{BW} \geq 5 \times f_{clk}$

A more accurate method to determine required oscilloscope bandwidth is to ascertain the maximum frequency present in your digital signals, which is not the maximum clock rate. The maximum frequency will be based on the fastest edge speeds in your designs. So the first thing you need to do is determine the rise and fall times of your fastest signals. You can usually obtain this information from published specifications for devices used in your designs.

Step 1: Determine fastest edge speeds

You can then use a simple formula to compute the maximum "practical" frequency component. Dr. Howard W. Johnson has written a book on this topic, "High-speed Digital Design – A Handbook of Black Magic."[1] He refers to this frequency component as the "knee" frequency (fknee). All fast edges have an infinite spectrum of frequency components. However, there is an inflection (or "knee") in the frequency spectrum of fast edges where frequency components higher than fknee are insignificant in determining the shape of the signal.

Step 2: Calculate f_{knee}

f_{knee} = 0.5 / RT (10% - 90%)
f_{knee} = 0.4 / RT (20% - 80%)

1. Johnson, Dr. Howard W. "High-speed Digital Design – A Handbook of Black Magic." Prentice Hall, 1993.

Required Bandwidth for Digital Applications (Continued)

For signals with rise time characteristics based on 10% to 90% thresholds, f_{knee} is equal to 0.5 divided by the rise time of the signal. For signals with rise time characteristics based on 20% to 80% thresholds, which is very common in many of today's device specifications, f_{knee} is equal to 0.4 divided by the rise time of the signal. Now don't confuse these rise times with a scope's specified rise time. We are talking about actual signal edge speeds.

The third step is to determine the oscilloscope bandwidth required to measure this signal, based on your desired degree of accuracy when measuring rise times and fall times. Table 1 shows multiplying factors for various degrees of accuracy for scopes with a Gaussian or a maximally-flat frequency response. Remember, most scopes with bandwidth specifications of 1 GHz and below typically have a Gaussian-type response, and most scopes with bandwidths greater than 1 GHz typically have a maximally-flat type response.

Step 3: Calculate scope bandwidth

Required accuracy	Gaussian response	Maximally-flat response
20%	$f_{BW} = 1.0 \times f_{knee}$	$f_{BW} = 1.0 \times f_{knee}$
10%	$f_{BW} = 1.3 \times f_{knee}$	$f_{BW} = 1.2 \times f_{knee}$
3%	$f_{BW} = 1.9 \times f_{knee}$	$f_{BW} = 1.4 \times f_{knee}$

Table 1: Multiplying factors to calculate required scope bandwidth based on desired accuracy and type of scope frequency response

Let's now walk through this simple example:

Determine the minimum required bandwidth of an oscilloscope with an approximate Gaussian frequency response to measure a 500-ps rise time (10 to 90%)

If the signal has an approximate rise/fall time of 500 ps (based on a 10% to 90% criteria), then the maximum practical frequency component (f_{knee}) in the signal would be approximately 1 GHz.

f_{knee} = (0.5/500ps) = 1 GHz

If you are able tolerate up to 20% timing errors when making parametric rise time and fall time measurements on your signals, then you could use a 1-GHz bandwidth oscilloscope for your digital measurement applications. But if you need timing accuracy in the range of 3%, then a scope with 2-GHz bandwidth would be the better choice.

20% timing accuracy:
Scope BW = 1.0 x 1 GHz = 1.0 GHz

3% timing accuracy:
Scope BW = 1.9 x 1 GHz =1.9 GHz

Let's now make some measurements on a digital clock signal with characteristics similar to this example, using various bandwidth scopes....

Digital Clock Measurement Comparisons

Figure 3 shows the waveform results when measuring a 100 MHz digital clock signal with 500 ps edge speeds (10 to 90%) using a 100-MHz bandwidth oscilloscope. As you can see, this scope primarily just passes through the 100 MHz fundamental of this clock signal, thus representing our clock signal as an approximate sine wave. A 100 MHz scope may be a good solution for many 8 bit, MCU-based designs with clock rates in the 10 MHz to 20 MHz range, but 100 MHz bandwidth is clearly insufficient for this 100-MHz clock signal.

Using a 500-MHz bandwidth oscilloscope, Figure 4 shows that this scope is able to capture up to the fifth harmonic, which was our first rule of thumb recommendation. But when we measure the rise time, we see that the scope measures approximately 800 ps. In this case, the scope is not making a very accurate measurement on the rise time of this signal. The scope is actually measuring something closer to its own rise time (700 ps), not the input signal's rise time, which is closer to 500 ps. We need a higher-bandwidth scope for this digital measurement application if timing measurements are important.

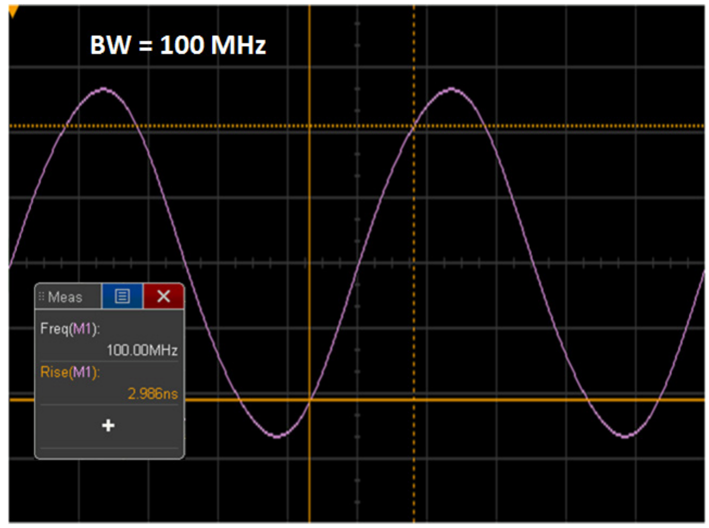


Figure 3: 100-MHz clock captured on a 100-MHz bandwidth scope

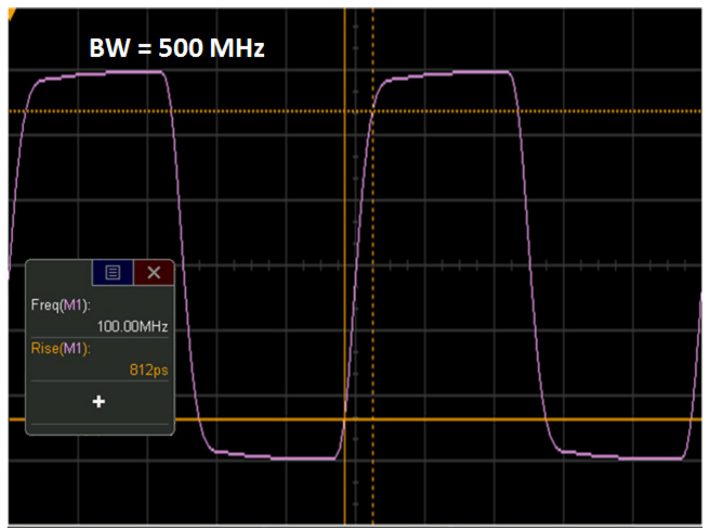


Figure 4: 100-MHz clock captured on a 500-MHz bandwidth scope

Digital Clock Measurement Comparisons (Continued)

With a 1-GHz bandwidth scope, we have a much more accurate picture of this signal, as shown in Figure 5. When we select a rise time measurement on this scope, we measure approximately 600 ps. This measurement is providing us with approximately 20% measurement accuracy and may be a very acceptable measurement solution–especially if budgets are tight. However, even this measurement using a 1-GHz bandwidth scope might be considered borderline. If we want to make edge-speed measurements with greater than 3% accuracy on this signal with 500 ps edge speeds, we really need to use a scope with 2-GHz bandwidth or higher, as we determined in the walk-through example earlier.

With a 2-GHz bandwidth scope, now we are seeing an accurate representation of this clock signal along with a very accurate rise time measurement of approximately 520 ps, as shown in Figure 6.

One thing nice about Keysight's InfiniiVision X-Series and Infiniium Series oscilloscopes is that the bandwidths of these scopes are upgradable.

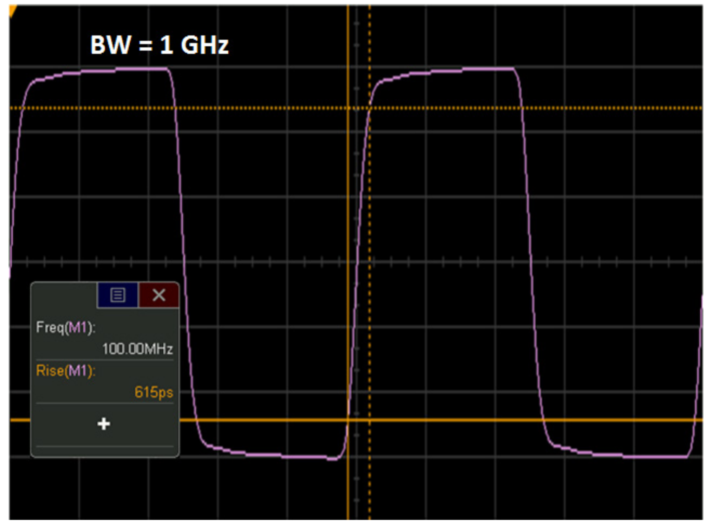


Figure 5: 100-MHz clock captured on a 1-GHz bandwidth scope

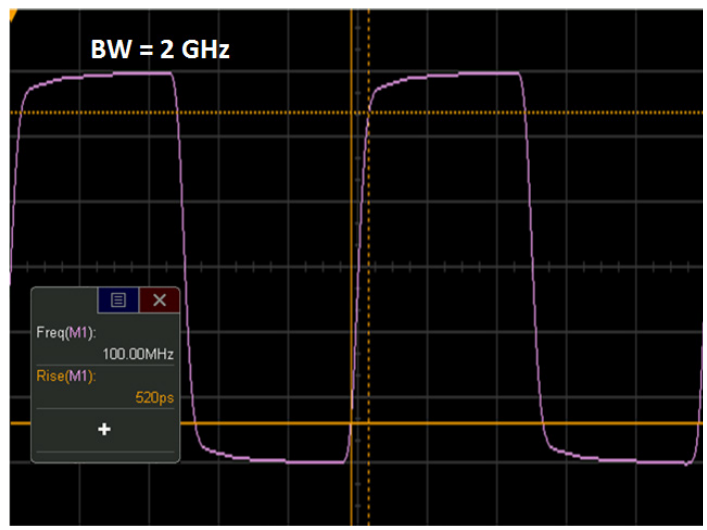


Figure 6: 100-MHz clock captured on a 2-GHz bandwidth scope

Required Bandwidth for Analog Applications

Years ago, most oscilloscope vendors recommended that your scope's bandwidth should be at least three times higher than the maximum signal frequency. Although this "3X" multiplying factor would not apply to digital applications, it still applies to analog applications, such as modulated RF. To understand where this 3-to-1 multiplying factor comes from, let's look at an actual frequency response of a 1-GHz bandwidth scope.

Figure 7 shows a swept response test (20-MHz to 2-GHz) on a Keysight 1-GHz bandwidth oscilloscope. As you can see, at exactly 1 GHz the input is attenuated by about 1.7 dB, which is well within the –3 dB limitation that defines this scope's bandwidth. However, to make accurate measurements on analog signals, you need to use the scope in the portion of the frequency band where it is still relatively flat with minimal attenuation. At approximately one-third the scope's 1-GHz bandwidth, this scope exhibits virtually no attenuation (0 dB). However, not all scopes exhibit this type of response.

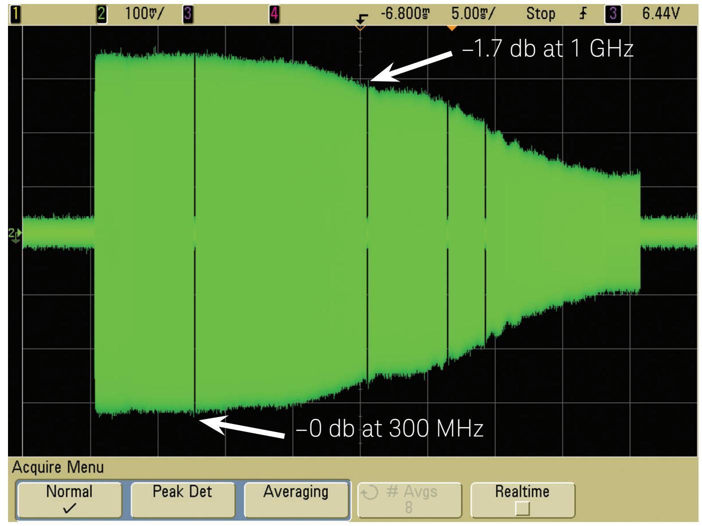


Figure 7: Swept frequency response test on Keysight's MSO7104B 1-GHz bandwidth scope

The swept frequency response test shown in Figure 8 was performed on a 1.5-GHz bandwidth scope from another scope vendor. This is an example of a very non-flat frequency response. The characteristics of this response are neither Gaussian nor maximally-flat. It appears to be "maximally bumpy" and very peaked, which can result in severe waveform distortion–on both analog and digital signals. Unfortunately, a scope's bandwidth specification, which is the 3 dB attenuation frequency, says nothing about the attenuation or amplification at other frequencies. Even at one-fifth this scope's bandwidth, signals are attenuated by approximately 1 dB (10%) on this scope.

So in this case, following the 3X rule of thumb would not be wise. When you are selecting a scope, it is a good idea to choose a reputable scope vendor and pay close attention to the relative flatness of the scope's frequency response.

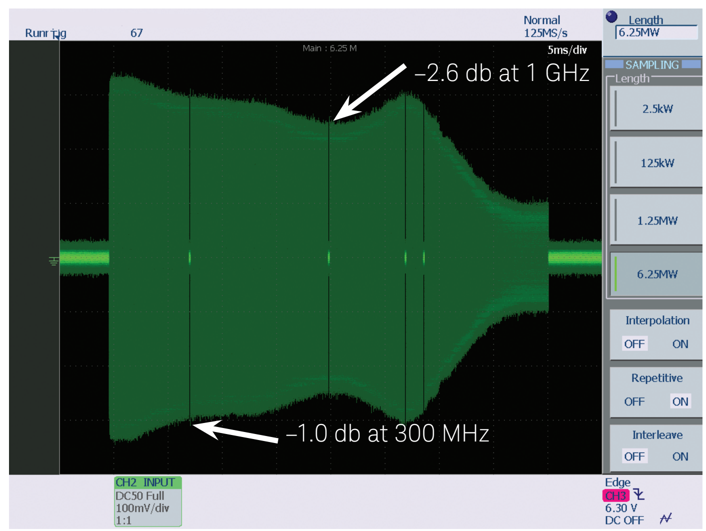


Figure 8: Swept frequency response test on a non-Keysight 1.5-GHz bandwidth scope

Summary

For digital applications, you should select a scope that has a bandwidth that is at least five times higher than the fastest clock rate in your design. But if you need to make accurate edge-speed measurements on your signals, you will need to determine the maximum practical frequency present in your signal.

For analog applications, select a scope that has a bandwidth that is at least three times higher than the highest analog frequency of your designs. But this rule-of-thumb recommendation only applies to scopes that have a relatively flat response in their lower frequency band. This is something you won't need to worry about with Keysight oscilloscopes.

And when you are considering a scope for today's applications, don't forget about tomorrow's applications. If your budget is flexible, buying a little extra margin today may save you money in the future. But, if you need higher bandwidth in the future, the bandwidth of most Keysight oscilloscopes can be upgraded.

Product Web site

For the most up-to-date and complete application and product information, please visit our product Web site at:
www.keysight.com/find/scopes

Glossary

Gaussian frequency response	A low-pass frequency response that has a slow roll-off characteristic that begins at approximately 1/3 the –3 dB frequency (bandwidth). Oscilloscopes with bandwidth specifications of 1 GHz and below typically exhibit an approximate Gaussian response.
In-band	Frequency components below the –3 dB (bandwidth) frequency.
Knee frequency	The maximum "practical" frequency (f_{knee}) that determines the shape of a digital pulse, which can be computed if the approximate input signal's rise time is known (usually obtained from device specification data books).
Maximally-flat response	A low-pass frequency response that is relatively flat below the –3 dB frequency and then rolls off sharply near the –3 dB frequency (bandwidth). Oscilloscopes with bandwidth specifications greater than 1 GHz typically exhibit a maximally–flat response.
Nyquist sampling theorem	States that for a limited bandwidth (band-limited) signal with maximum frequency f_{MAX}, the equally spaced sampling frequency f_S must be greater than twice the maximum frequency f_{MAX}, in order to have the signal be uniquely reconstructed without aliasing.
Oscilloscope bandwidth	The lowest frequency at which input signal sine waves are attenuated by 3 dB (–30% amplitude error).
Oscilloscope rise time	The fastest edge an oscilloscope can produce if the input signal has an infinitely fast edge speed. For scopes with an approximate Gaussian frequency response, the scope rise time can be computed as $0.35/f_{BW}$. Scopes with a maximally-flat frequency response typically have a rise time in the range of $0.4/f_{BW}$.
Out-of-band	Frequency components above the –3 db frequency (bandwidth).
Swept frequency response	A test using a signal generator where an output sine wave's frequency is repetitively "swept" from a user-defined lower frequency to a user-defined upper frequency to test the frequency response of an instrument or device.