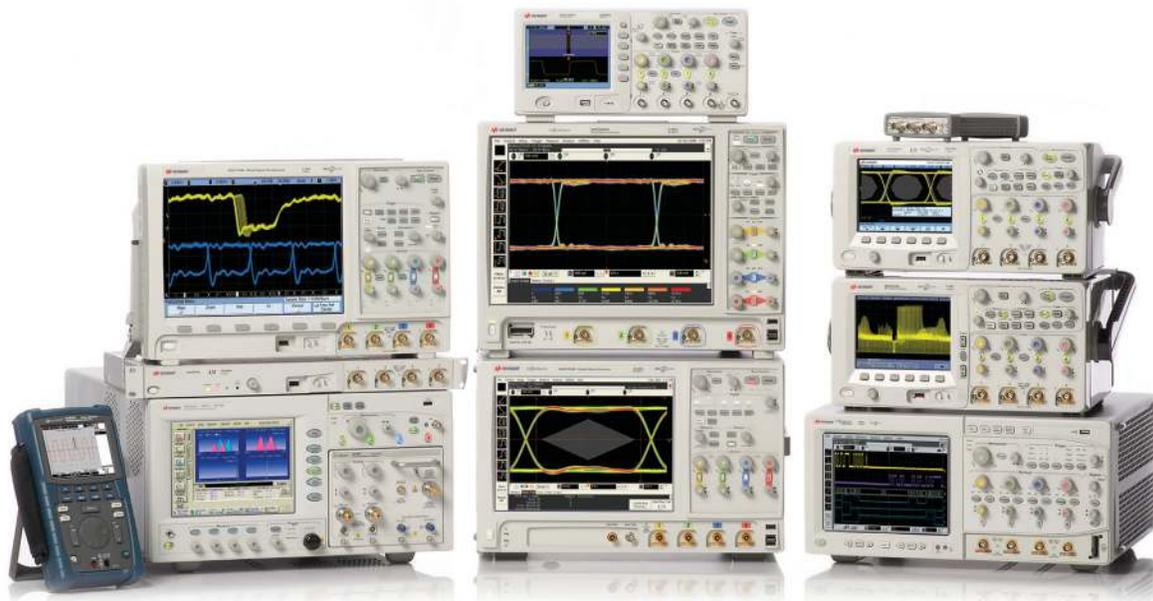


Keysight Technologies

Capturing the Fifth Harmonic: Tradeoffs Between Sampling and Real-Time Oscilloscopes

Application Note





Introduction

It is important to choose the right oscilloscope for your application. With today's tight budgets, it is even more critical that you purchase exactly the capabilities you need. There are two main types of oscilloscopes, real-time (RT) oscilloscopes and equivalent-time (ET) oscilloscopes. For each type of oscilloscope there are many different specifications you need to consider. One of the most important specifications is bandwidth. If your scope doesn't have enough bandwidth to satisfy the Nyquist criterion, you will see significant aliasing in your signal.

There is no simple way to decide how much oscilloscope bandwidth you will need. Scope vendors promote a "fifth harmonic" rule of thumb. They suggest you purchase a scope with sufficient bandwidth to capture the fifth harmonic of your signals. However, under typical conditions, even if the oscilloscope has enough bandwidth to theoretically capture the fifth harmonic, it is possible the oscilloscope will not capture any fifth harmonic content at all. Given today's economy, it may not be wise to purchase an oscilloscope to capture the fifth harmonic based on a rule of thumb, when despite its higher price, it can only capture to the third harmonic. You could purchase a lower-bandwidth oscilloscope that captures the same harmonic content for less money. This is why it is necessary to know exactly how much bandwidth you truly need and what features you require.

The higher cost of a high-bandwidth oscilloscope is not the only downside of buying more bandwidth than you really need. Higher-bandwidth oscilloscopes also generate more noise and cause more distortion. The increased noise impacts amplitude measurements and the accuracy of timing measurements, which sometimes defeats the purpose of having the extra bandwidth in the first place. The best compromise is to use a measurement system with just enough bandwidth to measure the signal accurately while minimizing the extra noise introduced by the measurement system.

Finally it is important to grasp the benefits and disadvantages of different oscilloscope types, including RT and ET oscilloscopes. Once you understand all these specifications (including noise floor, dynamic range, and bandwidth) and how they affect measurements, you can be sure you are purchasing the correct oscilloscope to meet your needs.

Why noise floor matters

Data rates continue to climb, and today's state-of-the-art technology may be out of date in just a few years. Serial data rates of 5 Gbps are now becoming common. As a result of these new data rates, there is no longer time to transition a bit from 0 to 1 with a 2-V signal. As the signal rate increases, the channel the signal travels through distorts the signal at the receiver. This can result in a partially or completely closed eye diagram. A number of serial technologies have peak-to-peak voltages of 800 mV or less. Every oscilloscope has an intrinsic noise floor that increases as the volts per divisions increases. If you are looking at an 800-mV peak-to-peak signal, you will require a voltage-per-division setting of at least 100 mV/div to see the entire signal and avoid saturating the oscilloscopes.

If the intrinsic oscilloscope noise at 100 mV/div is 50 mV, then 8% of the signal can be attributed to oscilloscope noise. Even worse, if the noise floor is 100 mV, 13% of the signal is oscilloscope noise. Assuming that a signal's eye is shrinking, 13% extra noise can cause an open eye to appear closed. The same 100 mV of noise translates to -23.3 dBm or -36.4 dBV. High noise floors can cause designers to overdesign their products. Typically, ET oscilloscopes have a lower noise floor than RT oscilloscopes. However, with proper research, you will find RT oscilloscopes that have noise floors that are less than 5% of the signal discussed above. The Keysight Technologies Inc. Infiniium 90000A Series real-time oscilloscopes meet this criterion; they offer the industry's lowest noise floor. For example, the 12 GHz model provides the low noise floor of 435 μ Vrms at 5 mV per division.

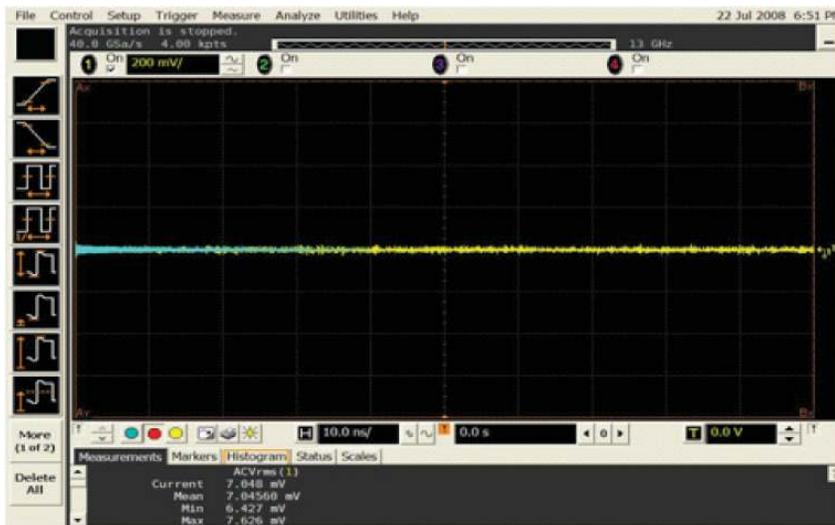


Figure 1: Measuring the noise floor at 200 mV/div

Capturing Frequency Content

Fourier synthesis theory states that all complex signals in simplest forms can be constructed by adding sine waves of different frequencies and phases together. You can see these frequencies in the frequency domain by plotting frequency against amplitude. The number of sine waves that are captured is known as the frequency content of a signal. Figure 2 shows the frequency content of a 100-MHz square wave. Notice that there are multiple spurs, known as harmonics, and each is well defined. Also notice that each harmonic is at a different power level. The first is the largest and each subsequent harmonic gets gradually smaller. We can reconstruct the original square wave by adding these harmonics back together. This means that the more harmonics (harmonic content) that an oscilloscope is able to capture, the more accurately it can display a signal when it is reconstructed in the time domain.

Harmonics occur at 0.5 times the bit rate. For example, a 4-Gbps signal would have significant harmonics at 2, 4, 6, 8, and 10 GHz, going to infinity. If you had a perfect square wave and an oscilloscope with infinite dynamic range and no noise floor, your instrument would need at least 10 GHz of bandwidth to capture the fifth harmonic. However, in real life, perfect square waves do not exist, especially in today's high-speed digital signals. A number of factors erode the strength of the harmonics and spread out the harmonic content. The most important factor is the signal's rise time.

An ideal square wave has a rise time of near 0 pS. This is not the case in real-world applications. In the best designs, rise times at the receiver rarely exceed 30 pS. Rise times are slowed by PCB material, connectors, traces, and distance. FR-4 is one of the most common materials used in PCBs. FR-4 is popular because of its low cost. FR-4 has an absolute maximum rise time of 45 pS. However, typically it will see maximum rise times of only 50 – 60 pS (80/20).

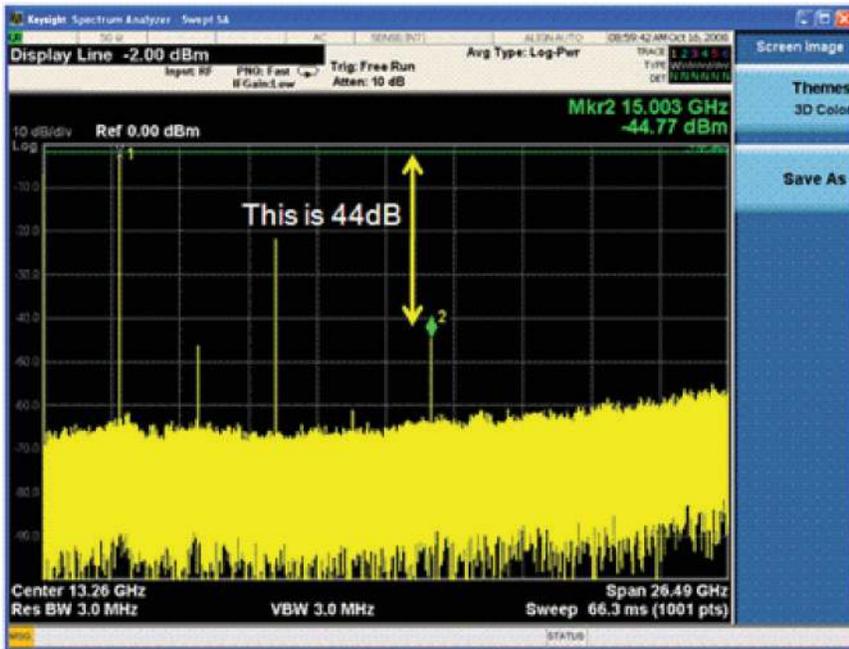


Figure 2: SATA 6G spectrum analysis

Consider the SATA 6G HFTP signal spectrum analysis displayed in Figure 2. It has a rise time of 45 pS and a bit rate of 6 Gbps (fifth harmonic at 15 GHz). However, the fifth harmonic's power is 45 dBm less than the first harmonic. For an oscilloscope to display any of its content in the time domain, it must have a noise floor of less than -58 dBV. Recall from our example, 100 mV of pk to pk noise is equivalent to -32 dBV, which means any signal that is -58 dBV down, will be lost in an oscilloscope's noise floor. For the fifth harmonic to significantly influence the measurement of a real-time oscilloscope (about 35 dBm below the carrier frequency), the rise time must be faster than 30 pS. Rise times this fast do not occur frequently in real-life signals. On the other hand, an equivalent-time oscilloscope has a lower noise floor to capture the entire fifth harmonic of a SATA 6G signal. You must decide between using a real-time oscilloscope that can capture through the third harmonic or an equivalent-time oscilloscope which can capture harmonic content equivalent to its bandwidth.

Another example: A PCI Express® Gen II signal has a data rate of 5 Gbps. To capture the fifth harmonic at this data rate, you would need an oscilloscope with at least 12.5 GHz bandwidth. However, typically the signal will have rise times between 50 and 70 pS at the receiver. As a result, the fifth harmonic is -48 dBm down from the zero crossing, meaning that a 12.5-GHz RT oscilloscope (dynamic range of 35-45 dBV) will not capture any of the fifth harmonic content. Despite the different bandwidths an 8-GHz and a 12.5-GHz real-time oscilloscope will capture the same harmonic content of the PCI Express Gen II signal. To capture the fifth harmonic content of this signal, it is necessary to use an ET oscilloscope with its even lower noise floor. This is evident in the two real-time eyes that are shown in Figures 3 and 4. Notice that despite the extra bandwidth, the real-time eyes look identical at 60 pS rise times.

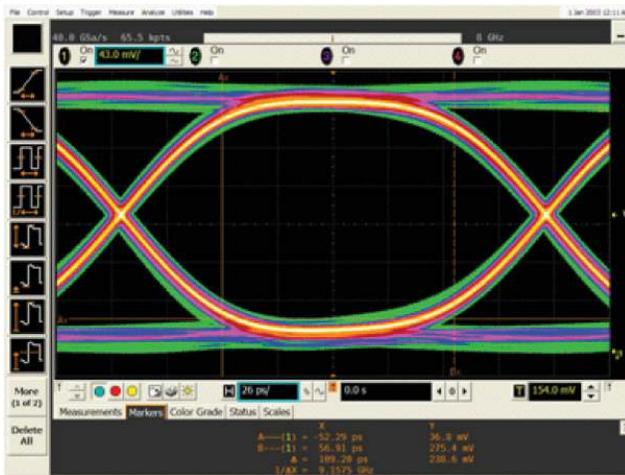


Figure 3: PCI Express® Gen II signal captured at 13 G with 60 pS rise time

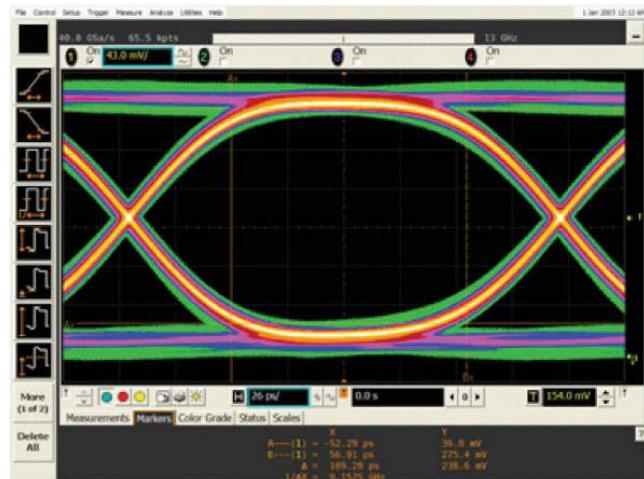


Figure 4: PCIe® Gen II 60-pS rise time captured 8 GHz

Another approach to calculating bandwidth

Another way to quantify how much bandwidth is required to capture the necessary frequency content of a signal is to integrate the spectral content of a signal until we reach a certain percentage of the total signal power (say 99.9%). This method ensures that we include all the spectral content with a large enough amplitude to significantly affect the signal.

Figures 5 and 6 compare the amount of bandwidth (in GHz) required to contain 99.9% of the signal power of a clock pattern and a 2^7-1 PRBS pattern. Both simulated data and live signal measurements are compared at many different combinations of bit rate and edge speed. The edge speeds in the simulation were created using a sum of cosines filter with linear phase. Measurements of the live signal were produced with a Keysight N4903A J-BERT and cascaded Picosecond Pulse Labs transition time converters measured with a 26.5-GHz E4440A performance spectrum analyzer.

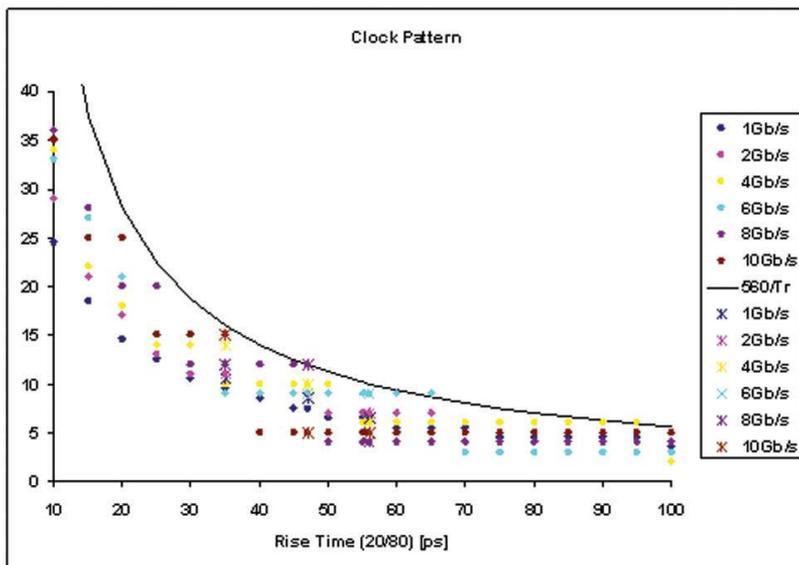


Figure 5: The amount of bandwidth (in GHz) required to contain 99.9% of the signal power of a clock pattern 0.56/Edge Speed

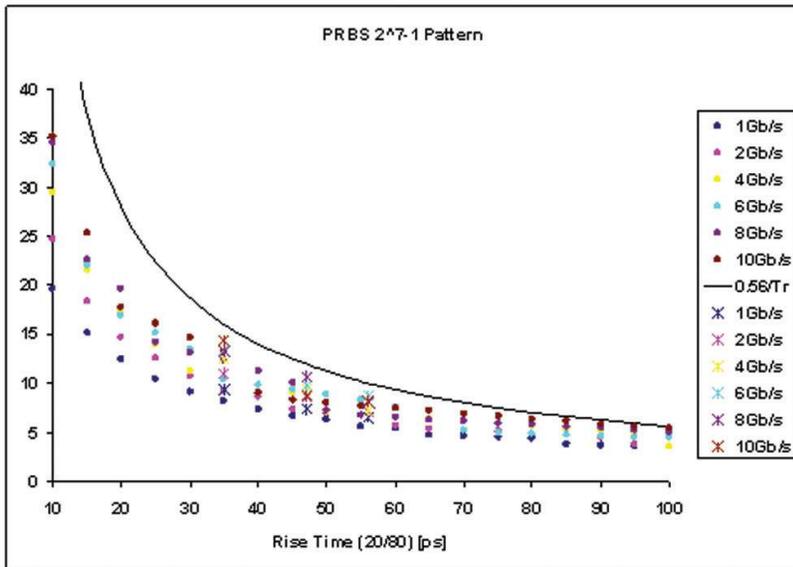


Figure 6: The amount of bandwidth (in GHz) required to contain 99.9% of the signal power of a 2^7-1 PRBS pattern

The rise time is clearly the dominant factor in determining the amount of bandwidth the signal requires. In some cases, a higher bit rate requires less bandwidth than a lower bit rate for a given rise time. If we analyze the data closely, we see that in most cases the clock pattern requires the most bandwidth for a given bit rate or rise time. Intuitively this makes sense, since the clock is switching states more often than the data pattern and thus contains more high-frequency energy

It is not practical to measure each signal with a wideband spectrum analyzer before you decide which oscilloscope to use. Although there is no easy way to predict exactly how much bandwidth is required for a given data pattern, bit-rate and rise time, we can see that a conservative approximation that works quite well is that the bandwidth required to capture 99.9% of a signal's power is $\sim 0.56/\text{rise time}$ [20–80%].

Tradeoffs Between RT and ET Oscilloscopes

If capturing the third harmonic provides enough harmonic content for today's 6 Gbps signals and above, RT oscilloscopes offer a number of features that ET oscilloscopes don't. The most significant difference is that RT oscilloscopes offer sampling rates and memory depths significantly higher than ET oscilloscopes offer. A RT oscilloscope also doesn't require an external trigger, as it will trigger itself. An ET oscilloscope requires an outside trigger and takes multiple single-point acquisitions to display the data.

Real-time oscilloscopes tend to have more automated compliance software applications, adding convenience and speed to measurements. For PCI Express Gen II, Keysight offers optional automated software for measuring a number of key specifications on its real-time oscilloscopes. With the PCI Express software, you can use the same oscilloscope you use for everyday debugging to perform automated testing and margin analysis based on the PCI-SIG[®]-specified tests. The Keysight N5393B PCI Express electrical test software automatically configures the oscilloscope for each test, and then displays the results in a flexible report format showing how closely your device passed or failed each test.

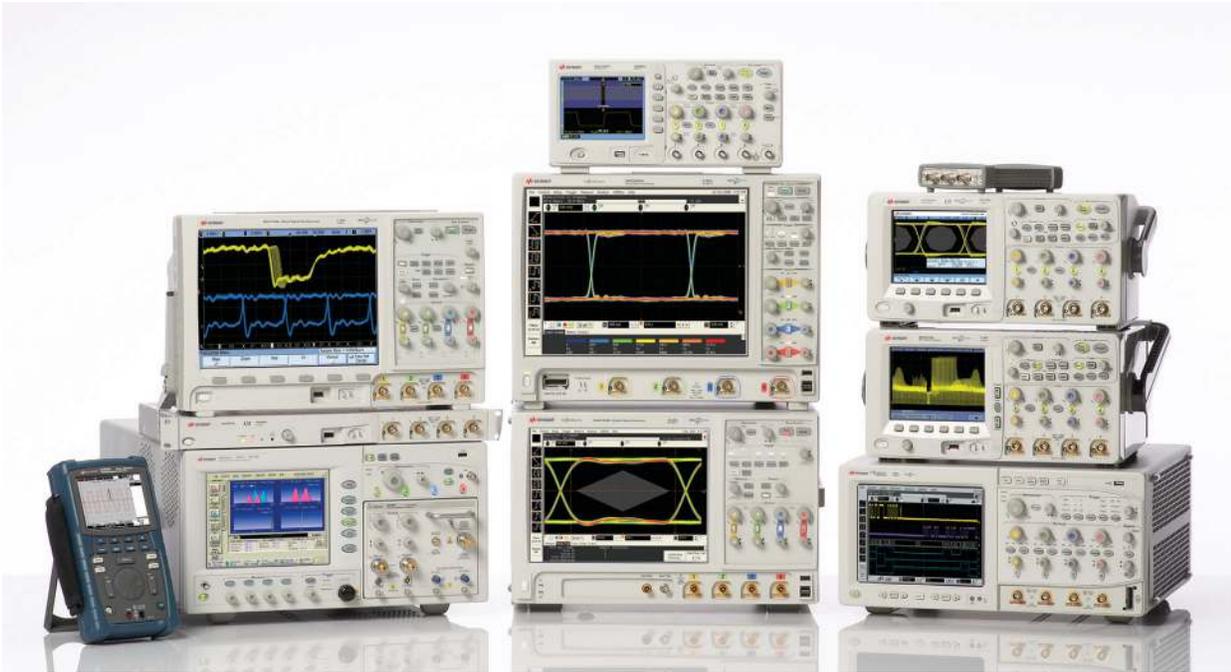
On the other hand, ET scopes offer more bandwidth and less noise. In addition, ET scopes typically include a module that allows you to make TDR measurements.

Conclusion

In today's difficult economy, it is critical that you select the right tool to do the job, you can't afford to pay for capability that you don't need or that doesn't give you a significant advantage. Many engineers use the fifth harmonic as a measure of how much bandwidth to purchase. However, for rise times that are slower than 30 pS, real time oscilloscopes will not capture any significant harmonic content outside the third harmonic, because of their high noise floor. In fact, at high data rates (6 Gbps and faster) at the receiver, in most cases real-time oscilloscopes will not capture the fifth harmonic at all, regardless of bandwidth. The fifth harmonic's content is below the noise floor of a real-time oscilloscope. For the fifth harmonic to actually be part of your measurement, you need to purchase an ET oscilloscope. ET oscilloscopes have low enough noise floors that in many cases they will capture the fifth harmonic. RT oscilloscopes offer features such as deeper memory and faster sampling rates. This means you must decide between capturing up to the third harmonic and getting the features of a real-time oscilloscope or capturing the fifth harmonic with an ET oscilloscope. It is worth noting that as rise times decrease to 30 pS and below, the fifth harmonic content will become much more prevalent, which means in the future real-time oscilloscopes will also be able to capture the fifth harmonic.

Related Literature

Publication title	Publication number
<i>Keysight Infiniium DSA/DSO90000 Series Oscilloscopes. Data sheet</i>	5989-7819EN
<i>Keysight 86100C Wide-Bandwidth Oscilloscope Mainframe and Modules. Data sheet</i>	5989-0278EN
<i>N5393B PCI Express 2.0 (Gen2) Electrical Performance Validation and Compliance Software for Infiniium Oscilloscopes. Data sheet</i>	5989-1240EN



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