

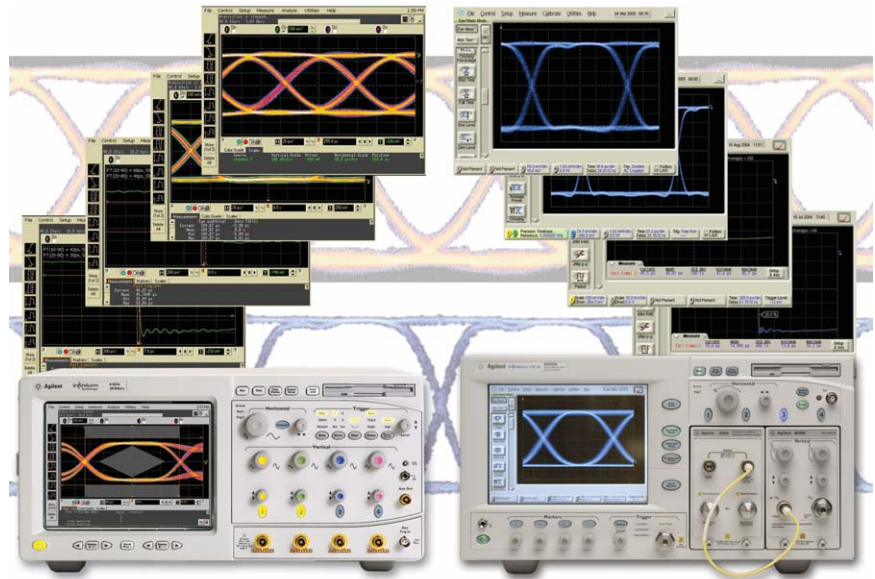
# Picking the Optimal Oscilloscope for Serial Data Signal Integrity Validation and Debug

Application Note 1556

## Introduction

In the past, it was easy to decide whether to use a real-time oscilloscope or an equivalent-time “sampling” oscilloscope. To view very-high-speed signals, you needed the bandwidth of the sampling scope. However, with real-time oscilloscopes now available with bandwidths well above 10 GHz, it is no longer obvious whether you should use a real-time oscilloscope or a sequential-sampling oscilloscope. The two instruments now have significant overlap in their ranges of operation. If you base your decision purely on measurement bandwidth, you would be missing much of the subtlety of the choice. However, bandwidth is certainly a primary consideration: If the scope doesn't have the bandwidth to reproduce your signal faithfully, other considerations don't matter.

A brief discussion on the fundamental architectural differences between the two scopes will help you understand why some capabilities exist for one



and not the other. From a simple point of view, the real-time scope is an ultra-fast analog-to-digital converter. To capture a fast waveform, the A-to-D sample rate must be significantly faster than the data. Sample rates now exceed 40 Gsa/s, allowing bandwidths as high as 13 GHz. An equivalent-time scope also digitizes and displays signals. However, the sample rate is lower than 1 Msa/s. A waveform is reconstructed through multiple observations of the signal. Thus it is restricted to looking at signals that repeat, or signals for which there is a synchronous timing reference to trigger the scope.

The key benefit of this approach is that although the sample rate is low, measurement bandwidths are extremely wide and can exceed 80 GHz.

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# Bandwidth

Having admitted that bandwidth is a key performance issue, let's consider it first. How do you know how much bandwidth you need? For purposes of this application note, we'll restrict the discussion to digital serial NRZ data signals with embedded clock.

For a given bit rate, an alternating 1-0-1-0 pattern will result in a square wave with a frequency equal to half the bit rate. Although the spectrum of real data is more complex, the square wave provides a good reference point for analysis, as it represents the fastest switching that takes place in the data stream. The frequency content for a variety of data rates is shown in Table 1. Columns 3 and 4 indicate the 3rd and 5th harmonic frequencies of this fundamental square wave. Why is this important? If the spectrum of a signal is modified by the oscilloscope, the observed waveform will not be an exact replica of the input. As the higher spectral components are rolled off, important features like rise and fall times will be slowed, and overshoot and ringing will be suppressed.

Another important criterion that determines the measurement bandwidth is the requirement to measure rise and fall times accurately. Figures 1 and 2 show comparisons of fall time measurements on a sequential-sampling scope with a 50-GHz bandwidth and on a real-time oscilloscope with 12-GHz bandwidth. The two agree quite well for a 46-ps fall time, but the real-time oscilloscope is grossly in error for a 15-ps fall time. Eventually you reach a point for any scope where you're measuring the rise time of the scope, not the rise time of the signal.

Technology and data rate	Fundamental frequency of 1-0-1-0 sequence	3rd harmonic of fundamental	5th harmonic of fundamental
<b>Fibre channel 4.25 Gb/s</b>	<b>2.125 GHz</b>	<b>6.375 GHz</b>	<b>10.63 GHz</b>
<b>Fibre channel 8.5 Gb/s</b>	<b>4.25 GHz</b>	<b>12.75 GHz</b>	21.25 GHz
<b>OC-192 9.95 Gb/s</b>	<b>4.98 GHz</b>	14.93 GHz	24.9 GHz

**Table 1. Data rates and frequency content of serial data signals. The bold entries indicate what is covered by today's real-time oscilloscope bandwidth.**



**A. Sequential sampling scope, 50 GHz bandwidth. Fall time measurement 15 ps.**



**B. Real-time scope, 10 GHz bandwidth. Fall time measurement 30 ps.**

**Figure 1. A 15 ps fall time measured on both scopes.**



**A. Sequential sampling scope, 50 GHz bandwidth. Fall time measurement 46 ps.**



**B. Real-time scope, 10 GHz bandwidth. Fall time measurement 46 ps.**

**Figure 2. A 46 ps fall time measured on both scopes.**

## Bandwidth (continued)

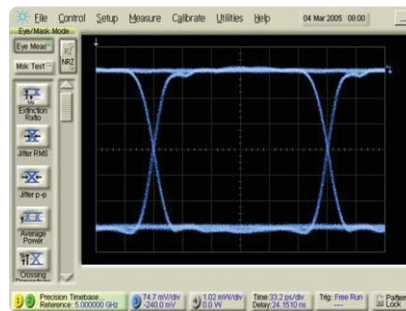
Today's real-time scopes can measure 40-ps rise and fall times with less than 5% error. If you need to measure faster rise and fall times, you need a sequential sampling scope.

If the scope does not have sufficient bandwidth to track the rising and falling edges in the signal, this will also be reflected as a closing of the eye diagram in eye measurements. Figures 3 and 4 show comparisons between eye diagrams seen on a 50-GHz sequential-sampling scope and on a 12-GHz real-time scope for various data rates. At 13.5 Gb/s, the eye has collapsed to a sine wave on the 12-GHz real-time scope. If there were problems with ringing or overshoot on the rising and falling edges, these would be clearly visible on the 50-GHz scope but not on the 12-GHz scope.

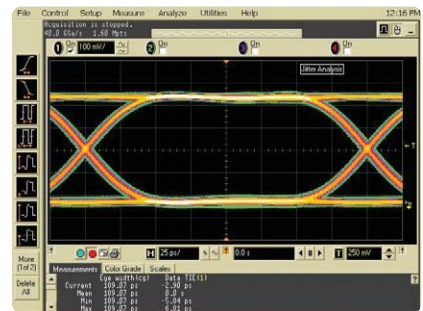
In optical transceiver compliance measurements, the oscilloscope bandwidth is intentionally reduced to a 3 dB bandwidth of 75% of the data rate. The higher order harmonics are almost completely suppressed. While this may initially seem like a questionable method to verify performance, it is important to remember the intent of the test, which is to determine if the transmitter will work in the communications system. Since the system receiver will not have a very wide bandwidth, testing the transmitter in a similar way makes sense. If you want to know the raw performance of the laser, you can increase the bandwidth.

Transition time	3% accuracy	5% accuracy	10% accuracy
100 ps	5.6 GHz	4.8 GHz	4 GHz
75 ps	7.5 GHz	6.4 GHz	5.3 GHz
50 ps	11.2 GHz	9.6 GHz	8 GHz
30 ps	18.7 GHz	16 GHz	13.3 GHz

**Table 2. Bandwidth needed to measure rise and fall times to a specific accuracy**

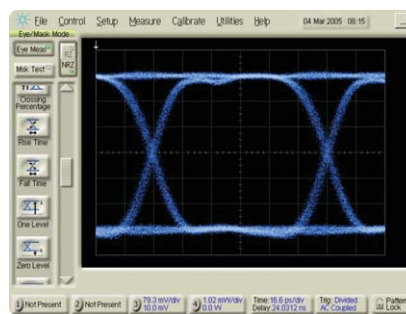


**A. Sequential sampling scope, 50 GHz bandwidth.**

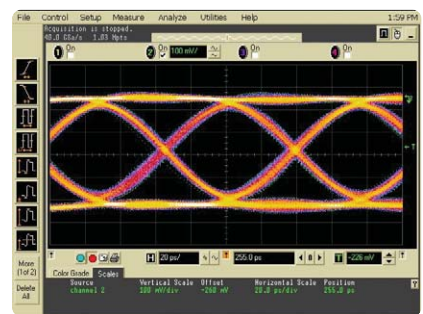


**B. Real-time scope, 10 GHz bandwidth.**

**Figure 3. 5 Gb/s eye diagram.**



**A. Sequential sampling scope, 50 GHz bandwidth.**



**B. Real-time scope, 12 GHz bandwidth.**

**Figure 4. 13.5 Gb/s eye diagram.**

## Define your task

The first thing you learn in a high-school shop class is to select the right tool for the job at hand. A hacksaw isn't very efficient for cutting down a tree, and it would be very challenging to cut a piece of pipe with a bow saw. Similarly, when you are selecting an oscilloscope, the first step is to ask yourself what you're going to do with it. The answer may be "everything," in which case the question then becomes, "Which tasks are most critical?"

### **Measuring signal integrity (rise and fall times, distortions, noise)**

If the most important requirement is to verify rise and fall times, propagation delay, and aberrations including overshoot, ringing, and reflections, bandwidth is the dominant factor of the oscilloscope that affects these measurements. Excess bandwidth (up to a point) is always better. Excess bandwidth beyond a 10X ratio between the scope's bandwidth and the frequency content of the signal is of little or no incremental benefit.

Noise, and the voltage precision with which you can measure the signal, are also important in signal integrity characterization. Sequential-sampling scopes have a typical noise floor on the order

of 250  $\mu\text{V}$  RMS, while a 12-GHz realtime scope has a typical noise floor of 350  $\mu\text{V}$  RMS. Sequential-sampling scopes have typically 9-bit resolution, which can be increased to 15+ bits on repetitive signals through the use of averaging. Real-time scopes typically have 8-bit resolution, which can be increased to 12 bits with averaging. The sequential sampling scope's lower noise and higher sampling precision may be helpful when you are measuring small signals or examining subtle waveform anomalies.

### **Measuring jitter**

Both types of scopes are available with jitter measurement packages. These additional measurement capabilities provide helpful insight into the nature of the jitter and its possible root causes. The factors that contribute to the accuracy of waveform analysis also come into play with jitter analysis. Insufficient bandwidth and excess noise relative to the signal being tested can degrade the accuracy of a jitter measurement. If cycle-to-cycle jitter analysis is required, keep in mind that only real-time scopes can measure cycle-to-cycle jitter, because this measurement requires capturing successive cycles in real time.

In the past, jitter due to intersymbol interference (ISI) was difficult to assess with a sampling scope. However a new architecture in Agilent's DCA-J sequential sampling scopes allows you to separate random from deterministic jitter and further decompose deterministic jitter down into ISI, duty-cycle-dependent, and periodic components. The method of analysis is beyond the scope of this application note; refer to "Precision jitter analysis using the Agilent 86100C DCA-J," Agilent publication number 5989-1146EN. This operation requires a repeating pattern, whereas a real-time scope can measure jitter on random data. The new EZJIT Plus analysis package (N5400A) implements these same proven algorithms developed for sampling scopes in Agilent real-time scopes.

The high resolution and wide bandwidth of the DCA-J sampling scope make it the most precise method for detailed jitter analysis.

A real-time scope has the diagnostic advantage of displaying the jitter trend time-correlated with the captured waveform in real time. This can yield insight into the cause of data-dependent jitter. It can also analyze and display the jitter spectrum.

## Define your task (continued)

### **Verifying logical operations or relationship between data content and signal integrity faults**

Some real-time scopes with serial data analysis packages can decode serial data to display 8b/10b coded data. They also are capable of searching for specified sequences of up to four symbols, and of triggering on the same sequences. For example, if a signal integrity failure often follows a comma symbol, this can be seen by observing failures and noting that they seem to follow comma symbols. The scope can then search for all instances of the comma symbol, to check the hypothesis. As the next step, you could have the scope trigger on comma symbols to further verify the hypothesis.

### **Compliance tests**

Industry standards for serial data including PCI Express and SATA call out standard procedures for measuring jitter and eye openings. These two standards and some others require a real-time scope to capture a specified number of unit intervals in sequence and then recover the clock in software. Obviously a real-time scope is required to run these compliance tests.

High-speed transmission using fiber optics requires scopes with optical front ends. The bandwidths of the optical-to-electrical converters are tightly specified and unique to a given data rate. This can be achieved with either a sampling or a real-time scope. However, a trend in the industry is to have transmitters or network equipment that operate at a variety of data rates, often at 10 Gb/s rates. Complete coverage is achieved with a sampling scope. Similar requirements may apply to electrical ports on communications equipment.

## Algorithm for deciding on scope type

Of course there are too many subtleties to expect that a single algorithm will always give the right answer, but here is a suggested algorithm that will cover most decisions.

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How much bandwidth do you require?	> 13 GHz - sequential sampling, end of process < 13 GHz - either will work, continue to next step
Need to measure signals below ~50 mV p-p, or measure amplitudes to > 12 bits quantization resolution? (For example, need to observe anomalies whose amplitude is < 2% of the signal amplitude)	Yes - sequential sampling, end of process No - either will work, continue to next step
Need to measure cycle-to-cycle jitter?	Yes - real-time, end of process No - either will work, continue to next step
Need to run standard compliance tests?	Yes - check manufacturers' data sheets to ensure they provide the needed test software No - either will work, continue to next step
Need to see real-time random data sequence, capture rare events such as glitches, or decode serial data to view 8b/10b coded symbol values?	Yes - real-time, end of process No - either will work

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### Price

Finally, of course, the choice may come down to budget. For the same bandwidth, the price of a sequential sampling scope can be 25% to 50% of the price of a real-time scope.

## Conclusion

The decision whether to use a real-time or an equivalent time “sampling” oscilloscope is no longer as simple as it used to be. To base the decision purely on measurement bandwidth would be missing much of the subtlety

of the choice. The decision should be based on what tasks are most important and which scopes perform best at those tasks, assuming your budget will accommodate either.

## Appendix: Comparing the two technologies

In real-time sampling scopes, all samples of the signal are acquired every time the scope triggers. The spacing between samples is dictated by the scope's sampling rate. The sampling rate needs to be some multiple of the scope's

bandwidth in order to avoid aliasing and to capture all of the information in the signal.

In a sequential-sampling scope, one sample is captured on each trigger event. On each successive

trigger, the point in time of the sample is advanced. The waveform record is built up over many successive triggers. The maximum sampling rate is less than 1 MHz.

Parameter or characteristic	Real-time	Sequential
Maximum bandwidth	13 GHz	80 GHz
Noise floor	~350 $\mu$ V at 13 GHz bandwidth	~250 $\mu$ V at 20 GHz bandwidth
Jitter noise floor	As low as 800 fs RMS	As low as 150 fs RMS
Trigger on channel input signal	Yes	Yes, but requires a recovered clock, or splitting the signal to provide a trigger
Single-shot (capture all waveform data on a single trigger)	Yes	No
Negative time (signal acquired before trigger)	Yes	No (unless a delay line is added on the signal path)
Capture transient events (glitches, runt pulses)	Yes	No
Spectral analysis of signal (FFT)	Yes	No
Spectral analysis of jitter	Yes	Yes
Measure cycle-to-cycle jitter	Yes	No
8b/10b decode, search, trigger	Yes	No
Automatic data pattern triggering/synchronization	Yes	Yes
Impedance/channel analysis (TDR)	No	Yes

### Comparison table

### Related Literature

Publication Title	Publication Type	Publication Number
<i>Precision jitter analysis using the Agilent 86100C DCA-J</i>	Product note 86100C-1	5989-1146EN
<i>Triggering wide-bandwidth sampling oscilloscopes for accurate displays of high-speed digital communications waveforms</i>	Product note 86100-5	5989-2603EN
<i>EZJIT and EZJIT Plus Jitter Analysis Software for Infiniium Series Oscilloscopes</i>	Data sheet	5989-0109EN
<i>E2688A, N5384A High-Speed Serial Data Analysis and Clock Recovery Software for Infiniium 54830 and 54850 Series Oscilloscopes</i>	Data sheet	5989-0108EN

### Product Web site

For the most up-to-date and complete application and product information, please visit our product Web site at:  
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