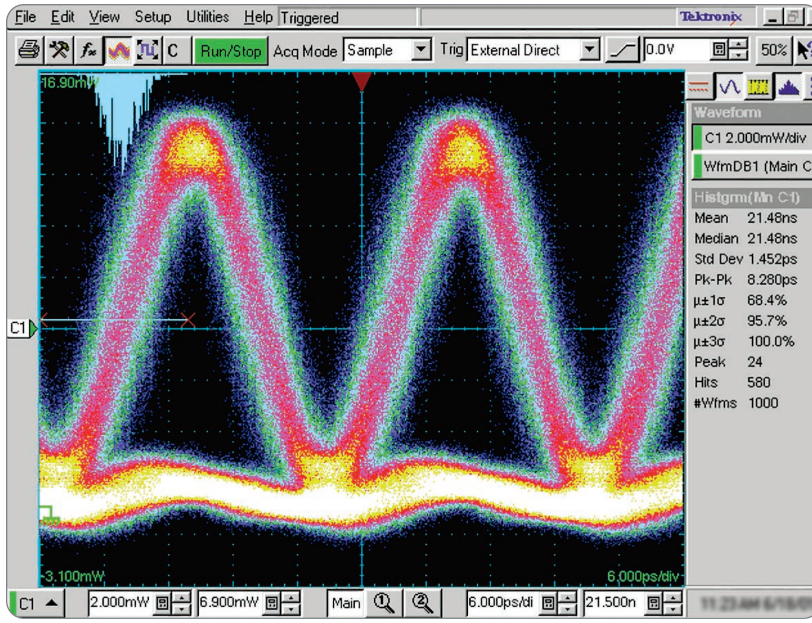


Eye Measurements on Optical RZ Signals

Introduction

The move to Return-to-Zero (RZ) signaling in optical communications systems requires new tools for evaluation and measurement.

Widespread use of RZ signaling in fiber communications is relatively new, and the corresponding measurements will be developing for some time to come. Standard test recommendations have not yet been defined; ANSI/TIA/EIA-526-4A-1997 “OFSTOP-4A Optical Eye Pattern Measurement Procedure” is primarily an NRZ standard, and new RZ standards are still in the early stages. To help manufacturers keep pace with demand, the test industry has begun to use a set of RZ eye measurements, some of them similar to traditional Non-Return-to-Zero (NRZ) eye measurements and others that address the unique properties of RZ signals.

This technical brief describes several automatic eye measurements for RZ signals contained in the Tektronix CSA/TDS8000 Series of Sampling Oscilloscopes.[1] Examples of real signals are presented, as well as guidelines to ensure valid test results. A method of building measurements using an oscilloscope math system is also described for those who need to use custom measurements and to accommodate new tests in the future.

Background

Throughout the 20th century, optical systems commonly used simple NRZ signaling for communications at ever-increasing bit rates. This approach has been in sharp contrast to the more complex signaling systems in copper media, where many physical layer standards came and went as performance needs increased. Optical communications could stay with NRZ for so long because the signaling rates had not yet stressed the properties of the media to the point of irreparably disturbing the fidelity of the pulses.

The exclusive use of NRZ signaling in the optical world is coming to an end. Higher bit rates and the growing number of DWDM channels are increasingly taxing the limits of NRZ signaling to the point where the benefits of adopting new schemes outweigh the advantages of staying with the familiar NRZ. Initially, the change is most evident in long haul, multi-channel systems, where RZ is rapidly becoming the signaling scheme of choice. RZ pulses propagate through the fiber with less distortion and load the fiber with less power in a multi-channel system, permitting longer transmission distances and more channels than would be possible with NRZ signaling.

1 Including TDS8000 and TDS8000B Digital Sampling Oscilloscopes, CSA8000 and CSA8000B Communications Signal Analyzers.

Changes and Challenges with RZ Eye Diagram Measurements

This brief compares each RZ measurement to an NRZ measurement, so some familiarity with NRZ eye measurements is assumed. The RZ eye diagram has a different shape than the NRZ eye, creating the need for some new and some changed measurements. For a complete description of optical signal measurements and more detailed information about the algorithms used in high speed communications, we recommend:

– Tektronix Application Note *Automatic Measurement Algorithms and Methods for High-Performance Communications Applications*. Algorithms for Pulse, NRZ, and RZ are given in detail, together with comments and examples of useful methods. The Application Note does not require familiarity with NRZ measurements.

For detailed instructions on how to set up a specific measurement, use the following resources:

– *CSA8000B / TDS8000B Online Help* (available on the instrument itself)

– *CSA8000B & TDS8000B User Manual* (available from the Tektronix web site, www.tektronix.com)

Note: Users of earlier versions of the CSA8000 and TDS8000 Series Sampling Oscilloscopes can use the above documents as long as their firmware has been updated to V1.3.x or higher; however, performance will be slightly different – see *CSA8000 & TDS8000 User Manual* (also available at www.tektronix.com).

Conventions and Definitions for Sampled Data

The eye diagram is a presentation of the highs, lows, and transitions made up of random data bits acquired from sampled NRZ and RZ signals. Measurement algorithms are complex because the eye diagram is multi-valued.

To determine levels of the RZ signal for an eye diagram analysis, CSA/TDS8000 Series Sampling Oscilloscopes digitize (sample) the signal and store it in a database. The database stores samples from successive overlaid waveforms, taken over a long time (many frames or packets) and plots them over a period of typically two to three unit intervals (UIs). In addition to standard amplitude and timing information, the database contains a third dimension of *count* that represents the number of times a specific amplitude-time point has been acquired from the waveforms. Measurements can then be made of the vertical or horizontal position of samples within a defined region of a UI. For example, in Figure 1 the lower blue histogram displays the distribution of vertical positions of the samples in the lower part of the eye, within the lower eye aperture.

This technical brief identifies multi-valued data by defining a set, or a population of samples within a region of the eye diagram in **boldface**. For example, in Figure 1, there exists a set s of N samples (s_1, s_2, … s_N) at the lower eye crossing within the eye aperture. In the histogram shown for the set, the vertical position of an individual sample is named *VertPos(s)*, and the total population of vertical positions is denoted by ***VertPos(s)***. The horizontal position of a sample is indicated as *HorPos(s)* and the set of horizontal positions of multiple samples is indicated as ***HorPos(s)***. The terms *stdev(**s**)* and *mean(**s**)* refer to the standard deviation and arithmetic mean of the data set **s**.

Amplitude (Vertical) RZ Measurements with the CSA/TDS8000 Series Sampling Oscilloscopes

High, Low, and Eye Amplitude

The fundamental vertical references of an RZ signal are its logical One (*High*) and logical Zero (*Low*) levels. The values of *High* and *Low* are used alone and in other standard and custom measurements, such as eye *Amplitude* and *Extinction Ratio*.

High and Low Levels

Figure 1 illustrates how the CSA/TDS8000 Series measures the *High* and *Low* references on an RZ signal. The measurement process is similar to that used for NRZ. However, due to the higher frequency spectra of RZ modulation, the eye aperture is only 5 percent of the UI, as opposed to 20 percent for NRZ signals. Therefore, typical RZ measurements need to acquire about four times as many waveforms (which takes about four times as long) to retain the same statistical significance as an equivalent NRZ measurement.

High is the logical One level of the RZ signal within the eye aperture:

$$High = mean(\textbf{VertPos}(\textbf{s}_{High})).$$

Low is the logical Zero level of the RZ signal within the eye aperture:

$$Low = mean(\textbf{VertPos}(\textbf{s}_{Low})).$$

Eye Amplitude *(Amplitude)* is simply the magnitude of the eye signal within the eye aperture:

$$Amplitude = High - Low$$

Extinction Ratio, Suppression Ratio, Eye Height, and Q Factor

As with NRZ signals, these measurements offer several ways to evaluate the quality and noise margin of the eye in RZ signals (Figure 2).

Extinction Ratio

In NRZ signals, the *Extinction Ratio* uses the ratio of the logic *High* to logic *Low* to characterize the quality of both the transmitter performance and the data stream from the receiver's point of view. For an RZ signal, the *Extinction Ratio* usually describes the receiver's view of the data stream, and another measurement, the *Suppression Ratio* (or *Contrast Ratio*), is used as the primary measure of the transmitter's performance. The method of measuring the *Extinction Ratio* for RZ signals is essentially the same method used for NRZ.

The *Extinction Ratio* is typically defined in dB:

$$ER_{dB} = 10\,log\left(\frac{High}{Low}\right)$$

The CSA/TDS8000 Series also provides percentage and ratio algorithms:

$$ER_{\%} = \left(\frac{Low}{High}\right)100\% \quad \text{and} \quad ER = \frac{High}{Low}$$

Note: This parameter is very sensitive to vertical offset error. It is essential to perform careful dark level compensation prior to making the measurement.

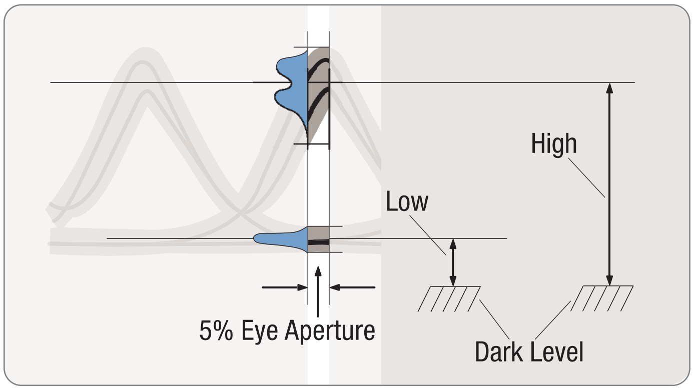


Figure 1. Basic RZ Amplitudes, Extinction Ratio.

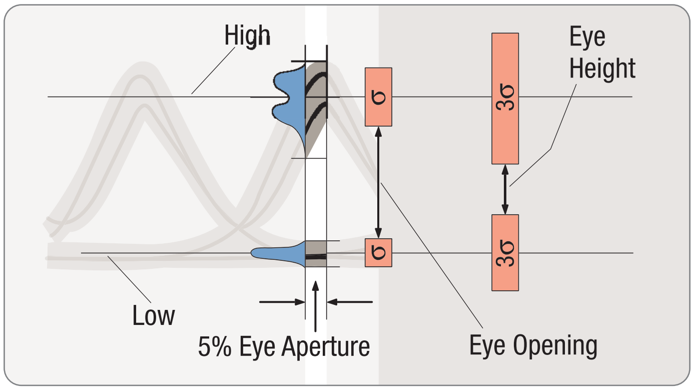
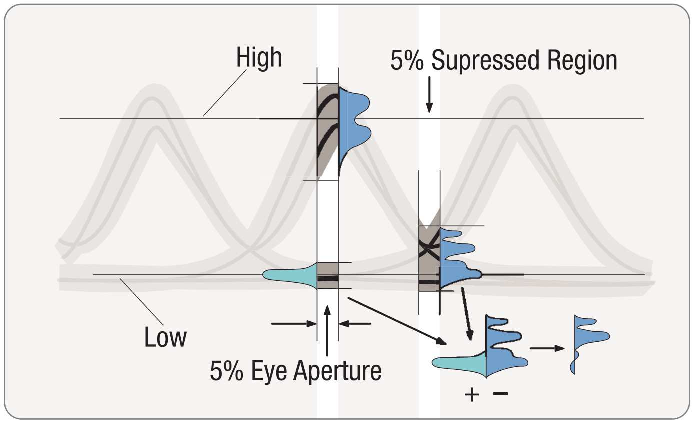


Figure 2. Eye Height, Eye Opening Factor.



▶ ***Figure 3.*** *Suppression Ratio measurement.*

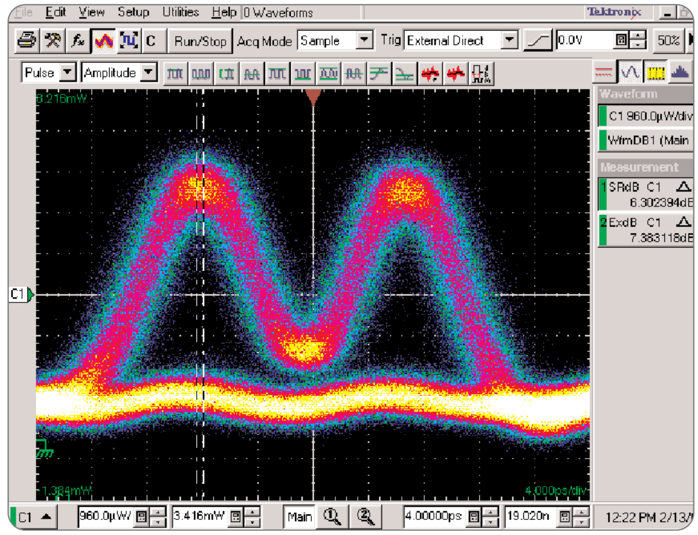
Suppression Ratio (RZ Contrast Ratio)

Suppression Ratio is the ratio of the average power level of the logic *High* to the average power level in the "corrected" suppressed level. In other words, it is a measure of how much of the falling edge of the previous logical *High* pulse is still present at the beginning of the current pulse within the suppressed region of the signal. This measurement is also known as the *Contrast Ratio*.

In order to extract the effects of the falling edge of the previous pulse from the *Low*-to-*Low* and *Low*-to-*High* transitions, this measurement subtracts the distribution of samples in the *Low* area from the total distribution of samples in the suppressed region. See the lower two histograms in Figure 3.

$$SR = \frac{High}{mean\left(histogr(\mathbf{VertPos(s_3)}) - histogr(\mathbf{VertPos(s_{Low})})\right)}$$

The region s_3 is the suppressed region – horizontally offset by a one-half bit interval from the eye aperture, and equal to the width of the eye aperture.



▶ ***Figure 4.*** *Suppression Ratio – valid measurement.*

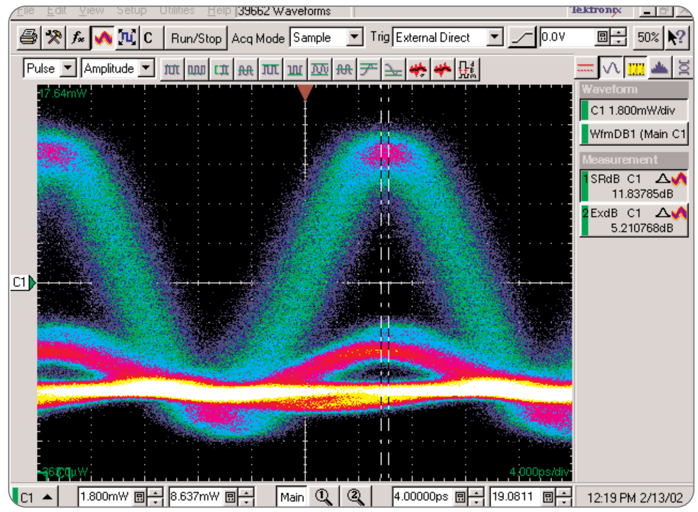
This measurement is not valid for signals whose *Low [0]* level changes substantially in the time between the eye aperture and the end of the eye. Here are two examples of suppression ratio measurements on a CSA8000B Communications Signal Analyzer.

Figure 4 illustrates a *Suppression Ratio* on a signal which lends itself to the algorithm. Note that the waveform in the *Low* area within the eye aperture is very similar to that in the suppressed region, so that the subtraction of the two distributions is valid. The measured results in the top right of the display (*Measurement* window) show that the *ER* and *SR* readings are in agreement, given the shape of the waveform.

In contrast, Figure 5 displays a signal whose trajectory in the *Low* area of the eye aperture does not match that in the suppressed region; making the subtraction of distributions in the algorithm problematic. The *Measurement 1* result shows a rather high *SR* value compared with the *ER* value, indicating a questionable outcome.

Note: As with *Extinction Ratio*, this parameter is very sensitive to vertical offset error, so it is essential to perform careful dark level compensation prior to making the measurement.

At this stage of RZ signaling development, it is not yet clear which of the two signals will be the more typical of those in actual use, so care must be exercised when making *Suppression Ratio* measurements until a standard practice emerges.



▶ ***Figure 5.*** *Suppression Ratio – questionable measurement.*

Other Vertical Measurements

Q Factor. The Q (Quality) Factor of a waveform is similar to the Eye Opening Factor.

$$Q\ Factor = \frac{High - Low}{stdev(\mathbf{VertPos(s}_{High})) + stdev(\mathbf{VertPos(s}_{Low}))}$$

Eye Height is the ratio of the height of the eye opening within three standard deviations to the *Amplitude*:

$$Eye\ Height = \mathbf{(}High - 3stdev(\mathbf{VertPos(s}_{High}))\mathbf{)} - \mathbf{(}Low + 3stdev(\mathbf{VertPos(s}_{Low}))\mathbf{)}$$

Eye Opening Factor is the ratio of the height of the eye opening within one standard deviation to the *Amplitude*:

$$Eye\ Opening\ Factor = \frac{(High - stdev(\mathbf{VertPos(s}_{High}))) - (Low + stdev(\mathbf{VertPos(s}_{Low})))}{High - Low}$$

Note: In some cases, under carefully controlled conditions, the relationship between the *Q Factor* measurement and the *Bit Error Rate* of an RZ signal can be used to displace the need for separate BERT verification.

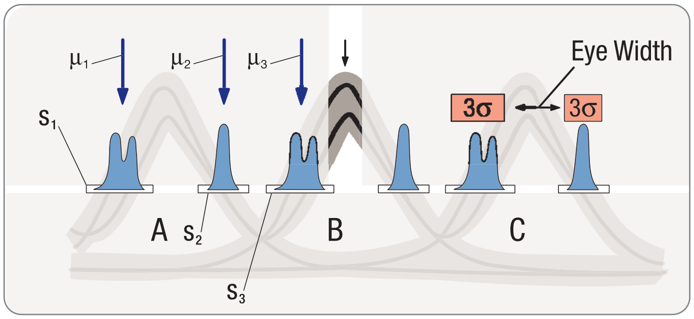


Figure 6. *RZ Eye Timing, Jitter, Symmetry.*

Noise Considerations

Noise measurements on eye patterns include the noise of the acquisition system (total noise equals the square root of the sum of the squares of each noise source). Wherever possible, signal amplitudes should be kept away from the minimum of the dynamic range of the signal analyzer to avoid having the noise in the acquisition system become a factor in the measured noise of the signal.

Timing (Horizontal) RZ Measurements with the CSA/TDS8000 Series

Bit Time, Bit Rate

The *Bit Time* is the interval between two consecutive rising and falling edges:

$$\textit{Bit Time} = \textit{mean}(\mathbf{HorPos}(\mathbf{s_3})) - \textit{mean}(\mathbf{HorPos}(\mathbf{s_1}))$$

Where s_1 and s_3 are the sets of samples in horizontal slices at the first two consecutive crossings on the same slope at the mid-reference level (Figure 6). Similarly, the *Bit Rate* is defined as the inverse of *Bit Time*:

$$\textit{Bit Rate} = \frac{1}{\textit{Bit Time}}$$

The measurement itself does not differ from the one performed on NRZ signals. However, for NRZ signals the *NRZ Period* always equals twice the *NRZ Bit Time*, and the *NRZ Frequency* (the inverse of the *NRZ Period*) describes the frequency when a '010101' pattern is being transmitted. In RZ signaling, the maximum frequency, which corresponds to a '11111' pattern transmission, equals the *RZ Bit Rate* – so the terms *Frequency* and *Period* are redundant in RZ signaling.

Pulse Width

The traditional way to measure *Pulse Width* is:

$$\textit{Pulse Width} = \textit{mean}(\mathbf{HorPos}(\mathbf{s_2})) - \textit{mean}(\mathbf{HorPos}(\mathbf{s_1}))$$

Where s_1 and s_2 are the sets of samples in a horizontal slice at mid-reference level at the first positive and following negative edge, respectively (Figure 6).

Duty Cycle

This measurement characterizes the basic shape of the RZ signal. Standards bodies are likely to specify *Duty Cycle* rather than the *Pulse Width* for RZ signals.

$$\textit{Duty Cycle} = \textit{Pulse Width}/\textit{Bit Time}$$

Eye Width

Eye Width is the 3-sigma guarded delta between the rising and falling edge crossings:

$$Eye\ Width = \left(mean(\mathbf{HorPos(s_2)}) - 3stdev(\mathbf{HorPos(s_2)})\right) - \left(mean(\mathbf{HorPos(s_1)}) + 3stdev(\mathbf{HorPos(s_1)})\right)$$

Where s_1 and s_2 are the sets of samples in a horizontal, mid-reference slice at the first positive and following negative crossings (Figure 6). This algorithm is similar to the NRZ measurement of the same name. However, the RZ jitter is not necessarily the same on the rising edge (sample set s_1) and falling edge (sample set s_2). Jitter would be the same for any crossing in an NRZ signal, simplifying the algorithm.

Pulse Symmetry

Pulse Symmetry expresses the percentage to which the peak of the logic One pulse is symmetrical about the center between the rising and falling edges:

$$Pulse\ Symmetry = \left(\frac{HorPos_{VertMax}(\mathbf{s_{1-2}}) - mean(\mathbf{HorPos(s_1)})}{mean(\mathbf{HorPos(s_2)}) - mean(\mathbf{HorPos(s_1)})} \right) 100\%$$

Where s_1 and s_2 are the sets of samples in a horizontal, mid-reference slice at the first positive and following negative crossings, respectively, $s_{1\text{-}2}$ is the set of all samples between $mean(\mathbf{HorPos(s_1)})$ and $mean(\mathbf{HorPos(s_2)})$, and $HorPos_{VertMax}$ is the time a vertical histogram of the eye aperture width returns the largest value (Figure 7).

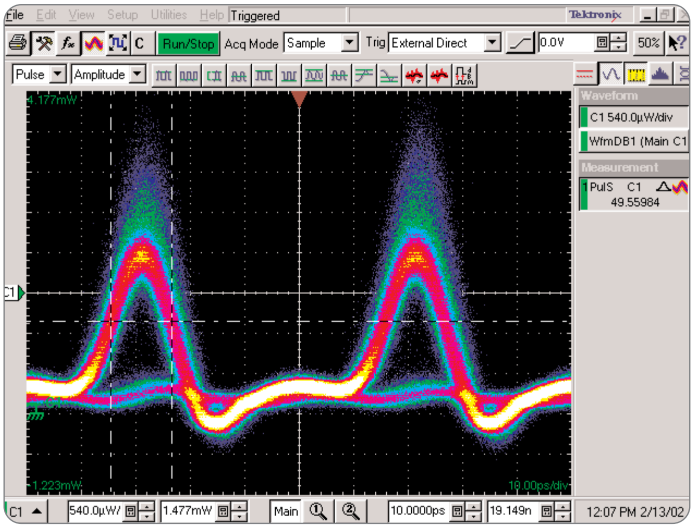
Note: While RZ measurements mostly reference the logical *High* level within the eye aperture, symmetry measurements can seem surprising if the vertical peak is located outside the eye aperture.

Phase measurement returns values in the range ± 180º:

$$Phase = \left(\frac{mean(\mathbf{HorPos(S_{12})}) - mean(\mathbf{HorPos(S_1)})}{mean(\mathbf{HorPos(S_3)}) - mean(\mathbf{HorPos(S_1)})} \right) 360°$$

Where s_1 and s_3 are the sets of samples in horizontal slices at the first two consecutive edges with the same slope at the mid–reference level, and s_{12} is the set of samples at the mid-reference level on the first edge, second source.

Note: The denominator is one *Period*, which is two *Bit Times* in an NRZ signal, but is only one *Bit Time* in an RZ signal (see *Bit Time*).



▶ ***Figure 7.*** *Practical Pulse Symmetry Measurement.*

Jitter, Peak-to-Peak (Pk-Pk) Jitter

The definition of this parameter is again similar to NRZ:

$$Pk\text{-}Pk\ Jitter = Max(\mathbf{HorPos(s)}) - Min(\mathbf{HorPos(s)})$$

and

$$RMS\ Jitter = stdev(\mathbf{HorPos(s)})$$

where $\mathbf{s}$ is the set of samples in a horizontal slice at mid-reference level.

Note: Because the jitter is not necessarily the same on the rising edge (sample set s_1) and falling edge (sample set s_2) of an RZ signal, the *Jitter* measurements may need to be done on both edges, reporting both, or the worse of the two results.

Other Measurement Challenges for RZ Signals

Triggering to Capture Aggregate or Individual RZ Pulse Streams

RZ pulses often do not resemble one another in a given bit stream; for example, the *Suppression Ratio* can be lower at every second UI. The RZ signal is typically created from n sub-harmonics multiplexed together to create the faster stream. When one of the sub-harmonics triggers the signal analyzer, the eye diagrams will take n cycles to repeat, and the unique characteristics of every stream will be visible. This can be desirable when trying to isolate a sub-harmonic contributor, or not, when the goal is to measure the aggregate performance of the multiplexed stream.

A conventional sampling oscilloscope expects the trigger to have a constant phase relation to the UI, but otherwise to be random. Therefore, different shapes present in different UI cycles would be overlaid into every eye pattern. However, at trigger frequencies greater than 3 GHz the oscilloscope trigger is pre-scaled (divided), which will independently cause a cycle of trigger periods (with different phase each time the prescaler is started.) This cycle will be noticeable immediately if the captured pulses look different from one another at screen positions of a period similar to that of the prescaler cycle.

This situation can be remedied with CSA/TDS8000 Series Sampling Oscilloscopes, which are designed specifically for communications applications. They allow users to scan the unit intervals in the data stream in order to overlay all eye patterns within the prescaler cycle into a single eye diagram.

Optical Reference Receiver

Receiver systems are usually designed to ignore the very high frequency details that do not describe important parameters of the signal. For measurements on NRZ eye diagrams, the standards bodies specify an integrating filter (known as the Optical Reference Receiver, or "ORR") in order to ensure consistent test results from different instruments by removing those high frequency contributions. For NRZ signals, the ORR –3 dB point is typically at 0.75 X bit rate (1.5 X bit frequency).

As of this writing, RZ signaling does not have a standard for the ORR. It is not even clear at which frequency such filtering would be done, although it is likely that it will be somewhere above the *Bit Frequency*, which in RZ is the same as the *Bit Rate*.

New and Emerging Measurements

Optical Modulation Amplitude (*OMA*) is a good example of an emerging new measurement. IEEE 802.3ae is in the process of adopting *OMA* as one of the more important parameters of the optical transmission for the 10 Gigabit Ethernet. *OMA* describes the absolute difference between the optical power at the logic One level and the optical power at the logic Zero level, as measured on a specific pattern (e.g., 00001111) in a 20% aperture. The utility of this measurement is similar to that of *Extinction Ratio* and *Average Optical Power* folded in one.

Even though *OMA* is not yet available as a standard function in the CSA/TDS8000 Series, the custom math operations can be used to calculate the parameter with ease.

In IEEE 802.3ae, the standard method of measuring *OMA* is to generate and capture a slow square wave test signal. The test uses pulse measurements (not an eye diagram) to calculate the *mean* of the high area and the *mean* of the low area. The high and low areas are defined with gating to be 20% apertures. Then, the math system calculates

$$OMA_{dB} = 10log((mean_{High} - mean_{Low}) / 1\ mW)$$

If the math system produces this result as a waveform, the single value parameter can be obtained by simply measuring the *mean* of that waveform.

While *OMA* is a simple calculation, it is a good example of the flexibility that the CSA/TDS8000 Series provides with custom math functions. The ability to define new measurements is especially important when developing products for standards such as RZ signaling that are still evolving.

Conclusion

The use of RZ signaling in fiber communications is quite new, and the corresponding measurements will be evolving for some time to come. CSA/TDS8000 Series of Sampling Oscilloscopes offer a sophisticated set of RZ measurement algorithms and detailed control over all measurement parameters with intelligent defaults. The built-in custom math operations and flexible data handling functions ensure that the instruments will continue to keep pace with new signaling developments as they emerge. The CSA/TDS8000 Series allow users to concentrate their efforts on design and manufacturing process issues, decreasing design and manufacturing debug times.

Complete list of RZ measurements in the CSA/TDS8000 Series

Here is a complete list of the 41 RZ measurements currently (as of Spring of 2002) available in the Tektronix CSA/TDS8000 Series of Sampling Oscilloscopes. Details are available in the companion Application Note, *Automatic Measurement Algorithms and Methods for High-Performance Communications Applications*.

RZ Measurements – Amplitude (Vertical):

AC RMS	Amplitude	Average Optical Power (dBm)
Average Optical Power (watts)	Extinction Ratio	Extinction Ratio (%)
Extinction Ratio (dB)	Eye Height	Eye Opening Factor
Gain	High	Low
Max	Mean	Mid
Min	Peak-to-Peak	Peak-to-Peak Noise
Q Factor	RMS	RMS Noise
Signal-to-Noise Ratio	Suppression Ratio	Suppression Ratio (%)
Suppression Ratio (dB)		

RZ Measurements – Timing (Horizontal):

Bit Rate	Bit Time	Cross+
Cross–	Delay	Duty Cycle
Eye Width	Fall Time	Phase
Peak-to-Peak Jitter	Pulse Symmetry	Pulse Width
Rise Time	RMS Jitter	

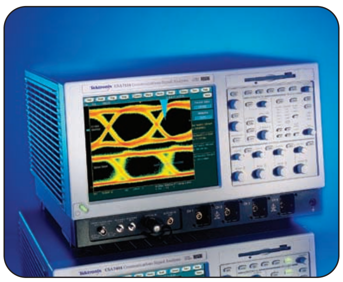
RZ Measurements – Area:

Area	Cycle Area

Notes:

OTS Product Family

The OTS Product Family is a highly-customizable modular solution featuring three different chassis designs and flexible testing capabilities designed to concurrently support multiple tests, including jitter analysis, multi-rate transmission test, 155 Mb/s to 10 Gb/s and swept wavelength measurements.



CSA7000 Series

Versatile, high-performance, real-time digital oscilloscopes dedicated to rapid design analysis and verification of communications signals up to 2.5 Gb/s rates (OC-48/STM-16 or Fibre Channel FC2125).

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