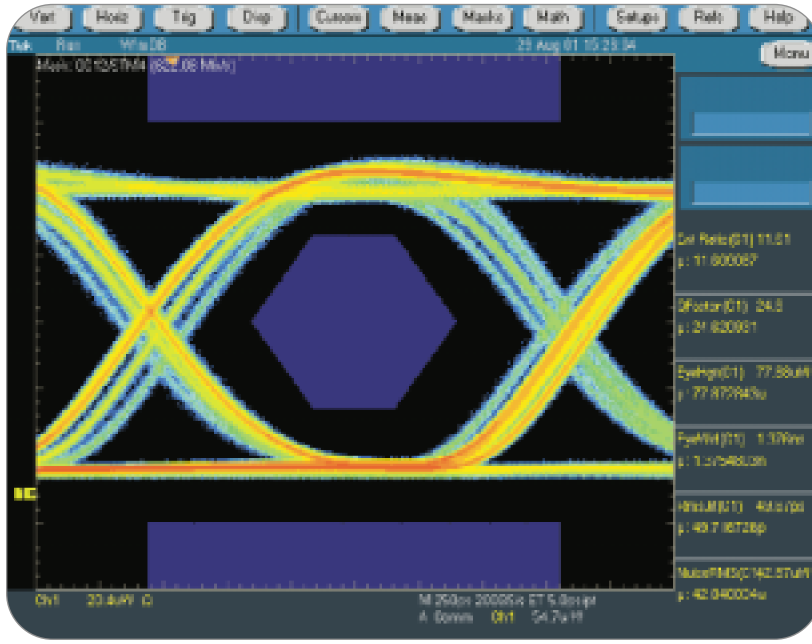
Network Communications Physical Layer Testing with a CSA7000 Series Communications Signal Analyzer



Physical layer testing of electrical and optical telecom and datacom signals up to 2.5 Gb/s.

The CSA7000 Series real-time communications signal analyzer provides the versatility needed to test design outputs for standard compliance and to analyze critical circuit parameters.

In designing wired communications network equipment, a key element of signal testing is testing the equipment's physical layer. The physical layer is the lowest layer in the Open Systems Interconnection (OSI) network model. Today's high-performance digital phosphor oscilloscopes (DPOs), such as the CSA7000 Series communications signal analyzer, have the electrical and optical bandwidth to perform complete eye pattern measurements and mask testing for signals at data rates of up to 2.5 Gb/s. DPOs provide the versatility that design engineers need to test both the output of their design for standards compliance and to analyze critical internal circuit parameters such as signal integrity, timing margins and jitter.

The measurements highlighted in this application note show some of the oscilloscope's capabilities for design debugging and verification of compliance with industry standards.

All example tests are done with a Tektronix CSA7000 Series communications signal analyzer (for electrical signals and optical signals).

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Table 1. Wired Communications Network Physical Layer Specifications Covered in this Application Note

SONET/SDH GR 253-CORE	OC-1/STM0 OC-3/STM1 OC-12/STM4 OC-48/STM16
ITU-T G.703	DS1 Rate, DS2 Rate Sym Pair, DS2 Rate Coax, DS3 Rate E1 Sym Pair, E1 Coax, E2, E3 E4 Binary 0, E4 Binary 1 32 Mb, 97 Mb STM 1E 0/ Bin 0, STM 1E 1/ Bin 1
ANSI T1.102-1993	DS1, DS1A, DS1C, DS2, DS3, DS4NA, DS4NA Max Output STS-1 Pulse, STS-1 Eye STS-3, STS-3 Max Output
Ethernet IEEE Std 802.3 and ANSI X3.263-1995	100 Base-T STP, 100 Base-T UTP 1000 Base-SX Short Wave Optical 1000 Base-LX Long Wave Optical
Fibre Channel Optical	FC133, FC266, FC531, FC1063, FC1063 Draft Rev 11 FC2125
Fibre Channel Electrical	FC133E, FC266E, FC531E FC1063E FC1063E Normalized Beta, Delta, Gamma Transmit FC1063E Absolute Beta, Delta, Gamma Transmit FC1063E Absolute Beta, Delta, Gamma Receive FC2125E Normalized Beta, Delta, Gamma Transmit FC2125E Absolute Beta, Delta, Gamma Transmit C2125E Absolute Beta, Delta, Gamma Receive
USB 1.1 / 2.0	FS:T1, T2, T3, T4, T5, T6 HS:T1, T2, T3, T4, T5, T6
InfiniBand	2.5 Gb/s Optical 2.5 Gb/s Electrical
IEEE1394	S400ß Optical S400ß T1, S400ß T2 S800ß Optical S800ß T1, S800ß T2 S1600ß Optical S1600ß T1, S1600ß T2
Serial ATA	G1, G1 Rx, G1 Tx G2, G2 Rx, G2 Tx

Design Debug with a DPO

Wired communications network equipment must not only meet performance specifications, but also conform to industry standards, and offer interoperability between various standards. When designing and debugging these very complex systems, insight into signal interaction and behavior is critical. For example, when designing a communications transmitter, engineers need to capture intermittent failures that can occur and observe the device's output to determine if its parameters are within acceptable limits.

Today's high-performance DPOs, such as the CSA7000 Series communications signal analyzer, allow users to observe high data rate signals such as OC-48/STM-16. In addition, their real-time acquisition captures many infrequent events that sampling oscilloscopes would miss. Sampling oscilloscopes acquire data using one point per trigger, and therefore use hundreds of triggers in order to build a waveform. This low duty cycle acquisition works well for high data rate signals whose characteristics are repetitive. However, the time required to acquire enough waveform data using a sampling oscilloscope reduces the possibility of capturing infrequent events.

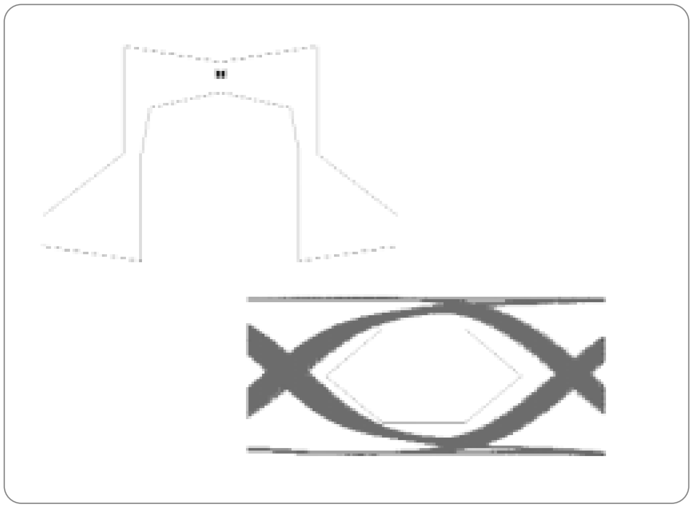
For communications hardware debugging at rates up to 2.5 Gb/s, a real-time oscilloscope is often the best test instrument. When a transmitter is not working or is only "partially" working, a real-time oscilloscope is invaluable for debugging the design. The DPO graphical display makes finding the problem easier. If the design is not working, a bit error rate tester (BERT) alone cannot help a designer determine the source of the problem. A BERT can be very effective in finding errors that occur very infrequently, but only if the communication device under test is working well enough to accept inputs and/or transmit data. The BERT transmitter outputs a known data pattern to stimulate the device-under-test. The BERT receiver accepts the device's output data and looks for bit errors to occur. The BERT receiver typically only has a numeric display that shows bit error rate.

A high-performance DPO is a valuable companion to the BERT because its intensity-graded display enables the user to observe a transmitter's output and immediately see if there are intermittent problems. For example, a common technique for isolating intermittent problems is to use an analyzer to trigger on a network event. The event usually is a network error condition—an occurrence of a certain frame or a network statistic reaching a certain level. The problem can also be pattern dependent and generates a spike on the output transmitter or jitter. These types of problems can cause intermittent signal loss as well as total link failures that are not easily caught by a sampling scope or even a BERT. The advanced triggering available in a DPO allows quick location of signal errors. The TDS7000 Series and CSA7000 Series DPOs offer several categories of advanced triggers including communications logic triggering, pulse width triggering, and unique serial pattern triggering.

Standards Verification

For network equipment to be accepted by the industry it must comply with industry telecom standards such as SONET/SDH, ANSI T1.105, ITU-T G. or datacom standards including IEEE802.3 and ANSI T11.2. These standards specify physical layer characteristics and measurement conditions such as the following.

- **Electrical specifications:** The 1000 BASE-CX transmitter specifications define data rate, clock tolerance, nominal signaling speed, differential amplitude, rise/fall time and differential skew. They also include an eye diagram requirement when measured in a specified transmitter test load.
- **Eye diagram shape specifications:** The minimum eye openings at the Fibre Channel receiver is only about 200 ps wide for FC2125.
- **Optical specifications:** SONET optical measurements require an ORR (optical reference receiver) with a Bessel-Thompson characteristic. Optical Fibre Channel requires the same filter, an 850 nm wavelength optical receiver and clock recovery from the data. For most standards, a variety of measurements in the time domain are taken to characterize the shape of the waveform being transmitted. These measurements include period, rise time, fall time, clock-to-data jitter, extinction ratio, Q-factor, crossing %, eye height, eye width and duty cycle distortion
- **Jitter specifications:** Fibre channel is the originator of random, deterministic and total jitter. The measurements must be made differentially (if differential electrical), because asymmetries in the electrical signaling or the physical PCB traces add jitter.
- **BER specifications:** The InfiniBand specification calls for eye diagram and jitter tests to ensure a low bit error rate (BER).



▶ ***Figure 1.*** *An example of each type of mask.*

Mask Testing Requirements

One of the key requirements for testing telecom equipment is the ability to guarantee interoperability of equipment from various vendors. Mask testing was developed with this requirement in mind. Mask testing can ensure that most of the key wave shape parameters (period, rise/fall times, clock-to-data jitter, overshoot, ringing, noise, signal to noise ratio) are within acceptable tolerances. Because the shape of the measured waveform is dependent on the frequency response (i.e. bandwidth) of the measurement system, the standards bodies have specified a standard "reference receiver" which should be used for these measurements. By tightly controlling the frequency response of the measurement system (via the use of a standard reference receiver), repeatability of measurements between various test and measurement vendors equipment can be guaranteed.

A mask that defines the region where the signal must reside on the oscilloscope's display specifies the eye diagram mask test. These masks vary by the type of signal being tested. For many of the lower data rate electrical signals, a mask for a single positive or negative pulse is defined. For the high-speed electrical and optical signals, an eye diagram mask is defined (Figure 1).

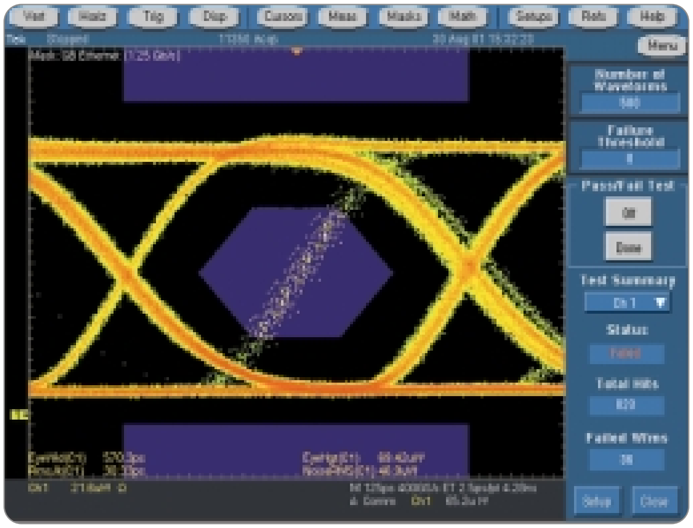


Figure 2. A gigabit ethernet eye diagram being tested for pass or fail.

Pass/Fail Testing

The TDS7000 Series and CSA7000 Series DPOs are capable of displaying many industry standard communications masks for data rates up to 2.5 Gb/s. When a mask is displayed on the DPO screen, the AUTOSET button allows the user to quickly center the test signal within the mask boundaries. In addition, with its advanced built-in DSP processing, the DPO can compare the currently acquired waveform to the mask boundaries to see if any mask violations (also called "hits") occur. The DPO display shows the user where the mask hits occur and how many occur. Finally, an automatic pass/fail mask test can be setup to determine whether a device exceeds the mask boundaries when a user-defined number of waveforms are acquired. The DPO readouts in Figure 2 show how many waveforms are desired and how many have been acquired. In addition, the "passing" readout shows the current status of the test. If the number of mask violations exceeds a user-specified threshold, the readout will change to "failed." This type of testing allows unattended mask testing in a lab as well as automatic testing in manufacturing.

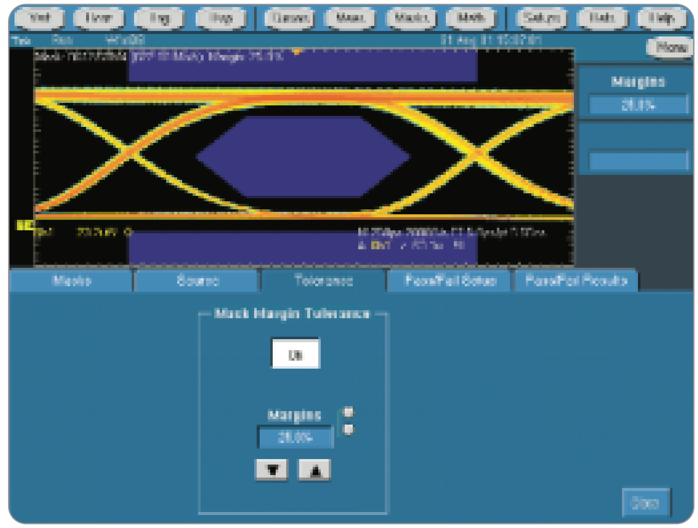
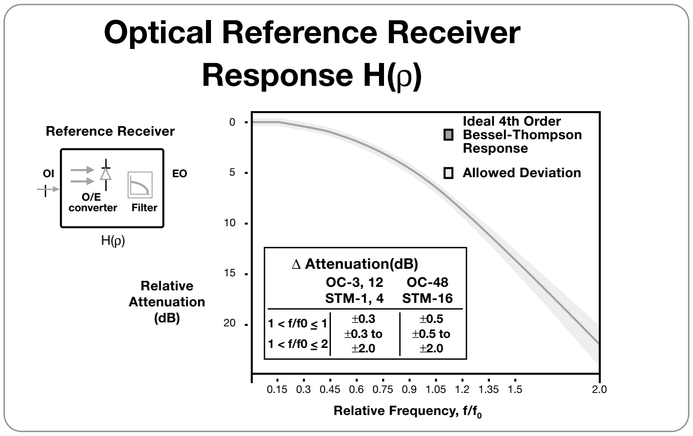


Figure 3. Mask margin tolerance menu.

Mask Margin Testing with a DPO

In addition to ensuring standards compliance, masks can be used to determine the amount of margin in a signal relative to the standard requirements. Testing a design's margin level ensures that a system still complies with a standard under worst-case conditions. It could also ensure a mass produced system would comply with industry standards as well as the original design that was tested in the lab. To check a device for margin using a mask, percent margin can be added to the mask. Then a mask test can be run and checked for failures. Mask margin testing can be performed with the TDS7000 Series and CSA7000 Series DPOs by using the mask margin tolerance feature. Figure 3 shows the mask margin tolerance menu in which the user can select the percentage of tolerance to apply to the eye diagram mask test.

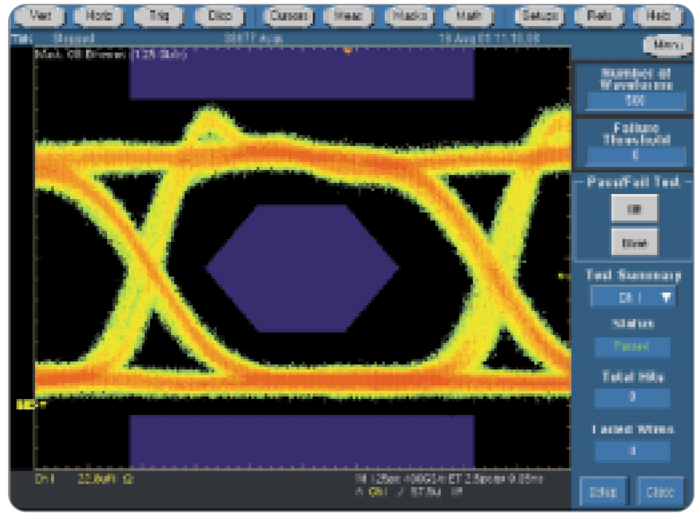


▶ ***Figure 4.*** *Frequency response of the CSA7000 Series.*

Optical Signal Debugging

Built-in Optical Reference Receiver

Performing tests of optical signals such as OC-48/STM-16 or optical Fibre Channel with an oscilloscope requires conversion of the optical signal from optical power to electrical voltage and an optical reference receiver for mask testing. A system used for optical mask testing must have a frequency response such as the curve shown in Figure 4. To provide flexibility and more reliability at higher data rate (up to 2.5 Gb/s), the complete functionality of the optical reference receiver, including the O-to-E converter, has been integrated within the CSA7000 Series communications signal analyzer. The optical reference receiver frequency response is achieved by using built-in, advanced digital filtering. This integrated architecture provides a test instrument that is fully calibrated and matched to optical network communication standard requirements.



▶ ***Figure 5.*** *Gigabit ethernet eye diagram with the optical reference receiver filter turned off.*

Table 2. Optical Reference Receiver Filters and Masks

	CSA7154	CSA7404
SONET/SDH	OC-1/STM0, OC3/STM1, OC-12/STM4	OC-1/STM0, OC-3/STM1, OC-12/STM4, OC-48/STM16
Gigabit Ethernet	1000 Base-SX, LX	1000 Base-SX, LX
Fibre Channel	FC133 – FC1063	FC133 - FC2125
IEEE 1394b	S400ß, S800ß	S400ß, S800ß, S1600ß
InfiniBand		2.5 Gb/s

The digital filter for the optical reference receiver provides a digital filter response that is closer to the ideal frequency response. This improved filter response results in more margin relative to the industry-standard limits. The CSA7000 Series communications signal analyzer can match the optical reference receiver frequency response required for measuring SONET signals up to OC-48, Fibre Channel up to 2.5Gb/s as well as Gigabit Ethernet and InfiniBand optical signals (See Table 2 for optical reference receiver characteristics). The user can quickly and easily switch between the various data rates using the digital filtering. This eliminates the need for external modules or plug-ins.

Optical Reference Receiver On/Off

While comparing a SONET/SDH signal to a mask, the limited frequency response of an optical reference receiver is required. For device characterization, a bandwidth several times wider than the bit rate is recommended. To see a signal at full oscilloscope bandwidth, it's often desirable to disable the optical reference receiver filtering. On the CSA7000 Series communications signal analyzer, turning off the optical reference receiver filter is as easy as a single button push. Without an optical reference receiver filter, the signals in Figure 5 show faster edges as well as more ringing and overshoot. Many of the modern receiver components, such as photo detectors, have bandwidths significantly wider than the signal's bit rate. Characterizing the signal at full bandwidth allows observation of the signal aberrations, as the wider bandwidth receiver actually sees them. Using the standard compliance test without characterizing a design could lead to tributary signal transmitters that have intermittent problems in manufacturing and in the field.

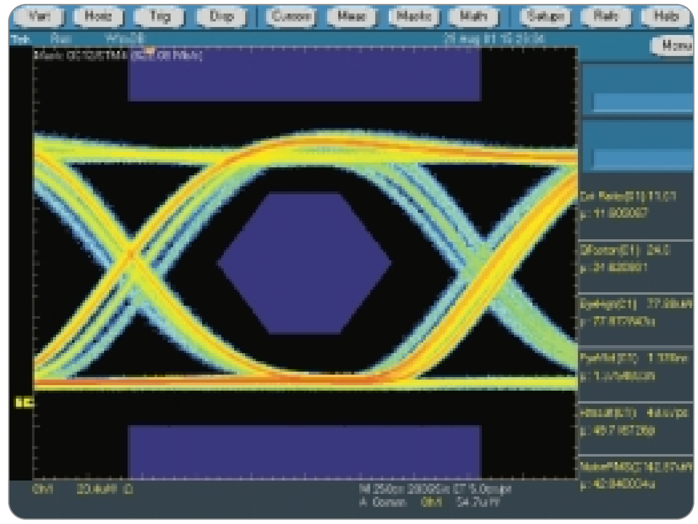
Communication Measurements

In addition to amplitude and time-related measurements, other eye-pattern related measurements are possible with the DPO: noise, Q-factor, jitter and eye diagram measurements and extinction ratio. Figure 6 shows an OC-3 eye diagram measurements' CSA7404 extinction ratio measurement with the mean (μ) and standard deviation(s) of the extinction ratio displayed.

Extinction Ratio

Extinction ratio, an optical compliance measurement specified by the optical network communication standards, is the ratio of the average power level for a logical one (E1) to the average power level of a logical zero (E0): Extinction Ratio = $10\log(E_1/E_0)$.

Extinction ratio is a measure of the digital signal's modulation depth. The higher this ratio, the more the margins the transmission system has to resist distortions before the BER increases. A desired range for a system's extinction ratio is set by the standard and data rate requirements. The CSA7000 Series communications signal analyzer can make the extinction ratio measurement automatically. As a result, the measurement is not difficult.



▶ ***Figure 6.*** *Verifying compliance with a communications standard requires several tests such as pulse width, amplitude, extinction ratio, Qfactor, eye height and width, noise and jitter measurements. Using a DPO, many of these tests can be performed in the development lab, in manufacturing or on-site at a network installation.*

Follow these recommendations to ensure accurate measurements:

1. Use the optical reference receiver for the extinction ratio measurement. The extinction ratio needs to be done on a full data rate signal. Since the data rate will be high and the average power levels are desired, the reference receiver's integrating effect will give a good approximation of the logic one and logic zero power levels.

2. Because one possible source of error is DC voltage offsets in the oscilloscope, to ensure an accurate extinction ratio measurement null out any offsets. This procedure is called a dark level or zero light level calibration. The zero light level corresponds to the voltage level measured by the DPO when no light is input to the OE converter. With the CSA7000 Series, users can select and run an automatic zero light level calibration function The extinction ratio value can change significantly if the zero light level changes. See Figure 7 for examples how a different zero light level reference can affect the extinction ratio value.

On the left side of Figure 7, the logic zero level is measured as 2.5 µW above the reference. The logic one level is measured as 13 µW above the reference. The extinction ratio calculated from these values is 7.2 dB. On the right side of the figure, a different zero light level is shown after the calibration has been run. With this new reference, the resulting logic zero and logic one levels are 1.5 and 12 µW respectively. Using these values to calculate extinction ratio yields 9.0 dB, a significant increase.

An additional potential source of error is the oscilloscope and OE converter measurement uncertainty. Depending on the extinction ratio value, the accuracy specification of the OE and oscilloscope can cause significant error in the extinction ratio measurement. For example, consider a signal with an extinction ratio of 8 dB. If the logic one level of this signal as measured by the oscilloscope is 100 µW, the logic zero level is measured as 16 µW. If the uncertainty in the measurement is ±1 µW, the extinction ratio will vary from 7.7 dB to 8.2 dB. The 0.3 dB change in the measurement is probably acceptable. However, if the signal's extinction ratio is 14 dB and the logic one level of the signal is 100 µW at the oscilloscope, the logic zero level will be 4 µW. Now the ±1 µW measurement variance has a more significant affect. The extinction ratio will vary from 13 dB to 15.2 dB, a 1 dB to 1.2 dB variance.

To avoid or minimize this type of measurement error, follow these recommendations:

1. Set the DPO voltage range so that the optical signal uses as much of the oscilloscope's dynamic range as possible.

2. Make multiple measurements when measuring extinction ratio and use an average value.

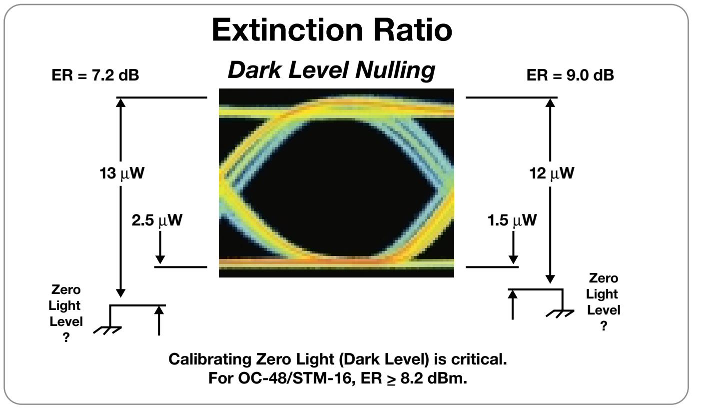


Figure 7. *A zero light level change can affect the extinction ratio value.*

Waveform Database and Parametric Measurements

The CSA7000 Series communications signal analyzer acquire and store a much larger sample of data into a waveform database. This database accumulates the source waveform data as it is continuously acquired. This database can be displayed with a color grading which provides a way to qualitatively validate the signal tested over a large amount of samples. The user can verify the stability of the signal and also run statistical measurements including histogram-based measurements.

Clock Recovery

With all telecommunications signaling, no separate clock is transmitted with the data and therefore the clock must be recovered from the data. Both the TDS7000 Series and CSA7000 Series DPOs offer clock recovery capability up to 2.5 Gb/s for NRZ eye patterns (optional on TDS7000 Series). Clock recovery allows users to perform more reliable and accurate mask testing and communication measurements.

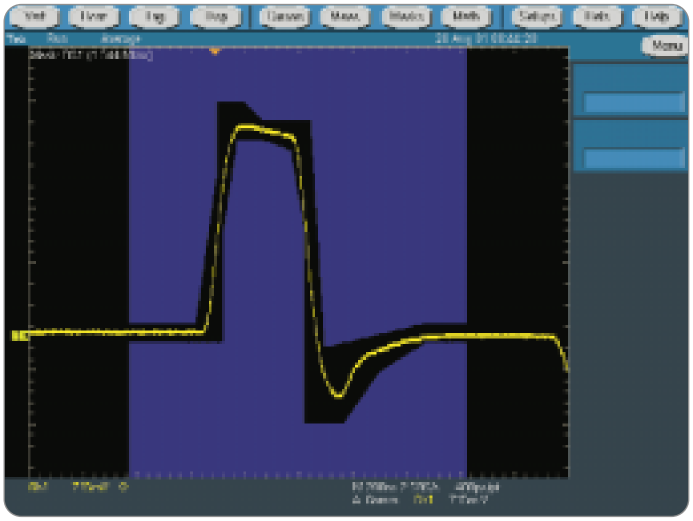


Figure 8. A DS1 mask where the leading and trailing bits surrounding the logic one pulse must be zero for at least one bit time. The signal shown is known as an isolated one.

Communication Pattern Triggering

A standard mask test requires that the oscilloscope have a unique data identification capability that many conventional digital oscilloscopes lack—a trigger capability that can find and trigger on data patterns such as positive pulses with leading and trailing zeros. Many of the standard masks defined for testing signals have regions where the signal must be zero long enough to enter and exit the mask without causing a violation. For example, the ANSI T1.102 specification for the DS1 signal requires a pulse with four leading zeros and one trailing zero for the signal that is tested by the DS1 mask. See Figure 8 for an example of an isolated one pulse. TDS7000 Series and CSA7000 Series DPOs have communications triggers that allow them to find and trigger on any isolated ones that exist in a random data stream. Masks for other signals are designed to test specific wave shapes such as the code mark inversion (CMI) positive one, negative one, or zero wave shapes. Without communications triggering, properly performing a mask test requires that the transmitter output a specified bit pattern such as all ones. To test a device with realistic traffic signals such as pseudo-random data, the oscilloscope must be able to find and trigger on the specific bit pattern before performing the mask test.

Jitter Measurements

For many designers, complying with an industry standard is not enough. They want to fully characterize their system to find its operating limits. If necessary, the device can be designed with a tolerance to prevent failures in manufacturing test or in the field after years of operation.

As the speed of digital designs and communications systems increase, characterizing jitter becomes more important to ensure proper operation of a system. Jitter can reduce a system's margin for error. Jitter can be defined as a phase variation or a timing deviation from an ideal. In digital communications systems, excessive jitter leads to unacceptable bit error rates (BER). The sources of jitter can be data dependent as well as random. Data-dependent jitter is a timing error in one bit caused by the state of one or more of the preceding bits in the transmission sequence. Random jitter is defined as timing errors that are not correlated to the data being transmitted. A simple measurement of jitter could measure both jitter types and result in a total jitter value. However, when trying to eliminate jitter, it's best to measure the random and data-dependent components separately. Then if one type of jitter is dominant, a systematic approach can be used to reduce the random or data-dependent jitter first.

Random Jitter

Measuring random jitter is possible using the histogram measurements available in the TDS7000 Series and CSA7000 Series DPOs. The steps for measuring the random jitter component are:

1. Stimulate the transmitter with a simple low-frequency repeating pattern. An example low-frequency pattern would be five high bits, then five low bits. This low-frequency pattern avoids inducing data-dependent jitter into the output.

2. Acquire the signal using the fast statistical database in the DPO.

3. Use a horizontal histogram to measure the distribution of the random jitter. For jitter that's truly random, one standard deviation of the histogram data is equal to the random or RMS jitter.

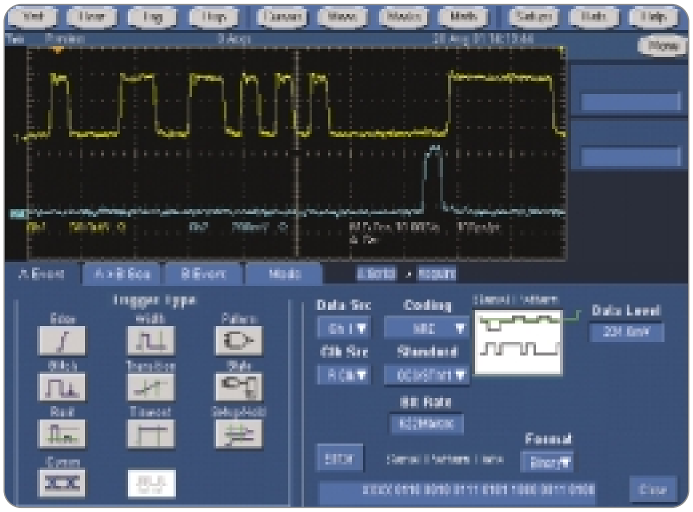


Figure 9. *CSA7000 Series serial pattern trigger menu.*

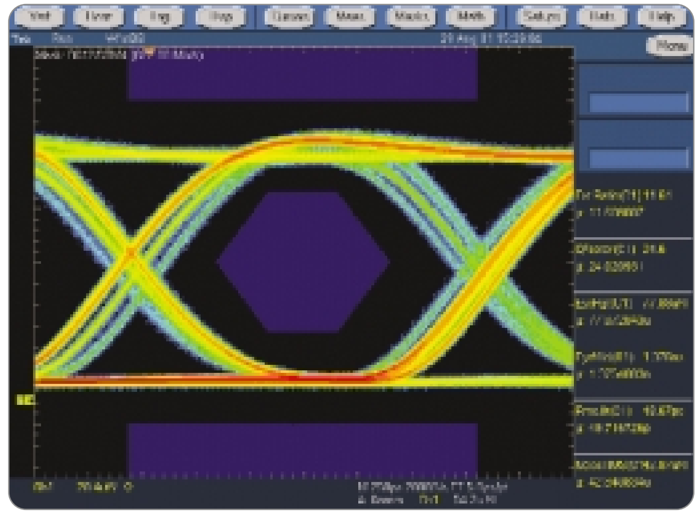


Figure 10. *Intensity-graded eye crossing display.*

For random jitter measurements, it's necessary to collect sufficient amounts of data to have a statistically valid jitter distribution. The histogram data should include many thousands or millions of acquisitions to yield valid statistics. When characterizing lower data rate tributary signals, the acquisition time can significantly slow down the jitter measurement if a conventional digital storage oscilloscope is used. TDS7000 Series and CSA7000 Series DPOs allow a histogram to be accumulated and measured much faster. Please refer to www.tektronix.com for additional information about Tektronix solutions for jitter measurements.

Data Dependent Jitter

Spotting a data dependency is easy with the DPO's intensity-graded persistence display. As data is acquired during multiple triggers, the intensity-graded display highlights areas in the waveform that are being hit more often. The intensity grading's highlighting often shows distinct edges in the waveform that are jittered. These distinct edges or modes indicate data pattern dependencies in the transmitter. Once these data dependencies are shown, the DPO can be used to quantify the effects of the various patterns. Observing the intensity-graded display or a histogram of the eye crossing can show data dependencies that cause different transitions through the eye crossing point.

In Figure 10, notice the bi-modal distribution of the edges at the eye crossing point. These distinct modes correspond to timing errors caused by different data patterns being transmitted by a laser. The timing errors induced by these different patterns are examples of data-dependent jitter.

Using Serial Pattern Triggers to Analyze Data Dependent Jitter

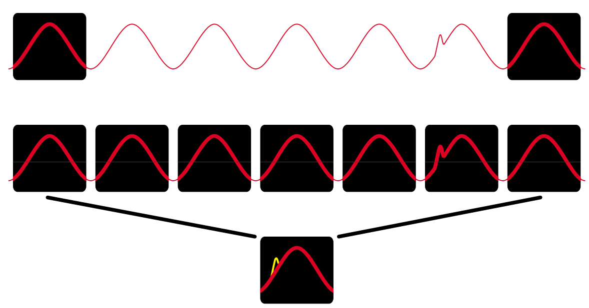
If a data dependency is present in the transmitter, the TDS7000 Series and CSA7000 Series DPOs serial pattern trigger can be used to capture one of several unique data patterns in NRZ serial data. Figure 9 shows the CSA7000 Series pattern triggers menu.This communications trigger feature offers up to 32 serial bit patterns that can be used to trigger the oscilloscope. By observing the behavior of the transmitter when out-putting an individual data pattern, it's possible to characterize data-pattern effects. This capability is available for signal rates up to 1.25 Gb/s.

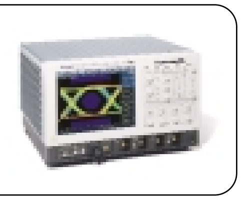
Conclusion

For communications hardware debugging at rates up to 2.5 Gb/s, a TDS7000 Series or a CSA7000 Series DPO is often the best test instrument. With its powerful signal acquisition system it has the ability to see problems that happen so infrequently that sampling scopes will miss them. Additionally, these DPOs are valuable companions to BERTs because their intensity-graded display enables the user to observe a transmitter's output and immediately see if there are intermittent problems. In many case, the advanced triggering available in these DPOs allows quick location of signal errors. In addition, the TDS7000 Series and CSA7000 Series DPOs provide the versatility that design engineers need to test the output of their design for standards compliance as well as to analyze critical internal circuit parameters such as signal integrity, timing margins and jitter with the same instrument. Lastly, the CSA7000 Series communications signal analyzer with its built-in optical reference receiver, optical-to-electrical converter and clock recovery provides a complete and easy-to-use solution for optical communication hardware debugging and verification.

The DPO with DPX™ Acquisition Advantage: Unrivaled Design Insight

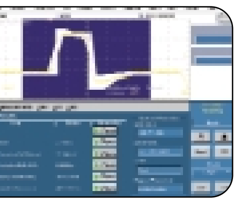
Before you can see a signal you have to capture it. That's easy with many signals, but much more challenging with the rare or random glitches that can occur during the 99.9% of the time that ordinary digital storage oscilloscopes are re-arming. Tektronix proprietary DPO with DPX ™ technology enables the oscilloscope to capture up to 400,000 or more waveforms per second—200 times more than other digital oscilloscopes. Statistically speaking, runt pulses, glitches and transition errors can be detected in seconds that could take hours with other oscilloscopes. DPX ™ technology also reveals subtle modulation patterns in dynamic shaded images. Dynamic characteristics with in eye diagrams and I-Q patterns are seen graphically.





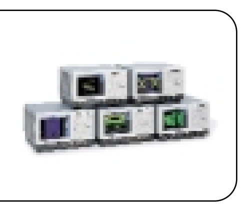
CSA 7000 Series

High performance digital phosphor oscilloscopes for physical layer testing of electrical and optical telecom and datacom signals up to 2.5 Gb/s.



TDSCPM2 (Option CP2)

User-installed, oscilloscope-resident software provides compliance measurements and Pass/Fail Indication on Pulse Amplitude, Spectral Power, Pulse Imbalance, Pulse Symmetry and Zero Level for ANSI T1.102 and ITU-T G.703 industry standards.



TDS7000 Series
Digital Phosphor Oscilloscopes

TDS7000 Series oscilloscopes, with bandwidth from 500 MHz to 4 GHz and up to 20 GS/s real-time sample rate, are high-performance real-time oscilloscopes for verification, debug and characterization of sophisticated electronic designs.

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