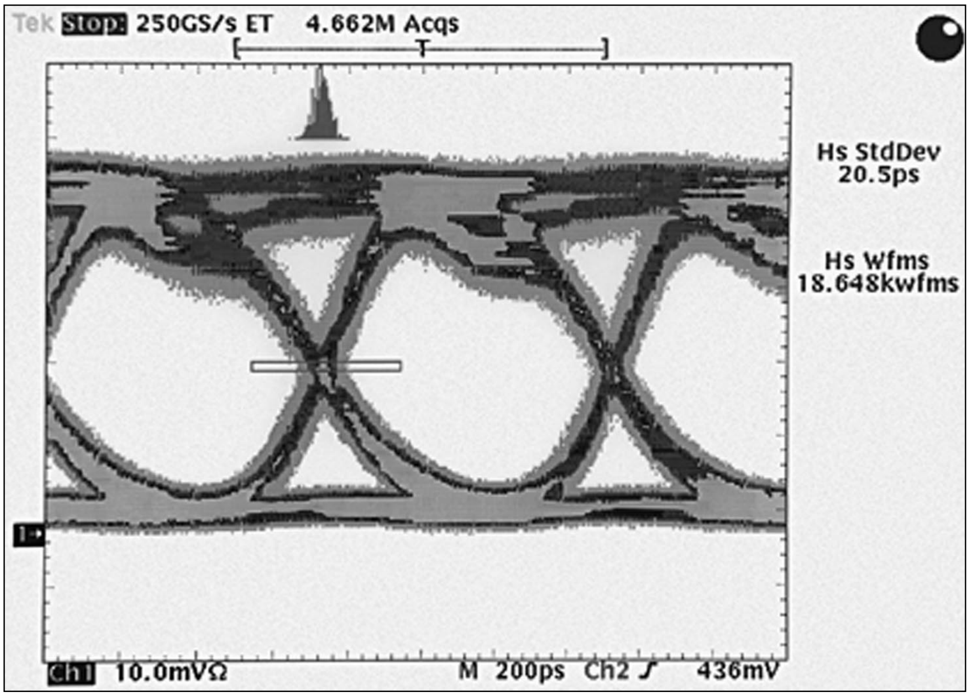
Tektronix

Application Note

Physical Layer Testing of Data Communications Signals



Introduction To Physical Layer Measurements

To ensure reliable information transmission over a network, industry standards specify performance requirements for the network's physical layer. The requirements encompass multiple measurement domains including DC voltage measurements, immunity to interference, bit error rate, network analysis, frequency domain measurements, and time-domain measurements.

The ISO Open Systems Interconnection (OSI) network reference model defines the physical layer as the specifications of the cable medium, segment length, and data rate. The electrical and optical physical layer data communications interfaces are discussed in this application note.

Examples of physical layer measurements listed in the ANSI and IEEE standards are shown in Table 1.

While there are many devices that can be used as verification tools for data communication devices, this application note describes measurements that can be made with a Digital Phosphor Oscilloscope (DPO). Oscilloscopes are one of the primary debug and verification tools used by all electronic designers. This application note discusses the use of a TDS 700D/500D Series oscilloscope to make some of the time domain measurements required by industry standards. Digital Phosphor Oscilloscopes such as the TDS 700D/500D can be used to debug designs, verify compliance with IEEE or ANSI standards, and characterize the performance of a network device's transmitter. Example measurements of Ethernet, Fibre Channel and Fibre Distributed Data Interface (FDDI) signals are used to illustrate these tests.

Table 1. Physical Layer Measurements

Measurement Type/Domain	Example Measurements
AC/Time	AC common-mode voltage, peak differential voltage, extinction ratio, data rate (period), jitter, rise time, fall time, slew rate, overshoot, and template testing
DC	Common-mode voltage
Immunity	Short-circuit tolerance, high-voltage impulse fault tolerance, common-mode voltage rejection
Bit Error Rate (BER)	Eye opening, bit error rate
Network analysis	Input and output impedance, attenuation, crosstalk, return loss
Frequency	Data rate (frequency), harmonic content, noise

Physical Layer Debugging with a DPO

Of the multiple applications for oscilloscopes in physical layer testing, the first use is often debugging a new design. When a system's firmware or a protocol test indicates that the bit error rate is too high, it's necessary to find a cause. Often the easiest method is to look at the transmitter output. Observing the transmitted signal with an oscilloscope can reveal problems such as excessive noise or jitter. It also indicates whether or not the signal's power levels are as expected. In addition, the DPO's advanced triggering functions can find pulses that are too narrow or too wide.

Baseline Wander

Debugging a data communications design often involves searching for clues to why the design is not working. Visual information from the DPO display can provide key information for locating a problem. Baseline wander is a problem that can cause bit errors in a 100Base-TX receiver. Baseline wander is an undesirable low-frequency component in the multi-level transition – three-level (MLT-3) signal. Baseline wander results from long data streams without transitions. A lack of transitions eventually "pumps up" the signal and exceeds the receiver's voltage threshold, causing an error in the received symbols.

Identifying and eliminating baseline wander is made easy with a TDS 700D/500D DPO. By observing an entire frame of data, the fact that baseline wander may be occurring can be identified much easier thanks to the intensity information shown in the DPO display. The intensity information in Figure 1 allows quick identification of where the signal is spending most of its time.

Notice the bumps in the signal just to the left of center in the DPO display. The baseline wander in this area causes the top of the MLT-3 pulses to wander up and down due to a DC offset. Once the occurrence and location of the baseline wander condition has been clearly identified, the acquisition of the frame can be zoomed. Figure 2 shows MLT-3 data at a 10 times finer time resolution (500 nsec/division).

With this time scale, the DC offset of the baseline wander can be seen and quantified. In Figure 2, the TDS 700D/500D cursors have been used to measure the baseline wander of the pulses. The measurement on the right shows a baseline wander of 64 mV. Locating the source of a problem in long data streams can take hours of searching through good data before the problem is found. The visual cues available with a DPO can allow quick identification of a signal anomaly. Once the anomaly is found, it can be captured and analyzed.

Compliance Testing

Masks. Another physical layer application for DPOs is verifying a signal's compliance with the requirements of industry standards. Standards mandate the signal's physical layer characteristics such as voltage, optical power level, data rate, jitter, and overshoot. All of these parameters can be quickly observed and verified using a DPO. Many standards also specify compliance via a mask (or template) test with an oscilloscope. While performing a mask test, the signals are often observed as pulses or pseudo random data streams in an eye diagram. With a persistence display mode and on-screen mask displays, an oscilloscope can easily verify whether or not a signal complies with the standard's requirements.

A mask test is often the best method to quickly verify that the transmitted signal meets industry standard requirements. Masks are defined so that signal distortions such as excessive overshoot, jitter, incorrect rise and fall times, etc., will all cause the mask test to fail. For some standards such as 10BaseT,

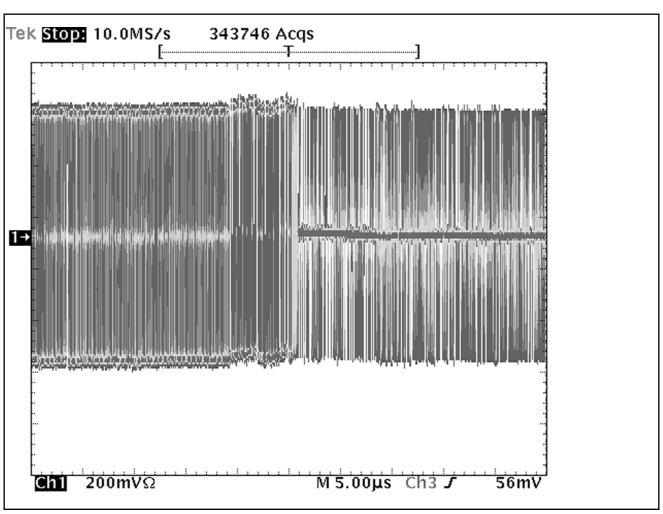


Figure 1. Baseline wander in a 100Base-TX signal observed with DPO.

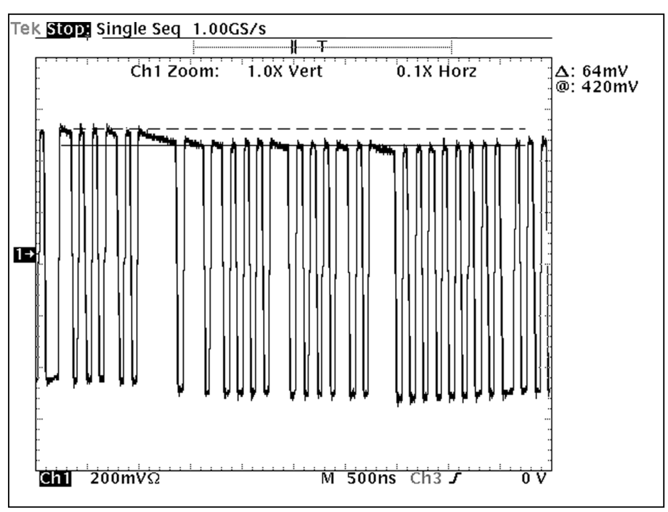


Figure 2. Baseline wander in a 100Base-TX frame at higher resolution.

masks are defined for a single pulse such as the idle pulse mask shown in Figure 3.

For pulse mask testing, the signal being tested should fall between the top and bottom portion of the mask. Any idle pulse that doesn't lie within the mask boundaries is non-compliant.

Table 2. Common Data Communications Standards Supported by TDS 700D/500D DSOs

Standard	Common Names	Data Rate (Mb/s)
IEEE 802.3	Ethernet, 10BaseT	10
ANSI X3.263, X3.166, IEEE 802.3u	FDDI, Fast Ethernet, 100BaseT	125
ANSI X3.230	Fibre Channel	133, 266, 531, 1063
IEEE P802.3z	Gigabit Ethernet, 1000BaseX	1250

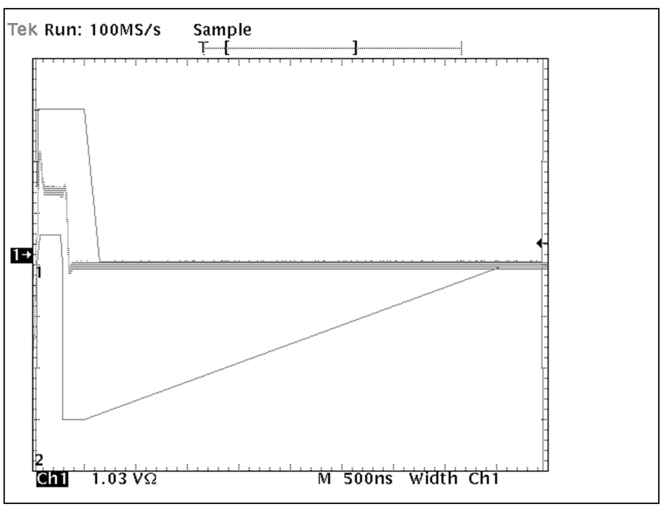


Figure 3. 10BaseT idle pulse mask.

Other mask tests are performed on eye diagrams of the data. The Fibre Channel (FC) specification defines a set of eye diagram masks for each of its standard data rates (i.e., 133 Mb/s, 266 Mb/s, 531 Mb/s, and 1063 Mb/s). The masks all have three exclusion regions that the transmitter's signal cannot enter. The masks boundaries are defined such that the mask can be easily scaled and used for verifying signals at different power levels or at different locations in the network. Figure 4 shows an eye diagram mask test for FC531.

To further increase the speed of compliance testing, the TDS 700D/500D oscilloscopes include the capability to automatically find and count mask violations. The eye diagram mask test in Figure 4 shows an automatic mask test running and counting mask hits (violations).

With so many standards, testing a system for compliance can often entail mask testing at 10 Mb/s, 100 Mb/s, and perhaps even 1 Gb/s. The TDS 700D/500D DPOs have the most popular industry standard masks for data rates of 1250 Mb/s and below built-in. Table 2 lists the standards and data rates supported by the built-in masks.

For standards that don't have mask definitions but where the speed of mask testing may be desirable, user-defined masks can be created on the TDS 700D/500D DPOs. For example, the IEEE 1394 standard doesn't currently include masks. However, an eye diagram mask can be created point-by-point. Figure 5 shows an eye diagram mask for use with a 400 Mb/s IEEE 1394 signal. Once created, user-defined masks can be saved on disk and recalled for use on any TDS 700D/500D DPO.

Automatic Measurements. In addition to mask test requirements, minimum and maximum values for parameters such as rise time, fall time, overshoot, peak-to-peak voltage, etc., are specified in the industry standards. The automatic measurement system of a TDS DPO can quickly measure these parameters and give answers. Also, specific measurements such as duty cycle distortion (DCD) and pulse amplitude symmetry can be done semi-automatically using the TDS automatic measurement system.

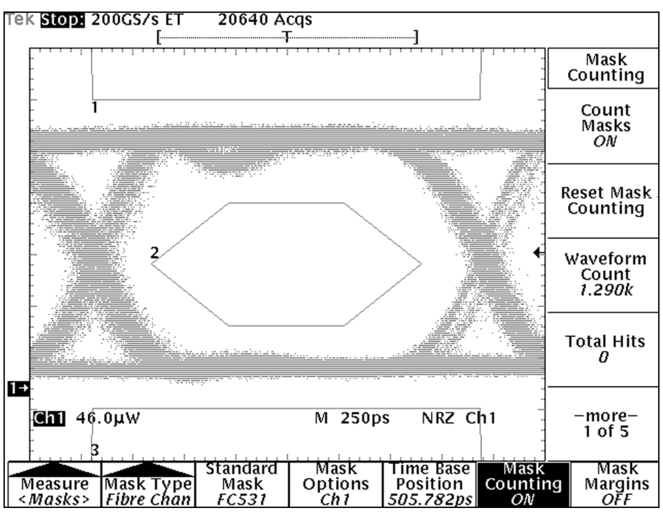


Figure 4. Fibre channel eye diagram mask test.

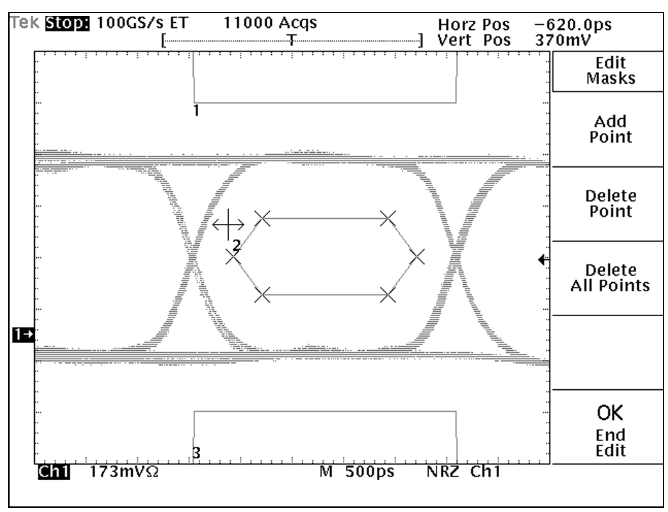


Figure 5. Creating a user-defined mask for IEEE 1394.

- **Duty Cycle Distortion (DCD).** To measure DCD, the widths of positive and negative polarity MLT-3 pulses that are nominally 16 ns wide need to be measured. The TDS pulse width function can measure positive and negative polarity pulses. However, the TDS normally measures pulse widths by determining the 50% amplitude point of the pulse and then measures the pulse at that level. If the pulses in Figure 6 were measured with the automatic measurement system, the 50% point would be set very close to the center of the display (0 V) and it's probable that no value would be determined for pulse width. Using the TDS 700D/500D cursors, the waveform area being measured can be gated. In Figure 6, the cursors have been placed such that the positive polarity pulse is between the cursors' vertical bars.

  With measurement gating on, the 50% point will be set correctly for the pulse – half way between the high voltage (933 mV) and low voltage (32 mV) levels of the pulse. A positive pulse width measurement of 15.78 ns is determined automatically. With this measurement setup, the negative pulse width is undefined since there is no negative pulse between the cursors (see Figure 6).

  To measure the width of the negative polarity pulse, the cursors are moved to the right half of the waveform as shown in Figure 7. With the gated measurement setup, the negative pulse width measurement is made at the 50% voltage point of the negative polarity pulse. The negative pulse width is measured as 15.91 ns. The ANSI X3.263 specification states that the positive and negative pulses should be nominally 16 ns ±0.25 ns. The pulses measured in this example (15.78 ns and 15.91 ns) would both meet the standard's requirement for compliance.

- **Signal Amplitude Symmetry.** Another measurement that can be accomplished using the TDS' automatic measurement system is signal amplitude symmetry. This measurement compares the peak voltage of two 112 ns wide positive and negative MLT-3 pulses. The TDS automatic high- and low-voltage measurements can be used to quickly determine the output voltage levels of the pulses. The high- and low-voltage automatic measurements in the TDS use a histogram technique to find

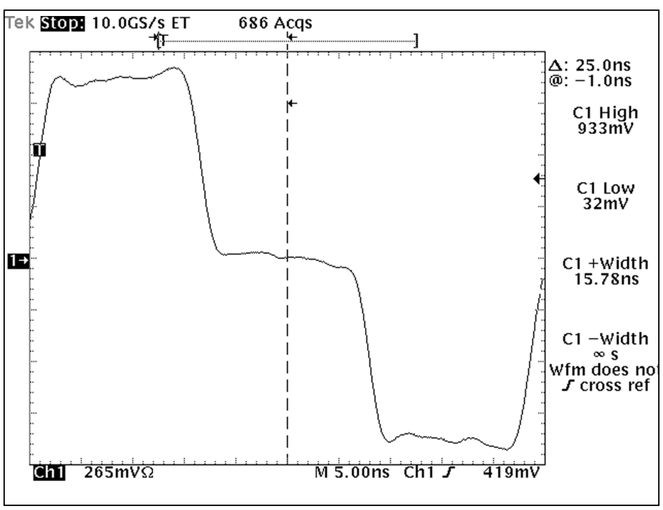


Figure 6. Duty cycle distortion measurement, positive pulse width.

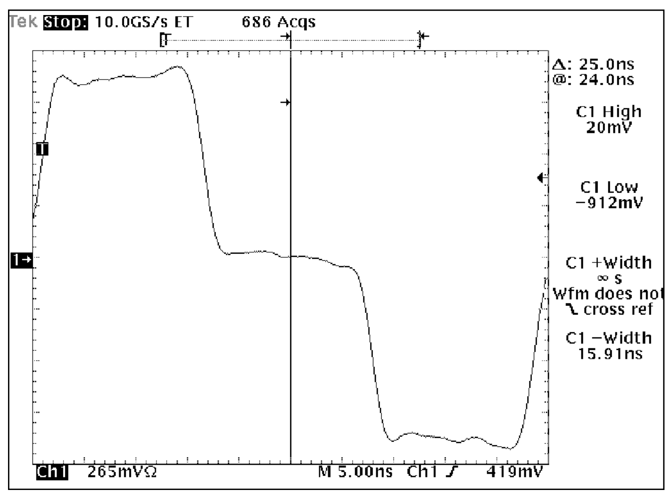


Figure 7. Duty cycle distortion measurement, negative pulse width.

the mean value at the top and bottom of a pulse. Figure 8 shows a high measurement and a vertical histogram waveform at the top of the positive pulse. The peak histogram value is the vertical level where the high measurement value is taken.

Figure 9 shows a negative polarity pulse being measured as the second half of the signal amplitude symmetry measurement. In this figure, a histogram of the low-voltage level has been turned on to illustrate where the low automatic measurement takes its reading.

Once the high and low voltage values have been measured, signal amplitude symmetry can be calculated as follows:

$$\text{Symmetry} = \frac{|+V_{out}|}{|-V_{out}|} = \frac{|high|}{|low|}$$

For the high and low values measured above, the calculated symmetry value is 0.465/0.469 = 0.99, which meets the range allowed by ANSI X3.263 of 0.98 to 1.02.

- **Automatic Optical Measurements**. For the data communication standards using optical transmission such as Gigabit Ethernet, Fibre Channel, and FDDI, two measurements that are important are extinction ratio and mean launch power. Extinction ratio is the ratio of the average power value of a logical one to the average power value of a logical zero. Extinction ratio represents the modulation depth of the communications signal. A high extinction ratio is desirable, because the signal will exhibit a greater margin to resist noise. Mean launch power is measured at the output of the optical transmitter. A high mean launch power is desirable because it results in the ability of the digital signal to travel further down a fiber optic cable without errors. The TDS 700D/500D oscilloscopes have both extinction ratio and mean launch power measurements built in to their automatic measurement system.

Signal Characterization

For many designers, complying with an industry standard is not enough for their design. Designs that barely pass when tested for compliance may fail after hours or days of operation. Failures that occur after installation can cost many times more to repair than identifying and fixing the problem early in the design stage. To ensure continued operation and standards compliance over the life of a product; it is often necessary to fully characterize the performance of a design. Characterizing a system involves finding its operating limits. DPOs are a key element in physical layer characterization measurements as well. This section discusses jitter measurements and margin testing – two measurements that characterize a design.

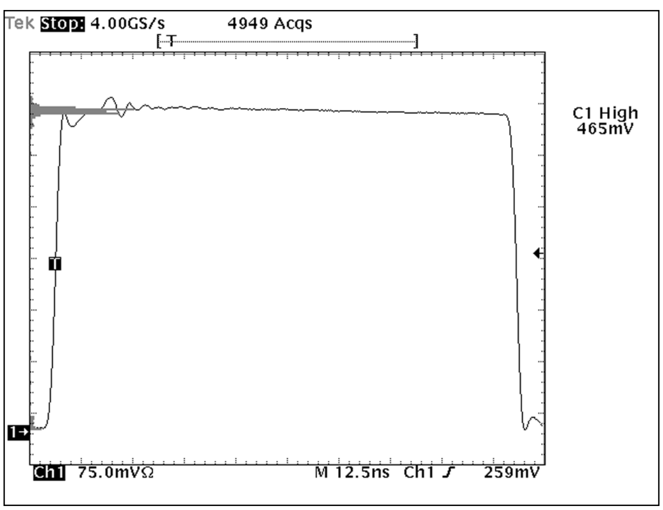


Figure 8. Positive MLT-3 pulse with high automatic measurement.

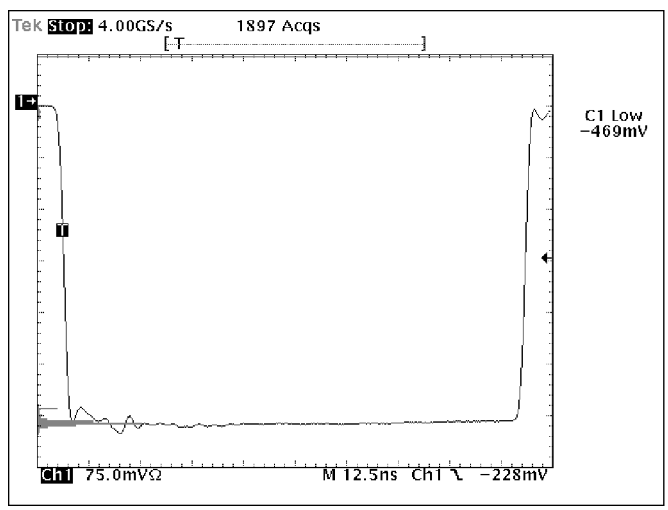


Figure 9. Negative MLT-3 pulse with low automatic measurement.

Probes for Physical Layer Tests

The variety of data communications interfaces requires various adapters for the measurement equipment. For example, optical communications signals often have to be converted to electrical signals before they can be measured; differential electrical signals must be converted to single ended before measuring them with a DPO.

OE Converters

To convert an optical signal to an electrical voltage for display on an oscilloscope, an optical to electrical (OE) converter is used. OE converters are often optimized for use over specified wavelengths. Typical OE converters are specified as short wavelength, covering 500 to 950 nm wavelengths, and long wavelength, covering 1100 to 1700 nm. Data communication signals such as GE and Fibre Channel are typically transmitted with short wavelength – 780 or 850 nm – lasers. Some applications are planned at longer wavelengths (1310 nm) as well.

The Tektronix P6701B and P6703B OE converters cover short and long wavelength applications and are designed to work with Tektronix TDS 700D/500D Digital Phosphor Oscilloscopes.

Reference Receiver Filtering

To create a standard frequency response for comparable and reliable measurements, the Fibre Channel and GE standards place an additional requirement on the measuring device when doing compliance measurements. An optical reference receiver that consists of the OE converter and a fourth order Bessel-Thompson low-pass filter is necessary. The optical reference receiver limits the bandwidth of the measurement equipment reducing the impact of overshoot and noise.

The Tektronix TDS 700D/500D Digital Phosphor Oscilloscopes have integrated optical reference receivers for the Fibre Channel standard.

Differential Probes

Electrical signals such as Ethernet, Fast Ethernet, and IEEE 1394 are differential signals. Probing the transmitted signal with good fidelity requires a differential probe that can convert the signal to single-ended voltage suitable for measuring with an oscilloscope. Signal fidelity is often determined by the specifications such as probe bandwidth, and common-mode rejection ratio. Characterizing a high data rate signal such as 100Base-TX requires a probe with a bandwidth of at least five times the signals clock rate. The common-mode rejection ratio (CMRR) is a specification of how effectively the probe can block a common-mode voltage such as power-line noise and still measure the differential data signal. The best choice for bandwidth and high CMRR is an active probe that uses a differential amplifier.

The Tektronix P6246 and P6247 have bandwidths of 400 MHz and 1 GHz respectively. They also exhibit high CMRR at bandwidth of >30 dB.

Jitter Measurements. Jitter can be defined as a phase variation or a timing deviation from an ideal. As the speed of communications systems increase, characterizing jitter becomes more important to ensure proper operation of a system. Jitter can reduce a system's margin for error. In digital communications systems, excessive jitter makes clock or data recovery at the receiver more difficult and results in unacceptable bit error rates (BER).

To characterize the jitter in a communications system, a couple of measurements can be accomplished with a DPO.

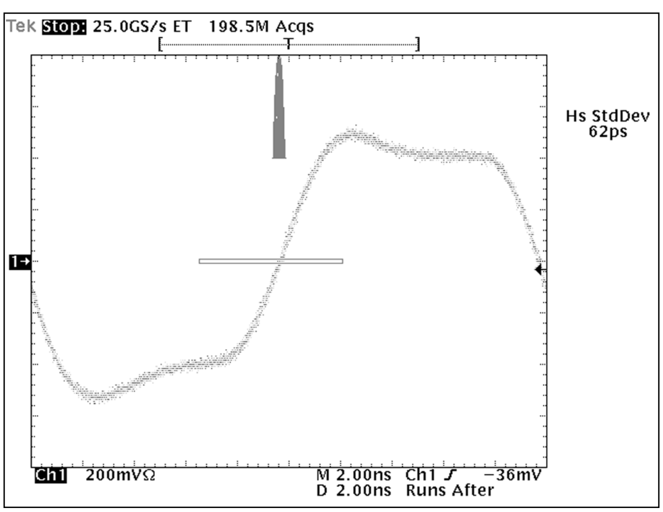


Figure 10. Random jitter measurement.

The first measurement of jitter is to determine the stability of the transmit clock. In Figure 10, a histogram is used to measure the jitter on a clock signal a fixed delay from a reference point – the scope's trigger time. The measurement of the histogram data is shown to the right of the waveform. One standard deviation of the histogram data is 62 ps.

Since the histogram waveform is a gaussian or normal shaped curve, one standard deviation of the histogram can be shown to be the RMS jitter value of the clock and scope combined. If the oscilloscope jitter is less than 10% of the measured jitter, it can be ignored. Alternatively, if the jitter of the scope has been characterized, it can be subtracted from the measured jitter using the square root of the sum of the squares formula shown below:

$$J_{clock} = \sqrt{J_{meas}^2 + J_{scope}^2}$$

A second jitter measurement determines the effect of various data patterns on the transmitter output. Excessive data-dependent jitter can cause clock and data recovery problems in the receiver. To measure the effect of data patterns on the transmitted signal, send a user-defined or pseudo-random data set through the transmitter. Then observe the output as an eye diagram using a DPO. Figure 11 shows the eye crossing point after several thousand data patterns have been acquired. As in the previous measurement, histograms can be used to measure the RMS and peak-to-peak jitter values.

In addition, observing the eye crossing with a color-graded display can show data dependencies that cause different transitions through the eye crossing point. Color-graded displays show more frequent data occurrences as brighter colors. In Figure 11, 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.

In general for jitter measurements, it's necessary to collect sufficient data samples to have a statistically valid jitter distribution. The histogram data should include many thousands or millions of acquisitions to yield good statistics. When characterizing lower data rate signals, the DSO acquisition time can slow the jitter measurement. The DPOs allow a histogram to be accumulated and measured much faster than traditional DSOs. Tektronix DPOs acquire and measure histograms 1000 times faster than traditional DSOs.

Mask Margin Testing

While the use of masks to determine compliance is a well-known testing technique, the speed advantage of mask testing can also be used in device characterization. Enlarging an industry standard mask by a small amount can help determine the amount of margin in a system relative to the standard requirements. To check a device for margin using a mask, a larger mask is created. Then, the mask test can be run and checked for failures. Mask margin testing can be performed with the TDS 700D/500D DPOs. Figure 12 shows a set of eye diagram masks with the original boundaries (center mask) and larger, less tolerant masks being used for margin testing.

The larger masks used in this test were set to 20% margin. A test was run with the 20% larger masks; after 27,584 acquisitions, there were no mask hits in either the original or the larger, less-tolerant new masks. From this test, it can be concluded that the device being tested has at least 20% margin relative to the standard requirements.

Conclusion

This application note has covered several of the measurements required for physical layer testing. A DPO is a useful tool for many aspects of physical layer measurements, debug, compliance, and characterization. The communications analysis and automatic measurement capability of the TDS 700D/500D Digital Phosphor Oscilloscopes make them ideal for physical layer measurements.

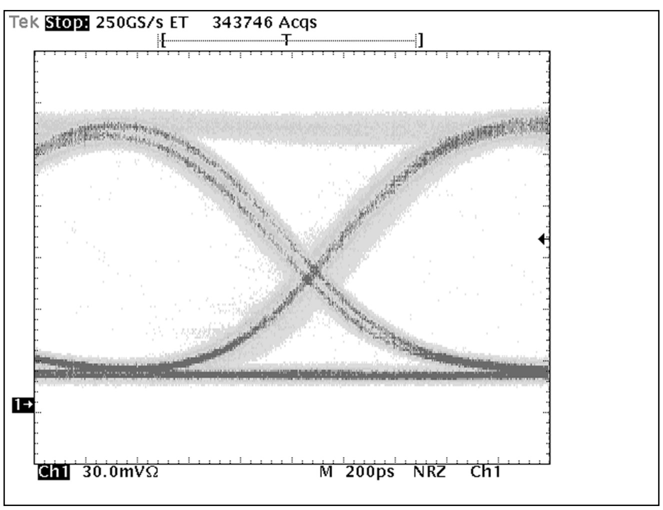


Figure 11. Color-graded eye crossing display.

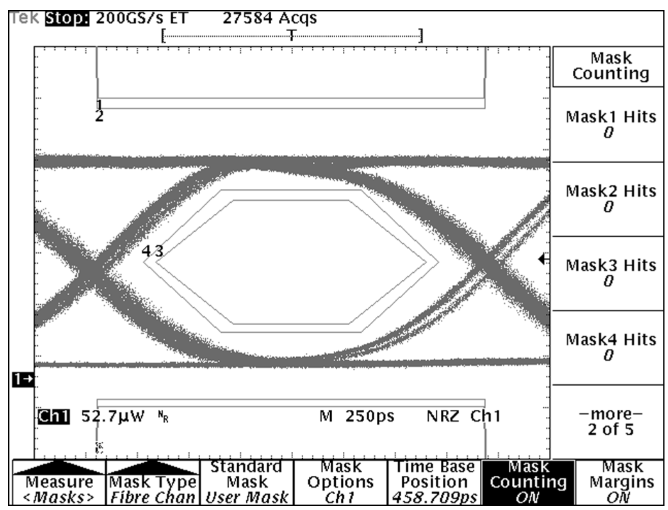


Figure 12. Eye diagram masks with 20% margin added.

Related Products

In addition to the TDS 700D/-TDS 500D Digital Phosphor Oscilloscopes, Tektronix offers several other products suitable for data communication system testing – see Table 3.

Table 3. Additional Data Communication Test Products

Model Number	Description
CSA 803C	Communications Signal Analyzer
11801C	Digital Sampling Oscilloscope
GB700, GB1400	Bit Error Rate Testers
ATM150	ATM Test Set
MTS200	MPEG Test System

Reference Documents

ANSI/IEEE 802.3-1996 Carrier Sense Multiple Access with Collision Detection (CSMA/CD) Access Method and Physical Layer Specifications.

ANSI X3.166-1990 American National Standard for Information Systems – Fibre Data Distributed Interface (FDDI) – Token Ring Physical Layer Medium Dependent (PMD).

ANSI X3.230-1994 for Information Technology – Fibre Channel – Physical and Signaling Interface (FC-PH).

ANSI X3.263-1995 American National Standard for Information Systems – Fibre Data Distributed Interface (FDDI) – Token Ring Twisted Pair Physical Layer Medium Dependent (PMD).

IEEE 803.3u-1995 Media Access Control (MAC) Parameters, Physical Layer, Medium Attachment Units, and Repeater for 100 Mb/s Operation, Type 100BaseT.

IEEE Draft P802.3z-1997 Supplement to Carrier Sense Multiple Access with Collision Detection (CSMA/CD) Access Method and Physical Layer Specifications: Media Access Control (MAC) Parameters, Physical Layer, Repeater and Management Parameters for 1000 Mb/s Operation.

IEEE 1394-1995 IEEE Standard for a High Performance Serial Bus.

ML6673 and Baseline Wander. Micro Linear Corporation, Application Brief 3.

For further information, contact Tektronix:

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