Optical transceiver tests verify compliance

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When optical communications systems were first deployed, verifying the physical-layer performance was fairly easy, because the entire network was usually installed and owned by a single company. If the system worked, extensive testing of the subcomponents was unnecessary. Today, however, optical networks often use components from a variety of suppliers, so you need a specification and test strategy to ensure all the components meet system-level requirements.

A digital communications system, whether it's a telecommunications link or an interface bus within a laptop computer, must operate with an acceptable BER (bit-error ratio), typically one error in $10^{12}$ bits. When a transmitter is paired with a receiver through a fiber and the system doesn't achieve the desired BER, you must determine if the fault lies with the transmitter, the receiver, or both.

Network specifications should guarantee that any receiver will interoperate with a worst-case transmitter. Likewise, transmitters must provide a signal with sufficient quality to interoperate with a worst-case receiver.

**FIGURE 1.** The eye diagram provides a good indication of the quality of a transmitter.
Precisely defining "worst case," however, can be complicated. If a receiver needs a minimum level of power to achieve the system BER target, then that level will dictate the minimum allowed output power of the transmitter. If the receiver can only tolerate a certain level of jitter, this will be used to define the maximum acceptable jitter from the transmitter. Transmitter parameters may specify wavelength and shape of the output waveform while the receiver parameters may specify tolerance to jitter and bandwidth.

An eye diagram is the common tool used to view a transmitter's output. It provides a wealth of information about overall transmitter performance. In an eye diagram, all the combinations of data patterns are superimposed on each other over a common time axis, usually less than two bit periods. **Figure 1** shows a signal with good signal amplitude and low jitter. You can envision how an eye diagram is constructed by drawing the eight possible sequences of a three-bit waveform (000, 001,...110, 111) overlapped on a common time axis.

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**FIGURE 2.** a) Masks placed in an eye diagram let you quickly verify if the eye is open. b) Expanding the size of the mask provides margins of error.

Rather than make several measurements to determine the quality of the eye, you can use an eye-mask test. A mask consists of several polygons placed in and around the eye diagram, indicating
areas where the waveform shouldn't intersect. A "good" waveform will never intersect the mask, while a "bad" waveform will cross, or violate, the mask. Stepping back and taking a system-level view, an eye that is open indicates that the receiver will easily distinguish a logic 1 level from a logic 0 level. If the eye closes, the likelihood of mistakes (bit errors) increases. Figure 2 shows a waveform that easily passes an eye-mask test.

Wide-bandwidth oscilloscopes let you perform optical eye-mask tests. These instruments go by several names, including digital communications analyzers. The oscilloscope can perform the test and determine if any waveform samples fall on the mask.

Laser manufacturers want their lasers to pass the mask test with no violations, and they also look for measurements with significant margin. Expanding the mask dimensions as large as possible without incurring any mask hits provides the maximum margin.

**How many samples?**

Most industry standards define a transmitted signal as being out of compliance if any waveform samples violate the mask. This brings up an interesting problem: A larger population of waveform samples should provide a more accurate assessment of the transmitter performance, but unfortunately, every eye diagram has random characteristics in both amplitude (noise) and time (jitter). Thus, as an oscilloscope collects more data, the likelihood of mask violations increases.

In theory, if you acquire enough samples, almost any transmitter will eventually fail a mask test. The probability for mask violations may be very low, but mask testing generally doesn't account for probabilities. It is an all or nothing test, pass or fail. So, how many samples must you acquire to perform the test?

At a minimum, you need enough samples to let the oscilloscope have sufficient data to align the mask to the waveform. Typically, a small population is enough. If there is significant space (margin) between waveform samples and the mask, then collecting more data will change the result only slightly. The problem occurs when a device barely passes the mask test, because collecting more samples could lead to a failure.

Industry standards such as IEEE 802.3ah (a short-reach optical standard), IEEE 802.3aq (which covers 10-Gbps transmission using lower-quality installed multimode fiber), and IEEE 802.3ba (40- and 100-Gbps Ethernet) recognize the problem and allow mask failures to occur, although they allow only a very small ratio of hits to samples (one failed sample for every 20,000 samples measured). These standards let you collect a large population, possibly yielding a more accurate measurement, without an increased likelihood of failure.

To help engineers deal with the question of how many samples to take, some oscilloscopes now include a modified version of the classic eye-mask test. These oscilloscopes perform an automatic
eye-mask margin test once you’ve acquired the desired number of samples. The test lets you
determine how far you can expand the mask dimensions before the ratio of mask hits to total
waveform samples exceeds the ratio allowed by the standard.

In Figure 3, the mask dimensions are expanded until 332 "hits" appear. (The hit ratio was set to
1:1000 for easy visibility, with 332,000 samples between the crossing points of the eye to which the
mask is aligned). You can significantly expand the mask from the standard dimensions, which
indicates a very good transmitter.

**Instrumentation effects**
An oscilloscope's frequency response can strongly impact the shape of the eye diagram. To achieve
consistent results throughout the industry, many instruments use a reference receiver. Here, eye-
mask tests are performed using a test system that has a frequency response that follows a fourth-
order Bessel filter response. The 3-dB bandwidth is at 75% of the data rate. For example, a 10-Gbps
reference receiver would have a 7.5-GHz bandwidth.

Compared to other filter designs, the Bessel response achieves minimal distortion of a waveform in
the time domain. The 75% bandwidth is the lowest bandwidth that doesn't cause vertical closure of
the eye. This specific design is commonly called a Bessel-Thomson reference receiver. Industry
standards typically define the exact response required to perform transmitter tests. Oscilloscopes
integrate these reference receivers as part of the complete test system.

In addition to measuring the shape of a transmitter's waveform, you should measure signal strength.
While an average-power measurement is useful, it doesn't provide much information about how well
a transmitter carries information. The average power of a laser that carries no information (constant
optical power level) is virtually the same as a laser that is highly modulated.

Extinction ratio is a parameter that indicates how efficiently laser power is converted to information
power. The extinction ratio is the ratio of the power level of the logic 1 to the power level of the logic
0. Consider a laser that is turned almost all the way off to transmit a 0 and turned on to transmit a 1.
The ratio of 1 to 0, and hence the extinction ratio, will be high. On the other hand, if significant
power is used to transmit a 0, the extinction ratio will be low, indicating that some laser power is
wasted.

The extinction ratio is derived from the eye diagram. An oscilloscope can construct histograms in the
central 20% of the eye to determine the mean value of the composite 1 bits and the mean value of
the composite 0 bits.

OMA (optical-modulation amplitude) is similar to extinction ratio, except that rather than being the
ratio of the '1' to '0' levels, it is the difference between them. While you can derive OMA from the
eye diagram, many industry standards extract this parameter from a special square-wave pattern
that consists of five 0's followed by five 1's, with the middle 0 and middle 1 being used for the
computation.

Which is more important, extinction ratio or OMA? They both indicate modulation power, but from
different perspectives. Long-haul transmission systems that employ optical amplifiers shouldn’t
waste available power while transmitting a logic 0. A high extinction ratio minimizes power loss.
Short-haul systems generally minimize the high cost associated with tuning a laser for a high
extinction ratio. But they need to guarantee a minimum separation between logic 1 and logic 0
levels. In those cases, OMA is more important.
Receiver tests

Testing a receiver boils down to verifying an acceptably low BER when the receiver is presented with the worst-case signal. As systems became more complex, faster, and less expensive, engineers had to begin testing receivers using nonideal signals with different types of impairments. These are commonly referred to as "stressed" signals.

The first types of stressed signals that gained wide acceptance in high-speed fiber-optic communication were for long-haul applications that used EDFAs (erbium-doped fiber amplifiers). The ASE (amplified spontaneous emission) noise could cause excess errors on receivers that otherwise performed well when tested under typical ideal conditions. Vendors of long-haul network equipment required test signals intentionally degraded by ASE noise. These tests are still in wide use today.

Shorter-span systems such as Ethernet and Fibre Channel also use the stressed-eye concept. A well-defined combination of impairments is added to an ideal signal and is presented to the receiver under test. In these systems, the signal degradations are dominated by different mechanisms than they are in long-haul systems. The degradations emulate the worst-case noise, attenuation, jitter, and ISI (intersymbol interference) that might occur in a system.

In short-haul systems, measuring receiver BER is a straightforward process, and producing a distorted signal is easy. Producing a precision distorted signal, however, can be difficult. If the signal distortion is too small, a bad receiver may appear good. If the distortion is too severe, a good receiver may appear bad.

Newer BER testers have pattern generators that produce calibrated levels of distortion, or stress. A stressed signal will typically have the ability to produce a data signal that has precise amounts of timing jitter, bandwidth-limiting ISI, and attenuation. Figure 4 shows the difference between a clean eye and a stressed eye.

Most optical receivers employ some form of clock recovery to extract a timing reference for the decision circuit. Clock-recovery systems generally have a limit on how fast they can track jitter. To verify proper operation of the clock-recovery system, standards often require that receivers tolerate both low-frequency and high-frequency jitter. A jitter-tolerance template, consisting of specific jitter frequency/amplitude pairs, is applied to every receiver.
While the standards require compliant receivers for all jitter amplitude/frequency pairs on the jitter-tolerance curve, the typical manufacturing compliance test focuses on the highest frequency case. That’s because receivers tend to easily tolerate low-frequency jitter. A receiver test that emulates real system conditions helps ensure the interoperability of network components.

Testing transceivers has evolved to accommodate the changes in system architecture and performance. As data rates increase, the basic eye-mask test is still viable, but important changes that have shown up in recent standards are gaining in popularity and likely will be used in future standards. Receiver testing using complex "stress" signals is also becoming more common.

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