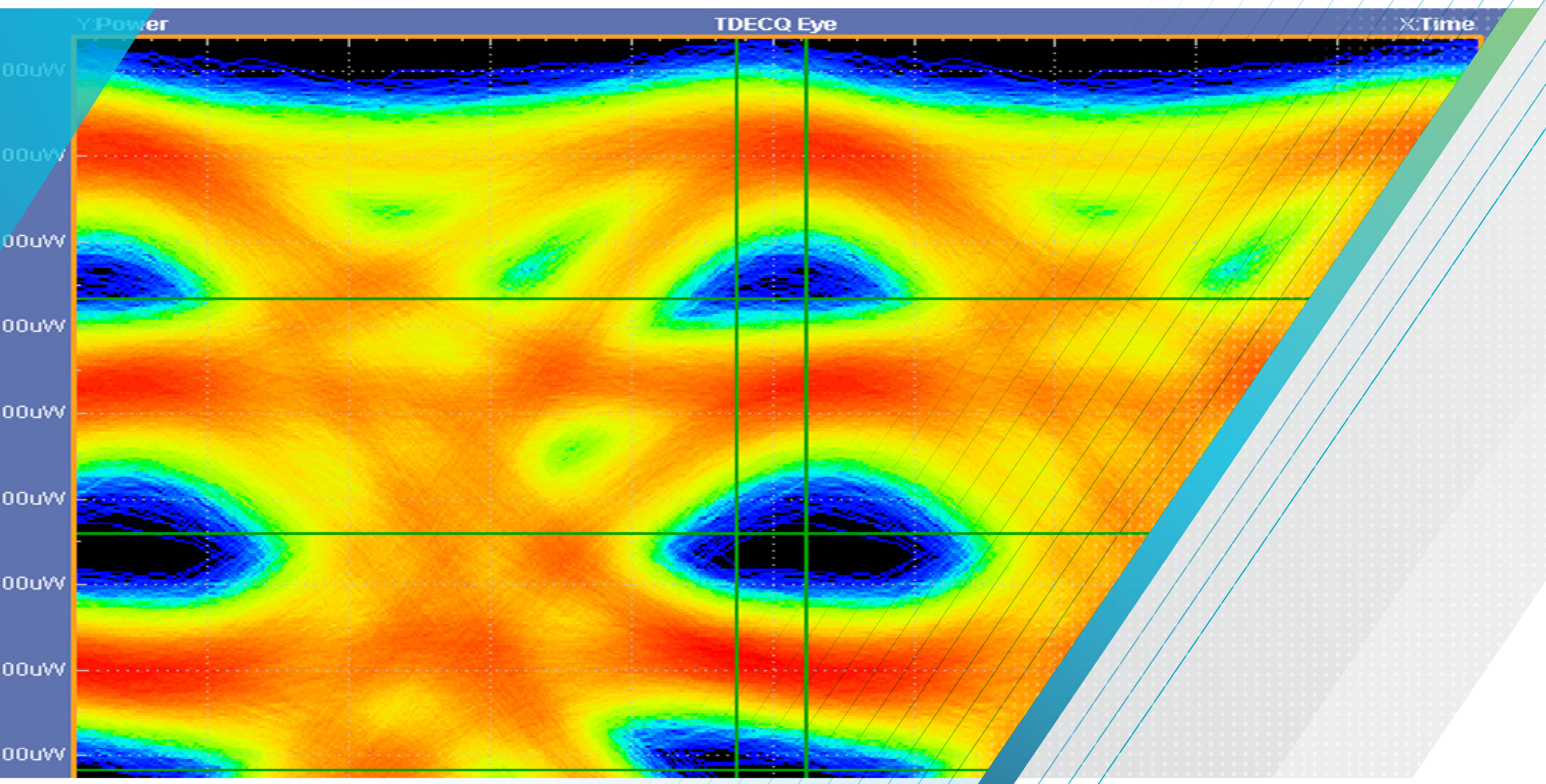
PAM4 Signaling in High-Speed Serial Technology: Test, Analysis, and Debug

APPLICATION NOTE



Tektronix

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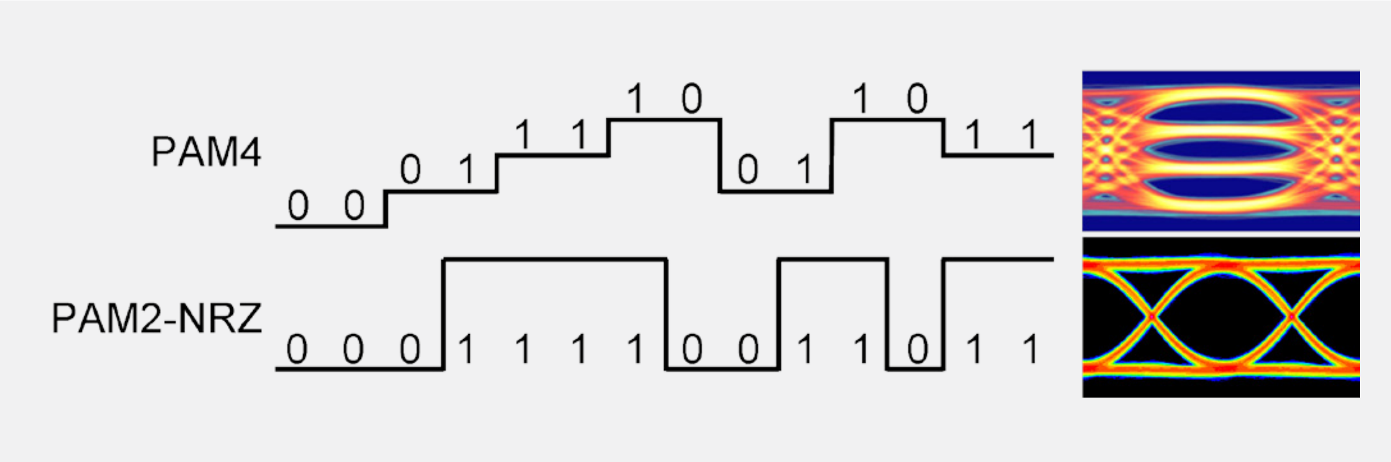

FIGURE 1. PAM2-NRZ and PAM4: baseband signaling and eye diagrams.

1. 4-Level Pulse Amplitude Modulation–PAM4

As serial data rates surpass 50 Gb/s per channel, signal impairments caused by increasing bandwidth have compelled the high-speed serial data industry to make a considerable shift in approach. In many applications, simple, baseband, NRZ (non-return to zero) signal modulation is being replaced by more bandwidth efficient PAM4 (4-level pulse amplitude modulation).

PAM4 cuts the bandwidth for a given data rate in half by transmitting two bits in each symbol, as indicated by Figure 1. With two bits per symbol, we must distinguish the data or bit rate, Gb/s, from the symbol or baud rate, GBd.

The abbreviation NRZ has been used informally to describe intuitive high/low signaling, but the formal description is 2-level pulse amplitude modulation, or PAM2. Since PAM4 signals do not return to zero after each symbol, they are also an NRZ signaling scheme. In this paper, we'll refer to the two schemes as PAM2-NRZ and PAM4 for both clarity and accuracy.

The eye diagrams in Figure 1 indicate how the multiple symbol levels make PAM4 more sensitive to amplitude noise than PAM2-NRZ is. While PAM4 signals also suffer greater ISI (inter-symbol interference) than PAM2-NRZ at a given baud rate, they suffer much less at the same data rate. PAM4's greater resilience to ISI at a given data rate on lossy electrical channels like backplanes is the primary reason for switching from PAM2-NRZ. A close look at Figure 1 also reveals that increments in the signal levels do not consistently correspond to increments in the binary values of the PAM4 symbols; we'll see why in Section 2.3.

For optical systems, the motivations to switch from NRZ-PAM2 to PAM4 include cost, power, and seamless optical to electrical signal conversion.

PAM4 signal analysis borrows a great deal from the jitter and noise analysis developed for PAM2-NRZ by applying them separately to PAM4's three-eye diagrams but also introduces new techniques to account for the interrelationships among the three eyes and to optimize conflicting and interdependent design parameters.

In this paper, we examine techniques for evaluating PAM4 technology with emphasis on the performance requirements that enable SerDes and transceivers to operate and interoperate in PAM4 systems. In Section 2 we describe the details of PAM4 signaling. Sections 3 and 4 cover evaluation of optical and electrical transmitters, respectively. The concept of stressed eye tolerance tests is explained in Section 5, and evaluation of optical and electrical PAM4 receivers described in Sections 6 and 7. We conclude with a look at the direction high-speed serial data technology is taking at 100+ Gb/s data rates.

2. High-Speed Serial PAM4 Technology

Table 1 shows examples of 50 Gb/s to 400 Gb/s high-speed serial PAM4 technologies. The highest data rates are achieved by combining multiple lanes of lower rate signals. It's tempting to think of these as parallel systems, but since each lane is independently clocked, inter-lane skew isn't a concern the way it for genuine parallel busses.

PAM4 has been adopted at data rates of 25+ Gb/s per lane in IEEE 50/100/200/400 GbE 802.3bj, 802.3bs, and 802.3cd, OIF-CEI 4.0, and likely adoption in 64GFC, 256GFC (Gigabit Fibre Channel), and Infiniband HDR (high data rate) at 50, 200, and 600 Gb/s.

Electrical PAM4 specifications consist of multi-lane, hot plug, low voltage, balanced differential pairs with embedded clocking and either transmitter or receiver equalization or both. The length, or "reach," of electrical lanes can be defined as physical distance or loss, its engineering equivalent. Optical PAM4 can be used with SM (single mode) or MM (multi-mode) fibers—though modal dispersion limits the reach on MM fibers.

Each standard applies to a particular purpose in a unique signal integrity environment. For example, Table 1 shows separate specifications for cables, backplanes, and both SM and MM fiber optics. Figure 2 shows the roles of different components in the high-speed serial electro-optical network. Electrical signals are transmitted from chip to chip, chip to optical module, and module to chip on cables, backplanes, and across circuit boards. Each application comes with its own set of compliance requirements.

STANDARD		MEDIA	REACH	RATE	PRE-FEC BER / POST-FEC FLR
50 GbE	50GBASE-SR	1•MM	100 m	26.56 GBd	BER ≤ 2.4•10^{-4} FLR ≤ 9.2•10^{-13}
100 GbE	100GBASE-SR2	2•MM	100 m	2•26.56 GBd	
	100GBASE-KP4	4 Traces PCB	33 dB	4•13.6 GBd	BER ≤ 10^{-5} FLR ≤ 6.2•10^{-10}
	100GBASE-CR2	2•Cable	3 m	2•26.56 GBd	BER ≤ 2.4•10^{-4} FLR ≤ 6.2•10^{-10}
200 GbE	200GBASE-SR4	4•MM	100 m	4•26.56 GBd	BER ≤ 2.4•10^{-4} FLR ≤ 1.7•10^{-12}
	200GBASE-DR4	4 WDM SM	500 m		
	200GBASE-FR4	4 WDM SM	2 km		
	200GBASE-LR4	4 WDM SM	10 km		
	200GAUI-4	4 Traces PCB	~250 mm		
400 GbE	400GBASE-FR8	8 WDM SM	2 km	8•26.56 GBd	
	400GBASE-LR8	8 WDM SM	10 km		
	400GAUI-8	8 Traces PCB	~250 mm		
	400GBASE-DR4	4•SM	500 m	4•53.13 GBd	
OIF-CEI	CEI-56G-VSR	1 Trace PCB	~150 mm	18-29 GBd	BER ≤ 10^{-6}
	CEI-56G-MR		~500 mm		
	CEI-56G-LR		~1 m		BER ≤ 10^{-4}
Fibre Channel	64GFC/256GFC	4•MM	~150 mm	29.03 GBd	TBD
		4•SM	2 km		
		4 Traces PCB	~150 mm		

TABLE 1. Examples of PAM4 standards covering 50 Gb/s, 100 Gb/s, 200 Gb/s, and 400 Gb/s.

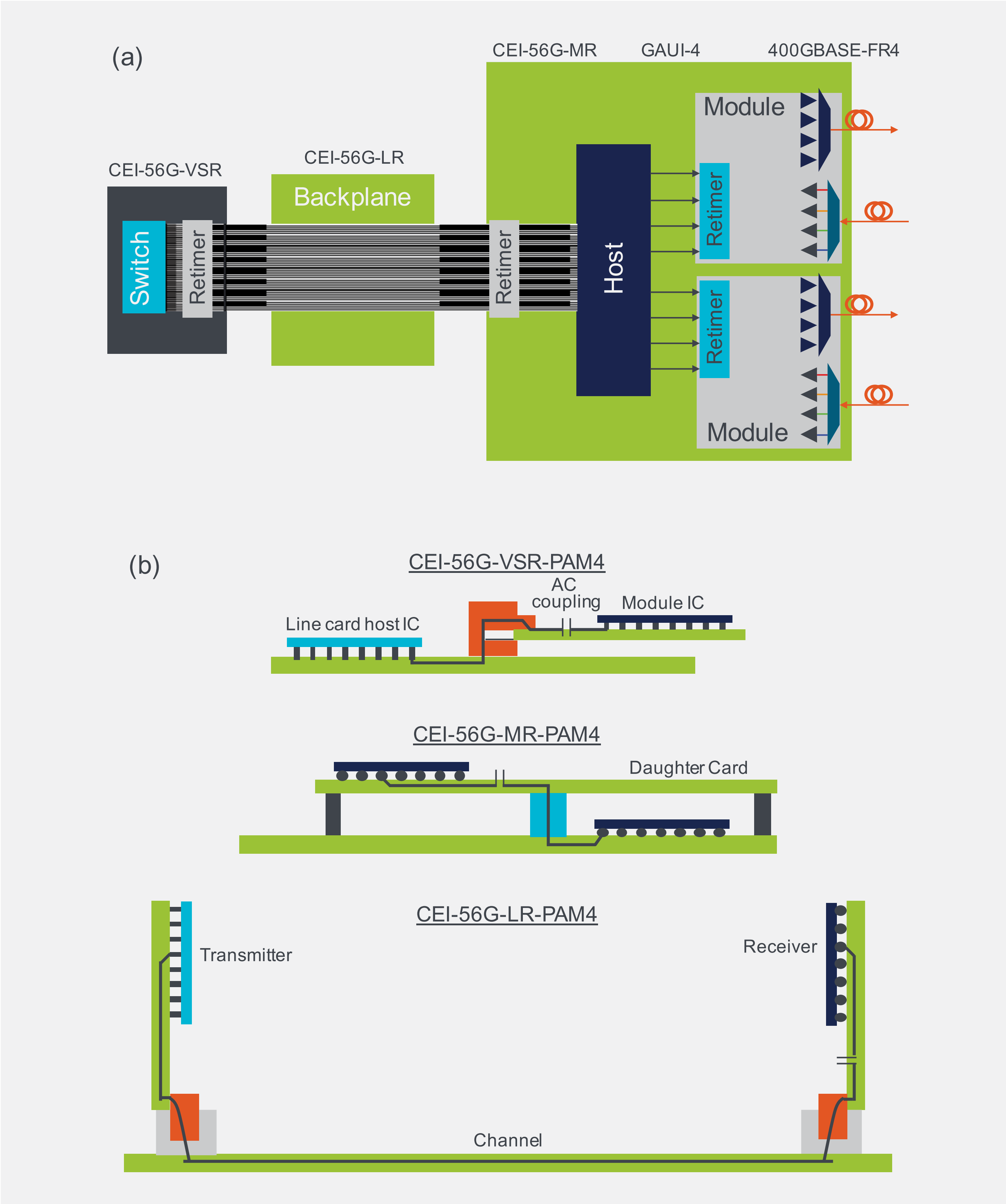

FIGURE 2. The components that make up an integrated electro-optical serial data transmission system.

2.1 PROPERTIES OF PAM4 SIGNALS

Table 2 and Figure 3 compare characteristics of PAM4 and PAM2-NRZ signals. If you've never drawn a PAM4 eye diagram, it's a simple and effective way to grasp the complexity of PAM4's four separate symbol levels, three eyes, six rising and falling edges, 12 distinct transition possibilities, and four different non-transitions. Even the 50% bit transition density of PAM2-NRZ changes to 75% PAM4 symbol transition density.

	PAM4	PAM2-NRZ
Bits per symbol	2	1
Symbol levels	4	2
Rising/falling edges	6	2
Distinct transitions	12	2
Eye diagrams per UI	3	1
Average transition density	75%	50%

TABLE 2. Comparison of PAM2-NRZ and PAM4 signal traits.

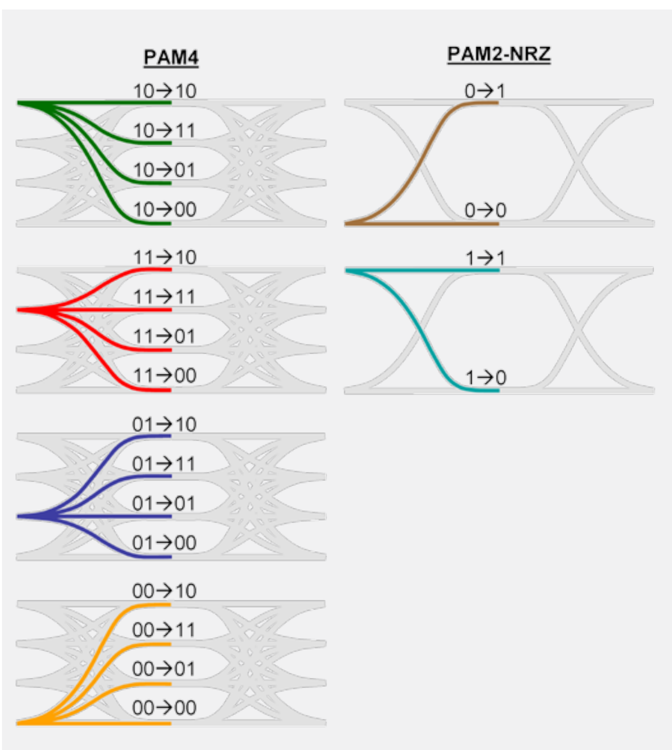

FIGURE 3. Properties of PAM4 signals.

The PAM4 symbols are S0, S1, S2, and S3 with corresponding power levels for optical signaling, P0, P1, P2, and P3, and voltage levels for electrical signaling, V0, V1, V2, and V3, which are sometimes also referred to as {-1, -1/3, 1/3, 1}.

The PAM4 eye diagram spans one unit interval and consists of a single "outer eye" with three inter-dependent "inner eye" diagrams—interdependent because transitions from one symbol to another can affect more than one eye. The inner eye diagrams are called low, middle, and upper, Figure 4. Since noise affects each eye, PAM4 signals are at least three times more sensitive to amplitude noise than PAM2-NRZ. For electrical signaling the effective threefold increase in amplitude noise reduces the SNR (signal-to-noise ratio) by at least 9.5 dB and for optical signals by 4.7 dB—the factor-of-two difference between electrical and optical signaling comes from converting the SNR of electrical voltages to power.

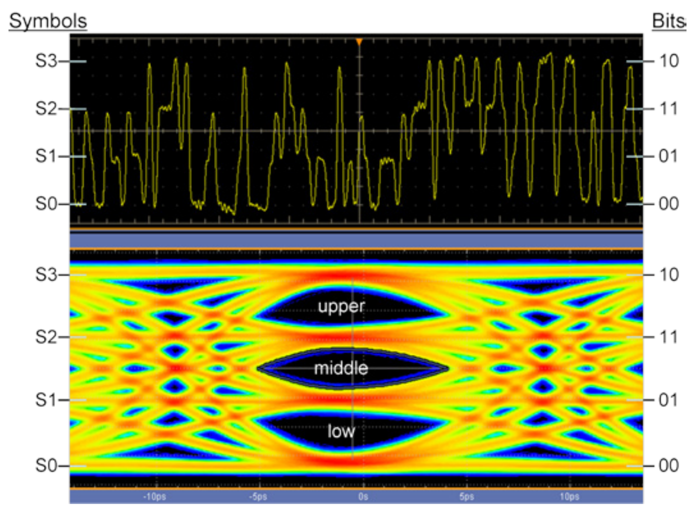

FIGURE 4. Some notation for PAM4 eye diagrams.

Each of the three eyes can be analyzed the way that PAM2-NRZ eyes are analyzed. That is, we can measure jitter, noise, EW (eye width), and EH (eye height) separately for the lower, middle, and upper eye diagrams.

The biggest change in the transition from PAM2-NRZ to PAM4 is the relative positions of the three eyes. There are two categories of nonlinearity: Inter-eye timing skew describes the difference in the horizontal positions and widths of the three eyes. Eye compression describes variations from uniform separation of the vertical positions and heights of the eyes.

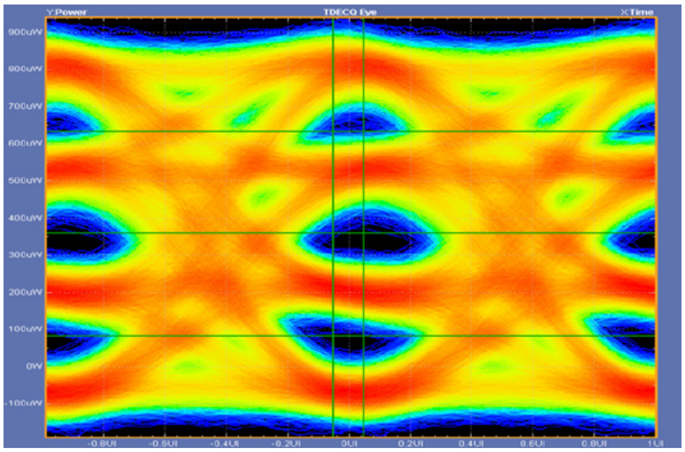

FIGURE 5. A PAM4 Eye diagram with both timing skew and eye compression.

2.2 FEC–FORWARD ERROR CORRECTION

The impact of SNR on PAM4 signals is addressed in most applications by the use of FEC (forward error correction). FEC allows the maximum uncorrected BER (bit error ratio) to be increased from as low as 1E-15 to as high as 2.4E-4.

From the test perspective, the introduction of FEC and consequent relaxation of the BER requirement is a huge advantage. We can now measure BER down to the required pre-FEC BERs in seconds on real-time oscilloscopes. In the past, we either had to extrapolate oscilloscope measurements from BER ~ 1E-6 down to BER = 1E-12 or 1E-15 or spend large fractions of an hour to perform the measurement on a BERT (BER tester).

Many types of FEC have been used in digital communications. High-speed serial applications use Reed-Solomon FEC. The RS-FEC scheme uses an algebraic technique to encode redundancy at the transmitter. The receiver then inverts the algebra in a way that can correct a certain number of bit errors. The number of bit errors that RS-FEC is capable of correcting depends on the order of errors within FEC codewords.

The terminology can be confusing. The word “symbol” in the context of RS-FEC is not related to PAM4 symbols. The symbols used in RS-FEC are purely abstract sets of bits. RS-FEC encodes k symbols of data with $2t$ parity symbols into an n symbol codeword in such a way that t symbol errors can be corrected, Figure 6. For example, the GbE and OIF-CEI standards in Table 1 use RS-FEC(544, 514). Each symbol consists of ten bits. Each codeword consists of 544 symbols, totaling 5,440 bits that includes 5140 encoded data bits. RS-FEC(544, 514) can correct at most 15 symbols, regardless of how many bit errors occur in each symbol. If each bit in every one of the 15 symbols is an error, the scheme can correct 150 errors. If only one bit is an error in each symbol, the scheme can correct at most 15 errors. If there are 16 bit errors, but each is in a separate symbol within one RS-FEC codeword, then depending on how RS-FEC decoding is implemented some errors may still be corrected but not all.

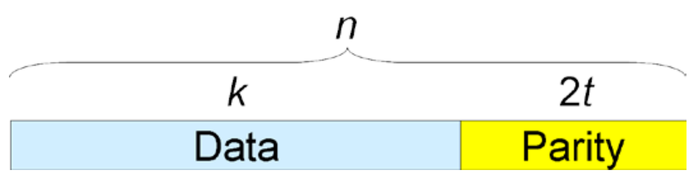

FIGURE 6. Reed Solomon forward error correction scheme. RS-FEC(n, k) is capable of correcting up to t errors in each word. FEC-symbols and Reed Solomon FEC.

The capacity for FEC to correct errors relaxes the BER compliance requirement at the expense of latency, power, and chip circuitry. To account for FEC limitations, maximum values for both the BER and FLR (frame loss rate) are specified. Some standards specify the maximum allowed burst error lengths; for example, CEI-56G-VSR limits the allowed burst length to 15 PAM4 symbols per 1E20 symbols, CEI-56G-MR limits it to 94 out of 1E20, and for CEI-56G-LR, 126 out of 1E20.

Where BER is defined as the ratio of the number of bits in error to the total number of bits transmitted, FLR is defined as the ratio of validated 64 octet frames to the total number of frames received. The pre-FEC BER and burst error length requirements are designed to assure that the corrected, post-FEC FLR meets the specification. For example, 400GBASE-DR4 requires pre-FEC BER less than or equal to 2.4E-4 and post-FEC FLR less than or equal to 1.7E-12, which should assure operation at BER < 1E-15.

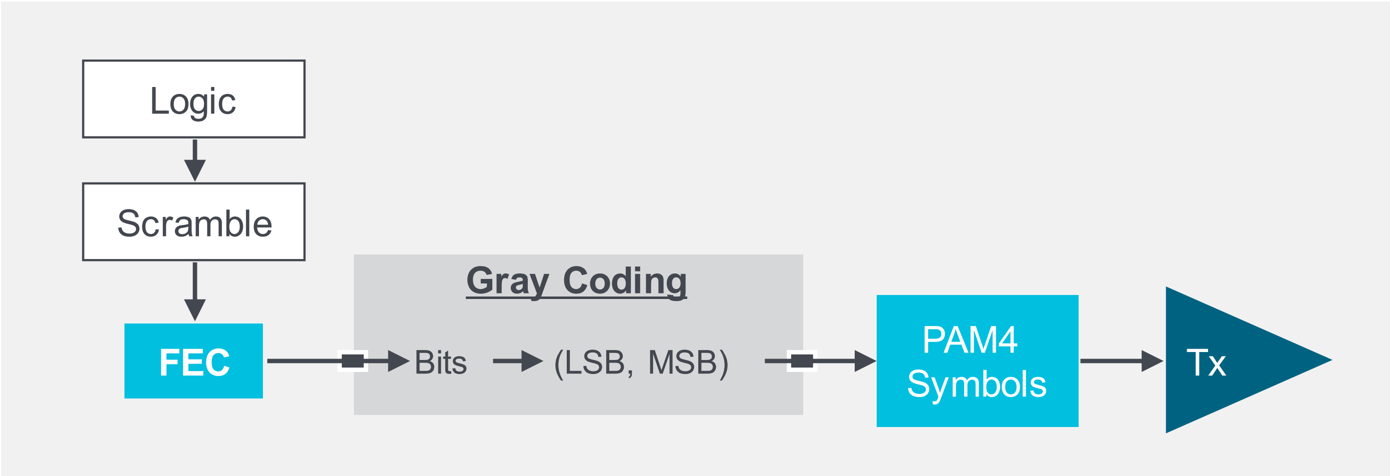

FIGURE 7. The Gray coding conversion from logic "bits" to FEC encoded PAM4 symbols.

2.3 GRAY CODING

Figure 7 shows how FEC encodes binary logic into sets of data bits that include the overhead of FEC's parity bits. The resulting bit stream is then Gray coded and formatted into the PAM4 symbols that are transmitted. The receiver detects PAM4 symbols, Gray decodes them into bits, and then processes the bits through RS-FEC to reproduce the data.

In Figure 1 and Figure 4 the Gray coding of S2 and S3 do not follow numerical order: S0 = 00, S2 = 01, S2 = 11 and S3 = 10. Since each PAM4 symbol carries two bits, one symbol error can result in either one or two bit errors. By assigning 11 to S2 and 10 to S3, Gray coding increases the probability that symbol errors caused by amplitude noise will result in one bit error rather than two. In this way, Gray coding helps SER (symbol error ratio) converge to BER. On the other hand, jitter is as likely to cause two bit errors per symbol error.

2.4 CLOCK RECOVERY AND EQUALIZATION IN PAM4 SYSTEMS

Clock recovery was one of the enabling technologies that made high-speed serial technology based on PAM2-NRZ signaling so successful and it too is more difficult with PAM4 signals. In a clock-forwarded or, equivalently, embedded clock system, a data-rate clock is recovered from the timing of signal transitions by a CR (clock recovery) circuit. The cleaner the transition, the more seamless the clock recovery. Like PAM2-NRZ, the sharp transitions between PAM4 symbols are softened by loss and ISI, but unlike PAM2-NRZ transitions, most PAM4 transitions do not swing between the minimum and maximum power or voltage levels. Just 1/6 of PAM4 transitions swing between S0 and S3; half of PAM4 signal transitions span just 1/3 of the peak-to-peak levels.

The recovered clock sets the timing position or phase of the symbol decoder. The difference is that PAM4 systems have three slicers. The three slicers do not have to be simultaneous, though most of the first PAM4 systems use common timing for all three. We'll revisit the signal integrity issues that can cause timing skew between the three eyes below.

With such narrow eye openings, we have to expect ISI to close electrical PAM4 eyes. ISI is caused by the low-pass nature of the channel frequency response. Transmitter FFE (feed-forward equalization), which includes de-emphasis, is used to equalize PAM4 signals the same way that it has been used in PAM2-NRZ signaling.

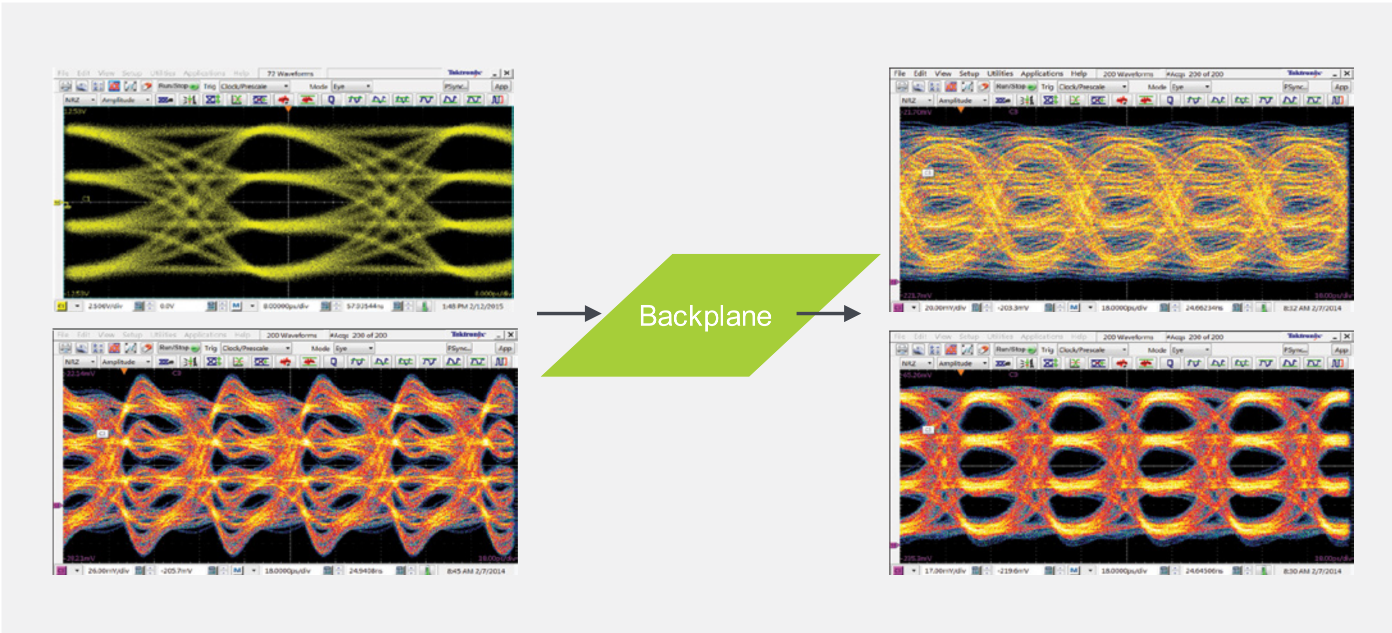

FIGURE 8. PAM4 eye diagrams prior to and after propagating through a backplane: top, without transmitter FFE and, bottom, with transmitter FFE.

Figure 8 shows the eye diagram of a signal with 2 "taps" of transmitter FFE. The voltage levels of symbols prior to transitions are boosted by a constant factor relative to the voltage levels of non-transition bits.

The de-emphasis concept is easily generalized to longer FFE filters. Symbol voltage levels are called "cursors" and their correction factors are constants called "taps." Cursors that precede the bit being transmitted, $C(n)$, are called pre-cursors, e.g., $C(n\text{-}1)$, and those that follow are called post cursors, e.g., $C(n+1)$. Each cursor is multiplied by a tap and taps are chosen so as to cancel the frequency response of the channel to as great an extent as possible.

The situation differs for optical signals. CD (chromatic dispersion) describes the wavelength-dependent response of optic fibers. Optical signals are centered at specific wavelengths, but their spectral shapes have nonzero width. CD causes each wavelength to travel at slightly different speeds, smearing symbols together and causing optical ISI. Optical systems use FFE at the receiver to compensate CD.

Electrical PAM2-NRZ receivers have done well with a combination of CTLE (continuous time linear equalization) and DFE (decision feedback equalization). Electrical PAM4 receivers are taking many different approaches to decoding PAM4 symbols. The standards specify the receiver's maximum allowed FLR and BER, but do not prescribe how they must meet those requirements. A wide variety of proprietary techniques are being developed and some may barely resemble the receiver designs familiar from PAM2-NRZ.

CTLE carries over to PAM4 receivers with greater flexibility. CTLE boosts the high frequency components of electrical waveforms to invert the gross low pass filter effects of the channel. The CTLE filters used for PAM2-NRZ systems consist of a single pole filter with gain that could be adjusted in 1 dB steps. PAM4 uses a two-pole filter adjustable in ½ dB steps, Figure 9.

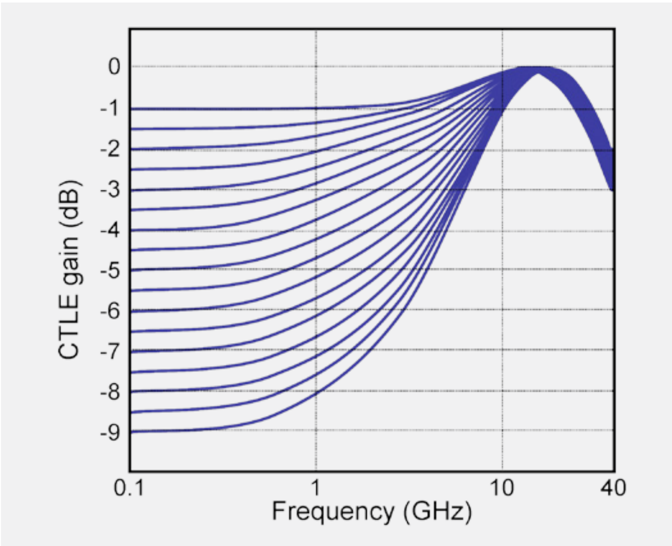

FIGURE 9. CTLE frequency response.

DFE was another innovation that enabled PAM2-NRZ. DFE uses the values of already decoded symbols to correct the incoming symbol. When one symbol error occurs, the DFE feedback can corrupt the signal and cause burst errors. RS-FEC(544, 514) can accommodate burst errors of 30 or more bits without a problem, but when there are too many errors, FEC fails. With a pre-FEC BER higher than 1E-6, FEC failure can be problematic. Many PAM4 electrical receiver designs are replacing DFE with receiver FFE.

At the receiver, FFE uses a shift register to multiply the analog voltage levels of symbols (cursers) by correction constants (taps). The combination of CTLE and FFE to open eye diagrams, followed by three voltage slicers timed by a CR circuit, demonstrates the evolution of receiver technology from PAM2-NRZ to PAM4, but the evolution might not be so gradual. Once ADC is introduced to receiver technology the price-power-performance equation shifts. DSP (digital signal processor) based receivers can combine the effects of CR, CTLE, FFE, and DFE into a single symbol decoding algorithm that can accommodate inter-eye timing skew and vertical eye compression.

2.5 PAM4 TEST PATTERNS

The five test patterns in Table 3 are used for compliance testing but also serve most diagnostic test needs. PRBS*n*Q (pseudo-random binary sequence *n* quaternary) patterns are derived from the corresponding binary PRBS*n* patterns. The quaternary version, PRBS*n*Q, is derived by Gray coding bits from repetitions of the binary PRBS*n* pattern into the LSB (least significant bit) and MSB (most significant bit) of PAM4 symbols. Just as a PRBS*n* pattern consists of 2^n-1 bits, the PRBS*n*Q consists of 2^n-1 PAM4 symbols.

PATTERN DESCRIPTION	LENGTH
Square wave: eight S3 + eight S0	16 symbols
PRBS31Q	over 2.1 billion symbols
PRBS13Q	8,191 symbols
Scrambled idle	
SSPRQ	65,535 symbols

TABLE 3. PAM4 test patterns.

The simplest of the test patterns, the square wave composed of alternating runs of eight consecutive S3 and S0 symbols is used in tests that concentrate on the power or voltage levels of the signal rails. PRBS13Q is used in most transmitter tests and to calibrate receiver tests while PRBS31Q is used to test receivers. Since PRBS13Q consists of just 8,191 symbols, it's short enough for several repetitions of the waveform to be captured by an oscilloscope. With many repetitions, exhaustive signal analysis can be performed: signal impairments that are correlated or uncorrelated to the pattern can be separated, random jitter and noise can be measured, periodic jitter and noise can be identified and distinguished from crosstalk, and so on. PRBS31Q, on the other hand, has over two billion symbols; while a single repetition can't be captured by an oscilloscope with even the deepest memory available, it provides a huge variety of symbol sequences that challenge the receiver's ability to recover and lock to a clock, equalize the signal, and decode symbols.

The fifth test pattern, SSPRQ (short stress pattern random quaternary), is composed of four sequences, each based on key "stressors" from PRBS31. It is a stressful pattern, and at 65,535 symbols, is short enough to allow for advanced analysis of jitter, noise, BER, and Equalization. SSPRQ is used for both transmitter and receiver testing.

Most transmitter tests should be performed with either the PRBS13Q or SSPRQ test pattern. Receiver tests should be set up and calibrated with PRBS13Q but performed with PRBS31Q.

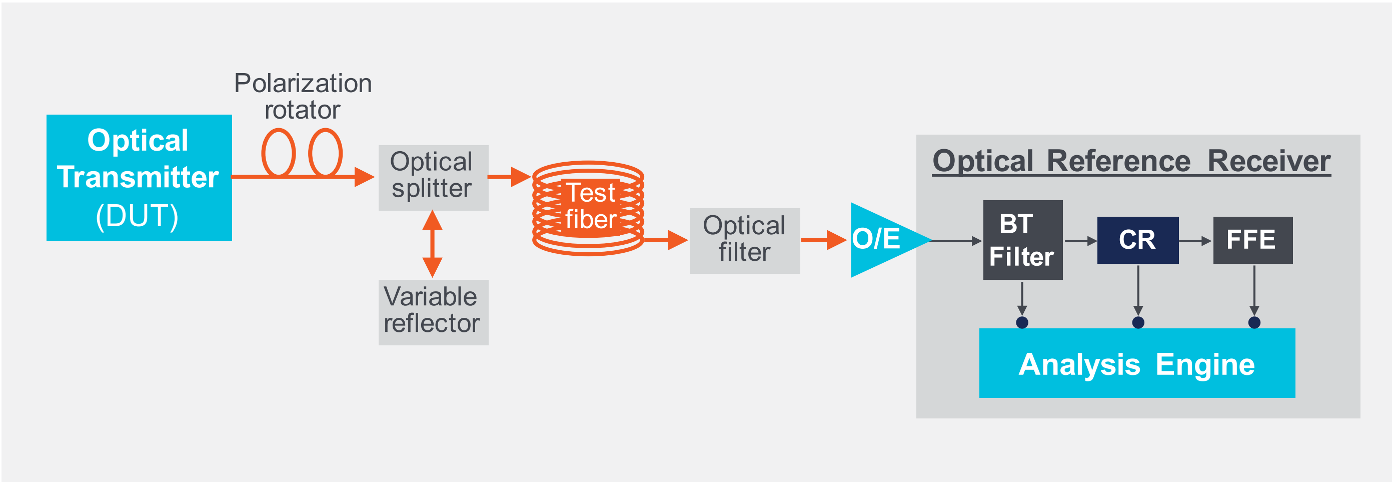

FIGURE 10. Optical transmitter test setup.

3. Evaluating Optical PAM4 Transmitters

In this section we cover techniques for evaluating optical transmitters. We use the compliance tests required by the standards as a guide but include additional measurements that can help diagnose signaling problems and help determine how a transmitter will perform in different systems.

Figure 10 shows a setup for testing optical PAM4 transmitters. An optical signal is transmitted through a fiber that generates CD and is received by an optical reference receiver. Both real-time and equivalent-time sampling oscilloscopes can perform the role of reference receiver and, of course, test instrument. The O/E (optical-to-electrical) convertor plays the key role of faithfully reproducing the optical power signal in a voltage waveform.

The capabilities and response of reference receivers are prescribed by each standard to meet minimally compliant performance requirements. The standards specify filters so that test instruments analyze optical signals with the same frequency response as actual receivers. For example, the reference receiver for 400 GbE optical signal testing includes a 4th Order Bessel Thomson Filter with -3 dB bandwidth at half the baud rate, a CR (clock recovery) circuit with a 4 MHz bandwidth and 20 dB/decade roll off, and a 5 tap FFE (feed-forward equalizer) with taps spaced by one symbol period.

Optical signals should be analyzed with test instrument bandwidth that can accommodate the frequency response of the reference receiver filter, usually slightly higher than the symbol rate.

Real-time oscilloscopes tend to be more flexible in the role of reference receiver than equivalent-time sampling oscilloscopes because the BT filter and CR can be implemented in software. Sampling scopes usually have lower noise for a given bandwidth and are less expensive.

PAM4 signaling requires new tests and adds complexity to tests established for PAM2-NRZ. For example, TDECQ (transmitter and dispersion eye closure quaternary) is a new test that encompasses many signal quality metrics—transmitter noise, attenuation, dispersion, and equalization—all centered around launch power.

Optical transmitters have different linearity problems than differential electrical transmitters. In some modulation implementations, transitions from low- to high-power states occur faster than high to low, which can cause inter-eye timing skew and eye compression. Many of the compliance tests for electrical signals can also help gauge the quality of optical signals: eye height, eye width, and especially the eye linearity tests, eye symmetry mask width, and level separation mismatch ratio.

QUANTITY	TYPICAL OPTICAL SIGNAL REQUIREMENTS			
Baud per lane	25.56 GBd			53.13 GBd
Reach, fiber	100 m, MM	500 m, SM	10 km, WDM	500 m, SM
Min avg launch power	≥ -6 dBm	≥ -5.1 dBm	≥ -2.8 dBm	≥ -2.9 dBm
Max avg launch power	≤ 4 dBm	≤ 3 dBm	≤ 5.3 dBm	≤ 4 dBm
Min OMAouter	≥ -4 dBm	≥ -3 dBm	≥ 0.2 dBm	≥ -0.8 dBm
Max OMAouter	≤ 3 dBm	≤ 2.8 dBm	≤ 5.7 dBm	≤ 4.2 dBm
ER	≥ 3 dB	≥ 3.5 dB	≥ 3.5 dB	≥ 3.5 dB
TDECQ	≤ 4.9 dB	≤ 3.4 dB	≤ 3.3 dB	≤ 3.4 dB

TABLE 4. Examples of PAM4 optical signal requirements for different rates, reaches, and fibers from 25-53 GBd.

Guided by our experience in the field and ongoing contributions to the standards, we quote examples of performance parameters in Table 4 that should assure adequate PAM4 transmitter performance in most applications. That said, prior to making any compliance test it is imperative that you double-check the specific interoperability standards that apply to the technology you're testing!

Compliance tests should be performed in a representative crosstalk environment with every lane enabled and transmitting. To prevent correlation between the test lane and crosstalk aggressors, every lane should either transmit a different pattern, transmit the same patterns but displaced by at least 31 UI (unit intervals) from each other, or operate at slightly different baud rates. All the transmitters should operate with the same equalizer settings.

3.1 OMAOUTER–OUTER OPTICAL MODULATION AMPLITUDE

The OMA (optical modulation amplitude) requirement assures a properly modulated signal and the ER (extinction ratio) requirement ensures that the signal isn't obscured by CW (constant wave) light power.

Power levels should be measured on either the PRBS13Q or SSPRQ test pattern. P3 is the power averaged over the center two unit intervals of a run of seven consecutive S3 symbols and P0 is averaged over the center two unit intervals of a run of six consecutive S0 symbols.

For WDM systems, either the signal under test must be isolated from the other signals by a suitable optical filter or the total optical power of all other signals must be less than -30 dBm.

The PAM4 version of the OMA measurements are essentially the same as their NRZ counterparts. The PAM4 compliance version of OMA is called OMAouter; it's built from the power levels of just the "outer" eye diagram: the difference between the average S3 and S0 levels of the PAM4 signal:

$$\text{OMAouter} = P3 - P0. \quad (1)$$

By comparing the OMAs of the three inner eyes,

$$\text{OMAlow} = P1 - P0,$$

$$\text{OMAmid} = P2 - P1, \text{ and}$$

$$\text{OMAupp} = P3 - P2$$

you can get a quantitative handle on the transmitter's eye compression.

3.2 ER–EXTINCTION RATIO

The ER (extinction ratio) measurements should be performed the same way as the OMA measurements. The PAM4 version of the ER measurement is essentially the same as its NRZ counterpart but performed on only the outer eye diagram. The extinction ratio is the ratio of the average S3 power to the average S0 power:

$$\mathrm{ER} = 10\log\frac{P3}{P0}. \tag{2}$$

3.3 TDECQ–TRANSMITTER AND DISPERSION EYE CLOSURE QUATERNARY

The most complicated compliance test for optical transmitters is TDECQ, but it is also a fully automated oscilloscope measurement.

TDECQ replaces the mask tests and TDP (transmitter dispersion penalty) measurements required of PAM2-NRZ optical transmitters. Using the setup shown in Figure 10, the SSPRQ test pattern is transmitted and at least one complete waveform is acquired by an oscilloscope that doubles as reference receiver.

Each lane is tested separately but with all other lanes operating. The optical splitter and variable reflector should be tuned so that the test signal experiences the specified level of return loss. The polarization rotator should be set to generate maximum RIN (relative intensity noise). The optical filter should isolate the test signal from any others on the fiber by at least 20 dB.

The transmitter being tested has its own jitter, noise, crosstalk, nonlinearities, etc, and is measured on a device with a noise floor, σS. The long spool of optical fiber further degrades the test signal with a level of chromatic dispersion specified by the standard. An example of the TDEQ fiber specifications is given in Table 5. The reference receiver frequency response includes both the 5-tap receiver FFE and the fourth order Bessel Thomson filter with -3 dB bandwidth at half the baud rate.

TDECQ is a measure of the additional signal power necessary for the test signal to achieve the SER of an ideal signal. An equivalent way to say this is that TDECQ is a measure of the power depleted by the imperfections of the test signal combined with CD from the test fiber after reference receiver FFE.

TRANSMITTER COMPLIANCE FIBER REQUIREMENTS		
Applications	Dispersion (ps/nm)	
	Minimum	Maximum
2 km, WDM 4•26.56 and 8•26.56 GBd	0.0465 λ [1 - $(1324/\lambda)^4$]	0.0465 λ [1 - $(1300/\lambda)^4$]
10 km, WDM 4•26.56 and 8•26.56 GBd	0.2325 λ [1 - $(1324/\lambda)^4$]	0.2325 λ [1 - $(1300/\lambda)^4$]

TABLE 5. Sample transmitter compliance fiber requirements.

TDECQ compares the test signal with a simulated ideal signal. The ideal and test signals are related by the requirement that they both have the same value of OMAouter.

Simulated Gaussian noise, σ_{Ideal}, is added to the ideal signal waveform until its SER matches the specified target SER, 4.8E-4 (notice that the target SER is twice the maximum allowed pre-FEC BER). Since the ideal signal starts with no noise or jitter of any kind and the added noise is purely Gaussian, σ_{Ideal} can be calculated directly,

$$\sigma_{Ideal} = \frac{OMAouter}{6Q_t}, \tag{3}$$

where Q_t = 3.414, the Q-scale value for SER = 4.8E-4.

Similarly, simulated Gaussian noise, σ_G, is added to the measured waveform until its SER also matches the target SER. TDECQ is the ratio of the noise that must be added to the ideal signal to the noise that must be added to the real signal, keeping in mind that the noise on the measured signal also includes the oscilloscope noise floor, σ_S:

$$\text{TDECQ} = 10\log_{10}\frac{\sigma_{Ideal}}{R} \tag{4}$$

where

$$R = \sqrt{\sigma_G^2 + \sigma_S^2}\,. \tag{5}$$

Determining TDECQ is an iterative numerical minimization process that involves trying different levels of added noise, σ_G.

Tektronix uses the technique recommended in the 802.3bs specification: A set of histograms is used to calculate the SER of the signal. To build the histograms, the average power and timing of both crossing points are determined from an eye diagram as in Figure 11. Nominal slicer thresholds are determined from the average power and OMAouter with 1% adaptive optimization allowed. Two vertical histograms with width 0.04 UI, separated by 0.1 UI, and positioned for optimum TDECQ are measured from the eye diagram.

The SER of the lower, middle, and upper eyes is calculated separately from the left and right histograms to get: SER-L-low, SER-L-mid, SER-L-upp and SER-R-low, SER-R-mid, SER-R-upp. Two values of the PAM4 SER are then derived: SER-L is the sum of the SERs contributed by the three eyes from the left histogram and SER-R is the sum of the SERs from the right histogram. The net PAM4 SER is the larger of SER-L and SER-R.

The crucial steps, where i is the number of iterations:

1. Add Gaussian noise, σ_{Gi}.
2. Impose the effect of the fourth order Bessel Thomson filter on the added noise.
3. Optimize the receiver FFE taps to minimize SER subject to the constraint that the sum of the taps is 1.
4. Calculate SER from the two histograms:

   If SER > 4.8E-4, decrease the Gaussian noise to get σ_{Gi+1} and return to step 2.

   If SER < 4.8E-4, increase the Gaussian noise to get σ_{Gi+1} and return to step 2.
5. When SER ~ 4.8E-4, use the resulting value of σ_{Gi} in Eq. (5) and calculate TDECQ, Eq. (4).

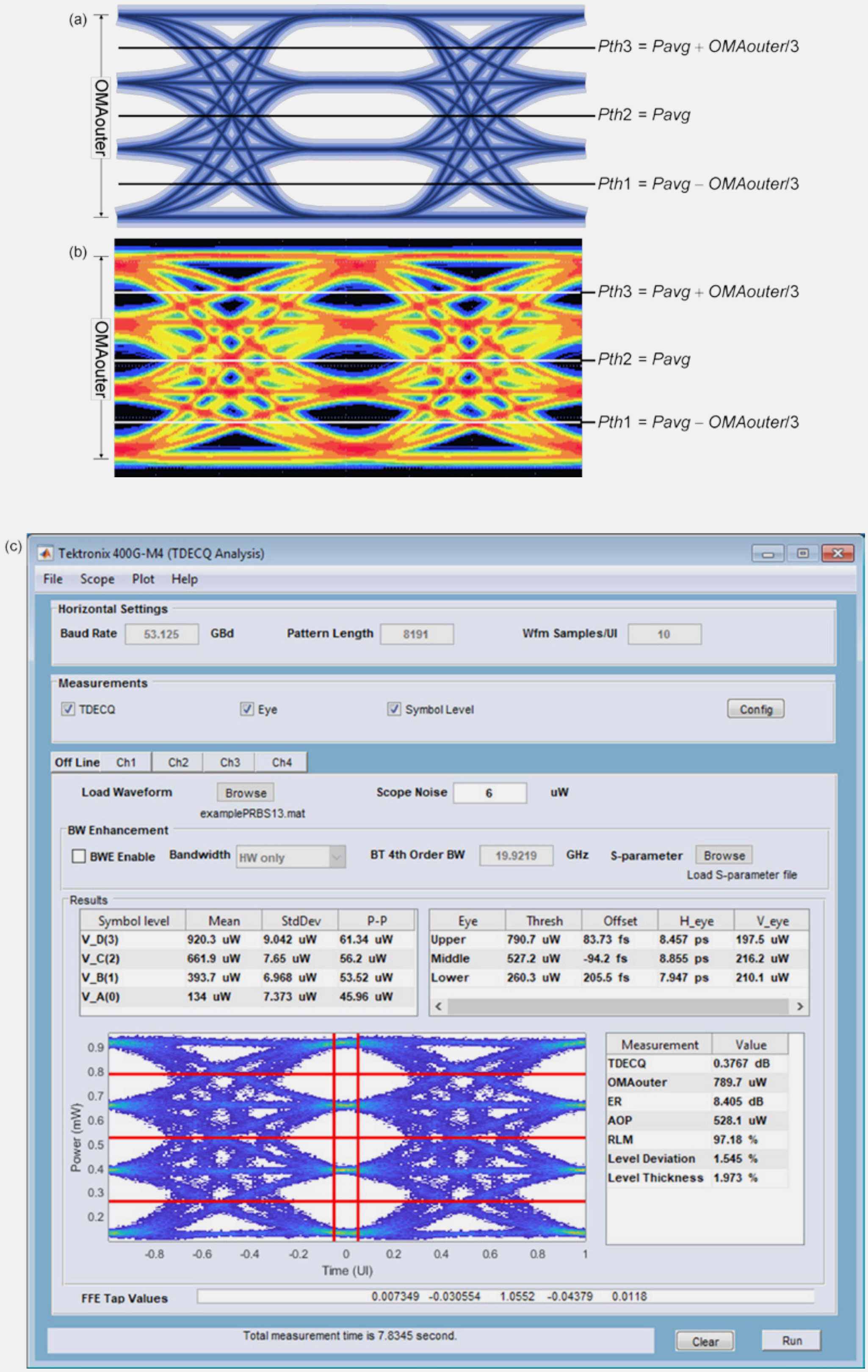

FIGURE 11. TDECQ Measurement, (a) the ideal signal with applied Gaussian noise and (b) a test signal with the same OMAouter as the ideal but also with jitter, noise, crosstalk, chromatic dispersion, etc., (c) the TDECQ Analysis display.

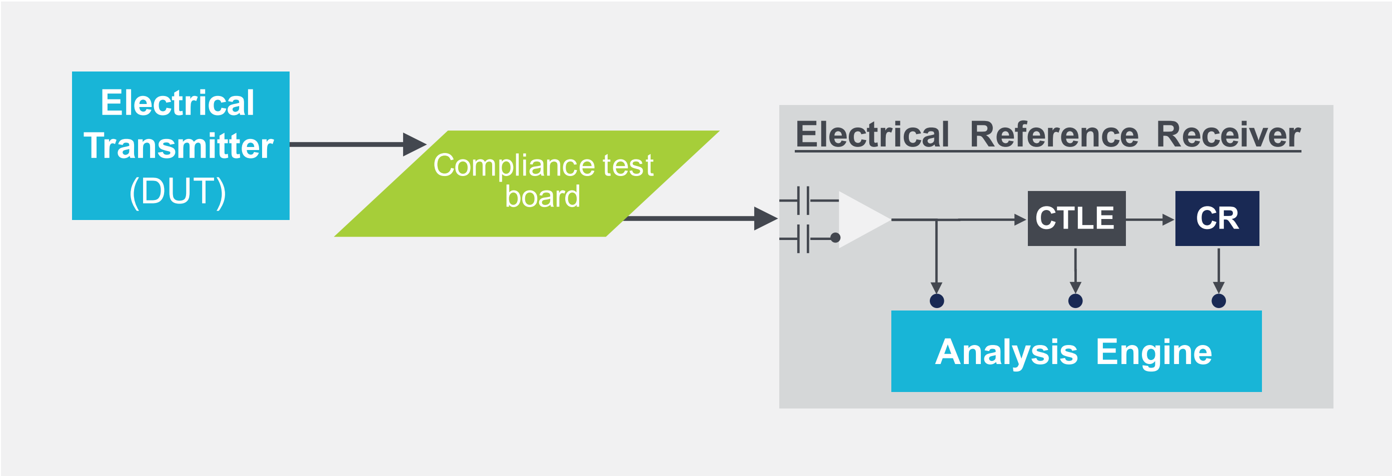

FIGURE 12. Electrical transmitter test setup.

4. Evaluating Electrical PAM4 Transmitters

Figure 12 shows a test setup for electrical transmitter testing. An electrical signal is transmitted through a compliance test board that challenges transmitter equalization by introducing loss and ISI (inter-symbol interference). Cabling, connectors, and/or probes are usually required to deliver the electrical signal to the oscilloscope. If you provide the relevant *S*-parameters, the oscilloscope can embed the desired effects of the compliance test board and/or de-embed the undesired effects of the cables. The electrical reference receivers are specified by each standard. Most PAM4 reference receivers include an AC coupled front end, a CR circuit, and CTLE with response and gain given in Figure 9.

Electrical signals should be analyzed with test instrument bandwidth that can accommodate the frequency response of the reference receiver filter, usually slightly higher than the symbol rate.

Table 6 provides examples of performance requirements. The range of values indicates the variation in performance requirements for different electrical subsystems, Figure 2: chip to chip, chip to optical module, and module to chip on across circuits and backplanes including connectors. Prior to making any compliance test it is imperative that you double-check the specific interoperability standards.

Again, compliance tests should be performed in a representative crosstalk environment with every lane enabled and transmitting uncorrelated signals.

EXAMPLES OF SIGNAL REQUIREMENTS FOR 18-29 GBD PAM4 ELECTRICAL SIGNALS			
Reach	**50 mm**	**500 mm**	**1 m**
Differential VPP	≤ 900 mV	≤ 1200 mV	≤ 1200 mV
Jitter:			
J_{RMS}		≤ 0.023 UI rms	≤ 0.023 UI rms
J4u		≤ 0.118 UI	≤ 0.118 UI
EOJ	≤ 0.019 UI	≤ 0.019 UI pp	≤ 0.019 UI pp
UBHPJ	≤ 0.05 UI		
UUGJ	≤ 0.01 UI rms		
Near end EW6	≥ 0.265 UI		
Near end EH6	≥ 70 mV		
Far end EW6	≥ 0.2 UI		
Far end EH6	≥ 32 mV		
Steady state voltage, V_f		$0.4 \leq V_f \leq 0.6$	$0.4 \leq V_f \leq 0.6$
Linear fit pulse peak		$\geq 0.83 \cdot V_f$	$\geq 0.83 \cdot V_f$
SNDR	≥ 31 dB	≥ 31 dB	≥ 31 dB
Near end eye linearity	≥ 0.85		
RLM		≥ 0.95	≥ 0.95

TABLE 6. Examples of electrical signal requirements for 18-29 GBd PAM4.

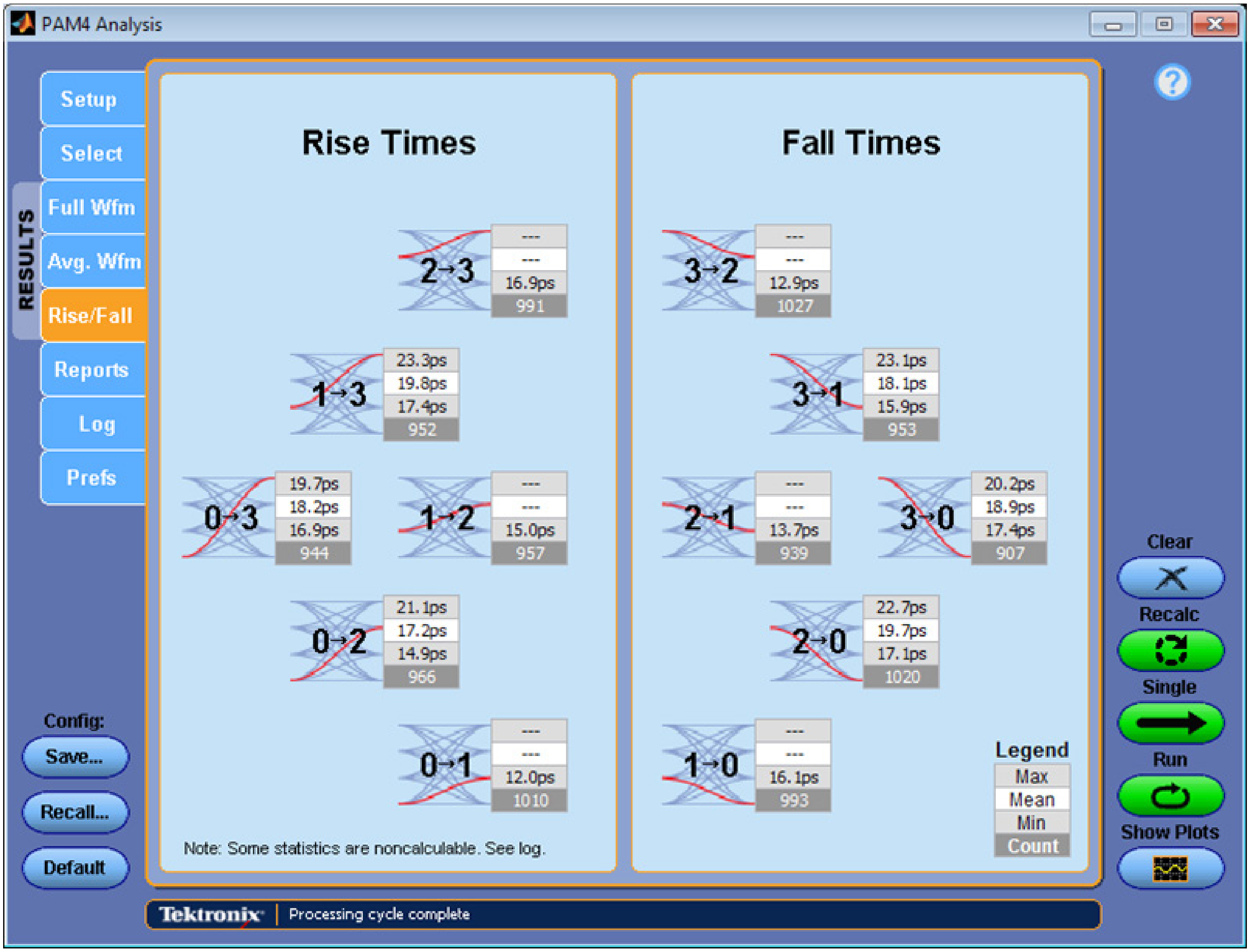

FIGURE 13. PAM4 analysis display of rise and fall time measurements.

4.1 TRANSITION TIME

First generation PAM4 technologies have reference receivers whose symbol decoders sample all three eyes at a common time-delay, t_{center}, usually defined at the midpoint of the middle eye. Inter-eye timing skew misaligns the centers of the three PAM4 eye diagrams. More advanced PAM4 receivers will use symbol decoders with independent slicers for each eye, but the tolerable amount of skew will always be limited.

Variation of the 12 rise and fall times, Figure 13, indicates inter-eye timing skew. For the three eyes to align, the rise/fall times for transitions like 0-1, 0-2, 0-3 should be nearly the same, but the slew rates for these transitions should follow the ratio 1:2:3.

Transition times are required to be longer than specified minimum values to reduce high frequency content that can aggravate crosstalk. Depending on the application and whether the signal has traversed appreciable lengths of PCB, minimum allowed values for $t_{rise/fall}$ fall in the range 7.5-12 ps for 18-29 GBd signals.

4.2 JITTER

Jitter is the variation of the timing of symbol transitions with respect to edges of the recovered data-rate clock. Eye width measures the eye opening defined at an SER in the same way that TJ (total jitter) measures eye closure; its measurement is discussed below in Section 4.3. The PAM4 standards generalize jitter analysis from simple RJ (random jitter) and DJ (deterministic jitter) to the more precisely defined quantities described in this section.

Jitter is measured in units of time, e.g., ps or UI.

4.2.1 J_{RMS}, J4u, and J3u

Three types of ISI-independent jitter are specified for electrical PAM4 signals: J4u, JRMS, and EOJ.

Jitter is measured independently of ISI by analyzing jitter at 12 specific transitions within the PRBS13Q test pattern. The 12 transitions consist of a single occurrence of each of the 12 transition possibilities: 0→1, 0→2, 0→3, 1→0, 1→2, 1→3, 2→0, 2→1, 2→3, 3→0, 3→1, and 3→2. ISI for each transition is reduced by choosing transitions surrounded by long runs of consecutive identical symbols.

The non-ISI jitter distribution is built by accumulating the deviations in the timing of transitions from their averages. For example, a jitter sample from the 0→1 transition is given by the deviation $dt(0\text{-}1)_i = t(0\text{-}1)_i - t(0\text{-}1)_{avg}$ where $t(0\text{-}1)_i$ is the time-delay of the i^{th} 0-1 transition and $t(0\text{-}1)_{avg}$ is the average time-delay that 0-1 transition measured with respect to the recovered clock specified for the reference receiver.

For a sufficient number of $\{dt(n\text{-}m)_i\}$ samples, the combined set is a measure of the jitter probability density function.

Since the tails of the jitter distribution are unbounded, peak-to-peak jitter is ill-defined. J4u resembles a peak-to-peak measurement but gets around the problem of unbounded tails by truncating the distribution. J4u is the time interval that includes the center 99.99% of the jitter distribution, $\{dt(n\text{-}m)_i\}$, from 0.005% to 99.995%. It's called J4u because it includes all but 1E-4 of the distribution.

J_{RMS} is the standard deviation of the distribution, Figure 14.

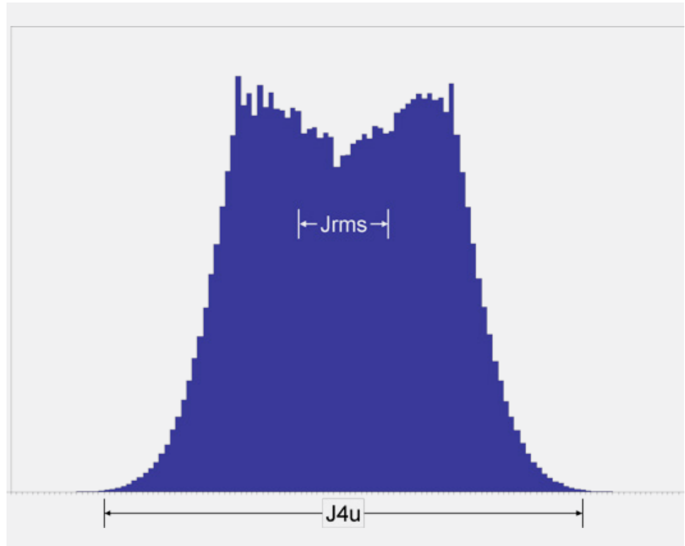

FIGURE 14. A crossing point histogram example of J4u and J_{RMS}.

Some standards specify J3u for PAM4 transmission across cables instead of J4u. J3u is the time interval that includes all but 1E-3 of the distribution, from 0.05 to 99.95%

4.2.2 EOJ—even-odd jitter

EOJ (even-odd jitter) is the difference between the average deviations of even-numbered and odd-numbered transitions. It is a type of DCD (duty-cycle distortion).

Separate values of EOJ are measured for each of the 12 symbol transitions. PAM4 EOJ is the largest of the 12.

As above, in Section 4.2.1, 12 representative symbol transitions are chosen within the PRBS13Q test pattern. ISI is reduced by choosing transitions surrounded by long runs of consecutive identical symbols.

The following procedure is repeated for each of the 12 symbol transitions:

The oscilloscope triggers once on three consecutive repetitions of the PRBS13Q test pattern. The average time of the transition in the first repetition is called T3 and the average time for the same transition in the second repetition of the pattern is T4. The period of the pattern timed from that transition is the difference, T4 – T3.

In the next step, the oscilloscope triggers once on two consecutive repetitions of PRBS13Q. T1 is the time of the transition in the first repetition and T2 is the time of that transition in the second repetition. EOJ is the difference in the period of the symbol transition in an even number of pattern repetitions and an odd number of repetitions:

$$\mathrm{EOJ}_i = |\ (\mathrm{T2}_i - \mathrm{T1}_i) - (\mathrm{T4}_i - \mathrm{T3}_i)\ |, \tag{6}$$

where the subscript indicates each of the 12 transitions. EOJ for the PAM4 signal is

$$\mathrm{PAM4\ EOJ} = \max\ \{\mathrm{EOJ}_i,\ I = 1,\ \ldots,\ 12\} \tag{7}$$

The 18–29 GBd PAM4 standards require EOJ less than about 0.02 UI.

Since EOJ is a small difference between two large numbers, after all T2–T1 and T4–T3 are both about 8,191 UI and their difference should be less than 0.02 UI, the required measurement precision has to be better than 0.02/8191 ~ one part in a million.

4.2.3 UBHPJ—uncorrelated, bounded, high probability jitter

UBHPJ (uncorrelated, bounded, high probability jitter) consists of variations in symbol transitions that are both deterministic and uncorrelated to the data. It excludes ISI but includes EOJ and uncorrelated sources of jitter like PJ (periodic jitter), SJ (sinusoidal jitter), and the jitter effects of crosstalk.

UBHPJ is measured on each of the three PAM4 eye diagrams. Some standards require that the largest of the three be less than a specified number, about 0.05 UI for 18–29 GBd signals.

4.2.4 UUGJ—uncorrelated, unbounded, Gaussian jitter

UUGJ (uncorrelated, unbounded, Gaussian jitter) is for all practical purposes the same quantity that has been referred to as RJ (random jitter). UUGJ follows an unbounded Gaussian distribution that does not depend on the specific symbol sequence.

The RMS values of UUGJ are measured on each of the three PAM4 eye diagrams. Some standards require that the largest of the three be less than about 0.01 UI RMS for 18–29 GBd signals.

4.3 EH AND EW–EYE HEIGHT AND EYE WIDTH

Eye height and eye width are the post-equalization eye openings measured with respect to BER along the vertical and horizontal axes. For example, EH6 is the vertical distance across the SER=1E-6 contour, the “height” of the eye opening at SER=1E-6. Similarly, EW6 is the horizontal distance across the SER=1E-6 contour. EH and EW are measured separately for each of the three eyes, the PAM4 EH is the smallest of the three EH measurements and PAM4 EW is the smallest of the three EW measurements.

Different standards define EH and EW with respect to different SERs, usually either 1E-5 (EH5 and EW5) or 1E-6 (EH6 and EW6). In our discussion, we’ll use SER=1E-6.

Standards often have both near and far end requirements on EH and EW. Near end measurements are made close to the output of the transceiver package prior to the test compliance board and far end measurements are made after the signal has propagated through the compliance test board or its equivalent.

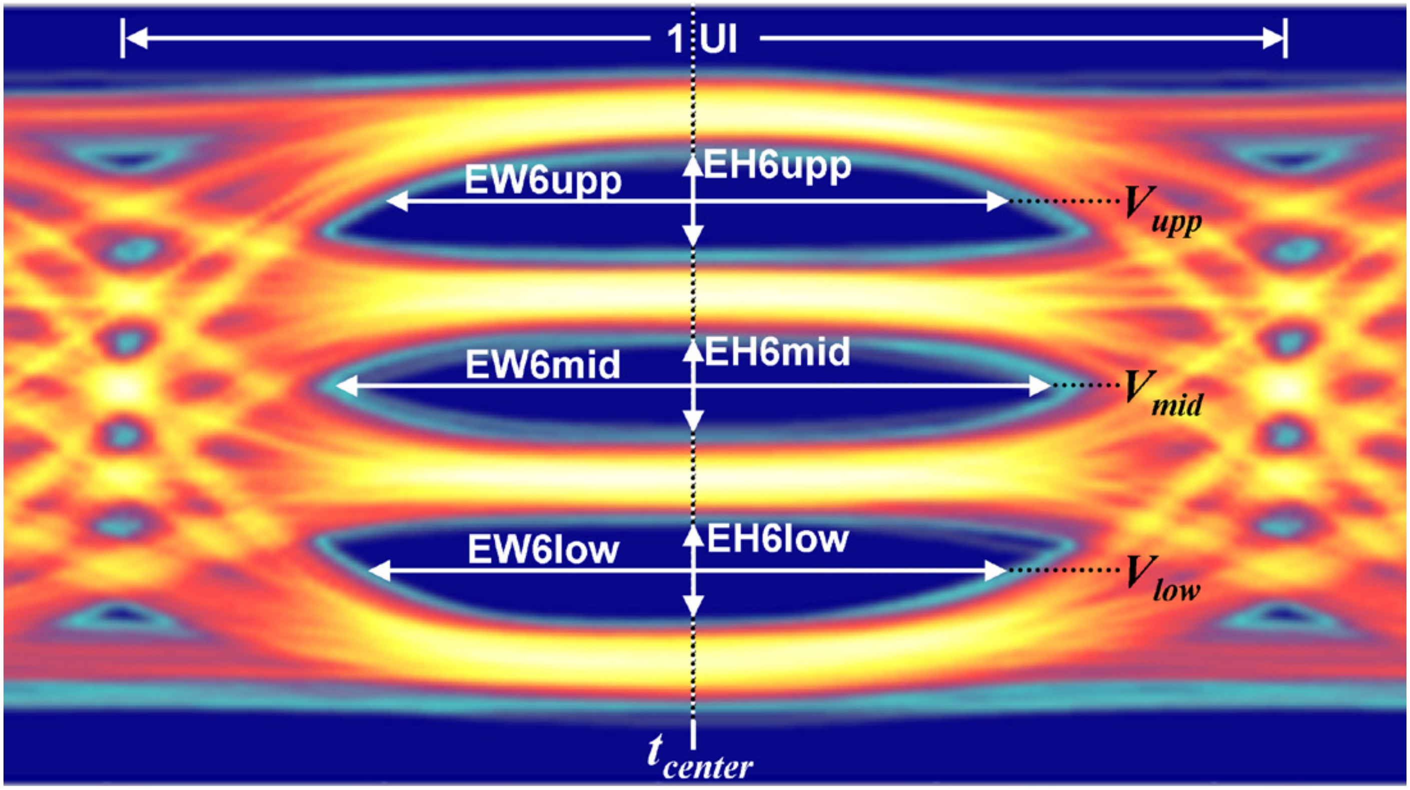

FIGURE 15. Measurement of EH6 and EW6 for each eye from the BER = 10^{-6} contours, definition of eye center and nominal slice thresholds, V_{low}, V_{mid}, and V_{upp}.

Far end measurements put transmitters in systems with lossy, ISI-inducing channels and crosstalk. EH and EW are measured on all three PAM4 eyes after they've been opened by the optimized test transmitter FFE and the reference receiver CTLE in Figure 12.

The frequency response of the compliance test board in Figure 12, is specified by the standard in terms of the insertion loss S-parameters, S_{DD12}. The required insertion loss response can be achieved with either compliance test boards or by providing the oscilloscope the desired S-parameters so that it can embed the response.

EH and EW are measured with a PRBS13Q test pattern and all potential crosstalk sources transmitting signals that are uncorrelated to the test signal. Some standards require that the CTLE gain be optimized for maximum eye openings and some require a specific value for the gain.

The center of the PAM4 eye, t_{center}, is defined as the center of the longest line that reaches across the SER = 1E-6 contour of the middle eye, Figure 15. The vertical eye openings for each eye, EH6low, EH6mid, and EH6upp, are all measured at t_{center}. The vertical eye centers V_{low}, V_{mid}, and V_{upp}, are given by the midpoints of EH6low, EH6mid, and EH6upp.

The three nominal eye centers are therefore given by (t_{center}, V_{low}), (t_{center}, V_{mid}), and (t_{center}, V_{upp}).

By defining the same t_{center} for each eye, the standards make assumptions about receiver symbol decoder design. First generation PAM4 receivers use synchronized slicers with equally distributed voltage thresholds. Later generations will implement symbol decoders that better accommodate variation among the centers of the eyes.

Since the system BER is limited by the smallest eye opening, the weakest link in the chain, the standards specify minimum acceptable values for the smallest of the three eye widths and heights:

$$\begin{aligned} &EW6 = \min(EW6low, EW6mid, EW6upp) \text{ and} \\ &EH6 = \min(EH6low, EH6mid, EH6upp). \end{aligned} \quad (8)$$

After reference receiver equalization, satisfactory transmitters should have far end EW6 ≥ 0.2 UI and EH6 ≥ 30 mV for 18–29 GBd signals.

4.4 STEADY-STATE VOLTAGE AND LINEAR FIT PULSE PEAK

Steady-state voltage and linear fit pulse peak are measured at the transmitter output and account for transmitted signal impairments independent of insertion loss and ISI (inter-symbol interference).

A linear fit to the transmitter waveform in the absence of transmitter FFE or with FFE taps at their preset default values is used to derive the steady state voltage, v_f, and the peak of the pulse response, p_{max}.

The fit is performed on the acquisition of at least one repetition of the PRBS13Q waveform. The captured waveform is given by $y(k)$ where k is the total number of waveform samples. That is, if each UI is sampled M times, then k runs from 1 to the product of M and the length of the test pattern, N. The ideal PRBS13Q symbol levels are given by $x(n)$. The pulse response, $p(k)$, is extracted from the measured waveform, given the ideal symbol levels that it represents.

The pulse response is the waveform of an isolated symbol. In the language of PAM2-NRZ, the pulse response is also called the single bit response. For PAM4, the pulse response corresponds to a single S3 symbol isolated by long runs of consecutive S0 symbols that precede and follow it. Just as a waveform can be calculated by convolving the pulse response with the test pattern the pulse response, $p(k)$, can be extracted from the measured waveform, $y(k)$, and ideal symbols, $x(n)$. The fitted waveform, $f(k)$, is the convolution of the calculated pulse response and ideal symbols.

The steady state voltage is the sum of the pulse response divided by the number of samples per symbol:

$$v_f = \sum_{k=1}^{MN} \frac{p(k)}{M}. \quad (9)$$

The linear fit pulse peak is the maximum value of the pulse response,

$$p_{max} = \max\{p(k), k = 1, \ldots, MN\}. \quad (10)$$

The number of symbols included in calculating v_f and p_{max}, varies with standard. It's usually much shorter than the full pattern length because the fitted pulse response damps out to zero in a few dozen UI.

At 18-29 GBd, the standards restrict the steady state voltage, vf, to a range of voltages, 0.4 ≤ vf ≤ 0.6 V and the linear fit pulse peak to a minimum fraction of the steady state value, $p_{max} \geq 0.76 \cdot v_f$.

4.5 SNDR–SIGNAL-TO-NOISE AND DISTORTION RATIO

Signal-to-noise-and-distortion ratio (SNDR) compares electrical signal strength to the combination of random noise and harmonic distortion.

Like steady state-voltage and linear fit pulse peak, SNDR is measured at the transmitter output and accounts for transmitter noise and distortion but is independent of insertion loss and ISI.

SNDR is derived from the linear fit to the transmitter pulse response. The fit error is $e(k) = f(k) - y(k)$, the deviation of the fit and the measurement. It indicates the variation of the test signal from the ideal symbols. The signal distortion, σ_e, is given by the root mean square of the fit error, $e(k)$:

$$\sigma_e = \sqrt{\sum_k e(k)^2}.$$

The signal noise is measured at each of the four symbol levels on low slope runs of at least six consecutive PAM4 signals. The average of the four measurements gives σ_n.

SNDR is

$$SNDR = 20\log\sqrt{\frac{p_{\max}^2}{\sigma_e^2 + \sigma_n^2}} \quad (6)$$

For 18–29 GBd signals SNDR must be larger than 31 dB.

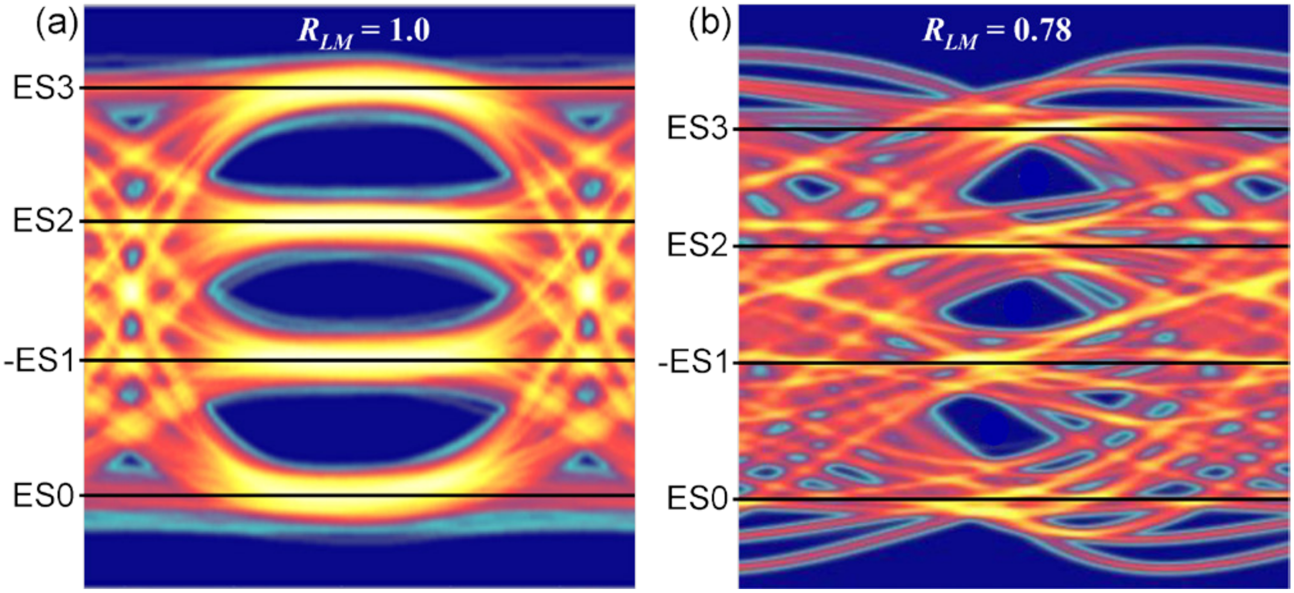

FIGURE 16. Equivalent symbol levels for (a) a good eye with R_{LM} = 1 and (b) an imperfect eye with R_{LM} =0.78.

4.6 PAM4 LINEARITY TESTS

We've already seen that the relative dimensions and orientations of PAM4's three eyes present challenges with inter-eye timing skew and eye compression. In this section, we look at ways to quantify variations in the centers, levels, heights, and widths of each eye. An obvious transmitter design goal is to assure that each eye contributes equally to the SER.

4.6.1 R_{LM}—level separation mismatch ratio

The level separation mismatch ratio indicates the vertical linearity of the signal. It measures amplitude compression in a parameter, R_{LM}, that runs from zero to one; R_{LM} = 1 indicates that the three eyes are equally spaced and R_{LM} = 0 indicates that at least one of the three eyes has collapsed.

R_{LM} compares the vertical variation of the symbol levels to an equal distribution. The symbol levels are the mean levels V0, V1, V2, and V3. The midrange voltage is

$$Vmid = \tfrac{1}{2}(\mathrm{V0} + \mathrm{V3}),$$

and the mean symbol voltages are mapped into normalized effective symbols, Figure 16: $V0 \rightarrow ES0$ = -1 and $V3 \rightarrow ES3$ = +1 with $ES1$ and $ES2$ given by

$$ES1 = \frac{V1 - Vmid}{V0 - Vmid} \text{ and } ES2 = \frac{V2 - Vmid}{V3 - Vmid}.$$

The level separation mismatch ratio is

$$R_{LM} = \min[3{\cdot}\mathrm{ES1},\ 3{\cdot}\mathrm{ES2},\ (2 - 3{\cdot}\mathrm{ES1}),\ (2 - 3{\cdot}\mathrm{ES2})].$$

A signal that is linear in voltage would have equally spaced symbol levels: (-1, -1/3, +1/3, +1) = ($ES0$, -$ES1$, $ES2$, $ES3$) and R_{LM} = 1.0. At 18–29 GBd R_{LM} should be larger than 0.95.

4.6.2 VEC—vertical eye closure and eye linearity

Eye linearity is a measure of vertical linearity that is similar to level separation mismatch ratio, R_{LM}. Rather than compare settled inter-symbol voltage levels to the settled peak-to-peak PAM4 voltage swing, eye linearity measures the ratio of the largest to smallest mean voltage swing between symbols with active data patterns.

For the eye linearity and VEC (vertical eye closure) tests, the mean symbol levels are given by the average values of the four histograms formed by projecting the vertical data as shown in Figure 17. Depending on the transmitter FFE tap values, the mean symbol levels are likely to differ from the settled values used to measure R_{LM}, but the average inter-symbol voltage swings should be nearly the same.

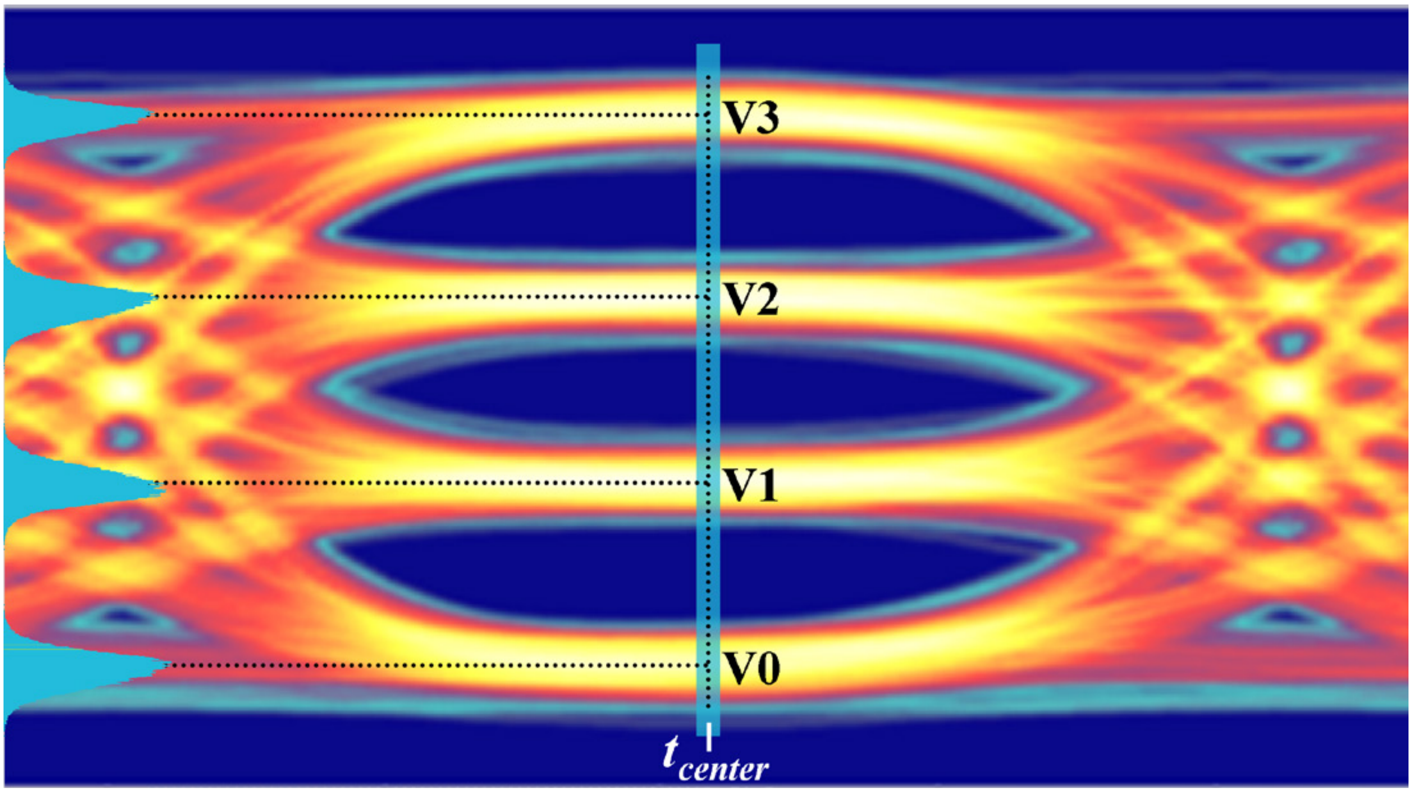

FIGURE 17. Measuring symbol levels with histograms.

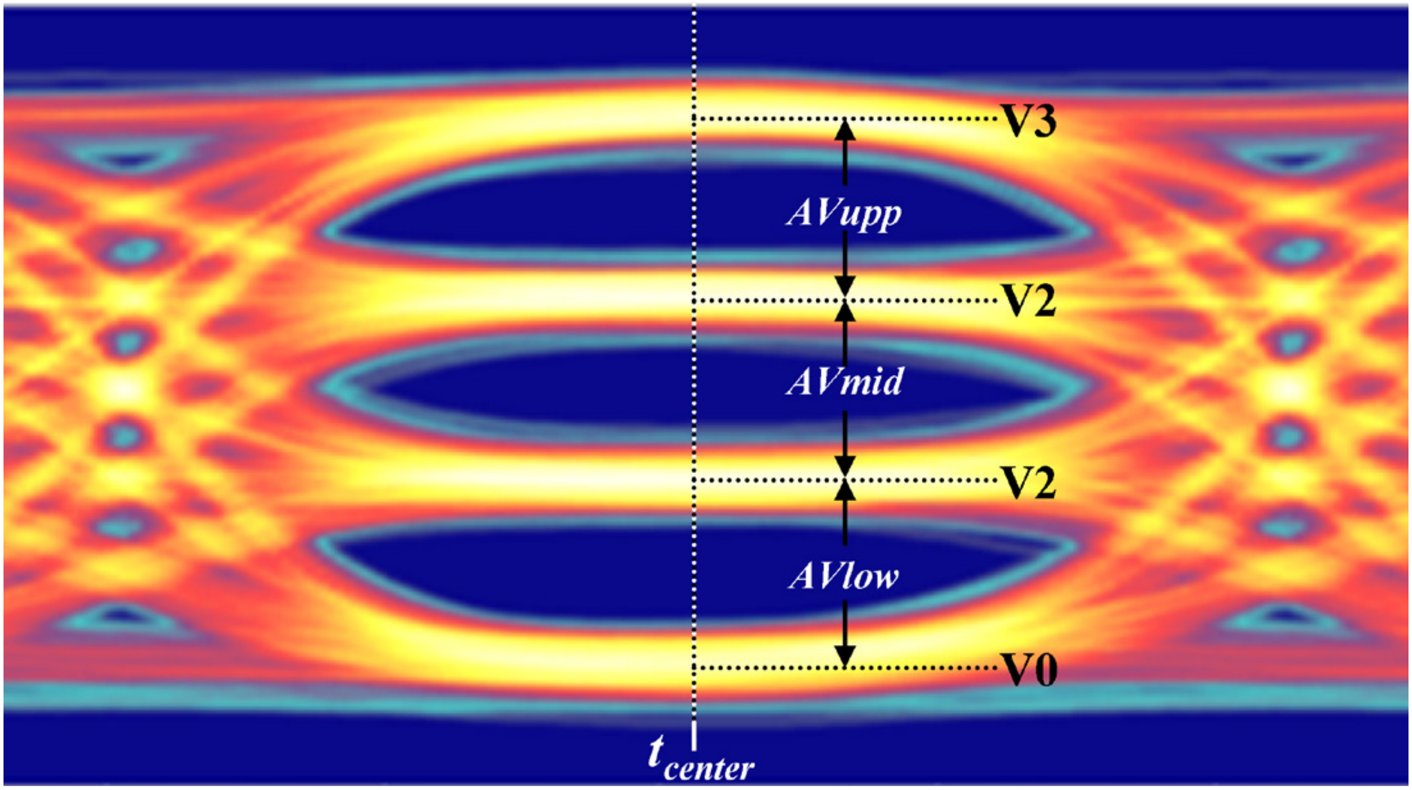

FIGURE 18. Using a horizontal mask to determine the symbol levels and their separations.

The separations of the symbol levels are given by $AVlow$ = V1 – V0, $AVmid$ = V2 – V1, and $AVupp$ = V3 – V2. Eye linearity is the ratio of the largest to smallest voltage separations of adjacent symbols:

$$\text{Eye linearity} = \frac{\min(AVlow, AVmid, AVupp)}{\max(AVlow, AVmid, AVupp)}$$

and vertical eye closure is the smallest of the ratios of voltage swing to eye height, given in dB by:

$$\text{VEC} = 20\log\left(\min\left(\frac{AVlow}{\text{EH6low}}, \frac{AVmid}{\text{EH6mid}}, \frac{AVupp}{\text{EH6upp}}\right)\right).$$

Some 18–29 GBd standards require near end eye linearity larger than 0.85. As this is written, the standards have no requirements on VEC, but a reasonable maximum would be about 6 dB.

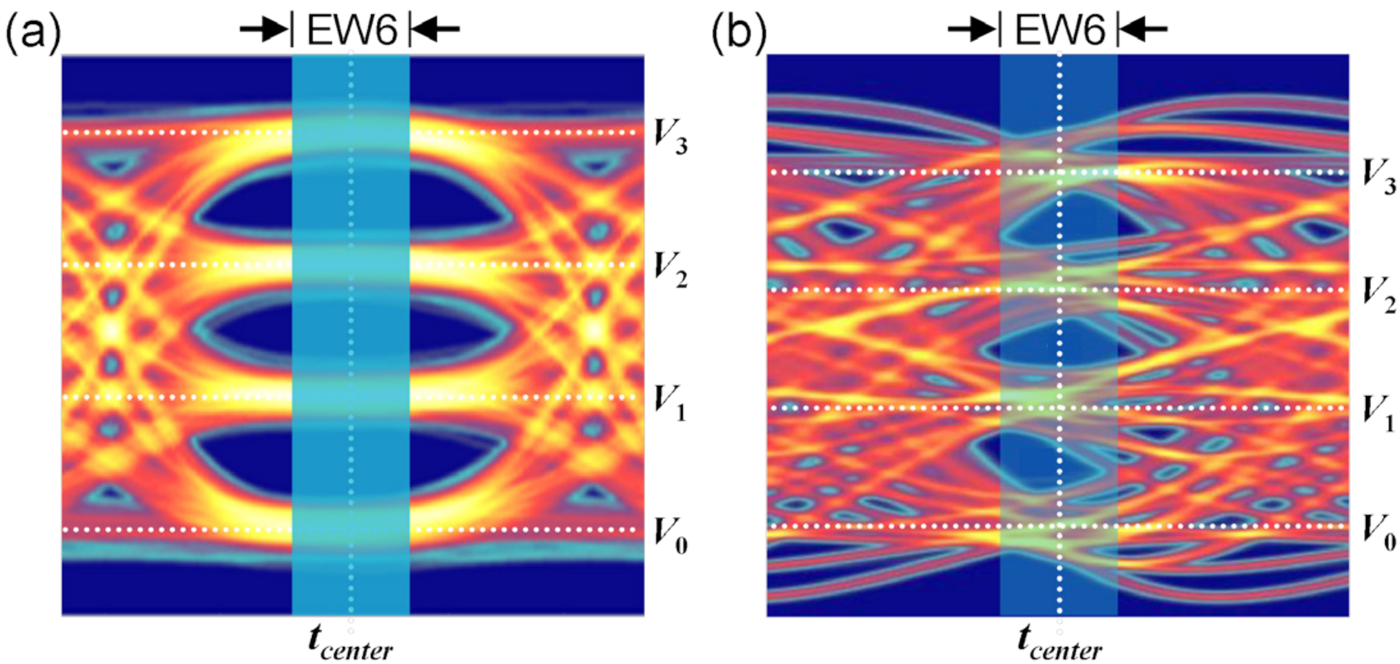

FIGURE 19. The Eye symmetry mask width test: (a) passes because the mask does not extend horizontally beyond the SER=1E-6 contours of any of the eyes, (b) fails because the mask extends horizontally beyond the lower and upper SER=1E-6 contours.

4.6.3 ESMW—eye symmetry mask width

The ESMW (eye symmetry mask width) test is unlike mask tests performed on PAM2-NRZ eye diagrams. The ESMW mask, Figure 17, is a vertical stripe with width defined by the standard centered on the midpoint of the middle eye, t_{center}. The width of the mask is usually identified with the minimum allowed EW value. A signal passes if the horizontal eye openings of all three eyes extend at least to the mask.

The ESMW test is especially effective with signals whose three PAM4 eye diagrams aren't aligned vertically. All three eyes can be wide open and have ideal level separation mismatch ratio, R_{LM} = 1, but if they aren't aligned in time, a compliant receiver that samples all three eyes simultaneously won't be able to achieve the minimum required SER. Figure 17b shows a PAM4 signal with inter-eye timing skew that fails the mask test.

5. Introduction to PAM4 Receiver Tolerance Tests

The ultimate measure of a receiver's performance is its BER performance in the worst possible conditions.

Both electrical and optical PAM4 receivers are subject to stress tolerance tests. The idea is to probe a receiver's weaknesses in a wide variety of difficult environments. Electrical PAM4 receivers are subject to jitter and noise tolerance tests plus separate interference tolerance tests.

When we say that a receiver "tolerates" a stressed signal, we mean that the receiver operates at or below the BER specified for the application before the signal is subjected to FEC.

Setting up the stress signal, that is, calibrating SECQ (stressed eye closure quaternary), is the most difficult part of the tests.

The test pattern is our first tool for determining receiver performance. The PRBS13Q and PRBS31Q patterns serve different purposes. QPRBS13 has 8192 symbols, short enough for both real-time and sampling oscilloscopes to analyze many pattern repetitions and accurately calibrate stressful signals. On the other hand, to excite every possible ISI impairment, the test pattern should include every permutation of consecutive identical symbols that extends over the length of the pulse response. The PRBS31Q pattern has over two billion unique sequences of 31 symbols, enough to accommodate a pulse response that extends up to 15 PAM4 UI. The standards almost universally require the PRBS31Q pattern for compliance testing.

The SSPRQ test pattern—or one like it, perhaps of your own devising—that incorporates long, ISI-aggravating symbol sequences, but is short enough for both real-time and sampling oscilloscopes to make their most accurate measurements, provides a nice compromise that can be used to debug receivers.

To determine an optical receiver's performance margin, increasing levels of stress can be applied to the test signal as the receiver's pre-FEC BER or post-FEC FLR is monitored. Different types of stress challenge different abilities of a receiver: clock recovery performance can be challenged by long runs of consecutive identical symbols, equalization by wide varieties of symbol sequences, and slicer sensitivity by jitter and noise. Innovative PAM4 receiver designs that combine CR, equalization, and symbol decoding in DSP filters may be more difficult to debug than receivers with distinct CR, equalization, and symbol decoders.

6. Evaluating Optical PAM4 Receivers

Table 7 shows typical required stresses for 25–53 GBd optical receiver tolerance tests. Applications with longer reaches and higher baud rates tend to require receivers capable of tolerating greater stress. For example, 400GBASE-LR8 at 25.6 GBd with 8 WDM lanes on one SM fiber and maximum reach of 10 km has more strict requirements than the single lane, 100 m reach, MM 50GBASE-SR standard.

A receiver's performance margin can be tested by increasing the complexity of the test pattern as OMAouter is decreased and SECQ is increased.

TRANSMITTER COMPLIANCE FIBER REQUIREMENTS				
Baud per lane	**25.56 GBd**			**53.13 GBd**
Reach, fiber	**100 m, MM**	**500 m, SM**	**10 km, WDM**	**500 m, SM**
Stressed receiver sensitivity OMAouter	≤ -3 dBm	≤ -4.1 dBm	≤ -4.7 dBm	≤ -1.9 dBm
SECQ	4.9 dB	3.4 dB	3.3 dB	3.4 dB
Aggressor OMAouter	3 dBm	2.8 dBm	-0.2 dBm	4.2 dBm

TABLE 7. Ranges of typical optical receiver tolerance criteria.

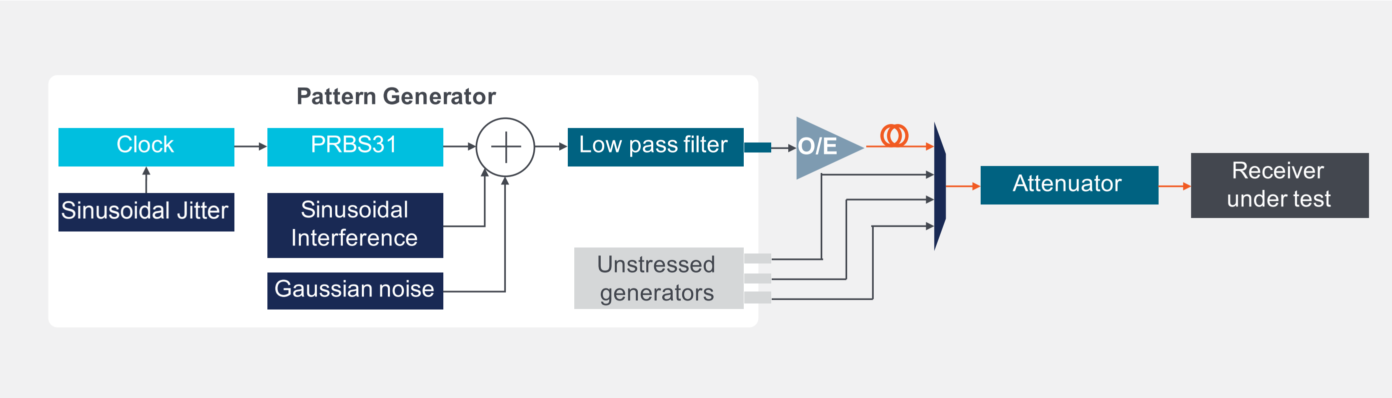

FIGURE 20. Optical receiver test setup.

6.1 STRESSED OPTICAL RECEIVER SENSITIVITY

The test setup for evaluation of optical receivers is shown in Figure 20. The frequency modulated clock that defines the pattern generator timing applies SJ (sinusoidal jitter) to the signal with frequency dependent amplitudes as in Figure 21. The high amplitude SJ at low frequencies rolls off to low amplitude at higher frequencies.

The pattern generator introduces adjustable levels of Gaussian amplitude noise and sinusoidal amplitude interference. Sinusoidal interference can usually be applied at a fixed frequency between 100 MHz and 2 GHz provided that the frequency has no harmonic relationship with the signaling rate, pattern repetition rate, or applied SJ frequencies.

The combined frequency response of the low-pass filter and the E/O convertor should cause at least half of the specified SECQ prior to application of sinusoidal interference and Gaussian noise.

The test begins with the signal directed to the oscilloscope to calibrate the stressed receiver sensitivity OMAouter and SECQ. The oscilloscope calibrates the signal with the CR and FFE of the required reference receiver.

All module channels are active and transmitting signals with specified OMAouter that are uncorrelated to the pattern of the test signal.

SECQ calibration is an iterative process. SJ is applied at a frequency well above the roll off and at the amplitude specified by Figure 21. Gaussian and sinusoidal amplitude noise along with SJ are added to the signal, closing the post-reference receiver eye. The extinction ratio of the E/O converter should be the minimum allowed for compliant transmitters and maintained at that level as Gaussian noise and sinusoidal amplitude interference is adjusted. SECQ is calibrated when the combination of interference, noise, and jitter result in the required SECQ and the signal has the minimum compliant extinction ratio.

Once calibrated, the stressed PAM4 signal is routed to the test receiver. WDM signals require the optical demultiplexer.

The stressed receiver sensitivity test requires receivers to function with pre-FEC BER and post-FEC FLR no higher than specified for SJ amplitudes and frequencies of applied SJ described by a template like that shown in Figure 21. The SJ tolerance probes the receiver's ability to track high amplitude low frequency jitter.

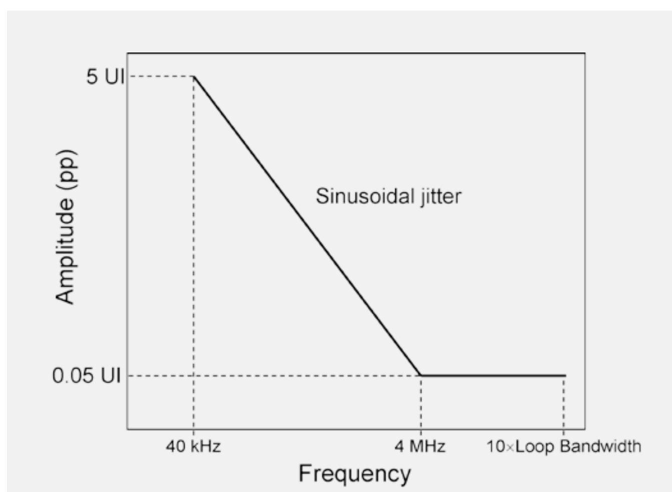

FIGURE 21. Example of a receiver tolerance sinusoidal jitter template.

7. Evaluating Electrical PAM4 Receivers

Depending on the reach or expected loss and number of connectors from transmitter to receiver, electrical PAM4 receivers must pass different tolerance tests. The key issue is the same in all cases: Can the receiver tolerate the worst case but compliant combinations of transmitters and channels? In this context "tolerate" means that the receiver must operate at, or better than, the required pre-FEC BER and/or post-FEC FLR without burst errors longer than the specified maxima.

The tests fall under two categories: jitter tolerance and interference tolerance. When just one test is required, it's often simple called a "stressed input" test but almost always includes a jitter tolerance test.

Interference tolerance tests often consist of two separate compliance tests: one with high interference noise and low ISI/insertion loss and another with lower interference and higher ISI/insertion loss.

7.1 RECEIVER JITTER TOLERANCE AND STRESSED INPUT TESTS

When a standard requires that a receiver pass a "stressed input test" rather than separate jitter and interference tolerance tests, crosstalk is usually incorporated with explicit requirements rather than simply requiring that all lanes be active with uncorrelated signals.

The worst-case compliant signal corresponds to the minimum required properties of compliant transmitters, like those in Table 6 of Section 4.

The test setup is shown in Figure 22. The pattern generator incorporates the ability to apply calibrated levels of impairments to the transmitted signal including SJ, UUGJ, and UBHPJ. UUGJ (uncorrelated unbound Gaussian jitter) provides random jitter and UBHPJ (uncorrelated bounded high probability jitter) provides DJ that cannot be equalized.

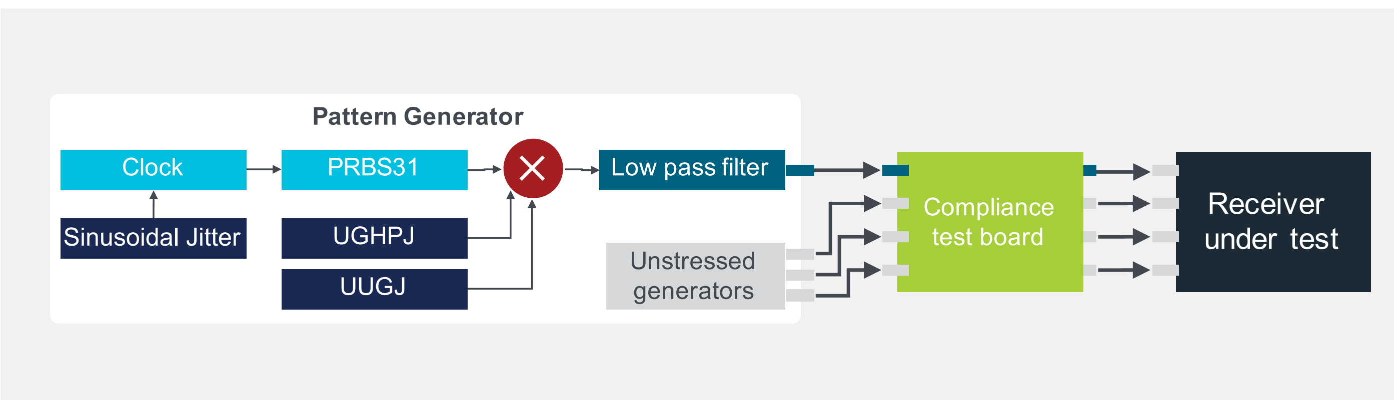

FIGURE 22. Receiver tolerance test setup.

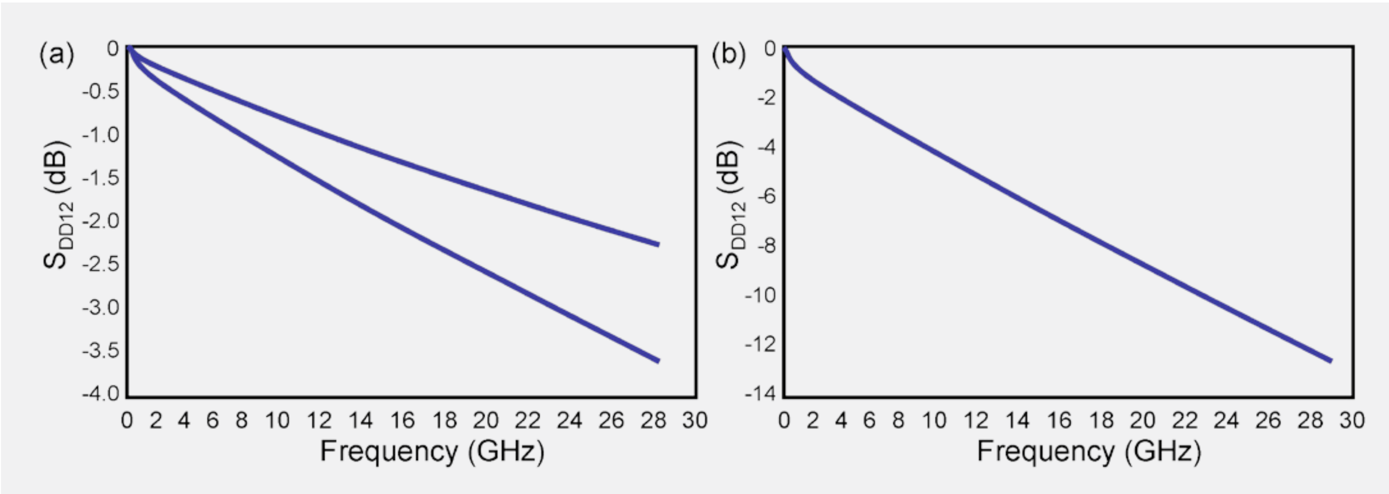

FIGURE 23. Examples of compliance test boards with trace lengths of (a) 25 mm and (b) 125 mm.

ISI is generated by compliance test boards and connectors between them. The number of compliance test boards and connectors varies by application; as few as one test board with no connectors and as many as three test boards with two connectors. The primary issue is not to replicate the application but to apply its loss characteristics. Compliance test boards are specified in terms of their insertion loss frequency response, Sdd21. Naturally, the longer the reach, the greater the loss of the compliance test boards. Very short reach applications are likely to use compliance test boards with frequency responses like those in Figure 23.

The worse case transmitted signal usually includes the minimum allowed transmitter FFE, but in some very short reach applications, the receiver must tolerate a signal transmitted without FFE.

The amplitudes and transition times of crosstalk aggressors are often set to required values, at 19–28 GBd, for example, the aggressor V_{PP} = 900 mV and 20-80% transition time = 19 ps.

An oscilloscope equipped with the reference receiver specified for the transmitter tests is used to calibrate the stressed signal. The PRBS13Q test pattern is used for calibration and PRBS31Q is used in the test. Calibration requires adjusting the contributing signal impairments to obtain the minimum EH and EW permitted for the worst-case transmitter.

UBHPJ and UUGJ are added to a clean PAM4 signal. SJ is applied at the high frequency, low amplitude end of the jitter template. PAM4 eye compression, R_{LM}, is adjusted so that the upper and lower eyes are smaller than the middle eye. Together with crosstalk and ISI from the compliance test board(s) and optimized reference receiver equalization, the signal amplitude and impairments are adjusted to at once match the maximum allowed jitter levels and nonlinearity, while achieving the minimum allowed far end EH and EW.

Juggling all the signal parameters can be difficult; the minimum values of EH and EW are more important than tuning precise levels of their ancillary components.

With the signal calibrated, SJ is applied according to an amplitude-frequency template like the one in Figure 24. Compliant receivers must tolerate the stressed signal across the SJ template. In particular, the receiver should be tested at one high amplitude low frequency point, a point along the clock recovery bandwidth roll off, a point just above the roll off, and a couple of high frequency low amplitude points.

A receiver passes if it operates at or better than the specified per-FEC BER across the SJ template.

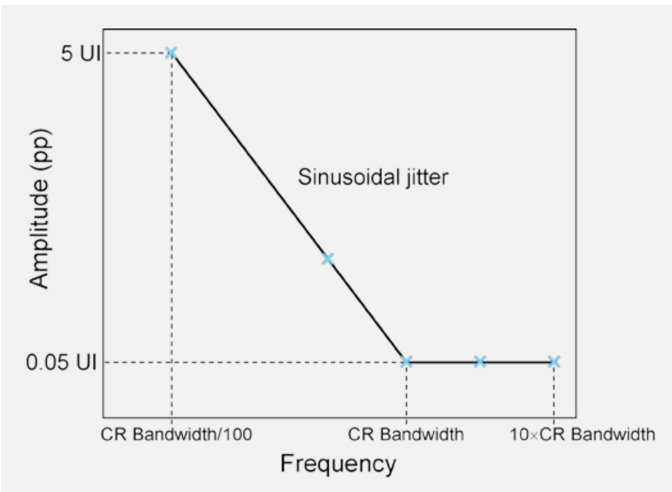

FIGURE 24. Example of an applied jitter template for Jitter tolerance and stressed input tests.

7.2 RECEIVER INTERFERENCE TOLERANCE TESTS

Interference tolerance tests probe a receiver's ability to operate in high crosstalk environments.

Interference tolerance tests for PAM4 differ from their PAM2-NRZ counterparts. With the dramatic drop in SNR, the PAM4 interference test takes on greater importance. The PAM2-NRZ interference tolerance tests probe a receiver's ability to tolerate crosstalk in high and low loss environments by a combination of near and far end crosstalk summed over all aggressors in terms of a quantity called ICN (integrated crosstalk noise). The PAM4 approach also challenges the receiver in two separate tests, one with high interference and comparatively low loss and another with lower interference and higher loss, but rather than introduce interference in the form of ICN, the PAM4 approach at 19–28 GBd prescribes high loss and low loss tests with interference levels controlled b y COM (channel operating margin), Table 8.

Where the low and high loss are explicitly specified, the high and low interference conditions are specified implicitly by requiring COM ≤ 3 dB for both tests.

COM is an SNR-like parameter: the ratio of the signal amplitude to aggregate noise. The noise term includes all signal impairments, the effects of the signal channel, and crosstalk.

EXAMPLE OF 19-29 GBD PAM4 ELECTRICAL RECEIVER INTERFERENCE TOLERANCE TEST REQUIREMENTS				
Reach:	**500 mm PCB**		**1 m PCB**	
	Test 1	**Test 2**	**Test 1**	**Test 2**
Insertion Loss at Nyquist	≤ 10 dB	≤ 20 dB	≤ 15 dB	≤ 30 dB
COM	≤ 3 dB			
Pre-FEC BER	≤ 1E-4			

TABLE 8. Examples of requirements for electrical PAM4 receiver interference tolerance tests.

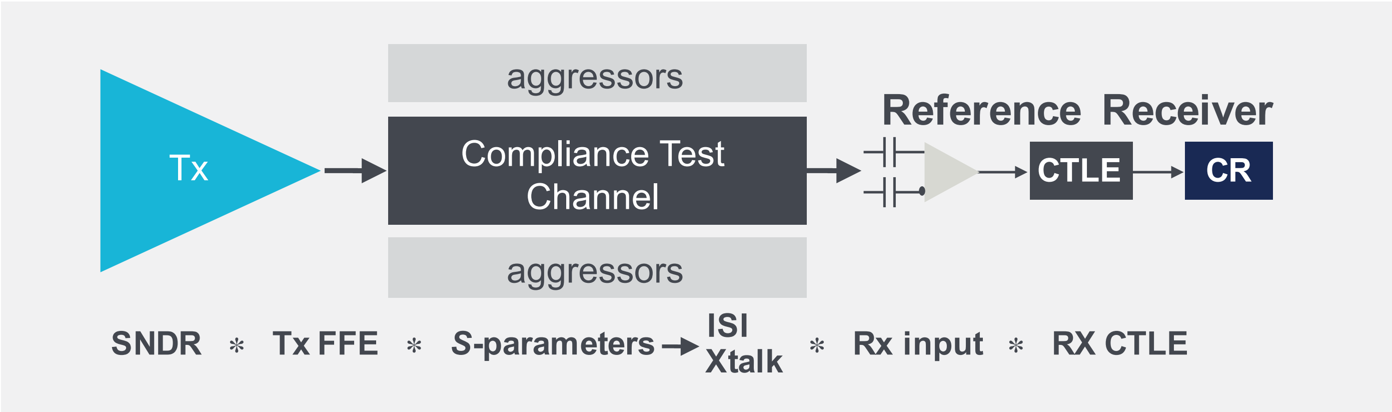

FIGURE 25. Ingredients of transfer function used to calculate COM.

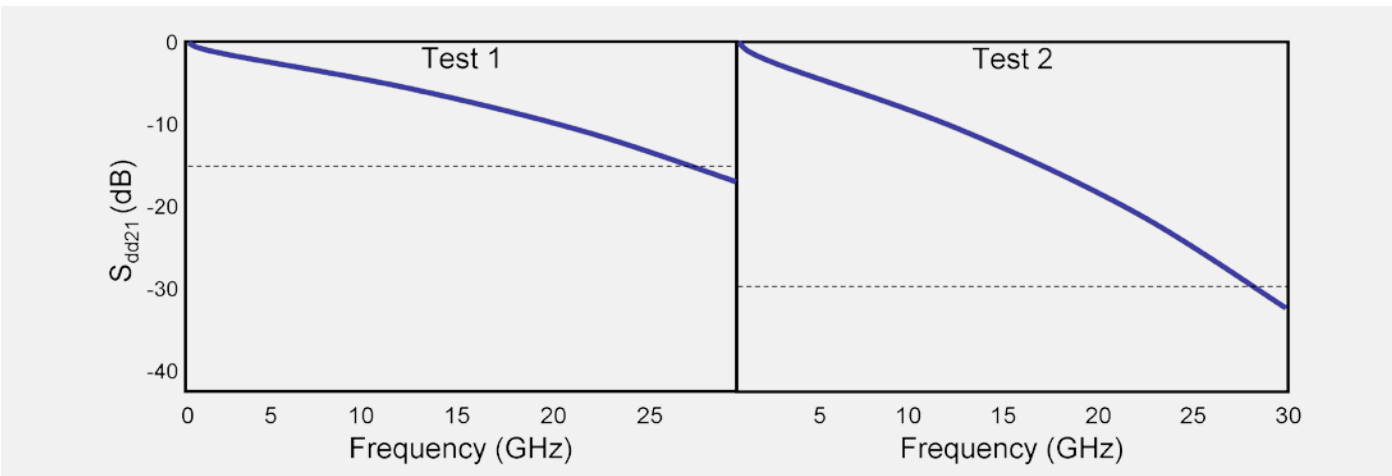

FIGURE 26. Examples of channel response, IL(*f*) = S_{DD21}, for Test 1 and Test 2.

COM can't be measured directly, rather, it's calculated by combining channel *S*-parameters—including the test channel and aggressor channels—with the combined transfer function of the transmitter, channel, and reference receiver, Figure 25. The transfer function includes models of the transmitted and aggressor signals including transmitter FFE and reference receiver equalization, random and deterministic jitter, and voltage noise. COM includes ISI and crosstalk through the *S*-parameters.

The COM calculation for PAM4 differs from PAM2-NRZ: The transmitter package is not included; SNDR takes the role of transmitter noise; transmitter output levels are set slightly nonlinear, RLM ~ 0.95; the transmitted peak-to-peak voltage swing, including FFE, is limited to 800 mV and the transmitter FFE taps are constrained within maximum and minimum values; and the reference receiver follows the specified frequency response including CTLE.

The maximum loss of the channels for each test is specified at the Nyquist rate, as shown in Table 8, and the channel frequency responses, Sdd21, drop exponentially with slopes that depends on reach, like those shown in Figure 26.

Since insertion loss is incorporated into COM, fixing COM at 3 dB or less for both tests while using a low loss compliance test board for Test 1 and a high loss board for Test 2, dictates that Test 1 is low loss/high interference and Test 2 is high loss/low interference.

Compliant receivers must operate, at or better than, the prescribed pre-FEC BER, for both tests.

8. PAM4

In advancing beyond 25 Gb/s, high-speed serial data technology crossed an inflection point. For many applications, the technical advances that enabled multi-gigabit electrical data rates with PAM2-NRZ signal modulation can no longer economically produce the signal integrity required for reliable data transfer.

Development of PAM4 has led to new techniques to account for PAM4 signal properties like the relative orientation and proportions of the three eye diagrams. In this paper we've expressed what we've learned from our participation on the standards committees and from collaborating with you, our customers, on the development of 19–53 GBd PAM4 designs, components, and systems.

Predicting the future of PAM4 designs and compliance criteria is precarious, but the introduction of requirements on parameters like TDECQ, SNDR, and COM that combine multiple measurements into figures of merit indicate that we're moving away from strict requirements on quantities that can be measured in one step. Using figures of merit to balance interdependent quantities allows designers to optimize the performance of transceivers, SerDes, and channels in different ways.

Receiver technology, especially the use of elaborate CR, CTLE, and DFE internal circuitry, is changing rapidly and our test and measurement equipment is changing with it. As we advance beyond lane rates of 112 Gb/s to 200+ Gb/s, PAM4 transceivers will have to decode each of the three eye diagrams independently. We're already seeing PAM4 receivers that integrate the roles of clock recovery and equalization into symbol decoding DSP algorithms that train their parameters on power up and can adapt as conditions change.

As we have for generations, Tektronix provides multiple approaches to analyze and produce PAM4 signals to fit your application:

- The DPO70000SX 70 GHz bandwidth real-time oscilloscopes with appropriate O/E convertors—DPO7OE1 with 33 GHz bandwidth or DPO7OE2 with 59 GHz bandwidth—have the lowest noise in the industry and the flexibility to emulate the filtering, clock recovery, and receiver equalization requirements of both optical and electrical reference receivers: The tools you need to analyze PAM4 signals, evaluate transmitters, and calibrate stressed receiver sensitivity, jitter, and tolerance tests. When equipped with our PAM4-O and PAM4 Analysis Applications compliance measurements are automatic.

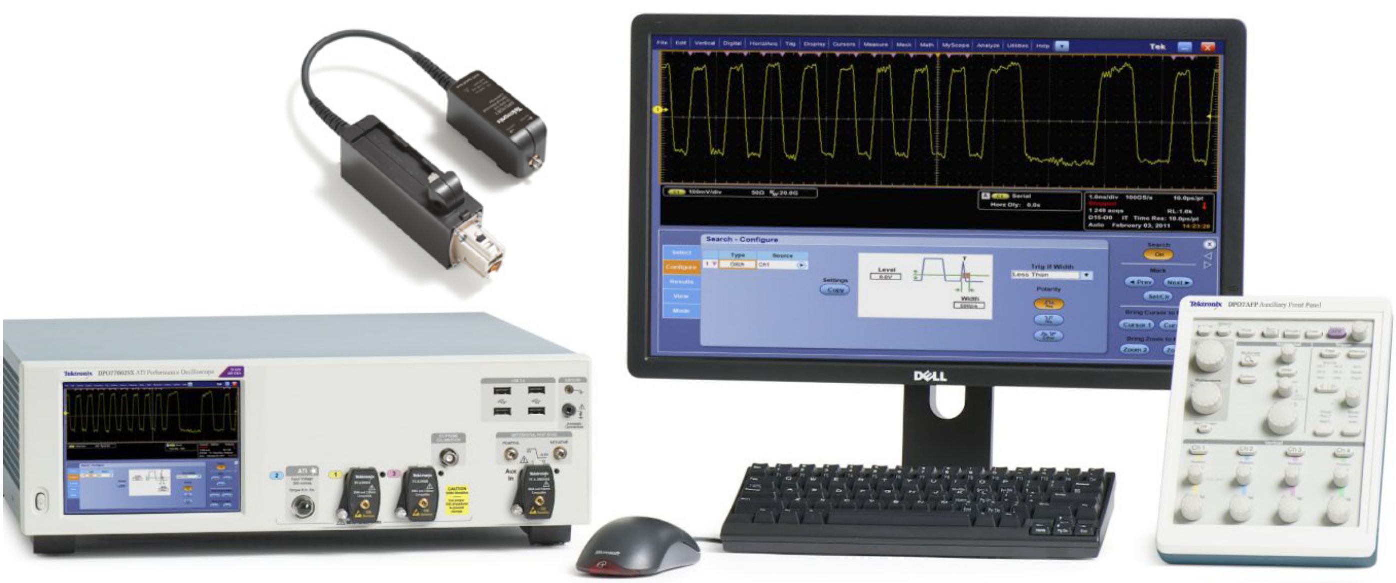

FIGURE 27. DPO70000SX 70 GHz bandwidth real-time oscilloscope.

- The DSA8300 equivalent-time sampling oscilloscope analyzes both electrical and optical signals, serves as an excellent reference receiver, and can perform all required transmitter measurements and stressed receiver tolerance test calibrations. Its TDR/TDT features can also measure the S-parameters needed for de-embedding test fixtures and calculating COM. The PAM4 software analysis package, 80SJNB Advanced, requires DSA8300 Option ADVTRIG. The acquisition of precise electrical waveforms requires the 82A04B Phase Reference Module and an 80E09B 60 GHz Electrical Sampling Module for electrical signals. For optical signals, use the appropriate sampling oscilloscope module: 80C14 for SM/MM fibers up to 16 GBd, 80C15 for SM/MM up to 32 GBd, or 80C10C for SM from 25 GBd to 60+ GBd.

The advantage of a real-time oscilloscope, the DPO70000SX, is flexibility and troubleshooting ability. The advantage of an equivalent-time sampling oscilloscope, DSA8300, is the economical combination of high bandwidth and low noise.

FIGURE 28. DSA8300 equivalent-time sampling oscilloscope.

- The Tektronix PAM4 BERT system consists of separate transmitters and receivers. The PPG3202 with PSPL5380 PAM4 Kit generates Gray coded PAM4 stressed test patterns. The PED3202 BERT Error Detector plus PAM4DEC reference receiver includes clock recovery and Gray decoding along. PAM4 BERT Control and Analysis provides a complete suite of BER contour analysis tools for analyzing transmitter quality and calibrating stressed receiver tolerance tests.

Tektronix will continue to provide the tools and measurement expertise you need to design, test, and manufacture this exciting new technology through both instrumentation and application support. We have representatives of the OIF and IEEE 400G standards bodies and local AEs steeped in high-speed serial technology experience available to help.

FIGURE 29. The Tektronix PAM4 BERT system.

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