Introduction to Jitter Techniques for High Speed Serial Technologies
Fast Data Rates, More HF Loss

Clean, open, logical 1 & 0 at launch from transmitter

Logical 1 & 0 can be hard to distinguish at end of long interconnects; (this is often called a “closed eye”)

Fast, sharp, edges at transmitter launch

Smeared edges at end of long interconnect.

Reference Maxim Note HFDN-27.0 (Rev. 0, 09/03)
Multiple Lanes Result in Crosstalk

Serial data *can* be a single differential signal...

...but generally there are multiple "lanes" of serial data running side by side; these can **CROSSTALK** with each other.
Anatomy of a Serial Data Link

Aspirational goal: 0 errors
Practical Goal: Bit Error Rate < Target BER

• Since BER is the ultimate goal, why not measure it directly?

Note that some points may not be accessible for physical probing.
Transition points involve combinations of **solder joints, circuit board vias, and connectors**: these all can have substantial effect on the total link performance.

*TDR also is capable of producing **S-parameters***
Jitter Basics

Definitions
Jitter Plot?
Bandwidth & Harmonics

Digital Square Wave – Odd Fourier Sums

ROT: Specify the Oscilloscope + Probe with System BW to be 3 - 5 times greater than the Signal Frequency to be measured.
Bandwidth & Harmonics

Digital Square Wave – Odd Fourier Sums

ROT: Specify the Oscilloscope + Probe with System BW to be 3 - 5 times greater than the Signal Frequency to be measured.
What is Jitter?

- **Definitions**
  - “The deviation of an edge from where it should be”
  - ITU Definition of Jitter: “Short-term variations of the significant instants of a digital signal from their ideal positions in time”
Jitter is caused by many things…

- **Causes of Random Jitter**
  - Thermal noise
    - Generally Gaussian
    - External radiation sources
    - Like background conversations…random and ever changing

- **Causes of Periodic Jitter**
  - Injected noise (EMI/RFI) & Circuit instabilities
    - Usually a fixed and identifiable source like power supply and oscillators
    - Will often have harmonic content
    - Transients on adjacent traces
    - Cabling or wiring (crosstalk)
  - PLL’s problems
    - Loop bandwidth (tracking & overshoot)
    - Deadband (oscillation / hunting)

- **Causes of Data Dependent Jitter**
  - Transmission Losses
    - There is no such thing as a perfect conductor
    - Circuit Bandwidth
    - Skin Effect Losses
    - Dielectric Absorption
    - Dispersion – *esp. Optical Fiber*
    - Reflections, Impedance mismatch, Path discontinuities (connectors)
Types of Jitter

- Period Jitter
Types of Jitter

- Period Jitter
Types of Jitter

- **Period Jitter**
- **Cycle-to-Cycle Jitter**

---

- **Cycle-to-Cycle Jitter** is the first-order difference of the **Period Jitter**
Types of Jitter (Visualization)

- Modulated Clock
  - Period Jitter: 1010 nsec, 1000 nsec, 990 nsec
  - Cycle-Cycle Jitter: 20 nsec, -20 nsec
Types of Jitter

- **Period Jitter**
- **Cycle-to-Cycle Jitter**
- **TIE (Time Interval Error)**

\[ P_n = TIE_n - TIE_{n-1} + K \]
Types of Jitter (Visualization)

**Modulated Clock**

- **Period Jitter**
  - 1010 nsec
  - 1000 nsec
  - 990 nsec

- **Cycle-Cycle Jitter**
  - 20 nsec
  - -20 nsec

- **Time Interval Error**
  - 40 nsec
  - -40 nsec
Advanced Jitter - Decomposition

Rj / Dj Separation
Motivations for Jitter Decomposition

- **Speed**: Directly measuring error performance at $1 \times 10^{-12}$ requires directly observing MANY bits ($1 \times 10^{14}$ or more). This is *time consuming*! Extrapolation from a smaller population can be done in seconds instead of hours.

- **Knowledge**: Jitter decomposition gives *great insight* into the root causes of eye closure and bit errors, and is therefore invaluable for analysis and debug.

- **Flexibility**: Already have a scope on your bench? You can do Jitter@BER measurements without acquiring more, perhaps somewhat specialized equipment.
Common Terms

- Random Jitter (RJ)
- Deterministic Jitter (DJ)
  - Periodic Jitter (PJ)
  - Sinusoidal Jitter (SJ)
  - Duty Cycle Distortion (DCD)
  - Data-Dependent Jitter (DDJ)
  - Inter-Symbol Interference (ISI)
- Bit Error Rate (BER)
- Total Jitter ~ (TJ or TJ@BER)
- Eye Width @BER
  - versus Actual or Observed Eye Width
Random Jitter (RJ)

- Jitter of a random nature is assumed to have a Gaussian distribution (Central Limit Theorem)
- Histogram (estimate) ↔ pdf (mathematical model)
- Peak-to-Peak = … unbounded!
Deterministic Jitter (DJ)

- Deterministic jitter has a bounded distribution: the observed peak-to-peak value will not grow over time
- Histogram = pdf (close enough)
Periodic Jitter (PJ, SJ)

- TIE vs. time is a repetitive waveform
- Assumed to be uncorrelated with the data pattern (if any)
- Sinusoidal jitter is a subset of Periodic Jitter
Duty Cycle Distortion (DCD)

- DCD is the difference between the mean TIE for rising edges and the mean TIE for falling edges

- Causes
  - Asymmetrical rise-time vs. fall-time
  - Non-optimal choice of decision threshold

- For a clock signal, the pdf consists of two impulses
Data-Dependent Jitter

- DDJ or PDJ – used interchangeably
- ISI – usually considered to be the physical effect that causes DDJ
- Characterizes how the jitter on each transition is correlated with specific patterns of prior bits
  - Due to the step response of the system
  - Due to transmission line effects (e.g. reflections)
Composite Jitter Rj/Dj using dual-dirac or Spectral method?

- “Turn it on and run it for a while…”
- Historical Eye-Closure Measurement
- Jitter value including all Rj+Dj components
- Expressed as 1 sigma RMS or Pk-Pk
- Unbounded, result depends on measurement interval

1000 Hits, 10 ps RMS, 40 ps Pk-Pk

644M Hits, 44 ps RMS, 166 ps Pk-Pk
Histograms vs. Eye Diagrams: Dual Dirac method, Rj and Dj

- How open is the eye, anyway?
  
  (…depends how long you watch)
Elements of the Dual-Dirac Model

\[
[\delta(x - \mu_L) + \delta(x - \mu_R)]^* \frac{1}{\sqrt{2\pi\sigma}} \exp\left(-\frac{x^2}{2\sigma^2}\right) = \frac{1}{\sqrt{2\pi\sigma}} \left[ \exp\left(-\frac{(x - \mu_L)^2}{2\sigma^2}\right) + \exp\left(-\frac{(x - \mu_R)^2}{2\sigma^2}\right) \right]
\]

\[
\mu_L \quad \mu_R
\]

Dual-Dirac DJ \quad \text{Gaussian RJ}

DJ(p-p) = \mu_R - \mu_L \quad \text{RJ} = \sigma

Tj = Dj \otimes RJ \quad \text{(convolution)}

Ppk-Ppk: Tj = (N*Rj) + Dj, where N is desired sigma
Total Jitter @ BER

Deterministic components

Dj Peak-to-Peak

Rj rms

Random components
More about Bathtub
\( R_{j_\delta} / D_{j_\delta} \) from \( T_j @ BER \)

Assume bi-modal distribution (dual-Dirac), measure \( T_j \) at two BER

Fit curve to points, slope is \( R_j \), Intercept is \( D_j \)

- \( \frac{1}{2} D_{j_\delta} \)
- \( \frac{1}{2} x R_{j_\delta} \)

Measured
\( T_j @ 10^{-4} \)
\( x \approx 7.4 \sigma \)

Estimated
\( T_j @ 10^{-12} \)
\( x \approx 14.1 \sigma \)

Conditions: only where Gaussian.

Dual Dirac model
DJ(dd): Model Dependence of DJ (2)

\[ DJ(\delta\delta) \leq DJ(p-p) \]

… Is the reason dual-Dirac is controversial

- It’s okay for a model to have model-dependent parameters
- Make sure to use \( DJ(\delta\delta) \) in \( TJ(BER) = 2Q_{BER} \times RJ + DJ \)

Besides

- It’s easier to measure \( DJ(\delta\delta) \) than \( DJ(p-p) \)
- For getting \( TJ(BER) \), \( DJ(\delta\delta) \) is more useful than \( DJ(p-p) \)

<table>
<thead>
<tr>
<th>BER</th>
<th>( Q_{BER} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^{-10}</td>
<td>6.35</td>
</tr>
<tr>
<td>10^{-11}</td>
<td>6.70</td>
</tr>
<tr>
<td>10^{-12}</td>
<td>7.05</td>
</tr>
<tr>
<td>10^{-13}</td>
<td>7.35</td>
</tr>
<tr>
<td>10^{-14}</td>
<td>7.65</td>
</tr>
</tbody>
</table>
Spectral Method Rj/Dj but Pj DCD and ISI

- Start with
  - TIE
  - PLL TIE

- Perform FFT
  - Determine frequency and pattern rate
  - Measure RMS of background bins
  - Sum pattern related bins
  - Sum unrelated periodic bins via iFFT
  - Estimate BER
Bounded Uncorrelated Jitter

- Interconnect and board layout technology is advancing and the greatest area of focus is in reducing the insertion loss and Signal-to-Crosstalk ratio.

- The implications of complex channel interaction can be observed and identified by examining the type and amount of Bounded Uncorrelated Jitter or BUJ.

- There is a strong Cause–and-Effect relationship between Crosstalk and BUJ which often gets classified as Random if special steps are not observed.
Bounded Uncorrelated Jitter (BUJ)

- **Definitions of Jitter Properties:**
  - **Bounded:** Having a PDF (histogram) that does **not grow in width** as the observation interval increases
  - **Uncorrelated:** Specifically, not correlated to the pattern of data bits
    - Note that PJ (Periodic Jitter) is both bounded and uncorrelated $\rightarrow$ BUJ!
  - **Deterministic:** Future behavior can be predicted based on observed past.
    - Deterministic jitter is always bounded
    - But… bounded jitter isn’t necessarily deterministic
  - **RJ:** By convention, random jitter with a Gaussian histogram
  - **NPJ or NP-BUJ:** Non-Periodic (Bounded Uncorrelated) Jitter. This is basically random jitter with a bounded PDF
Jitter Measurement in the Presence of Crosstalk: Problem Summary

- Crosstalk-caused jitter typically is Bounded Uncorrelated Jitter (BUJ); depending on the spectra this should be separated as either
  - PJ (Periodic BUJ)
  - NPJ (Non-Periodic BUJ)

- In traditional oscilloscope-based jitter measurement methodology the more spectrally diffuse BUJ components (i.e. NPJ) are not distinguished from RJ.
  - The inflated RJ is multiplied by a factor, thereby grossly inflating TJ.

  Example: \[ TJ = DJ + 14 \times RJ \] (at BER = 1e-12)

- This is well known and was documented e.g. in “Method of BER Analysis of High Speed Serial Data Transmission in Presence of Jitter and Noise”, Zivny at all, DesignCon 2007.
Crosstalk Problem Summary (Graphical Version)

**Case 1:**
RJ + PJ

Spectral separation works very well

**Case 2:**
RJ + NPJ

Spectral separation is no help at all
Theory: Q-Scale Analysis for Detecting NPJ

- Cumulative Distribution Function (CDF) for a Gaussian Distribution:

\[
CDF(x_{Gauss}) = \frac{1 + \text{erf}\left(\frac{x}{\sigma \sqrt{2}}\right)}{2}
\]

- Q Scale Definition:

\[
Q(x) = \sqrt{2} \times \text{erf}^{-1}(2CDF(x) - 1)
\]

- Q Scale for a Gaussian:

\[
Q(x_{Gauss}) = \frac{x}{\sigma}
\]

- This is a straight line with a slope of $1/\sigma$!
Separation of BUJ and RJ Jitter Components

Methodology

- After PJ and DDJ are removed using the spectral approach, RJ + NPJ is converted to a histogram and then plotted using the Q Scale.
- Straight lines are fitted to the left and right tails to determine both the RJ sigma and the dual-dirac weight of the NPJ.

Simulated Jitter, Population = 1e6 observations

Blue = Gaussian RJ, 2 ps rms
Red = Uniformly Distributed NPJ, 8 ps p-p
Black = RJ + NPJ = TJ

Spectral-Only Method: \( TJ(1e^{-12}) = 0.00 + 3.056 \times 14 = 42.8 \) ps
Spectral+BUJ Method: \( TJ(1e^{-12}) = 2.79 + 2.303 \times 14 = 35.0 \) ps
DPOJET Setup for BUJ / NPJ Measurements

- **Enable** Spectral+BUJ either through the Preferences Setup or the Jitter Map
- **Minimum # of UI** control is only available via Preferences Setup
  - Default is 1M but it can be reduced as low as 10k.
  - Agilent EZJIT has a similar (non-adjustable) population requirement, ~ 150k
DPOJET Results for BUJ / NPJ Measurements

- Clock NPJ measurement shows actual progress toward the population requirement
Jitter Visualization

Gaussian Random Noise

Sinusoidal Jitter
Jitter Visualization – Bathtub Plot

- Shows the Eye Opening at a Specified BER Level
- Note the eye closure of System I vs. System II due to the RJ - RJ is unbounded so the closure increases as BER level increases
  - System I has .053UI of RJ with no PJ
  - System II has .018UI of RJ and .14UI of PJ @ 5 and 10Mhz
Jitter Visualization – Time Trend

- Histogram does not have any context of time
- Time Trend can reveal repeating patterns that may indicate modulation on the signal
  - For example 5 cycle of SSC @ 30khz as shown below
Jitter Visualization – Spectral Plot

- Frequency domain view of the signal content
- Deterministic components show as lines above the noise
  - DDJ is at frequencies of the bit rate / pattern length (example below is 5Gb/s PRBS7) Note the spikes at intervals of 40Mhz in the plot.
- Constant Clock CR was used
TIE Jitter needs a Reference Clock

- The process of identifying the reference clock is called **Clock Recovery**.
- There are several ways to define the reference clock:
  
  - **Constant Clock with Minimum Mean Squared Error**
    - This is the mathematically “ideal” clock
    - But, only applicable when post-processing a finite-length waveform
    - Best for showing very-low-frequency effects
    - Also shows very-low-frequency effects of scope’s timebase
  
  - **Phase Locked Loop (e.g. Golden PLL)**
    - Tracks low-frequency jitter (e.g. clock drift)
    - Models “real world” clock recovery circuits very well
  
  - **Explicit Clock**
    - The clock is not recovered, but is directly probed
  
  - **Explicit Clock (Subrate)**
    - The clock is directly probed, but must be multiplied up by some integral factor
Reference Clock for Jitter: Clock Recovery?

In a receiver

- The clock positions the sampling point
- Comparator determines logic level

How can we reduce the effect of jitter in the decision circuit?
“Obvious approach” with an absolute reference clock:

\[ UI = \frac{1}{T_{\text{Bit}}} \]

Skew = \( \text{mod}(\Delta t, T_{\text{BIT}}) \)

Rx samples at the center of each bit…

doesn’t it?
Phase Locked Loop Clock Recovery

To extract a useful clock, the data must...

- Have plenty of logic transitions
  - No long runs of identical bits
- Be DC balanced

Data signals are encoded, e.g., 8B/10B encoding
JTF vs PLL Loop Bandwidth

- Configuring the correct PLL settings is key to correct measurements

- Most standards have a reference/defined CR setup
  - For example, USB 3.0 uses a Type II with JTF of 4.9Mhz

- Type I PLL
  - Type I PLL has 20dB of roll off per decade
  - JTF and PLL Loop Bandwidth are Equal

- Type 2 PLL
  - Type II PLL has 40dB of roll off per decade
  - JTF and PLL Loop Bandwidth are not Equal
    - For example, USB 3.0 uses a Type 2 PLL with a JTF of 4.9Mhz. The corresponding loop bandwidth is 10.126 Mhz
    - Setting the Loop Bandwidth as opposed to JTF will lead to incorrect jitter measurement results
PLL Loop Bandwidth vs. Jitter Transfer Function (JTF)

A: Constant Clock Recovery  B: PLL Clock Recovery  Ratio of B/A
Effect of CR Bandwidth on Eye Opening
Results depend on CR Settings USB 3.0 Example

- The example below shows the effects of using a JTF set to 4.9Mhz vs. Loop Bandwidth set to 4.9Mhz for a Type II PLL.
- Note the difference in the jitter that is tracked:
  - The results on the left are correct as the JTF was properly set to 4.9Mhz, as opposed to the loop bandwidth.

Note: More LF Attenuation for case where JTF set to 4.9Mhz and lower TJ.
Further Comparison of PLL Types using Spectrum Plots

Constant Clock
All Jitter Passes Through

Type I
20 dB roll off per decade @ 4.9Mhz

Type II
40 dB roll off per decade @ 4.9Mhz

Type II
40 dB roll off per decade @ 2.3Mhz
(JTF to illustrate JTF ! = Loop Bandwidth

First Cursor in each plot is @ 33Khz to illustrate effect on SSC
Further Comparison of PLL Types using Transfer Function Plots

Type I
20 dB roll off per decade @ 4.9Mhz

Type II
40 dB roll off per decade @ 4.9Mhz

Type II
40 dB roll off per decade @ 2.3Mhz (JTF to illustrate JTF ! = Loop Bandwidth)
JTF Filtering Effects based on different PLL bandwidths

- $f_{3dB} = 30$ kHz
- $f_{3dB} = 300$ kHz
- $f_{3dB} = 3$ MHz
Open Closed Eyes
Apply Receiver Equalization

- The example below shows a PCI Express 3.0 signal at the far end (input to the receiver)
  - Note that the eye is closed
  - Note that clock recovery would have failed due to the channel loss
  - After applying DFE equalization the signal can be measured with DPOJET
The problem is the channel …
Channel exhibits large frequency dependent loss

- Loss/dispersion of the channel closes the eye
- Receivers now incorporate methods to compensate for loss (equalization)

Graph from IEEE 802.3ap effort
Equalization: The solution #1: High Frequency “Boost”

The problem is just what you’d think it would be:

- To compensate for this channel response …
- …you need to boost the channel so much.

The noise amplification is huge, and it hurts the improvement you get (Signal to noise)
Equalization: CTLE frequency response

- CTLE – Continuous Time Linear Equalization
- Linear HF filter/boost
- Advantages: Low power & Simple implementation
- … but it amplifies noise
Channel Testing

Simulate Compliance Channels

(a) Waveforms
- Shrinkage in high frequency section of pattern
- Decision threshold
- Potential bit error after several long sequences of zeroes

(b) Eye diagrams
- All bits laid upon each other, shows partial eye closure due to ISI

(c) BER bathtub
- Shows timing jitter (blue is RJ, green is DJ). DJ increases due to ISI.
Channel Testing

Simulate Compliance Channels

[Diagram showing channel testing setup with various filters and waveforms]
Trois Instruments pour la même mesure Tx?
Real-time Scope, Sampling Scope, BERT Scope

Scope BW 70GHz
AWG BW 18GHz
Standard tool for Tx test Datacom
Rx test < 6.25Gbits

Optical and Electrical BW 80GHz
Standard tool for Tx test Telecom

BERT Scope 28.6Gbits Tx/Rx
PPG 40Gbits Tx/Rx
Standard tool for Rx test Super High speed
No Tx test

No Rx test
Real-time Scope

Advanced trigger on signal
No clock need

Built in Clock recovery

One sample every 5ps with continue acquisition (depend on memory)

Dual-Dirac /spectral and Q-scale method for complete Tx analysis

(PJ = Periodic Jitter, e.g., interference, crosstalk etc.)
(ISI = Inter-Symbol Interference, e.g., from BW limitations)
High Speed Serial Data solution TX + RX

AWG70000

Serial Express

HSSD with Jitter, ISI, Channel, SSC & emphasis up to 12.5Gbits

Tx Analysis with DPOJET & SDLA
Compliance with Tekexpress

Device Under Test (DUT)

To One box for Error detector & Jitter analysis

BER Tester 6.25Gbit with ERRDT

loopback

Tektronix®
Sampling Scope

- **Electrical and Optical acquisition**
- **Need external trigger clock**
- **Need external Clock recovery**
- **Only Tx measurement**
  - 80GHz BW but only repetitive acquisition at 300kS/s
  - Very precise Rj measurement.
  
  Trigger Jitter scope <100fs

**A.**
Take a sample, *sleep.* Take a sample, *sleep…*  

**B.**
Relatively shallow

**A.**
Add Pattern Trigger  

- Short to medium length patterns: Target 1 sample per pattern repetition, but know which bit samples come from - helps math.

**B.**
Focus on one edge - ISI removed, leaves RJ & PJ

**C.**
FFT gives aliased spectral histogram of edge placements - below threshold assumed RJ

**D.**
Average placement of all edges – ISI, helps get DJ.

**E.**
- Use dual - Dirac or similar model to get TJ
- Pattern trigger helps depth a little by allowing targeting of samples on an edge.
- Enables insight into components of jitter.
BERT Scope

Need external trigger clock

Need external Clock recovery

28.6Gbit Rx and Tx

See all bit and can measure Tj directly (no extrapolation)

Stressed Eye capability

Eye diagram and Jitter map capability

Error Location capability

PRBS31 length capability

1. Plots the crossing point in BER terms
2. From plot, can fit dual-Dirac model and derive RJ & DJ.
3. Can extrapolate to get TJ, but extrapolation is short, because of inherent depth, helping accuracy.
   - Can also directly measure TJ if you wait long enough.
   - TJ is available for any pattern length.
1. Recall stressed eye configuration
2. Apply stressed eye signal to DUT’s receiver
3. DUT loops received bits back to BERTScope Error Detector
4. BERTScope counts any errors
2. Creating the Stressed Signal

Dynamically change Data Rate, Stress, Pattern

1. 2.5 Gb/s
   PRBS-7
   DJ: X
   SJ: X
   RJ: X
   SI: X

2. 2.5 Gb/s
   PRBS-7
   DJ: ✓
   SJ: ✓
   RJ: ✓
   SI: ✓

3. 2.5 Gb/s
   PRBS-7
   DJ: ✓
   SJ: ✓
   RJ: ✓
   SI: ✓
3. BER-Based Analysis

Deep Insight with the BERTScope Toolkit

- Jitter
  - Horizontal slice
  - Eye opening at $10^{-12}$ BER level

- Eye Height
  - Vertical slice
  - Eye opening at $10^{-12}$ BER level

- BER Contour
  - $10^{-16}$ eye opening
4. Drilling Down From Eye to Errors

Linked Tools Enable Deep Insight

1. Deep Eye Test
   - Eye diagram I understand
   - Much more information so I can see infrequent events…

2. Deep Eye Test

3. Trap Eye Violations in BER domain
   - Able to link directly to BER…

4. Pin-Point Clues
   - Quickly get insight
5. Jitter Map

RJ varies by edge in the data pattern, shown plotted with the data pattern and in a histogram.

TJ is measured using an MJSO-compliant BERScant (or “BER bathtub”) method.

BUJ is measured on single edges of the data pattern using the BER bathtub method.

SRJ is measured for a number of user-defined sub-rates.

DDJ, ISI, and DCD are measured based on histograms of rising and falling average edge timings. Edge timings are also plotted with the data pattern.
6. The Right Companion Products
The BERTScope Product Family Makes Compliance Easy

A Typical Receiver Test Setup

1. DPP provides pre-emphasis to emulate compliant transmitter

2. CR recovers a clock from the retransmitted data from the DUT

Device Under Test (DUT)

From Stressed Pattern Generator

loopback

To Error Detector
BERTScope® Family of Products

- BSA Family is a series of BERT and Analysis tools spanning 500Mbps to 28.6Gbps. Upgrades avenues from lower performing units to higher performing ones will continue to be preserved.
Tektronix LE320/LE160
32 & 16Gbps Linear Equalizer Product Introduction

- Compact two channel 32Gbps 9 Tap linear equalizer design in a “remote module” configuration
- +/-20dB tap controls offer flexible pre-emphasis or channel de-embed capabilities.
- User (and PI) configurable filter properties allows flexible parametric equalization
- Electronically switchable frequency dependent filter capability permits DDJ tolerance testing and testing against known reference channel models
- Front-end signal path (CTLE) for Sampling or BERT Instruments
Tektronix LE320
32G Linear Programmable Equalizer

9 Tap linear equalizer design, supporting 14-32Gbps operation

“iPhone-ish” size

Mechanical Evolution

DPP125B size

9-tap UI
- Controlled by 4-tap UI
- Can also be controlled directly

Output gain or attenuation control

Traditional 4-tap UI

9-tap Response Calculated from 4-tap Input
PPG/PED

**PPG Base Instruments**

- **PPG1251** 12.5Gb/s PPG
  - Jitter insertion (LF+HF)

- **PPG300X** 30Gb/s PPG
  - 1/2/4 Channel
  - LF jitter insertion
  - HF jitter insertion

- **PPG320X** 32Gb/s PPG
  - 1/2/4 Channel
  - Adjustable output
  - LF jitter insertion
  - HF jitter insertion

- **PPG4001** 40Gb/s PPG
  - LF jitter insertion
  - HF jitter insertion

**PED Base Instruments**

- **PED320X** 32Gb/s PED
  - 1/2 Channel
  - Full or half rate clock input
  - AC or DC coupled input

- **PPG400X** 40Gb/s PED
  - 1/2 Channel
  - Full or half rate clock input
  - AC or DC coupled input
32Gb/s and 40Gb/s SERDES JTOL testing

**Advantages**

- Separate PPG and PED for users with on-chip BER capabilities
- Low intrinsic jitter
- Fast rise-fall times and high signal integrity
- SJ/RJ/BUJ insertion for standards compliance tests
- Software analysis tools (*bathtubs, JTOL, J2/J9, etc*)
- Easy-to-use touchscreen and USB programmability

Some ASICs/FPGAs have built-in BER testing and don’t require loop back with a PED.
100G Ethernet SR4/LR4/ER4 transceiver testing

Advantages

- Flexible multi-channel solution
- Low intrinsic jitter
- Fast rise-fall times and high signal integrity
- SJ/RJ/BUJ insertion for standards compliance tests
- Software analysis tools (*bathtubs*, *JTOL*, *J2/J9*, etc)
- Easy-to-use touchscreen and USB programmability

Note: Tektronix CR286 may be added for clock recovery
What is PAM?

**Pulse Amplitude Modulation**

- PAM4 combines two bit streams and uses 4 levels to encode 2 bits into 1 UI
- For Example, 56 Gbit/s PAM4 runs at a symbol rate of 28 GBaud

<table>
<thead>
<tr>
<th>MSB</th>
<th>LSB</th>
<th>PAM4 LEVEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>
What are the differences between PAM4 and NRZ?

- **PAM4**
  - 4 Levels → 3 Eyes
  - Sensitive to SNR (eyes smaller)
  - 2 bits into 1 UI
  - \( \frac{1}{2} \) Symbol Rate for same data throughput (28 GBaud = 56Gbps)
  - Adds complexity/cost to Tx/Rx

- **NRZ**
  - 2 Levels → 1 Eye
  - Less Sensitive to SNR
  - 1 bit in 1 UI
  - 2X Symbol Rate for same data throughput (28 GBaud = 28Gbps)
Considerations for a PAM4 Signal Generation Engine

**Arbitrary Waveform Generators**
For applications that place top priority on flexibility
- Deep pattern length
- Flexible multi-level signaling & modulation
- Easy waveform creation using Tek software or MATLAB

**Pattern Generators**
Consistent application of patterns for validation & compliance at 40 Gbaud
- Easy to setup signal and add jitter impairments
- Real-time signal adjustability
- High BW, fast edge rates
- PRBS7-31 and user patterns

Baud Rate

56Gbaud

28Gbaud
PAM4 Generation & BER Analysis using Pattern Generators

BERT products bundled into a PAM4 system:
- Programmable pattern generator
- Programmable error detector
- Analysis software
- Broadband components (power combiners/attenuators)

PAM4 Pattern Generator
- Phase-aligned channels simplify multi-level signal generation
- User-programmable data patterns allow test of PAM4 custom data

PAM4 Error Detector
- BER measurements analyzes every bit of each pattern
- Contour plots, bathtub curves, total jitter analysis via software tools
- Can be used for BER measurements generated by PPG and/or AWG
**Test Methodologies for PAM Signaling Validation**

*Tektronix provides complete support for validation of PAM4 at 28 & 56G*

**Signal Generation**
- **PPG3204** 32Gb/s Pattern Generator
- **AWG70000 Series AWG**

**Device Under Test**
- Transceiver chipset,
- Gearbox

**Test Signal**
- or

**Signal Acquisition**
- Ped4000 40Gb/sec Error Detector
- DSA8300 Sampling Oscilloscope
- DPO70000 Real Time Oscilloscope

**Analysis Software**
- PED PAM4 BER Contour Analysis
- 80SJARB Jitter & Timing Analysis