Measuring Jitter in Ethernet and Fibre Channel Components

1 Overview

Accurate jitter measurement is a challenge for Ethernet and Fibre Channel components. While test equipment designed specifically for jitter measurement is available from multiple sources, this equipment can be cost-prohibitive or just too specialized for some applications. However, using a probe and a regular off-the-shelf digital sampling oscilloscope, accurate, reasonably fast deterministic-jitter measurements can be made - with nowhere near the financial outlay that designers have come to expect. Read on for step-by-step instructions on how this can be done for relatively short patterns.

2 Understanding Deterministic Jitter

Jitter can be grouped into two types: random (or unbounded) and deterministic (or bounded). Deterministic jitter includes all jitter that can be reproduced by controlled conditions. Some subsets of deterministic jitter are periodic jitter (PJ), pattern-dependent jitter (PDJ), duty-cycle distortion (DCD), and bounded uncorrelated jitter (BUJ).

These are the main causes of DJ:

- Baseline wander due to the presence of a low-frequency cutoff in the system. This effect creates jitter near long consecutive identical digits (CID) .
- Low system bandwidth can prevent some pulses from reaching a steady-state level. This causes jitter on isolated pulses (..010.. or ..101.. data sequences).
- Amplifier offsets cause pulse-width distortion (sometimes called duty-cycle distortion) on every transition.
- Nonlinear amplifier effects have unpredictable jitter effects, but often cause jitter after long CID.
- Power-supply noise and crosstalk are effects that can result in jitter not related to the data input; sometimes called bounded uncorrelated jitter (BUJ).

3 Pattern Selection

Measurement of deterministic jitter requires a known data pattern. "K28.5" is a pattern commonly specified for jitter measurement in Fibre Channel and Ethernet systems operating between 1Gb/s and 3.125b/s. This pattern is a special character in the 8B/10B-coding table, and often marks the beginning or end of a frame. A repeating K28.5 sequence (composed of alternating K28.5+ and K28.5-) contains the symbols 00111110101100000101. This pattern contains five consecutive 1's and five consecutive 0's, (the longest consecutive identical digits found in 8B/10B coded data.) It also contains an isolated 1- '010' and an isolated 0 - '101'. A repeating K28.5 pattern has a 50% transition density and a 50% mark density. These characteristics make the K28.5 pattern useful for measuring deterministic jitter caused by baseline wander, low bandwidth, and offset. Other patterns may be more appropriate for measuring jitter due to nonlinear effects.

4 Why Measure DJ?

In a fiber optic communications system, jitter accumulates at each component (see Figure 1). At the receiver, a clock and data recovery circuit (CDR) analyzes the data and extracts the serial rate clock. At the CDR, jitter appears as small frequency changes in the clock rate. Slow changes (low-frequency jitter) can be tracked easily. Fast changes (high-frequency jitter) cannot be easily tracked. A typical jitter-tolerance requirement is 0.75UI (1/4 of the eye is open). If too much high-frequency jitter is present at the receiver, the clock cannot be extracted, and data communications contain excessive errors. To prevent this situation, systems designers use a jitter budget, as shown in Table 1. Note that deterministic jitter accumulates linearly (all sources are added together in a worst-case situation), whereas random jitter accumulates geometrically (square root of sum of squares). This assumes that the noise sources causing random jitter are independent and uncorrelated. Separating these jitter components allows the individual components to generate more random jitter, and has several benefits such as longer link distance or lower-cost components. Note that a DJ measurement error (which makes a component's DJ appear larger) is subtracted directly out of the budget. An RJ measurement error is not as severe.

5 Deterministic Jitter Measurement

Three common methods for measuring DJ with an oscilloscope are the eye diagram, the averaged eye diagram, and the averaged crossing measurement. Table 2 compares the properties of these methods.

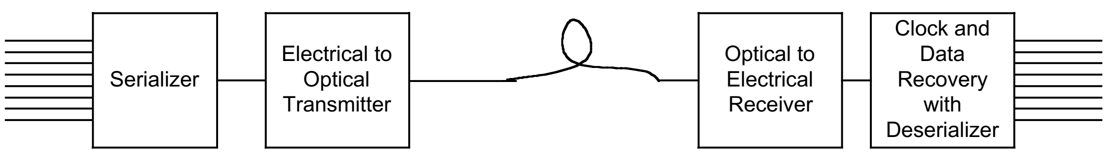

Figure 1. Typical fiber optic link

Table 1. Example of a Jitter Budget

System Element	Total Jitter UI	Deterministic Jitter (UI)	Random Jitter (UI)
Serializer	0.240	0.100	0.140
Optical Transmitter Output	0.284	0.100	0.184
Fiber Optic Cable	0.170	0.050	0.120
Receiver	0.332	0.212	0.120
Summed Jitter at CDR Input	0.749	0.462	0.287

Table 2. Comparison of Jitter Measurement Methods

	Oscilloscope Measurement Method		
Measurement Features (assuming a K28.5 pattern is used)	**Eye Diagram**	**Averaged Eye Diagram**	**Averaged Crossing Measurement**
Measurement Speed	Fast	Slow	Slow
Accuracy and Repeatability	Poor	Good	Good
Capability to Make Low-Jitter Measurements by Removing DJ from Source and Measurement Device	No	No	Yes

6 Eye Diagram

The eye diagram provides a quick measurement of total jitter (deterministic and random jitter combined). Multiple waveform crossings are displayed simultaneously on an overlaid time base. The primary advantages of the eye diagram are speed and ease of setup. A typical setup showing the test equipment and device under test (DUT) is shown in Figure 2. Unfortunately, the eye diagram does not allow separation of random and deterministic jitter, nor does it allow removal of jitter caused by the test system.

When using eye diagrams, be aware that the triggering method can hide much of the DJ. For example, suppose that a pattern generator provides a trigger on every tenth clock cycle. If the pattern length is even, the oscilloscope will never trigger on an odd bit, effectively hiding some of the transitions. Using an odd-length pattern or triggering on the pattern generator clock output will avoid this problem.

If the device under test includes a time regenerating circuit (Clock recovery or retimer), a Golden PLL should be used to recover a clock for oscilloscope triggering. The properties of a Golden PLL are protocol specific. Also, if the device under test includes optical components, it will be necessary to add appropriate optical transducers (optical to electrical, or electrical to optical converters). For simplicity, it is assumed that optical convertors or Golden PLL's are are included in the test equipment if needed.

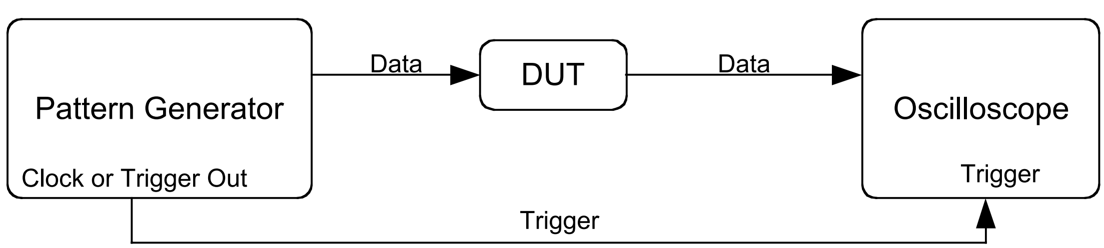

Figure 2. Measurement setup for the eye diagram and the averaged eye crossing measurement

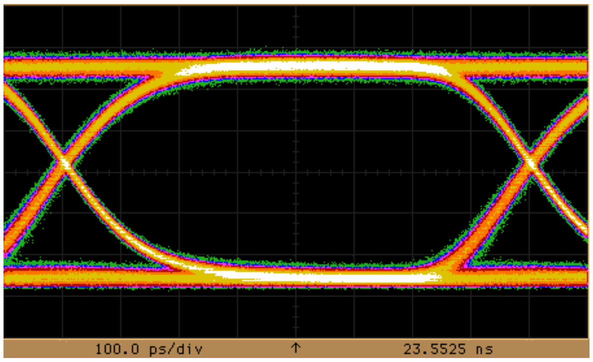

Figure 3. Eye diagram

6.1 Oscilloscope Averaging Mode

Some oscilloscopes provide an averaging mode that removes random jitter in eye-diagram mode. This mode provides more accuracy and repeatability than a basic eye diagram, but the same cautions about triggering apply.

6.2 Averaged Crossing Measurement

The averaged crossing measurement method provides an accurate measurement of most sources of deterministic jitter on a K28.5 pattern. The procedure is as follows:

1. Connect the DUT as shown in Figure 2. Trigger the oscilloscope on the pattern.
2. Display the entire K28.5 pattern on the oscilloscope screen.
3. Calculate the expected crossing times for each transition on the screen (ideally, they are one-unit interval apart, skipping unit intervals where no transition occurs).
4. Average heavily.
5. Tabulate the crossings and calculate the jitter.

Table 3. Averaged Crossing Jitter Calculation

Unit Interval	Pattern Data	Crossing #	Measured Crossing Time	Normalized Time	Expected Crossing Time	Jitter
0	0					
1	0					
2	1	1	t_1	$tn_1 = t_1 - t_1 = 0$	$et_1 = 0$	$J_1=0$
3	1					
4	1					
5	1					
6	1					
7	0	2	t_2	$tn_2 = t_2 - t_1$	$et_2 = et_1$+5UI	$J_2 = tn_2 - et_2$
8	1	3	t_3	$tn_3 = t_3 - t_1$	$et_3 = et_1$+6UI	$J_3 =t\ n_3 - et_3$
9	0	4	t_4	$tn_4 = t_4 - t_1$	$et_4 = et_1$+7UI	$J_4 = tn_4 - et_4$
10	1	5	t_5	$tn_5 = t_5 - t_1$	$et_5 = et_1$+8UI	$J_5 = tn_5 - et_5$
11	1					
12	0	6	t_6	$tn_6 = t_6 - t_1$	$et_6 = et_1$+10UI	$J_6 = tn_6 - et_6$
13	0					
14	0					
15	0					
16	0					
17	1	7	t_7	$tn_7 = t_7 - t_1$	$et_7 = et_1$+15UI	$J_7 = tn_7 - et_7$
18	0	8	t_8	$tn_8 = t_8 - t_1$	$et_8 = et_1$+16UI	$J_8 = tn_8 - et_8$
19	1	9	t_9	$tn_9 = t_9 - t_1$	$et_9 = et_1$+17UI	$J_9 = tn_9 - et_9$
20	0	10	t_{10}	$tn_{10} = t_{10} - t_1$	$et_{10}= et_1$+18UI	$J_{10} = tn_{10} - et_{10}$
				Peak-to-peak DJ = max ($J_1..J_{10}$) - min($J_1..J_{10}$)		

6.3 To Obtain Best Accuracy

- Ensure that the signal fills at least 2/3 of the vertical area available. This optimizes the digitizing capabilities of the oscilloscope.
- Set the main position of the scope as small as possible (keep the delay from trigger to display as short as possible, to reduce trigger jitter).
- Use maximum horizontal resolution (many horizontal points).
- Use heavy averaging (64 - 1000 averages) to remove random jitter.
- Note that periodic jitter and bounded uncorrelated jitter are not captured with an averaged oscilloscope waveform. Other methods should be used to measure these types of jitter. The averaged crossing measurement is appropriate when it can safely be assumed that the DUT does not generate these types of jitter.
- This technique is difficult to apply to systems employing scramblers, because the test patterns are much longer. For example, the 2^{23}-1 PRBS (pseudo-random binary sequence) pattern commonly used to test scrambled data systems is over 8 million bits in length. The averaged crossing measurement would be slow and inaccurate on such a long pattern.

7 Enhanced Accuracy

Many modern components have jitter that is comparable or less than the jitter of pattern generators and oscilloscopes. Accurately determining the jitter of these components requires determining the jitter introduced by the test system, then adjusting the measurement. The error of the measurement system can be measured by removing the DUT from the measurement setup, and determining the jitter on each transition of the data pattern. When the DUT is replaced in the measurement system, and jitter values are re-measured, the jitter contribution of the DUT can be determined mathematically. An enhanced accuracy setup is shown in Figure 4 and Table 4.

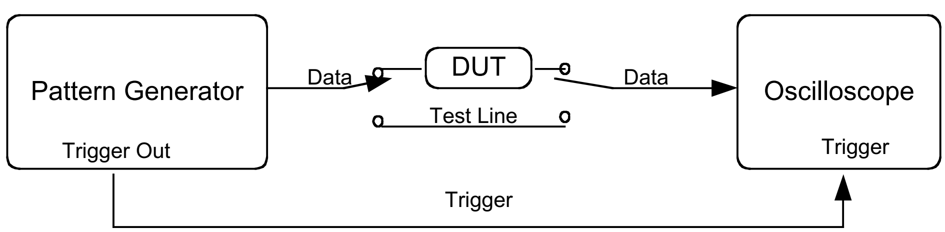

Figure 4. Test setup for enhanced accuracy

Table 4. Averaged Crossing Jitter Calculation with Enhanced Accuracy

Crossing #	System Time Crossing	DUT and System Time Crossing	Corrected Time Crossing	Normalized Time Crossing	Expected Crossing Time	Jitter
1	st_1	dt_1	$ct_1 = dt_1 - st_1$	$tn_1 = ct_1 - ct_1 = 0$	$et_1 = 0$	$J_1 = 0$
2	st_2	dt_2	$ct_2 = dt_2 - st_2$	$tn_2 = ct_2 - ct_1$	et_2	$J_2 = tn_2 - et_2$
3	st_3	dt_3	$ct_3 = dt_3 - st_3$	$tn_3 = ct_3 - ct_1$	et_3	$J_3 = tn_3 - et_3$
n	st_n	dt_n	$ct_n = dt_n - st_n$	$tn_n = ct_n - ct_1$	et_n	$J_n = tn_n - et_n$
		Peak-to-peak DJ = max $(J_1..J_n)$ - min$(J_1..J_n)$				

7.1 Removing Oscilloscope Wander

In Figure 4 and Table 4, oscilloscope time-base wander can be a substantial source of error. This is particularly severe in sequential time sampling oscilloscopes. A typical sequential time sampling scope can have a 100kHz sampling rate. If the horizontal resolution is 4000 points, then the time expired between the first and the last samples on the screen is 40ms. Significant time-base wander could occur in this time. The circuit shown in Figure 5 is suggested to reduce the wander error.

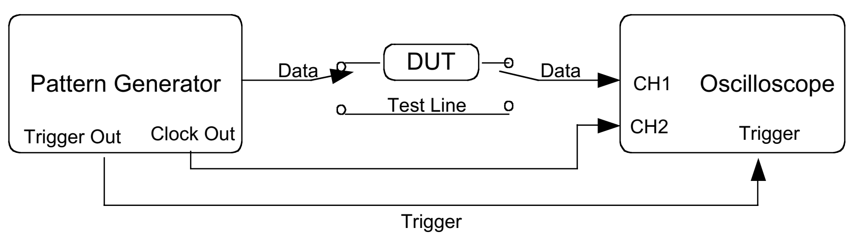

Figure 5. Setup for averaged crossing measurement with reduced oscilloscope wander

Table 5. Jitter Calculations for Averaged Crossing Measurement with Reduced Wander

Cross-ing #	**System Time Cross-ing**	**System Clock Crossing**	**Corrected System Crossing**	**DUT and System Time Crossing**	**DUT and System Clock Cross-ing**	**Corrected DUT and System Crossing**	**Corrected time Crossing**	**Normalized Time crossing**	**Expected Crossing Time**	**Jitter**
1	st_1	sc_1	$csc_1=st_1-sc_1$	dt_1	dc_1	$cdc_1=dt_1-dc_1$	$ct_1=cdc_1-csc_1$	$tn_1 = ct_1 - ct_1 = 0$	$et_1=0$	$J_1=0$
2	st_2	sc_2	$csc_2=st_2-sc_2$	dt_2	dc_2	$cdc_2=dt_2-dc_2$	$ct_1=cdc_2-csc_2$	$tn_2 = ct_2 - ct_1$	et_2	$J_2=tn_2 - et_2$
3	st_3	sc_3	$csc_3=st_3-sc_3$	dt_3	dc_3	$cdc_3=dt_3-dc_3$	$ct_1=cdc_3-csc_3$	$tn_3 = ct_3 - ct_1$	et_3	$J_3=tn_3 - et_3$
n	st_n	sc_n	$csc_n=st_n-sc_n$	dt_n	dc_n	$cdc_n=dt_n-dc_n$	$ct_1=cdc_n-csc_n$	$tn_n = ct_n - ct_1$	et_n	$J_n=tn_n - et_n$
								Peak to Peak DJ= max $(J_1..J_n)$ - min$(J_1..J_n$		

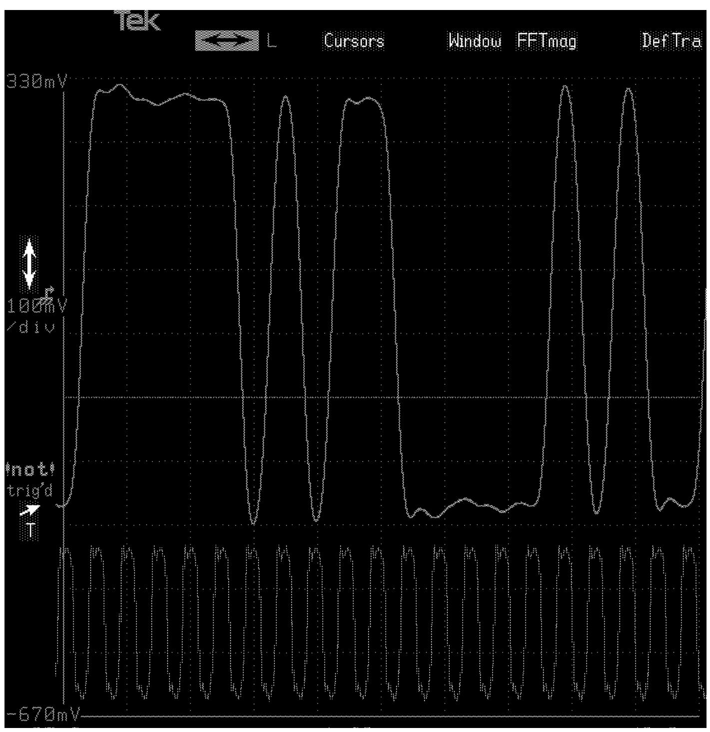

Figure 6. Example using the averaged eye crossing measurement with reduced oscilloscope wander

Table 6. Calculations for the Figure 6 Example

Crossing #	System Jitter	Total Jitter	DUT Jitter
1	0	0	0
2	11.8	-14.67	-26.15
3	-1.89	8.51	10.4
4	8.69	-12.61	-21.3
5	1.62	14.08	12.46
6	9.42	-17.81	-27.23
7	1.64	6.83	5.19
8	7.54	-11.72	-19.26
9	-1.72	8.37	10.09
10	8.64	-2.68	-11.32

Peak-to-peak jitter is (12.46 - -26.15) = 38.6 ps_{pp}

References:

- Fibre Channel FC-PH-3 Specifications
- Fibre Channel Methodology for Jitter Specification (MJS)
- Takasaki, Yoshitaka, *Digital Transmission Design and Jitter Analysis,* Artech House, Boston, 1991