Comparative Analysis of Date-Dependent Jitter
-Cases for PRBS and SDH/SONET Frames-

By Ken Mochizuki

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1. Introduction

When performing Jitter generation tests on optical transmitters for SDH/SONET/OTN, most device vendors use a data pattern with randomly generated transitions like a Non-Framed Pseudo-Random Bit Sequence (PRBS) as a test pattern. In contrast, when these devices are installed in transmission equipment, the final Jitter evaluation is performed with an actual data pattern used by SDH/SONET/OTN which is Framed. As a consequence, there is often a problem of inconsistent Jitter values between device vendors and equipment vendors. There are two main reasons for this difference. First, the theoretical difference of jitter values of the device under test (DUT) for the Non-Framed and Framed signals, and parameters of DUT causing the difference, have never been verified quantitatively. Second, the measurement error of the measurement method used by many Jitter testers (convert Data signal to Clock and measure Clock Jitter) for the Non-Framed and Framed signals has never been quantified and verified. This paper examines how the test data pattern affects the jitter results by simulating measuring equipment modeling the DUT and Jitter measurement method.

2. Evaluation Procedure

When signal Jitter components are classified according to their characteristics, we find Deterministic Jitter (DJ) and Random Jitter (RJ). Additionally, the Deterministic Jitter can be separated into Data Dependent Jitter (DDJ) and Periodic Jitter (PJ). Since DDJ is directly impacted by the transmission data pattern, only the measuring instrument simulation examines the DDJ Jitter component. The cause of DDJ is understood to be due to waveform distortion caused by the DUT frequency bandwidth and reflection of the transmission signal[1].

In this simulation, we evaluate quantitatively that DDJ can be caused by the frequency bandwidth of the DUT and Jitter measurement instrument, as well as the amount of DDJ difference between data patterns. First, in Evaluation 1, we quantified the DDJ measurement error of the Jitter measurement method used by most Jitter testers (convert Data signal to Clock signal and measure Clock Jitter) as illustrated in the setup in Fig. 1. Here, the Non-Framed or Framed signals is used as the evaluation input signal. Next, in Evaluation 2, we quantified theoretically how the Jitter in the DUT output signal changes with the Non-Framed and Framed signals using the setup shown in Fig. 2. Here, the HPF and LPF are used to model the frequency bandwidth of DUT due to AC coupling and high-frequency cutoff components. The impact on DDJ caused by changing the cutoff frequency of the HPF and LPF is examined.

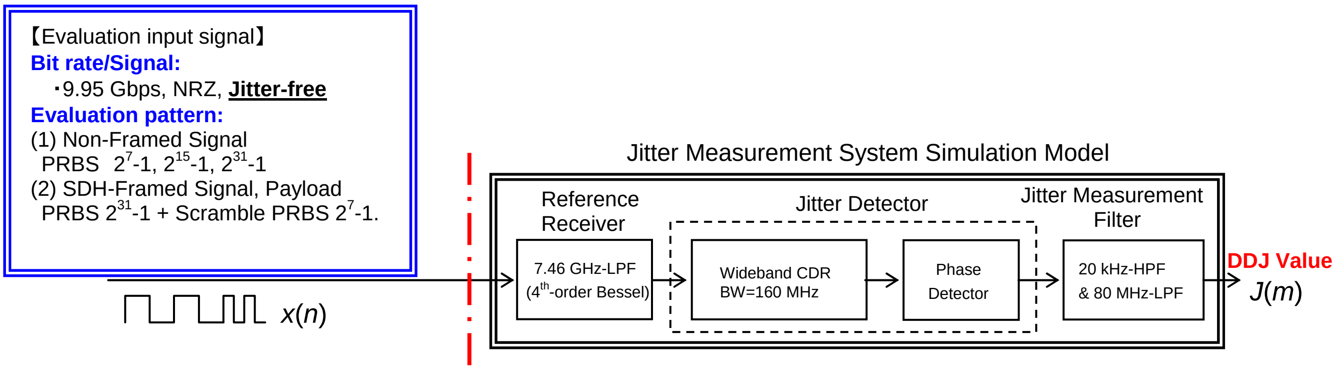


Fig. 1 Evaluation 1 of Data-Dependent Jitter Error for Jitter Measurement Method used by Jitter Testers

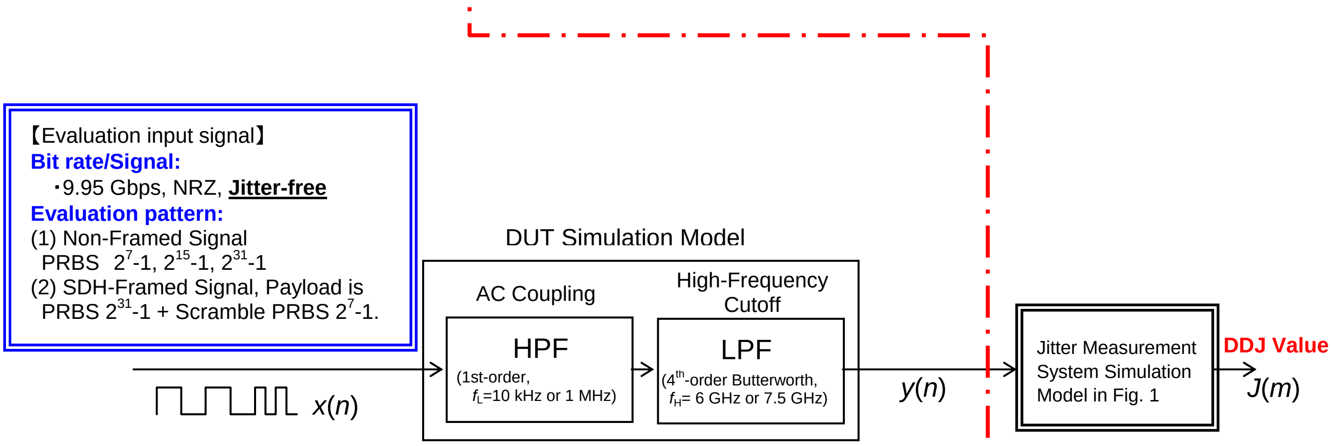


Fig. 2 Evaluation 2 of DUT Data-Dependent Jitter

3. Evaluation 1: Data Dependent Jitter error due to Jitter Measurement System

3.1 Evaluation 1 Simulation Method

Figure 1 shows a measurement system in which a pseudo-random Jitter-free NRZ 9.95 Gb/s data signal with the discrete series *x*(*n*) (*n* = 0, 1, 2,....) is input as the evaluation signal. Here the *x*(*n*) value is either 1 (High level) or -1 (Low level), The sampling interval is set to 1/1000th of the assumed 1 unit interval (UI) to obtain a simulation resolution of 1 mUI (Refer *x*(*n*) in Figure.3). Three Non-Framed PRBS 2^7-1, 2^{15}-1, and 2^{31}-1 signals and a STM-64 SDH Framed signal were used as the *x*(*n*) data pattern. The SDH Framed payload was a PRBS 2^{31}-1 pattern scrambled by a PRBS 2^7-1 pattern. Each PRBS (below) was generated using a polynomial complying with ITU-T Rec. O.150, and O.151.

PRBS 2^7-1: $1 + X^6 + X^7$

PRBS 2^{15}-1: $1 + X^{14} + X^{15}$

PRBS 2^{31}-1: $1 + X^{28} + X^{31}$

The transfer function of the reference receiver configuring the Jitter measurement system uses a 4^{th}-order Bessel filter with a cutoff frequency of 0.75 times the data rate (i.e. 7.46 GHz) in compliance with ITU-T Rec. ANNEX B/G.957. The Jitter detector simulation model, the second element, refers to the phase detection method under discussion in ITU-T Q5/Study Group 4[2]. In this phase detection method, after the input data signal is converted to a clock signal with a center frequency of 9.95 GHz by wideband clock recovery (W-CR), the Jitter at each rising edge of the clock signal is found using phase detection. In this simulation, the W-CR passband was set to 160 MHz which was twice the upper Jitter measurement band (80 MHz). The Jitter measurement filter, the third element, is a filter for suppressing high and low Jitter as described in ITU-T Rec. G.783 and G.825. It is defined as a 20-kHz 1^{st}-order HPF and a 80-MHz 3^{rd}-order LPF. A DDJ series of *J*(*m*) (*m* = 0, 1, 2, …) with a sampling interval equivalent to 1 UI is output from the Jitter measurement system.

3.2 Evaluation 1 Simulation Results

Table 1 lists the peak-to-peak DDJ values for the *J*(*m*) time series (*m* = 0, 1, 2, …, *M* -1) obtained from the evaluation system shown in Fig. 1. DDJ is generated in the measurement system even though the input signal is Jitter-free, because when the data signal is converted to a clock signal by W-CR of the phase detector. Timing errors occur in the recovered clock signal corresponding to the variance of time intervals of High and Low levels in the data. Table 1 shows that the data-dependent measurement error for the Jitter measurement method used by most Jitter testers is 5 mUIpp max. This is much smaller than the 100 mUIpp maximum permissible Jitter for measurement equipment specified by

ITU-T Rec. G.783.

Table 1 Jitter Measurement System DDJ Error for Evaluation 1 Simulation

Units: mUIpp

Data Pattern			
Non-Framed Signal			SDH Framed Signal
PRBS 2^7-1 (M = 127)	PRBS 2^{15}-1 (M = 32767)	PRBS 2^{31}-1 ($M = 20\times10^6$)	Payload; PRBS 2^7-1 +Scramble PRBS 2^{31}-1 ($M = 20\times10^6$)
1	**4**	**5**	**4**

Here, the sample size M for $J(m)$ used at DDJ evaluation is $M = 2^7-1 = 127$ for a Non-Framed PRBS 2^7-1 and $M = 2^{15}-1 = 32767$ for Non-Framed PRBS 2^{15}-1. In the case of Non-Framed PRBS 2^{31}-1 and an SDH Framed signal, the sample size M was based on 2 x 10^6 samples. This size is used because an extremely large amount of computation time is required for the maximum pattern length of a Non-Framed PRBS 2^{31}-1 and an SDH Framed signal. However, this 20 x 10^6 sample was adjusted to include a contiguous High level of 31 UI for PRBS 2^{31}-1, or a contiguous High level of 38 UI for the payload of SDH Framed signal. This High level length occurs only once in each maximum pattern length. Consequently, despite using a 20 x 10^6 sample, it is possible to obtain approximately the same DDJ as in evaluation using the maximum pattern length. Note that DDJ depends not only on the maximum length of High level (or Low level) included in the pattern but also on its adjacent patterns. This means that the results different from Table 1 are predicted when using other polynomials to generate PRBS.

4. Evaluation 2 DUT Data Dependent Jitter

4.1 Evaluation 2 Simulation Procedure

The laser driver in an actual optical transmitter often has AC coupling at both the input and output sections[3]. AC coupling cuts off low-frequency components including DC, degrading the data signal waveform. In Fig. 2, the DUT AC coupling was modeled using a 1st-order HPF with a cutoff frequency f_L of 10 kHz or 1 MHz. In contrast, a 4th-order Butterworth LPF with a cutoff frequency f_H of 6 GHz or 7.5 GHz was used to model the optical transmitter high frequency cutoff. Generally, it is believed that the primary factor generating DDJ is the HPF cutting off DC components, but the LPF distorting the data signal waveform is also a significant cause of DDJ [3]. A Butterworth filter is used as LPF, because some frequency characteristics of actual optical transmitters resemble a Butterworth filter.

The same four data patterns as used in Evaluation 1 were used as the DUT input signal $x(n)$. The DDJ of the DUT output signal $y(n)$ was detected using the same jittter measurement system simulation model as in Fig. 1. Figure 3 shows an example of the DUT input and output signals *x(n)* and *y(n)* obtained by the simulation shown in Fig. 2.

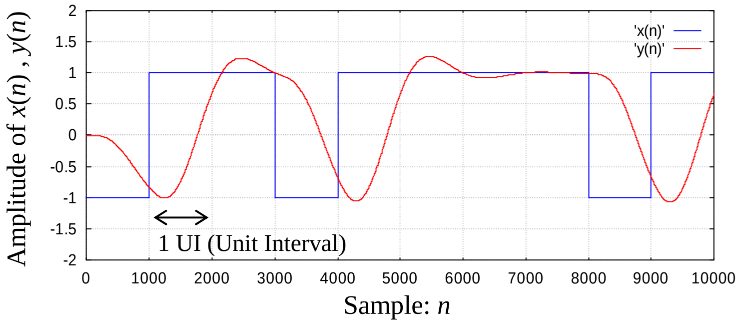


Fig. 3 DUT Input/Output Waveform from Evaluation 2 Simulation
(HPF: f_L = 10 kHz, LPF: f_H = 6 GHz)

4.2 Evaluation 2 Simulation Results

Table 2 shows the DDJ values for the DDJ time series *J(m)* (*m* = 0, 1, 2, …, *M*-1) obtained using the simulation model in Fig. 2. In simulations No. 1 to No. 8, the DUT was modeled with a combination of HPF and LPF with different cutoff frequencies (f_L and f_H). The results are explained in sequence below.

Table 2 DDJ of DUT using Evaluation 2 Simulation Units: mUIpp

Sim. No.	DUT Bandwidth Limit (–: No Frame)		Data Pattern			
			Non-Framed Signal			SDH Framed Signal
	f_L of HPF	f_H of LPF	PRBS 2^7-1 (*M* = 127)	PRBS 2^{15}-1 (*M* = 32767)	PRBS 2^{31}-1 (*M* = 20×10^6)	Payload: PRBS 2^{31}-1 +Scramble PRBS 2^7-1 (*M* = 20×10^6) (See Fig. 4.)
1	10 kHz	–	**1**	**4**	**5**	**4**
2	1 MHz	–	**1**	**4**	**5**	**4**
3	–	7.5 GHz	**1**	**5**	**8**	**7**
4	–	6 GHz	**1**	**7**	**37**	**60**
5	10 kHz	7.5 GHz	**1**	**5**	**8**	**7**
6	1 MHz	7.5 GHz	**1**	**7**	**16**	**8**
7	10 kHz	6 GHz	**1**	**7**	**38**	**61**
8	1 MHz	6 GHz	**1**	**8**	**45**	**61**

(Simulations No. 1 – No. 2)

Simulations No. 1 and No. 2 modeled the DUT using only a HPF. The DDJ values for each data pattern are extremely small and are the same as the Jitter measurement error in Table 1. In other words, the DDJ resulting from the HPF is sufficiently small to be ignored as measurement error.

(Simulations No. 3 – No. 4)

Simulations No. 3 and No. 4 modeled the DUT using only a LPF. With a Non-Framed

PRBS 2^{15}-1, 2^{31}-1 and SDH Framed signal, the DDJ increased. Especially in simulation No. 4, the DDJ values with a Non-Framed signal of PRBS 2^{31}-1 and an SDH Framed signal are extremely large at 37 mUIpp and 60 mUIpp, respectively. This corresponds with the large waveform distortion for *y(n)* due to the low value of f_H as shown in Fig. 3.

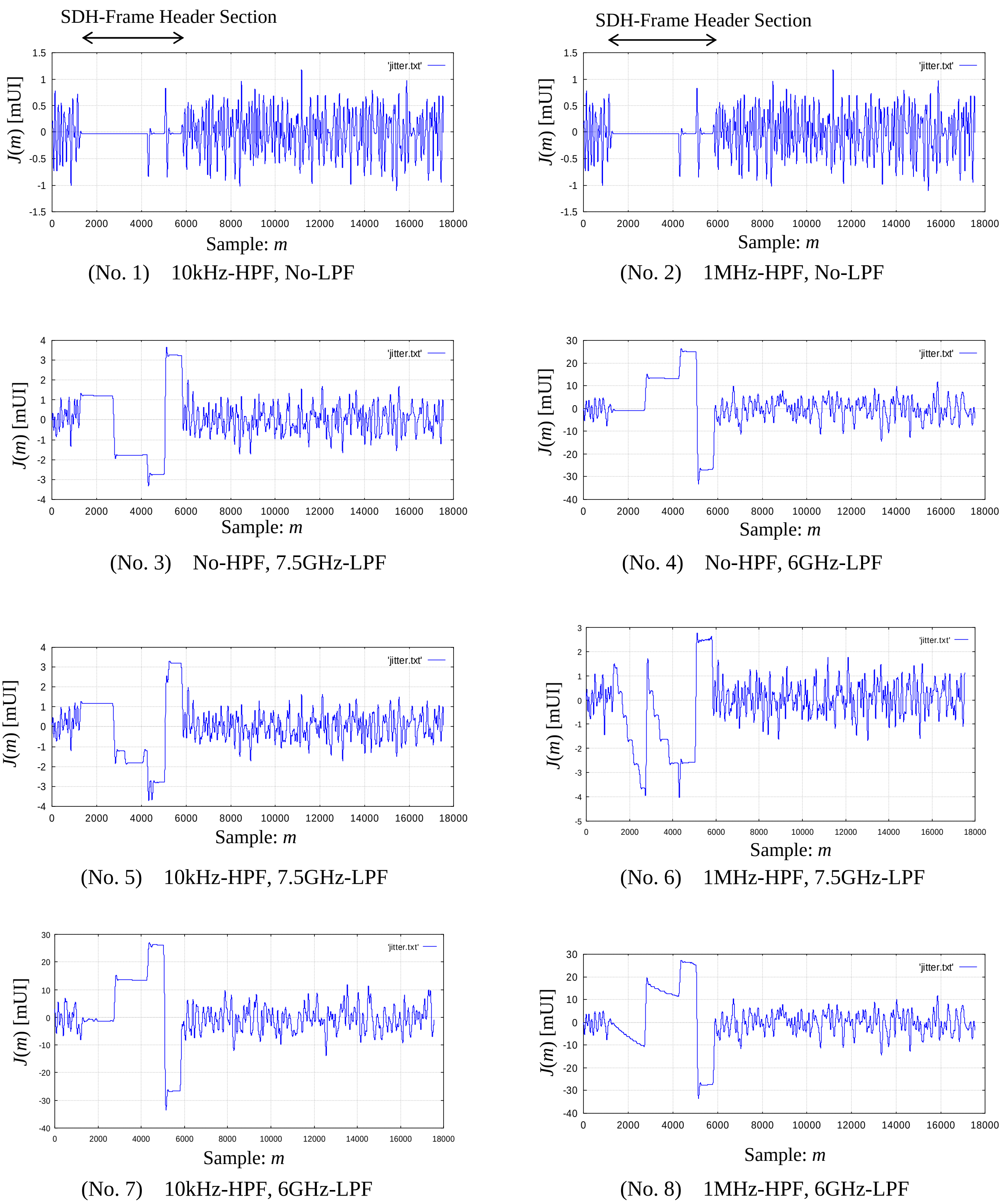
(Simulations No. 5 – No. 8)
Simulations No. 5 to No. 8 modeled a DUT using both a HPF and LPF. Due to the effect of both the HPF and LPF, with a Non-Framed PRBS 2^{31}-1 signal, the DDJ is larger than with only a LPF. For example, the DDJ for No. 4 is 37 mUIpp but 45 mUIpp for No. 8. In contrast, with an SDH Framed signal the effect of adding a HPF is small.

Figure 4 shows parts of the DDJ time series $J(m)$ when using an SDH Framed signal in simulations No. 1 to No. 8. In each graph, J(m) for m = 1000 to 6000 are the DDJ samples at the header section of the SDH frame. (Note that the header section is not scrambled by PRBS 2^7-1.) In simulations No. 1 and No. 2, which modeled the DUT as a HPF only, DDJ is determined by Jitter generated at the payload section. Alternatively, in simulations No. 3 to No. 8, which all took a LPF into account, DDJ is determined by Jitter generated at the header section[4].

4.3 Remarks on Evaluation 2

In each of the simulations in Table 2, the difference in the DDJ generated with Non-Framed PRBS 2^7-1 and PRBS 2^{31}-1 has a wide range from 5 to 45 times. The increase in the DDJ with the long maximum pattern length of the PRBS is thought to be due to the occurrence of long High and Low levels contained in the data pattern.
Since the SDH Framed signal payload is a PRBS 2^{31}-1 pattern scrambled by a PRBS 2^7-1 pattern, the longest High level is 38 UI, This length is longer than for the Non-Framed PRBS 2^{31}-1. Irrespective of this, the DDJ for the SDH Framed signal in simulations No. 1 to No. 3, No. 5, and No. 6 is smaller than for the Non-Framed PRBS 2^{31}-1 pattern. This occurs because a 3-tap polynomial generates the PRBS 2^{31}-1 pattern in which the long High (or long Low) level strings occur closely, making it relatively easy to generate large DDJ by filtering.
On the other hand, with an SDH Framed scrambled PRBS 2^{31}-1 pattern, it is hard to generate a large DDJ because the above-described bias is dispersed.
As is clearly indicated in Fig. 4, with an SDH Framed signal, there is a tendency to generate larger DDJ in the header section due to the LPF effect. As a result, there is significant inconsistency in the Jitter values between an SDH Framed signal and a

Non-Framed signal even when the SDH Framed payload is a PRBS2^{31}-1 pattern. Consequently, the best test pattern to use for evaluating DUT Jitter should be the SDH Framed pattern used at the final equipment testing.



(No. 1) 10kHz-HPF, No-LPF

(No. 2) 1MHz-HPF, No-LPF

(No. 3) No-HPF, 7.5GHz-LPF

(No. 4) No-HPF, 6GHz-LPF

(No. 5) 10kHz-HPF, 7.5GHz-LPF

(No. 6) 1MHz-HPF, 7.5GHz-LPF

(No. 7) 10kHz-HPF, 6GHz-LPF

(No. 8) 1MHz-HPF, 6GHz-LPF

Fig. 4 DDJ Time Series for SDH Framed Signals in Table 2

6. Conclusion

We generated DDJ using the DUT low- and high-frequency cutoff. The dependency of DDJ on the transmission data pattern was verified by a computer simulation model. Evaluation No. 1 using the Jitter measurement method used by most Jitter testers confirms that the DDJ theoretical value is 5 mUIpp max. (@9.95 Gbps). Moreover, Evaluation No. 2 combining a HPF and LPF as the DUT model shows that DDJ is increased more by the LPF than HPF. Additionally, the difference between DDJ for Non-Framed PRBS 2^7-1 and PRBS 2^{31}-1 pattern signals varies significantly from 5 to 45 times depending on the HPF and LPF combination. With an SDH Framed signal, larger DDJ is generated at the unscrambled header section than the payload section due to the LPF effect. As a result, it is clear that there is significant inconsistency in the Jitter values between an SDH Framed signal and a Non-Framed signal even when the SDH Framed payload is a PRBS2^{31}-1 pattern. In other words, we have confirmed that the test pattern used for device Jitter evaluation must be identical to the Framed pattern used at the final equipment testing.

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