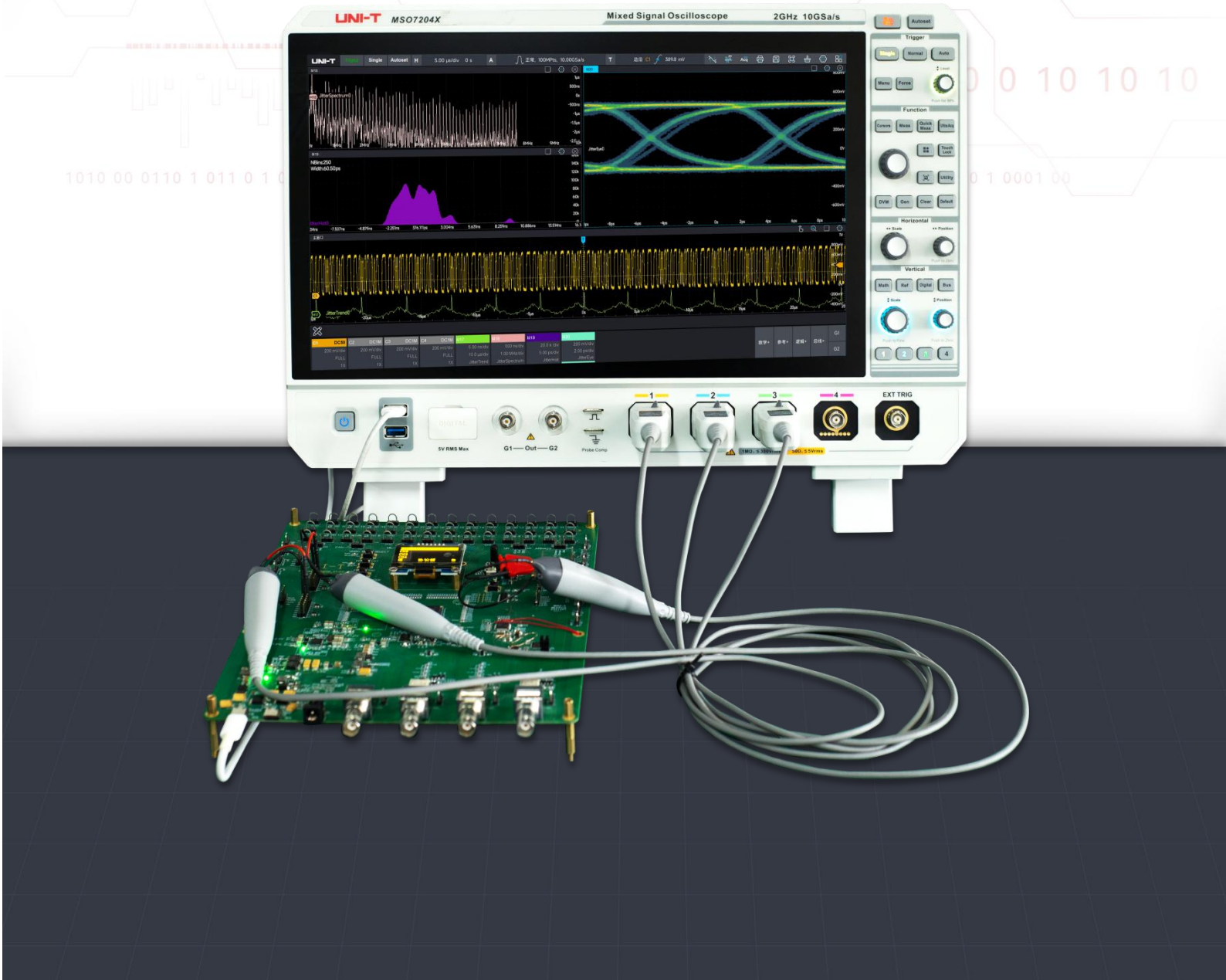
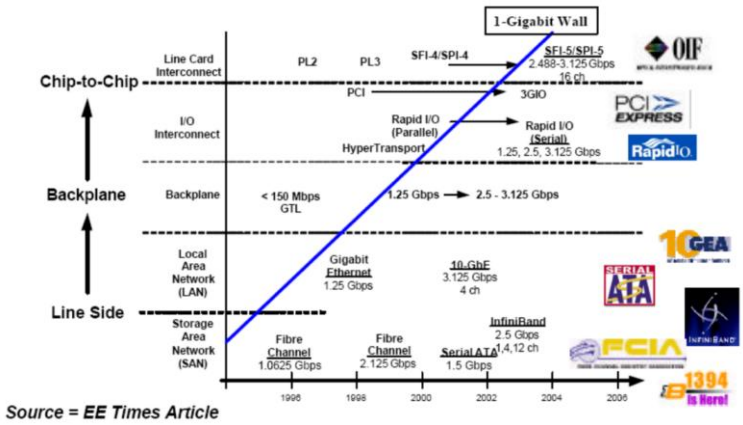
UNI-T

Jitter Analysis and Eye Diagram in High-Speed Signal Integrity Testing



The Significance of High-Speed Signal Integrity Testing

With the rapid development of electronic technology, the transmission rate of digital signals continues to increase, and the symbol period (the duration or period of a symbol) becomes narrower and narrower. This makes the signal more susceptible to various interferences and losses during transmission. Signal integrity testing can help engineers accurately evaluate signal quality and predict the performance of the system in actual operation, thereby avoiding potential problems in the design stage. Through signal integrity testing, circuit design can be optimized, appropriate components and wiring methods can be selected, and the anti-interference ability and stability of the system can be improved.



Introduction to High-Speed Serial Bus

Advantages:

1. The clock rate of the parallel bus is physically limited to around 1 GHz, 2 GHz because the skew introduced by a single clock and data line will cause errors at higher rates. The serial bus effectively solves this problem.

2. It transmits with differential signals and has a high common-mode rejection ratio.

3. It uses an embedded clock, eliminating the delay error between clock and data transmission.

4. Multiple serial links can be coherently bundled together to achieve higher data throughput, and PCB wiring is also more concise.

5. Longer transmission distance and faster transmission speed. For example, the transmission rate of a single lane of USB3.2 can reach 10 Gbps, and the higher USB4.0 can reach 20 Gbps.

Disadvantages:

1. The symbol period is getting narrower. When the signal is higher than 5 Gbps, the signal quality will bring great challenges to analog design.

A symbol is the basic unit in a digital communication system. A symbol can include one binary digit "1" or "0", or two binary digits "00", "01", "10", "11", and of course, it can also include three or more

binary digits. The length of the duration of this symbol is the symbol period. The narrower the symbol period, the higher the signal rate because more symbols need to be transmitted in a unit time, which requires a shorter symbol period.

2. High-quality PCBs, connectors, and cables are required to ensure the perfect transmission of high-speed signals.

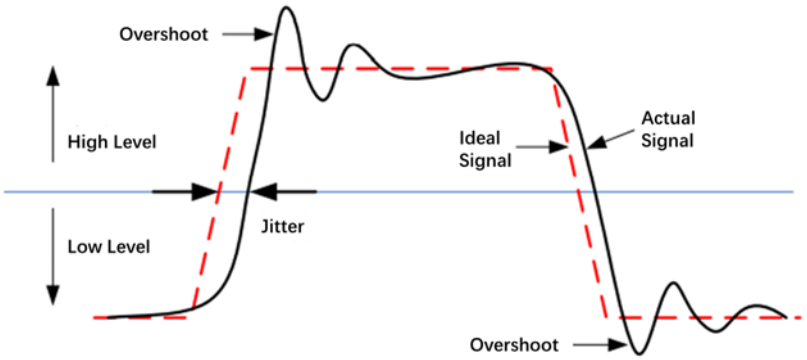
3. Appropriate technologies need to be considered when designing high-speed serial links to minimize signal distortion.

In such a fast signal environment, signal integrity testing becomes particularly important. Especially the jitter of data and the evaluation of signal quality using eye diagrams are the most commonly and directly used methods by engineers.

Jitter in High-Speed Signals

The Concept of Jitter:

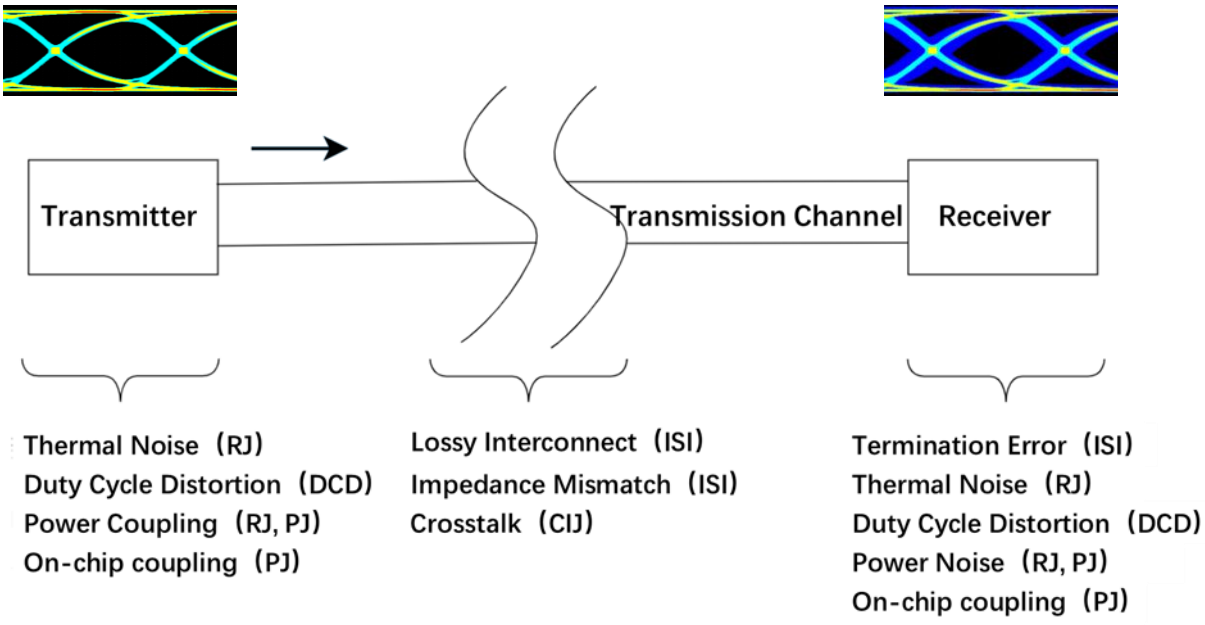
Jitter refers to the deviation between the ideal edge and the actual edge of a signal. The sampling clock is the reference for signal communication. If the sampling clock contains jitter, it will cause the signal waveform to deform. The deviation of the actual signal from the ideal situation can be analyzed from two aspects: amplitude offset and timing offset. The offset of the signal amplitude is defined as amplitude noise (referred to as noise for short), and the offset in time is defined as timing jitter (referred to as jitter for short). Noise and jitter are essentially errors. The difference is that noise is an error in the vertical direction and always exists, while jitter is an error in the horizontal direction and only exists at the signal edge transition moment.



The Sources of Jitter:

When the signal passes through a long transmission channel between the transmitter and the receiver, due to various factors such as noise, mechanical noise, crosstalk between signals, scattering effect, impedance mismatch, or signal jitter (PSIJ) caused by poor power quality, the signal will not maintain its original characteristics when it reaches the receiver. As shown in the following figure: if the signal jitter is too large and the eye diagram closes, the receiver will not be able to

recognize the information transmitted by the signal, resulting in errors, information loss, system failure, or communication interruption.

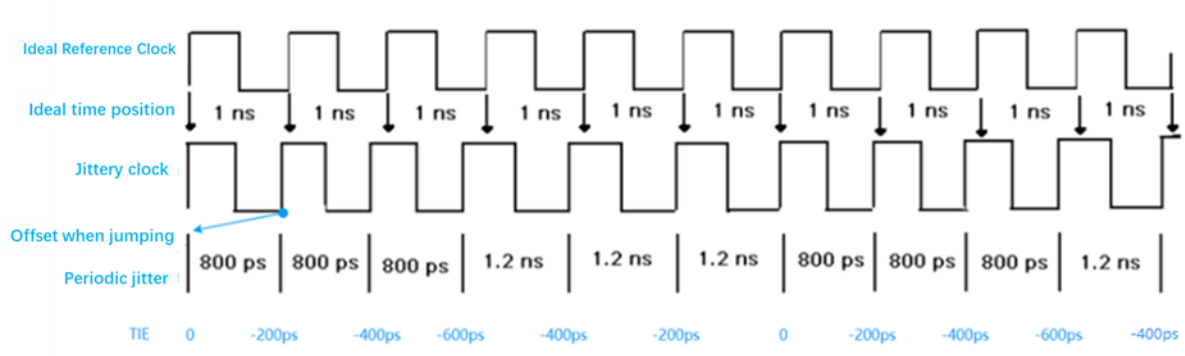


TIE (Time Interval Error):

TIE is the timing error of the signal relative to the reference clock. In a high-speed digital system, TIE is jitter. In jitter measurement, the edge of the measured signal is compared with the ideal edge established by clock recovery, and all signal intervals are measured according to the ideal data rate. The calculation method of TIE is as follows:

TIE_n represents the jitter of the Nth edge of the signal, t_n represents the time of the Nth edge of the signal, and t_n (ref) represents the time of the Nth edge of the reference clock.

$$TIE_n = t_n - t_n^{(ref)}$$



Period Jitter

Period jitter refers to the deviation of each period in a periodic signal from its average period. Specifically, it involves measuring the length of a single clock cycle (from rising edge to rising edge), waiting for a random number of clock cycles, calculating the average period, and determining the period jitter as the difference between each period length and the average period. The calculation formula is as follows:

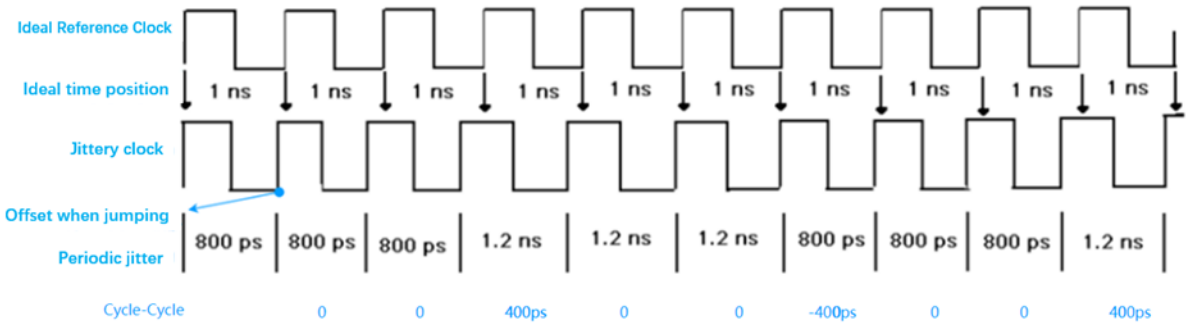
$$DJ=max\ (|T_i-T_{avg}|)\ -min\ (|T_i-T_{avg}|)$$

where: DJ represents the period jitter, Ti represents the length of the its period, and T_{avg} represents the average period length.

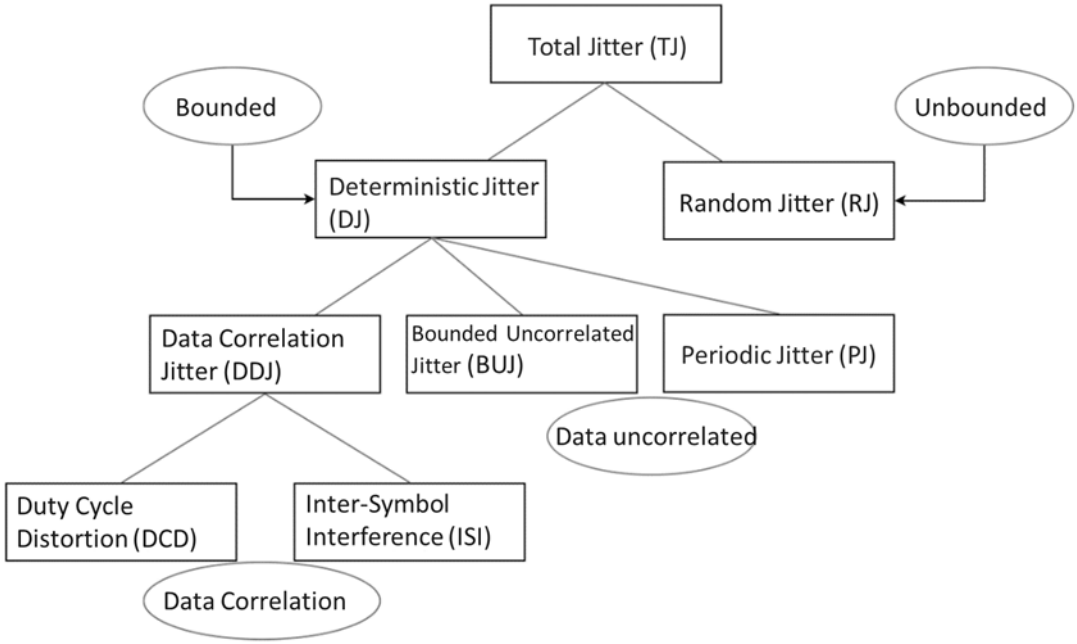
Cycle-Cycle Jitter

Cycle - cycle jitter: the jitter of adjacent cycles. Measure the first signal cycle, and then subtract the first signal cycle from the second signal cycle, and so on.

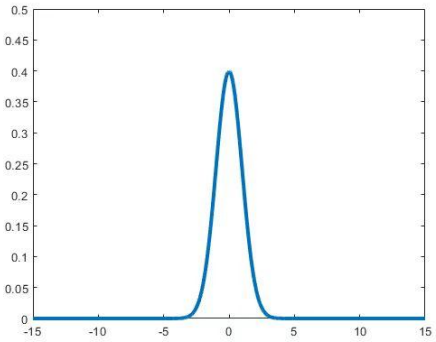
$$P_{(n+1)} - P_{(n)}$$



Jitter Decomposition:

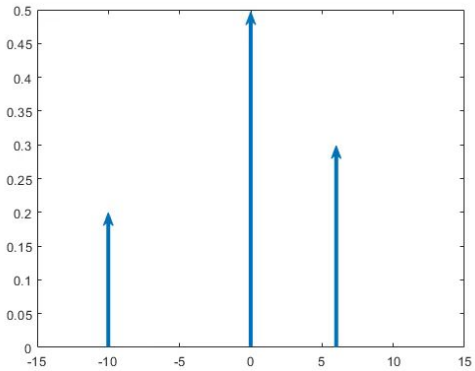


RJ (Random jitter): Generally, the probability density function (PDF) of random jitter conforms to the Gaussian normal distribution. Theoretically, the more samples, the wider the test distribution range. When the sample size is large enough, its distribution range approaches infinity. Therefore, it is unbounded. Its size is usually represented by the standard deviation σ. RJ mainly comes from internal thermal phenomena, vibrations of thermal molecules and atoms, mechanical noise, external cosmic rays, etc., and cannot be eliminated.



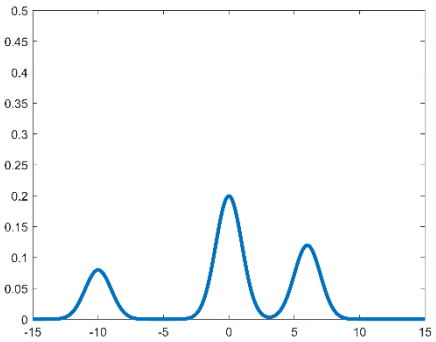
Random jitter is Gaussian distributed and unbounded

DJ (Deterministic jitter): DJ is not Gaussian distributed. DJ is bounded, and its probability density function (PDF) is discretely distributed.



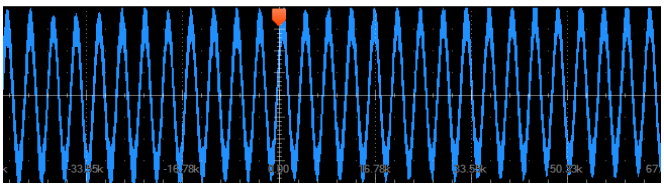
Deterministic jitter is discretely distributed with bounded

TJ (Total jitter): The total jitter estimated based on the bit error rate. The jitter distribution we see in the jitter histogram is TJ, and its probability density function is the convolution of DJ and RJ.

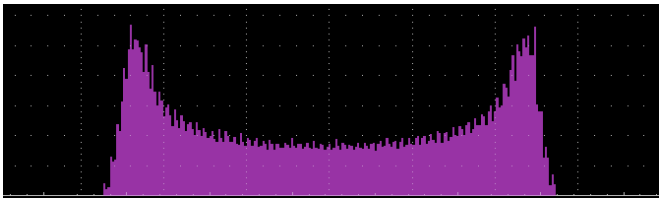


TJ can be approximated as a convolution of DJ and RJ,
and its histogram contains the components of DJ and RJ

PJ (Periodic jitter): Refers to the repetitive and periodic variation of TIE (Time Interval Error) over time. The reason for its generation may be that the system is modulated or interfered by a specific frequency signal inside, and its trend graph also shows periodic changes, such as switching power supply noise or local RF carrier. In addition, the instability of the clock recovery PLL may also cause periodic jitter.

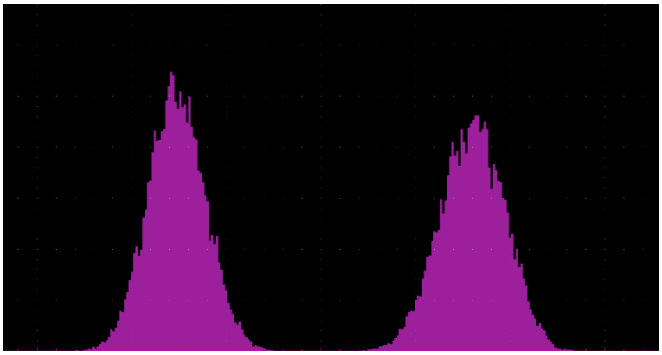


Trend plot with periodic jitter



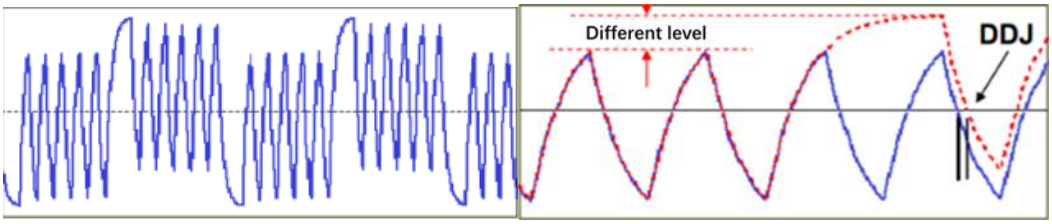
Histogram with periodic jitter

DDJ (Duty cycle distortion): The reason for its generation is that the rise time and fall time of the measured signal are asymmetric, or the selected reference level for testing is inappropriate, resulting in a non-standard 50% duty cycle of the clock.



Duty cycle distortion histogram with bimodal distribution

ISI (Inter-symbol interference): For the high-frequency signal that frequently switches "1, 0, 1, 0,...", the attenuation is more severe than that of the low-frequency signal of continuous "1, 1, 1, 1, 0, 0, 0, 0,...". Therefore, the long continuous unchanged code reaches a higher level, and it takes more time to reach the threshold level when jumping, resulting in signal jitter. In addition, due to the impedance mismatch of the transmission link, the signal is reflected, and the reflected signal is superimposed on the original transmission signal, resulting in an increase in the signal amplitude, which makes the final level transition consume more time and generate jitter.



Jitter is usually measured at the zero-crossing point of the reference signal. It usually comes from crosstalk, synchronous transition output, and other regularly occurring interference signals. Therefore, the measurement and quantification of jitter can be visually estimated by an oscilloscope

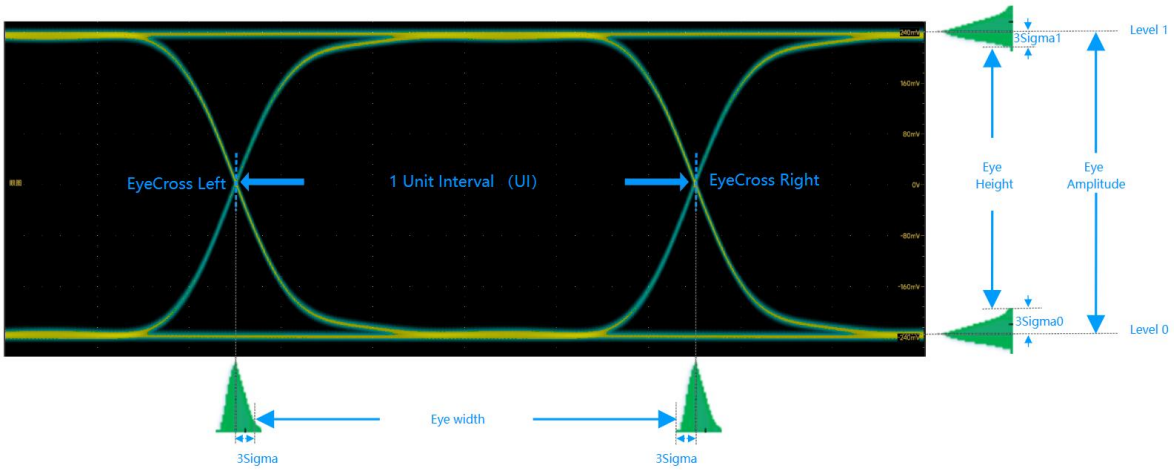
in the second-level jitter range, or measured by statistical methods.

Jitter Measurement Methods

The following are several jitter measurement methods using statistical methods with an oscilloscope, which are also relatively intuitive and convenient measurement methods.

1. Eye Diagram

The eye diagram is also a timing analysis tool that can intuitively view timing errors and level errors. In reality, jitter is difficult to quantify because it often changes and the changes are very small. The eye diagram is generated by superimposing UIs and can accurately find the maximum jitter. It can also find measurement deviations, rise time, fall time, and other errors.



Eye Amplitude = Level 1 - Level 0 *Eye Height = (Level 1 - 3σ1) - (Level 0 + 3σ0)*

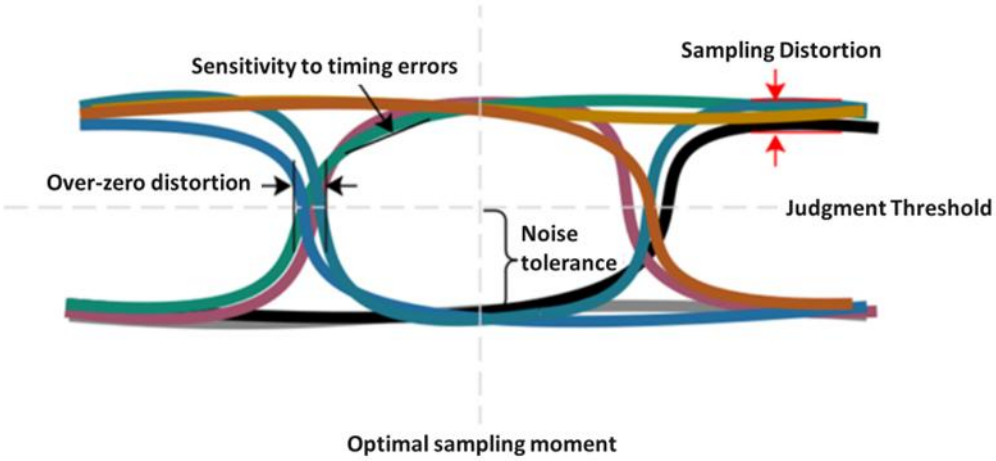
Eye Width = (Eye Cross left - 3σ) - (Eye Cross right + 3σ)

Duty cycle time = median of rise time - median of fall time

Duty cycle = (duty cycle time / bit period) × 100%

Eye Cross = (Eye Width Line - Zero) / (One - Zero) × 100% *Q = (Level 1 - Level 0) / (σ1 - σ0)*

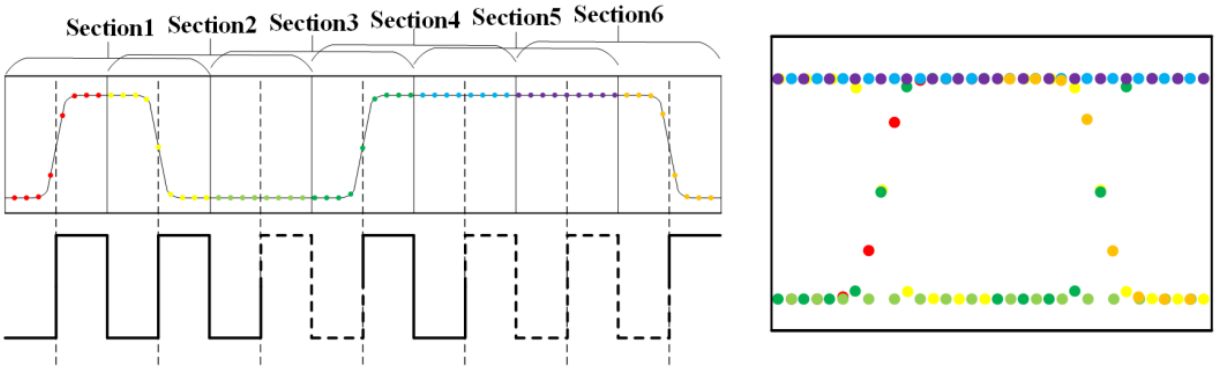
The eye diagram reflects the signal quality under a high number of samples. By superimposing the eye diagrams, many waveform details that cannot be found when measuring the waveform in the time domain can be found. Strictly speaking, the eye diagram belongs to the measurement method in the statistical domain.



For example, the steeper the slope of the eye diagram, the more sensitive the system is to timing errors. If the instantaneous value of the noise exceeds the noise margin, an incorrect decision may occur. The larger the eye opening, the smaller the inter-symbol interference and the more stable the system. These signal quality problems can only be accurately observed by superimposing the eye diagrams for a long time.

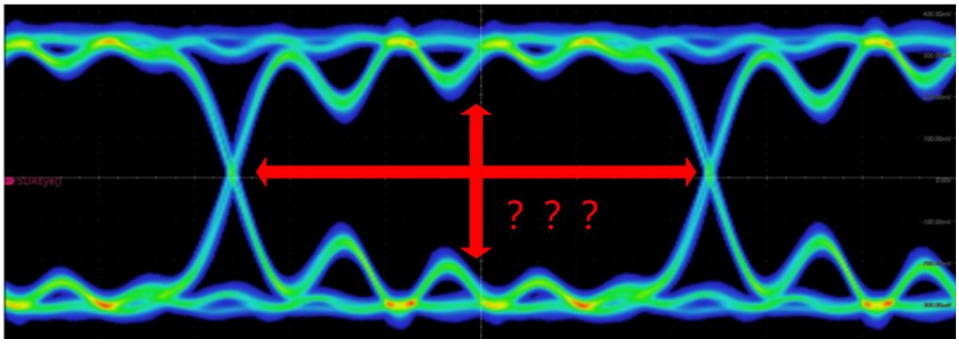
The Superposition Method of the Eye Diagram:

Synchronous cutting + superimposed display: Obtain a continuous serial data, use the recovered clock to cut the symbol, and the cut symbols are superimposed and displayed to form an eye diagram.



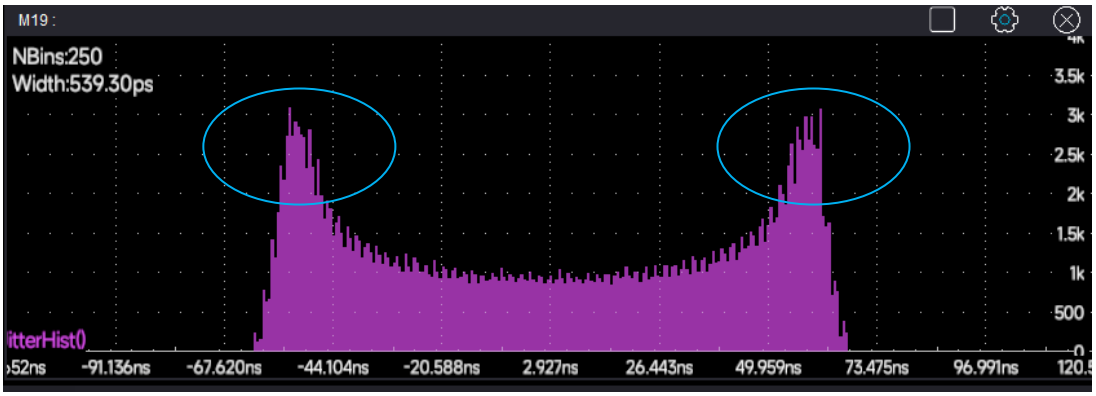
The opening of the eye diagram is related to the observation time:

The total jitter TJ (BER) = DJ + α (BER) * RJ. Since RJ is unbounded and infinite, as the number of samples in the eye diagram superimposition increases, RJ also increases. Eventually, it is reflected in the eye diagram that the opening of the observed eye diagram will become smaller and smaller. Therefore, the size of the eye diagram opening depends on the observation time and the number of samples.

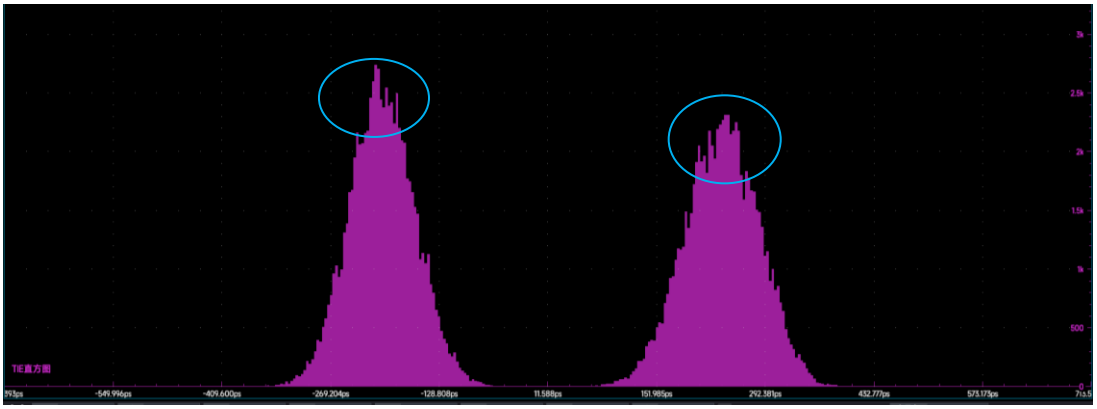


2. TIE Histogram

As mentioned above, the observed total jitter can be decomposed, and the DJ is bounded while RJ is unbounded. This raises the question: can the jitter distribution be analyzed statistically? The answer is yes. The TIE histogram is such a tool. The TIE histogram analyzes the offset of jitter statistically, and the histogram can directly show the distribution of different jitters. The horizontal direction of the histogram represents the offset of jitter, and the vertical direction represents the cumulative number of times at any offset. As shown in the following figure:



The histogram shows a sinusoidal distribution, indicating that there is a periodic component in the jitter.



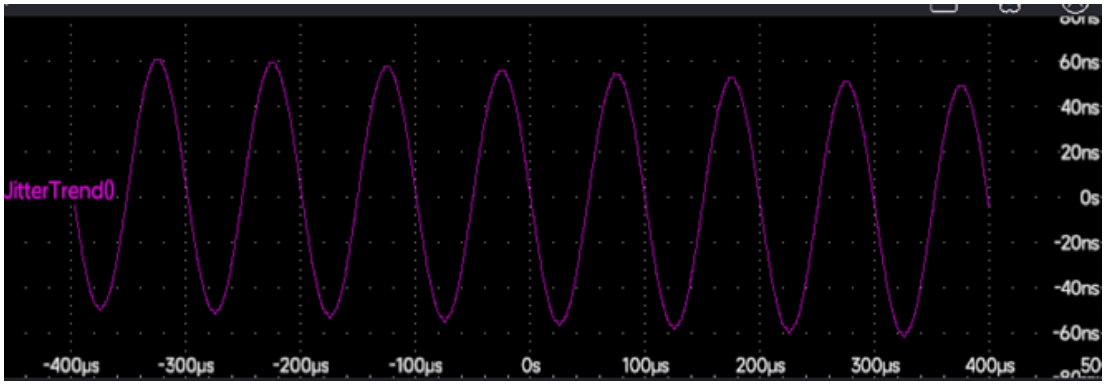
The histogram has a bimodal distribution, with deterministic jitter and random jitter rolled up

Even if the deterministic jitter and the random jitter are convolved, we can also intuitively observe the distribution of the deterministic jitter. Thus, further analysis of the jitter can be carried out.

3. TIE Trend Graph

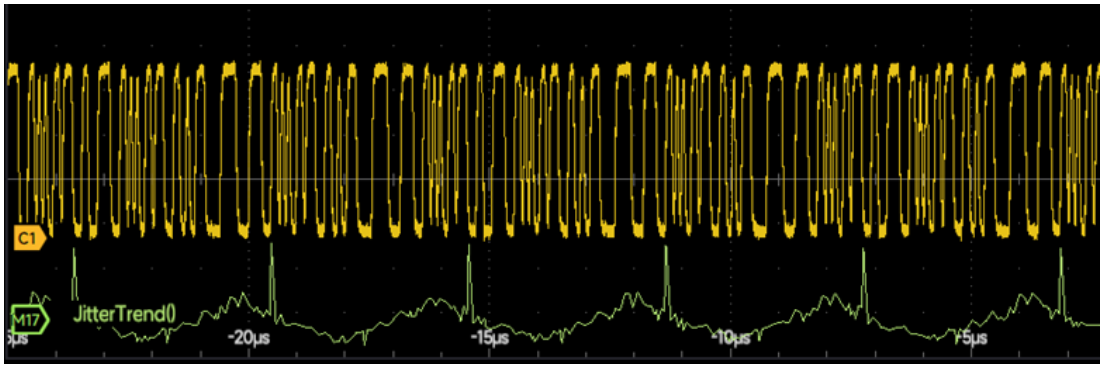
The histogram belongs to the measurement method in the statistical domain, which tells us the distribution of jitter and only has statistical characteristics. However, we also want to know the

performance of jitter in the time domain. Then the TIE trend graph can help us see this information. The horizontal axis represents the time corresponding to each edge sequence, and the vertical axis represents the value of TIE. The trend graph can show the jitter offset of each cycle, so as to understand the time trend of the signal jitter. The trend graph can also tell us whether there is a specific frequency modulation or interference in the waveform.



Trend plots characterize specific frequency disturbances within a waveform.

For example, the jitter period measured by the TIE trend graph is 100 µs each, and the converted frequency is 10 kHz. Coincidentally, the signal measured by this trend graph has a fundamental frequency of 1 MHz but is phase-modulated by a 10 kHz sine wave. It can be concluded that the cause of the signal jitter comes from the 10 kHz sine wave modulation. Therefore, the circuit can be improved and the modulation wave can be eliminated to reduce the jitter.

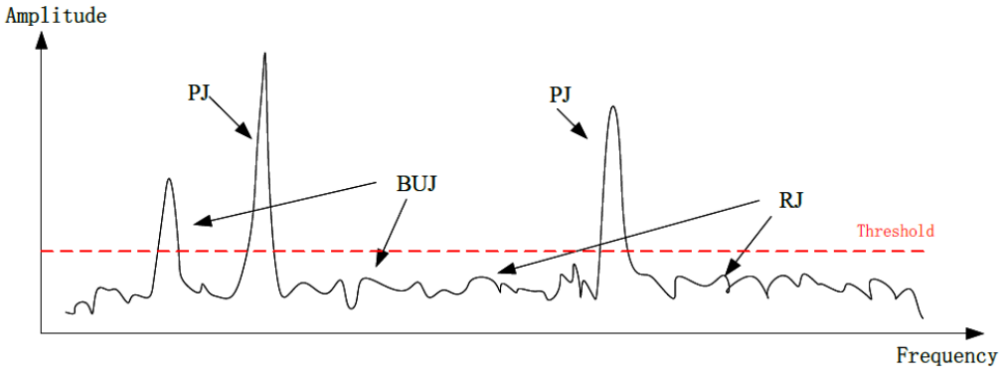


Trend plot characterizing the signal as affected by the switching frequency

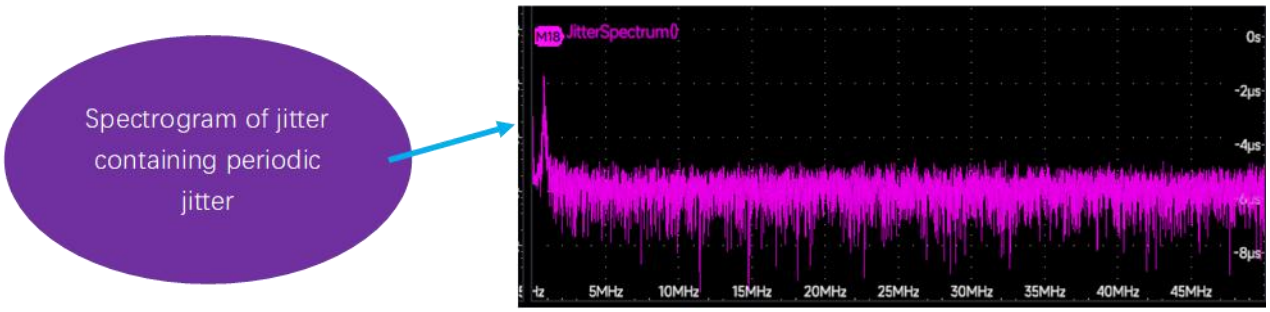
For example, this trend graph tests a signal board with a power supply switching frequency of 200 kHz, which can emit a fixed 15 MHz serial data. However, from the test results, there is a periodic jitter of about 5 µs in the signal cycle, and the converted frequency is exactly 200 kHz. It can be concluded that the cause of the signal jitter is the interference of the switching frequency of the switching power supply.

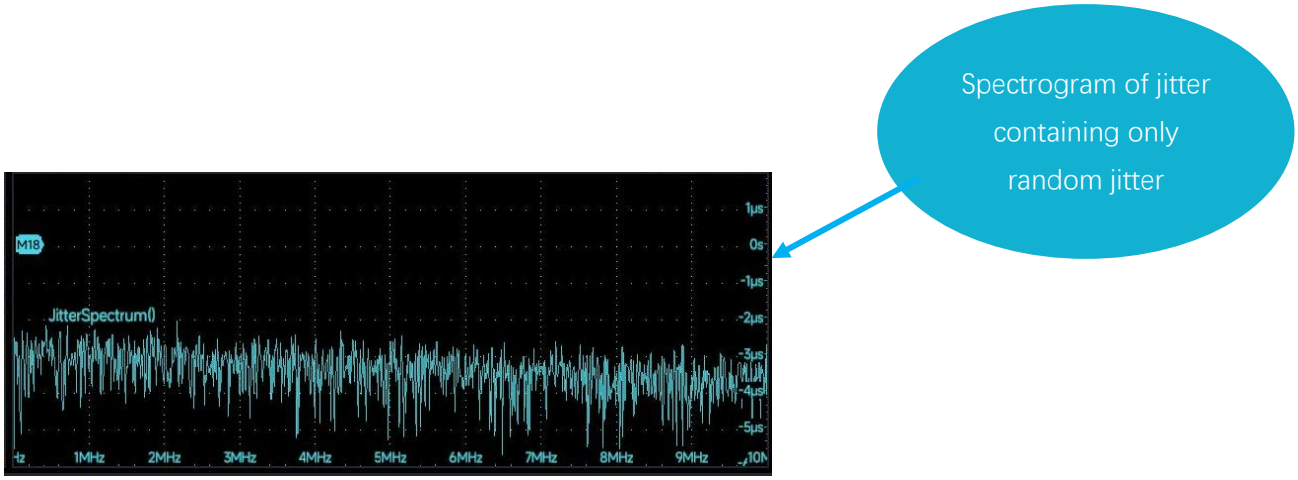
4. TIE Spectrum Graph

Measuring the TIE trend and performing FFT (Fast Fourier Transform) on the TIE waveform can further decompose the deterministic jitter. From the TIE spectrum graph, the frequency distribution of the jitter can be easily analyzed, so as to find the source of the jitter and guide the circuit debugging to remove the jitter.



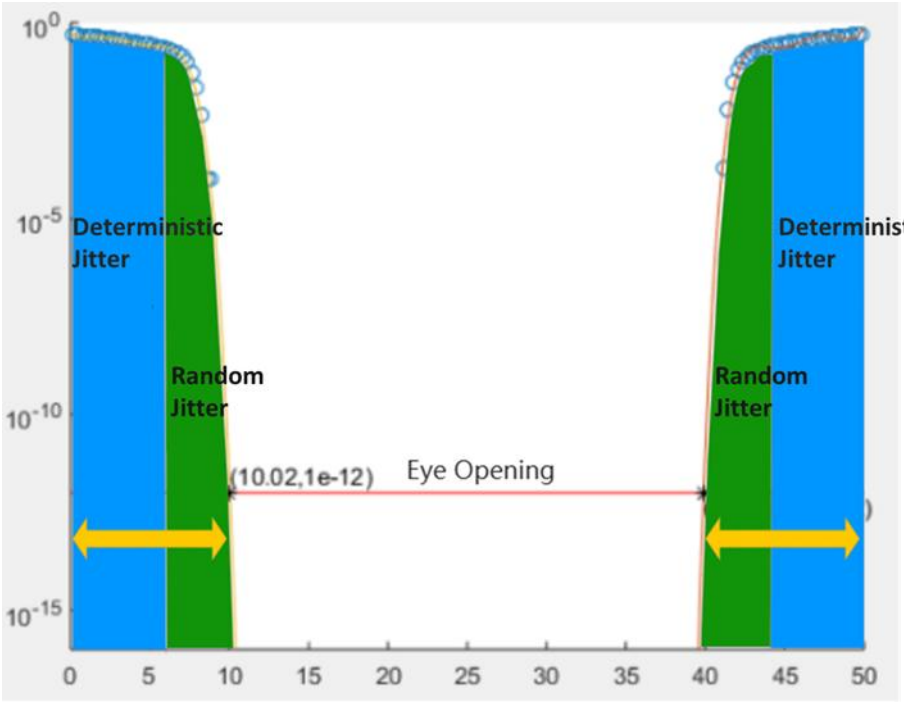
DDJ and PJ are narrowband spectra (triangle spectra or spectral lines). DDJ is related to the code pattern, and its frequency is generally an integer multiple of the data rate. BUJ (Bounded Uncorrelated Jitter) is mainly caused by crosstalk and is divided into narrowband and broadband. RJ is a broadband spectrum with a very small amplitude.



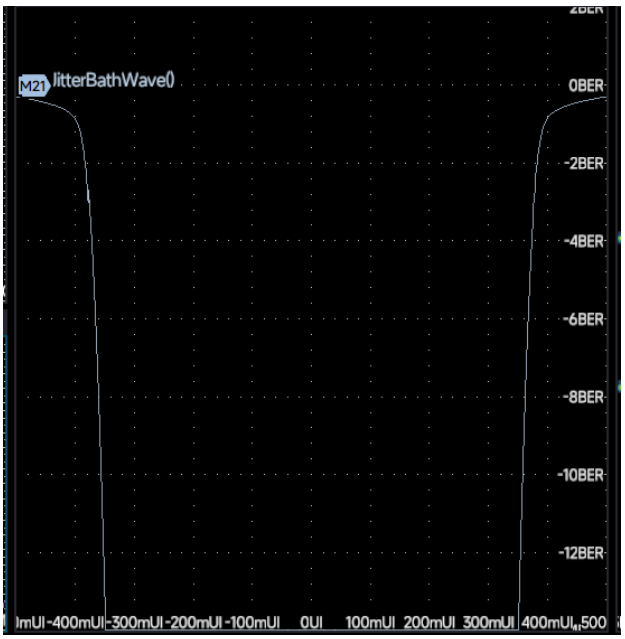


5. Bathtub Curve

The bathtub curve represents the relationship between the eye opening and the BER (Bit Error Rate). In high-speed serial communication, working at a maximum bit error rate BER=10^{-12} has become an inevitable requirement. The vertical axis of the bathtub curve represents the bit error rate, and the horizontal axis is the sampling time, with a range of one symbol period (1UI).



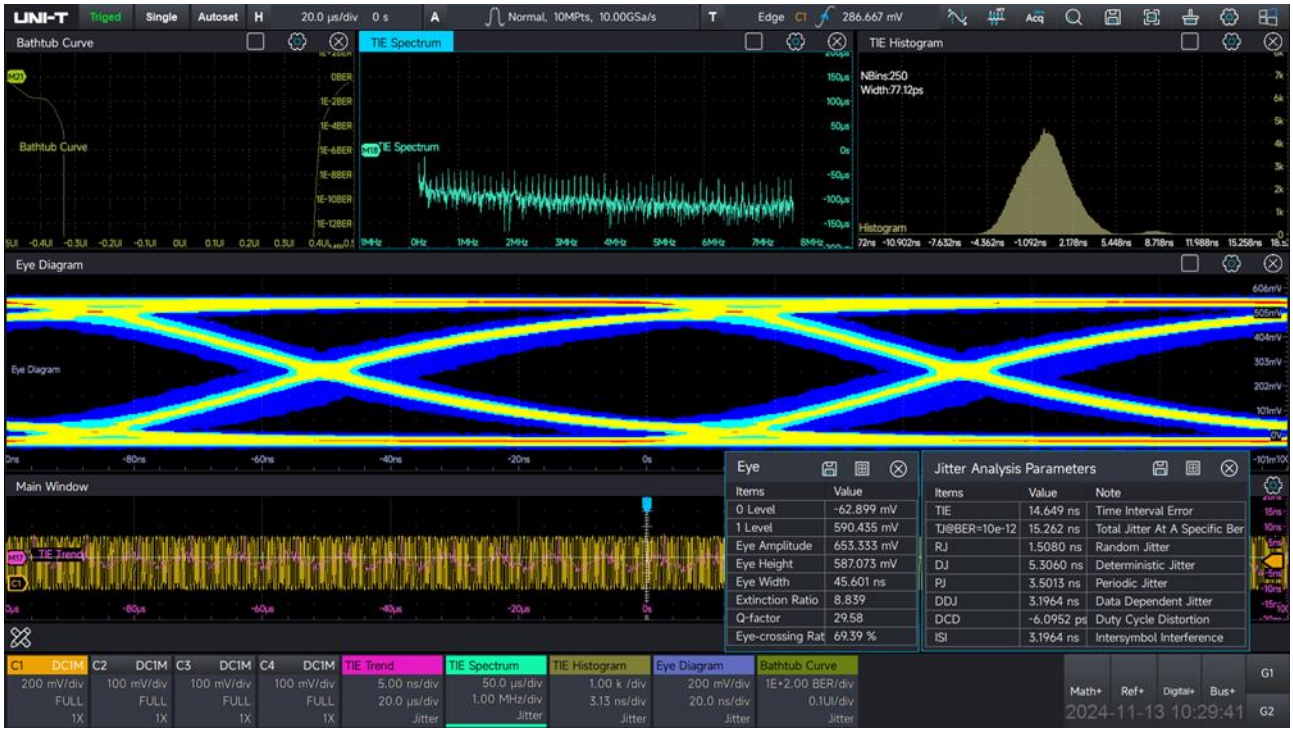
The bathtub curve can represent the total jitter at a bit error rate BER=10^{-12}. TJ (BER) = DJ + α (BER) * RJ. The relatively smooth curve in the front half of the bathtub represents the measured deterministic jitter, with BER=10^{-4} or BER=10^{-5}. At this point, it is the real measurement value. The relatively steep part in the back can be understood as the curve fitted by calculation with the increase of random jitter in a long time or with a high number of samples. At this point, the measurement value is derived by fitting the bit error rate, and the outer area of the bathtub curve correspond to the derived eye diagram opening.



For example, the smooth part of the bathtub curve in the above figure accounts for about 0.8 UI (added on both sides), which can be judged that the deterministic jitter is the main component. Eliminating this part of the jitter will effectively improve the stability of the system.

UNI-T Jitter Analysis and Eye Diagram Solution: MSO7000X - JITTER

UNI-T MSO7000X - JITTER provides a set of algorithm systems for TIE measurement and includes all the measurement tools mentioned in the above article. Its oscilloscope platform is equipped with the Windows 10 operating system and a 15.6 - inch capacitive touch screen, which has taken the algorithm processing ability and waveform display ability to a new level.

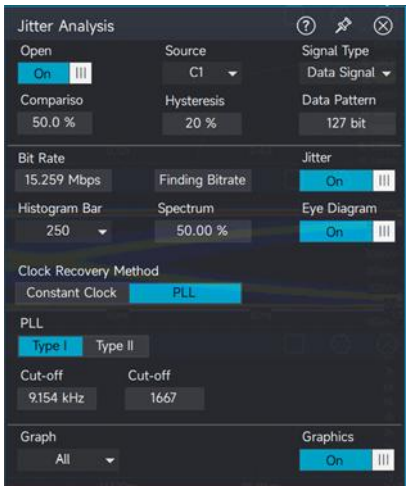


MSO7000X - JITTER Jitter and Eye Diagram Measurement Parameters

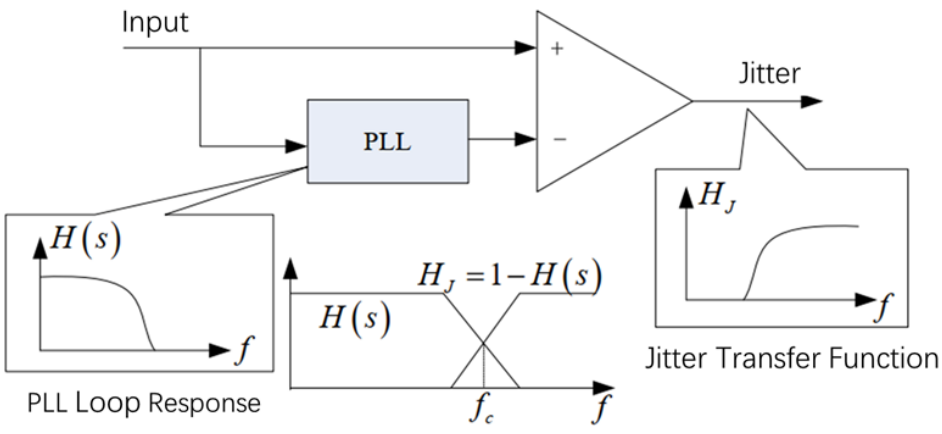
- Eye Diagram Measurement Parameters: Eye amplitude, eye height, eye width, 1 level, 0 level, Q factor, eye cross ratio, extinction ratio.
- Jitter Measurement Parameters: TIE, TJ@BER = 10^{-12}, RJ, DJ, PJ, DDJ, DCD, ISI.

Clock Recovery:

MSO7000X - JITTER provides a variety of clock recovery algorithms including constant clock, first-order phase-locked loop, second-order phase-locked loop, etc. The golden PLL helps track low-frequency jitter during jitter measurement and significantly attenuates low-frequency jitter to obtain a better eye diagram opening. Its algorithm can also support automatically finding the signal rate for high-speed signal measurement with an unknown rate.

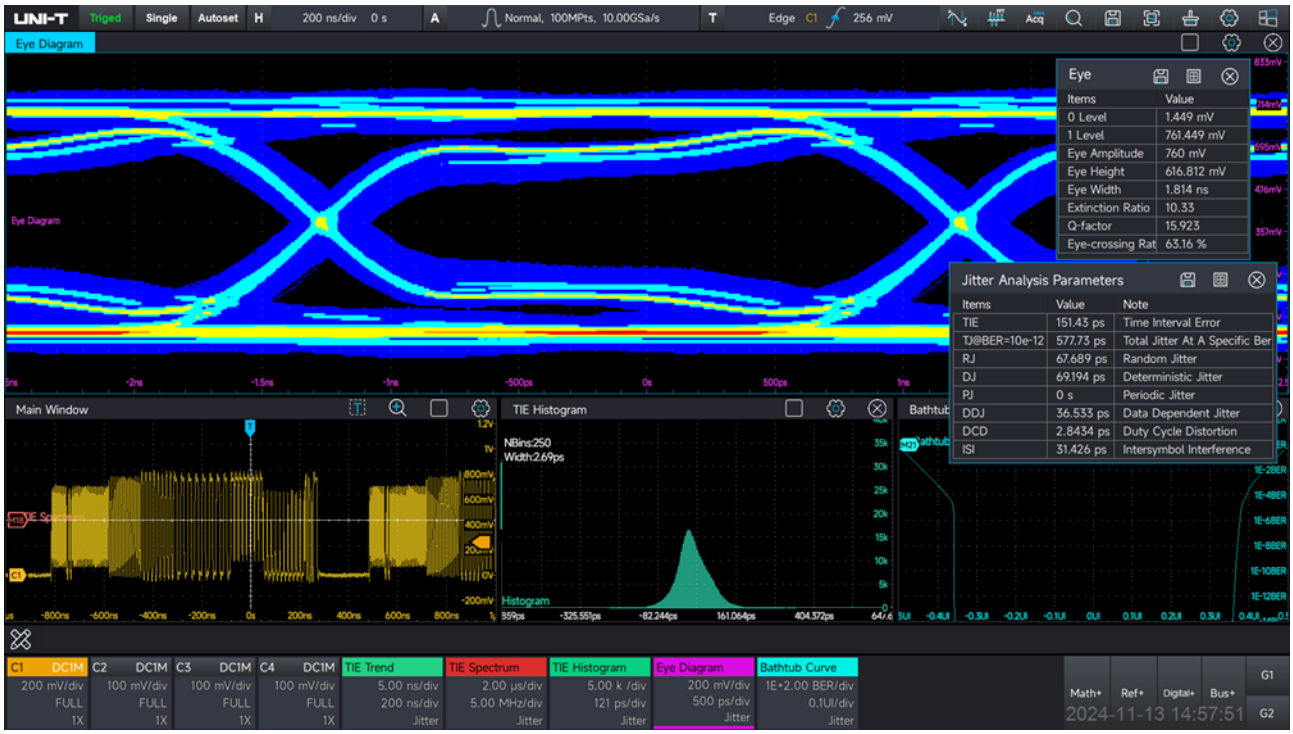


When the jitter change frequency of the measured signal is low, that is, from DC to the cutoff frequency of the PLL, the PLL can track the data transition edge in time (that is, lock the phase), so the jitter is zero. When the jitter change of consecutive edges is too fast (that is, there is high-frequency jitter), the PLL cannot track the edge change in time, so the output clock and the edge of the measured signal have jitter. Therefore, the CDR at the receiving end cannot filter out the jitter higher than the cutoff frequency, and its jitter transfer function (Jitter Transfer Function, abbreviated as JTF) has a high-pass filter characteristic. The CDR at the receiving end is also called the high-pass filter of TIE jitter.



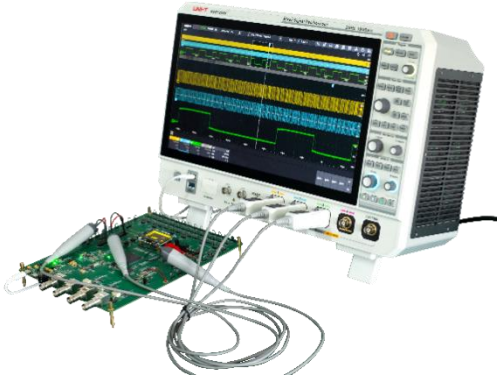
Sufficient Sample Capacity to Support High-Speed Signal Analysis:

The memory depth of the oscilloscope is an important indicator in jitter analysis, which directly affects the number of samples for jitter and eye diagram testing. Sufficiently long waveform data can not only provide longer clock cycles or data UIs for more accurate jitter analysis but also means that lower-frequency jitter can be captured. This is also one of the important values of the long storage of the oscilloscope. MSO7000X series, the mixed-signal oscilloscope has a standard maximum memory depth of 1 Gpts, which is very suitable for measuring low-frequency jitter.



The above figure shows the jitter analysis and test of a USB2.0 flash drive. The jitter analysis software captures the protocol packet and performs eye diagram and jitter analysis on it.

Solution Configuration



MSO7204X



MSO7000X-JITTER (Option)



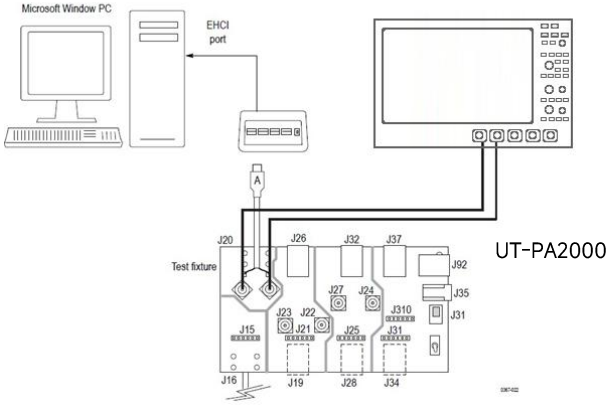
UT-PA2000 Active single-ended probe (2 GHz)



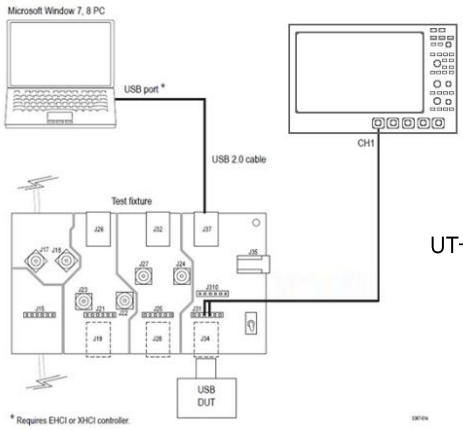
UT-PD2500 Active differential probe (2.5 GHz)



USB2.0 signal quality test fixture (used for USB2.0 high-speed signal quality analysis)



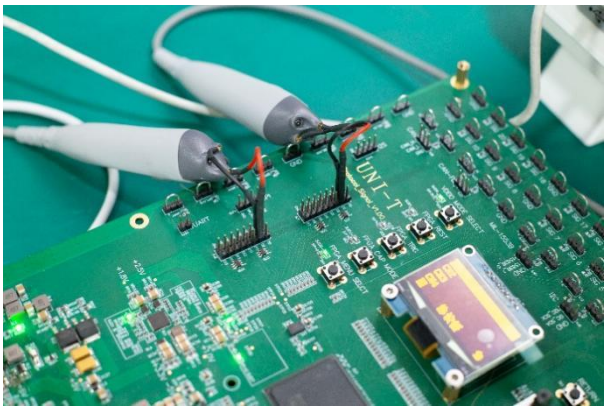
UT-PA2000



UT-PD2500

Probe Connection





Solution List

MSO7204X MSO7104X	Mixed-signal oscilloscope. Bandwidth: 1 GHz / 2 GHz, sample rate: 10 GSa/s, memory depth: 1 Gpts, waveform capture rate: 2,000,000 wfms/s.
MSO7000X-JITTER	MSO7000X jitter analysis and eye diagram option. Eye diagram, TIE trend graph, TIE histogram, TIE spectrum graph, bathtub curve.
UT-PA2000	Active single-ended probe. Bandwidth: 2 GHz, rise time: 175 ps, probe attenuation ratio: 10:1, dynamic range: ± 4 V, input capacitance: ≤ 1.2 pF
UT-PD2500	Active differential probe. Bandwidth: 2 GHz, input resistance: 200 kΩ (differential mode), 100 kΩ (single-ended mode), input common-mode range: ±15 V, DC attenuation ratio: 10:1, input dynamic range: 8 Vpp
USB2.0 signal quality test fixture	Used for evaluating the signal quality of USB2.0 at low speed, full speed, and high speed.