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INCITS Technical Report for Information Technology – Fibre Channel – Methodologies for Jitter and Signal Quality Specification (FC-MJSQ)

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Abstract

This technical report enhances the jitter and signal specifications found in the Fibre Channel Physical layer standards and in the technical report Methodologies for Jitter Specification (MJS). It provides extended definitions and test methodologies to enable more effective execution of specifications relating to the phase timing features of high speed serial signals. A generalization of jitter concepts to include events that occur at other than the nominal receiver detection threshold provides a stronger coupling between the jitter measured in a signal and the errors produced by the receiver of the signal. The methodologies described use a structured approach to describe the tests that recognize the contributions from test fixtures, instrumentation and calibration schemes to the reported values. Although this report uses 1.0625 GBd for some examples it is intended to be fully applicable to speeds well in excess of the existing 4.25 GBd jitter specifications in FC-PI-n.

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Foreword (This foreword is not part of Technical Report INCITS TR-35-2004.)

Requests for interpretation, suggestions for improvement and addenda, or defect reports are welcome. They should be sent to the INCITS Secretariat, ITI, 1250 Eye Street, NW, Suite 200, Washington, DC 20005-3922.

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Introduction

This document is an INCITS technical report on the definitions, measurement requirements, and allowed values of jitter on FC links. MJSQ supersedes the previously published MJS technical report (INCITS TR-25-1999). MJSQ represents a significant advance over MJS and obsoletes some concepts documented in MJS.

This technical report compiles and provides additional information beyond that supplied in MJS to clarify the jitter and signal quality specification clauses of the FC-PH-n and FC-PI-n standard set. The existing jitter specifications are incomplete as a result of changes in how the electronics industry is implementing Fibre Channel systems today compared to how systems were expected to be implemented in the past. Examples of such changes are the requirements for practically effective interoperability and signal margin specifications for SAN applications, use of adaptive or predictive compensation schemes implemented in active elements or ports, and higher speed at longer distance.

The goals of this technical report are:

- To define and describe the relationships between different kinds of jitter

- To document the jitter and signal quality measurement requirements that allow Fibre Channel developers to design low-cost, multi-Gbaud links having bit error ratios below 10^{-12} using interoperable and interchangeable components between the interoperability points

- To specify measurement methods that are reproducible and that more closely relate to observed bit error ratios in operating links

- To enable standardized specification enforcement for compliance testing.

It was originally a goal to document detailed measurement specifications for the different kinds of variant and interoperability points defined in FC-PH-n and FC-PI. This goal was superseded by a more attainable goal of specifying some representative measurements in sufficient detail to demonstrate the requiredmethods.

This Methodologies for Jitter and Signal Quality (MJSQ) technical report is generated by an Ad Hoc group of companies interested in providing a standard low cost interface for FC applications. This Ad Hoc group is sanctioned by and operates under the jurisdiction of the T11.2 technical committee of INCITS.

This technical report is informative and advisory only. Certain contents of this document may be incorporated into appropriate standards in the future.

INCITS Technical Report for Information Technology - Fibre Channel - Methodologies for Jitter and Signal Quality Specification (FC-MJSQ)

1 Scope

MJSQ supersedes the previously published MJS technical report (INCITS TR-25-1999). MJSQ represents a significant advance over MJS and obsoletes some concepts documented in MJS.

The measurement methods and specifications are intended to be used as part of a total signal performance compliance requirement set where the phase content of the signal is involved. A more generalized concept for jitter compliance testing is developed where the phase properties of the signals at signals levels other than the nominal receiver switching point are considered as well as the phase properties at the nominal receiver detection threshold. The purpose of this report is to provide background information for revising and expanding the signal specifications presently contained within the FC-PH-n, FC-PI-n, and 10GFC standards and draft standards. The MJSQ technical report is used as a basis for many of the signal specification methodologies in these documents. A further purpose is to increase the general understanding of jitter in multi-Gbaud serial transmissions for application to transports other than FC. Documenting high speed serial signal measurement methods provides encouragement to instrument companies to create compatible measurement systems and fixturing capable of supporting 1 Gbaud and higher transmission rates and more generalized jitter concepts.

Although this document is optimized for use with Fibre Channel, the measurement methodologies are applicable to a broad range of serial transmission schemes.

This technical report applies to fully functional Fibre Channel subsystem and FC port implementations as well as to the individual components that comprise the link. This allows device and enclosure level qualification and the inclusion of system jitter contributions such as power supply noise, motor noise, crosstalk, and signal rejuvenaters.

A major goal of MJSQ is to improve the relationship between measurements on signals and receiver performance in terms of bit errors.

The report adds to or extends previous work in the following areas:

a) Exposing serious implementation errors commonly found from improper use of BERT's and sampling oscilloscopes (improper use of time references and improper extraction of total jitter from sampling oscilloscopes)
b) Algorithms for separating jitter components
c) Complete specifications for executing tests including test fixtures, instrumentation specifications, calibration schemes, measurement processes, and data output formats - examples for several electrical and optical applications
d) Methodology for specifying launched and received signals when pre-emphasis or receiver signal processing is used
e) Inclusion of events occurring at all signal levels within the allowed eye opening at the specified total population probability (e.g., 10^{-12})
f) Extending the receiver tolerance methodology to consider effects of different population distributions.

The MJSQ Technical Report is informative and advisory only. Certain contents of this document may be incorporated into the appropriate INCITS standards in the future.

2 References

2.1 General

The documents named in this section contain provisions that, through reference in this text, constitute provisions of this document. At the time of publication, the editions indicated were valid. All standards and technical reports are subject to revision, and parties to agreements based on this technical report are encouraged to investigate the possibility of applying the most recent editions of the following list of documents. Members of IEC and ISO maintain registers of currently valid international standards.

Some references may not be specifically cited in the text but contain information generally related to the subject matter of MJSQ.

The URL's cited in this clause were valid at the time of publication.

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IEEE standards may be obtained at http://standards.ieee.org/catalog/olis/index.html.
IEEE 802.3 documents may be obtained at http://www.ieee802.org/3/ae.
EIA/TIA documents may be obtained at http://www.tiaonline.org/standards/

2.2 Approved references

Approved references are those that have been approved by a standards organization.

Approved ANSI standards;
Approved and draft regional and international standards (ISO, IEC, CEN/CENELEC and ITU); and
Approved foreign standards (including BSI, JIS and DIN).
Approved ANSI technical reports

[1] ANSI X3.230-1994, Fibre Channel - Physical and Signaling Interface (FC-PH)

[2] ANSI X3.297-1997, Fibre Channel Physical and Signalling Protocol - 2 (FC-PH-2)

[3] ANSI X3.303-1998, Fibre Channel Physical and Signalling Protocol - 3 (FC-PH-3)
The three documents above are collectively referred to as FC-PH-n

[4] INCITS TR-18-1996, 10-bit Interface Technical Report (10-bit Interface TR)

[5] INCITS TR-25-1999, Methodologies for Jitter Specification (MJS)

[6] IEEE 802.3z, Media Access Control Parameters, Physical Layer, Repeater and Management Parameters for 1000 Megabit per Second Operation, May 06, 1998 (Gigabit Ethernet)

[7] ANSI INCITS 352-2002, Fibre Channel Physical Interfaces, Rev 13 (FC-PI)

[8] Synchronous Optical Network (SONET) Transport Systems: Common Generic Criteria (GR-253-CORE, Sept 2000)

[9] ANSI T1.105-2001, *Synchronous Optical Network (SONET) Basic Description Including Multiplex Structures, Rates, and Formats*

[10] ANSI T1.105.06-2002, *SONET: Physical Layer Specifications*

[11] ANSI INCITS 364-2003, Fibre Channel 10 Gigabit (10 GFC)

[12] IEEE P802.3ae, Media Access Control Parameters, Physical Layer, Repeater and Management Parameters for 10 Gb/s Operation (10 Gigabit Ethernet)

[13] IEEE Std 1057-1994, IEEE Standard for Digitizing Waveform Recorders

[14] IEEE Std. 181-1977, Transitions, Pulses, and Related Waveforms

[15] IEEE Std. 194-1977 Pulse Terms and Definitions

[16] OFSTP-4A (EIA/TIA-526-4A) - Optical Eye Pattern Measurement Procedure, Nov. 1997

[17] IEEE Std. 610.7-1995

2.3 References under development

At the time of publication, the following referenced standards were still under development. For information on the current status of the documents, or regarding availability, contact the relevant standards body or other organization as indicated.

[18] INCITS T11 1506-D, Fibre Channel Physical Interfaces - 2 (FC-PI-2)

[19] INCITS T11 1625-D, Fibre Channel Physical Interfaces - 3 (FC-PI-3)

[20] INCITS T11 1647-D, Fibre Channel Physical Interfaces - 4 (FC-PI-4)
These three documents above and FC-PI are collectively referred to as FC-PI-n.

2.4 Informative references

[21] Gigabit Ethernet Networking - MacMillan Technical Publication, ISBN 1-7870-062-0 Chapter 9, the gigabit ethernet optical link model

[22] Cunninghan and Lane, Gigabit Ethernet Networking, MacMillan (ISBN 1578700620)

[23] SFF-8410 - Testing and performance requirements for high speed serial and parallel - serial electrical links

[24] SFF-8415 - HPEI (High Performance Electrical Interconnect) Measurement Methodology and Signal Integrity Requirements (under development)

[25] SFF-8412 - High speed serial testing and performance requirements for passive duplex optical connections

[26] Bockelman and Eisenstadt, *IEEE transactions on microwave theory and techniques*, V 43, No 7, p 1530 (1995)

[27] Jacques Rutman et al, "Characterization of Frequency Stability in Precision Frequency Sources", Proceedings of the IEEE, vol 79, number 6, pages 952-960, June 1991.

[28] Donald B. Percival, "Characterization of Frequency Stability: Frequency-Domain Estimation of Stability Measures", P. IEEE, vol 79, number 6, pages 961-972, June 1991.

[29] David W. Allan et al, "Statistics of Time and Frequency Data Analysis", Chapter 8 of "Time and Frequency: Theory and Fundamentals", NBS Monograph 140, May 1974.

[30] PCI Sig, "PCI Express Base Specification" Rev 1.0, 2002 found at: http://www.pcisig.com/specifications/pciexpress/

[31] Serial ATA working group, "Serial ATA: High Speed Serialized AT Attachment" Rev 1.0 2001 found at: http://www.serialata.org/collateral/index.shtml.

[32] M. Li, J. Wilstrup, R. Jessen, D. Petrich, "A New Method for Jitter Decomposition Through Its Distribution Tail Fitting", ITC Proceeding, 1999.

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[35] Link model for 10 GBE found at: http://www.ieee802.org/3/ae/public/adhoc/serial_pmd/documents/10GEPBud3_1_16a.xls

[36] Link model for 1 GFC found at www.T11.org - document 98-271v0

[37] Dennis Kucera and Paul Meyers, "Automated extraction of pulse-parametrics from multi-valued functions"; US Patent 5,343,405, Tektronix, Inc. Aug. 30, 1994.

[38] GR-253 - Issue 2 December 1995 - SONET

[39] Transmission Line Transformers", second edition, Jerry Sevick, American Radio Relay League, 1990.

[40] Twisted Magnet Wire Transmission Line" Peter Lefferson, IEEE Trans on Parts, Hybrids, and Packaging, Vol. PHP-7, No. 7, pp 148-154, December 1971.

[41] D. H. Wolaver, <u>Phase-Locked Loop Circuit Design</u>, Englewood Cliffs, NJ: Prentice Hall, 1991.

[42] Tektronix, Sampling oscilloscope techniques, Technique primer 47W-7209 found at: http://www.tek.com/Measurement/cgi-bin/framed.pl?Document=/Measurement/App_Notes/sampling_primer/sampling2.html&FrameSet=oscilloscopes.

3 Definitions and conventions

3.1 Overview

The acronyms, definitions, conventions, and symbols in clause 3 apply in this document.

3.2 Conventions

All drawings in this document conform to the conventions in figure 1.

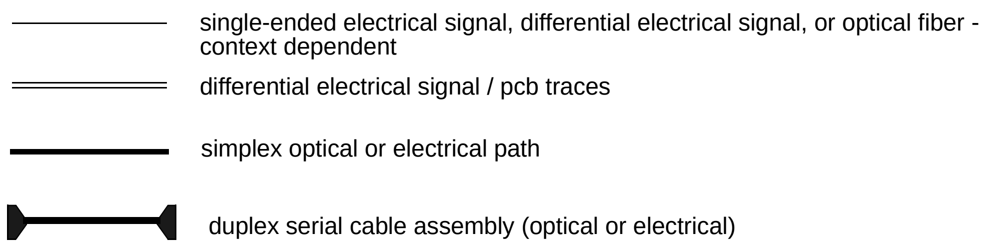


Figure 1 - Drawing conventions

In the event of conflicts between the text, tables, and figures in this document, the following precedence shall be used: text, tables, and figures.

Certain words and terms used in this American National Technical Report have a specific meaning beyond the normal English meaning. These words and terms are defined either in clause 3 or in the text where they first appear.

All parametric data are specified in terms of fundamental MKSA units - meters, kilograms, seconds, amperes - and their derivatives - ohms, henrys, mhos, farads, volts, coulombs, etc.

Decimals are indicated with a comma (e.g., two and one half is represented as 2,5).

Decimal numbers with more than three significant digits on either side of the decimal point are separated into groups of three digits by means of a space, for example, 2,997 924 58 x 10^8 or 1 062,5 Megabaud.

Units prefixed by k, M, and G refer to 1E3, 1E6, and 1E9 respectively, not 2^{10}, 2^{20}, and 2^{30}.

An alphanumeric list (e.g., a, b, c or A, B, C) of items indicate the items in the list are unordered.

A numeric list (e.g., 1,2,3) of items indicate the items in the list are ordered (i.e., item 1 shall occur or complete before item 2).

Bold fonts, when used in body text, indicates additional emphasis.

3.3 Keywords

Expected: anticipated to be true, assumed to exist

May: Indicates flexibility of choice with no implied preference; also means that the ability exists in the referenced topic.

Optional: Features that are not required to be implemented by this document. However, if any optional feature defined by this document is implemented, it shall be implemented as defined in this document.

Shall: Indicates a requirement for compliance to this document. Since this is a technical report there are no enforceable requirements.

Should: Indicates flexibility of choice with a preferred alternative; equivalent to the phrase “it is recommended”.

3.4 Acronyms

ARB	A specific primitive bit sequence as defined in FC-PH
BER	Bit Error Ratio
BERT	Bit Error Rate Tester
BUJ	Bounded Uncorrelated Jitter
BWJ	Baseline Wander Jitter
CDF	Cumulative Distribution Function
CDR	Clock and Data Recovery
CJTPAT	Compliant Jitter Tolerance PATtern
CRC	Cyclic Redundancy Check
CRPAT	Compliant Random PATtern
CRU	Clock Recovery Unit
CSPAT	Compliant SSO pattern
DCD	Duty Cycle Distortion
DJ	Deterministic Jitter
DDJ	Data Dependent Jitter
DIJ	Dispersion Induced Jitter
DTS	Direct Time Synthesis
DUT	Device Under Test
EOF	End Of Frame; a primitive bit sequence as defined in FC-PH
EQ	EQuivalent time (OscilloScope)
ESD	Electrostatic Discharge
FC	Fibre Channel
FCS	Fibre Channel Standard
FFT	Fast Fourier Transform
FUT	Fiber Under Test
HA	Host Adapter
HDD	Hard Disk Drive
IDLE	A specific primitive bit sequence as defined in FC-PH
ISI	Inter-Symbol Interference
JBOD	Just a Bunch Of Disks
JTPAT	Jitter Tolerance test PATtern
LPDDJ	Low Probability Data Dependent Jitter
MM	Multi Mode (fiber)
OFSTP	Optical Fiber System Test Practice
PBC	Port Bypass Circuit
PDF	Probability Density Function
PLL	Phase Locked Loop
PMD	Physical Media Dependent sublayer
R_RDY	Receive Ready, a specific primitive bit sequence as defined in FC-PH
RBC	Recovered Byte Clock (one tenth of signaling rate as defined in 10 bit TR [4])
RJ	Random Jitter
RIJ	Reflection Induced Jitter
RPAT	Random Pattern
RSS	Root-Sum-of-Squares

RT	Real Time (oscilloscope) or retimer (link component)
RX	Receive
SERDES	SERializer and DESerializer function. The CDR function is included in the deserializer.
SM	Single Mode (fiber)
SPAT	Simultaneous Switching Outputs (SSO) Pattern
SOF	Start Of Frame; a primitive bit sequence defined in FC-PH
SSO	Simultaneous Switching Outputs
TBC	Transmit Byte Clock
TIA	Timing Interval Analyzer
TJ	Total Jitter
TX	Transmit
UI	Unit Interval
WMV	Waveform Mask Violation (event where the allowable limits are exceeded)

3.5 Definitions

3.5.1 **α_T, α_R:** Alpha T, Alpha R; reference points used for establishing signal budgets at the chip pins of the transmitter and receiver in an FC device or retiming element.

3.5.2 **β_T, β_R:** Beta T, Beta R; **i**nteroperability points used for establishing signal budget at the internal connector nearest the alpha point unless the point also satisfies the definition for delta or gamma where it is either a delta or a gamma point

3.5.3 **δ_T, δ_R:** Delta T, Delta R; interoperability points used for establishing signal budget at the internal connector of a removable PMD element.

3.5.4 **γ_T, γ_R:** Gamma T, Gamma R; interoperability points used for establishing signal budgets at the external enclosure connector.

3.5.5 **Alpha T, Alpha R:** see α_T, α_R.

3.5.6 **attenuation:** the transmission medium power loss expressed in units of dB.

3.5.7 **average power:** the optical power measured using an average reading power meter when transmitting valid 8B/10B transmission characters.

3.5.8 **bandwidth:** in jitter context, the corner frequency of a low-pass transmission characteristic, such as that of an optical receiver. The modal bandwidth of an optical fiber medium is expressed in units of MHz-km.

3.5.9 **bathtub curve:** a description of the shape of a BER or CDF curve that has steep walls to a noise floor (a flat bottom) where the probability of population is small

3.5.10 **baud:** a unit of signaling speed, expressed as the maximum number of times per second the signal may change the state of the transmission line or other medium. (Units of baud are symbols/sec) Note: With the Fibre Channel transmission scheme, a symbol represents a single transmission bit. [(Adapted from IEEE Std. 610.7-1995 [A16].12)].

3.5.11 **Beta T, Beta R:** see β_T, β_R.

3.5.12 **bit error ratio (BER):** the probability of a correct transmitted bit being erroneously received in a communication system. For purposes of this report BER is the number of bits output from a receiver that differ from the correct transmitted bits, divided by the number of transmitted bits.

3.5.13 **bit clock:** clock used in a jitter measurement that generates a single positive and a single negative transition per unit interval for the purpose of triggering the measuring device. Note that the bit clock frequency is twice the fundamental frequency of an alternating 1010... data stream and is equal numerically to the baud.

3.5.14 bulkhead: the boundary between the shielded system enclosure (where EMC compliance is maintained) and the external interconnect attachment

3.5.15 cable plant: all passive communications elements (e.g., optical fiber, twisted pair, coaxial cable, connectors, splices, etc.) between a transmitter and a receiver.

3.5.16 clock data recovery (CDR): the function is provided by the SERDES circuitry responsible for producing a regular clock signal from the serial data and for aligning this clock to the serial data bits. The CDR uses the recovered clock to recover the data.

3.5.17 character: a defined set of n contiguous bits where n is determined by the encoding scheme. For FC that uses 8b10b encoding, n = 10.

3.5.18 coaxial cable: an unbalanced electrical transmission medium consisting of concentric conductors separated by a dielectric material with the dimensions and material arranged to give a specified electrical impedance.

3.5.19 compliance point: an interoperability point where the interoperability specifications are met. Compliance points may include beta, gamma, and delta points for transmitters and receivers.

3.5.20 component: entities that make up the link. Examples are connectors, cable assemblies, transceivers, port bypass circuits and hubs.

3.5.21 connector: electro-mechanical or opto-mechanical components consisting of a receptacle and a plug that provides a separable interface between two transmission media segments. Connectors may introduce physical disturbances to the transmission path due to impedance mismatch, crosstalk, etc. These disturbances may introduce jitter under certain conditions.

3.5.22 coupler: a connector that mates two like media together.

3.5.23 cumulative distribution function (CDF): the integral of the PDF from - infinity to a specific time or from a specific time to + infinity.

3.5.24 delta function: a pulse with zero width and unity amplitude. See also Dirac delta function.

3.5.25 Delta T, Delta R: see δ_T, δ_R.

3.5.26 deterministic jitter, (level 1 DJ): the value returned by the calculation for DJ defined in clause 8. Any valid CDF may be used as input to this calculation. DJ used for compliance and budgeting is level 1 DJ. See also jitter, deterministic.

3.5.27 Dirac delta function: a pulse with zero width and unity area. See also delta function.

3.5.28 dispersion: (1) A term in used to denote pulse broadening and distortion from all causes. The two causes of dispersion in optical transmissions are modal dispersion, due to the difference in the propagation velocity of the propagation modes in a multimode fiber, and chromatic dispersion, due to the difference in propagation of the various spectral components of the optical source. Similar effects exist in electrical transmission lines. (2) Frequency dispersion caused by a dependence of propagation velocity on frequency, that leads to a pulse widening in a system with infinitely wide bandwidth. The term ‘dispersion’ when used without qualifiers is definition (1) in this document.

3.5.29 dual-Dirac: a pair of Dirac delta functions.

3.5.30 duty cycle distortion (DCD): (1) The absolute value of one half the difference in the average pulse width of a ’1’ pulse or a ’0’ pulse and the ideal bit time in a clock-like (repeating 0,1,0,1,...) bit sequence. (2) One-half of the difference of the average width of a one and the average width of a zero in a waveform eye pattern measurement. Definition (2) contains the sign of the difference and is useful in the presence of actual data. DCD from definition (2) may be used with arbitrary data and is approximately the same quantitatively as that observed with clock like patterns in definition (1). DCD is not a level 1 quantity. DCD is considered to be correlated to the data pattern because it is synchronous with the bit edges. Mechanisms that produce DCD are not expected to change significantly with different data patterns. The observation of DCD may change with changes in the data pattern. DCD is part of the DJ distribution and is measured at the average value of the waveform.

3.5.31 effective DJ: DJ used for level 1 compliance testing, and determined by curve fitting a measured CDF to a cumulative or integrated dual-Dirac function, where each Dirac impulse, located at +DJ/2 and -DJ/2, is convolved with separate half-magnitude Gaussian functions with standard deviations sigma1 and sigma2. Equivalent to level 1 DJ. See clause 8.

3.5.32 electrical fall time: the time interval for the falling edge of an electrical pulse to transit between specified percentages of the signal amplitude. In the context of MJSQ the measurement points are the 80% and 20% voltage levels.

3.5.33 electrical rise time: the time interval for the rising edge of an electrical pulse to transit between specified percentages of the signal amplitude. In the context of MJSQ, the measurement points are the 20% and 80% voltage levels.

3.5.34 enclosure: the outermost electromagnetic boundary (that acts as an EMI barrier) containing one or more FC devices.

3.5.35 event: the measured deviation of a single signal edge time at a defined signal level of the signal from a reference time. The reference time is the jitter-timing-reference specified in 6.2.3. Events are also referred to as jitter events or signal events without changing the meaning. Examples include a sample in a sampling oscilloscope, a single TIA measurement, an error or non error reported by a BERT at a reference time and signal level.

3.5.36 external connector: a bulkhead connector, whose purpose is to carry the FC signals into and out of an enclosure, that exits the enclosure with only minor compromise to the shield effectiveness of the enclosure.

3.5.37 eye contour: the locus of points in signal level - time space where the CDF = 1E-12 in the actual signal population determines whether a jitter eye mask violation has occurred. Either time jitter or signal level jitter may be used to measure the eye contour.

3.5.38 FC device: an entity that contains the FC protocol functions and that has one or more of the connectors defined in this document. Examples are: host bus adapters, disk drives, and switches. Devices may have internal connectors or bulkhead connectors.

3.5.39 FC device connector: a connector defined in this document that carries the FC serial data signals into and out of the FC device.

3.5.40 Gamma T, Gamma R: see γ_T, γ_R.

3.5.41 Golden PLL: a function that conforms to the requirements in Subclause 6.10.2 that extracts the jitter timing reference from the data stream under test to be used as the timing reference for the instrument used for measuring the jitter in the signal under test.

3.5.42 internal connector: a connector, whose purpose is to carry the FC signals within an enclosure (may be shielded or unshielded).

3.5.43 internal FC Device: an FC device whose FC device connector is contained within an enclosure.

3.5.44 Intersymbol Interference (ISI): reduction in the distinction of a pulse caused by overlapping energy from neighboring pulses. (Neighboring means close enough to have significant energy overlapping and does not imply or exclude adjacent pulses - many bit times may separate the pulses especially in the case of reflections). ISI may result in DDJ and vertical eye closure. Important mechanisms that produce ISI are dispersion, reflections, and circuits that lead to baseline wander.

3.5.45 jitter: the collection of instantaneous deviations of a signal edge times at a defined signal level of the signal from the reference times for those events. The reference time is the jitter-timing-reference specified in 6.2.3 that occurs under a specific set of conditions.

3.5.46 jitter, baseline wander induced (BWJ): a form of DDJ that is caused by the effects of the transfer function of a of a high-pass filter circuit in the signal transmission process. Coupling circuits may cause ISI effects that produce correlated deterministic jitter.

3.5.47 jitter, bounded and uncorrelated (BUJ): the part of the deterministic jitter that is not aligned in time to the HPDDJ and DCD in the data stream being measured. Sources of BUJ include, (1) power supply noise that affects the launched signal, (2) crosstalk that occurs during transmission and (3) clipped Gaussian distributions caused by properties of active circuits. BUJ usually is high population DJ, with the possible exception of power supply noise.

3.5.48 jitter, data dependent (DDJ): jitter that is added when the transmission pattern is changed from a clock like to a non-clock like pattern. For example, data dependent deterministic jitter may be caused by the time differences required for the signal to arrive at the receiver threshold when starting from different places in bit sequences (symbols). DDJ is expected whenever any bit sequence has frequency components that are propagated at different rates. For example when using media that attenuates the peak amplitude of the bit sequence consisting of alternating 0,1,0,1... more than peak amplitude of the bit sequence consisting of 0,0,0,0,1,1,1,1... the time required to reach the receiver threshold with the 0,1,0,1... is less than required from the 0,0,0,0,1,1,1,1.... The run length of 4 produces a higher amplitude that takes more time to overcome when changing bit values and therefore produces a time difference compared to the run length of 1 bit sequence. When different run lengths are mixed in the same transmission the different bit sequences (symbols) therefore interfere with each other. Data dependent jitter may also be caused by reflections, ground bounce, transfer functions of coupling circuits and other mechanisms.

3.5.49 jitter, deterministic (DJ): jitter with non-Gaussian probability density function. Deterministic jitter is always bounded in amplitude and has specific causes. Deterministic jitter comprises (1) correlated DJ (data dependent (DDJ) and duty cycle distortion (DCD)), and (2) DJ that is uncorrelated to the data and bounded in amplitude (BUJ). DJ is characterized by its bounded, peak-to-peak value. Level 1 DJ, per 3.5.26 and 3.5.66 , is defined by an assumed CDF form and may be used for compliance testing.

3.5.50 jitter, dispersion induced (DIJ): a form of DDJ that is caused by dispersion in the signal transmission process. Dispersion may cause ISI effects that produce correlated deterministic jitter.

3.5.51 jitter, periodic (PJ): spectral peaks in the BUJ frequency spectrum

3.5.52 jitter, reflection induced (RIJ): a form of DDJ caused by reflections in the signal transmission process. Reflections may cause ISI effects that produce correlated deterministic jitter.

3.5.53 jitter, sinusiodal (SJ): single tone jitter applied during signal tolerance testing.

3.5.54 jitter distribution: a general term describing either PDF or CDF properties.

3.5.55 jitter eye opening (horizontal): the time interval, measured at the signal level for the measurement (commonly at the time-averaged signal level), between the 10^{-12} CDF level for the leading and trailing transitions associated with a unit interval (see figure 20 and figure 21).

3.5.56 jitter frequency: the frequency associated with the jitter waveform produced by plotting the jitter for each signal edge against bit time in a continuously running bit stream. See 6.11

3.5.57 jitter output: the quantity of jitter at a specific physical position in the link.

3.5.58 jitter, random, RJ: jitter that is characterized by a Gaussian distribution and is unbounded.

3.5.59 jitter, residual: jitter that remains after the DDJ and the DCD is removed.

3.5.60 jitter, total, TJ: total jitter in UI is calculated from (1 - jitter eye opening) where jitter eye opening is measured in UI.

3.5.61 jitter timing reference: the signal used as the basis for calculating the jitter in the signal under test. The jitter timing reference has specific requirements on its ability to track and respond to changes in the signal under test (see 6.2.3). The jitter timing reference may be different from other timing references available in the system.

3.5.62 jitter transfer: the ratio as a function of jitter frequency between the jitter output and jitter input for a link element (component, device, or system) often expressed in dB. A negative dB jitter transfer indicates the element removed jitter. A positive dB jitter transfer indicates the element added jitter. A 0 dB jitter transfer indicates the element had no effect on jitter.

3.5.63 jitter tolerance for links: the ability of the link downstream from the receive interoperability point (γ_r, β_r, or δ_r) to recover transmitted bits in an incoming data stream in the presence of specified jitter in the signal. Jitter tolerance is measured by the amount of jitter required to produce a specified bit error ratio. The required jitter tolerance performance depends on the frequency content of the jitter. Since detection of bit errors is required to determine the jitter tolerance, receivers embedded in an FC Ports require that the Port be capable of reporting bit errors. For receivers that are not embedded in FC Ports the bit error detection and reporting may be accomplished by instrumentation attached to the output of the receiver. Jitter tolerance is always measured using the minimum allowed signal amplitude unless otherwise specified. See also signal tolerance.

3.5.64 jitter tolerance for receivers: the ability of a receiver to recover transmitted bits in an incoming data stream in the presence of specified jitter in the signal. Jitter tolerance is measured by the amount of jitter required to produce a specified bit error ratio. The reference point for the jitter tolerance of the receiver is the α_R point. The required jitter tolerance performance depends on the frequency content of the jitter. Since detection of bit errors is required to determine the jitter tolerance, receivers embedded in an FC Port require that the Port be capable of reporting bit errors. For receivers that are not embedded in an FC Port the bit error detection and reporting may be accomplished by instrumentation attached to the output of the receiver. Jitter tolerance is always measured using the minimum allowed signal amplitude unless otherwise specified. See also signal tolerance.

3.5.65 level:
1. A document artifice, e.g. FC-0, used to group related architectural functions. No specific correspondence is intended between levels and actual implementations.
2. In FC-PI-n context, a specific value of voltage or optical power (e.g., voltage level).
3. The type of measurement: level 1 is a measurement intended for compliance, level 2 is a measurement intended for characterization/diagnosis

3.5.66 level 1 DJ: term used in this document for the effective DJ value that is used for DJ compliance purposes.

3.5.67 limiting amplifier: an active non-linear circuit with amplitude gain that keeps the output levels within specified levels, but are generally not designed to reduce jitter and may increase jitter.

3.5.68 media: (1) General term referring to all the elements comprising the interconnect. This includes fiber optic cables, optical converters, electrical cables, pc boards, connectors, hubs, and port bypass circuits. (2) May be used in a narrow sense to refer to the bulk cable material in cable assemblies that are not part of the connectors. Due to the multiplicity of meanings for this term its use is not encouraged.

3.5.69 optical fall time: the time interval required for the falling edge of an optical pulse to transit between specified percentages of the signal amplitude. For lasers the transitions are measured between the 80% and 20% points.

3.5.70 optical fiber: any filament or fiber, made of dielectric material, that guides light.

3.5.71 optical modulation amplitude: the positive difference in power between the settled and averaged value of a long string of contiguous logic one bits and the settled and averaged value of a long string of contiguous logic zero bits. A long string for 8B10B encoding should be considered to be 5 bits high or 5 bits low.

3.5.72 optical rise time: the time interval required for the rising edge of an optical pulse to transit between specified percentages of the signal amplitude. For lasers the transitions are measured between the 20% and 80% points.

3.5.73 physical media dependent (PMD): a transmit and receive network used to launch into a specific type of electrical or optical interconnect or to receive from a specific type of electrical or optical interconnect. The details of the network design depend on the type of interconnect.

3.5.74 Port (or FC Port): a generic reference to a Fibre Channel Port. In this document, the components that together form or contain the following: the FC protocol function with elasticity buffers to re-time data to a local clock, the SERDES function, the transmit and receive network, and the ability to detect and report errors using the FC protocol.

3.5.75 Port bypass circuit (PBC): an active multiplexer that is used to bypass FC ports or other ports that are unused or nonfunctional. PBC's that do not re-time the signals to a local clock are considered part of the interconnect.

3.5.76 probability density function (PDF): a histogram of the jitter event population.

3.5.77 random: random in this document always refers to Gaussian distribution. These distributions may apply to time jitter or signal level noise.

3.5.78 receiver (Rx): an electronic component (Rx) that converts an analog serial input signal (optical or electrical) to an electrical (retimed or non-retimed) logic output signal.

3.5.79 receive network: a receive network consists of all the elements between the interconnect connector inclusive of the connector and the deserializer or repeater chip input. This network may be as simple as a termination resistor and coupling capacitor or this network may be complex including components like photodiodes and transimpedance amplifiers.

3.5.80 reclocker: a type of repeater specifically designed to modify data edge timing such that the data edges have a defined timing relation with respect to a bit clock recovered from the (FC) data at its input.

3.5.81 repeater: an active circuit designed to modify the (FC) signals that pass through it by changing any or all of the following parameters of that signal: amplitude, slew rate, and edge to edge timing. Repeaters have jitter transfer characteristics. Types of repeaters include retimers, reclockers and amplifiers.

3.5.82 retimer (RT): a type of repeater specifically designed to modify data edge timing such that the output data edges have a defined timing relation with respect to a bit clock derived from a timing reference other than the (FC) data at its input. A retimer shall be capable of inserting and removing words from the (FC) data passing through it. In the context of jitter methodology, a retimer resets the accumulation of jitter such that the output of a retimer has the jitter budget of alpha T.

3.5.83 return loss: the ratio (expressed in dB) of incident power to reflected power, when a component or assembly is introduced into a link or system. May refer to optical power or to electrical power in a specified frequency range.

3.5.84 run length: number of consecutive identical bits in the transmitted signal e.g., the pattern 0011111010 has a run lengths of five (5), one (1), and indeterminate run lengths at either end.

3.5.85 running disparity: A binary parameter indicating the cumulative disparity (positive or negative) of all transmission characters since the most recent of (a) power on, (b) exiting diagnostic mode, or (c) start of frame.

3.5.86 signal: the entire voltage or optical power waveforms within a data pattern during transmission

3.5.87 signal level: the instantaneous intensity of the signal measured in the units appropriate for the type of transmission used at the point of the measurement. The most common signal level unit for electrical transmissions is voltage while for optical signals the signal level or intensity is usually given in units of power: dBm and microwatts.

3.5.88 signal amplitude: a property of the overall signal that describes the peak or peak to peak values of the signal level . When signal transitions interfere with or overlap each other in a signal the effective signal amplitude may be expressed as a vertical waveform eye opening (e. g. optical modulation amplitude).

3.5.89 signal tolerance: the ability of the link downstream from the receive interoperability point (γ_r, β_r, or δ_r) to recover transmitted bits in an incoming data stream in the presence of a specified signal. Signal tolerance is measured by the amount of jitter required to produce a specified bit error ratio at a specified signal amplitude. The required signal tolerance performance depends on the frequency content of the jitter and on the amplitude of the signal. Since detection of bit errors is required to determine the signal tolerance, receivers embedded in an FC Port require that the Port be capable of reporting bit errors. For receivers that are not embedded in an FC Port the bit error detection and reporting may be accomplished by instrumentation attached to the output of the receiver. Signal tolerance is always measured using the minimum allowed signal amplitude and maximum allowed jitter unless otherwise specified. See also jitter tolerance.

3.5.90 spectral noise floor: the Fourier transform of the jitter remaining after BUJ is removed from residual jitter.

3.5.91 transceiver: a transmitter and receiver combined in one package.

3.5.92 transmission bit: a symbol of duration one unit interval that represents one of two logical values, 0 or 1. For example, for 8b10b encoding, one tenth of a transmission character.

3.5.93 transmission character: any encoded character (valid or invalid) transmitted across a physical interface. Valid transmission characters are specified by the transmission code and include data and special characters.

3.5.94 transmission code: a means of encoding data to enhance its transmission characteristics. The transmission code specified by FC-FS is byte-oriented, with both valid data bytes and special (control) codes encoded into 10-bit transmission characters.

3.5.95 transmit network: a transmit network consists of all the elements between a serializer or repeater output and the connector inclusive of the connector. This network may be as simple as a pull-down resistor and ac capacitor or this network may include laser drivers and lasers.

3.5.96 transmitter (Tx): a circuit (Tx) that converts a logic signal to a signal suitable for the communications media (optical or electrical).

3.5.97 TxRx connection: the complete signal path between a transmitter in one FC device and a receiver in another FC device.

3.5.98 unit interval (UI): the normalized (dimensionless) nominal duration of a single transmission bit. Unit interval is a measure of time that has been normalized such that 1/baud seconds is 1 UI.

3.5.99 waveform mask violation, WMV: a recorded signal event where an incursion occurs into the jitter eye opening in the signal level/time space defined for a particular CDF level for the signal population. For some compliant receivers this event could produce a link bit error. Note that a maximum of one WMV event may be recorded within a single bit period. Multiple incursions into the eye opening from the same signal within the same bit time shall be counted only once. WMV's are not failures unless the number exceeds that allowed.

3.5.100 word: in Fibre Channel protocol, a string of four contiguous bytes occurring on boundaries that are zero modulo 4 from a specified reference.

4 Background for MJSQ

4.1 Overview

Clause 4 describes the historical background of MJS and MJSQ and some of the reasons that the original MJS technical report was produced. The concepts and terminology in this clause are more fully developed throughout MJSQ and may not be fully understood without exploring the remainder of MJSQ.

4.2 Relationship to SONET and receiver tolerance requirements

The methodologies in this document are extensions of the SONET [8], [9], [10] jitter specification concepts. In SONET the term ‘network interface jitter’ is used in approximately the same way as the term ‘jitter’ is used in this document. SONET also defines a term ‘frame jitter’ that is not equivalent to the term ‘jitter’ used in this document.

The extensions to SONET implicitly specify the assumed receiver CDR characteristic. The specification for the frequency response of the clock recovery circuit is determined by defining a jitter tolerance mask for the clock and data recovery function. Jitter occurring below the characteristic frequency is tracked and modifies the recovered clock frequency whereas jitter above the characteristic frequency is not tracked. This PLL characteristic exists for digital as well as analog (PLL-based) CDR’s. Figure 2 schematically shows this tracking or frequency response characteristic. Additionally, at certain frequencies jitter peaking may occur whereby the output jitter is greater than the input jitter. It should be noted that the jitter peaking and CDR bandwidth property of some CDR’s is a potential source of jitter degradation when used in repeaters within the interconnect. This document does not specify a separate requirement for jitter peaking and CDR bandwidth.

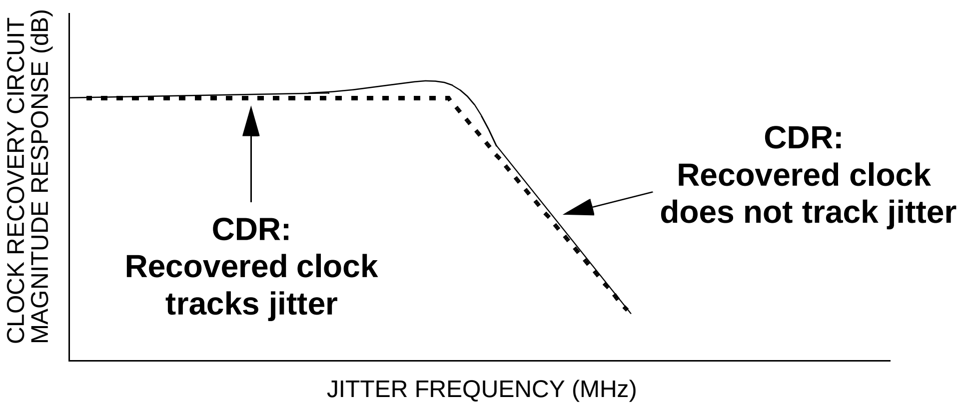


Figure 2 - PLL response

A spectral characteristic is imposed on the specification to differentiate between jitter that may be benign to a link’s bit error ratio performance because of the receiver’s ability to track low frequencies and jitter that is detrimental to a link’s bit error ratio performance. The jitter tolerance specification in figure 3 creates a jitter tolerance spectral requirement that is not currently specified in the FC-PH document. The implication of this specification is that jitter output specifications at all compliance points include frequency content based on the jitter tolerance mask.

When comparing this jitter specification to SONET jitter specification, the jitter tolerance masks are based on different test conditions.

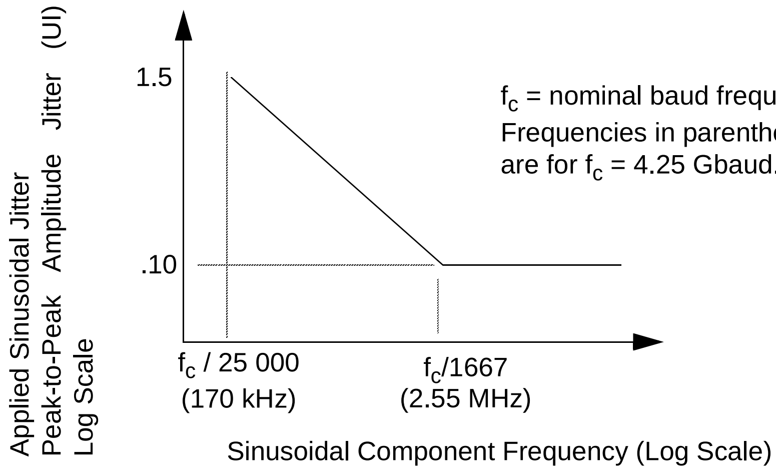


Figure 3 - Mask of the sinusoidal component of jitter tolerance - Log-Log Plot

For most receivers high frequency jitter has greater impact on bit error ratio than low frequency jitter because the receiver is capable of tracking the low frequency jitter. Jitter specifications that include frequency content require additional testing; but lower systems costs may be achieved with the relaxation of the clock stability requirements.

A real example of being able to build lower cost systems by imposing the spectral characteristics to jitter relates to using lower cost reference clocks for the serializer clock multiplier PLL. Clock synthesizers are lower cost than crystal oscillators. Analysis of low-cost clock synthesizers shows an unacceptably large jitter content. Further analysis shows that most of the clock jitter is low frequency that passes unattenuated out of the optical or electrical transmitter. However, the receiver CDR reliably tracks this low frequency jitter and recovers the data.

4.3 Relationship to earlier FC standards

The ANSI Fibre Channel specification X3.230-1994 (FC-PH) [1] only specifies measurement techniques for jitter. Two jitter generation measurement techniques are specified in X3.230-1994. One measurement is for deterministic jitter using a special Fibre Channel K28.5 pattern that contains the longest and shortest runs. The other measurement is for random jitter using a special Fibre Channel defined character, K28.7, that is a “clock-like” data sequence assumed not to contain deterministic jitter. The deterministic jitter measurement results in a peak to peak value and the random jitter measurement results in an RMS value. Per the FC-PH Annex J, the peak to peak value of random jitter is 14 times the RMS value for a 10^{-12} bit error ratio. Total jitter is equal to peak to peak random jitter plus peak to peak deterministic jitter.

The methodology relying on repeated K28.7 characters for measuring RJ and repeated K28.5 for measuring DJ are flawed for the following reasons:

First, the assumption that all deterministic jitter is absent in the square-wave-like K28.7 is often incorrect. For instance, deterministic sub harmonic processes in the transmitter may show up in this measurement. Ten picoseconds of such DJ could be accounted as 14*10/2=70 pS of RJ.

Second, while the maximum and minimum run length pulses in K28.5 are ideal for measuring data-dependent jitter due to cable skin effect, this method may completely miss some components of DJ. For instance, the sub harmonic process described above (or any jitter effect not synchronous with the K28.5 pattern) would be completely removed by averaging. Also, transmitter mistiming of any of the 5 edges out of 10 missing in K28.5 would go undiscovered.

In addition to differentiating between trackable and non-trackable jitter, a need exists to clarify the existing receiver jitter tolerance allocation indicated in the informative Annex J of the FC-PH document. What is 70% eye closure? What is this intended to test? Two CDR characteristics are important for reliable serial communication: CDR loop dynamics and CDR strobe error. These CDR characteristics becomes increasingly important as repeaters are used in Disk Arrays and Hubs.

Some of the features described in MJSQ are implemented in FC-PI but some significant extensions are not. MJSQ is being developed in parallel with FC-PI-2 where most extensions are implemented.

4.4 Traditional measurement methodology risks

The workhorse for evaluating signals has been the sampling oscilloscope for many years. For the properties required of high speed serial signals ordinary sampling oscilloscopes may not be suitable.

Using oscilloscope waveform eye mask methods with histogram measurements in present oscilloscope technology does not provide the statistical population required to accurately represent behavior at 10^{-12} population levels in a reasonable measurement time period. See figure 4 for examples of this issue. See also Annex H. See clause 9 for more information on different measurement methodologies. Measurements are made at the appropriate physical point in the link.

The actual signal quality may be very different at the low population levels from the appearance at high populations as seen in a typical waveform eye diagram from an oscilloscope. Figure 4 shows the waveform eyes as would result on a sampling oscilloscope from two different jitter distributions that have the same jitter eye opening at the 10^{-12} level. The distributions are taken at the nominal switching threshold level of the signals. Notice that EYE “A” seems to be considerably worse than EYE “B” but is actually equivalent in terms of its total jitter.

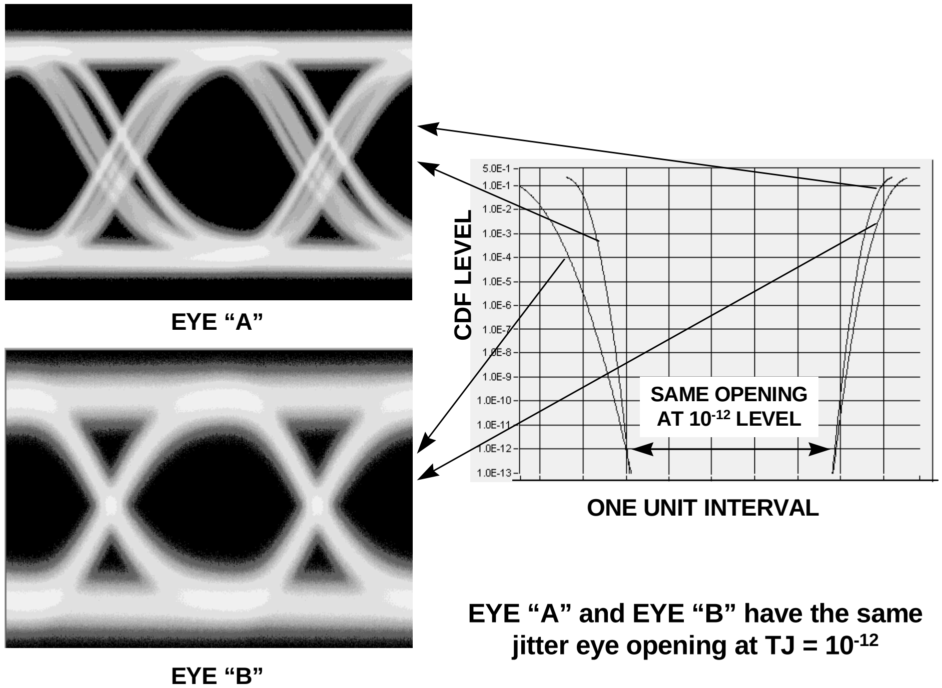


Figure 4 - Waveform eye diagrams from different jitter distributions

Traditional measurements are all recorded at the nominal receiver switching level. The most common nominal switching levels are zero differential volts for balanced electrical links and the average optical power level. Behavior at signal levels other than the nominal switching threshold is also important. For example if a signal enters the eye mask above or below the nominal switching threshold, errors may occur.

More detail concerning the important signal properties is contained in 6.2.

A signal quality measurement needs a reference time to quantify the timing properties. See 6.8.

Signal quality acceptance criteria are specified within the allowed jitter eye opening at the specified total population probability (e.g. CDF = 10^{-12}).

A major goal of MJSQ is to specify signal quality measurement methodologies that more closely approximate the observed bit error ratio of receivers.

Signal quality measurements that include results at signal levels other than the nominal switching threshold may be termed 2-dimensional or eye contour in this document.

5 Jitter overview

5.1 Serial transmissions

Serial data communication complements parallel communication schemes where the clock and data transmissions are on physically separate paths and the clock path is used as a timing reference for the others in the receiver. These separate paths behave slightly differently due to physical and bandwidth differences with resulting timing differences between the clock and data signals. Although one may employ methods to compensate the propagation time skew between the different parallel signals, ultimately the same clock signal shall be used for all data signals. This limits the bandwidth of parallel schemes that use a single clock.

In serial data communication, a separate data clock is not transmitted with the data. Rather the transmit clock is embedded along with the data so the problem of maintaining the temporal alignment between the clock signals and the data signals is eliminated. However, other problems are created in that signal transitions need to be available at intervals that are not too long so that a clock signal may be reconstructed from the single serial stream and the relationship of the reconstructed clock to the bits in the serial stream are maintained within strict limits. Even in the case of serial transmissions there is a basic requirement to maintain adequate alignment between the recovered clock (or whatever timing reference is used by the receiver to latch the bits) and the incoming data. A requirement in high speed serial communication is management of jitter involved with the data transmission and detection so that high quality data extraction from the serial signal is possible.

MJSQ assumes that a recovered clock methodology is used for the receivers.

MJSQ does not address the issues associated with encoding schemes where the phase and signal level contain information, for example phase modulation or multi-level encoding. Simple NRZ schemes are assumed.

5.2 Jitter output context

The term “jitter” refers to the deviation of the timing properties of a signal with respect to a specified reference time. Historically, the jitter is measured at the nominal switching threshold of the signal. The Subclauses in this clause provide detailed description of the context and general requirements to do an effective specification of generalized jitter.

When the term “jitter” is used in this document it refers to the time behavior of the signal at a specific signal level. If the signal level is not specified, either the context of the usage defines the meaning or the signal level is the nominal switching threshold for the receivers expected in the link.

Jitter is characterized by two generalized types of jitter, deterministic (DJ) and random jitter (RJ). The two categories of jitter are used in jitter analysis because each category accumulates differently in the link and because compliance and budgeting schemes require some restrictions on the jitter distributions.

Deterministic jitter is jitter that is due to non-Gaussian jitter event distributions. Deterministic jitter is always bounded in amplitude and has specific causes. Three kinds of deterministic jitter are identified: duty cycle distortion, data dependent, and uncorrelated (to the data) bounded. Examples of deterministic jitter that is uncorrelated to data are power supply noise injection into the serial link and cross talk from other parts of the system. Deterministic jitter is measured as a peak to peak value for any distribution. Both the peak to peak value and the distribution contribute to the overall system performance.

Random jitter is all jitter that is Gaussian in nature. The overall observed random jitter may consist of a collection of random jitter sources. Because root-sum-of-squares (rss) addition is used in this document independence of the constituent jitter sources is required. Dependence could occur in some cases. For example, if truly random data was transmitted through an AC coupling network, the jitter pdf will be essentially Gaussian. If that data traveled through multiple stages of such networks, the jitter mechanisms would be correlated and Gaussian accumulation would be more linearly additive than rss additive. Since 8b10b encoding imposes a structure on all data we don't have truly random data for 8B10B. The surviving random jitter after encoding is therefore jitter that is uncorrelated to the data. Random jitter after 8b10b encoding is composed only of independent sources and we are therefore allowed to use rss addition for random jitter. This also validates the use of convolution where independence is required.

Because random jitter is practically measured as an RMS value (the same as the standard deviation for a Gaussian distribution), a seemingly small amount of RMS random jitter corresponds to a large peak to peak value. The RMS value for random jitter is multiplied by approximately 14 to result in a peak to peak random jitter value that corresponds to a 10^{-12} bit error ratio; refer to the jitter mathematics in 6.5. A 10 ps RMS random jitter measurement represents a 140 ps peak-to-peak value, or almost 15% of the bit period, for Fibre Channel at 1063 Mbaud.

5.3 Jitter tolerance context

CDR circuits, whether analog PLL-based (Phase-Locked Loops) or digital-based, react differently depending on the rate of change or frequency of the timing misplacement. If the rate of change is gradual and "trackable" by the CDR, no bit errors occur. If jitter is instantaneous (within one bit time) and of sufficient amplitude (such as 50% of a bit time), the CDR cannot track the timing shift and the recovered bit may be in error.

The ability to recover data successfully in the presence of jitter is called jitter tolerance. Jitter tolerance is measured as the jitter amplitude over a jitter spectrum where the link achieves a specified bit error ratio. A jitter tolerance measurement is performed as a bit error ratio measurement under the presence of a controlled amount of jitter.

Since BER performance also depends on the signal amplitude (many receivers tolerate more jitter if the signal is larger), a complete signal tolerance that includes both amplitude and jitter is required to determine compliance. If the amplitude is not separately specified in a tolerance measurement, it is assumed that the jitter tolerance is measured with the smallest allowed signal amplitude.

5.4 Jitter assumptions summary

The basic assumptions used in this document are summarized below:

The acquisition of the raw data is based on the assumptions listed immediately below:

a) Simple NRZ schemes are used.
b) JItter is composed of a collection of jitter events that occur at most once per bit period.
c) Clock recovery schemes are used in the link receivers.

In order to separate DJ from TJ and to do signal budgeting based on that separation the following assumptions apply:

a) RJ is uncorrelated to anything else.
b) DJ does not have a Gaussian probability density function when measured with the repeating data patterns prescribed in this document.
c) 8B10B encoding is used and has a DJ ceiling around BER~1E-4 for the data and around 1E-6 when BUJ (e.g.,crosstalk is included) - other encoding schemes that have similar DJ ceilings are also applicable.
d) These methods may use extrapolation, requiring the assumption that CDF/BER floors are less than 10E-12.

e) Spectral noise floors have a Gaussian PDF.
f) Jitter budgeting (separation of DJ and TJ and assigning values to each) is done by a single curve fitting method regardless of the method used to acquire the raw data.
g) Coding other than 8b10b may violate the assumptions above and not produce accurate budgeting results with the methods described.

The methods described for acquisition of TJ and the jitter population distribution (PDF or CDF) are applicable down to the noise floor regardless of the encoding scheme used.

5.5 FC-0 and MJS(-1) interface overview

The physical architecture within a transmitter interface and a receiver interface is assumed to be representable by the forms shown in figure 5 and figure 6. For simplicity, the entire interface structure is termed transmitter or receiver in this document and the transmitter and receiver shown in figure 5 and figure 6 are subsumed.

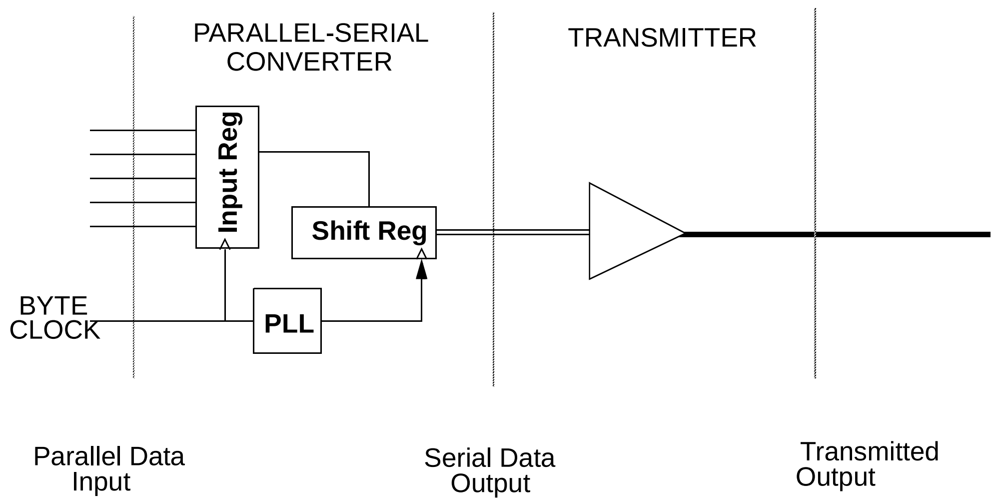


Figure 5 - FC-0 transmitter interface (FC-PH figure 9, page 17)

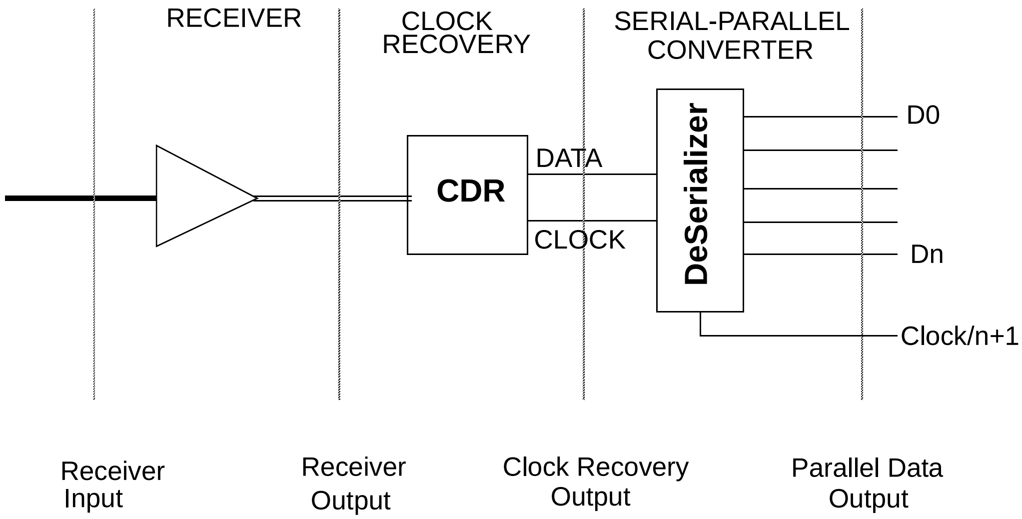


Figure 6 - FC-0 receiver interface (FC-PH figure 10, p 17)

The reference times used to quantify the jitter and signal quality vary with specific method and physical location. See details in later sections.

5.6 Fibre channel physical architecture

A brief description of the FC physical architecture is contained in this Subclause. See FC-PI for a more complete description.

A Fibre Channel fabric link consists of the functional blocks shown in figure 7. The TxRx connection in an FCAL architecture is the same as for fabrics for MJSQ purposes. From a timing and jitter perspective, the following characteristics shall be noted. Fibre Channel uses plesiochronous timing where the port may transmit data at a slightly different frequency from its receive data frequency. Elastic storage exists within the protocol function to absorb the frequency differences as well as the maximum wander present in the link. The serializer function is responsible for suppressing jitter components present in the port from propagating onto the link. The deserializer recovers a bit clock from the serial data that reliably allows the deserializer to provide parallel data and a recovered byte clock to the protocol function.

A Fibre Channel fabric link is a duplex serial data connection between two ports including the serializer, deserializer, PMD, connectors, and cable assemblies. A link is necessary for communication between two ports. A link includes a minimum of a pair of transmitter-receiver connections. A TxRx connection is a simplex link consisting of one transmitter-receiver pair. A link and a TxRx connection are shown in figure 7.

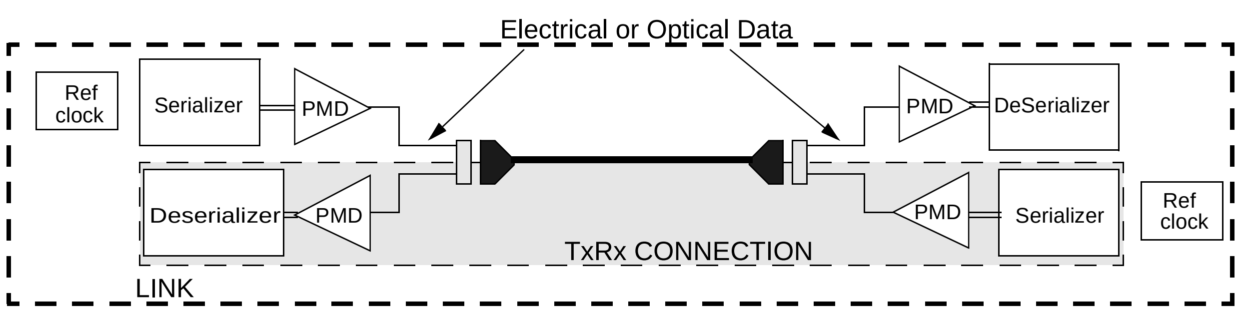


Figure 7 - Fibre channel fabric link

A port by definition contains protocol intelligence, elasticity mechanisms to absorb wander, and locally timed serial data transmission. Other components in a TxRx connection may be used that attenuate jitter or re amplify the signal to improve the signal quality. In actual system implementations, these may include active buffers, port bypass circuits, or reclockers. An example of a complex system implementation for storage application using Fibre Channel Arbitrated Loop is as shown in figure 8. In this system, a link between the host adapter Port and the disk drive in Port 2 is rather complex. This link would include a HA Tx to HDD Rx connection through a hub with repeaters, an enclosure with repeaters, and a backpanel with one PBC and a HDD Tx to HA Rx connection through multiple HDD Ports acting as retimer circuits, several port bypass circuits, an enclosure repeater, and a hub repeater.

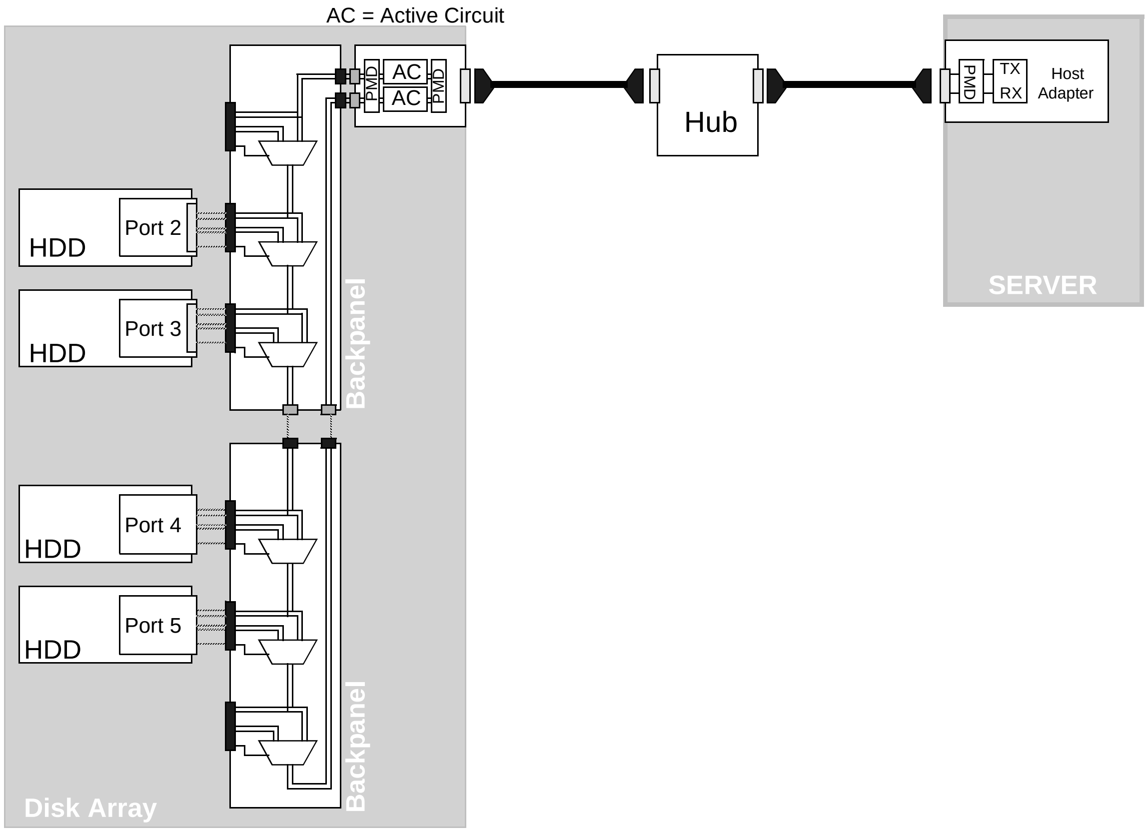


Figure 8 - Example fibre channel link storage system implementation

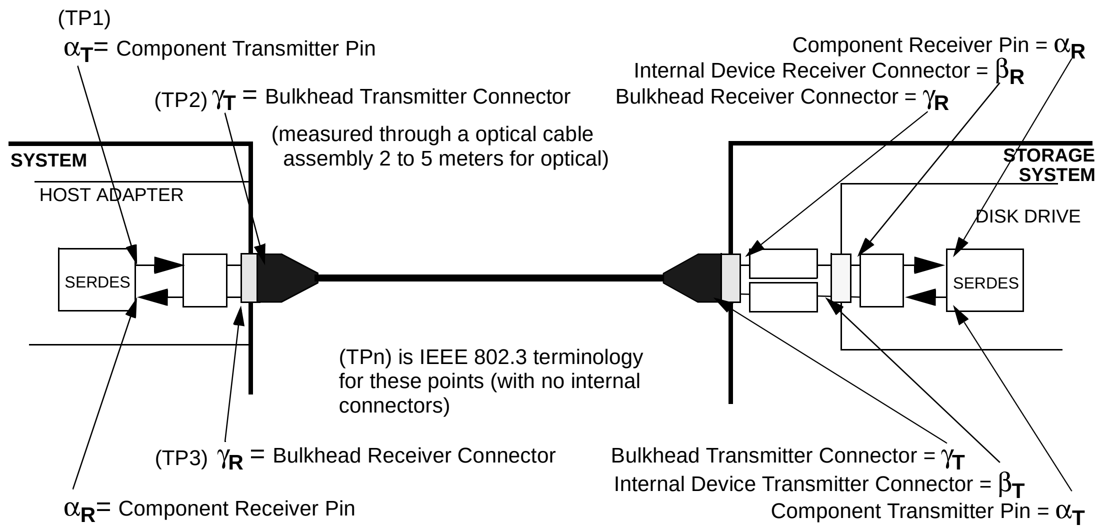
As shown in figure 8, a Fibre Channel Arbitrated Loop is not necessarily a point to point link with only bulkhead compliance points. It shall be clearly understood where TxRx connection interfaces exist within a system, so that jitter allocation compliance may be enforced at those points.

Figure 9 shows two examples illustrating the interoperability / compliance points with and without the use of internal connectors for media interchange and with and without the use of retimers. Interoperability points are defined at the internal device (β), the internal PMD connector (δ), and the external enclosure (or equivalently, system bulkhead) connector (γ). A reference point (α) is defined at the serialize/deserializer chip containing the re-timing function. A device such as a host adapter or disk drive intended for embedding into a larger system may have a connector that is not the actual system bulkhead connection. An enclosure is something that houses a Fibre Channel port that passes emissions and safety certification.

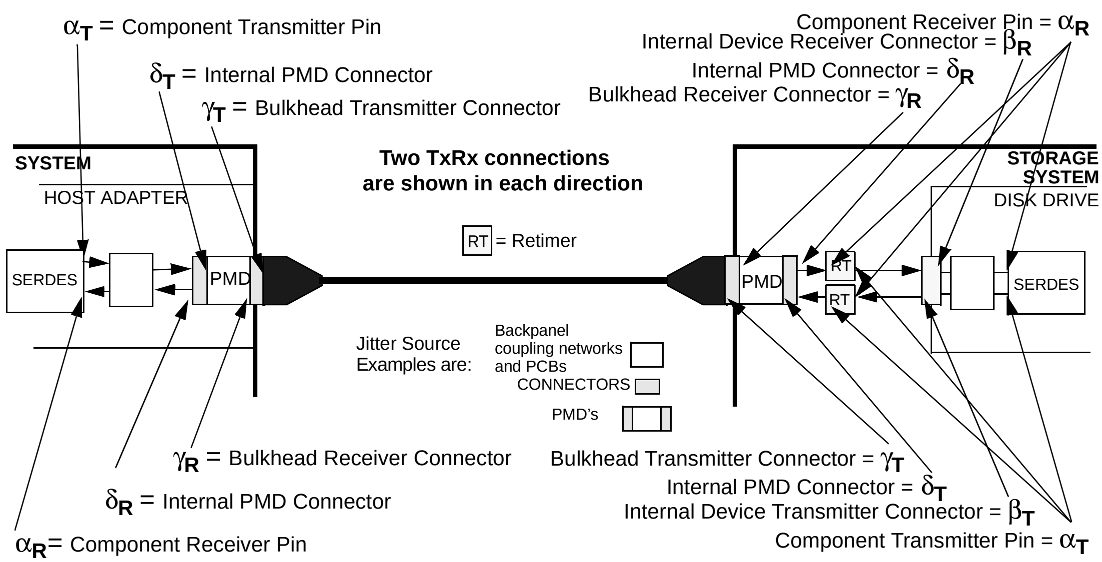
All measurements shall be made through mated connectors, as appropriate (β, δ, γ). For signal output measurements the mated connectors are always upstream of the signal measurement point. For signal tolerance measurements the signals to be applied to the DUT are calibrated with the connector upstream of the calibrating instrument but the actual tolerance measurement is made with the calibrated signal applied to the connector on the DUT that is downstream of connector separation point.

A system bulkhead connector (γ) is equivalent to the current S and R points in the FC-PH specification. The terminology, TPx, used in IEEE 802.3 for γ and α for applications with no internal connectors, is also shown in the upper left portion of figure 9.

The β point is defined to be the internal connector closest to the retimer element as shown in the upper right and lower right examples. If a β point is connected to a δ point a retimer is required between the β and the δ points in order to isolate the internal TxRx connections from the external TxRx connections. The retimer resets an internal compliance point such that all the jitter elements used internal to the storage array may use all the jitter budget allowed from β_T to β_R (not shown).



Without use of Internal δ Connectors



With use of internal δ connectors and retimers

(α is a reference point, not an interoperability point)

Figure 9 - Interoperability points examples at connectors

6 Jitter fundamentals

6.1 Purpose of addressing all important signal levels

In order to have the measurement of signal properties relate in a definitive way to the performance of receivers one recognizes that receivers may react to signals at other than the nominal switching threshold and may react differently to different jitter distributions or other signal properties. As a consequence, the jitter distribution at other than the nominal switching threshold level may be critical. The method for specifying acceptable performance limits at these other signal levels is an eye mask similar to that used for oscilloscopes as described in 6.6 along with bathtub curves described in 6.4.

6.2 Essential properties of signals

6.2.1 Introduction

Fundamentally, a signal is a specific relationship between signal level and time.

The level of a signal, or signal level, is its instantaneous intensity measured in the units appropriate for the type of transmission used at the point of the measurement. The most common signal level unit for electrical transmissions is voltage while for optical signals the signal level or intensity is usually given in units of power: dBm and microwatts (optical modulation amplitude).

Electrical signals are assumed to be baseband (i.e., not the result of modulation).

Since the information of interest in optical serial communications is transmitted as an amplitude modulation of a single carrier wavelength, the signal level of interest is the average optical power around an instant in time at the carrier wavelength. This average is taken in the optical receiver where the optical signal is converted into an electrical signal. The details of the averaging process are not important to this document since the data rates of interest are orders of magnitude lower that the optical carrier frequency for all practical Fibre Channel applications.

Even though the baseband electrical signal and the envelope of the modulated optical carrier may appear similar for similar data content, the physical mechanisms of transmission are very different. Nevertheless, from a signal quality point of view there is a great deal of commonality and in many cases in this document there is no distinction drawn between electrical and optical signals.

A number of properties of signals may affect the response of receivers. Since real signals may have very complex shapes and different receivers may react differently to the same signal it is important to define the most important signal properties that are known to affect receivers. Among the properties that could be important are: distribution of signal level, distribution of jitter population, whether rising edge or falling edge, slew rate, rise/fall time, spectral content, common mode content, and imbalance. The methodologies described in MJSQ consider the signal level, the timing distribution (at different signal levels), and the rising or falling edge (for some methodologies) in full recognition that other properties may be important. The effort required to address the signal level, timing distribution, and signal edge is significant. These properties are described in the remainder of 6.2.

6.2.2 Signal amplitude vs. signal level

Signal amplitude is a property of the overall signal that describes the peak or peak to peak values of the the signal level. When signal transitions interfere with or overlap each other in a signal the effective signal amplitude may be expressed as a vertical waveform eye opening.

6.2.3 Time, timing reference and jitter timing reference

Time measurements require a reference time in order to be reproducible. In other words, all time measurements are the difference between a reference time and the time where the measured event is recorded. For MJSQ the time reference used for calculating jitter is called the jitter timing reference. This reference may be different from other timing references available in the system.

In order to comply with the methodologies in MJSQ the jitter timing reference shall be derived only from the data stream. See 6.10. No other jitter timing reference shall be used including: reference bit clocks supplied externally by the transmitting device (e.g. BERT's) and internal clocks used to create the transmit signal.

Present state of the art requires that the same jitter timing reference be used for all parts of the signal. It is beyond the scope of this document to create a relationship between different jitter timing references at different signal levels. This statement is similar to stating for oscilloscope based measurements that the trigger level shall remain constant for all measurements. Some choices for jitter timing reference are discussed in 6.8.

The jitter timing reference choice is perhaps the single most important part of selecting a practical measurement method for signal quality.

6.2.4 Considerations when using hardware based jitter timing references

Since jitter timing references are the references in much the same way that a ground is the reference for a single ended electrical signal any noise in the reference directly affect the accuracy of the basic measurement. In general if the jitter timing reference has jitter, X_t, then the jitter that is measured is X_m minus X_t where X_m is the actual time of the measured signal. MJSQ does not deal with jitter in the jitter timing reference other than that required for Golden PLL's. It is up to the suppliers of the instrumentation to deliver very low noise jitter timing references.

6.2.5 Jitter and noise relationship

Consider a portion of a signal as shown in figure 10. When the nominal signal is disturbed by noise or jitter the position of the signal changes. Figure 10 shows two disturbed signals that were derived from the nominal signal. Noise properties and jitter properties may both be measured in the immediate neighborhood of a point in signal level - time space. Noise may cause jitter and jitter may cause noise. However, the cause of the disturbance to the nominal signal does not intrinsically alter the measured noise or measured jitter.

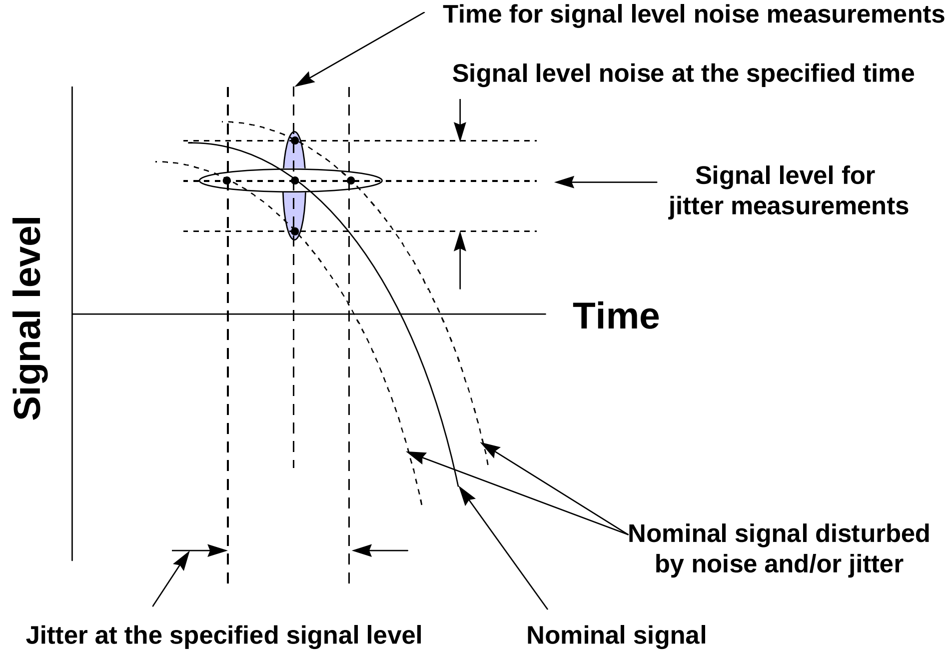


Figure 10 - Noise and jitter in the same portion of the signal

Most of the content of MJSQ assumes the constant signal level (constant measurement threshold), jitter condition. For many purposes a constant sample time (within the eye), signal level noise condition could also be a valid representation of the disturbed signal. Noise, like jitter, is also comprised of deterministic and random components that may degrade the signal quality and lead to data errors. Effective signal amplitude reduction (or vertical waveform eye closure) is a predominant limitation in many links.

For measurements near the nominal receiver switching threshold the jitter method is traditional. For measurements near the center of the bit time the signal noise method is traditional. In fact, either method allows a complete mapping of the signal level - time space.

If one knows the shape of the signal in the vicinity of the measurement then a jitter measurement may be converted to a signal level noise measurement and vice versa. In fact, the jitter optimized oscilloscope data acquisition method described later in this document is partially based on that conversion.

If a conversion is required between noise and jitter, limitations may exist to the validity range for this conversion. The nonlinearity of the signal, the bit time of the data pattern, and the amplitude of the signal may all impose limits on this conversion. For example, in the case of a Gaussian noise (that is unbounded) the conversion to unbounded jitter cannot be based on the properties of a signal transition since that signal transition is bounded by the amplitude of the signal. Jitter derived via conversion from noise in this way is limited to a single rise time that is clearly bounded. There are other limitations with conversions. In general conversion limitations may lead to large understatement of the Gaussian jitter. This document assumes that any conversions done remain valid over the 1E-12 range within a single bit time.

Another important issue is the validity of extrapolations that are used. The conditions required for a valid extrapolation depend on the specific conversions used and on the point in signal level - time space of interest. For example in figure 10 the changing slope of the signal causes distortions in the noise induced jitter distribution - a Gaussian noise source may not produce a Gaussian jitter distribution. In general one should attempt to validate that the conditions of the measurement support the assumptions required for the extrapolation.

This topic is expected to be further explored in MJSQ-2.

6.2.6 Rising edges and falling edges

One consideration for acquiring signal quality data is whether the reference time and/or event being measured are associated with a rising or falling signal “edge”. Whenever the signal level changes state from high to low or low to high a signal edge or transition is produced. Usually, the signal in the transition period between the states has a monotonically changing signal level. However, conditions may exist in acceptable links where slope reversals occur during this transition.

The signal quality measurement results may depend on the choice of whether the timing reference is derived from rising edges, falling edges, or a combination. Complete signal quality specification methodology requires examination of all combinations of rising and falling edges for both the jitter timing reference and the signal under consideration.

It may be useful for diagnostic purposes to separate results from specific combinations of rising and falling edges.

In order to avoid effect of DCD in the jitter timing reference only the rising edge or the falling edge (but not both) may be used from the jitter timing reference signal.

6.3 Number of events per bit-period

A major goal of MJSQ is to specify methodology that enables direct comparison of signal events with bit errors experienced by a link receiver. One key requirement toward realizing this goal is that no more than one event be reported from the signal in any single bit time since receivers cannot generate more than one bit error per bit time. As a corollary, the total number of signal events reported shall not exceed the total number of bits transmitted in any given time period.

The signal is assumed to be continuous in time and if instrumentation were fast enough, theoretically multiple events per bit-period could be captured for some signals. For example, detection of multiple events per bit-period is possible for measurements of slow edges when using over-sampled real time digitizing oscilloscope technology. In data acquisition schemes that allow multiple signal events per bit period some scheme to filter the reported WMV events to no more than one per bit-period shall be used.

This single event per bit-period constraint is useful when dealing with signals that have slope reversals because it guarantees that no double counting is possible for the same bit time.

The number of times the signal crosses the signal level of interest per bit-period is affected by the pulse time compared to the bit-period, the level of the signal being examined, whether slope reversals are present, whether distinction is made between rising and falling edges, and the positioning of the timing reference with respect to the signal edges. Slope reversals are common in links operating at less than 1 Gb/s electrical applications due to reflections and crosstalk. Optical transmitters are also capable of producing slope reversals through relaxation oscillations for example.

The number of events could be seriously misreported if one had the possibility of multiple events per bit time. There are several possibilities for the number of events occurring at different signal levels as shown in the signal level vs. time example shown in figure 11. Since the ultimate goal of signal quality specifications is to relate the signal quality to the receiver performance and the receiver reports at most one bit error per bit received, it would be possible for the signal to be measured as producing six signal events where only one detected bit is possible in this time period.

Figure 11 only shows multiple counting due to slope reversals occuring in conjunction with a signal transition. Noise and transmitter signal distortions allow multiple counting to be theoretically possible anywhere in the bit time including during signal transitions, in the center region of the bit time, and when the signal state is not changing due to the data pattern (several 1's or 0's in a row).

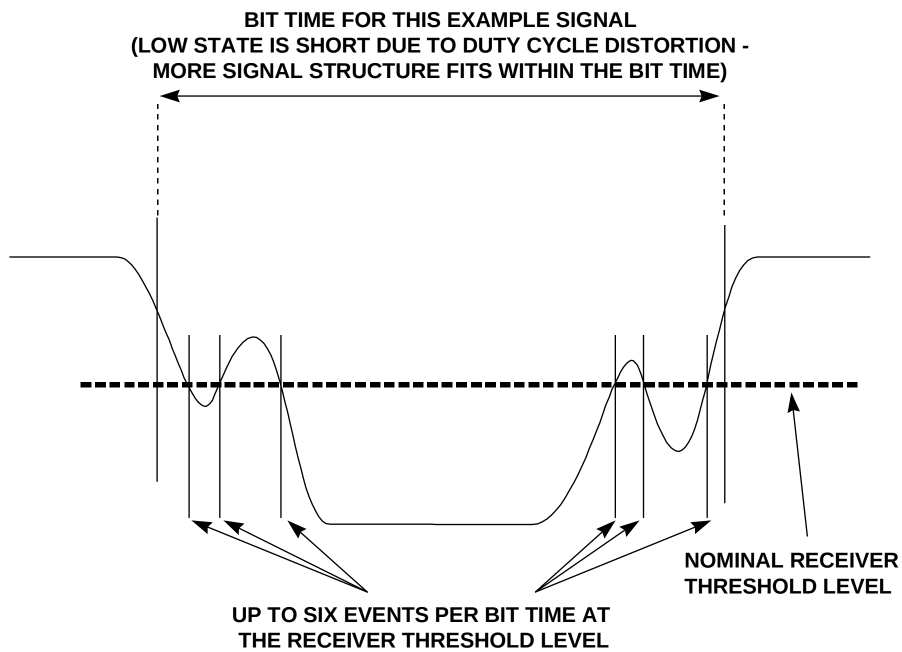


Figure 11 - Example of multiple events within the same bit time

At most a single event per rising of falling edge shall be reported.

Signal quality measurements are significantly coupled to receiver detected errors by the same counting statistics maintaining at any signal level measured.

6.4 Statistical distribution at a specific signal level

A requirement that signal quality data be acquired at specified signal levels pervades this document. The more signal levels examined the more complete the signal quality measurement.

The population of times observed (events) when the signal crosses a specified level of interest may be compiled into a histogram. This histogram constitutes the statistical distribution.

Statistical distribution properties are critically important to the way receivers set their internal timing references (the one used to detect the bits in the receiver). More discussion of this issue is in 6.13.

6.5 Basic relationships within statistical jitter distributions

6.5.1 Overview

Subclause 6.5 describes the mathematical basis for jitter distributions and specification methodologies. Concepts and terminology that lead to the jitter eye mask and signal eye contour are developed. Insight into the relationship between jitter events, PDF's, CDF's, RJ, DJ, jitter eye opening, waveform eye opening, and bit error ratio results.

The bit error ratio in the signal in this clause is based on the population of signal events that exist at time positions where there should be no signal events in the known data pattern and data rate being used. This population of erroneous signal events may be detected, for example, by a BERT strobed at a specific time and signal level within the unit interval. The signal bit error ratio is the number of erroneous signal events divided by the total number of bits transmitted over the measurement time period. A BERT with an instrumentation quality receiver is assumed.

Using a BERT methodology for signal quality measurements is different from using the same BERT to determine the bit error ratio as detected by the actual receiver in the link. This distinction is important because events reported as bit errors when performing a signal quality measurement may have only a loose relationship to link bit error ratio reported by a real link receiver. The closer the real link receiver comes to being a ‘worst case’ receiver the tighter the relationship between signal event errors and link errors. Signal event errors are conditions that are capable of producing link bit errors in a compliant (but perhaps just barely compliant) link receiver.

The mathematics that apply to the statistics of bit errors in signals are derivable from those that apply to schemes that sample the signal level and time properties of signals. One integrates the population of signal events from the time of the strobe point to infinity (or to - infinity) to determine the total population of erroneous signal events.

The distinction between BERT measurements on signals and direct signal level and time measurements from other instruments may be easy to miss since the distributions have similar shape over the Gaussian tail regions (the integral of an exponential function is still an exponential function). The numbers associated with the probability distributions are significantly different, however.

In figure 12, consider a portion of a typical eye diagram display that may be seen near the receiver switching threshold signal level. This discussion assumes that the source used to trigger the instrument is the same as that used to create the signal being measured and that the trigger source itself has no jitter. Typically only the rising or falling edge (not both) of the trigger source is used. In this case duty cycle distortion on the trigger source is not a concern. Jitter in the signal at the signal threshold level is indicated by the time between the trigger source and the time of the crossings of the threshold signal level as the data toggles between logic states. Histograms of the recorded population of the times of threshold crossings may be calculated as shown in figure 12.

The timing reference used for this Subclause was chosen for ease of conceptual understanding. Using different timing references leads to different distributions but the treatment of jitter and bit errors has the same mathematical basis. Actual measurements shall use the jitter timing references specified in 6.2.3.

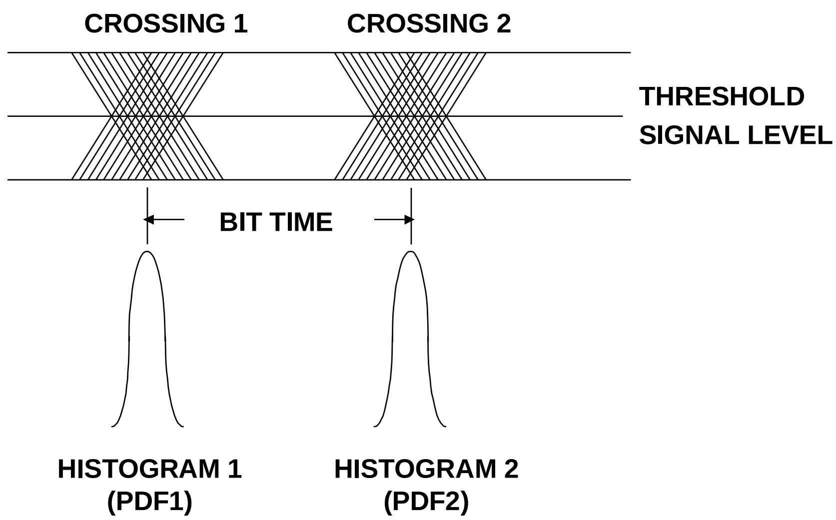


Figure 12 - Signals crossing a threshold level at different times

In the limit of infinite number of events these histograms represent continuous probability density functions (PDF's) of the population of signal events at different times when the signals cross the signal level defined. The means of the PDF's determine the bit cell boundaries. To simplify matters, the time scale is given in terms of unit intervals (UI) with 0.5 located at the exact center of the bit time as determined by the two means.

In figure 13, the BERT receiver is shown measuring the errors in the signal at the center of the eye opening at the sampling time where the tails of the transition histograms are small. A signal error occurs if a transition is on the wrong side of the sample time, st. The error conditions are (1) when a transition from histogram 1 occurs to the right of (after) st, and/or (2) when a transition from histogram 2 occurs to the left of (before) st. Because the tails of a normal (Gaussian) function are infinitely long there is always some population from all transitions in every measurement (even from transitions well before or after the transitions of primary interest). Fortunately it is usually possible to ignore contributions from non-adjacent edges because the population is very small. The remainder of this subclause considers only contributions from adjacent signal transitions.

To calculate the probability of either transition causing a signal event error due to jitter, the area under its PDF tail on the errored side of st is calculated. This calculation assumes that each PDF may be analyzed independently and that they are the same functions but displaced by exactly one unit interval. This displacement does not imply that the left and right tails of the same PDF are symmetrical. Under this assumption in figure 12 PDF1 is PDF (t) and PDF 2 is PDF (t-UI). Practically, if there is significant overlap between PDF's from adjacent edges it may be difficult to determine which edge is responsible for the population.

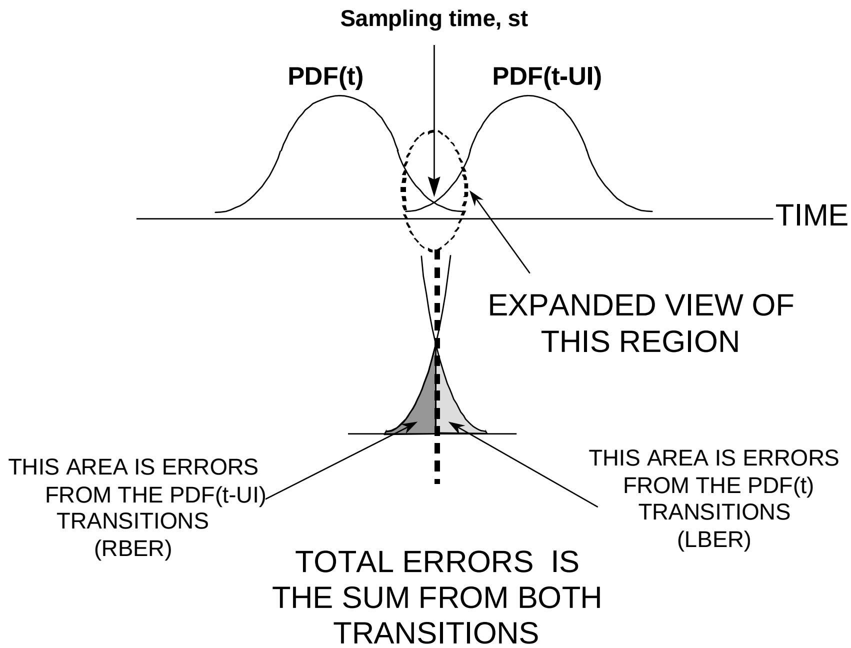


Figure 13 - Probability of signal event errors from adjacent signal transitions

note: st is shown at the midpoint of the bit time but may be at any point.

This area under the tail for each PDF is the cumulative distribution function, or CDF, and is the bit error contribution from that tail. For PDF (t), the CDF is produced by integrating the right tail of PDF (t) from st to $+\infty$; for PDF (t-UI) the CDF is produced by integrating the left tail of PDF (t-UI) from $-\infty$ to st. The overall probability of bit errors due to both transitions is the sum of the two CDF's (assuming that the tails from neighboring bits contribute negligibly to the probability of error).

In normal statistics, a CDF is simply the integral of its PDF where the final value of the CDF is unity. However, in this document, to calculate a CDF that matches a bit error ratio (BER) concept for the signal, the probability of a transition-caused error is multiplied by the probability of actually having transitions at 50% (usually interpreted as the average transition density). This discussion assumes typical data streams have a transition at 50% of the bits (i.e., a transition density, TD, of 50%).

The following describes the properties of the jitter CDF:

a) Each total jitter PDF has an area of unity
b) BER = CDF = TD * integral of PDF (the jitter CDF includes the transition density factor)
c) The CDF reaches a maximum value of TD, not unity

From this point on in the document the term CDF refers to the jitter CDF only.

6.5.2 Description of mathematical model

Assume a general jitter PDF, JT (t,W,σ), centered at 0 where t is time, W is the pk-pk value of deterministic jitter, and σ is the rms value of random (Gaussian) jitter. The right tail of the PDF from the left signal transition, JT (centered @ 0) causes bit errors as:

Equation 1 – Left bit error ratio

$$\mathrm{LBER}\,(st,W,\sigma) = \mathrm{TD} \cdot \int_{st}^{\infty} \mathrm{JT}(\tau, W, \sigma)\,\delta\tau$$

where st is the sampling instant in time, and TD is the transition density. LBER is the CDF for the right tail of PDF(t). Similarly, the left tail of the PDF from the right signal transition JT (shifted and centered @ 1 UI) causes bit errors as:

Equation 2 – Right bit error ratio

$$\mathrm{RBER}\,(st,W,\sigma) = \mathrm{TD} \cdot \int_{-\infty}^{st} \mathrm{JT}(\tau - \mathrm{UI}, W, \sigma)\,\delta\tau$$

RBER is the CDF for the left tail of PDF(t-UI).

The total BER due to jitter from both transitions, TBER, is given by (see figure 13):

Equation 3 – Total bit error ratio

$$\mathrm{TBER}\,(st, W, \sigma) = \mathrm{LBER}\,(st, W, \sigma) + \mathrm{RBER}\,(st, W, \sigma)$$

In a BERT scan, BER (CDF) is measured as the sample time, st, is swept between the two bit time boundaries. From these BERT scan results, the jitter in the signal may be estimated.

This is also done (simulated) below with the model by generating the CDF's. Again, summing the two CDF's yield the total probability of error from both transitions. This expression indicates the BER as a function of st and PDF width. This is commonly known as a BER bathtub curve.

6.5.3 Relationship between jitter and BER for random jitter distributions

This sub-clause demonstrates the model using only random, or Gaussian, jitter (RJ). For RJ, the key parameter to be specified is the standard deviation, σ, of the PDF. W, the deterministic jitter magnitude, is 0 in this case. $\mathrm{JT}\,(\tau, W, \sigma)$ for Gaussian jitter, centered at 0, is:

Equation 4 – Gaussian jitter PDF

$$\mathrm{JT}\,(t, W, \sigma) = \frac{1}{\sqrt{2 \cdot \pi}} \cdot \frac{1}{\sigma} \cdot e^{-\left(\frac{t^2}{2 \cdot \sigma^2}\right)}$$

The CDF (BER distribution) for a Gaussian PDF (jitter distribution) involves error functions. Figure 14 shows plots of the PDF's (dashed) and corresponding CDF's (solid) plotted on a linear scale. (The PDF's displayed have been normalized to unity-height to make them plot better - the CDF's were generated from unity-area PDF’s as required for all PDF’s). The CDF includes the multiplier for transition density (50%). In this example, the standard deviation of the PDF’s is 0.05 UI rms.

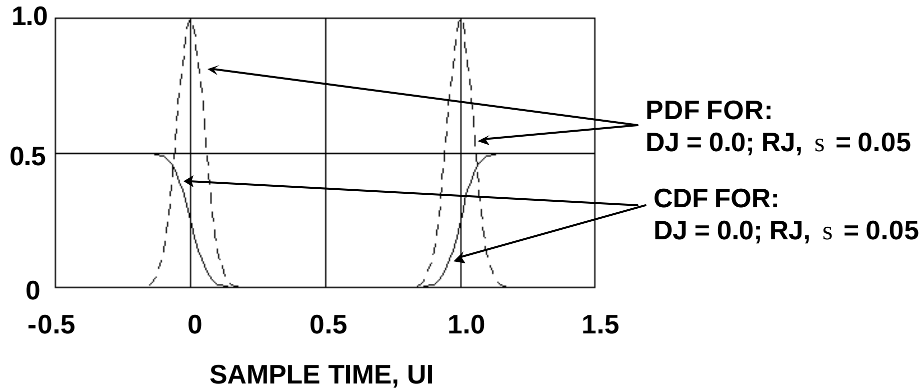


Figure 14 - Jitter eye diagram statistics, linear scale

The sum of the CDF’s, shown as total BER in figure 15, from the two sides shows the bathtub shape. The bathtub appears to have a wide central region where the probability of error is small. Fibre Channel specifies the bit error ratio to be better than 10^{-12}. In order to visualize such small values of probability, a log scale is used for the BER axis. See figure 15. The eye opening based on the BER distribution is approximately 0.3 UI at 10^{-12}. Eye opening is based on CDF’s not PDF’s.

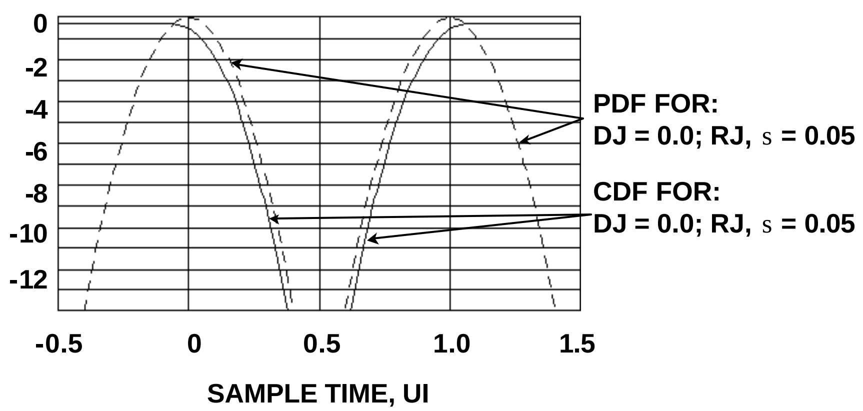


Figure 15 - Jitter eye diagram statistics, log scale

For example, a visual estimate in figure 15 based on the PDF eye opening at 10^{-12} suggests a smaller opening than the opening for the BER based at the same level. This interpretation is incorrect due to the normalization used for the displaying the (PDF) and because of the integration required to produce bit error ratios from PDF’s.

BER eye opening, CDF eye opening and jitter eye opening are all equivalent terms. The total jitter (TJ) is defined by this eye opening at a specified BER. The term jitter eye opening is preserved in this document but is not the eye opening of the PDF (the jitter population).

Total jitter measurements made by some common oscilloscopes may differ significantly from the jitter eye opening based on the CDF as defined in 6.5.1.

In order to ensure that the behavior across the entire bit time is captured it is required that BERT measurements sweep "st" (see Figure 13 for the definition of "st") across the entire bit time. See also 6.3.

Summarizing: the concept of an excluded region, or opening, applies only to the CDF or to the bit error ratio. Instruments that record the timing of signal events (i.e. record elements of the PDF) calculate the CDF from the PDF's of the signal edges. Some instruments may do this calculation internally, other instruments may not. The calculations, whether internal or external, should be done using the methods required in this document.

6.5.4 Effects of changing the standard deviation for Gaussian PDF's

The plots in figure 16 show the error probabilities for σ values of 0.03, 0.05 and 0.1 UI rms. The curve for $\sigma = 0.1$ UI shows there is no margin against the 10^{-12} error ratio specification. The $\sigma = 0.03$ UI curve indicates a BER based eye opening of around 58% at 10^{-12}, and $\sigma = 0.05$ UI has a BER based opening of about 0.3 UI.

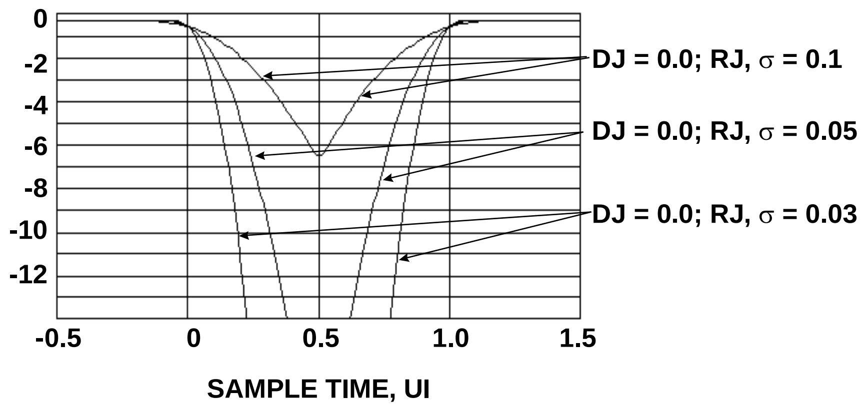


Figure 16 - Jitter eye diagram statistics pure Gaussian different sigmas

6.5.5 Common mistakes relating to statistical properties of measurements.

The following list documents common mistakes that may be made.

a) Drawing a narrow histogram box near the signal threshold on a normal oscilloscope and multiplying the calculated one standard deviation reported from the population in the histogram box by 14 and stating the result as the peak to peak total jitter. This generally yields significantly erroneous results because this standard deviation may include mostly DJ population.
b) Using the peak to peak jitter number reported by an oscilloscope histogram as the total jitter. This understates the total jitter required by MJSQ (as that existing at the 10^{-12} population level based on the CDF's).
c) Some scopes use +/- 3 sigma for peak to peak. Therefore, scope pk-pk may also overstate, for example, if the shape of the DJ pdf has a high moment and if the relative magnitude of RJ is very low.
d) In the oscilloscope eye diagram measurement mostly the deterministic components of the signal are seen due to the low 1000 to 10,000 population levels used to form the eye diagram - ineffective visibility to Gaussian content.
e) Not using the Golden PLL for jitter measurements and simulations (see 6.10).

6.5.6 Addition of deterministic jitter

Total jitter is usually comprised of both random and deterministic components. Consider now that the PDF's include deterministic jitter (DJ). The general theory for mapping total jitter PDF's with DJ to BER through the CDF is identical to the theory for RJ alone.

In general, the DJ component has its own PDF, and the combined total jitter PDF is a convolution of the DJ and RJ PDF's. For purposes of simplification in the present discussion, it is assumed that the DJ PDF is comprised only of a pair of Dirac delta functions (dual-Dirac). Other PDF's are certainly possible. An example of such a DJ PDF is pure duty cycle distortion (DCD). When convolved with RJ, two Gaussian functions result, one for each of the DJ terms. If they are close together (DJ small relative to RJ), the two density functions overlap.

The magnitude of DJ, W, is given as peak-to-peak. Therefore, each Dirac delta function is offset from the mean crossing position by the peak value of DJ, W/2. The magnitude of σ for RJ, in this case, is 0. The PDF for deterministic jitter, centered at 0, is given by:

Equation 5 – DJ PDF

$$\mathrm{JT}(t, W, \sigma) = \frac{\delta\left(t, -\frac{W}{2}\right)}{2} + \frac{\delta\left(t, \frac{W}{2}\right)}{2}$$

When convolved with random jitter, the PDF, centered at 0, becomes:

Equation 6 – PDF for DJ convolved with RJ

$$\mathrm{JT}(t, W, \sigma) = \frac{1}{2 \cdot \sqrt{2 \cdot \pi}} \cdot \frac{1}{\sigma} \cdot \left(e^{-\left[\frac{\left(t - \frac{W}{2}\right)^2}{2 \cdot \sigma^2}\right]} + e^{-\left[\frac{\left(t + \frac{W}{2}\right)^2}{2 \cdot \sigma^2}\right]} \right)$$

Figure 17 shows the total jitter PDF and BER functions for 0.2 UI DJ pk-pk with low values of RJ (0.005 UI rms).

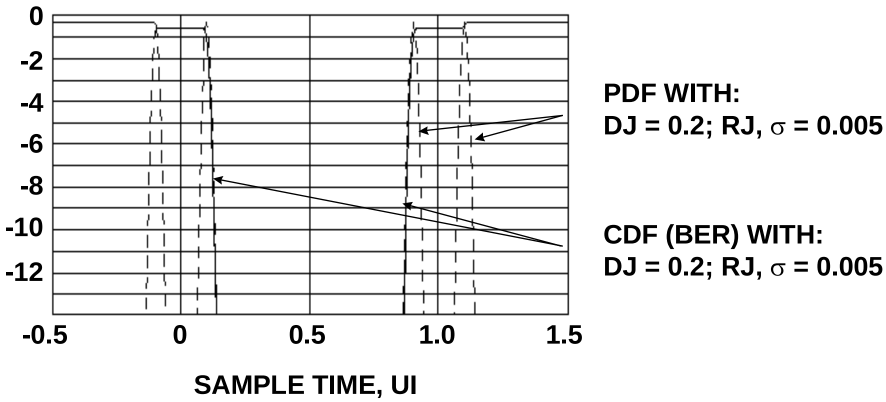


Figure 17 - Jitter eye diagram statistics, dual-Dirac function

The overall jitter eye opening at 10^{-12} is approximately 0.73 UI. Figure 18 shows the 10 base exponent of the total jitter PDF and BER functions again with DJ = 0.2 UI pk-pk, but now with RJ = 0.03 UI rms. Note how the dual-Dirac function / RJ convolution terms now overlap within each total jitter histogram. The jitter eye opening at 10^{-12} is approximately 0.38 UI in figure 18.

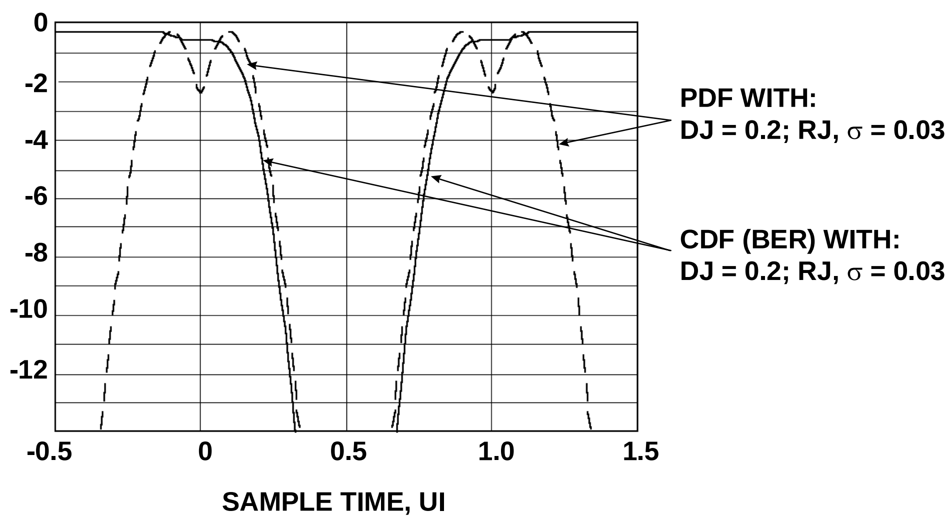


Figure 18 - Jitter eye diagram statistics, increased RJ

The eye may be closed by DJ and RJ in different combinations. Figure 19 shows 3 combinations, with each showing approximately 0.3 UI eye opening at 10^{-12}.

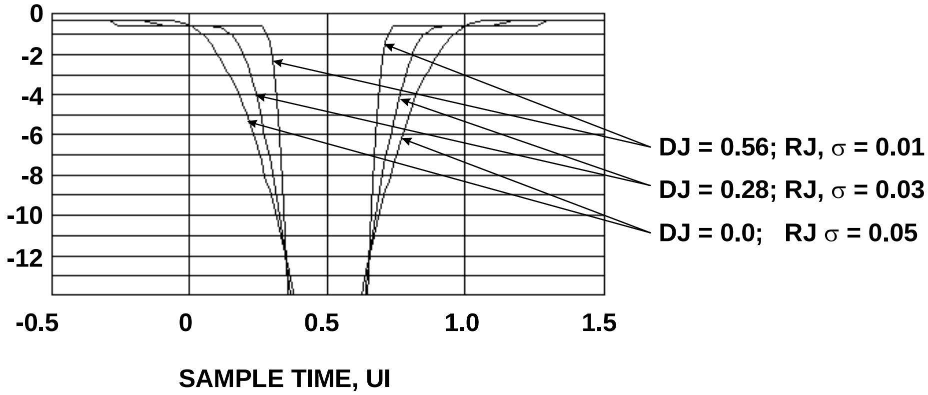


Figure 19 - Various combinations of DJ and RJ

A convenient way to present histogram results acquired at specific signal level is the bathtub format shown in Figure 20. This log-linear plot format shows approximately straight lines for normal distributions in the tail regions. Sometimes extrapolation to low population levels is convenient from this format.

6.6 Jitter eye mask methodology for signal quality specification

A generalized, simplified form of the CDF is shown in figure 20.

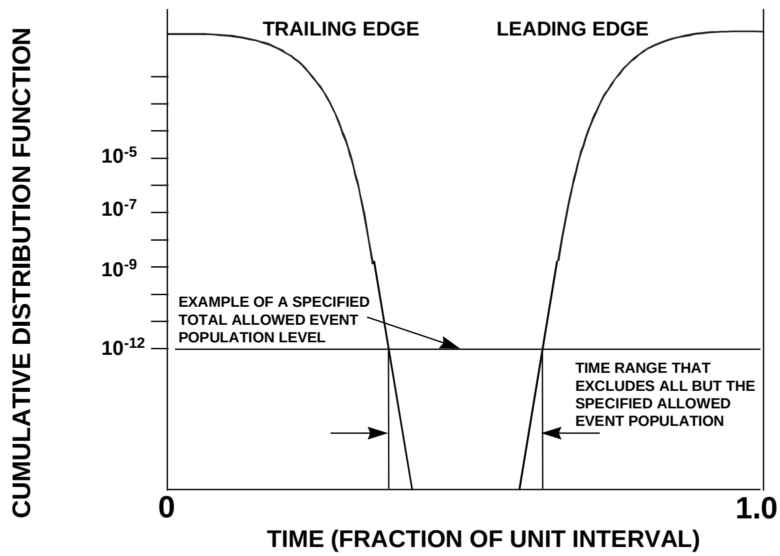


Figure 20 - General form for the CDF bathtub curve at the specified signal level

The CDF bathtub curve is a convenient way to specify the acceptable limits for the time range where all except the allowed population of events may occur. In Figure 20 a 10^{-12} fractional population is shown as an example where the time range is measured. Since this time range may be expressed as a simple number it lends itself to use in describing the acceptable limits at other signal levels.

Notice that the low population time range occurs near the center of the bit time where the signal is the most stable and where the internal strobe in the receiver (if an internal strobe methodology is used) latches the signal as a high or low state.

When the time range and time values at the allowed population (see Figure 20) and at all signal levels are combined into a single graphical representation the result is a concise specification of the total signal quality requirements at all signal levels. A direct connection between a small family of limiting bathtub curves at different signal levels is shown three dimensionally in figure 21.

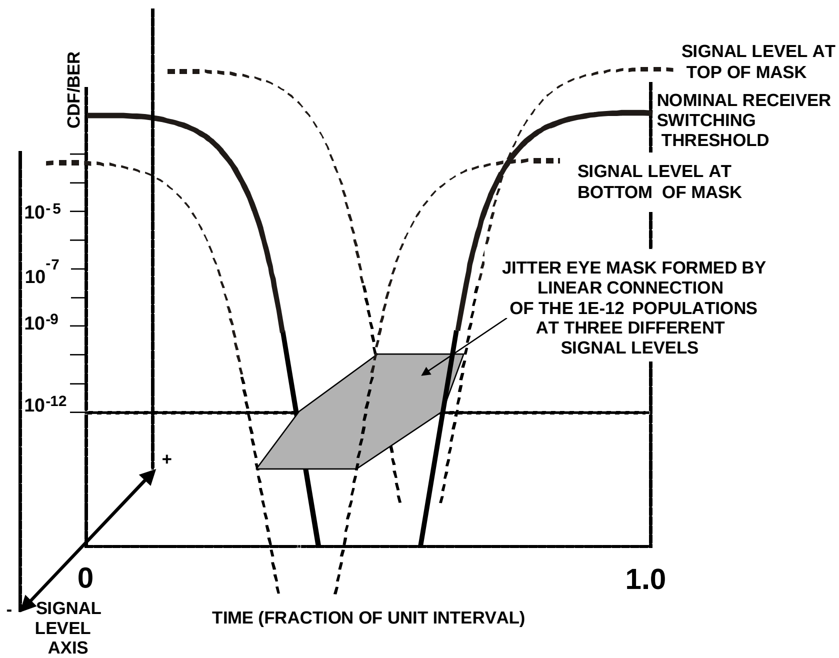


Figure 21 - Relationship of a jitter eye mask to a family of limiting bathtub curves

Two key points concerning the relationship of a jitter eye mask to bathtub curves:

a) The shape and size of the mask is expected to depend significantly on the CDF level chosen. For example if 10^{-9} were used instead of 10^{-12} in figure 21 the mask would be larger in all time dimensions.
b) The bathtub curves represent a signal that just meets the eye requirement at the specified CDF level - actual bathtub curves depend on the sample under test and measurement details and are NOT used to define the jitter eye mask.

Only the limiting behavior at a single CDF level and for a single signal measurement process is specified by the mask.

The signal should not exist (as detected by sampling) within the excluded region more often than the allowed population for any signal level. In other words, bathtub curves from compliant signals at all signal levels shall not encroach inside the mask at the specified population level. This is the essence of determining whether a signal is compliant with the jitter eye mask as described in more detail in 6.7.

Jitter eye masks are usually drawn two dimensionally as shown in Figure 22.

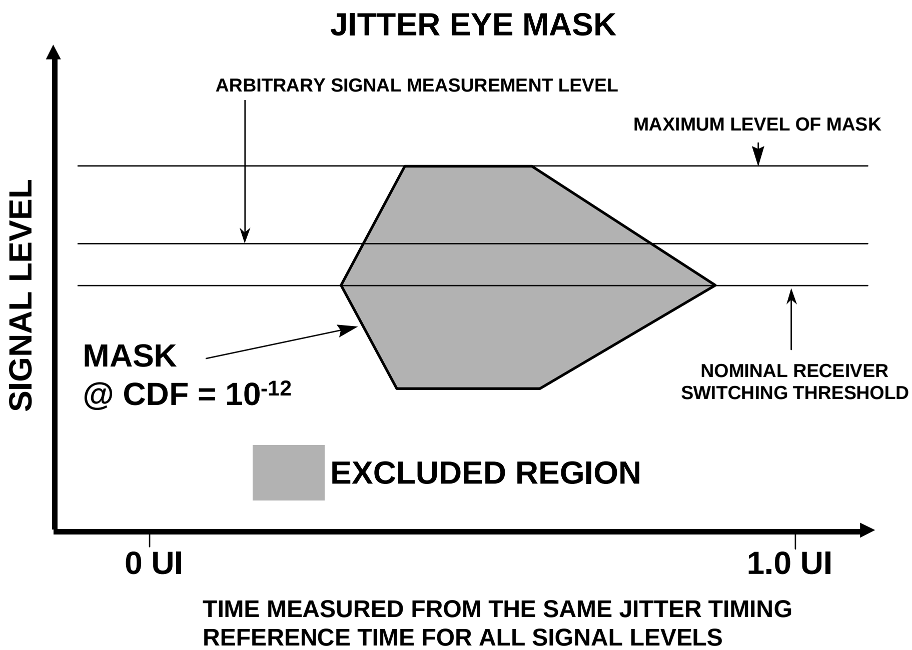


Figure 22 - General form of a jitter eye mask used for signal quality specification

Notice that since there is at most one event per bit-period per signal level and that there are the same number of signal edges at all signal levels, that the signal level that has the CDF with the greatest fractional population within the excluded region is the lowest margin level. For some systems this lowest margin level occurs at or near the nominal switching threshold of the receiver as has been the tradition in the past. However, the lowest margin point may be the upper or lower mask corners in optical links or in electrical links with high amounts of dispersion.

The signal specifications in FC-PI-n are ambiguous about the intent of the masks in those standards. FC-PI-n specifies the X1 point (at the nominal receiver switching threshold) to be at the CDF = 10^{-12} population but is silent on the meaning of the points at other than X1. In order to comply with the jitter eye mask described in this MJSQ document all points on the jitter eye mask are at the CDF = 10^{-12} population. MJSQ does not address the ambiguity in the FC-PI-n standards as that is a matter for those standards.

6.7 Signal measurements vs. jitter eye mask signal quality specifications

The general idea described for jitter eye masks (i.e., the definition of the allowed boundaries of the CDF of signals at the specified population level over the entire signal level - time space) is also useful for displaying signal measurements.

In a signal measurement one does not necessarily expect to see the sharp corners commonly found in jitter eye mask specifications. Real signals rarely have sharp corners. The locus of points in signal level - time space where the CDF = 1E-12 in the actual signal population determines whether a jitter eye mask violation has occurred. Such a locus in a signal measurement is called an ‘eye contour’. If the eye contour encroaches into the jitter eye mask at any point then the signal fails to meet the signal quality requirements.

Figure 23 shows a hypothetical example of an eye contour plotted on the same axes as the jitter eye mask.

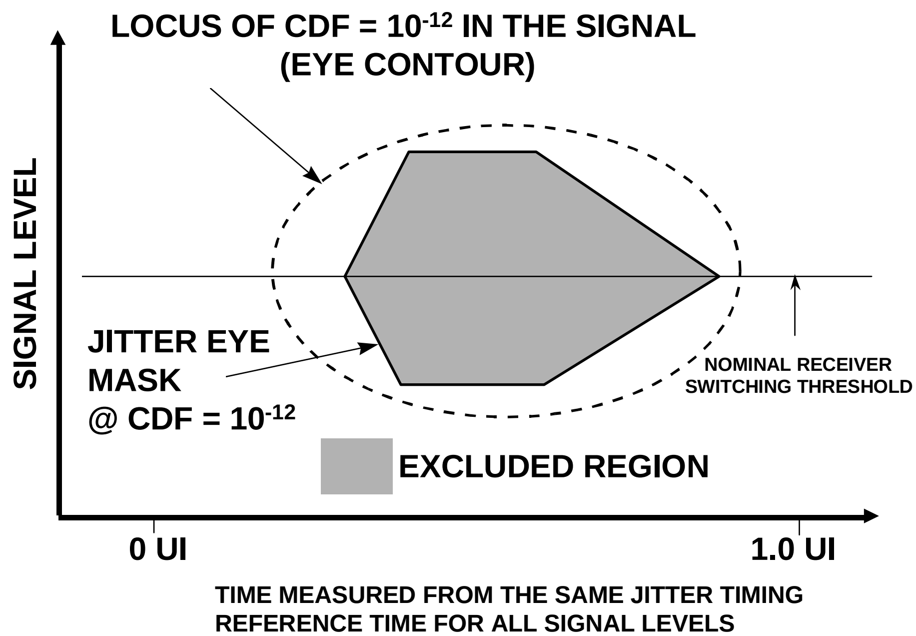


Figure 23 - Example of an eye contour with a jitter eye mask

Since the eye contour does not penetrate the excluded region defined by the jitter eye mask the signal passes the requirements defined by the jitter eye mask at CDF = 1E-12.

6.8 Jitter timing reference at different signal levels during data acquisition

The jitter timing reference is the point in time that is used as the zero for the measurement of reported timing events. Events may occur at signal levels other than that used for establishing the jitter timing reference.

Due to different DJ values at different signal levels, MJSQ requires that only the nominal switching threshold level be used to generate the jitter timing reference for any signal level. The nominal switching threshold is the only point where the jitter does not depend on the signal level of the signal. Allowing other signal levels to be used for the jitter timing reference would effectively allow different answers from different laboratories or different operators. The data pattern and jitter timing reference shall remain constant for data acquisition at all levels.

In order to avoid effect of DCD in the jitter timing reference only the rising edge or the falling edge (but not both) may be used from the jitter timing reference signal.

6.9 Example of a 2-dimensional jitter measurement

A practical example of a simple 2-dimensional time jitter measurement using a TIA at three different signal levels is shown in Figure 24. Measurements were acquired at the signal levels at the top and bottom of the mask and at the nominal switching threshold. From the raw jitter measurements the CDF was calculated prior to plotting the measured distributions in figure 24 and the 10^{-12} CDF level is the edge of the plotted measured distribution (indicated by the RJ arrow with the black head). Some separation of the components of the populations into the different types (as described in 6.5) was also done with the RJ boundary and the DJ boundary indicated. The DJ boundary is the mean of the left and right Gaussian distributions. See 9.2. The RJ boundary is the time where the CDF = 10^{-12}. Since the measured RJ boundary does not intersect the mask boundaries in Figure 24 this signal meets the total signal quality requirements.

A linear connection between the three measured points (high signal level, nominal threshold level, and low signal level) was made on both sides of the signal distributions for ease of graphical presentation. Additional measurements at other signal levels are required to validate that these linear interpolations are accurate. In many cases the distributions are convex away from the mask between the end points and the switching threshold and the high and low signal levels represent the worst case. However, if reflections or synchronous crosstalk are present, the distribution may not be convex and could have its closest approach to the mask between the nominal threshold and the high/low levels. In this case the use of only the high and low level and nominal switching threshold level would not reveal the true signal quality.

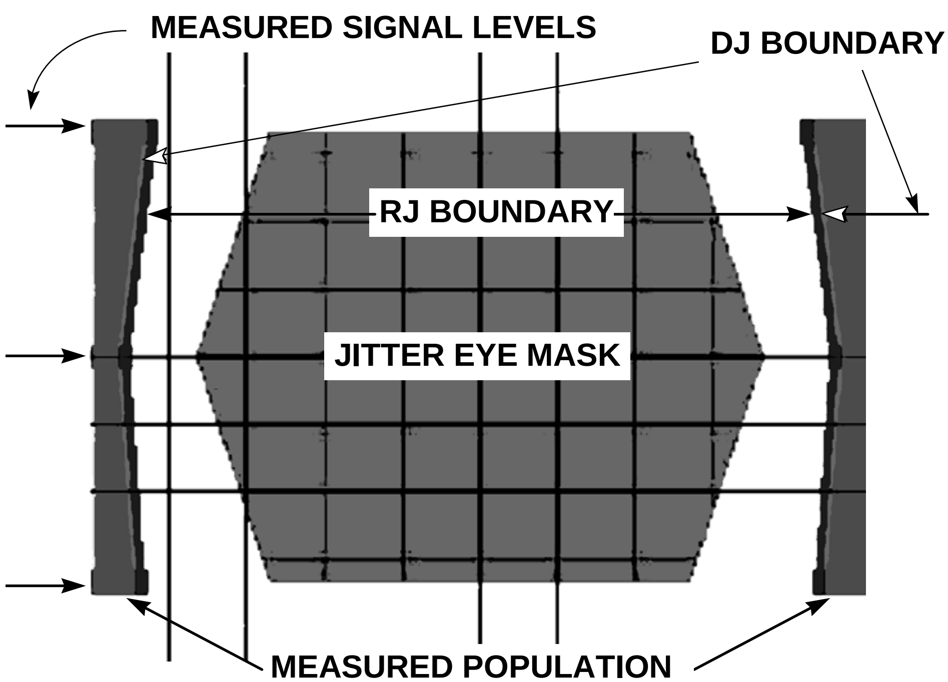


Figure 24 - Practical example using a TIA at three different signal levels

6.10 Jitter timing reference frequency response requirements

6.10.1 Overview

Serial data communication embeds the clock signal in its transmitting data bit stream. At the receiver side, this clock needs to be recovered through a clock and data recovery device where PLL circuits are commonly used. It is well known that a PLL typically has certain phase modulation frequency response characteristics. Therefore, when a receiver uses the recovered clock to time/retime the received data, the jitter seen by the receiver will follow certain frequency response functions as well. Figure 25 shows a receiver that incorporates a typical clock and data recovery system.

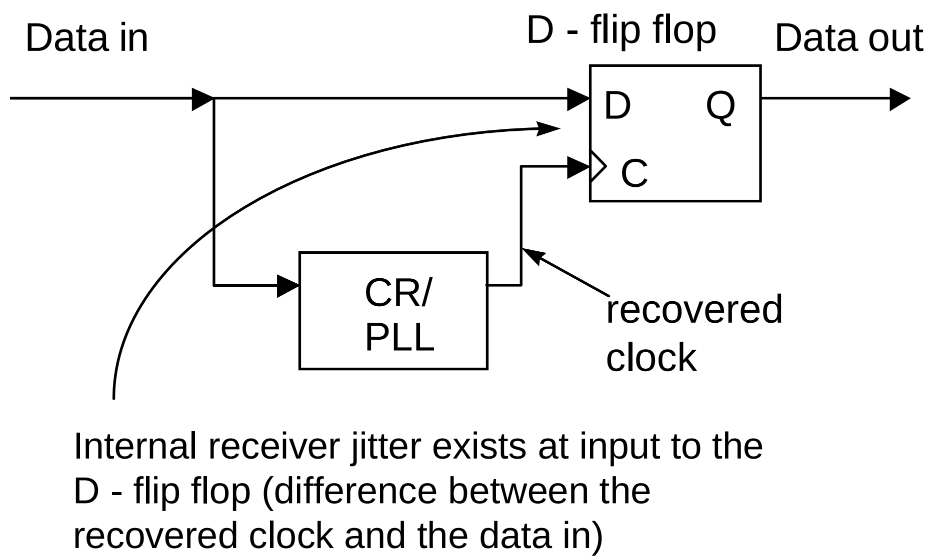


Figure 25 - Block diagram for a serial receiver with clock and data recovery

A PLL typically has a low-pass phase modulation frequency tracking response function $H_L(f)$ with roughly the characteristics shown in figure 26.

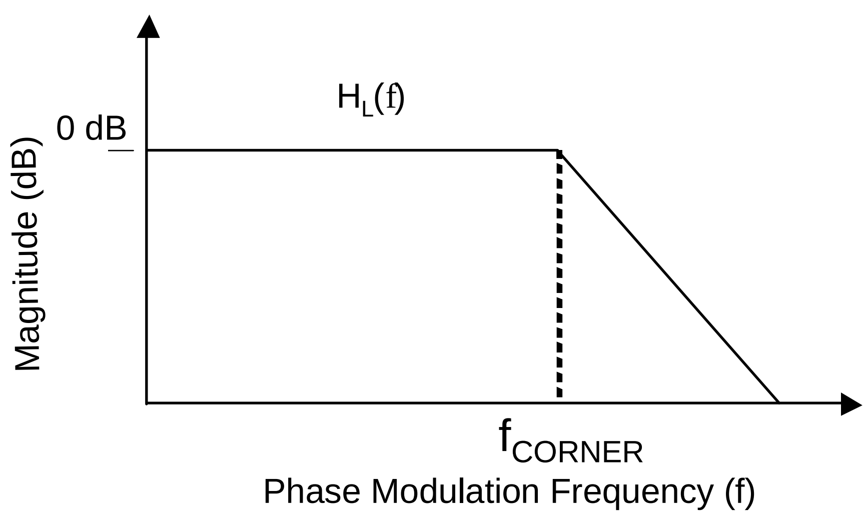


Figure 26 - A typical PLL phase modulation frequency tracking response

Any good signal measurement methodology should emulate the actual device behavior. The measurement setup should be such that it measures the jitter in the same way as it would affect the receiver. A receiver detects bits based the timing of its recovered clock with respect to the data, therefore this timing is a difference function from recovered clock to data as shown in figure 27. The measurement of jitter on the signal is executed with a measurement system (figure 27) that is functionally identical to the receiver (figure). The data latch function of "D" flip-flop in figure is replaced by the time difference function to emulate the receiver jitter behavior.

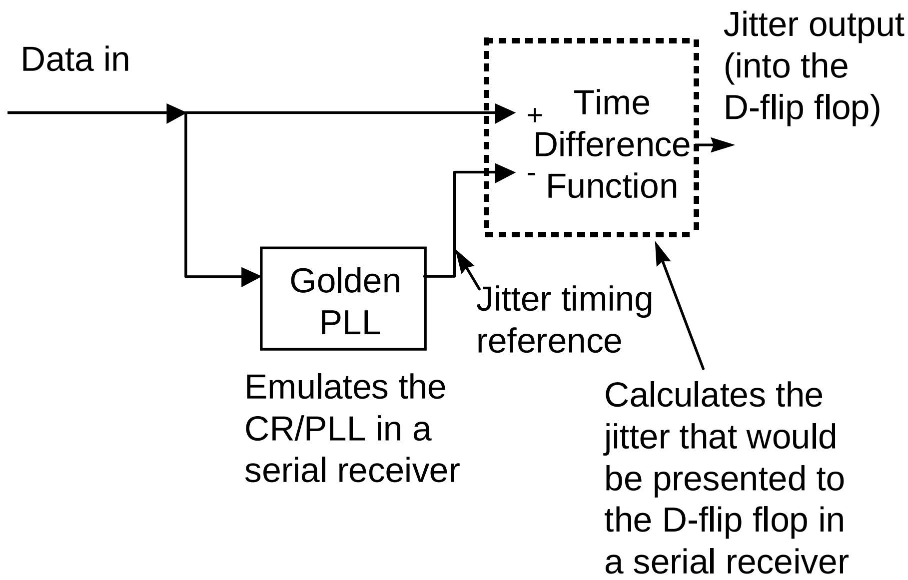


Figure 27 - Schematic of a basic measurement system

If the data edge occurs before the jitter timing reference the jitter out is negative.

The PLL has a low-pass transfer tracking function H_L (f). The time difference function is given by 1 - H_L The time difference function has the form of a high-pass transfer function H_H (f) as shown in figure 28. In general the vector sum H_L (f) + H_H (f) = 1.

H_H (f) may actually attain values slightly higher than unity ('peaking') in the vicinity of the crossover frequency because of the time delay (phase shift) through the PLL. Our current delay specs do allow about 0.3 dB of peaking. The delay matching should be from the point the Golden PLL taps the signal to the inputs of the actual sampler function. Any relative delays anywhere within those paths contribute to the delay, and in the case of some instruments, there may be delays not due to the Golden PLL at all (such as internal scope trigger delays).

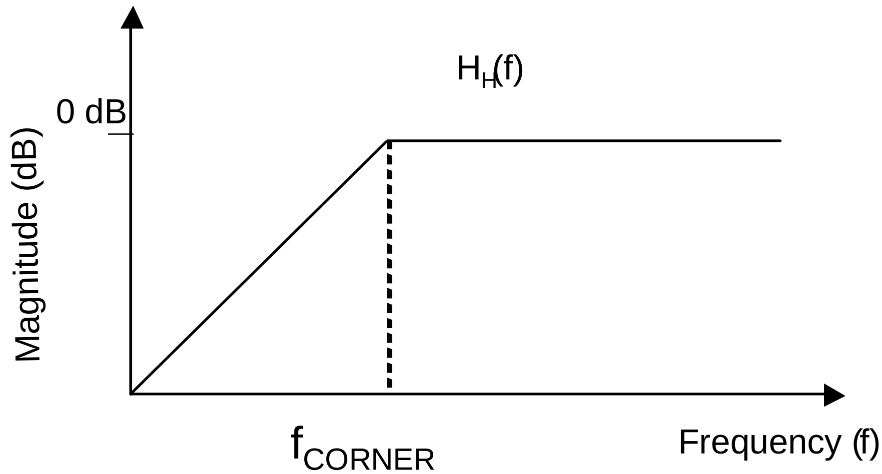


Figure 28 - Phase modulation frequency response of the time difference function

The time difference function shown in figure 28 suggests that a receiver is able to track more low frequency jitter at frequencies of $f < f_{corner}$ than at higher frequencies of $f > f_{corner}$. This implies that a receiver may tolerate more low frequency jitter than high frequency jitter. Assuming that the data rate is f_c, then f_{corner} is typically set to be $f_{corner} = f_c/1667$, this is the case for Fibre Channel (FC), SAS, and others. Gigabit Ethernet (GBE) uses 637 kHz at a baud of 1.25 G. Sonet uses $f_{corner} = f_c/2500$.

Most serial data standards specify the slope as 20 dB/decade. If the clock recovery device (or Golden PLL) has the characteristics required by the standard for $H_L(f)$ response, then the clock-to-data jitter measurement emulates the receiver jitter behavior.

The jitter timing reference shall be synthesized from the data stream by passing the time phase information from the data stream through the Golden PLL that incorporates both the high and low frequency responses according to the spectral mask requirement shown in figure 29. The reported jitter is the difference between the output of the Golden PLL and the signal (at the appropriate signal level threshold). The jitter timing reference may be implemented in hardware as shown in figure 27 or by post processing of the acquired data. The properties of a hardware implementation are described in 6.10.2.

If post processing is used to include the required Golden PLL frequency response properties in the reported jitter, the timing reference for the instrument used to acquire the raw data may be derived from the source clock that generated the signal, from a pattern marker in the data stream, from the same bit in a repeating pattern, or from a clock synthesized from sampling a long series of bits.

If the corner frequency is too low or if frequency tracking is not implemented in the signal measurement, the measured signal will typically appear more degraded, due to more low frequency jitter (drift) being present in the measured signal, than would be measured with the Golden PLL response or by the real receiver. Signals calibrated in this way make the receiver tolerance appear better than it should. If the corner frequency is too high then the measured signal will appear with less jitter than it should.

Similarly, if the high frequency response is not implemented in the signal measurement then the signal measurement will not show the jitter content seen by the receiver such as when the transition density changes abruptly as in the CJTPAT. The signal will appear better than it should.

By adding appropriate guardbands, determined by characterization of representative samples tested with and without the Golden PLL, it may be possible to eliminate the use of the Golden PLL for pass-fail applications but this is beyond the scope of this document.

Even if the specified Golden PLL is used for measuring the jitter, the measured bit error ratio in a link may be significantly different from the jitter population that exceeds the specified limit in the signal. This is caused by receivers having different frequency and amplitude response from that specified for the Golden PLL used to measure the signal quality. Receiver designers should consider how the signal quality measurement is specified when executing the designs. See 6.13.

Jitter output measurements shall be done with a Golden PLL that meets the passband characteristics found in figure 29. The plot in figure 29 depicts the asymptotic response. The actual response should be -3 dB (0,707) at f_c/1 667.

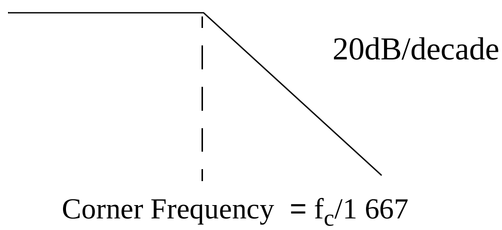


Figure 29 - Single pole low-pass filter passband characteristic for a Golden PLL

Contributors to low frequency jitter include but are not limited to: source drift, low frequency sinusoidal noise, and other uncorrelated effects occurring below a lower cutoff frequency. Low frequency deterministic jitter may also be caused by broadband changes in transition density coupled with ISI mechanisms.

If the jitter out is plotted against bit position in a data pattern the format may be presented in way similar to that shown in figure 30. In figure 30 the jitter measurement system emulates jitter as seen by a serial data receiver.

Figure 30 shows the measured jitter at the nominal threshold crossing point in an ISI intensive link, using a pattern marker method with averaging around each transition point, with two different receiver response functions. This method records only the DDJ and the DCD. See 7.2.3. The unfiltered trace is what one would obtain if, for example, a BERT timing reference (external reference clock) were used. The filtered trace is obtained by using a high pass function with a corner frequency of bit clock (baud) / 1667 that is intended to emulate the frequency response of the receiver. One may implement this function by using the Golden PLL specified in 6.10 or apply a high pass filter function meeting the same criteria to the data stream as was done in Figure 30 using a TIA.

Notice that immediately after the change from the low transition density section to the high transition density that the highest negative peak is found when using the filter. The highest positive peak is found immediately after the change from the high transition density section to the idles section using the filter. The filtered peak to peak value is 30 to 40% higher than the unfiltered value. Up to 2x difference between the filtered and unfiltered measurements have been reported for other similar measurements.

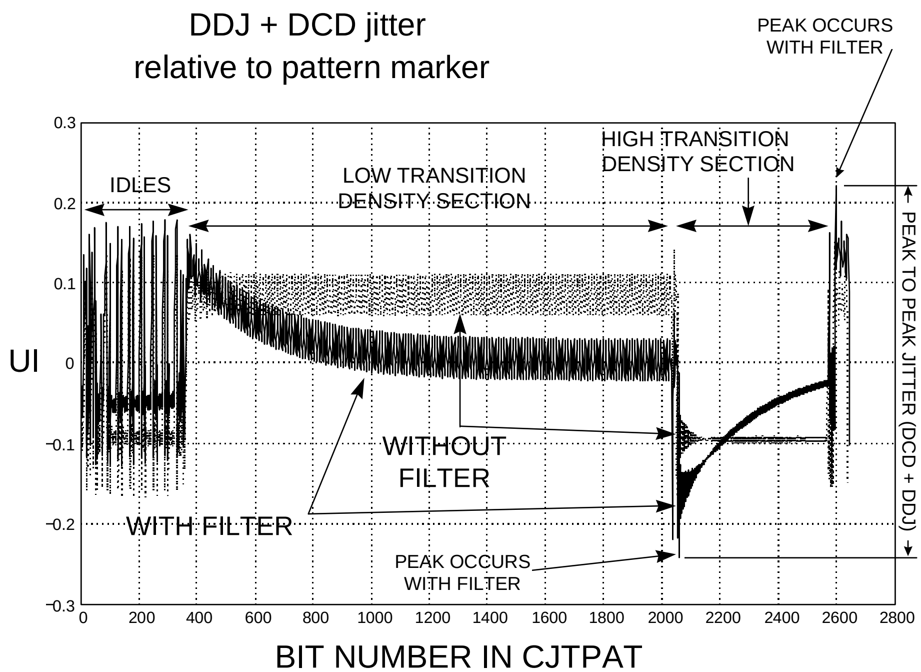


Figure 30 - Example of DJ effects caused by rapid transition density changes in CJTPAT

6.10.2 Performance specification for a hardware implementation of a Golden PLL

Table 1, table 2, and table 3 define the properties needed for a hardware implementation of a Golden PLL.

Table 1 - Input characteristics for a Golden PLL

Parameter	Units	1.0625 GBd	2.125 GBd	4.25 GBd
Data rate, Note 1	Mbaud	1062.5	2125	4250
Data rate tolerance	ppm	+/- 100	+/- 100	+/- 100
Data encoding		8b10b	8b10b	8b10b
Differential input signal amplitude				
Maximum	mV peak-to-peak	2500	2500	2500
Minimum	mV peak-to-peak	50	50	50
Return Loss between lower and upper frequency limits				
Minimum	dB	20	20	20
Lower frequency limit	MHz	10	10	10
Upper frequency limit	MHz	2000	4000	8000
Input rise/fall times 20-80%, Note 2				
Maximum	nsec	2	1	0.5
Minimum	nsec	0.05	0.025	0.0125
Max input Jitter f > fc/1667, Note 3, Note 4				
Data-Dependent (DDJ)	UI pk to pk	0.38	0.38	0.38
Sinusoidal (SJ)	UI pk to pk	0.10	0.10	0.10
Random (RJ)	UI @ 1E-12	0.6	0.6	0.6
Total Jitter, all sources	UI @ 1E-12	0.70	0.70	0.70
Other requirements				
Input impedance	Ohms, nominal	50	50	50
Frequency response low frequency corner	kHz	10	20	40
Note 1: It is desirable that the 1062.5 Mbaud unit also be able to operate at 1250 Mbaud to support Gigabit Ethernet testing.				
Note2: measured with square wave at {data rate/10} Hz or equivalent				
Note 3: as measured with an ideal Golden PLL				
Note 4: DDJ + RJ shall not exceed 0.6 UI				

Table 2 - Output characteristics for a Golden PLL

Parameter	Units	1.0625 GBd	2.125 GBd	4.25 GBd
Frequency, Note 1		exactly the same as the average input frequency		
Amplitude, Note 2	mV peak-to-peak,	1000 +/- 30%	1000 +/- 30%	1000 +/- 30%
Output waveshape		binary or sinusoidal as desired		
Output Impedance	ohms, nominal	50	50	50
Output return loss, sine, Note 3				
Minimum	dB	12	12	12
Lower frequency limit,	MHz	900	1800	3600
Upper frequency limit,	MHz	1200	2400	4800
Note 1: This is the whole purpose of the phase-locked loop				
Note 2: AC coupled				
Note 3: If the 1062.5 Mbaud unit also handles 1250 Mbaud, the upper frequency limit becomes 1400 MHz				

Table 3 - Jitter transfer characteristics for a Golden PLL

Parameter, Note 1	Units	1.0625 GBd	2.125 GBd	4.25 GBd
Function shape		identical to a single-pole low pass		
Corner frequency, Note 2	kHz	637.5 +/-5%	1275 +/-5%	2550 +/-5%
High frequency response, Note 3				
f1	kHz	637.5	1275	2550
f2	MHz	20	40	80
f3	MHz	531	1063	2125
Amplitude congruence to single-pole high-pass filter, Note 4	dB	+/- 0.1 from DC to f1 +/- 0.5 from f1 to f2		
Frequency response	dB	<-40 from f2 to f3		
Maximum delay from input phase step to output (see figure 31)	nsec	10	5	2.5
Maximum output jitter not attributable to input jitter				
Random	psec, rms	2	1	1
DJ	psec peak-to-peak	12	6	3
Note 1: All specifications are operative with a transition density of 50%, a typical figure, but not necessarily always the case				
Note 2: If the 1062.5 Mbaud unit also handles 1250 Mbaud, the corner frequency shall remain at 637 kHz				
Note 3: If the 1062.5 Mbaud unit also handles 1250 Mbaud, the amplitude congruence frequencies may remain the same as for 1062.5 Mbaud				
Note 4: Congruence is the absolute difference at any frequency				

Figure 31 shows the response from a candidate Golden PLL and a CDR compared to the input signal at 1.0625 GBd. The data pattern is ISI intensive and consists of 200 D30.3's and 200 D21.5's. The candidate Golden PLL has a delay of approximately 140 ns and therefore does not meet the 10 ns maximum delay from input phase step to output requirement at 1.0625 GBd. The CDR shown is 720 kHz @ Transition Density = 0.5 and almost meets the delay specifications (15 ns compared to a requirement of 10 ns).

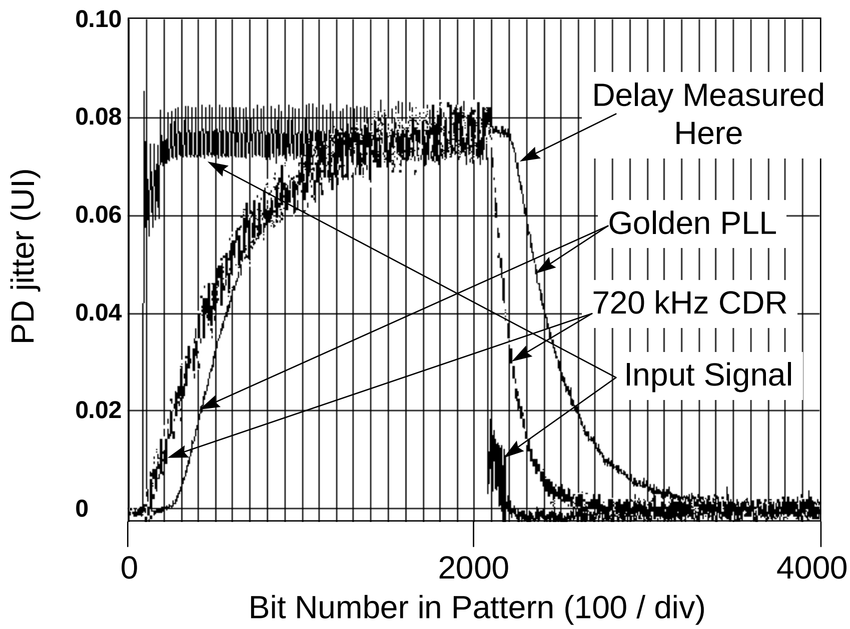


Figure 31 - Golden PLL delay property

Hardware Golden PLL's may be verified by using the configuration shown in figure 27 with a jitterless data source. The time difference function reports the jitter contribution of the Golden PLL. Since jitterless sources may be impractical, an independent calibration of the jitter in the data source may be done and accounted for in the time difference function.

Care is required to minimize the distortion from tapping the signal under measurement with the Golden PLL. Tapping is discussed in Annex B and examples are shown in clause 14. If the Golden PLL function is executed in software this issue does not exist.

6.11 Jitter frequency concepts

A concept of jitter frequency is sometimes useful for specifying the spectral content of the jitter for example. A jitter event itself is a just a number measured in units of time and has no intrinsic frequency properties. However, when a continuous stream of data is present one may plot the discrete jitter event values (deviation from the jitter timing reference) vs. bit number or time for a sequence of adjacent bits.

The result appears much as a sampled waveform would appear on a sampling oscilloscope except that the time intervals between jitter events is generally not uniform due to non clock-like data patterns. In order to convert to frequency using FFT methods some type of interpolation is used to fill in the gaps where there is no signal transition between bits. This interpolated sampled jitter waveform may be analyzed by the same methods used on any sampled waveform. The jitter frequency is the frequency associated with some part of the FFT. For signals that have only a single tone sinusoidal jitter content, the jitter frequency is that of the tone.

Validity of the jitter frequency concept is similar to the validity of the frequency content derived from any sampled signal. When there are many samples per period validity is high. As the number of samples per period decreases the validity reduces. Jitter frequency in this document may be assumed to be much less than the fundamental operating frequency of the link for low frequency tracking purposes or may be high when constructing a jitter frequency spectrum from an FFT.

6.12 Jitter output measurement methodologies

6.12.1 Time domain

The following methods are described for making jitter output signal quality measurements in the time domain:

a) **Equivalent Time (ET) Oscilloscope** – uses a jitter timing reference signal derived from the data stream via a Golden PLL to trigger an equivalent time sampling oscilloscope. An analog signal eye diagram and waveform mask (not to be confused with a jitter eye mask that is based on the CDF at the 10^{-12} level) is created. The DCD component and the high probability DDJ component of DJ may be extracted. A version that is optimized for jitter measurements is described in clause 10.

b) **Time Interval Analysis (TIA)** – based on accurate measurement of the time interval between signal crossings at a defined signal level of the signal. The jitter timing reference, including the required Golden PLL properties, is created within the instrument from the input signal for some methods. Others require the Golden PLL. RJ, DJ, and BER are calculated within the instrument using the methodologies defined in MJSQ from the time intervals measured.

c) **BERT scan -** based on comparing detected data at a predefined signal threshold and strobe time with the expected data. The jitter timing reference signal is derived from the data stream via a Golden PLL and is used as the strobe time reference. The signal level and strobe time are retained constant until an error ratio at the set conditions is determined. The strobe time is scanned across the bit time to directly measure the value of the CDF at each strobe position. For statistical validity, a target number of errors is required at each strobe position before moving to the next position.

d) **Real-Time (RT) Oscilloscope** – based on over-sampled Real-Time oscilloscope measurements. A real-time eye diagram and waveform mask (not to be confused with a jitter eye mask that is based on the CDF at the 10^{-12} level) is created. In addition, a method is described for estimating RJ, DJ, and BER using a spectrum approach.

More detail on these methods is given in clause 10.

6.12.2 Frequency domain

Frequency domain measurements are based on spectrum analyzer measurements with clock-like data patterns. They may be useful for diagnostic applications (level 2, see 13.1) but are not suitable for total signal quality specification. See Annex D for more information.

6.13 Effects of varying jitter distributions on BER

As shown in 6.10 the distribution of the jitter population may affect the way the receiver sets its internal timing reference that it uses to sample the signal level for purposes of determining whether a logical one or a logical zero is detected. It therefore follows that presenting the same receiver with different distributions will have different outcomes and that if the distribution is not specified, an intrinsic disconnect between the signal quality measurement and the observed bit error ratio in the link results.

There are only limited standardized requirements on receivers that specify how the receiver shall react to different jitter distributions. One constraint is that the sinusoidal portion of the deterministic jitter specified by the jitter tolerance mask shall be tolerated by compliant receivers.

Similarly, there are only limited requirements on the jitter distributions allowable in the signals. The separation of the jitter budget into a deterministic portion and the total places some bounds on the distributions for signals. The distribution within the deterministic portion for signals is presently unconstrained except for the Delta T point. Optical Gamma T jitter is indirectly constrained by the waveform eye mask methodology in OFSTP-4A [16], where the mask location is determined by the mean of the histogram of the jitter population at the receiver threshold.

Fundamentally, this partially constrained distribution methodology for signal specification results in receivers needing to be able to handle any deterministic distribution that may exist within the limits allowed by the budget and causes receiver to be over designed for many applications.

These effects of distribution have first order impact on the practical methods used for measuring signals. The measurement method shall create a timing reference from the signal. Unless the method used for extracting the timing reference is essentially the same as that used by the receiver for setting its internal timing reference, a difference between the BER of the receiver and the jitter population lying outside the allowed values is expected.

See Annex E for a more detailed discussion on this topic.

6.14 Methodology for jitter and signal quality specification for “processed” signals

6.14.1 Background

It has been recognized for many years that it is possible to compensate for predictable signal degradation caused by the transmission process.

The most popular of these compensations attempt to flatten the frequency response of the interconnect by boosting signals at frequencies where the interconnect attenuates (active filter) and/or by attenuating frequencies where the interconnect has low loss such that the low frequency loss becomes the same as the high frequency loss (passive filter). When the attempt is to compensate for non-constant frequency response of the cable plant, the general methodology is called “equalization”.

Other types of compensation may remove skew in differential electrical. Certain filtering in optical receivers may be used to compensate for known high frequency noise (e.g., relaxation oscillations) from certain types of optical sources. Yet others may apply some optimization scheme within the receiving device that adjusts to the properties of the incoming signal. All of these compensation / optimization schemes are termed “signal processing” in this document.

In all cases except the cable plant, the methodology for measuring the signals takes into account that part of the processing that is expected to be in place. Failure to take the processing into account may make signal quality specification effectively impossible in one extreme and make it significantly misleading in another view.

The general approach to dealing with signal specifications in the presence of transmitter or receiver processing is to emulate the expected processing to the signal before measuring the signal’s properties. To do this intrinsically requires knowledge of the processing that is expected.

6.14.2 Link components that contain compensation properties (equalization)

6.14.2.1 Compensation

Compensation is the attempt to mitigate the deleterious effects occurring during signal transmission by adding or subtracting features from the signal. Compensation may be executed in the transmitter, in the interconnect, and in the receiver. Compensation may be applied to properties of the signal that depend on the specific data pattern and to properties that are predictable upon subsequent use such as line to line propagation time skew and DCD. The basic assumption for compensation is that the degradation intensity and type remains stable over periods of at least several bit times.

Compensation schemes that may adjust the parameters of the compensating mechanism are termed “adjustable”. Compensation schemes that use active circuitry are termed “active”. Compensation schemes that pass the signal through a transfer function are termed “filtered” or “equalized”, the latter being derived from the common practice of matching the transmission losses across part of the frequency spectrum. Adjustable schemes that change the parameters of the compensating mechanism in response to specific received signal measurements are termed “adaptive”. It is usually assumed that adaptive schemes will use some sort of automatic means to do the adapting.

For purposes of MJSQ only linear, non-adaptive schemes are considered.

The mechanisms of degrading signals fall broadly into two modes: (1) primary losses along the transmission path such as attenuation, reflections, and resonances and (2) secondary losses due to causes that are external to the transmission path such as crosstalk noise. In some cases the secondary losses may exceed the primary losses. Losses may be amplitude or timing precision or both.

Details concerning the important differences between the location of the compensation are explored in the following Subclauses.

6.14.2.2 Transmitter compensation

Any compensation scheme that is implemented in the transmitter either (a) makes assumptions concerning the nature and intensity of the degradation that occurs during the transmission or (b) has some sort of feedback from the receiver that allows adjustment of the parameters of the compensation scheme. As such a mechanism relies on higher level protocol (as yet not specified) MJSQ does not consider any schemes that incorporate transmitter feedback compensation schemes.

When transmitter compensation is used, the results are visible in the signal launched from the transmitter. However, it may be necessary to use special methods to determine the quality of the signal from the transmitter since the compensation process may significantly alter the signal.

The general method for verifying transmitter compensation is to pass the transmitter signal through a transfer function that emulates the loss mechanism, in both magnitude and phase, for a standard interconnect attached to the transmitter before examining the signal. One measurement set up for such a methodology is shown in Figure 32 where models are used instead of hardware where possible.

The mathematical description of a compliance interconnect is not a specification for the interconnect itself (although the specifications for the compliance interconnect are derived from assumptions about the interconnect); it is a specification of the load that is placed on the transmitter for purposes of enabling measurement of transmitter signals.

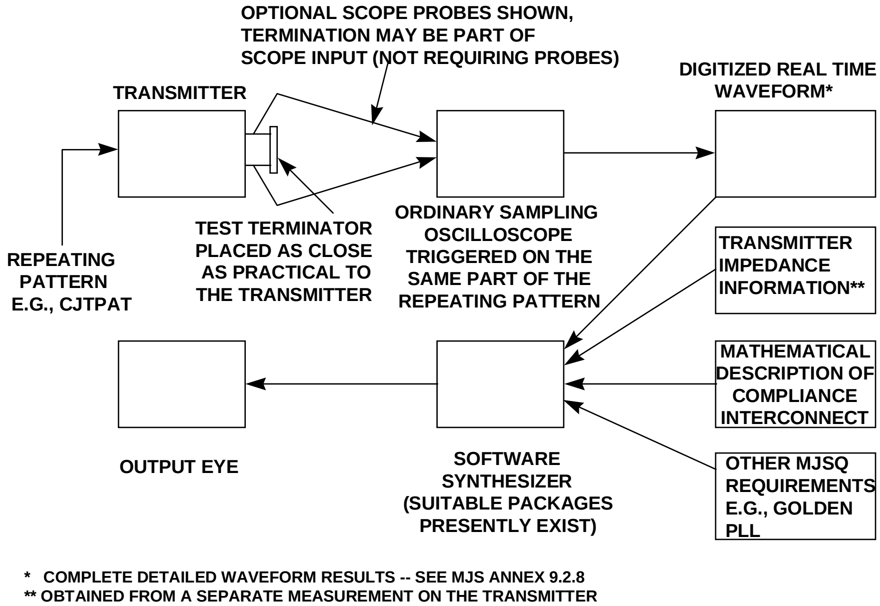


Figure 32 - Measurement set up for evaluating transmitters

It is also possible to evaluate the transmitter by using a golden physical sample of compliance interconnect attached to the transmitter. In this case the mathematical description of the compliance interconnect is built into the golden hardware and direct observation of the output eye is possible without the software synthesizer. Even in this case the specification for a physical compliance interconnect is not the same as the specification for the link interconnect where a much more complete set of requirements are specified including items such as crosstalk and EMI performance.

6.14.2.3 Interconnect compensation

Interconnect is specified by its ability to transport a minimum quality launched signal to an adequate quality signal coming out the far end. If compensation is incorporated into the interconnect itself then the interconnect includes the compensation as part of its performance and no special treatment is required.

6.14.2.4 Receiver compensation

Figure 33 shows the basic scheme used to specify input signals for devices whose internal circuity (receiver itself or other circuitry) incorporates compensation. If this compensation is included as part of the link budgeting process the effects of this compensation must be visible at the connector where the interoperability specifications apply. In an extreme example the signal may exhibit no jitter eye opening and/or no waveform eye opening at all at the connector unless the effects of the compensation are included in the signal measurement process. The device itself is evaluated based on its ability to produce small error ratios with a minimum quality incoming signal. This evaluation demands the ability to specify and calibrate a signal at the interoperability point for use with signal tolerance measurements.

Since the device with the receiver processes the signal internally, the observed signal at the connector needs to be processed to emulate the internal signal in the device at point “A” during the signal measurement. This is done by passing the signal at the connector through a standard compensation transfer function (possibly, but not necessarily, the same as that used internally in the device) before evaluating the signal. The standard compensation transfer function is that assumed when creating the link budgets. Real receivers need not implement exactly the same function or method but the properties of the signal used for signal tolerance measurements are known and the device may be designed to work with this signal. The standard compensation function allows

a) Visibility of the signal properties at the receiver device interoperability point
b) Use of the same signal quality specification methodology as for non-compensated signals
c) Link budgeting to be done without compromising the ability to do proprietary receiver designs.

For signal tolerance testing the signal observed downstream of the standard compensation function is then adjusted to have the properties of a minimum quality signal. This calibrated signal then applied to the device and the device bit error ratio is measured. Bit errors are detected at point "B" after passing through the internal receiver.

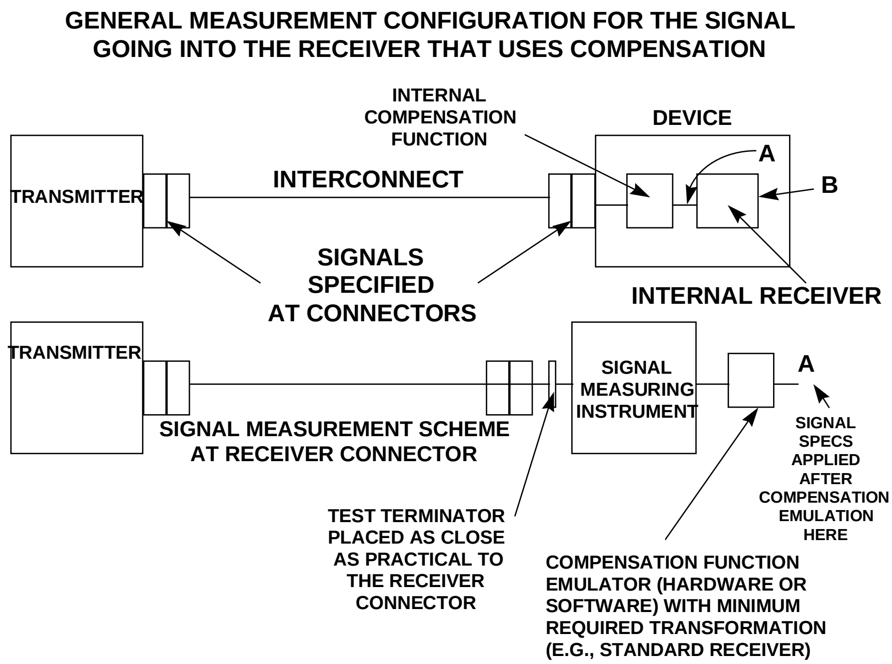


Figure 33 - Measurement set up for evaluating receivers

Since the measurement system shown in figure 33 is linear, one could place the compensation function before the signal measurement instrument by using a hardware version of a golden receiver signal processor. In all cases specification of a standard compensation function is required.

6.15 Determination of compliance

Signal quality compliance is determined by the standard that specifies the requirements. The MJSQ document does not alter the specifications in existing standards in any way. However, it is possible that existing standards may not have fully considered the requirements for predicting link bit error ratio performance from signal quality measurement. The more complete approach taken in this document is now available for consideration and adoption by the various governing standards bodies to reduce that risk.

The requirement for no more than a single event being recorded within the same bit time as described in 6.3 allows direct application of population requirements specified at the nominal receiver threshold crossing to the population requirements at every signal level within the range of the maximum and minimum values of the eye opening.

The jitter eye opening specification may require modification if compensation schemes are used in the transmitted signal or in the receiver. See 6.14. If modifications to the jitter eye opening specification are used then the modified jitter eye opening shall be used to determine the population at each signal level.

The jitter population at every signal level shall be determined using the methodologies specified in 6.4, 6.8, and 6.10.

Compliance to a more general jitter population specification that considers different signal levels requires that the jitter population at every signal level be less than that allowed for the bit error ratio for the link.

For electrical links the masks and specifications shown in FC-PI-n apply into special test loads - not to the system in operation - and they apply at all interoperability points, not just for the transmitter. However for signal tolerance measurements (e.g. receiver response properties) the link downstream from the interoperability point shall tolerate the worst case signal. This is accomplished by setting up the signal from an instrumentation quality source into a special test load with nearly ideal termination. The test load is then replaced with the downstream link under test and the BER from the receiver is measured. Any departure from ideal termination in the downstream link under test will further degrade the signal but does not change the requirements on the signal tolerance for the downstream link. In this way the downstream link is appropriately penalized for not having good termination. For receiver testing the downstream link consists of only the receiver. Signal output requirements are specified in the context of measuring into a test load placed at the interoperability point.

6.16 Extremely stressful data patterns and scrambling

As shown in figure 30, some data patterns are capable of producing high stress in the receiver under some conditions. For example, the CJTPAT is capable of producing 30 to 40% greater DDJ + DCD compared to CRPAT or repeating K28.5's in dispersion related ISI dominated links. These stress conditions are possible in compliant frames and are a legitimate way to stress the transmission process.

Annex A contains descriptions of several data patterns that contain various types of stress conditions.

Even more stressful conditions may exist when scrambling is used on encoded data streams after encoding. Scrambling is sometimes used in an attempt to limit the peak energy at any specific frequency for EMI management purposes. This occurs because the deterministic nature of the code (8b10b for example) is eliminated by the probabilistic nature of the scrambling. However, an undesirable side effect with probabilistic coding schemes is that it is statistically possible to produce very unusual bit pattern relationships and excessive run lengths. One therefore needs to consider the probability of truly excessive stress resulting from the probabilistic nature and the allowed error ratio.

MJSQ does not include any methodologies that specifically accommodate effects caused by scrambled transmissions.

If scrambling is done before encoding into 8b10b then only the payload data is scrambled and the run length is limited by 8b10b. However, the spectral distribution in the transmitted data stream will be changed by the scrambling so one cannot assume that the link stresses caused by the data stream, notably those that are caused by transition density changes, are the same as without scrambling. In this case it is necessary to pre-unscramble before transmission so that the 8b10b characters required by the pattern are actually present on the transmission media and are presented to the CDR as specified.

Annex H contains more information concerning low probability issues.

7 Jitter causes and jitter distribution

7.1 Jitter contribution elements

The implementation examples in figure 9 shows several elements that degrade signal quality or enhance signal quality and ports that re-time to a local clock. The typical effect of each of these elements on signal quality is summarized in table 4.

Table 4 - Signal quality contribution elements (Part 1 of 2)

Element	Typical effect on signal	Description
FC Ports / other protocol aware PMD sublayer Ports	Originating signal source - defines the quality of the launched signal - used as the signal quality reference for other points in the transmit/receive connection	A fabric Port that launches a signal with original jitter and amplitude content. Generally amplitude decreases and jitter increases during the transmission process. A full FC-AL Port also launches a signal with original jitter and amplitude content by amplifying and re-timing the incoming signal to its local clock. An elasticity buffer is included that absorbs the worst-case frequency mismatch between the receive data (recovered clock) and the local clock for the maximum frame length.
Retimer repeater	Originating signal source - defines the quality of the launched signal - used as the signal quality reference for other points in the transmit/receive connection	A re-timer is a serial data in and serial data out node that re-times data to a local transmit clock. The use of a retimer element has the same effect on resetting the jitter and amplitude budget as an FC Port. An elasticity mechanism is included that absorbs the worst-case frequency mismatch between the receive data (recovered clock) and the local transmit clock for the maximum frame length.
Reclocker repeater	Amplify amplitude, attenuate jitter, restores rise and fall time	A reclocker repeater, or ‘reclocker’, is a serial data in and serial data out node that attenuates jitter by re-generating the serial data using the recovered and filtered bit clock derived from the incoming data stream and resets the launch amplitude typically by amplifying.
Amplifier repeater, buffer element (e.g., limiting amplifier)	Amplify amplitude, increase jitter, restores rise and fall time	An amplifier repeater, or ‘amplifier; amplifies the incoming signal, but typically transfers all the jitter present at the input to the output and may introduce additional jitter through duty cycle distortion, crosstalk, power supply noise, and data dependent jitter. Duty cycle distortion may be exacerbated or reduced depending on the direction of the duty cycle distortion.
PMD repeater	Change signal type, effect on jitter depends on the type of repeater	Circuits for converting or coupling serializer output to transmission media or transmission media to deserializer input. Behaves like amplifier, reclocker, or retimer depending on design.
Passive equalizer	Attenuate jitter, may increase usable amplitude	A passive filter that improves signal quality by compensating the frequency dependent effects of a bandwidth limited medium. Although the peak amplitudes are attenuated due to the passive nature of the filter, the usable signal may have significantly greater amplitude due to the reduction in jitter.

Table 4 - Signal quality contribution elements (Part 2 of 2)

Element	Typical effect on signal	Description
Transmission media	Attenuate amplitude, increase jitter	Fiber optics or electrical cables attenuate amplitude due to losses and increase intersymbol interference (ISI) jitter due to dispersion. May also increase jitter and/or decrease amplitude through crosstalk, reflections, and resonances.
Connector	Attenuate amplitude, increase jitter	Electrical and optical connectors introduce reflections, crosstalk and attenuation that causes loss of transmitted amplitude and increased jitter

7.2 Jitter distribution

7.2.1 Basic types - bounded and unbounded, correlated and uncorrelated

For ease of analysis this document divides jitter two basic types: bounded and unbounded. The jitter distribution consists of combinations of bounded and unbounded components. The total jitter is the time interval where all but a specified fraction of the population falls. The specified fraction is frequently 10^{-12}. The allowed total jitter varies with signal level. Total jitter is abbreviated TJ.

The remainder of 7.2 describes the bounded and unbounded types in more detail.

The jitter distribution is the histogram of all the jitter components in the data stream.

Jitter that has a defined timing relationship with a specific data edge in a repeating data pattern for the signal under test is correlated to the data pattern. Jitter that does not have such a defined relationship is uncorrelated. Uncorrelated jitter has a mean value of zero with respect to the same signal edge in a repeating data pattern.

7.2.2 Unbounded (definition, concept, quantitative description)

Unbounded jitter has the property that some finite population exists at all values of jitter (assuming an infinite sample size). Unbounded jitter of practical interest to MJSQ has a Gaussian distribution.

The word ‘random’ is sometimes used correctly to describe Gaussian jitter and is sometimes used incorrectly to describe jitter in general. Unbounded jitter, or random jitter, is abbreviated RJ and is uncorrelated to anything.

7.2.3 Bounded (definition, concept, quantitative description)

7.2.3.1 Overview

Bounded jitter has the property that no population exists beyond specific limits regardless of the number of events obtained.

All bounded jitter is deterministic (by definition) and all unbounded jitter is Gaussian. The word ‘deterministic’ does not exclusively apply to data dependent jitter. Data dependent jitter is one of the classes of deterministic jitter. The word ‘deterministic’ implies that something determines the value of the jitter and the word is retained in this document because of common usage. If jitter is deterministic it may or may not come from a known cause.

Bounded jitter consists of one or more of the following classes: duty cycle, applied sinusoidal, data dependent, and uncorrelated (to the data stream in the link under test). Bounded jitter, or deterministic jitter, is abbreviated DJ and may or may not be correlated to the data pattern used on the signal under test. DJ is commonly used for compliance and budgeting as a level 1 quantity.

7.2.3.2 Duty cycle distortion (correlated)

Duty cycle distortion jitter (DCD) has the dual Dirac delta function distribution and is due to different pulse widths for logical “1” signals compared to logical “0” signals. Duty cycle distortion jitter is most easily observed in a clock-like data pattern. DCD is synchronous to the data pattern and is considered to be correlated to the data pattern in the signal being measured even though DCD does not change with changes in the data pattern. There are also benefits from using arbitrary data with DCD definition 2. (See 3.5.30.)

DCD is compensatable in principle by inversing the DCD.

7.2.3.3 Data dependent (correlated)

7.2.3.3.1 Overview

Data dependent jitter (DDJ) is jitter that varies if the data pattern changes. The data is strictly the data transmitted in the same path as the signal being measured. Data on other paths contribute to crosstalk jitter and is not considered data dependent in this document. Data dependent jitter is abbreviated DDJ and is commonly caused by ISI.

ISI is general term for one signal feature causing a distortion in the signal away from the signal feature itself. For example, if the signal feature is a signal edge the ISI distortion may be seen in the neighboring signal edges, in the nominally stable portion of the signal, or far away from the signal edge. The ISI distortion is predictable and is correlated to the data pattern. The signal distortion is the ISI and the jitter that results from that distortion is the DDJ component.

The details of the link determine where and how the distortion exists. ISI commonly is caused by high frequency dispersion, reflections, low frequency coupling or control components, and other mechanisms related to the frequency response of the link. The three most common forms of jitter that result from the different ISI mechanisms are identified as follows: dispersion induced jitter (signal edge roll off occurring during signal transmission), reflection induced jitter, and baseline wander induced jitter. Other less important forms of ISI induced DDJ are also possible. For example, in differential electrical links common mode reflections may create differential noise with resulting jitter in the differential signal. Because the manifestation of ISI is widely varying depending on the causal mechanism the term ‘ISI induced jitter’ is not as useful as refering to the causal mechanisms directly.

ISI induced jitter is compensatable in principle by inverting the high frequency response properties of the link that caused the ISI. The compensation required will be significantly different depending on the causal mechanisms and the intensity of the distortions.

DDJ may also be caused by non ISI mechanisms such as power supply noise on the transmitter device that correlates to the data pattern and ground bounce.

It is possible that any ISI mechanism may be affected by crosstalk (crosstalk is an uncorrelated mechanism). For example, cross talk may affect the differential and common mode impedance of the signal path under test or may affect the shape of the original signal edge that caused the ISI. In this case the crosstalk is affecting the jitter in the signal under test and introducing some BUJ via an ISI mechanism. The ISI mechanisms that apply to DDJ are only the correlated portions.

7.2.3.3.2 Dispersion induced jitter

Dispersion induced jitter (DIJ) is a form of DDJ caused by signal edge dispersion or roll off in the signal transmission process. Dispersion causes ISI effects that produce correlated deterministic jitter. DIJ is most important for long lossy links. Historically, some people have referred to DIJ as being the same as

DDJ and it is common for people to use the term ISI and DDJ interchangeably. MJSQ uses these terms more carefully.

7.2.3.3.3 Reflection induced jitter

Reflection induced jitter (RIJ) is a form of DDJ caused by reflections in the signal transmission process. Reflections cause ISI effects that produce correlated deterministic jitter. RIJ is most important for short, low loss links with poor return loss in the transmitter device or the receiver device or both.

7.2.3.3.4 Baseline wander induced jitter

Baseline wander induced jitter (BWJ) is a form of DDJ caused by by inadequate low frequency response in a link. One good example is the use of A. C. coupling components, such as an RC circuit, where the low frequency corner is too high. The transfer function of the coupling circuit causes ISI effects that produce correlated deterministic jitter. Another good example is where the loop bandwidth of an average power laser diode control circuit is too high.

7.2.3.3.5 High probability DDJ

High probability data dependent jitter (HPDDJ) is DDJ jitter that comes from relatively short data patterns. In 8b10b FC the longest data pattern presently defined for measurement purposes is CJTPAT that has 2640 bits. HPDDJ is defined for this document as DDJ resulting from the CJTPAT and shorter data patterns.

7.2.3.3.6 Low probability DDJ

Low probability data dependent jitter (LPDDJ) is DDJ that is associated with patterns having repeating structures longer than CJTPAT. Encoding schemes and associated data patterns such as scrambling and 64/66 encoding may require dealing with LPDDJ. For data patterns that have no significant population of LPDDJ existing equipment is expected to be able to acquire sufficient data in practically useful times. Extrapolation to 10^{-12} CDF levels may be significantly in error if data patterns with LPDDJ are used. To avoid these extrapolation errors direct measurement at 1E-12 levels may require BERT methodologies. A more detailed discussion of low probability issues is contained in Annex H.

7.2.3.4 Uncorrelated DJ

7.2.3.4.1 Overview

Uncorrelated DJ, (BUJ) is the part of the deterministic jitter that is not aligned in time to the HPDDJ and DCD in the data stream being measured. There are three main sources of BUJ, (1) power supply noise that affects the launched signal, (2) crosstalk that occurs during transmission and (3) sinusoidal applied to the receiver input for jitter tolerance measurements. Clipped Gaussian distributions caused, for example, by active circuits is also considered BUJ. BUJ usually is high population DJ, with the possible exception of power supply noise and the ‘tails’ of clipped Gaussian distributions.

BUJ may or may not be compensatable. Inversing the PJ peaks in the BUJ frequency distribution may be partially effective.

7.2.3.4.2 Power supply noise

Jitter in the launched signal caused by power fluctuations within the transmitting chip is the power supply induced BUJ. Power supply noise may also affect the BER produced by receivers but in this case does not directly affect the methodologies for making signal quality measurements.

7.2.3.4.3 Crosstalk / external noise

Jitter caused by crosstalk from adjacent lines or from other sources not part of the transmission path under test is crosstalk jitter. Power supply noise from supplies other than that used for the launched signals are unlikely to couple into the signal under test because of the low frequency of the power supply (including switching power supplies). Such coupling, if any, is conductive and affects the power supply for the launched signal. Since most crosstalk comes from adjacent lines or from other high frequency sources, the populations of crosstalk jitter is expected to be relatively high (> 10^{-6}) even though the crosstalk noise may only occasionally have a phase match to the signal transition in the signal being measured. The fraction of transmitted bits that are significantly affected by crosstalk from adjacent uncorrelated links is typically > 1E-6. Crosstalk that comes from low frequency or only occasionally occurring conditions (like lightning strikes) may cause low population DJ (i.e., low population BUJ). Cross talk may or may not have discrete spectral peaks and so may be difficult to isolate from RJ.

7.2.3.4.4 Applied sinusoidal

Applied sinusoidal jitter consists of a sequence of jitter events that vary sinusoidally as one moves from one signal edge to the next signal edge, reaches a peak and then decreases again. The sinusoidal jitter oscillates with a frequency significantly less than the data rate of the signal under test. Sinusoidal jitter is abbreviated SJ. PJ (periodic jitter) is not a type of jitter but rather is a way to describe peaks in the jitter frequency spectrum of residual jitter.

Sinusoidal jitter may be purposefully launched in the signal for jitter tolerance measurement for example or may be induced into the data stream by crosstalk mechanisms.

7.2.4 Residual jitter and variance record

Jitter that remains after the DDJ and the DCD is removed is called residual jitter. Residual jitter is important because several practical measurements methodologies are capable of determining the DDJ and DCD. Extraction of the RJ intrinsically involves working with residual jitter.

Residual jitter consists of RJ and BUJ. Properties of residual jitter include:

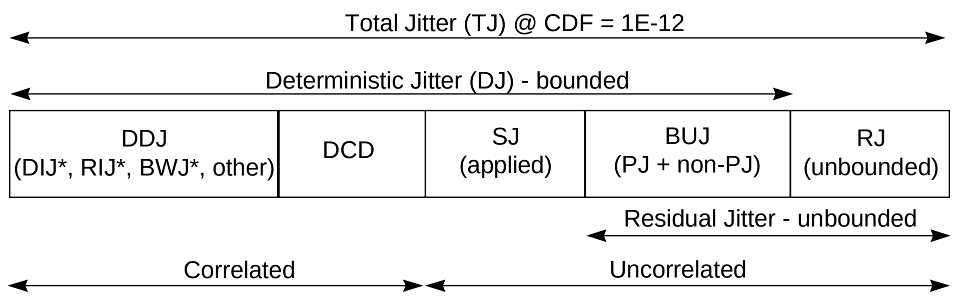
a) Uncorrelated to the data patterns
b) Is the focus for calculating total jitter
c) Unbounded because it includes RJ
d) Contains all the low population events

Residual jitter is a key differentiator amongst various measurement methodologies because the population of residual jitter events may be sparse. Removing the DDJ and the DCD increases the noise margin available for determining total jitter.

The square of the standard deviation of the residual jitter distribution for a specific signal edge is the variance for that edge. The collection of variance values for consecutive edges is the variance record for that data stream. Variance records are useful for producing FFT’s (i.e. power spectrum) of the residual jitter. This power spectrum is especially useful, using existing mathematical algorithms, for separating the PJ, RJ and BUJ.

7.2.5 Summary of jitter taxonomy

Figure 34 shows the terminology and relationships related to jitter distributions.



DDJ = Data Dependent Jitter
DCD = Duty Cycle Distortion Jitter
SJ = Sinsoidal Jitter (applied periodic jitter during signal tolerance testing)
BUJ = Bounded Uncorrelated Jitter
RJ = Random Jitter (Gaussian - unbounded)
DIJ = Dispersion Induced Jitter
RIJ = Reflection Induced Jitter
BWJ = Baseline Wander Induced Jitter
PJ = Periodic Jitter refers to spectral peaks in the jitter frequency distribution of BUJ
* Crosstalk may also induce uncorrelated jitter via these mechanisms -
only the correlated portions apply to DDJ

Figure 34 - Taxonomy of jitter terminology and relationships

8 Calculation of jitter compliance values (level 1)

8.1 Overview - separation of jitter components

Calculations defined in this clause are required to extract the DJ and TJ values that are used for budgeting and compliance. These calculations are derived from the methods used in FC-PI termed ‘equivalent jitter’. The term ‘effective jitter’ has also been used for this same purpose. In this document, the term ‘level 1 DJ’ refers to the level 1 result.

The CDF distribution resulting from the measurement scheme used is the input to the calculations and the method described in this Subclause shall be used to calculate DJ and TJ for level 1 uses. Measurement schemes that produce PDF outputs shall convert the PDF distribution to a CDF distribution prior to applying the equivalent jitter calculations. This process is graphically shown in figure 35.

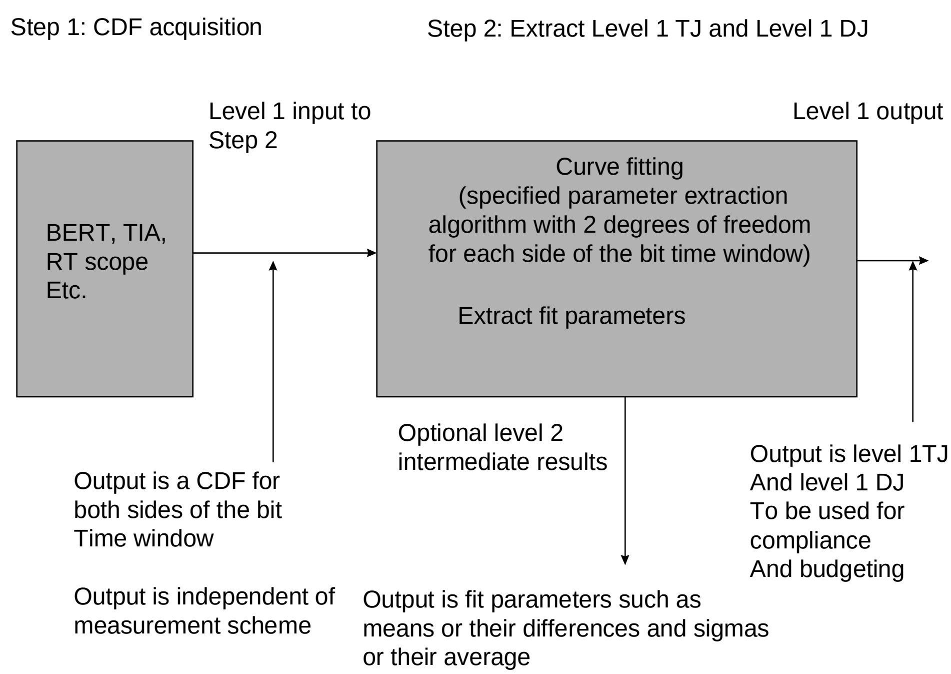


Figure 35 - The two step process for calculating level 1 DJ and TJ

The CDF itself is a level 1 quantity that may be used if there are no requirements on DJ or TJ.

A primary goal of using the same calculations to produce the compliance values is to reduce the error from attempting to extract DJ, RJ, and TJ from any particular measurement scheme. Several measurement schemes included in this document define methods for calculating DJ, RJ, and TJ. These calculations associated with particular measurement schemes produce level 2 results that may be useful for characterization or diagnosis. Measuring the same signal with different schemes may or may not produce the same level 2 DJ, RJ, and TJ results. An RJ value is extracted in the process of calculating level 1 DJ and level 1 TJ but this RJ value is not used specifically for budgeting or compliance purposes and is therefore not a level 1 parameter.

The only valid method for producing a level 1 TJ or DJ value is via the calculations in this subclause.

It is expected that a fitted curve to the raw CDF data has been done as part of the process of producing the CDF output and that accurate expected time values associated with exactly the 10^{-6} and 10^{-12} CDF levels are available as input to the equivalent jitter calculation. Level 1 jitter calculations assume a functional form for the CDF output below the DJ ceiling but do not execute any curve fitting. The burden of producing an accurate CDF output lies with the individual measurement scheme.

The assumed form is a dual-Dirac PDF function, where each Dirac impulse, located at +DJ / 2 and -DJ / 2, is convolved with separate half-magnitude Gaussian functions.

Level 1 DJ ‘weights’ the measured distribution (after removing the RJ) in a manner that rewards benign DJ and penalizes harsh DJ. A benign DJ distribution is where the majority of the events are near the center of the distribution. A harsh DJ distribution is where the majority of the events are near the boundaries of the distribution. Therefore, level 1 DJ is usually less than pk-pk of the measured deterministic distribution, because the peaks of measured distribution usually occur with some lower probability. Total jitter must always be the same regardless of whatever form of DJ is used.

The constraints of an assumed CDF form and of using values at specific population levels are required to enable data acquisition methodology independence.

The choice of the dual Dirac is based on the historical forms used in MJS and FC-PI. The assumed form allows a simple calculation.

Level 1 DJ is *not* only a BERT method; it may be used by any instrument that measures or calculates a histogram (PDF) or CDF. Level 1 DJ does not understate DJ any more than pk-pk DJ overstates DJ. They are different definitions. Neither is the ‘real’ or ‘true’ DJ.

8.2 Examples comparing level 1 DJ with peak to peak DJ

Figure 36 shows three different DJ PDF’s that all have the same peak-to-peak value of 0.1 UI.

The uniform distribution is harsh, the triangular distribution is less harsh, and the raised cosine distribution is relatively benign.

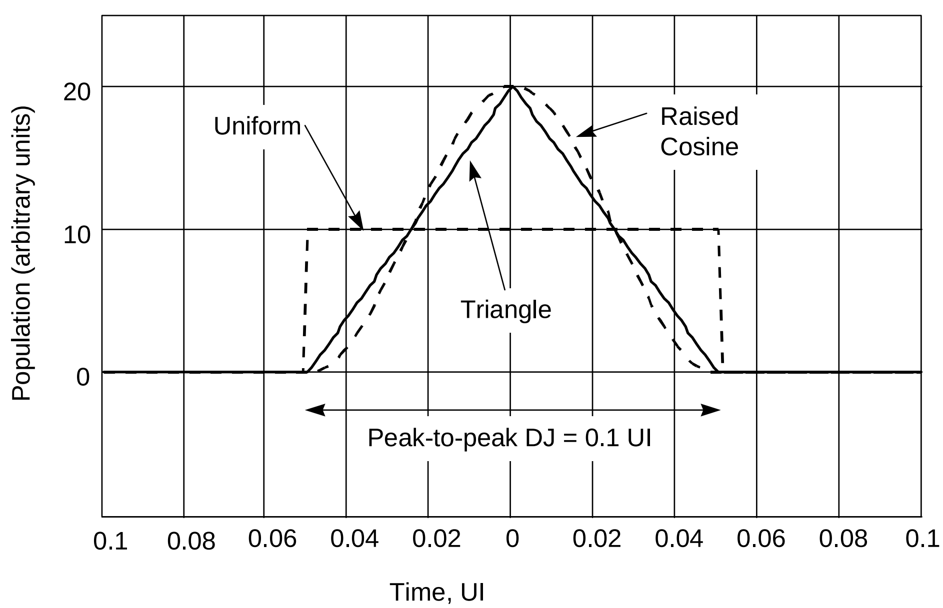


Figure 36 - Three different DJ PDF’s used to create CDF’s in figure 37

Figure 37 shows the CDF's that result when the DJ PDF's in figure 37 are convolved with RJ of exactly 0.020 UI rms.

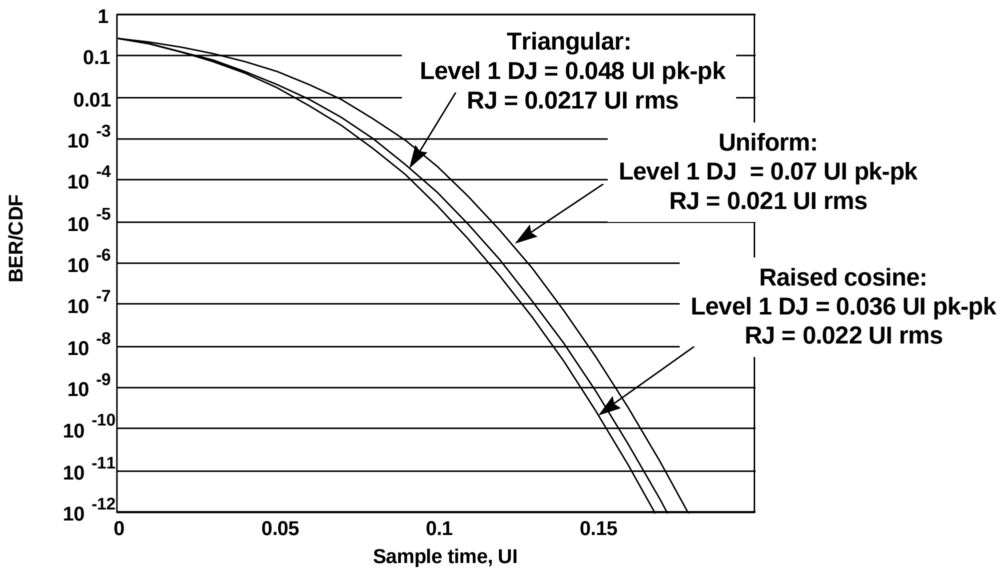


Figure 37 - CDF's and associated level 1 DJ values from PDF's in figure 36

Also shown in figure 37 are the values of RJ and level 1 DJ and that result from the calculations required in clause 8. Notice that the different level 1 DJ values account for the different TJ values and that the RJ values are almost exactly 0.02 UI. The shape of the DJ distribution makes a difference and is important for compliance.

Figure 38 shows an example of real data and the associated PDF's calculated from the methods in this clause. The term level 1 TJ PDF is used for convenience because it resulted from the level 1 calculations but there is presently no compliance requirement for TJ PDF's. The measured DJ PDF's and the measured pk to pk DJ were derived from a TIA measurement where no BUJ (bounded uncorrelated DJ) is present. In this case, the DJ may be separated from the RJ by averaging out all the uncorrelated jitter (i.e., by removing the RJ).

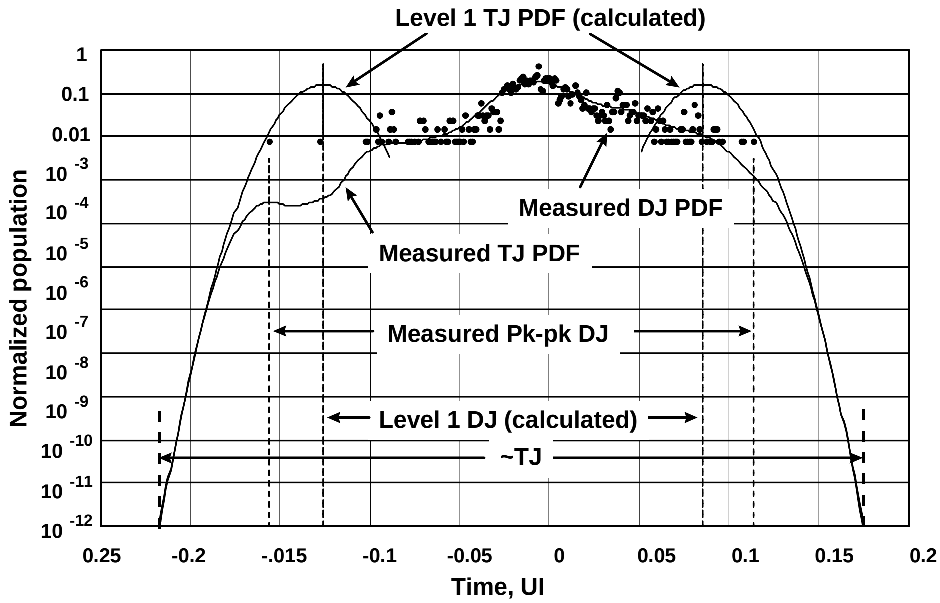


Figure 38 - Real data comparisons using PDF's

Figure 39 shows the CDF's that result from the PDF's in figure 38.

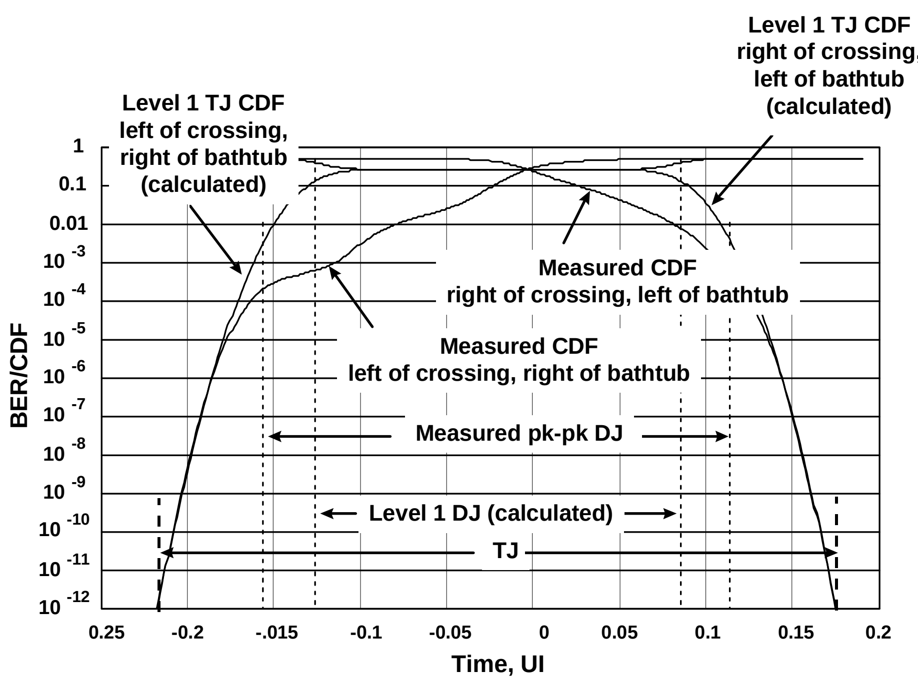


Figure 39 - Real data comparisons using CDF's

8.3 Methodology details for calculating level 1 DJ and level 1 TJ

A CDF measured by any valid means is used as the starting point for the calculations specified in this Subclause. Valid extrapolation methods may have been used in the measurement of this CDF - direct measurement at CDF = 1E-12 is not explicitly required.

Define the jitter eye opening at the CDF = 10^{-6} level as t_0 and the jitter eye opening at the CDF = 10^{-12} level as t_1. Both sides of the bathtub curve are required to determine the jitter eye opening.

Calculate Q_0 = -qnorm[(2/TD)*10^{-6},0,1] where qnorm is defined in Mathcad™ and the transition density, TD, is assumed to be 0.5 for 8b10b encoded data.

Calculate Q_1 = -qnorm[(2/TD)*10^{-12},0,1] where qnorm is defined in Mathcad™ and the transition density, TD, is assumed to be 0.5 for 8b10b encoded data.

The resulting values under these assumptions are:

$Q_0 = 4.465$

$Q_1 = 6.839$

Calculate the jitter results from the equations below. RJ_{rms} is the rms (1 sigma) value for RJ. DJ and TJ are given as pk-pk values.

Q_n is the peak number of RMS jitter magnitudes for the given BER. TJ may then be expressed as:

Equation 7 – Level 1 Total jitter

TJ = UI - t_1 = DJ + 13.68 RJ_{rms} where UI is the bit period (e.g., 941.2 psec for 1062.5 Gbaud).

Equation 8 – Level 1 Deterministic jitter

$$DJ = UI - t_0 - (2xQ_0xRJ_{rms}) = (UI - t_0 - 8.93xRJ_{RMS})$$

DJ and TJ when presented without subscripts are the level 1 values.

RJ_{rms} for use in equation 7 and equation 8 may be calculated from:

$$RJ_{rms} = 0.5\left|\frac{t_1 - t_0}{Q_1 - Q_0}\right| = 0.2106|t_1 - t_0|$$

This is not a level 1 RJ_{rms} since RJ_{rms} is not a level 1 parameter.

9 Basic data forms, analysis, and separation of jitter components

9.1 Overview

9.1.1 Introduction

Clause 9 describes the basic data forms, analysis methods and methods for separating the components of the jitter distribution in addition to accurately determining the total jitter. These methods may be required to produce the CDF that is used for the level 1 calculations in clause 8 and are useful for characterization, design, diagnosis, and other level 2 uses. The method described in clause 8 is required to produce DJ and TJ values for compliance purposes (level 1). The values of level 2 DJ, RJ and TJ produced from the methods described in clause 9 and in some Subclauses of clause 10 may vary between the methods and before MJSQ was developed this was a source of error between measurements. Since TJ is directly contained in the CDF one does not expect significant differences in TJ from different measurement methods. However, even in the TJ case, only the method described in clause 8 may be used for level 1 purposes.

This clause is written without always making the distinction between level 1 values and level 2 values. Similar lack of distinction may also persist in documentation for specific instruments. It is up to the user to be diligent in avoiding using any DJ or TJ values calculated by methods other than that described in clause 8 for level 1 purposes.

9.1.2 Basic data forms

There are five basic data forms considered:

a) Time domain measurement of jitter events at a specific signal level from a jitter timing reference
b) Measurement of error rate at specific signal level and time from a jitter timing reference
c) Single shot capture of a signal waveform
d) Measurement of the time between a known number of signal edges at a specific signal level
e) RF power spectrum

Each of these data forms is accessible via known measurement processes and each has its own advantages and disadvantages. See table 5 for a mapping.

9.1.3 Data analysis methods

There are five data analysis methods considered:

a) Direct PDF/CDF analysis on jitter events
b) Over-sampled sequential time analysis on a waveform
c) Under-sampled sequential time analysis on residual jitter from specific signal edges
d) Statistical bin analysis on time between n signal edges
e) Spectral density analysis on the jitter population

Each of these data analysis methods, or combinations of these data analysis methods, may be used in the process of generating the CDF required for use in clause 8 to calculate the level 1 DJ and TJ. See table 5 for a mapping.

9.1.4 Summary of overview

Table 5 provides a brief comparison of the methods.

Table 5 - Comparison of basic data forms and analysis methods (Part 1 of 2)

Analysis method	Data form	Processing to prepare CDF	Assumptions & comments	Other potential information (level 2) from data form	Instrument types described in this document that are capable of creating the data form (See also table 6)
PDF/CDF analysis	Time-based PDF of many jitter events or direct measurement of CDF at specific times via bit error measurements	• Some form of smoothing and/or extrapolation may be required • If PDF integrate into CDF	• Bit-timing reference and Golden PLL are already applied • Sufficient number of events for accurate fitting and/or extrapolation of tails • If extrapolation is required, assumes tails are Gaussian	• Pk-pk DJ, • Other DJ PDF or CDF details • Cannot isolate sub components of DJ	• BERT • TIA (clocked, pattern marker, markerless) • RT scope • Enhanced EQ scope
Over-sampled sequential time analysis	Single shot sampled capture of multiple pattern repetitions	• Interpolate jitter events between samples, interpolate missing signal edges, calculate FFT • Isolate DDJ • Isolate PJ from RJ • Calculate inverse FFT's for DDJ and PJ • Apply SW Golden PLL • Convolve DJ*RJ terms • Integrate into CDF	• Sufficient number of pattern repetitions for statistical relevance • Noise floor is Gaussian and uncorrelated • Broadband crosstalk in the measured signal may affect the validity of the CDF due to separation of DJ from RJ required prior to producing the CDF	• Any components from CDF preparation (pk-pk DJ, frequency content, PJ terms, etc.) • Info on run lengths, transition density, etc. • Can isolate DCD • Provides other waveform information including eye patterns	• RT scope
Under-sampled sequential time analysis on residual jitter from specific signal edges	Under-sampled waveform of residual jitter from specific signal edges in a repeating pattern	• Calculate FFT and create histogram • Isolate PJ from RJ • Remove PJ (remaing spectrum contains the RJ) • Intgrate to produce the RJ value • Deconvolve RJ from the uncorrelated histogram to determine spectral peaks in the BUJ • Create composite PDF and integrate into CDF	• Bit-timing reference and Golden PLL are already applied • Broadband BUJ is not present • No important information is lost by the aliasing of high freqency components • Noise floor is Gaussian	•	• Enhanced EQ scope