Fibre Channel
Methodologies for Signal Quality Specification - MSQS

1. Scope

MJSQ supersedes the previously published MJS technical report (NCITS 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 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 X3.303-1997 - Fibre Channel Physical and Signalling Protocol - 3 (FC-PH-3)
The three documents above are collectively referred to as FC-PH-n

[4] ANSI X3.TR-18:1997 - 10-bit Interface Technical Report (10-bit Interface TR)

[5] INCITS TR-25-1999 01-Sept-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] 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, *Synchronous Optical Network (SONET) Basic Description Including Multiplex Structures, Rates, and Formats*

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

[11] 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.

[33] M. Li, J. Wilstrup, R. Jessen, D. Petrich, “Method and Apparatus for Analyzing Measurement”, US Patent No: US 6 298 315 B1, 2001.

[34] J. Patrin, M. Li, “Comparison and Correlation of Signal Integrity Measurement Techniques”, DesignCon 2002, 2002.

[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, Phase-Locked Loop Circuit Design, 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

Definitions and conventions apply in this document.

3.2. Conventions

All drawings in this document conform to the conventions in **Error! Reference source not found.**.

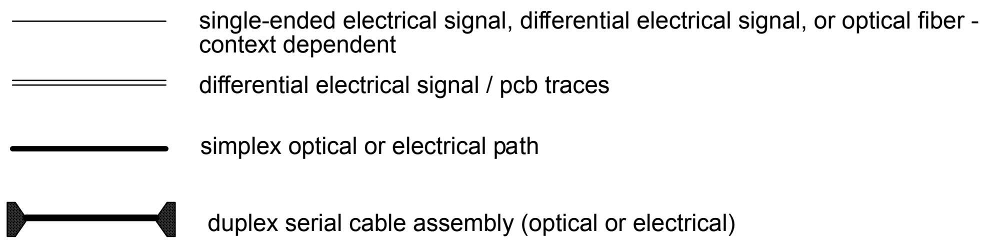


Figure 1 - Drawing conventions

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

Definitions and conventions 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 ANSI X3.TR-18:1997 - 10-bit Interface Technical Report (10-bit Interface TR))
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 **Error! Reference source not found.**. 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 **Error! Reference source not found.**.

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 x. 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 sub clause x 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 x 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 **deterministic jitter, (level 1 DJ):** and **level 1 DJ:**, 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 x and x).

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 x

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 x). 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: t**he 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 MSQS

[previous text shown…Dean Wallace to supply new text.]

4.1. Overview

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 Synchronous Optical Network (SONET) Transport Systems: Common Generic Criteria (G, ANSI T1.105, , ANSI T1.105.06, 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. **Error! Reference source**

not found. 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.

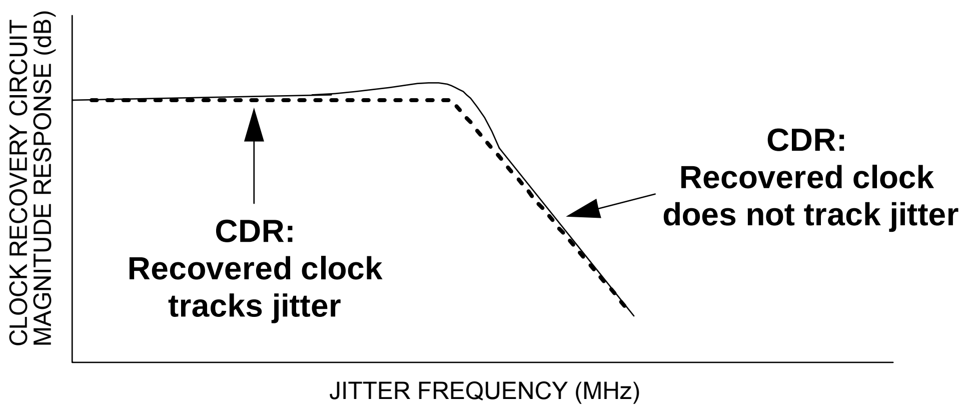


Figure 1 - PLL response

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 **Error! Reference source not found.** 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.

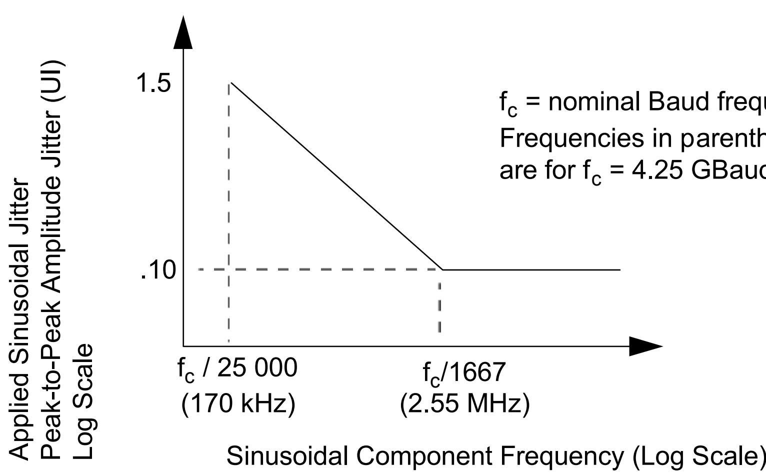


Figure 2 - Mask of the sinusoidal component of jitter tolerance - Log-Log Plot

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) ANSI X3.230-1994 - Fibre Channel - Physical and Signaling Interface (FC-PH) 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 Waveform eye diagrams from different jitter distributions **for examples of this issue. See also x.** See **Error! Reference source not found.** 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. Waveform eye diagrams from different jitter distributions 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 3 - 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 **Error! Reference source not found.**.

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

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. Performance Measures in the Time Domain: Jitter

5.1. Dual-Dirac Measures for Jitter

[Intro goes here.]

5.2. Metrics derived from an averaged waveform

A high-resolution oscilloscope, time interval analyzer, or other instrument with equivalent capability may be used to measure DDJ and DDPWS. A repeating JSTPAT is used. For electrical jitter measurements, the measurement bandwidth is at least 12 GHz. If the measurement bandwidth affects the result, it can be corrected for by post-processing. However, a bandwidth above 12 GHz is expected to have little effect on the results.

5.2.1. Data Dependent Jitter (DDJ)

DCD and Pulse Width Shrinkage (DDPWS) are components of DDJ.

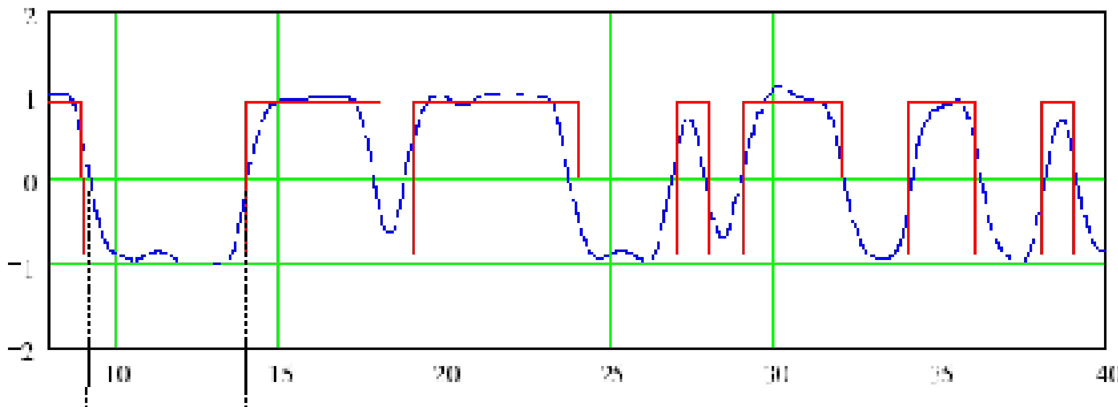
Establish a crossing level equal to the average value of the entire waveform being measured. Synchronize the instrument to the pattern repetition frequency and average the waveforms or the crossing times sufficiently to remove the effects of random jitter and noise in the system. The mean time of each crossing is then compared to the expected time of the crossing, and a set of timing variations is determined. DDJ is the range (max-min) of the timing variations. Keep track of the signs (early/late) of the variations. Note, it may be convenient to align the expected time of one of the crossings with the measured mean crossing.

The following DDJ Test Method illustrates the method. The vertical axis is in arbitrary units, and the horizontal axis is plotted in UI. The waveform is AC coupled to an average value of 0, therefore 0 is the appropriate crossing level. The rectangular waveform shows the ideal crossing times, and the other is the waveform with jitter that is being measured. The waveforms have been arbitrarily aligned with ($\Delta t_2 = 0$) at 14 UI.

DDJ is defined as

$$\mathbf{DDJ} = \mathbf{max}(\Delta \mathbf{t}_1, \Delta \mathbf{t}_2, \ldots \Delta \mathbf{t}_\mathbf{n}) - \mathbf{min}(\Delta \mathbf{t}_1, \Delta \mathbf{t}_2, \ldots \Delta \mathbf{t}_\mathbf{n})$$

Every edge, 1...n, in a complete repetition of the pattern is measured.



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DDJ Test Method

5.2.2.Data dependent pulse width shrinkage (DDPWS)

Data dependant pulse width shrinkage (DDPWS) is the difference between one symbol period and the minimum pulse width of the repeating data sequence JSPAT. The pulse width is the difference in time between two adjacent edges of the averaged signal measured at the mean signal level. The mean signal level will be zero for an ac coupled signal.

The pulse width T_{PW} is defined by the **Error! Reference source not found.**.

The waveform displayed is an average one containing only the data dependent jitter. All uncorrelated jitters (i.e. PJ, RJ, and Bounded Uncorrelated jitter) are averaged out.

The DDPWS is determined from all the pulses within the pattern.

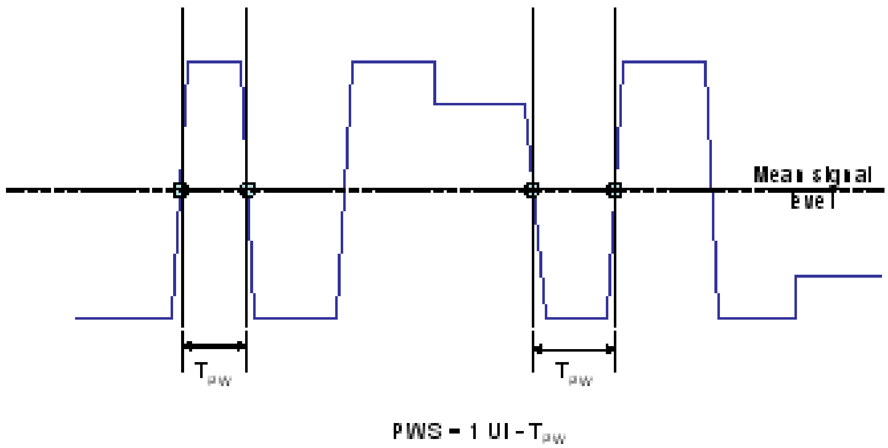


Figure A.6 – Pulse width and data dependent pulse width shrinkage

5.3. Uncorrelated, Deterministic, and Total Jitter

5.3.1. Uncorrelated jitter (UJ)

UJ as defined by IEEE 802.3 clause 68 (reference [27]) is a measure of any jitter that is uncorrelated to the data stream. The definition and test procedure for UJ are identical to those defined in IEEE 802.3 clause 68.6.8 with the following considerations:

The transmitter shall comply while the receiver is operating with asynchronous data and all other ports operating as in normal operation, including proper termination.

For purposes of this document the procedures defined for optical testing also applies to electrical testing. Optical terms (such as power) and units, such as in figure 68-9 in IEEE 802.3, can be converted to corresponding electrical terms (such as voltage) and units, etc.

The 4th-order Bessel-Thomson response is to be used only for optical measurements of UJ. UJ in the electrical domain is defined in a bandwidth of 12 GHz.

JSPAT is suitable as a test sequence for all applications unless specified otherwise.

The bandwidth of the CRU is the signaling speed divided by 1667.

5.3.2 Deterministic and total jitter measurements

The jitter output specifications apply in the context of a 10^{-12} bit error rate (BER). Deterministic jitter (DJ) and total jitter (TJ) may be measured with methods as described in the FC-MJSQ technical report. The optical measurement system may have a low pass fourth-order Bessel-Thomson transfer function or equivalent.

5.4 Difficulties with Dual-Dirac Jitter Measures

[Into text to be added.]

5.4.1 Effect of Random Jitter on Deterministic Jitter

[Contents of 08-559v0 go here.]

5.4.2 Disappearing Deterministic Jitter Dilemma

[Contents of 09-037v0 go here.]

5.4.3 Receiver Sensitivity and Random Jitter

[Contents of 08-686v0 go here.]

6. Performance Measures in the Frequency Domain

[Introductory text goes here.]

6.1 Basic S-parameters for Single Ended Signals

[Text needed here. Discussion to include linearity, causality, passivity, and site references to basic S-parameter literature.]

6.2 S-parameters for differential signals

[Text needed here.]

6.2.1 Common mode to differential mode conversion

[Text needed here.]

6.2.2 Differential mode to common mode conversion

[Text needed here.]

6.3 Touchstone format

[Text needed here.]

[Question: should channel effects section go in 6.4?]

7. Budgeting and Performance Measures for Non-Equalizing Links

7.1 10GbE Spreadsheet Link Model

7.1.1 Scope of the link model

A 10GbE link model has been developed as a tool to facilitate optical physical layer specifications for laser-based links using both single mode (SMF) and multimode (MMF) fiber. The model is intended to perform a reasonable worst case analysis. Testing of actual links should show the model to be slightly pessimistic in its prediction of link reach capability. This assures interoperability among diverse optical manufacturers. An objective of the model is to be uncomplicated such that it can be implemented in a spreadsheet for the widest possible dissemination among potential users.

7.1.2 Concept

The link model is based on a power budget calculation. Power penalties are allocated for link impairments such as noise or dispersion. Power loss is also included to account for connectors and fiber attenuation. The power penalties and losses arre added linearly in decibels to determine the total link penalty as a function of length.

Early versions of the link model emphasized optical power, with separate constraints on allowed extinction ratio (ER). More recent versions introduce Optical Modulation Amplitude (OMA) as an alternative measure which is more conducive to directly modulated lasers, hence more cost effective implementations.

A sketch of the relationships between the various transmit and receive optical powers in OMA and in average powers are shown in figure 7.1. The figure also shows how the power penalties are added within the model.

The following notation has been used in the figure:

P_{TXOMA}, the transmit power (minimum) in OMA (dBm),
SRS_{OMA}, the stressed receiver sensitivity in OMA (dBm),
S_{OMA}, the nominal sensitivity in OMA (dBm),
$\langle P_{TX} \rangle$, the average transmit power (minimum, dBm),
$\langle P_s \rangle$, the nominal receiver sensitivity (average power, dBm),
ChIL, the channel insertion loss (dB),
P_{mpn}, the mode partition noise power penalty (dB),
P_r, the reflection noise power penalty (dB),
P_{rin}, the power penalty due to RIN (dB),
P_{mn}, the power penalty due to modal noise (dB),
M is the power margin (dB),
P_c is the correction due to penalty interactions (dB),
P_{isi} is the power penalty due to ISI (dB),

P_{er} is the power penalty due to the extinction ratio (dB).

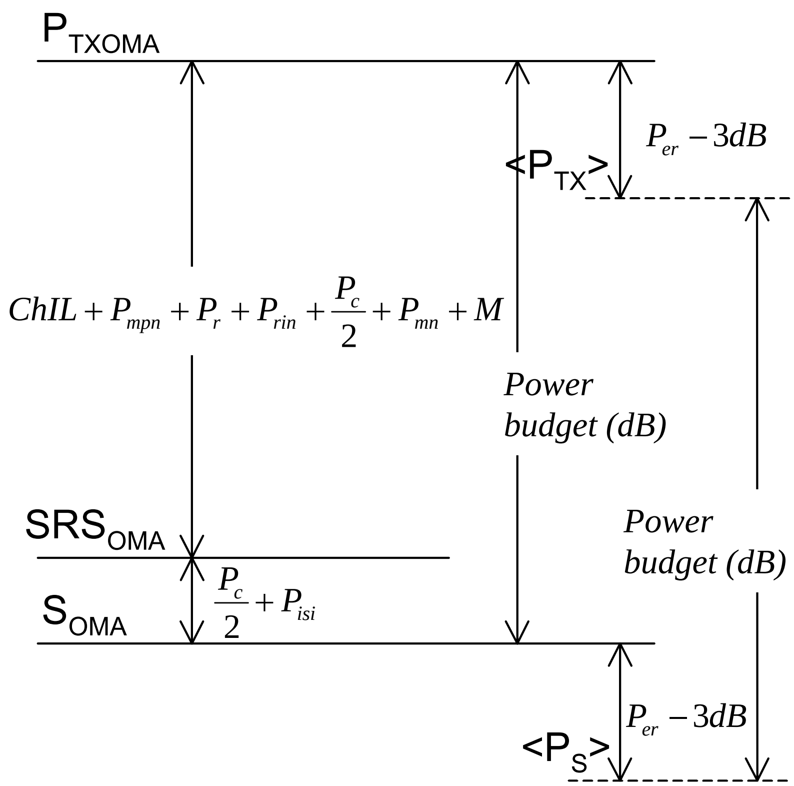


Figure 7.1 – The 10Gigabit Ethernet power budget

7.1.3 Time domain assumptions

To achieve a suitable simple model, it is assumed that the laser and fiber impulse responses are Gaussian. The optical receiver is non-equalized, with a raised cosine response. The model includes expressions that convert the rms impulse width of the laser transmitter, fiber, and optical receiver to rise times, fall times, and bandwidths. Rise and fall times are assumed to be equal; only risetime is mentioned hereinafter. Risetime is 10%-90%; conversion to 20%-80% is a simple factor assuming Gaussian impulse response.

7.1.4 Penalty Details

Dispersion related penalties

To calculate the ISI penalty, P_{isi}, the exit response time of the composite channel needs to be calculated. With the assumption that the fiber exit impulse response is Gaussian, the fiber 10% to 90% exit response time (T_e) is:

$$T_e = \sqrt{T_s^2 + 10^6 \cdot \left[\left(\frac{C1}{BW_{me}} \right)^2 + \left(\frac{C1}{BW_{cd}} \right)^2 \right]} \quad (7.1)$$

where T_s is the 10% to 90% laser rise time, $C1$ = 480 ns MHz, BW_{me} and BW_{cd} are the 3 dB optical (6 dB electrical) bandwidths due to modal and chromatic dispersion respectively. It is assumed that the fiber has a Gaussian response.

The bandwidth due to chromatic dispersion of a fiber link is [2-5]:

$$BW_{cd} = \frac{0.187}{L \cdot \sigma_\lambda} \cdot \frac{10^6}{\sqrt{D_1^2 + D_2^2}} \quad (7.2)$$

where

$$D_1 = \frac{S_0}{4} \cdot \left(\lambda_c - \frac{\lambda_0^4}{\lambda_c^3} \right) \quad (7.3)$$

and

$$D_2 = 0.7 \cdot S_0 \cdot \sigma_\lambda \quad (7.4)$$

λ_0 is the zero dispersion wavelength of the fiber, λ_c is the laser center wavelength, S_0 is the dispersion slope parameter at λ_0, L is the fiber length and σ_λ is the RMS width of the laser spectrum. The effects of chirp are not accounted for in the link model. Therefore, for cases where chirp is important (mainly 10GBASE-E), the 10Gigabit Ethernet committee has developed separate conformance tests.

For multimode fiber, the modal bandwidth, BW_m, is dependent on the fiber type, wavelength and launch characteristics. Worst-case modal bandwidth values for particular PMD cases can be found in the 10Gigabit Ethernet draft standard or relevant building wiring standards. In the 10Gigabit Ethernet link model the effective modal bandwidth, BW_{me}, of a link of length L is calculated as:

$$BW_{me} = \frac{BW_m}{L} \quad (7.5)$$

Polarization mode dispersion can reduce the bandwidth of single-mode fiber. For the single mode case BW_{me} is calculated using the following equation:

$$BW_{me} = \frac{L_{\max}}{3 \cdot DGD} \cdot 10^6 \quad (7.6)$$

where L_{max} is the maximum interoperation link length specified in the 10Gigabit Ethernet standard and DGD is the worst-case differential group delay for that maximum link length.

The approximate 10% to 90% composite channel (transmitter, fiber and optical receiver) exit response time (T_c) is then:

$$T_c = \sqrt{T_e^2 + T_r^2} \quad (7.7)$$

T_r is given by [3, 4, 7]:

$$T_r = \frac{C2}{BW_r} \cdot 10^3 \quad (7.8)$$

where $C2$ = 329 ns·MHz and BW_r is the 3 dB electrical bandwidth of the optical receiver.

Inter-Symbol Interference (ISI) power penalty

For a channel having a Gaussian impulse response, P_{isi} is the power penalty (in dB), due to ISI [7]:

$$P_{isi} = 10 \cdot \log\left(\frac{1}{2 \cdot h(0) - 1}\right) \quad (7.9)$$

where:

$$h(t) = \frac{1}{2} \cdot \left(\operatorname{erf}\left[\frac{2.563}{2 \cdot \sqrt{2}} \cdot \frac{(2 \cdot t + T_{eff})}{T_c}\right] - \operatorname{erf}\left[\frac{2.563}{2 \cdot \sqrt{2}} \cdot \frac{(2 \cdot t - T_{eff})}{T_c}\right]\right) \quad (7.10)$$

and,

$$T_{eff} = \left(\frac{1}{B \cdot 10^6} - DCD \cdot 10^{-12}\right) \cdot 10^{12} \quad (7.11)$$

B is the signaling speed ("base rate") for the optical link and *DCD* is the maximum value of duty cycle distortion for the link.

The Gigabit Ethernet link model used an approximate equation for the worst case ISI penalty [4-7]. The approximation (black line with crosses) is compared with the exact equation (yellow line with circles) in Figure 7. Also plotted are experimental results, presented to the 10Gigabit Ethernet committee, for a large number of cases. The experimental results were obtained using many combinations of multimode fiber and laser launch conditions. It can be seen that the ISI penalty represents a reasonable worst-case contour.

Mode Partition Noise (MPN) power penalty

Another effect, which causes a power penalty due to dispersion, is mode partition noise (MPN). In a multimode laser, partitioning of laser power between laser modes does not change the total laser output power and does not cause an additional amplitude noise at the laser output. However, when the laser output field propagates through dispersive fiber, different laser modes travel with different speeds. Consequently, power fluctuations between modes lead to an additional noise, MPN, at the fiber output. The power penalty due to MPN has been shown to be [8]:

$$P_{mpn} = \frac{1}{\sqrt{1 - (Q \cdot \sigma_{mpn})^2}} \quad (7.12)$$

where the value of the digital signal to noise ratio, *Q*, is determined by the maximum acceptable bit error rate (BER) using [8]:

$$BER = \int_Q^{\infty} \frac{1}{\sqrt{2\pi}} \cdot \exp\left(-\frac{x^2}{2}\right) \cdot dx \quad (7.13)$$

and

$$\sigma_{mpn} = \frac{k_{OMA}}{\sqrt{2}} \cdot \left\{1 - \exp\left[-(\pi \cdot B_{eff} \cdot D \cdot L \cdot \sigma_\lambda)^2\right]\right\} \quad (7.14)$$

where k_{OMA} is the laser mode partition factor ($0 \le k_{OMA} \le 1$), $B_{eff} = 1/T_{eff}$ and $D = \sqrt{D_1^2 + D_2^2}$ is the dispersion. The right hand side of Equation 7.13 is also known as erfc(Q). However, the function "erf" within Excel uses a slightly different definition. In Excel and in this paper, the function equivalent to Equation 7.13 is 0.5·erfc(Q/√2).

The MPN penalty of this sub-section is strictly only true for multi-longitudinal mode lasers, e.g. Fabry-Perot lasers. For multitransverse mode lasers (VCSELs) it is likely to overestimate the power penalty. To compensate for this overestimation of the MPN power penalty the k factor is usually set to a lower value (0.3-0.5).   Where DFB lasers are expected, k_{OMA} is set to zero.

Extinction Ratio (ER) power penalty

An extinction ratio power penalty occurs when a non-zero power level is transmitted for a "zero". The power penalty is given by [4, 5]:

$$P_{\varepsilon} = \frac{\varepsilon + 1}{\varepsilon - 1} \quad (7.15)$$

where ε is the laser extinction ratio; the ratio of the optical power on a "one" divided by the power on a "zero".

Relative Intensity Noise (RIN) power penalty

Another noise term due to the use of lasers is relative intensity noise (RIN). The noise is due to the fluctuations in the output intensity of the laser. The RIN induced power penalty, in dB, is then:

$$P_{rin} = 10 \cdot \log\left(\frac{1}{\sqrt{1 - \left(\frac{Q \cdot \sigma_{rin}}{ISI_r} \right)^2}} \right) \quad (7.16)$$

This is a slight modification of the expression that was used in the Gigabit Ethernet link model. The new expression includes the increase in the RIN penalty caused by ISI and reflection (interferometric) effects.

In the 10Gigabit Ethernet link model the noise variance, σ_{rin}^2, due to laser RIN is calculated using the following equation:

$$\sigma_{rin}^2 = \frac{k_{rin} \cdot ISI_{test}^{\ 2} \cdot 10^6}{\sqrt{\left(\frac{1}{BW_{me}} \right)^2 + \left(\frac{1}{BW_{cd}} \right)^2} + \frac{0.477}{BW_{test}} \cdot 10^{\left(\frac{-RIN_{OMA}}{10} \right)}} \quad (7.17)$$

where RIN_{OMA} is the laser intensity noise relative to OMA and k_{rin} is a scaling factor BW_{test} is the bandwidth of the of the test receiver, and

$$ISI_{test} = \frac{1 + O(DJ_{eff})}{2} \quad (7.18)$$

where the function O(x) is defined as:

$$O(x) = \mathrm{erf}\left[\frac{2.563}{2\cdot\sqrt{2}}\cdot\frac{(x+1)\cdot Teff}{T_c}\right] + \mathrm{erf}\left[\frac{2.563}{2\cdot\sqrt{2}}\cdot\frac{(1-x)\cdot Teff}{T_c}\right] - 1 \quad (7.19)$$

and,

$$DJ_{eff} = \frac{DJ - DCD}{T_{eff}} \quad (7.20)$$

where DJ is the worst-case deterministic jitter, DCD is the worst-case DCD. Note: in the current link model ISI_{test} has been set equal to unity to follow the current definition of OMA in 10Gigabit Ethernet, as effectively measured without ISI.

Also (see "reflection noise" below),

$$ISI_r = O(DJ_{eff}) - \frac{2\cdot R_{NF}\cdot 10^{\frac{-ChIL}{10}}\cdot GMR\cdot\sqrt{1+\varepsilon+2\cdot\varepsilon\cdot O(DJ_{eff})\cdot(\varepsilon-1)}}{(\varepsilon-1)} \quad (7.21)$$

R_{NF} = 0.6, ChIL is the channel insertion loss in dB, GMR is the geometric mean of the transmitter and receiver optical return loss and the other terms are as previously defined.

Reflection noise power penalty

The lasers used for 10Gigabit Ethernet are likely to be single frequency lasers. Therefore, interferometric noise will occur at the receiver. Interferometric or reflection noise results from the interference of the desired signal and its reflections at the receiver. Since the lasers used for Gigabit Ethernet were multimode the Gigabit Ethernet model ignored this noise term. The 10Gigabit Ethernet committee considered this effect in detail [9-17] and developed an expression for the reflection noise, P_r, (in dB) as follows:

$$P_r = -10\cdot\log\left[1 - \frac{2\cdot R_{NF}\cdot 10^{\frac{-ChIL}{10}}\cdot GMR\cdot\sqrt{1+\varepsilon+2\cdot\varepsilon\cdot O(DJ_{eff})\cdot(\varepsilon-1)}}{O(DJ_{eff})\cdot(\varepsilon-1)}\right] \quad (7.22)$$

Baseline wander power penalty

For scrambled binary pulse amplitude modulation (PAM-2) base line wander is Gaussian and can be treated as a noise term. The baseline wander will be exacerbated by ISI. In the model, the baseline wander penalty is calculated using the following equation:

$$P_{BLW} = 10\cdot\log\left(\frac{1}{\sqrt{1-\left(Q\cdot\sigma_{BLW}/ISI_{RX}\right)^2}}\right) \quad (7.23)$$

where σ_{BLW} is the rms baseline wander as a fraction of half the eye opening in amplitude,

$$ISI_{RX} = \mathrm{erf}\left[\frac{2.563}{2\cdot\sqrt{2}}\cdot\frac{(W_{eff}+1)\cdot Teff}{T_{RX}}\right] + \mathrm{erf}\left[\frac{2.563}{2\cdot\sqrt{2}}\cdot\frac{(1-W_{eff})\cdot Teff}{T_{RX}}\right] - 1 \quad (7.24)$$

W_{eff} is the effective eye opening (in UI) and

$W_{eff} = \frac{W}{T_{eff}}$ (if W and T_{eff} are in the same units),

$T_{RX} = \frac{C2 \cdot 10^3}{BW_{test}}$

In the power budget calculation only the portion of baseline wander penalty due to the interaction with ISI is included, as a component of P_c. The remainder of the baseline wander penalty is to be absorbed by the optical receiver. This is not too difficult as the total penalty is about 0.1 dB.

Eye opening power penalty

In the model the minimum eye opening at the decision circuit is given by the following expression:

$$W_{eff} = \frac{1 - 2 \cdot X2}{B_{eff}} \cdot 10^6 \quad (7.25)$$

where $X2$ is an x ordinate of one of the points on the 10Gigabit Ethernet eye mask and B_{eff} is the effective symbol rate $10^6/T_{eff}$. The eye-opening penalty is calculated as, P_{eye}, in dB using the following equation:

$$\mathrm{P_{eye}} = 10 \cdot \log\left[\frac{1}{O(W_{eff})}\right] - P_{isi} \quad (7.26)$$

where T_{eff} is the effective symbol period (in ps) given by Equation 7.11, and the function $O(x)$ has previously been defined.

Currently, the eye-opening penalty is not explicitly part of the 10Gigabit Ethernet link budget. Rather it is assumed that this penalty is implementation dependent and is absorbed by the optical receiver, which in most cases includes a clock and data recovery circuit. The receiver implementation must have enough additional sensitivity to allow for its required amount of eye opening. The current input parameters of the link model lead to a value of 0.25 dB for the eye-opening penalty.

Fiber attenuation

The attenuation, in dB, of cabled optical fiber for a particular length is modeled by:

$$Att = L \cdot \frac{R_\lambda}{C_\lambda} \cdot \left[\left(\frac{1}{9.4 \cdot 10^{-4} \cdot \lambda_c}\right)^4 + 1.05\right] \quad (7.27)$$

The equation is based on the maximum allowable attenuation specifications for MMF, but can be applied to SMF in the 1310 nm region. This equation does not model the OH^- absorption peak at ~1.4 µm. The equation models the shape of the attenuation versus wavelength curve around the two windows of operation and uses R_λ and C_λ as scaling factors. R_λ is the actual cable attenuation in dB/km at either 850 nm or 1300 nm. For short wavelength links (< 1000 nm), C_λ =3.5dB/km while for long wavelength links (> 1000 nm), C_λ=1.5dB/km.

Interaction penalty

For Gaussian noise terms the total noise variance is given by the sum of the variances of the individual noise terms. Thus the total power penalty, in dB, is not the simple sum of the individual power penalties. Additionally, ISI will exacerbate the penalty. Usually, the interaction or cross term is closely approximated by the summation of power penalties (in dB). The correction term, P_c, called Pcross in the spreadsheet is given by:

$$P_c = -10 \cdot \log\left[ISI_r \cdot \sqrt{1 - Q^2 \cdot \left(\sigma_{mn}{}^2 + \sigma_{mpn}{}^2 + \left\{ \left(\sigma_{BLW}{}^2 + \sigma_{rin}{}^2\right) \Big/ ISI_r{}^2 \right\} \right)} \right] - P_{isi} - P_{mpn} - P_r - P_{rin} - P_{mn} - P_{BLW}$$

(7.28)

Usually, P_c is less than 0.5 dB.

7.1.5 Shortcomings of the model

The model does have shortcomings, some examples of which are:

The mode partition noise penalty is not accurate for the type of lasers used by 10Gigabit Ethernet – the model tends to overestimate this penalty.
Since there is no simple model for the power penalty due to chirp, this effect is ignored.
Although some aspects of jitter are included in the link model, the jitter budget is not part of the model.

To overcome these shortcomings 10Gigabit Ethernet has specified additional conformance tests.

7.1.6 Example of a link spreadsheet calculation

[To be written.]

7.2 Stressed Eye

[To be written.]

7.3 Eye Mask Probability

The transmitter eye mask probability level is given in clause 6.3.2 and 6.4.2. The expectation of hit ratio of a compliant signal is to be below this limit.

The hit ratio HR is given by:

$$HR = N_{violations} / S$$

where $N_{violations}$ is the number of mask hits and S is the number of samples per unit interval in the measurement.

S is given by:

$$S = \frac{N_{waveforms} \times L_{record}}{N_{div} \times t_{div} \times B}$$

where $N_{waveforms}$ is the number of waveforms acquired by the oscilloscope, L_{record} is the record length of a waveform (sometimes called samples/waveform, samples/screen, or trace length), N_{div} is the number of divisions across the oscilloscope's screen, t_{div} is the time per division setting of the oscilloscope timebase, and B is the signaling rate.

For example, if the signaling rate is 8.5 GBd, an oscilloscope with 10 divisions across its screen measures for 20 waveforms at 1350 samples/screen, and the time-base is set to 20 ps/div,

$$S = \frac{20 \times 1350}{10 \times 20 \times 10^{-12} \times 8.5 \times 10^{9}} = 15882$$

and if HR < 10^{-3},

$N_{violations} < 10^{-3} \times 15\,882$

A transmitter with an expectation of less than 15.9 hits is compliant.

Likewise, if a measurement is continued for 200 waveforms, then an expectation of less than 159 hits is compliant. A careful measurement would have $N_{violations}$ of more than 10 at the specified transmitter eye mask probability level. A more extended measurement is expected to give a more accurate result, while measurements to "zero hits", which involve finding the position of the worst single sample in the measurement, have degraded reproducibility because random processes cause the position of such a single low-probability event to vary.

The hit ratio limit has been chosen for 8GFC to avoid misleading results due to measurement noise. However, care should be taken to avoid or correct for oscilloscope noise, if necessary.

8. Budgeting with Equalizing Links

8.1. Reference Equalizer and Power Penalty

8.2. Measures

8.2.1. Non-Compensable Data Deterministic Jitter

8.2.2 TWDP

8.2.3 WDP

8.2.4 dWDP

8.2.5 TDP

8.2.6 Relative Noise & Q_{sq}

Relative Noise (RN) is a measure of reciprocal Signal-to-Noise Ratio (SNR) for a signal and Q_{sq} is a measure of its SNR. RN is given by:

$$\mathbf{RN} = \frac{\mathbf{2xnoise(rms)}}{\mathbf{(xMA)}}$$

where xMA is OMA if an optical signal is being measured, or VMA if an electrical signal is being measured, and noise (rms) is measured on the same optical signal or electrical signal, respectively.

Important parts of the measurement procedure for RN and Q_{sq} can be found in IEEE Std. 802.3 CL 68.6.7 (reference [27]). Some comments:

For purposes of this document, the definitions and procedures generally apply to both optical and electrical signals. Optical terms (such as power) and units can be converted to corresponding electrical terms (such as voltage) and units, etc.

The test pattern defined for xMA in **Error! Reference source not found.** or **Error! Reference source not found.** shall be used, whether the RN or Q_{sq} measurement is being done on an optical or an electrical signal.

The fourth-order Bessel-Thomson response is to be used for optical measurements of RN. The bandwidth of the Bessel-Thomson response is called out in **Error! Reference source not found.**. RN in the electrical domain is defined in a bandwidth of 12 GHz.

Noises at both logic levels should be measured: logicONEnoise(rms) and logicZEROnoise(rms).

Apply the rms technique according to the equation:

$$\mathbf{noise(rms)} = \sqrt{\frac{(\mathbf{logicONEnoise(rms)}^2 + \mathbf{logicZEROnoise(rms)}^2)}{2}}$$

Qsq is given by:

$$Q_{sq} = \frac{xMA}{logicONEnoise(rms) + logicZEROnoise(rms)}$$

A calculation in units of dB/Hz, such as for transmitter RIN, is not required.

If logicONEnoise(rms) equals logicZERO(rms) then RN equals $1/Q_{sq}$.

8.2.7 Metrics Derived from an Averaged Waveform

Waveform distortion penalty (WDP)

WDP is a wave shape metric for waveform filtering or other sources of data-dependent distortion. WDP used in this document is based on the code as defined in annex I. The following modifications were made to the code in IEEE 802.3 clause 68.6.6:

- Addition of spectral line timing recovery and horizontal eye opening evaluation (NC-DDJ).
- Adjustment of P_{ALLOC} based on the calculated VMA.
- Anti-aliasing filter bandwidth scaled to 75% of the signaling speed in contrast to the static 7.5 GHz.
- For purposes of this document, the definitions and procedures generally apply to both optical and electrical signals. Optical terms (such as power) and units can be converted to corresponding electrical terms (such as voltage) and units, etc.
- JTSPAT is suitable as a test sequence for all applications unless specified otherwise.

Transmitter waveform and distortion penalty (TWDP)

The transmitter and waveform dispersion penalty (TWDP) is a measure of the deterministic dispersion penalty due to a transmitter device under test with the reference transmitter compliance transfer functions and receiver. TWDP limits are given in table 10 and table 33. Non-compensable data-dependent jitter (NC-DDJ) requirements for beta and epsilon are given in table 33. Other parameters are contained in the code in annex I.2.

The TWDP measured utilizes the procedure described in **Waveform distortion penalty (WDP)** to capture and post-process the transmitter waveform at the output of the compliance test card. The post-processing algorithm is further augmented as described below.

- Introduce the electrical stressors described by the transmitter compliance transfer functions (refer to **Error! Reference source not found.**).
- Assignment of an independent P_{ALLOC} value for each stressor.
- For beta and epsilon, it is expected that transmitter emphasis (pre-cursor and post-cursor) will be necessary to satisfy the requirements. For each stressor, the corresponding TWDP limit shall be satisfied for at least one equalization setting of the transmitter device under test.

For beta and epsilon, since the noise environment is not a function of VMA_T, VMA_T in excess of the minimum results in a larger P_{ALLOC}. An increase in P_{ALLOC} implies an increase in the permissible TWDP. Given the measured (estimated) VMA_T, P_{ALLOC} is adjusted in the TWDP algorithm. The TWDP result is also adjusted in the TWDP algorithm by the correction term, dTWDP, illustrated in figure 44.

8.3 Analytical Tools

8.3.1 MATLAB Code

```
% MATLAB (R) script to compute TWDP, WDP, and NC-DDJ %%%%%%%%%%%%%%%%%%%
%
% Version: 1.9 (includes optional eye diagram display)
% Date: April 24, 2008
%
% Based on original TWDP methodology described in IEEE Std 802.3aq(TM)-2006
%
% Reference: N. L. Swenson, P. Voois, T. Lindsay, and S. Zeng, "Standards
% compliance testing of optical transmitters using a software-based equalizing
% reference receiver", paper NWC3, Optical Fiber Communication Conference and
% Exposition and The National Fiber Optic Engineers Conference on CD-ROM
% (Optical Society of America, Washington, DC), Feb. 2007
%
% Syntax:
% [xWDP, ncDDJ, MeasuredxMA] = xWDPJ( WaveformFile, TxDataFile, usage, showEye )
%
% WaveformFile: The waveform consists of exactly N samples per unit interval T,
% where N is the oversampling rate. The waveform must be circularly shifted to
% align with the transmit data sequence. The file format is ASCII with a single
% column of chronological numerical samples, in signal level, with no headers
% or footers. Enter as a string.
% TxDataFile: The transmit data sequence should be one of the 8GFC test patterns
% defined in FC-PI-4. The file format is ASCII with a single column of chrono-
% logical ones and zeros with no headers or footers. Enter as a string.
% usage: String identifier that defines the parameter set specific to the variant
% and requirement to be verified. Permissible values are...
%    'GAMMA_SA_TWDP'
%    'GAMMA_SN_TWDP'
%    'GAMMA_SA_WDP'
%    'DELTA_EA_WDP'
%    'DELTA_CU_TWDP'
%    'DELTA_CU_WDP'
%    'BETA_EPSILON_TWDP'
%    'BETA_EPSILON_WDP'
% showEye: Integer value that controls the graphical display of the slicer input
% eye. A value greater than zero enables the display (and is the figure number
% for the first figure generated).
%
%% Function: xWDPJ %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [xWDP,ncDDJ,MeasuredxMA] = xWDPJ(WaveformFile,TxDataFile,usage,showEye)
%% Program constants %%
OverSampleRate = 16; % Oversampling rate, must be even
SymbolPeriod = 1/8.5; % Symbol period (ns) for 8GFC
Q0 = 7.03; % BER = 10^(-12)
%% Load input waveform and data sequence, generate filter and other matrices
yout0 = load(WaveformFile);
XmitData = load(TxDataFile);
PtrnLength = length(XmitData);
TotLen = PtrnLength*OverSampleRate;
Fgrid = [-TotLen/2:TotLen/2-1].'/(PtrnLength*SymbolPeriod);
%% Compute frequency response of 6.375 GHz 4th order Butterworth antialiasing
%% filter. Denominator polynomial for frequency response is a, numerator is b.
a = [1.0000e+000  1.0467e+002  5.4779e+003  1.6793e+005  2.5742e+006];
b = 2.5742e+006;
ExpArg = -j*2*pi*Fgrid;
H_r = b./polyval(a,-ExpArg);
ONE=ones(PtrnLength,1);
%% Normalize the received OMA (or VMA) to 1. Estimate the OMA of the captured
%% waveform by using a linear fit to estimate a pulse response, synthesize a
```

```
%% square wave, and calculate the OMA of the synthesized square wave per IEEE
%% Std 802.3(TM), clause 52.9.5.
ant=4; mem=40; % Anticipation and memory parameters for linear fit
X=zeros(ant+mem+1,PtrnLength);% Size data matrix for linear fit
Y=zeros(OverSampleRate,PtrnLength);% Size observation matrix for linear fit
for ind=1:ant+mem+1 % Wrap appropriately for linear fit
    X(ind,:)=XmitData(mod( (0:PtrnLength-1)-ind+ant+1, PtrnLength )+1)';
end
X=[X;ones(1,PtrnLength)]; % The all-ones row is included to compute the bias
for ind=1:OverSampleRate
    Y(ind,:)=yout0([0:PtrnLength-1]*OverSampleRate+ind)'; % 1 bit per column
end
Qmat=Y*X'*(X*X')^(-1); % Coefficient matrix resulting from linear fit. Each
%% column (except the last) is one bit period of the pulse response. The last
%% column is the bias.
SqWvPer=10; % Even number; sets the period of the sq wave used to compute OMA
SqWv=[zeros(SqWvPer/2,1);ones(SqWvPer/2,1)]; % One period of sq wave (column)
X=zeros(ant+mem+1,SqWvPer); % Size data matrix for synthesis
for ind=1:ant+mem+1 % Wrap appropriately for synthesis
    X(ind,:)=SqWv(mod( (0:SqWvPer-1)-ind+ant+1, SqWvPer )+1)';
end
X=[X;ones(1,SqWvPer)]; % Include the bias
Y=Qmat*X;Y=Y(:); % Synthesize the modulated square wave, put into one column
avgpos=[0.4*SqWvPer/2*OverSampleRate:0.6*SqWvPer/2*OverSampleRate];
ZeroLevel=mean(Y(round(avgpos),:)); % Average over middle 20% of "zero" run
%% Average over middle 20% of "one" run, compute OMA
MeasuredxMA=mean(Y(round(SqWvPer/2*OverSampleRate+avgpos),:))-ZeroLevel;
%% Subtract zero level and normalize OMA
youtn = (yout0-ZeroLevel)/MeasuredxMA;
%% Get usage parameters for the application
[EqNf, EqNb, H_chan, AAfilter, PAlloc, dBscale, xMAGain, useEdges] =...
    GetParams( usage, Fgrid, SymbolPeriod, MeasuredxMA );
%% Set search range for equalizer delay, specified in symbol periods. Lower end
%% of range is minimum channel delay less 5 for a guardband. Upper end of range
%% accounts for the FFE. Round up and add 5 to guardband for the channel and
%% antialiasing filter.
EqDelMin = -5;
EqDelMax = ceil(EqNf/2)+5;
%% Compute the minimum slicer MSE and corresponding xWDP and ncDDJ
X = toeplitz(XmitData, [XmitData(1); XmitData(end:-1:end+1-EqNb)]);
Xtil = toeplitz(XmitData(mod((0:PtrnLength-1)-EqDelMin, PtrnLength )+1), ...
    XmitData(mod(-EqDelMin:-1:-(EqDelMax+EqNb),PtrnLength)+1));
Rxx = X'*X; % Used in MSE calculation
for ii=1:size( H_chan,2 ) % index for stressor
    %% Compute the noise autocorrelation sequence at the output of the front-end
    %% antialiasing filter and rate-2/T sampler.
    N0 = SymbolPeriod/2 / (Q0 * 10^(PAlloc(ii)/dBscale))^2;
    Snn = N0/2 * fftshift(abs(H_r).^2) * 1/SymbolPeriod * OverSampleRate;
    Rnn = real(ifft(Snn));
    Corr = Rnn(1:OverSampleRate/2:end);
    C = toeplitz(Corr(1:EqNf));
yout = real(ifft(fft(youtn) .* fftshift(H_chan(:,ii))));
    if AAfilter
        %% Process signal through front-end antialiasing filter
        yout = real(ifft(fft(yout) .* fftshift(H_r)));
    end
    %% Compute the sampling function and sample the processed waveform
    [yk, tk, index1] = CDRSample( yout, OverSampleRate, PtrnLength, useEdges );
%% Compute MMSE-DFE %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    %% The MMSE-DFE filter coefficients computed below minimize mean-squared
    %% error at the slicer input. The derivation follows from the fact that the
    %% slicer input over the period of the data sequence can be expressed as Z =
    %% (R+N)*W - X*[0 B]', where R and N are Toeplitz matrices constructed from
    %% the signal and noise components, respectively, at the sampled output of
    %% the antialiasing filter, W is the feedforward filter, X is a Toeplitz
```

```
    %% matrix constructed from the input data sequence, and B is the feedback
    %% filter. The computed W and B minimize the mean square error between the
    %% input to the slicer and the transmitted sequence due to residual ISI and
    %% Gaussian noise. Minimize MSE over FFE delay and determine BER.
    Rout = toeplitz(yk, [yk(1); yk(end:-1:end-EqNf+2)]);
    R = Rout(index1:2:end, :);
    RINV = inv([R'*R+PtrnLength*C R'*ONE;ONE'*R PtrnLength]);
    R=[R ONE]; % Add all-ones column to compute optimal offset
    Rxr = Xtil'*R; Px_r = Rxr*RINV*Rxr';
    %% Minimize MSE over equalizer delay
    MseOpt = Inf;
    for kk = 1:EqDelMax-EqDelMin+1
        SubRange = [kk:kk+EqNb];
        SubRange = mod(SubRange-1,PtrnLength)+1;
        P = Rxx - Px_r(SubRange,SubRange);
        P00 = P(1,1); P01 = P(1,2:end); P11 = P(2:end,2:end);
        Mse = P00 - P01*inv(P11)*P01';
        if (Mse<MseOpt)
            MseOpt = Mse;
            B = -inv(P11)*P01'; % Feedback filter
            XSel = Xtil(:,SubRange);
            W = RINV*R'*XSel*[1;B]; % Feedforward filter
            Z = R*W - XSel*[0;B]; % Input to slicer
            %% Compute BER using semi-analytic method
            MseGaussian = W(1:end-1)'*C*W(1:end-1);
            Ber = mean(0.5*erfc((abs(Z-0.5)/sqrt(MseGaussian))/sqrt(2)));
        end
    end
%% Compute equivalent SNR %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    %% This function computes the inverse of the Gaussian error probability
    %% function. The built-in function erfcinv() is not sensitive enough for low
    %% probability of error cases.
    if Ber>10^(-12) Q = sqrt(2)*erfinv(1-2*Ber);
    elseif Ber>10^(-323) Q = 2.1143*(-1.0658-log10(Ber)).^0.5024;
    else Q = min(abs(Z-0.5))/sqrt(MseGaussian);
    end
%% Compute penalty and ncDD %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    RefSNR = dBscale * log10(Q0) + PAlloc(ii);
    xWDP(ii) = RefSNR-dBscale*log10(Q);
    xWDP(ii) = xWDP(ii)-xMAGain(ii); % Offset xWDP by the eligible xMA gain
    ncDDJ(ii) = AnalyzeEye( yout, tk, index1, W, B, XSel, MseGaussian, ...
        showEye, usage, ii, MeasuredxMA, Q, Q0, xWDP(ii), dBscale );
end
%% End of xWPDJ

%% Subfunction: GetParams %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [EqNf, EqNb, H_chan, AAfilter, PAlloc, dBscale, xMAGain, useEdges] =...
  GetParams( usage, Fgrid, SymbolPeriod, MeasuredxMA )
switch( upper( usage ) )
  case 'GAMMA_SA_TWDP'
        EqNf = 1; % Number of T/2-spaced feed-forward taps
        EqNb = 2; % Number of T-spaced feedback taps
        AAfilter = 0;
        useEdges = 0; % Clock extract by squaring method
        %% For purposes of FC-PI-4, BW = 0.187391/sigma where sigma is the RMS
        %% impulse response in ns, BW is the -3dB (optical) bandwidth, in GHz,
        %% of the Gaussian filter called out in the MMF tables in the standard.
        %% To convert to equivalent electrical bandwidth, divide the optical
        %% bandwidth by sqrt(2).
        sigma = sqrt(log(2)/2)/(pi*4.92); % GHz at -3dBo per FC-PI-4
        H_chan = exp(-2*(pi*Fgrid*sigma).^2); % Gaussian filter, freq. domain
        PAlloc = 5; % Total allocated dispersion penalty (dBo)
        dBscale = 10;
        xMAGain = 0;
  case 'GAMMA_SN_TWDP'
```

```
        EqNf = 1;
        EqNb = 0; % No equalizer
        AAfilter = 0;
        useEdges = 1;% Clock extracted from crossing times
        sigma = sqrt(log(2)/2)/(pi*9.84); % GHz at -3dBo
        H_chan = exp(-2*(pi*Fgrid*sigma).^2);
        PAlloc = 5;
        dBscale = 10;
        xMAGain = 0;
  case {'GAMMA_SA_WDP','DELTA_EA_WDP'}  % Can use either name
        EqNf = 1;
        EqNb = 2;
        AAfilter = 0;
        useEdges = 0;
        H_chan = 1; % Identity channel
        PAlloc  = 5;
        dBscale = 10;
        xMAGain = 0;
  case 'DELTA_CU_TWDP'
        EqNf = 1;
        EqNb = 3;
        AAfilter = 1; % Butterworth anti-aliasing filter in data path
        useEdges = 0;
        ChanResp = [ 0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5; ...
            0.0020 0.1993 0.3307 0.2215 0.0978 0.0423 0.0399 0.0277 0.0203 0.0123
0.0043 0.002;
1 0 0 0 0 0 0 0 0 0 0 0];
        Delays = ChanResp(1,:)*SymbolPeriod; % ns
        PCoefs = ChanResp(2,:)';
        H_chan = exp(-j*2*pi*Fgrid*Delays)*PCoefs/sum(PCoefs); % Normalized
        PAlloc = 7.5;
        dBscale = 10;
        xMAGain = 0;
  case 'DELTA_CU_WDP'
        EqNf = 1;
        EqNb = 3;
        AAfilter = 1;
        useEdges = 0;
        H_chan = 1;
        PAlloc = 7.5;
        dBscale = 10;
        xMAGain = 0;
  case 'BETA_EPSILON_TWDP'
        EqNf = 1;
        EqNb = 3;
        AAfilter = 1;
        useEdges = 0;
        %% Import stressor responses from file %%%%%%%%%%%%%%%%%%%%%%%%%%%
        %% stressorFile : Contains the stressor impulse response(s) sampled
        %% at an interval of "SymbolPeriod/OverSampleRate". The file format
        %% is ASCII with a column of chronological numerical samples for each
        %% stressor with no headers or footers.
        stressorFile = 'BETA_EPSILON_TX_TCTF.txt';
        stressor = load( stressorFile );
        H_chan = fftshift( fft( stressor, length( Fgrid ) ), 1 );
        %% Specify the total allocated dispersion penalty for each stressor.
        PAlloc = [18.6, 18.6, 20.7];
        dBscale = 20;
        %% Adjust allocated dispersion penalty based on the trade-off between
        %% xWDP and xMA.
        minxMA = [0.665, 0.665, 0.535];
        xMAGain = dBscale*log10( MeasuredxMA./minxMA );
        PAlloc  = PAlloc+xMAGain;
  case 'BETA_EPSILON_WDP'
        EqNf = 1;
```

```
        EqNb = 3;
        AAfilter = 1;
        useEdges = 0;
        H_chan = ones( 1, 3 );
        PAlloc = [16.8, 15.7, 15.7];
        dBscale = 20;
        xMAGain = zeros( 1, 3 );
  otherwise
    disp('usage type not recognised'); beep
end
%% End of GetParams

%% Subfunction: CDRSample %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [yk, tk, index1] = CDRSample( yout, OverSampleRate, PtrnLength, useEdges )
%% Derive normalized frequency grid from the input arguments
TotLen = OverSampleRate*PtrnLength;
Fgridn = (-TotLen/2:TotLen/2-1).'/PtrnLength;
%% Compute the frequency response for spectral line bandpass filter
w1 = 2*pi*(1-1/1667);   % Define the pass band (normalized to signaling speed)
w2 = 2*pi*(1+1/1667);
%% Denominator and numerator coefficients for the bandpass filter
ap = [1, w2-w1, w1*w2];
bp = [0, w2-w1, 0];
Hp = polyval( bp, j*2*pi*Fgridn )./polyval( ap, j*2*pi*Fgridn );
%% Compute the sampling function and sample the waveform
km1 = mod( (0:TotLen-1)-1, TotLen )+1;
kp1 = mod( (0:TotLen-1)+1, TotLen )+1;
if useEdges
    youtLim=sign(yout-mean(yout));
    yclk = real(ifft( fft((youtLim(kp1)-youtLim(km1)).^2).*fftshift(Hp) ));
else
    yclk = real( ifft( fft( (yout(kp1)-yout(km1)).^2 ).*fftshift( Hp ) ) );
end
yclk = yclk(kp1)-yclk(km1);
time = (0:TotLen).'/OverSampleRate;     % Wrap waveforms to ensure all edges are
yout = [yout; yout(1)];                 % are detected
yclk = [yclk; yclk(1)];
yclk = yclk/(max( yclk )-min( yclk ))+0.5;  % Normalize clock waveform
kr = find( diff( yclk > 0.5 ) > 0 );        % Eye center index
kf = find( diff( yclk > 0.5 ) < 0 );        % Eye crossing index
k = sort( [kr; kf] );
index1 = double( kr(1) > kf(1) )+1;         % Index of the first eye center
tk = time(k)-(1/OverSampleRate)*(yclk(k)-0.5)./(yclk(k+1)-yclk(k));
yk = interp1( time, yout, tk );
%% End of CDRSample

%% Subfunction: AnalyzeEye %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function ncDDJ = AnalyzeEye( yout, tk, index1, W, B, XSel, MseGaussian, ...
    showEye, usage, ii, MeasuredxMA, Q, Q0, xWDP, dBscale )
%% Extract required equalizer parameters from the input arguments.
EqNf = length( W )-1;   % Number of T/2-spaced feed-forward taps
EqNb = length( B );     % Number of T-spaced feedback taps
xr = XSel(:, 1);        % Error-free decisions
%% Define the axes of the bit error ratio map
dphi = 1/100;    % Phase step (unit interval)
dvee = 1/200;    % Eye diagram amplitude step (unit amplitude)
phiList = linspace( -0.5, 0.5, round( 1/dphi )+1 );
veeList = linspace( -0.5, 0.5, round( 1/dvee )+1 );
if ~(showEye > 0), veeList = 0; end
%% Compute the bit error ratio at each point in the time-amplitude grid.
PtrnLength = length( xr );
OverSampleRate = round( length( yout )/PtrnLength );
time = (0:OverSampleRate*PtrnLength).'/OverSampleRate;
yout = [yout; yout(1)];
for jj = 1:length( phiList )
```

```
    phi = phiList(jj);
    yk = interp1( time, yout, mod( tk+phi, time(end) ) );
    Y = toeplitz( yk, [yk(1); yk(end:-1:end-EqNf+2)] );
    Y = Y(index1:2:end, :);
    Y = [Y, ones( PtrnLength, 1 )];
    zk = Y*W-XSel*[0; B];
    %% Compute the minimum distance from the noiseless, equalized samples
    %% to the decision threshold.
    eyeLid0(jj) = max( zk(find( xr == 0 )) );
    eyeLid1(jj) = min( zk(find( xr == 1 )) );
    %% Compute the bit error ratio as a function of offset from the nominal
    %% sampling time and decision threshold.
    dk = ones( length( veeList ), 1 )*zk.'-veeList(:)*ones( 1, PtrnLength );
    dk(:, find( xr == 0 )) = 0.5-dk(:, find( xr == 0 ));
    dk(:, find( xr == 1 )) = dk(:, find( xr == 1 ))-0.5;
    berMap(:, jj) = mean( erfc( dk/sqrt( 2*MseGaussian ) )/2, 2 );
end
eyeList = 2*min( [0.5-eyeLid0; eyeLid1-0.5] );
%% Compute the non-compensable jitter.
kDDJ = find( abs( diff( eyeList > 0 ) ) > 0 );
phiDDJ = phiList(kDDJ)-dphi*eyeList(kDDJ)./(eyeList(kDDJ+1)-eyeList(kDDJ));
if length( phiDDJ ) == 0
    phiDDJ = [0, 0];
end
if length( phiDDJ ) == 1
    phiDDJ = sort( [phiDDJ, -sign( phiDDJ )/2] );
end
ncDDJ = 1-2*max( min( [-phiDDJ(1), phiDDJ(2)] ), 0 );
%% Display the bit error ratio map, if requested.
if showEye > 0
    figure( showEye-1+ii );
    clf;
    imagesc( phiList, veeList+0.5, log10( berMap ) );
    hold on
    plot( phiList, eyeLid0, '--', 'Color', 'white' );
    plot( phiList, eyeLid1, '--', 'Color', 'white' );
    hold off
    jetColors = jet;
    colormap( jet );
    caxis( [round( log10( erfc( Q0/sqrt( 2 ) )/2 ) ), 0] );
    colorbar;
    set( gca, 'YDir', 'normal' );
    set( gca, 'Color', jetColors(end, :) );
    if dBscale == 10, units = {'W', 'dBo'};
    else, units = {'V', 'dBe'}; end
    tapStr = sprintf( '\nxMA = %.3e %s', MeasuredxMA, units{1} );
    tapStr = [tapStr, sprintf( '\nW = [%.3f', W(1) )];
    for jj = 2:EqNf
        tapStr = [tapStr, sprintf( ', %.3f', W(jj) )];
    end
    tapStr = [tapStr, ']'];
    if EqNb > 0
        tapStr = [tapStr, sprintf( '\nB = [%.3f', B(1) )];
        for jj = 2:EqNb
            tapStr = [tapStr, sprintf( ', %.3f', B(jj) )];
        end
        tapStr = [tapStr, ']'];
    else
        tapStr = [tapStr, sprintf( '\nB = []' )];
    end
    eyeStr = sprintf( 'SNR = %.1f %s\n', dBscale*log10( Q ), units{2} );
    eyeStr = [eyeStr, sprintf( 'xWDP = %.1f %s\n', xWDP, units{2} )];
    eyeStr = [eyeStr, sprintf( 'NC-DDJ = %.3f UI\n', ncDDJ )];
    titleStr = sprintf( '[xWDPJ] %s', usage );
    titleStr = [titleStr, sprintf( '(%d): Bit error ratio map', ii )];
```

```
    text( -0.45, 0.90, tapStr, 'Color', 'white' );
    text( -0.45, 0.10, eyeStr, 'Color', 'white' );
    title( titleStr, 'Interpreter', 'none' );
    ylabel( 'Normalized amplitude' );
    xlabel( 'Time (UI)' );
end
%% End of AnalyzeEye
```

8.3.2 StatEye

[Tom Palkert to supply text.]

8.3.3 Comparison of modeling tools

[Cunningham 08-695v0.]

8.4 Correlation between link spreadsheet and TWDP methods

[Cunningham 09-028v0.]

9. Classes of Equalizers

9.1 Adaptation (training for transmit and receive equalizers)

9.2 Training

9.3 Scrambled data vs. non-scrambled

9.4 Coding: 64b/66b vs. 8b/10b

10.Compliance Test Methodology

10.1 Test Method General Overview

The interoperability points are defined in this document as being immediately after the mated connector. For the delta points this is not an easy measurement point, particularly at high frequencies, as test probes cannot be applied to these points without affecting the signals being measured, and de-embedding the effects of test fixtures is difficult. For delta point measurements reference test points are defined with a set of defined test boards for measurement consistency. The delta point specifications in FC-PI-5 are to be interpreted as being at the SMA outputs and inputs of the reference compliance boards.

In order to provide test results that are reproducible and easily measured, this document defines two test boards that have SMA interfaces for easy connection to test equipment. One is designed for insertion into a host, and one for inserting modules. The reference test boards' objectives are:

- Satisfy the need for interoperabiloity at the electrical level.
- Allow for independent validation of host and module.
- The PCB traces are targeted at 100 Ω differential impedance with nominal 7% differential coupling.

Testing compliance to specifications in a high-speed system is delicate and requires thorough consideration. Using common test boards that allow predictable, repeatable, and consistent results among vendors will help to ensure consistency and true compliance in the testing.

The reference test boards provide a set of overlapping measurements for module and host validation to ensure system interoperability.

10.2 Test Point Definitions

10.2.1 Host test points

Host system transmitter and receiver compliance are defined by tests in which a Host Compliance Board is inserted as shown in figure 10.1 in place of the module. Test card construction should be such that it meets the requirements specified in xx ***[reference? Where does annex G.4 go in MSQS?]***. The test points are B and C.

Host compliance points are defined as the following:

- B: host output at the output of the Host Compliance Board. Delta T output and host return loss specifications shall be met at this point.

- C: host input at the input of the Host Compliance Board. Delta R host return loss specifications shall be met at this point.

[Insert Figure G.1 from FC-PI-4 here.]
Figure 10.1 – Host Compliance Board

10.2.2 Module Test Points

Module transmitter and receiver compliance are defined by tests in which the module is inserted into the Module Compliance Board as shown in figure 10.2. Test card construction should be such that it meets the requirements specified by xx ***[Reference? Where does annex G.5 go in MSQS?]***. For improved measurement accuracy the reference test card responses may be calibrated out of the measurements and replaced with functions that represent the ideal responses defined in xx for the reference test cards.

[Insert Figure G.2 from FC-PI-4 here.]
Figure 10.2 – Module Compliance Board

Module test points are defined as the following:

- B': module transmitter input at the input of the Module Compliance Board. Delta T module return loss specifications shall be met at this point.
- C': SFP+ module receiver output at the output of the Module Compliance Board. Delta R output and module return loss specifications shall be met at this point.

10.2.3 Module Input Calibration Points

The module transmitter input tolerance signal is calibrated through the Module Compliance Board at the output of the Host Compliance Board as shown in figure 10.3. The opposite data path is excited with an asynchronous test source with the JSPAT signal. The module input calibration point is at B'' with specifications for input signals at Delta T being calibrated at B''. Note that point B'' has additional trace loss beyond the module pins.

[Insert Figure G.3 from FC-PI-4 here.]
Figure 10.3 – Module input calibration point B''

10.2.4 Host Input Calibration Point

The host receiver input tolerance signal is calibrated through the Host Compliance Board at the output of the Module Compliance Board as shown in figure 10.4. The host input calibration point is at C'' with specifications for input signals at Delta R being calibrated at C''. Note that the point C'' has additional trace loss beyond the SFF-8083 connector pins.

[Insert Figure G.4 from FC-PI-4 here.]

Figure 10.4 – Host input calibration point C''

11.Test Patterns

11.1 Test bit sequence characteristics

11.1.1 Introduction

Test bit sequences are the bit sequences that are transmitted by a serializer onto a link or bit sequences received by a deserializer from the link used to test an FC link's jitter compliance. Test bit sequences have a significant impact on stressing the link's jitter characteristics.

Several examples of test bit sequences are described in this annex to illustrate how bit sequences stress different aspects of a CDR circuit:

Continuous stream of idle primitives: This pattern is present during normal link operation when no frames are being transmitted. This primitive is also part of some of the more complex patterns listed below.

Low frequency pattern: This pattern contains bit sequences that generates low frequency spectral components that may produce severe signal distortion if the 3 dB low frequency cut-off of any high pass filter or component is not chosen correctly. Because it represents nearly the maximum signal bandwidth required for any pattern, it is suspected of suffering the most from signal distortion on a metallic transmission line. (This second point remains to be proven by simulations or experiments).

Low transition density patterns: These patterns contain bit sequences that have long runs of 1s or 0s.

High transition density patterns: These patterns contain bit sequences that have short runs of 1s and 0s.

Composite patterns: A composite pattern contains combinations of the above three types of patterns.

Low and high transition density patterns are meant to generate pattern dependent timing jitter from line distortions. Composite patterns tend to be patterns that test various components on the link, such as, the receiver clock recovery circuits.

11.1.2 Low frequency pattern

Low frequencies in the spectrum may be generated by following the outer contours of the trellis diagram of Figure 10.5 that represents the disparity versus time for the Fibre Channel 8B/10B code.

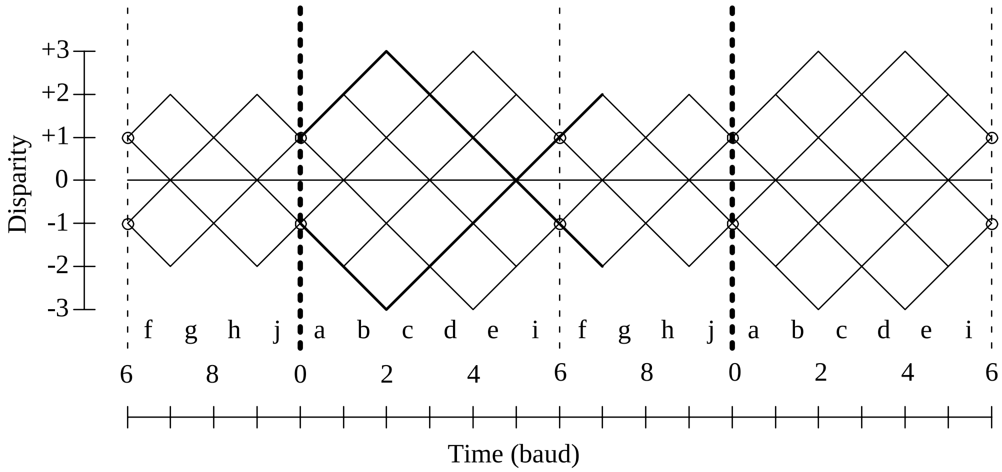


Figure 10.5 – 8B/10B code trellis diagram

Starting at a byte boundary with a running disparity of +1, the pattern '1101001010' (D11.5) follows the upper contour and encloses the maximum area between the zero disparity line and the upper envelope of all possible patterns. D11.5 is repeated for n bytes, where n is 12 or greater. Then a rapid transition is made to the lower envelope by the pattern '1101001000' (D11.7). Then the pattern '0010110101' (D20.2) follows the lower contour and is also repeated n times. The transition back to the upper contour is accomplished by the pattern '0010110111' (D20.7), followed by 2 bytes of D11.5. This sequence includes a run of 5 zeros followed by a single 1, and a run of 5 ones followed by a single 0. These 2 sequences are usually most prone to errors. The larger the value of n, the lower the frequencies generated. The worst case is approached asymptotically with increasing n.

Simulations with this kind of pattern, passing through a single pole high pass filter may cause amplitude and time penalties. Table 10.1 shows these penalties with the parameter n at 12 and the 3 dB cutoff at a frequency ‘f’ expressed as a fraction of the baud ‘fo.’ The eye closure penalty expresses the amplitude penalty in dB and in the time domain penalty as a fraction of a baud (UI). The simulation model includes also a low pass filter as specified for FC optical measurements with a cut-off at 0.75 of the baud.

Table 10.1 – Eye closure penalties for low frequency pattern with n=12

3dB Cut-off (f/fo)	Amplitude Penalty (dB)	Time Penalty (UI)
0.0001	0.02	

0.0002	0.03	
0.0005	0.08	0.015
0.0010	0.18	0.025
0.0025	0.53	0.04
0.005	1.12	0.06
0.01	2.15	0.1
0.02	4.10	0.175
0.04	8.13	0.23
0.05	10.1	0.275

For example, for a signaling rate of 1063 MBaud, a 3dB cutoff of 1.06 Mhz is approximately 0.001 (f/fo).

Patterns with n=100 and using the special character K28.5 for the transitions between the upper and lower contours have produced additional eye penalties from 0.05 dB for the lower values of f/fo up to 0.4 dB for the larger values.

From the above it is clear, that the recommendation for the lower 3dB cut-off at 0.04 of the baud as specified in the Table F.6 of Appendix F of the Fibre Channel (FC-PH) is misleading and would require extensive signal conditioning.

Table 10.2 shows the low frequency pattern as described above. As with all similar tables in this annex, the table is broken up into four representations of the pattern that include the FC characters (with the 8b hex values), encoded 10b hex, binary, and 40b hex word. The first row contains the FC characters used and defined in clause 11 of FC-PH. The second row contains the encoded 10b hex values for each character. These 10b values are in little endian format. They may be used when looking at the encoded/decoded parallel data. The third row contains the transmission in-order binary data. The fourth row contains the 40b hex version of the binary data. Both the third and fourth rows may be used to program pattern generators. As for running disparity, the value is indicated at the beginning and end of each word.

Table 10.2 – Low frequency pattern

+	D11.5 (ab)		D11.5 (ab)			D11.5 (ab)		D11.5 (ab)			+
	14b		14b			14b		14b			
	1101	0010	1011	0100	1010	1101	0010	1011	0100	1010	
	d	2	b	4	a	d	2	b	4	a	
	Byte = D11.5 is repeated > 12 times.										
+	D11.7(eb)		D20.2 (54)			D20.2 (54)		D20.2 (54)			-
	04b		2b4			2b4		2b4			
	1101	0010	0000	1011	0101	0010	1101	0100	1011	0101	
	d	2	0	b	5	2	d	4	b	5	
	Byte = D20.2 is repeated > 12 times.										
-	D20.2 (54)		D20.7 (f4)			D11.5 (ab)		D11.5 (ab)			+
	2b4		3b4			14b		14b			
	0010	1101	0100	1011	0111	1101	0010	1011	0100	1010	
	2	d	4	b	7	d	2	b	4	a	

11.1.3 Low transition density patterns

Overview

The code with the restrictions imposed by the FC standard cannot generate contiguous runs of 5 bits with the same value. For data characters, a maximum of 5 contiguous runs of 4 are possible, starting with bit ‘g’ of a coded byte. For positive starting disparity, the sequence is generated by (D14.7, D30.7, D7.6) and ends with negative disparity. For reverse polarities the sequence is (D17.7, D30.7, D7.1). It is recommended to include both versions.

The lowest transition density that may be maintained indefinitely is 3 per byte starting with the bit ‘b’ or ‘i’ with run lengths of 433433433... The data pattern for the run of 4 starting with bit ‘b’ is (m x D30.3), for either starting polarity, where m may be any integer number of 2 or greater. For the run of 4 to start with bit ‘i’, the pattern is generated by (D28.7, D3.7) when starting with positive disparity, and by (D3.7, D28.7) when starting with negative disparity.

To just measure jitter and amplitude distortion from this source, a short sequence should be sufficient. A suitable test pattern for both of these patterns is (D14.7, D30.7, D7.1, m x D30.3). Table 10.3 shows this pattern.

Table 10.3 – Low transition density pattern

<table>
<tr><td rowspan="4">+</td><td colspan="5">D14.7 (ee)</td><td colspan="5">D30.7 (fe)</td><td colspan="5">D7.6 (c7)</td><td colspan="5">D17.7 (f1)</td><td rowspan="4">+</td></tr>
<tr><td colspan="5">04e</td><td colspan="5">21e</td><td colspan="5">187</td><td colspan="5">3b1</td></tr>
<tr><td colspan="2">0111</td><td colspan="2">0010</td><td colspan="2">0001</td><td colspan="2">1110</td><td colspan="2">0001</td><td colspan="2">1110</td><td colspan="2">0001</td><td colspan="2">1010</td><td colspan="2">0011</td><td colspan="2">0111</td></tr>
<tr><td colspan="2">7</td><td colspan="2">2</td><td colspan="2">1</td><td colspan="2">e</td><td colspan="2">1</td><td colspan="2">e</td><td colspan="2">1</td><td colspan="2">a</td><td colspan="2">3</td><td colspan="2">7</td></tr>
<tr><td></td><td colspan="20"></td><td></td></tr>
<tr><td rowspan="4">+</td><td colspan="5">D30.7 (fe)</td><td colspan="5">D7.1 (27)</td><td colspan="5">D30.3 (7e)</td><td colspan="5">D30.3 (7e)</td><td rowspan="4">+</td></tr>
<tr><td colspan="5">1e1</td><td colspan="5">278</td><td colspan="5">0e1</td><td colspan="5">31e</td></tr>
<tr><td colspan="2">1000</td><td colspan="2">0111</td><td colspan="2">1000</td><td colspan="2">0111</td><td colspan="2">1001</td><td colspan="2">1000</td><td colspan="2">0111</td><td colspan="2">0001</td><td colspan="2">1110</td><td colspan="2">0011</td></tr>
<tr><td colspan="2">8</td><td colspan="2">7</td><td colspan="2">8</td><td colspan="2">7</td><td colspan="2">9</td><td colspan="2">8</td><td colspan="2">7</td><td colspan="2">1</td><td colspan="2">e</td><td colspan="2">3</td></tr>
<tr><td></td><td colspan="20"></td><td></td></tr>
<tr><td rowspan="4">+</td><td colspan="5">D30.3 (7e)</td><td colspan="5">D30.3 (7e)</td><td colspan="5">D30.3 (7e)</td><td colspan="5">D30.3 (7e)</td><td rowspan="4">+</td></tr>
<tr><td colspan="5">0e1</td><td colspan="5">31e</td><td colspan="5">0e1</td><td colspan="5">31e</td></tr>
<tr><td colspan="2">1000</td><td colspan="2">0111</td><td colspan="2">0001</td><td colspan="2">1110</td><td colspan="2">0011</td><td colspan="2">1000</td><td colspan="2">0111</td><td colspan="2">0001</td><td colspan="2">1110</td><td colspan="2">0011</td></tr>
<tr><td colspan="2">8</td><td colspan="2">7</td><td colspan="2">1</td><td colspan="2">e</td><td colspan="2">3</td><td colspan="2">8</td><td colspan="2">7</td><td colspan="2">1</td><td colspan="2">e</td><td colspan="2">3</td></tr>
<tr><td></td><td colspan="20">Byte = D30.3 is repeated > 2 times.</td><td></td></tr>
<tr><td rowspan="2">+</td><td colspan="5">D28.7 (fc)</td><td colspan="5">D3.7 (e3)</td><td colspan="5">D28.7 (fc)</td><td colspan="5">D3.7 (e3)</td><td rowspan="2">-</td></tr>
<tr><td colspan="5">21c</td><td colspan="5">1e3</td><td colspan="5">21c</td><td colspan="5">1e3</td></tr>
</table>

	0011	1000	0111	0001	1110	0011	1000	0111	0001	1110	
	3	8	7	1	e	3	8	7	1	e	

Half-rate and quarter-rate square patterns

The half rate square pattern (contiguous runs of 1010 ...) may be generated by (q x D21.5) that starts with a one, or by (q x D10.2) that starts with a zero.

Sequences using D21.5 followed by some slower pattern such as the quarter-rate square wave and then followed by a sequence of D10.2 and then again by a low transition pattern should be used to test circuit asymmetries.

For the quarter rate square pattern contiguous runs of two ones (00110011...) in phase with the byte boundaries may be generated by (p x D24.3), independent of the starting disparity. If p is an even number, the starting and ending disparity remain unchanged. The sequence [q x (D25.6, D6.1)], or [q x (D6.1, D25.6)] generate identical waveforms with a phase shift of 1 baud interval, also independent of the starting disparity. D6.1 starts with a single zero bit and D25.6 starts with a single one bit.

Table 10.4 contains both the half-rate and quarter-rate patterns.

Table 10.4 – Half-rate and quarter-rate patterns - see text

	D21.5 (b5)		D21.5 (b5)			D21.5 (b5)		D21.5 (b5)			
	155		155			155		155			
+	1010	1010	1010	1010	1010	1010	1010	1010	1010	1010	+
	a	a	a	a	a	a	a	a	a	a	
	Byte = D21.5 is repeated q times.										
	D24.3 (78)		D24.3 (78)			D24.3 (78)		D24.3 (78)			
	0cc		333			0cc		333			
+	0011	0011	0011	0011	0011	0011	0011	0011	0011	0011	+
	3	3	3	3	3	3	3	3	3	3	

Byte = D24.3 is repeated q times.									
D10.2 (4a)		**D10.2 (4a)**		**D10.2 (4a)**		**D10.2 (4a)**			
2aa		**2aa**		**2aa**		**2aa**			
0101	**0101**	**0101**	**0101**	**0101**	**0101**	**0101**	**0101**	**0101**	**0101**
5	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**
Byte = D10.2 is repeated q times.									
D25.6 (d9)		**D6.1 (26)**		**D25.6 (d9)**		**D6.1 (26)**			
199		**266**		**199**		**266**			
1001	**1001**	**1001**	**1001**	**1001**	**1001**	**1001**	**1001**	**1001**	**1001**
9	**9**	**9**	**9**	**9**	**9**	**9**	**9**	**9**	**9**
Byte = D25.6, D6.1 is repeated q times.									
D6.1 (26)		**D25.6 (d9)**		**D6.1 (26)**		**D25.6 (d9)**			
266		**199**		**266**		**199**			
0110	**0110**	**0110**	**0110**	**0110**	**0110**	**0110**	**0110**	**0110**	**0110**
6	**6**	**6**	**6**	**6**	**6**	**6**	**6**	**6**	**6**
Byte = D6.1, D25.6 is repeated q times.									

Ten contiguous runs of 3

Starting and ending with a positive disparity, the data pattern (D14.7, D7.7, D28.3, D17.1) generates ten contiguous runs of 3 starting in bit ‘g’ of the first byte. Similarly, the pattern (D17.7, D7.7, D3.3, D14.6), starting and ending with negative disparity also generates 10 contiguous runs of 3. Both sequences may be repeated as many times as desired.

Table 10.5 – Ten runs of 3 assuming positive disparity

<table>
<tr><td rowspan="4">+</td><td colspan="5">D14.7 (ee)</td><td colspan="5">D7.7 (e7)</td><td colspan="5">D28.3 (7c)</td><td colspan="5">D17.1 (31)</td><td rowspan="4">+</td></tr>
<tr><td colspan="5">04e</td><td colspan="5">1c7</td><td colspan="5">31c</td><td colspan="5">271</td></tr>
<tr><td colspan="2">0001</td><td colspan="2">0010</td><td colspan="2">0011</td><td colspan="2">1000</td><td colspan="2">1110</td><td colspan="2">0011</td><td colspan="2">1000</td><td colspan="2">1110</td><td colspan="2">0011</td><td colspan="2">1001</td></tr>
<tr><td colspan="2">7</td><td colspan="2">2</td><td colspan="2">c</td><td colspan="2">8</td><td colspan="2">e</td><td colspan="2">3</td><td colspan="2">8</td><td colspan="2">e</td><td colspan="2">3</td><td colspan="2">9</td></tr>
<tr><td></td><td colspan="20">Repeated q times.</td><td></td></tr>
</table>

-or-

Table 10.6 – Ten runs of 3 assuming negative disparity

<table>
<tr><td rowspan="4">-</td><td colspan="5">D17.7 (f1)</td><td colspan="5">D7.7 (e7)</td><td colspan="5">D3.3 (63)</td><td colspan="5">D14.6 (ce)</td><td rowspan="4">-</td></tr>
<tr><td colspan="5">3b1</td><td colspan="5">238</td><td colspan="5">0e3</td><td colspan="5">18e</td></tr>
<tr><td colspan="2">1000</td><td colspan="2">1101</td><td colspan="2">1100</td><td colspan="2">0111</td><td colspan="2">0001</td><td colspan="2">1100</td><td colspan="2">0111</td><td colspan="2">0001</td><td colspan="2">1100</td><td colspan="2">0110</td></tr>
<tr><td colspan="2">8</td><td colspan="2">d</td><td colspan="2">c</td><td colspan="2">7</td><td colspan="2">1</td><td colspan="2">c</td><td colspan="2">7</td><td colspan="2">1</td><td colspan="2">c</td><td colspan="2">6</td></tr>
<tr><td></td><td colspan="20">Repeated q times.</td><td></td></tr>
</table>

11.1.4 Composite patterns

For the measurement of jitter at various points of the link, patterns should combine low frequency, low transition density and high transition density patterns. All but the low frequency pattern may be kept short for measurements of the jitter. The low frequency pattern needs to be longer so that lower frequency jitter is included. By including all of the patterns, the resulting composite pattern stresses components within the link with low and high frequency jitter, asymmetrics, amplitude distortions, and low and high transition densities. Moreover, composite patterns should be used for specification compliance testing. Examples of composite patterns are discussed in subsequent sub clauses within this annex.

11.2 Compliant jitter test bit sequences

11.2.1 Introduction

The test methods specified in the FC-PH standard consist of using K28.5 and K28.7 sequences for DJ and RJ respectively. The K28.5 test sequence consists of the highest frequency and lowest frequency components (run length of 5 and run length of 1) in a concise 20 bit sequence if both disparities are used. The K28.7 has no data dependent components and is in essence a square wave with frequency of one tenth the Baud rate.

In addition to the test sequences already defined in the FC-PH standard, the following test bit sequences are defined for both jitter output and tolerance testing:

RPAT Random data pattern - sub clause Original RPAT

CRPAT Compliant random data pattern in a valid FC frame - sub clause Compliant RPAT (CRPAT)

JTPATJitter tolerance test pattern - sub clause

Receive jitter tolerance pattern - JTPAT

CJTPAT Compliant jitter tolerance pattern in a valid FC frame - sub clause Compliant receive jitter tolerance pattern - CJTPAT

SPAT Supply noise test sequence for maximum SSO noise for transceivers - sub clause Supply noise pattern - SPAT

CSPAT Supply noise test sequence in a valid FC frame - sub clause Compliant supply noise pattern - CSPAT

In their respective sub clauses, the original rationale for their application are given. However, for compliance testing of a particular device, the pattern(s) that produce(s) the worse case output or tolerance results shall be used. **Determining the pattern that produces the worst results is done only by experimentation.**

11.2.2 Random test bit sequence

Overview

The intent of the random test pattern is to provide a data pattern with broad spectral content and minimal peaking that may be used for component and system level (FC-AL type) architectures for the measurement of jitter output. The development of this pattern is specific to FC Tx jitter testing and provides both component and system vendors a common data pattern use when performing Tx jitter measurements. A flat spectral content pattern is used to insure that any peaking seen during Tx jitter testing may be attributed to the component and not the spectral content of the data.

Given the broad (white) spectral content of the RPAT test pattern, this may also be used as an industry standard for EMI testing bounded by IDLEs or ARBs. However, be aware that RPAT may not be an appropriate pattern for EMI agency compliance. The equipment supplier is responsible for determining the testing for all reasonably likely patterns, configurations, and conditions. For example, FC traffic frequently consists of sustained runs of IDLEs, that typically may be much more challenging for EMI agency compliance.

Background - Fibre Channel frame

For test bit sequences to be carried on active FC links the test bit sequences need to be embedded into the constructs of link traffic. These constructs include fill words and FC frames (see Fibre Channel frame). Between frames, a FC link is filled with primitive sequences such as IDLEs, R_RDYs, ARBs, etc. as required by the Fibre Channel protocol. At the N Port transmitter, Fibre Channel requires a minimum of six primitive sequences between frames.

Table A.7 - Fibre Channel frame

Name	SOF	Header	Payload	CRC	EOF
Bytes	4	24	0 to 2112	4	4

There are eight different SOF delimiter functions; all assume negative disparity; two are used for Class 3. The SOFi3 would only be used once when sending data and all subsequent SOF's are SOFn3. There are six EOF delimiter functions of either positive or negative disparity. The disparity of the EOF is determined by the value of the CRC. The CRC is determined by the contents of the header and payload. Valid SOF's and EOF's used with patterns in this annex are shown in Valid fibre channel frame delimiters

.

Table A.8 - Valid fibre channel frame delimiters

Delimiter& Function	Beginning Disparity	Ordered Set
SOFn3	Negative	K28.5 D21.5 D22.1 D22.1
EOFn	Negative	K28.5 D21.4 D21.6 D21.6
EOFn	Positive	K28.5 D21.5 D21.6 D21.6

Original RPAT

The original RPAT data pattern is designed specifically to provide a broad/flat frequency spectrum. RPAT's data codes are valid 8b/10b codes but are not FC compliant as a data payload due to character placement and disparity conflicts. The "10b" code represents the 10b encoded data bytes. The "10b hex" is the hex representation of the 10b encoded data. The RPAT pattern assumes negative running disparity.

8b: BC, BC, 23, 47, 6B, 8F, B3, D7, FB, 14, 36, 59

10b: k28.5, k28.5, D3.1, D7.2, D11.3, D15.4, D19.5, D23.6, D27.7, D20.0, D22.1, D25.2

10b hex: 3EB0 5C67 85D3 172C A856 D84B B6A6 65

Note: the next to last character in the 10b definition has been changed from D21.1 in MJS to D22.1 in MJSQ to be consistent with the code mappings for 8b and 10b hex.

Compliant RPAT (CRPAT)

Since most host adapters include Fibre Channel state machines, they cannot be made to transmit the original RPAT. What is needed to use a host adapter is a test bit sequence that complies with all Fibre Channel rules, specifically the frame construct. To generate an FC compliant RPAT (CRPAT) while attempting to maintain the flat spectrum characteristics of the original RPAT data pattern, some modifications are required. Modifications to the original RPAT include:

Removal of two consecutive K28.5 codes at the beginning of RPAT
Replacing K28.5s with D30.2 and D30.5
Re-arrangement of the data codes required to maintain disparity balance.

The modified RPAT is:

8b: BE, D7, 23, 47, 6B, 8F, B3, 14, 5E, FB, 35, 59

10b: D30.5, D23.6, D3.1, D7.2, D11.3, D15.4, D19.5, D20.0, D30.2, D27.7, D21.1, D25.2

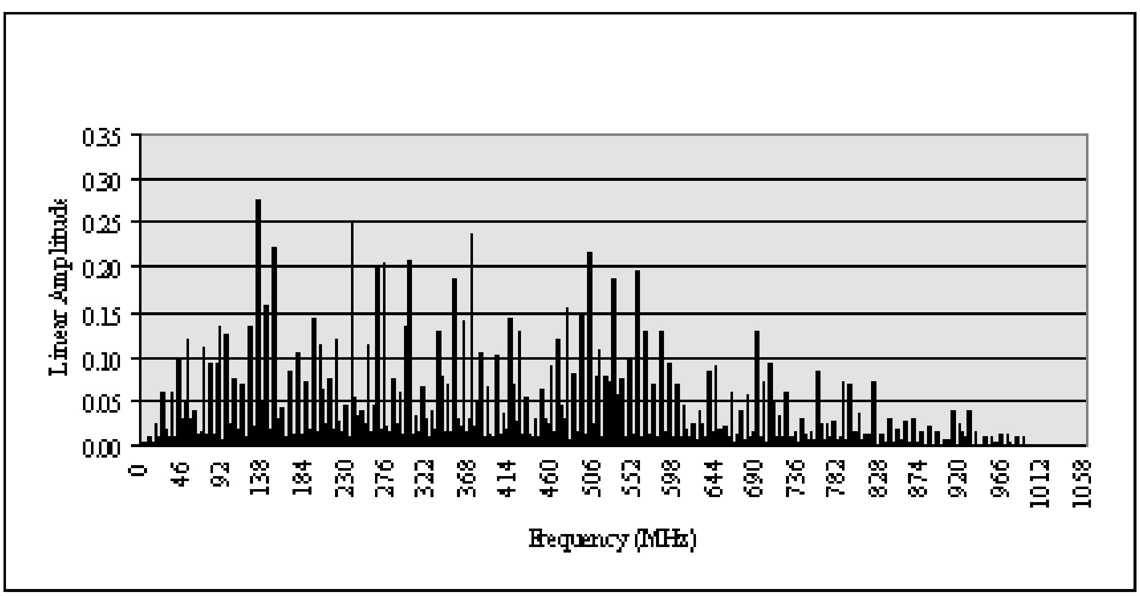
10b hex: 86BA, 6C64, 75D0, E8DC, A8B4, 7949, EAA6, 65

This is shown in the RPAT section of CRPAT test bit sequence .

The header for this purpose may be considered the same as the payload since all that is desired is that the host adapter transmit the data or the disk drive re-transmit the data. The payload consists of the modified RPAT repeated 16 times. Each frame is preceded or followed by six idle primitives.

The CRPAT pattern is specifically designed to have a broad spectrum that produces a worst case scenario with regard to deterministic jitter generation. By embedding the payload with 16 repeating modified RPAT's, the spectral contribution of the SOF, CRC, EOF, and idle primitives may be minimized.

Figure A.2 - The FFT, in FFT of original RPAT



, is for the 10b hex data as a pure 1s and 0s data stream. FFT of compliant RPAT is the FFT of the FC compliant RPAT (including the idles and SOF). The spectral content is fairly broad and flat, much like the original RPAT. Moreover, the spectrum analysis of both the original RPAT and the FC Compliant RPAT are almost equivalent. The FC compliant RPAT patterns shows some peaking near 100 MHz, but this should be insignificant.

Rise times are not accounted for and assumed perfect.

For overall jitter tolerance testing both the CJTPAT and the above CRPAT should be used.

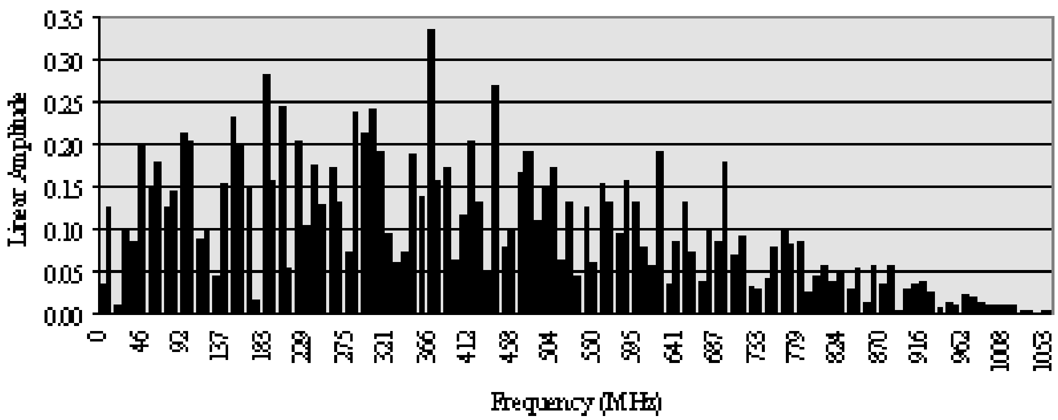


Figure A.2 - FFT of original RPAT

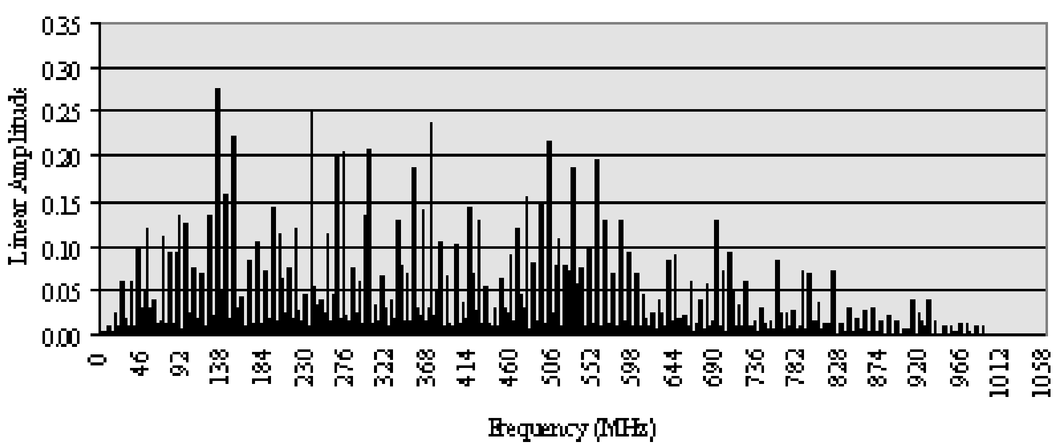


Figure A.3 - FFT of compliant RPAT

The pattern in CRPAT test bit sequence represents the CRPAT. It consists of six idle primitives, an SOF, the RPAT pattern repeated 16 times, a CRC, and a EOF. A repeating CRPAT may be used at all levels of development including system and component design.

Table A.9 - CRPAT test bit sequence

<table>
<tr><td rowspan="4">-</td><td colspan="5">K28.5 (bc)</td><td colspan="5">D21.4 (95)</td><td colspan="5">D21.5 (b5)</td><td colspan="5">D21.5 (b5)</td><td rowspan="4">-</td><td rowspan="4">Idle Primitive (repeated 6 times)</td></tr>
<tr><td colspan="5">17c</td><td colspan="5">115</td><td colspan="5">155</td><td colspan="5">155</td></tr>
<tr><td colspan="2">0011</td><td colspan="2">1110</td><td colspan="2">1010</td><td colspan="2">1010</td><td colspan="2">0010</td><td colspan="2">1010</td><td colspan="2">1010</td><td colspan="2">1010</td><td colspan="2">1010</td><td colspan="2">1010</td></tr>
<tr><td colspan="2">3</td><td colspan="2">e</td><td colspan="2">a</td><td colspan="2">a</td><td colspan="2">2</td><td colspan="2">a</td><td colspan="2">a</td><td colspan="2">a</td><td colspan="2">a</td><td colspan="2">a</td></tr>
<tr><td></td><td colspan="20">Above Idle Primitive is repeated 6 times.</td><td></td><td></td></tr>
<tr><td rowspan="4">-</td><td colspan="5">K28.5 (bc)</td><td colspan="5">D21.5 (b5)</td><td colspan="5">D22.1 (36)</td><td colspan="5">D22.1 (36)</td><td rowspan="4">+</td><td rowspan="4">Start of Frame: Class 3 normal (SOFn3)</td></tr>
<tr><td colspan="5">17c</td><td colspan="5">155</td><td colspan="5">256</td><td colspan="5">256</td></tr>
<tr><td colspan="2">0011</td><td colspan="2">1110</td><td colspan="2">1010</td><td colspan="2">1010</td><td colspan="2">1010</td><td colspan="2">0110</td><td colspan="2">1010</td><td colspan="2">0101</td><td colspan="2">1010</td><td colspan="2">1001</td></tr>
<tr><td colspan="2">3</td><td colspan="2">e</td><td colspan="2">a</td><td colspan="2">a</td><td colspan="2">a</td><td colspan="2">6</td><td colspan="2">a</td><td colspan="2">5</td><td colspan="2">a</td><td colspan="2">9</td></tr>
<tr><td></td><td colspan="20"></td><td></td><td></td></tr>
<tr><td rowspan="4">+</td><td colspan="5">D30.5 (be)</td><td colspan="5">D23.6 (d7)</td><td colspan="5">D3.1 (23)</td><td colspan="5">D7.2 (47)</td><td rowspan="4">+</td><td rowspan="5"></td></tr>
<tr><td colspan="5">161</td><td colspan="5">197</td><td colspan="5">263</td><td colspan="5">2b8</td></tr>
<tr><td colspan="2">1000</td><td colspan="2">0110</td><td colspan="2">1011</td><td colspan="2">1010</td><td colspan="2">0110</td><td colspan="2">1100</td><td colspan="2">0110</td><td colspan="2">0100</td><td colspan="2">0111</td><td colspan="2">0101</td></tr>
<tr><td colspan="2">8</td><td colspan="2">6</td><td colspan="2">b</td><td colspan="2">a</td><td colspan="2">6</td><td colspan="2">c</td><td colspan="2">6</td><td colspan="2">4</td><td colspan="2">7</td><td colspan="2">5</td></tr>
<tr><td></td><td colspan="20"></td><td></td></tr>
</table>

	D11.3 (6b)		D15.4 (8f)			D19.5 (b3)		D20.0 (14)				modified RPAT pattern (repeated 16 times)
	30b		2c5			153		0b4				
+	1101	0000	1110	1000	1101	1100	1010	1000	1011	0100	–	
	d	0	e	8	d	c	a	8	b	4		
	D30.2 (5e)		D27.7 (fb)			D21.1 (35)		D25.2 (59)				
	29e		1e4			255		299				
-	0111	1001	0100	1001	1110	1010	1010	0110	0110	0101	+	
	7	9	4	9	e	a	a	6	6	5		
	Above 12 byte modified RPAT pattern is repeated 16 times.											
	D14.7 (ee)		D3.1 (23)			D21.2 (55)		D22.0 (16)				CRC:
	04e		263			295		356				
+	0111	0010	0011	0001	1001	1010	1001	0101	1010	1011	+	
	7	2	3	1	9	a	9	5	a	b		
	K28.5 (bc)		D21.5 (b5)			D21.6 (d5)		D21.6 (d5)				End of Frame: (EOFn)
	283		155			195		195				
+	1100	0001	0110	1010	1010	1010	1001	1010	1010	0110	–	
	c	1	6	a	a	a	9	a	a	6		

11.2.3 Compliant receive jitter test bit sequences

Overview

For jitter tolerance testing, the data pattern exposes a receiver's CDR to large instantaneous phase jumps. To do this, the overall pattern should alternate repeating low transition density patterns with repeating high transition density patterns. The repeating 10b character durations should be longer than the time constants in the receiver clock recovery circuit. This assures that the clock phase has followed the systematic pattern jitter and the data sampling circuitry is exposed to large systematic phase jumps. This stresses the timing margins in the received eye. The following test bit sequences are suggested for receive jitter tolerance testing:

JTPATJitter tolerance pattern used to test receivers

CJTPATJitter tolerance pattern in a valid FC frame

Receive jitter tolerance pattern - JTPAT

JTPAT shows how low and high density patterns may be used. Here, the low density pattern is a repeating D30.3 and the high density pattern is a repeating D21.5. Using these two patterns together tests the systematic pattern jitter causing phase jumps. The run length of these two patterns are related to the time constants of the PLL. For the JTPAT the following assumptions were made:

a) Average FC traffic transition density is approximately 50%.
b) CDR time constant is inversely proportional to transition density.
c) To obtain at least 95% settling a pattern duration needs to be greater than 3 time constants.
d) The PLL's minimum bandwidth for FC transceivers is Baud/1667 @ the average transition density.

100 10 bit characters at 50% transition density meets these assumptions. The repeating D21.5 has a 100% transition density and the repeating 30.3 has a 30% transition density. Because of the above assumptions, the duration of the high transition density pattern needs to be at least 50 10 bit characters. As for the low transition density pattern, it needs to be at least 167 10 bit characters.

Table A.10 - JTPAT

<table>
<tr><td rowspan="4">-</td><td colspan="5">D30.3 (7e)</td><td colspan="5">D30.3 (7e)</td><td colspan="5">D30.3 (7e)</td><td colspan="5">D30.3 (7e)</td><td rowspan="4">-</td></tr>
<tr><td colspan="5">0e1</td><td colspan="5">31e</td><td colspan="5">0e1</td><td colspan="5">31e</td></tr>
<tr><td colspan="2">1000</td><td colspan="2">0111</td><td colspan="2">0001</td><td colspan="2">1110</td><td colspan="2">0011</td><td colspan="2">1000</td><td colspan="2">0111</td><td colspan="2">0001</td><td colspan="2">1110</td><td colspan="2">0011</td></tr>
<tr><td colspan="2">8</td><td colspan="2">7</td><td colspan="2">1</td><td colspan="2">e</td><td colspan="2">3</td><td colspan="2">8</td><td colspan="2">7</td><td colspan="2">1</td><td colspan="2">e</td><td colspan="2">3</td></tr>
<tr><td></td><td colspan="20">Byte = D30.3 is repeated > 167 times.</td><td></td></tr>
<tr><td>-</td><td colspan="5">D21.5 (b5)</td><td colspan="5">D21.5 (b5)</td><td colspan="5">D21.5 (b5)</td><td colspan="5">D21.5 (b5)</td><td>-</td></tr>
</table>

155		**155**			**155**		**155**		
1010	**1010**	**1010**	**1010**	**1010**	**1010**	**1010**	**1010**	**1010**	**1010**
a	**a**	**a**	**a**	**a**	**a**	**a**	**a**	**a**	**a**
Byte = D21.5 is repeated > 50 times.									

Compliant receive jitter tolerance pattern - CJTPAT

Creating a compliant receive jitter tolerance pattern (CJTPAT) requires adding SOF, CRC, EOF and Idles. In order to use the above JTPAT more fully, each of the possible phase shifts introduced has two polarity versions. That is, a phase change may start with a 0 and transition to a 1 or vise versa. Additional characters have been added to produce both polarity changes for each phase shift. CJTPAT shows the resulting CJTPAT. For overall jitter tolerance testing both the CJTPAT and the above CRPAT should be used.

Table A.11 - CJTPAT

	K28.5 (bc)		**D21.4 (95)**			**D21.5 (b5)**		**D21.5 (b5)**				
	17c		**115**			**155**		**155**				
-	**0011**	**1110**	**1010**	**1010**	**0010**	**1010**	**1010**	**1010**	**1010**	**1010**	-	Idle primitive (repeated 6 times)
	3	**e**	**a**	**a**	**2**	**a**	**a**	**a**	**a**	**a**		
	Above Idle Primitive is repeated 6 times.											
	K28.5 (bc)		**D21.5 (b5)**			**D22.1 (36)**		**D22.1 (36)**				
	17c		**155**			**256**		**256**				
-	**0011**	**1110**	**1010**	**1010**	**1010**	**0110**	**1010**	**0101**	**1010**	**1001**	+	SOFn3
	3	**e**	**a**	**a**	**a**	**6**	**a**	**5**	**a**	**9**		

Low density transition pattern

+

D30.3 (7e)	D30.3 (7e)	D30.3 (7e)	D30.3 (7e)
0e1	31e	0e1	31e

1000	0111	0001	1110	0011	1000	0111	0001	1110	0011
8	7	1	e	3	8	7	1	e	3

Above 4 byte pattern is repeated 41 times.

Transferring from low to high transition densities

+

D30.3 (7e)	D30.3 (7e)	D30.3 (7e)	D20.3 (74)
0e1	31e	0e1	0f4

1000	0111	0001	1110	0011	1000	0111	0000	1011	1100
8	7	1	e	3	8	7	0	b	c

- (start) / + (end)

D30.3 (7e)	D11.5 (ab)	D21.5 (b5)	D21.5 (b5)
31e	14b	155	155

0111	1000	1111	0100	1010	1010	1010	1010	1010	1010
7	8	f	4	a	a	a	a	a	a

High density transition pattern

+ (start) / + (end)

D21.5 (b5)	D21.5 (b5)	D21.5 (b5)	D21.5 (b5)
155	155	155	155

1010	1010	1010	1010	1010	1010	1010	1010	1010	1010
a	a	a	a	a	a	a	a	a	a

Above 4 byte pattern is repeated 12 times

Transferring from high to low transition densities

Running disparity: + (start) / + (end)

D21.5 (b5)	D30.2 (5e)	D10.2 (4a)	D30.3 (7e)
155	2a1	2aa	31e

1010	1010	1010	0001	0101	0101	0101	0101	1110	0011
a	a	a	1	5	5	5	5	e	3

Running disparity: + (start) / - (end)

D30.3 (7e)	D30.3 (7e)	D30.3 (7e)	D30.7 (fe)
0e1	31e	0e1	21e

1000	0111	0001	1110	0011	1000	0111	0001	1110	0001
8	7	1	e	3	8	7	1	e	1

CRC

Running disparity: - (start) / + (end)

D21.7 (f5)	D14.1 (2e)	D22.7 (f6)	D29.6 (dd)
1d5	24e	216	19d

1010	1011	1001	1100	1001	0110	1000	0110	1110	0110
a	b	9	c	9	6	8	6	e	6

EOFn

Running disparity: + (start) / - (end)

k28.5 (bc)	D21.5 (b5)	D21.6 (d5)	D21.6 (d5)
283	155	195	195

1100	0001	0110	1010	1010	1010	1001	1010	1010	0110
c	1	6	a	a	a	9	a	a	6

11.2.4 Supply noise test bit sequences

Overview

It has been found that a test bit sequence of repeating D31.3 characters creates the worst case power supply noise introduced by a transceiver. The noise is caused by the maximum simultaneously switching output (SSO). The following test bit sequences are proposed for SSO noise testing:

SPAT   Supply noise data pattern causing maximum SSO noise for transceivers
CSPAT   Supply noise data pattern in a valid FC frame

Supply noise pattern - SPAT

The pattern in Supply noise test bit sequence represents the SPAT. It is a test bit sequence that creates the SSO noise by causing all the individual Tx and Rx parallel data lines to switch per 10b character. This imortance of this pattern may be very dependent on the details of the system design.

Table A.12 - Supply noise test bit sequence

-	D31.3 (7f)		D31.3 (7f)			D31.3 (7f)		D31.3 (7f)			-
	335		0ca			335		0ca			
	1010	1100	1101	0100	1100	1010	1100	1101	0100	1100	
	a	c	d	4	c	a	c	d	4	c	
	Above 4 byte pattern is repeated 512 times.										

Compliant supply noise pattern - CSPAT

Just as the RPAT bit sequence may be packaged into a Fibre Channel frame for use in an operating system level test, the SPAT may be surrounded by SOF, CRC, and EOF to create a compliant SPAT (CSPAT).

Table A.13 - Compliant supply noise test bit sequence

-	K28.5 (bc)		D21.4 (95)			D21.5 (b5)		D21.5 (b5)			-
	17c		115			155		155			
	0011	1110	1010	1010	0010	1010	1010	1010	1010	1010	

Idle Primitive

	3	**e**	**a**	**a**	**2**	**a**	**a**	**a**	**a**	**a**		
	Above Idle Primitive is repeated 6 times.											
-	**K28.5 (bc)**		**D21.5 (b5)**			**D22.1 (36)**			**D22.1 (36)**		+	SOFn3
	17c		**155**			**256**			**256**			
	0011	**1110**	**1010**	**1010**	**1010**	**0110**	**1010**	**0101**	**1010**	**1001**		
	3	**e**	**a**	**a**	**a**	**6**	**a**	**5**	**a**	**9**		
+	**D31.3 (7f)**		**D31.3 (7f)**			**D31.3 (7f)**			**D31.3 (7f)**		+	Supply Noise Pattern (q = 512)
	0ca		**335**			**0ca**			**335**			
	0101	**0011**	**0010**	**1011**	**0011**	**0101**	**0011**	**0010**	**1011**	**0011**		
	5	**3**	**2**	**b**	**3**	**5**	**3**	**2**	**b**	**3**		
	Above 4 byte Supply Noise pattern is repeated 512 times.											
+	**D17.7 (f1)**		**D22.4 (96)**			**D27.6 (db)**			**D23.4 (97)**		-	CRC:
	231		**2d6**			**1a4**			**117**			
	1000	**1100**	**0101**	**1010**	**1101**	**0010**	**0101**	**1011**	**1010**	**0010**		
	8	**c**	**5**	**a**	**d**	**2**	**5**	**b**	**a**	**2**		
-	**K28.5 (bc)**		**D21.4**			**D21.6 (d5)**			**D21.6 (d5)**		-	EOFn
	17c		**115**			**195**			**195**			
	0011	**1110**	**1010**	**1010**	**0010**	**1010**	**1001**	**1010**	**1010**	**0110**		
	3	**e**	**a**	**a**	**2**	**a**	**9**	**a**	**a**	**6**		

11.3 Practical issues with compliant patterns in operating FC systems

CRPAT, CJTPAT, and CSPAT as defined in this report, include complete FC compliant frames and surrounding idles that are intended to represent conditions in operating FC systems. as well as for characterizing components and TxRx connections. In an operating FC system the idles, SOF and headers may be added by the port. In these cases the patterns defined should not include the idles, SOF and headers. Because the bit patterns are critical to the use of the patterns the disparity coming into the payload shall remain as specified with the header defined in this document. This requirement may present challenges in operating systems, especially where the addresses are changing from frame to frame. Making measurements in operating systems may present other challenges:

a) It may be necessary to modify the frame header plus CRC. If changing the header is required, attempt to do so in a manner that does not change the running disparity coming into the payload. The disparity going into the EOF is positive for CJTPAT and CRPAT.
b) Error measurements shall allow for normal changes to bits outside the Test Bit Sequence.
c) If bits other than the specified test pattern occupy a significant fraction of the total test time, they may dilute the test and affect the jitter output or tolerance and/or increase the test time.

11.4 Scrambled test patterns

11.4.1 General Overview

[Annex F] describes two test patterns that represent scrambled data and should be used for compliance testing of transmitters and receivers that will be operated using scrambling. When using these patterns the scrambler / de-scrambler must be disabled. Tables in this annex are read from left to right.

The previous compliance patterns described in FC-MJSQ (such as CRPAT and CJTPAT) shall still be used for 1GFC, 2GFC, and 4GFC.

11.4.2 Scrambled jitter pattern (JSPAT)

The JSPAT (scrambled jitter pattern) is a 500 bit pattern that has been developed for transmit jitter, DDPWS, WDP and RN testing. The pattern is a repetitive 500 bit pattern that has a negative starting and ending disparity. The pattern is listed in Scrambled jitter pattern (JSPAT). The D character is listed and the ten bit representation is listed below the D character.

Table F.1 – Scrambled jitter pattern (JSPAT)

D1.4	D16.2	D24.7	D30.4	D9.6	D10.5
0111010010	0110110101	0011001110	1000011101	1001010110	0101011010
D16.2	D7.7	D24.0	D13.3	D23.4	D13.2
1001000101	1110001110	0011001011	1011000011	0001011101	1011000101
D13.7	D1.4	D7.6	D0.2	D21.5	D22.1

1011001000	0111010010	1110000110	1001110101	1010101010	0110101001
D23.4	D20.0	D27.1	D30.7	D17.7	D4.3
0001011101	0010110100	1101101001	1000011110	1000110001	1101010011
D6.6	D23.5	D7.3	D19.3	D27.5	D19.3
0110010110	0001011010	1110001100	1100101100	1101101010	1100100011
D5.3	D22.1	D5.0	D15.5	D24.7	D16.3
1010010011	0110101001	1010010100	0101111010	0011001110	1001001100
D1.2	D23.5	D20.7	D11.7	D20.7	D18.7
0111010101	0001011010	0010110111	1101001000	0010110111	0100110001
D29.0	D16.6	D25.3	D1.0	D18.1	D30.5
1011100100	0110110110	1001100011	1000101011	0100111001	1000011010
D5.2	D21.6				
1010010101	1010100110				

11.4.3 Jitter tolerance scrambled pattern (JTSPAT)

The JTSPAT is a 1180 bit pattern intended to be used for receive jitter tolerance testing for scrambled systems. The JTSPAT pattern has two copies of JSPAT and an additional 18 characters intended to cause extreme late and early phases in the PLL followed by a sequence likely to cause an error (i.e. an isolated bit following a long run). This pattern was developed to stress the receiver within the boundary conditions established by scrambling. The pattern is listed in Jitter tolerance scrambled pattern (JTSPAT).

Table F.2 – Jitter tolerance scrambled pattern (JTSPAT)

D1.4	D16.2	D24.7	D30.4	D9.6	D10.5
0111010010	0110110101	0011001110	1000011101	1001010110	0101011010
D16.2	D7.7	D24.0	D13.3	D23.4	D13.2
1001000101	1110001110	0011001011	1011000011	0001011101	1011000101
D13.7	D1.4	D7.6	D0.2	D21.5	D22.1
1011001000	0111010010	1110000110	1001110101	1010101010	0110101001
D23.4	D20.0	D27.1	D30.7	D17.7	D4.3
0001011101	0010110100	1101101001	1000011110	1000110001	1101010011
D6.6	D23.5	D7.3	D19.3	D27.5	D19.3
0110010110	0001011010	1110001100	1100101100	1101101010	1100100011

D5.3	D22.1	D5.0	D15.5	D24.7	D16.3
1010010011	0110101001	1010010100	0101111010	0011001110	1001001100
D1.2	D23.5	D29.2	D31.1	D10.4	D4.2
0111010101	0001011010	1011100101	0101001001	0101011101	0010100101
D5.5	D10.2	D21.5	D10.2	D21.5	D20.7
1010011010	0101010101	1010101010	0101010101	1010101010	0010110111
D11.7	D20.7	D18.7	D29.0	D16.6	D25.3
1101001000	0010110111	0100110001	1011100100	0110110110	1001100011
D1.0	D18.1	D30.5	D5.2	D21.6	D1.4
1000101011	0100111001	1000011010	1010010101	1010100110	0111010010
D16.2	D24.7	D30.4	D9.6	D10.5	D16.2
0110110101	0011001110	1000011101	1001010110	0101011010	1001000101
D7.7	D24.0	D13.3	D23.4	D13.2	D13.7
1110001110	0011001011	1011000011	0001011101	1011000101	1011001000
D1.4	D7.6	D0.2	D21.5	D22.1	D23.4
0111010010	1110000110	1001110101	1010101010	0110101001	0001011101
D20.0	D27.1	D30.7	D17.7	D4.3	D6.6
0010110100	1101101001	1000011110	1000110001	1101010011	0110010110
D23.5	D7.3	D19.3	D27.5	D19.3	D5.3
0001011010	1110001100	1100101100	1101101010	1100100011	1010010011
D22.1	D5.0	D15.5	D24.7	D16.3	D1.2
0110101001	1010010100	0101111010	0011001110	1001001100	0111010101
D23.5	D27.3	D3.0	D3.7	D14.7	D28.3
0001011010	1101100011	1100010100	1100011110	0111001000	0011101100
D30.3	D30.3	D7.7	D7.7	D20.7	D11.7
0111100011	1000011100	1110001110	0001110001	0010110111	1101001000
D20.7	D18.7	D29.0	D16.6	D25.3	D1.0
0010110111	0100110001	1011100100	0110110110	1001100011	1000101011
D18.1	D30.5	D5.2	D21.6		
0100111001	1000011010	1010010101	1010100110		

11.4.4 Encapsulated JSPAT and JTSPAT

JSPAT or JTSPAT can be encapsulated in a valid FC frame, or a sync character can be added to the start of either pattern as long as the starting disparity of the data in Scrambled jitter pattern (JSPAT) and Jitter tolerance scrambled pattern (JTSPAT) is negative.

Unlike CJTPAT and other test patterns JTSPAT relies on specific running disparity to create the desired test bit pattern. In order to create a routable frame for some types of testing, the frame header with a valid D_ID and S_ID is needed. This can throw off the running disparity by the time the payload is reached.

Example

The only difference between the 2 frames is the header (FCH 0002), but the 1st byte of the payload is positive running disparity in the bad frame by having a different bit pattern than desired.

Table F.3 – Good frame with correct running disparity

FC 001	**8b hex**	BC	B5	56	56
	8b/10b byte	-K28.5	D21.5	D22.2	D22.2
	10b bits	0011111010	1010101010	0110100101	0110100101
FCH 001	**8b hex**	22	02	04	00
	8b/10b byte	+D2.1	-D2.0	-D4.0	-D0.0
	10b bits	0100101001	1011010100	1101010100	1001110100
FCH 002	**8b hex**	00	02	04	00
	8b/10b byte	-D0.0	-D2.0	-D4.0	-D0.0
	10b bits	1001110100	1011010100	1101010100	1001110100
FCH 003	**8b hex**	20	28	00	00
	8b/10b byte	-D0.1	+D8.1	-D0.0	-D0.0
	10b bits	1001111001	0001101001	1001110100	1001110100
FCH 004	**8b hex**	01	00	00	00
	8b/10b byte	-D1.0	-D0.0	-D0.0	-D0.0
	10b bits	0111010100	1001110100	1001110100	1001110100
FCH 005	**8b hex**	80	38	00	03
	8b/10b byte	-D0.4	-D24.1	+D0.0	+D3.0
	10b bits	1001110010	1100111001	0110001011	1100010100
FCH 006	**8b hex**	00	00	00	00

	8b/10b byte	-D0.0	-D0.0	-D0.0	-D0.0
	10b bits	1001110100	1001110100	1001110100	1001110100
Pld 0001	8b hex	81	50	F8	9E
	8b/10b byte	-D1.4	-D16.2	+D24.7	+D30.4
	10b bits	0111010010	0110110101	0011001110	1000011101

Table F.4 – Bad frame with wrong running disparity

FC 001	8b hex	BC	B5	56	56
	8b/10b byte	-K28.5	D21.5	D22.2	D22.2
	10b bits	0011111010	1010101010	0110100101	0110100101
FCH 001	8b hex	22	02	04	00
	8b/10b byte	+D2.1	-D2.0	-D4.0	-D0.0
	10b bits	0100101001	1011010100	1101010100	1001110100
FCH 002	8b hex	00	02	04	00
	8b/10b byte	-D0.0	-D2.0	-D5.0	+D0.0
	10b bits	1001110100	1011010100	1010011011	0110001011
FCH 003	8b hex	20	28	00	00
	8b/10b byte	+D0.1	-D8.1	+D0.0	+D0.0
	10b bits	0110001001	1110011001	0110001011	0110001011
FCH 004	8b hex	01	00	00	00
	8b/10b byte	+D1.0	+D0.0	+D0.0	+D0.0
	10b bits	1000101011	0110001011	0110001011	0110001011
FCH 005	8b hex	80	38	00	03
	8b/10b byte	+D0.4	+D24.1	-D0.0	-D3.0
	10b bits	0110001101	0011001001	1001110100	1100011011
FCH 006	8b hex	00	00	00	00
	8b/10b byte	+D0.0	+D0.0	+D0.0	+D0.0
	10b bits	0110001011	0110001011	0110001011	0110001011
Pld 0001	8b hex	81	50	F8	9E
	8b/10b byte	+D1.4	+D16.2	-D24.7	-D30.4
	10b bits	1000101101	1001000101	1100110001	0111100010

A method to correct the pattern starting disparity

All SOFs are negative running disparity, giving us a known starting point at the beginning of the frame. Running disparity changes only on a non-neutral running disparity character. By counting the number of neutral running disparity character leading up to the data pattern, it can be determined if the running disparity needs to be corrected. Correcting the running disparity can be done easily by substituting the last character before the data pattern begins.
Assume that the frame header is in an array Tx_frame(n). Value is hex without leading 0x. That the D_ID / S_ID or any other value are ready for transmit. Assumes that the PARAM value may be changed to correct the running disparity.

Tx_frame(0) 22020400 R_CTL / D_ID
Tx_frame(1) 00020500 CS_CTL / S_ID
Tx_frame(2) 20280000 Type / FCTL
Tx_frame(3) 01000000 SEQ_ID / DF_Ctl / SEQ_Cnt
Tx_frame(4) 80380003 OX_ID / RX_ID
Tx_frame(5) 00000000 PARAM

Code uses the neutral disparity 8B codes as shown in Neutral disparity bytes (8b hex).

Table F.5 – Neutral disparity bytes (8b hex)

00	01	02	04	08	0F	10	17	18	1B
1D	1E	1F	23	25	26	27	29	2A	2B
2C	2D	2E	31	32	33	34	35	36	39
3A	3C	43	45	46	47	49	4A	4B	4C
4D	4E	51	52	53	54	55	56	59	5A
5C	63	65	66	67	69	6A	6B	6C	6D
6E	71	72	73	74	75	76	79	7A	7C
80	81	82	84	88	8F	90	97	98	9B
9D	9E	9F	A3	A5	A6	A7	A9	AA	AB
AC	AD	AE	B1	B2	B3	B4	B5	B6	B9
BA	BC	C3	C5	C6	C7	C9	CA	CB	CC
CD	CE	D1	D2	D3	D4	D5	D6	D9	DA
DC	E0	E1	E2	E4	E8	EF	F0	F7	F8
FB	FD	FE	FF						

Here is an example code to correct the running disparity.

```
set neutral_running disparity_count 0;# initialize neutral running disparity count

for {set n 0} {$n <= 5} { incr n };# for each of the FC Hdr words
{;# pattern begins in 1st Payload word

set FC_Hdr_word $Tx_frame($n);# get the next FC Header word
puts "FC_Hdr_word: $FC_Hdr_word"
;# look at one byte at a time
set start_char_position 0;# set starting char position in word
set end_char_position 1;# set end char position in word
for {set byten 1} {$byten <= 4} { incr byten }
{;# for each byte

set hex_char "0x";# get the hex 8B code from Frame
append hex_char [ string range $FC_Hdr_word $start_char_position
$end_char_position ]

set found [lsearch $Neutral_Dis $hex_char];# lookup if 8B code is neutral disparity
if { $found != -1 }
{;# found in neutral running disparity table?
incr neutral_running disparity_count;# YES, increment count
}
incr start_char_position 2;# update for next byte position
incr end_char_position 2

};# for next byte of FC Hdr
};# for next word of FC Hdr

if { [expr $neutral_running disparity_count % 2] == 0 }
{;# neutral disparity count Even
set Tx_frame(5)00000003;# change the parameter word to cause
};# the proper disparity for SJTpat
```

Example frames after correcting running disparity is shown in Good frame with corrected running disparity.

Table F.6 – Good frame with corrected running disparity

FC 001	**8b hex**	BC	B5	56	56
	8b/10b byte	-K28.5	D21.5	D22.2	D22.2
	10b bits	0011111010	1010101010	0110100101	0110100101
FCH 001	**8b hex**	22	02	04	00
	8b/10b byte	+D2.1	-D2.0	-D4.0	-D0.0
	10b bits	0100101001	1011010100	1101010100	1001110100

FCH 002	8b hex	00	02	04	00
	8b/10b byte	-D0.0	-D2.0	-D4.0	-D0.0
	10b bits	1001110100	1011010100	1101010100	1001110100
FCH 003	8b hex	20	28	00	00
	8b/10b byte	-D0.1	+D8.1	-D0.0	-D0.0
	10b bits	1001111001	0001101001	1001110100	1001110100
FCH 004	8b hex	01	00	00	00
	8b/10b byte	-D1.0	-D0.0	-D0.0	-D0.0
	10b bits	0111010100	1001110100	1001110100	1001110100
FCH 005	8b hex	80	38	00	03
	8b/10b byte	-D0.4	-D24.1	+D0.0	+D3.0
	10b bits	1001110010	1100111001	0110001011	1100010100
FCH 006	8b hex	00	00	00	00
	8b/10b byte	-D0.0	-D0.0	-D0.0	-D0.0
	10b bits	1001110100	1001110100	1001110100	1001110100
Pld 0001	8b hex	81	50	F8	9E
	8b/10b byte	-D1.4	-D16.2	+D24.7	+D30.4
	10b bits	0111010010	0110110101	0011001110	1000011101
FC 001	8b hex	BC	B5	56	56
	8b/10b byte	-K28.5	D21.5	D22.2	D22.2
	10b bits	0011111010	1010101010	0110100101	0110100101
FCH 001	8b hex	22	02	04	00
	8b/10b byte	+D2.1	-D2.0	-D4.0	-D0.0
	10b bits	0100101001	1011010100	1101010100	1001110100
FCH 002	8b hex	00	02	04	00
	8b/10b byte	-D0.0	-D2.0	-D5.0	+D0.0
	10b bits	1001110100	1011010100	1010011011	0110001011
FCH 003	8b hex	20	28	00	00
	8b/10b byte	+D0.1	-D8.1	+D0.0	+D0.0
	10b bits	0110001001	1110011001	0110001011	0110001011
FCH 004	8b hex	01	00	00	00

	8b/10b byte	+D1.0	+D0.0	+D0.0	+D0.0
	10b bits	1000101011	0110001011	0110001011	0110001011
FCH 005	**8b hex**	80	38	00	03
	8b/10b byte	+D0.4	+D24.1	-D0.0	-D3.0
	10b bits	0110001101	0011001001	1001110100	1100011011
FCH 006	**8b hex**	00	00	00	00
	8b/10b byte	+D0.0	+D0.0	+D0.0	+D3.0
	10b bits	0110001011	0110001011	0110001011	1100010100
Pld 0001	**8b hex**	81	50	F8	9E
	8b/10b byte	-D1.4	-D16.2	+D24.7	+D30.4
	10b bits	0111010010	0110110101	0011001110	1000011101

11.5 PRBS test patterns

[Text needed here.]

12.Channel Effects

10.1 VCR, ICR, ILD

[Time domain (impulse) vs. frequency domain discussion. Adam Healey to supply text.]

12.2 Stressors