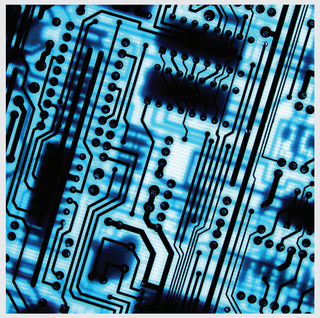
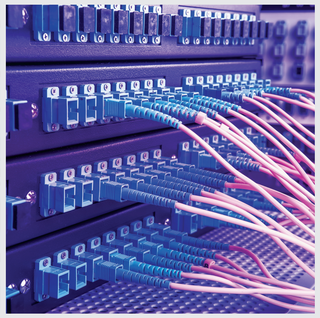
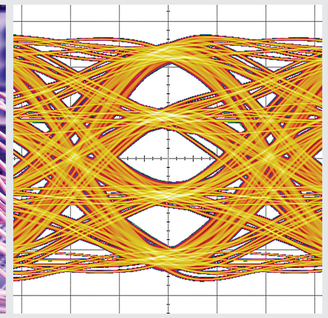
Master 400G

Intra Data Center

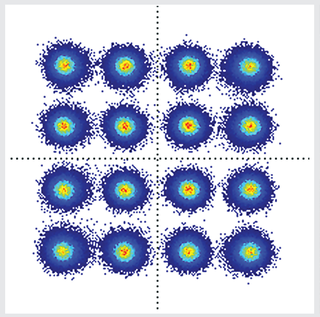






Inter Data Center

Metro



Long Haul

Data Center

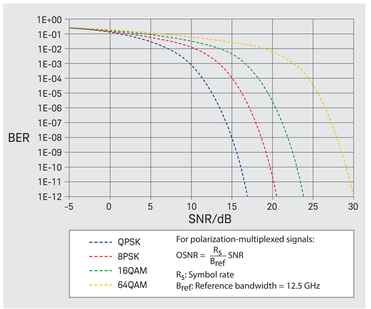
Standard / implementation agreement	IEEE (Institute of Electrical and Electronics Engineers) 802.3bs & 802.3cd											OIF-CEI 4.0 (Optical Internetworking Forum - Common Electrical Interface)							Fiber Channel PI-7		InfiniBand
	400GBASE-SR16	200GBASE-DR4	400GBASE-DR4	200GBASE-FR4 / 400GBASE-FR8	200GBASE-LR4 / 400GBASE-LR8	50GAUI-2 C2M / 100GAUI-4 C2M / 200GAUI-8 C2M / 400GAUI-16 C2M	50GAUI C2M / 100GAUI-2 C2M / 200GAUI-4 C2M / 400GAUI-8 C2M	50GAUI-2 C2C / 100GAUI-4 C2C / 200GAUI-8 C2C / 400GAUI-16 C2C	50GAUI C2C / 100GAUI-2 C2C / 200GAUI-4 C2C / 400GAUI-8 C2C	50G-KR / 100G-KR2 / 200G-KR4	50G-CR / 100G-CR2 / 200G-CR4	CEI-56G-XSR-NRZ	CEI-56G-XSR-PAM4	CEI-56G-VSR-NRZ	CEI-56G-VSR-PAM4	CEI-56G-MR-PAM4	CEI-56G-LR-PAM4	CEI-56G-LR-eNRZ	64GFC / 256GFC *		600G HDR *
Application	Fiber optic data link	Fiber optic data link	Fiber optic data link	Fiber optic data link	Fiber optic data link	Chip to pluggable optical module	Chip to pluggable optical module	Chip to chip on same circuit board	Chip to chip on same circuit board	Backplanes with daughter cards	Passive copper cable	Chip to adjacent chip	Chip to adjacent chip	Chip to pluggable optical module	Chip to pluggable optical module	Chip to chip on large circuit board	Backplanes / passive copper cable	Backplanes / passive copper cable	Fiber optic data link	Chip to pluggable optical module	TOR switch to blade server
Link media	Multimode fiber	Single-mode fiber	Single-mode fiber	Single-mode fiber	Single-mode fiber	Circuit board trace + 1 connector	Circuit board trace + 1 connector	Circuit board trace	Circuit board trace	Circuit board trace + 3 connectors	Twinax copper cable + 2 connectors	Circuit board	Circuit board	Circuit board + 1 connector	Circuit board + 1 connector	Circuit board trace	Circuit board + 2 connectors	Circuit board + 2 connectors	Multimode fiber & single-mode fiber	Circuit board trace + 1 connector	Electrical
Modulation format	NRZ	PAM-4	PAM-4	PAM-4	PAM-4	NRZ	PAM-4	NRZ	PAM-4	PAM-4	PAM-4	NRZ	PAM-4	NRZ	PAM-4	PAM-4	PAM-4	eNRZ	PAM-4	PAM-4	PAM-4
Symbol rate, per lane/wire	26.5625 GBd	26.5625 GBd	53.125 GBd	26.5625 GBd	26.5625 GBd	26.5625 GBd	26.5625 GBd	26.5625 GBd	26.5625 GBd	26.5625 GBd	26.5625 GBd	39.8 - 58.0 GBd	18.0 - 29.0 GBd	39.0 - 56.0 Gb/s	18.0 - 29.0 GBd	18.0 - 29.0 GBd	18.0 - 29.0 GBd	33.16 - 37.5 GBaud	29.027 GBd	29.027 GBd	26-5625 GBd
Maximum reach (channel loss at Nyquist frequency)	100 m	500 m	500 m	2 km	10 km	10.2 dB (= 100 mm)	10.2 dB (= 100 mm)	20 dB (= 25 cm)	20 dB (= 25 cm)	30 dB (= 1 m)	16.06 dB (≥ 3 m) (cable assembly only)	8 dB @ 29 GHz (= 50 mm)	4.2 dB @ 14.5 GHz (= 50 mm)	13 dB @ 28 GHz (Type A) 20 dB @ 28 GHz (Type B) (= 150 mm)	10.0 dB @ 14.5 GHz (= 150 mm)	20 dB @ 14.5 GHz (= 500 mm)	30 dB @ 14.5 GHz (= 1000 mm)	33.6 dB @ 18.75 GHz	100 m (MMF) 2 km (SMF)	≈ 150 mm	2 m
Number of parallel lanes	16	4	4	1	1	2/ 4/ 8/ 16	1/ 2/ 4/ 8	2/ 4/ 8/ 16	1/ 2/ 4/ 8	1/ 2/ 4	1/ 2/ 4	1 - n	1 - n	1 - n	1 - n	1 - n	1 - n	1 - n (each lane has 4 wires)	1/ 4	1/ 4	8
Number of wavelengths	1	1	1	4/ 8	4/ 8														1	1	
Forward error correction (FEC) overhead	Required	Required	Required	Required	Required	Required	Required	Required	Required	Required	Required	Not used	Not used	Not used	Assumed	Assumed	Assumed	Not used	Required	Required	Required
Pre-FEC bit error ratio (BER)	2.4 E-4	2.4 E-4	2.4 E-4	2.4 E-4	2.4 E-4	1E-6	1E-5	1E-5	1E-4	2.4 E-6	2.4 E-4	1 E-15	1 E-15	1 E-15	1 E-6	1 E-6	1 E-4	1 E-15	TBD	TBD	1 E-4
Frame loss ratio (for 64 octet frames)	1.7 E-12 (link only) 6.2 E-11 (with attachment unit interface)	1.7 E-12 (link only) 6.2 E-11 (with AUI)	1.7 E-12 (link only) 6.2 E-11 (with AUI)	1.7 E-12 (link only) 6.2 E-11 (with AUI)	1.7 E-12 (link only) 6.2 E-11 (with AUI)					50G-KR/100G-KR2: 1 E-10 (link only) 6.2 E-10 (with AUI) 200G-KR4: 1.7 E-12 (link only) 6.2 E-11 (with AUI)	50G-CR/100G-CR2: 1 E-10 (link only) 6.2 E-10 (with AUI) 200G-CR4: 1.7 E-12 (link only) 6.2 E-11 (with AUI)										
Transmitter and dispersion eye closure for PAM-4 (TDECQ), each lane max.	4.3 dB	2.5 dB	2.5 dB	2.4/2.2 dB	2.5/2.4 dB														TBD	TBD	
Novel test requirements	– Transmitter and dispersion eye closure for PAM-4 (TDECQ) – Outer optical modulation amplitude – Outer extinction ratio – Relative intensity noise (RINxOMA)					– Eye width (EW) – Eye height (EH) – Eye symmetry mask width (ESMW) – Transition time (specific edge)		– Signal-to-noise-and-distortion ratio (SNDR) – Output waveform measurements (R_{LM}, linear fit pulse peak,...) – Output jitter (J_{rms}, J4, even-odd jitter)				– Clock jitter (UUGJ-hf) – Clock phase noise – Output jitter (UBHRJ, UUGJ, even-odd jitter) – Eye width (EW) – Eye height (EH) – Eye linearity – Transition time		– Eye width (EW) – Eye height (EH) – Transition time – Vertical eye closure (VEC)	– Signal-to-noise-and-distortion ratio (SNDR) – Eye width (EW) – Eye height (EH) – Eye linearity – Transition time (specific edge)	– Signal-to-noise-and-distortion ratio (SNDR) – Output waveform measurements (R_{LM}, linear fit pulse peak,...) – Output jitter (UBHRJ, UUGJ, even-odd jitter)	– Signal-to-noise-and-distortion ratio (SNDR) – Output waveform measurements (R_{LM}, linear fit puls peak,)	Standard will likely leverage PAM-4 measurements outlined in IEEE 802.3bs and OIF-CEI 4.0.			
Challenges	Forward error correction (FEC), SNR Requirements for accurate eye analysis: Frequency response complies to industry standard tolerance – Low jitter relative to the bit period (unit interval) – Low noise (SNR degrades from NRZ to PAM-4) – Robust measurement algorithms Clock recovery is required for PAM-4 which adds complexity due to more transition possibilities. TDECQ: Transmitter Dispersion and Eye Closure Quaternary. A power penalty measurement (in dB) indicating the additional transmitter power required to compensate for PAM-4 eye closure and achieve the target symbol-error-ratio (relative to an ideal PAM-4 signal having the same optical modulation amplitude). Measured on the transmitter PAM-4 eye after passing through a virtual equalizer within the oscilloscope. A similar measurement, TDEC, is performed on NRZ multimode signals (no virtual equalizer used). Channel operating margin (COM) is a new figure of merit defined as follows: COM represents the signal-to-noise amplitude at the receiver pins of a channel after integrating the effects of loss, near-end crosstalk, far-end crosstalk, and statistical noise. A typical COM number might be 8.5dB and it would be the result of inputting multiple variables including S-parameter measurements into a large MATLAB program specifically written per the standard COM definition. Some test and measurement tools have cleverly integrated COM calculations to help automate this normally complex characterization technique.																				

Notes: * 64G Fiber Channel and Infiniband HDR standards are in early development at time of printing. Parameter values are subject to change as standard developments continue.

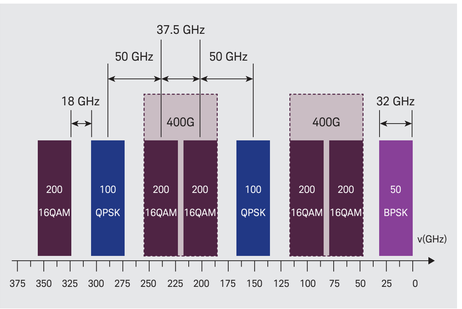
Core Network

Standard/ implementation agreement	Short haul		Metro				Long haul			Ultralong haul		
	OIF-proposed paths to 400G											
Link media	Single-mode fiber											
Modulation format	64QAM	16QAM	16QAM	16QAM	64QAM	Multiband-OFDM (16QAM)	QPSK	QPSK	16QAM	QPSK	8QAM	16QAM
Symbol rate per lane/wire	42.7 GBd	64 GBd	32GBd	64 GBd	14.2 GBd	8 GBd	64 GBd	32 GBd	16 GBd	32 GBd	42.7 GBd	21 GBd
Maximum reach	~ 100 km		< 1,000 km				~ 2,000 km			> 2,000 km		
Number of parallel lanes	1 PDM lane	1 PDM lane	2 PDM lanes	1 PDM lane	3 PDM lanes	8 PDM lanes	2 PDM lanes	4 PDM lanes	4 PDM lanes	4 PDM lanes	2 PDM lanes	3 PDM lanes
Channel occupancy	50 GHz	75 GHz/ 100 GHz	75 GHz/ 100 GHz	75 GHz/ 100 GHz	50 GHz	100 GHz	150 GHz	150 GHz	75 GHz/ 100 GHz	150 GHz	100 GHz	75 GHz/ 100 GHz
Forward error correction (FEC) overhead	~20%											
Pre-FEC Bit Error Ratio (BER)	~ 1E-2											
Required optical signal-to-noise ratio (OSNR) at BER = 10^{-2}	23.8	19.8	16.8	19.8	18.5	10.8	13.4	10.4	13.8	10.4	15	14.5
Novel test requirements	– Tighter tolerances regarding skew, nonlinearity, frequency-response calibration – Interchannel crosstalk -> frequency stability of carrier laser											
Challenges	– Interoperability of transceivers – Interchannel crosstalk – Power consumption/ efficiency											

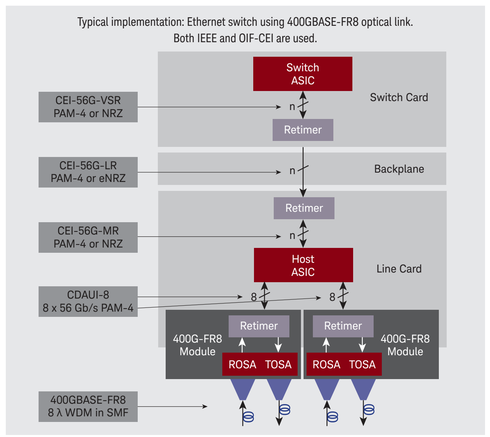
BER from SNR



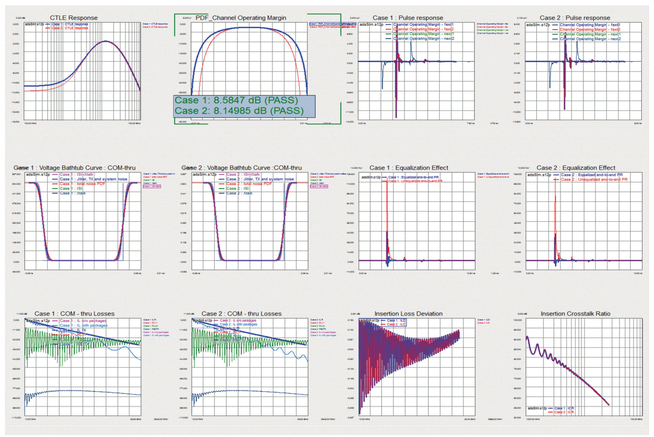
New Flexgrid Defined in ITU-T G.694.1 Recommendation



Understanding the Application Space



Channel Operating Margin (COM)



COM Parameter Definitions

	Draft parameter ref	Example setting	
Coding/port type	Coding/port type	NRZ clause 93 D1.1	Selector for port type
Unit interval (UI)	Unit interval (UI)	3.87879E-11	Unit interval in seconds
tx_ffe	tx_ffe	[1.4]	Transmitter equalizer max. pre and post cursor coefficient
ndfe	W	12	Victim single bit response exception window (in UI)
max_ctle	G_DC	12	Continuous tie filter, max. DC gain.
a_thru	A_v	0.4	Transmitter differential peak output voltage for victim.
a_fext	A_f	0.4	Transmitter differential peak output voltage for far-end aggressor.
a_next	A_n	0.6	Transmitter differential peak output voltage for near-end aggressor.
AG	1/(L-1)	1	Related to number of levels, L (symbol gain).
specBER	SER_0	1.00E-12	Target uncorrected symbol error ratio.
Allowance	COM_0	0	Minimum channel operation margin.
G_s_noise	sigma_G	0.01	Normalized RMS Gaussian noise.
g_dd_noise	A_DD	0.1	Normalized peak dual-Dirac noise.
Na_rms	–	0	Voltage sensitivity RMS Gaussian noise.
Samples per UI	M	32	–
Port order	Port order	[1 3 2 4]	For the 4 ports the first two listed are inputs and respective last two are outputs (RX).
G01	Gamma_01	0.01	Transmitter reflection coefficient DC value. Value < 0.01 disables.
G02	Gamma_02	0.01	Receiver reflection coefficient DC value. Value < 0.01 disables.
Fscale1	Fscale1	2	Transmitter reference coefficient reference frequency scale. Value > 2 disables.
Fscale2	Fscale2	2	Receiver reference coefficient reference frequency scale. Value > 2 disables.
ctle_step	–	1	Continuous time filter step size dB.
tx_ffe_step	–	0.02	Transmitter equalizer, pre/post cursor coefficient step size.
maxc1	–	1	Max. value for DFE1.
maxcx	–	1	Max. in W region.
f_v	f_v	0.55	Transmitter 3 dB bandwidth for victim. Set to > 2 to deactivate.
f_f	f_f	0.55	Transmitter 3 dB bandwidth for far-end aggressor. Set to > 2 to deactivate.
f_n	f_n	1	Transmitter 3 dB bandwidth for near-end aggressor. Set to > 2 to deactivate.
f_r	f_r	0.75	Receiver 3 dB bandwidth.

Hardware	Software	Hardware	Software
Infiniium Z-Series Oscilloscopes	N8827A & N8827B PAM-4 Analysis Software for Infiniium Real-time Oscilloscopes	M8196A 92 GSa/s Arbitrary Waveform Generator	81195A Optical Modulation Generator Software
86100D Infiniium DCA-X Wide-Bandwidth Oscilloscope with 86105D 34 GHz Optical, 50 GHz Electrical Module	86100D-9FP PAM-N Analysis Software for 86100D DCA-X Oscilloscopes N1085A PAM-4 Measurement Application for Ethernet and OIF-CEI	86100B Tunable Laser Sources	N7700A Photonic Application Suite
N1930B Physical Layer Test System (PLTS)	Physical Layer Test System (PLTS) Version 2017	N4373D Lightwave Component Analyzer	N4392A Option 430 Integrated Coherent Receiver Test
M8040A 64 GBaud High-performance BERT	M8070A System Software for M8000 Series of BER Test Solutions	N1077A Optical/Electrical Clock Recovery	N4391AU Optical Modulation Analyzer Software
		N4391A Optical Modulation Analyzer	

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