FEC for 100GBASE-SR4

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Outline

- Background
- Outline of method for link budget model with FEC
  - Fibre Channel starting point, and Ethernet initial parameters
- Summary results
  - Compared to earlier estimates
  - Observations on the impact of FEC on noise penalties
- Jitter through the optical link, and sensitivity analysis
- Conclusions

Background-1

- 802.3bj :
  - has adopted auto-negotiated FEC for NRZ backplane (*gustlin_01_0312*)
  - has adopted the same FEC for Cu (FEC required for 5m reach)
  - auto-negotiation not yet decided upon for shorter Cu reaches, but has several advantages
    - 'Always encoding and not decoding' increases the risk of MTTFPA (*cideciyan_01_0512*) - 64B/66B encoding has lower risk than uncorrected 256B/257B
    - Avoiding transcoding and FEC encoding and decoding can yield lowest latency and power (*dudek_02a_0312*)
    - 256B/257B transcoding precludes hosts which include MLGs (which rely on 64B/66B encoding), or links where 802.3bj and 802.3ba hosts are connected by legacy and Next Gen LR4 optics) - *Petrilla_01_0712*

Background-2

- It is highly desirable that 100GBASE-SR4 and 100GBASE-CR4 can plug into a common host port (*dudek_01_1111*)
  - The common CR4/SR4 host port would have FEC capability
  - Using available FEC for Next Gen 100G Optics dramatically improves the performance vs cost ratio of 100GBASE-SR4 (*king_01_1111*)
- Auto-negotiation of FEC for the common 100GBASE-CR4 and SR4 port is *a very good thing*
  - Matches backplane use
  - Better MTTFPA, power, latency for CR4
  - Allows benefits of FEC for 802.3bj compliant ports, and backward compatibility with 802.3ba, OIF-CEI-02.0 25G compliant ports without FEC capability
- Adoption of auto-negotiated FEC for the common port would suggest the need to specify 100G-SR4 reach with and without FEC enabled

Spreadsheet link modeling with and without FEC

- An update of earlier link modeling…
  - e.g. *king_01_1111, king_02_0112, petrilla_01_0112*

  … drawing on Fibre Channel work (single channel of 28.05 Gb/s), and tweaking parameter values where required to suit Ethernet (four lanes of 25.78 Gb/s)

  … and with reference to the preferred FEC scheme adopted by 802.3bj , in *gustlin_01_0312*

  … some observations on the impact of FEC on noise penalties, and a look at link margin and eye opening vs link parameters.

Fibre Channel

Fibre Channel is slightly ahead of Ethernet in specifying it's next rate (32G-FC)

- T11 has adopted FEC for 28.05 Gb/s single lane link
  - Relaxes the demands on component performance
  - Enables robust, low cost, 100 m OM4 links, and relaxes specs on host electrical traces
  - Though the precise link model parameters are still in development, link modeling shows:
    - Retiming and simple equalization do not enable 100 m reach.
    - FEC enables a retimed module to achieve 100 m reach without the need for active equalization.
      - Since an SRS test is expected, it can be left to the designer to decide if a fixed equalizer is included in the receiver

Initial link model values for Fibre Channel, and Ethernet:

Parameter	FC: 28 Gb/s single lane	IEEE: 25.8 Gb/s four lanes	Remarks
VCSEL fall time	21 ps		Effective, after Tx chain EQ
RIN_{OMA}	-128 dB/Hz	-130 dB/Hz*	*Value for IEEE assumes usual trade off between jitter, rise time, and RIN
Wavelength range	840 to 860 nm		
RMS spectrum	0.59 nm*	0.6 nm	*Compatible with 16GFC
Min OMA	-2 dBm	-2 dBm	
Rx sensitivity, equiv. at BER=10^{-12}	-8.5 dBm	-7.8 dBm*	*0.7 dB margin for multi-lane impairments and bit rate. Jitter calculations assume noise limited sensitivity is 1 dB lower than this.
Target Q*	*5	*4.5	*with FEC; 7.04 without FEC (for BER=10^{-12})
Uncorrected BER, Corrected BER	$2.7x10^{-7}$, 10^{-18}	$4.7x10^{-6}$*, 10^{-15}	*From *gustlin_01_0312*
TJ/DCD	8.6/2.1 ps	4.7/2.1 ps	
Rx bandwidth	19 GHz	19 GHz	

… a lot in common

Calculating FEC and non-FEC reach for 100G-SR4

- 10GE spreadsheet modified for rate, using values from slide 6
  - No explicit Rx chain equalization
  - Channel: OM4, 4400 MHz.km, 1.5 dB total connector loss
- FEC characteristics from *gustlin_01_0312*

Option	FEC Code RS(n, k, t, m)	Trans-coding	Effective Gain BER= 10^{-15}	Overall Latency	Total Area (40nm gates)	Total Power	Input BER for 10^{-15} BER	Input BER for 10^{-12} BER
1	RS(528, 514, 7, 10)	256b/257b	4.87 dB	94.3 ns	244k	90 mW	4.68×10^{-6}	2.34×10^{-5}

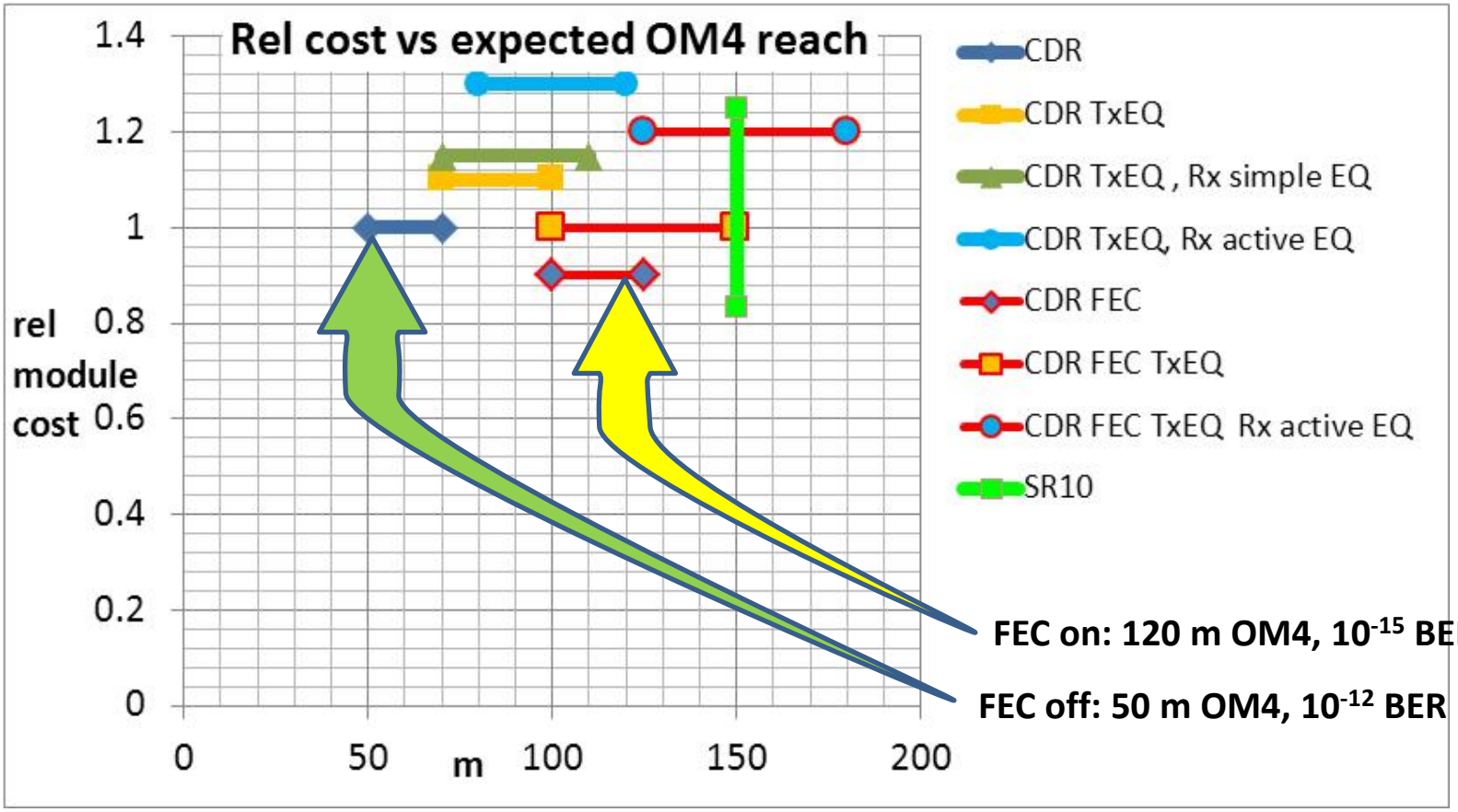
  - Target corrected error rate of 10^{-15}, requires input BER of 4.68×10^{-6}, corresponds to Q of ~4.5
  - Rx sensitivity at Q = 4.5 is -9.7 dBm

Summary results

	Reach limit	OM4 reach	OM3 reach	Notes
25.8 GBd, no FEC	power budget	50 m	50 m	~2.6 dB VCEP 10^{-12} BER
25.8 GBd, FEC	3.6 dB VECP	120 m	80 m	~1 dB margin 10^{-15} corrected BER

- Without FEC, expected link budget for 100GBASE-SR4 is 5.7 dB
  - compares to >7 dB for 10GBASE-SR, 40GBASE-SR4
  - link budget closes at shorter reaches
- FEC raises link budget to 7.6 dB
  - enables >100m reach on OM4
  - simultaneously guarantees worst case corrected BER ≤ 10^{-15}

How these results compare to earlier relative cost vs reach estimates - from *king_02_0112*

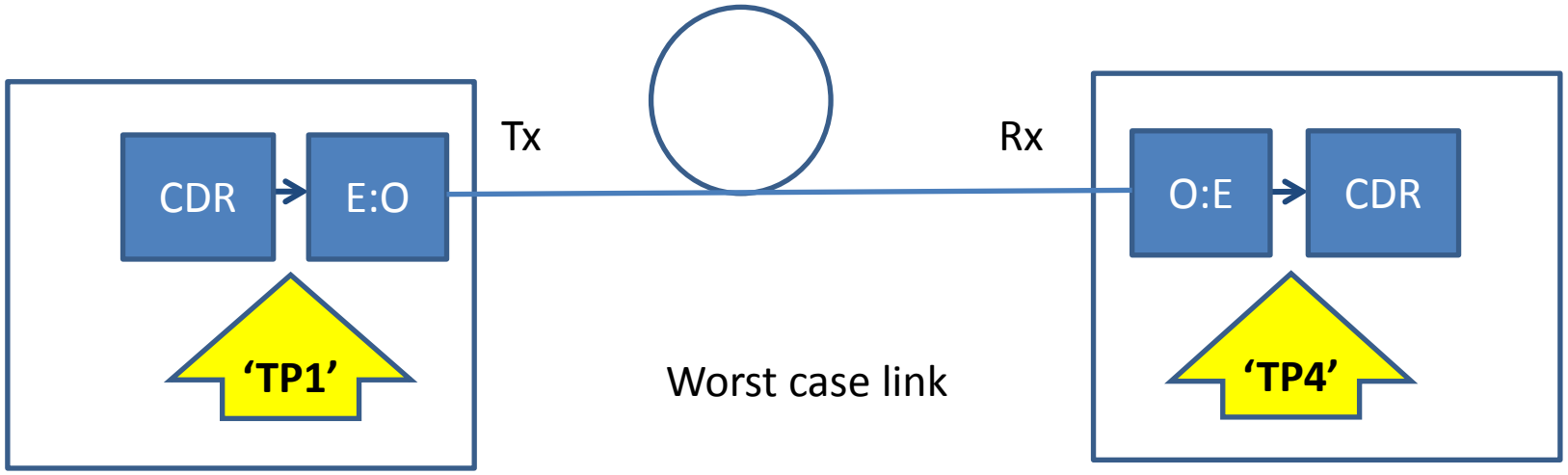


Observations on the effect of FEC on noise penalties

- FEC significantly reduces the penalties due noise terms as a result of the lower system Q required:
  - E.g., a system Q reduction from 7.04 (~ BER=10^{-12}, no FEC) to 4.5 (~raw BER = 4.68×10^{-6}, FEC corrected BER=10^{-15}) more than halves the MPN and RIN penalties.
    - Precise modeling of these effects becomes much less critical.
    - FEC corrected error rates can be significantly better than intrinsic noise floors would allow.
- FEC also allows relaxed design specs for the host electrical lanes, with negligible detriment to the FEC gain available for the optical link.
  - E.g., if the optical link contributes a raw BER of ~4×10^{-6}, then designing the electrical lanes for BER ~10^{-8} doesn't significantly impact the FEC gain available for the optics; but it does significantly reduce the Q (in amplitude and time domain) required from the electrical channel. Fibre Channel is currently studying this.

Jitter through the optical link

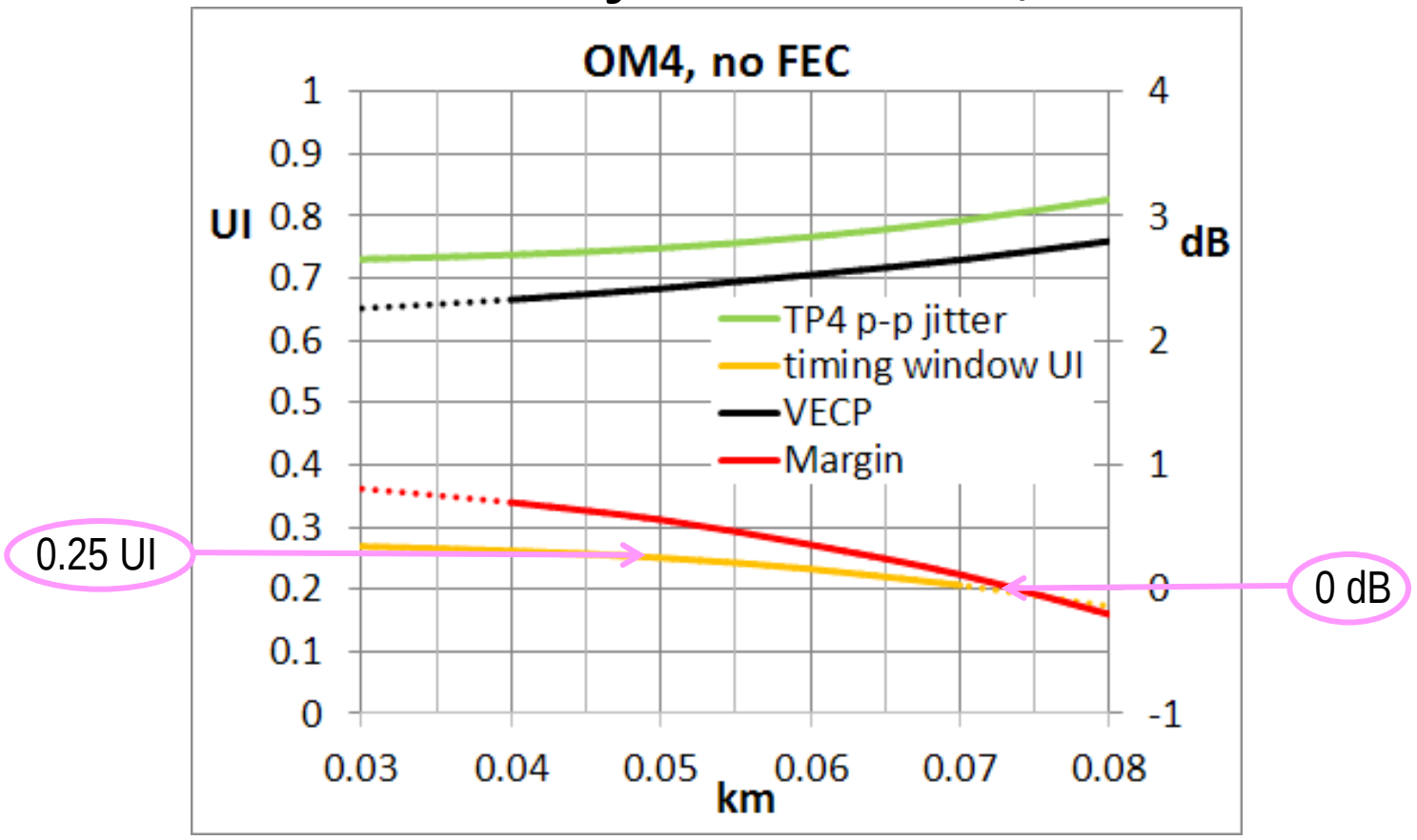
- Although these are retimed links, the worst case link jitter budget from the module input CDR (‘TP1’) to output CDR (‘TP4’) needs to be considered.



CDR output jitter
(per slide 6)

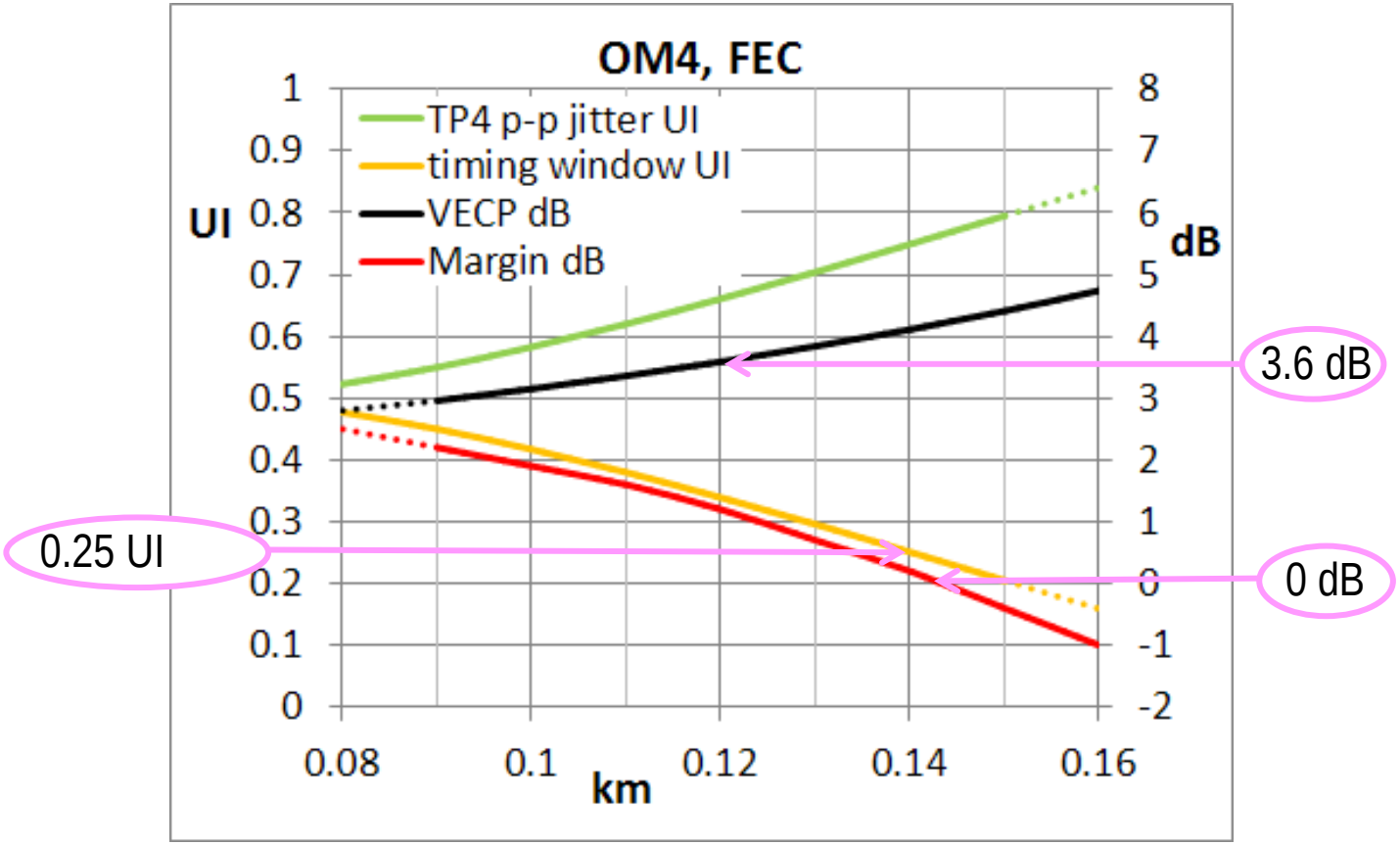
CDR input jitter tolerance
Max p-p jitter = 0.75 UI
at appropriate timing Q

Reach vs ‘TP4’ jitter: OM4, no FEC



- 50 m reach set by min 0.25 UI timing window

Reach vs TP4 jitter: OM4, FEC



- 120 m reach set by max 3.6 dB VECP

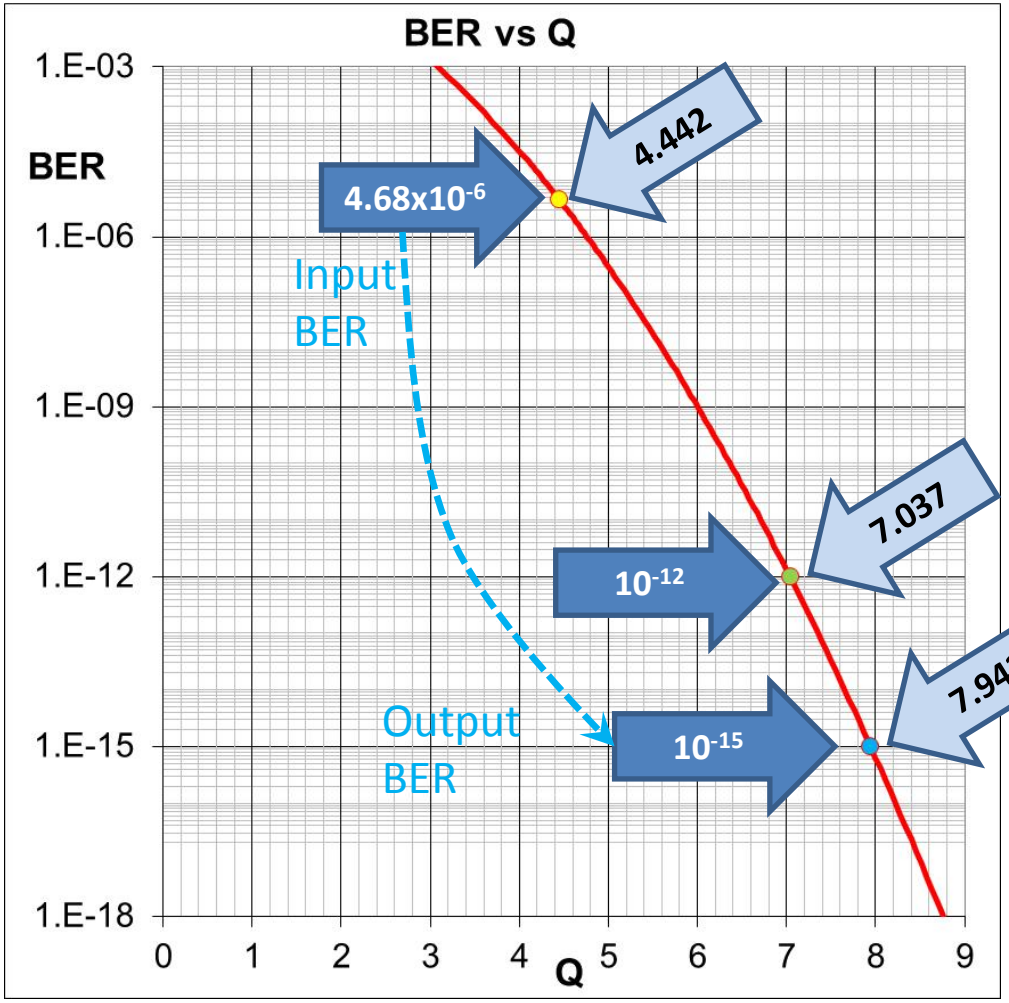
Conclusions

- 100GBASE-SR4 can benefit substantially from the FEC available at a common 100GBASE-CR4/SR4 port
  - Enables 120 m on OM4 with FEC enabled
  - Enables 10^{-15} corrected BER rate
  - Lowest module cost vs reach

- With FEC disabled, the same module would be capable of 50 m on OM4 (at BER = 10^{-12})

Back up

BER vs Q



For RS(528,524,7,10)

- Uncorrected BER = 4.68 x 10^{-6} yields corrected BER = 10^{-15}
- Uncorrected Q = 4.442 , corrected Q ≡ 7.943
- (Q = 7.037 for BER = 10^{-12})
  (Q = 7.943 for BER = 10^{-15})

Model snapshot: 25.8Gb/s, OM4, with FEC

Spreadsheet by Del Hanson, David Cunningham, Piers Dawe, David Dolfi Agilent Technologies — Rev. 3.2/3 — This file 10GEPBud3_1_16a.xls of 17-Oct-01 — Model/format rev 3.1.16a of 31-Oct-01

Basics	Input=	Bold		Ts(20-80)	21	ps	Case: 850nm serial	50MMF	Attenuation=	3.5	dB/km	NomSens OMA	-9.70	dBm	Margin	1.29	dB at
	Q=	4.05		Ts(10-90)	32	ps	*Target* Target reach	0.120	*Fiber* at	850	nm	*Receive* Refl Rx	-12	dB	*Answer!*		0.12 km
	Base Rate=	25781	MBd	RIN(OMA)	-130	dB/Hz	*and* L_start=	0.036	C_att=	1.00		Rec_BW=	#####	MHz	est Rx BW	18750	MHz
Transmitter				RIN at MinER	-138.0	dB/Hz	*graph* L_inc=	0.008	Attenuation=	3.62	dB/km	c_rx	329	ns.MHz			
Wavelength Uc		840	nm	RIN_Coef=	0.70		Power Budget P=	7.70	at	840	nm	T_rx(10-90)	17.3	ps	Test Source ER=		
Uw (see notes)		0.60	nm	Det.Jitter	4.7	ps inc. DCD	Connections etc	1.5	Disp. min. Uo=	1316	nm	TP4 Eye	8	ps	*Test Tx*	6.5	dB
Tx pwr OMA=		-2.00	dBm	DCD_DJ=	2.14	ps TP3	Pwr.Bud.-Conn.Loss	6.2	Disp. So=	0.1028	ps/nm^2*km	Opening		(=Tx ey	TestERper	1.98	dBo
Min. Ext Ratio=		3.65	dB	Effect. DJ=	0.07	(UI) ex DCD	C1=	480	Disp. D1=	-108.41	ps/(nm.km)						
Worst"ave.TxPwr		-1.0	dBm	MPN k(OMA)	0.3		Reflection Noise factor	0				RMS Baseline wander SD	0.013	fraction of 1/2 eye			
Ext. ratio penalty		4.01	dBo	Tx eye height	43.8%		Effective Rate	27287	(not in use)	10					V.E.C.P.	3.61	dBo
Tx mask X1=		0.3	UI	Refl Tx	-12	dB	Tb_eff=	37	BWm=	4400	MHz*km	P_BLW(no ISI)	0.01	dB			Stressed
	X2=	0.4	UI	ModalNoisePen	0.3	dB	Effective Rec Eye	0.21	Eff. BWm=	######	MHz*km	P_BLW	0.01	dB			Rx sens
	Y1=	0.25		Tx mask top	0.2	UI											

L	Patt	Ch IL	D1.L	D2.L	BWcd	effBWm	Te	Tc	Pisi	P Eye	P_DJ	P_DJ	Preflection					Pcross	Ptotal	<Ptotal	LP Pen		OMA
									central	corners	central	corners	central	Beta	SDmpn	Pmpn	Prin	central	central	corners	central	Margin	central
(km)	(dB)	(dB)	ps/nm	ps/nm	(MHz)	(MHz)	(ps)	(ps)	J=0, dB	(dB)	(dB)	(dB)	(dB)			(dB)	(dB)	(dB)	(dB)	(dB)	(dB)	(dB)	(dBm)
0.002	0.01	1.51	-0.22	0.00	1E+06	######	32	36	2.15	0.24	0.03	0.19		-1E-02	0.00	0.00		0.02	2.50	2.91	2.5	3.7	-5.1
0.036	**0.13**	**1.63**	**-3.9**	**0.00**	**79,857**	**######**	**33**	**37**	**2.28**	**0.24**	**0.03**	**0.19**	**0**	**-0.20**	**0.01**	**0.00**	**0.19**	**0.05**	**3.0**	**3.4**	**2.8**	**3.2**	**-5.4**
0.044	0.16	1.66	-4.8	0.00	64,749	99,099	33	37	2.34	0.25	0.03	0.20	0	-0.25	0.01	0.01	0.19	0.05	3.1	3.5	2.9	3.1	-5.5
0.053	0.19	1.69	-5.7	0.00	54,448	83,333	34	38	2.42	0.25	0.03	0.20	0	-0.29	0.02	0.01	0.19	0.05	3.2	3.6	3.0	3.0	-5.5
0.061	0.22	1.72	-6.6	0.00	46,975	71,895	34	38	2.52	0.25	0.03	0.20	0	-0.34	0.02	0.02	0.19	0.05	3.3	3.7	3.1	2.9	-5.5
0.07	0.25	1.75	-7.5	0.00	41,305	63,218	35	39	2.62	0.25	0.03	0.20	0	-0.39	0.03	0.03	0.19	0.06	3.5	3.9	3.2	2.7	-5.6
0.078	**0.28**	**1.78**	**-8.5**	**0.00**	**36,857**	**56,410**	**35**	**39**	**2.74**	**0.25**	**0.03**	**0.20**	**0**	**-0.43**	**0.04**	**0.05**	**0.19**	**0.06**	**3.7**	**4.1**	**3.4**	**2.5**	**-5.6**
0.086	0.31	1.81	-9.4	0.00	33,274	50,926	36	40	2.88	0.25	0.03	0.20	0	-0.48	0.04	0.07	0.19	0.07	3.9	4.3	3.5	2.3	-5.7
0.095	0.34	1.84	-10.3	0.00	30,325	46,414	37	41	3.03	0.25	0.03	0.20	0	-0.53	0.05	0.10	0.20	0.08	4.1	4.5	3.7	2.1	-5.8
0.103	0.37	1.87	-11.2	0.00	27,857	42,636	38	42	3.19	0.25	0.03	0.20	0	-0.58	0.06	0.13	0.20	0.10	4.3	4.7	4.0	1.9	-5.9
0.112	0.40	1.90	-12.1	0.00	25,760	39,427	39	43	3.37	0.25	0.03	0.20	0	-0.62	0.07	0.17	0.21	0.12	4.6	5.0	4.2	1.6	-5.9
0.12	**0.43**	**1.93**	**-13.0**	**0.01**	**23,957**	**36,667**	**40**	**43**	**3.56**	**0.25**	**0.03**	**0.20**	**0**	**-0.67**	**0.08**	**0.22**	**0.22**	**0.14**	**4.9**	**5.3**	**4.5**	**1.3**	**-6.0**

- Reach allowed by 3.6 dB vertical eye closure is 120 m on OM4
  - For a timing Q of 4.5, the p-p jitter at the input to the optical receiver CDR is 0.66 UI

Model snapshot: 25.8Gb/s, OM4, no FEC

Spreadsheet by Del Hanson, David Cunningham, Piers Dawe, David Dolfi Agilent Technologies — Rev. 3.2/3 — This file 10GEPBud3_1_16a.xls of 17-Oct-01 — Model/format rev 3.1.16a of 31-Oct-01

Basics				Case: 850nm serial	50MMF	Fiber				Margin	0.54 dB at
Input=	Bold		Ts(20-80)	21 ps	Target Target reach	0.050 km	Attenuation=	3.5 dB/km	NomSens OMA	-7.80 dBm	Answer!	0.05 km
Q=	7.04		Ts(10-90)	32 ps	and L_start=	0.036 km	at	850 nm	Receive Refl Rx	-12 dB		
Base Rate=	25781	MBd	RIN(OMA)	-130 dB/Hz	graph L_inc=	0.001 km	C_att=	1.00	Rec_BW=	##### MHz	est Rx BW	18750 MHz
Transmitter			RIN at MinER	-138.0 dB/Hz	Power Budget P=	5.80 dB	Attenuation=	3.62 dB/km	c_rx	329 ns.MHz		
Wavelength Uc	840	nm	RIN_Coef=	0.70			at	840 nm	T_rx(10-90)	17.3 ps	Test Source ER=	
Uw (see notes)	0.60	nm	Det.Jitter	4.7 ps inc. DCD	Connections etc	1.5 dB	Disp. min. Uo=	1316 nm	TP4 Eye	8 ps	Test Tx	6.5 dB
Tx pwr OMA=	-2.00	dBm	DCD_DJ=	2.14 ps TP3	Pwr.Bud.-Conn.Loss	4.3 dB	Disp. So=	0.1028 ps/nm^2*km	Opening	(=Tx ey	TestERper	1.98 dBo
Min. Ext Ratio=	3.65	dB	Effect. DJ=	0.07 (UI) ex DCD	C1=	480 ns.MHz	Disp. D1=	-108.41 ps/(nm.km)				
Worst"ave.TxPwr	-1.0	dBm	MPN k(OMA)	0.3	Reflection Noise factor	0 no units			RMS Baseline wander SD	0.013 fraction of 1/2 eye		
Ext. ratio penalty	4.01	dBo	Tx eye height	43.8%	Effective Rate	27287 MBd	(not in use)	10			V.E.C.P.	2.44 dBo
Tx mask X1=	0.3	UI	Refl Tx	-12 dB	Tb_eff=	37 ps	BWm=	4400 MHz*km	P_BLW(no ISI)	0.02 dB		Stressed
X2=	0.4	UI	ModalNoisePen	0.3 dB	Effective Rec Eye	0.21 UI	Eff. BWm=	###### MHz*km	P_BLW	0.02 dB		Rx sens
Y1=	0.25		Tx mask top	0.2 UI								

L	Patt	Ch IL	D1.L	D2.L	BWcd	effBWm	Te	Tc	Pisi central	P Eye corners	P_DJ central	P_DJ corners	Preflection central	Beta	SDmpn	Pmpn	Prin	Pcross central	Ptotal central	<Ptotal corners	LP Pen central	Margin	OMA central
(km)	(dB)	(dB)	ps/nm	ps/nm	(MHz)	(MHz)	(ps)	(ps)	J=0, dB	(dB)	(dB)	(dB)	(dB)			(dB)	(dB)	(dB)	(dB)	(dB)	(dB)	(dB)	(dBm)
0.002	0.01	1.51	-0.22	0.00	1E+06	######	32	36	2.15	0.24	0.03	0.19		-1E-02	0.00	0.00		0.05	2.53	2.95	2.5	1.8	-4.4
0.036	**0.13**	**1.63**	**-3.9**	**0.00**	**79,857**	**######**	**33**	**37**	**2.28**	**0.24**	**0.03**	**0.19**	**0**	**-0.20**	**0.01**	**0.01**	**0.64**	**0.18**	**3.6**	**4.0**	**3.4**	**0.7**	**-5.2**
0.037	0.14	1.64	-4.1	0.00	76,867	######	33	37	2.29	0.24	0.03	0.20	0	-0.21	0.01	0.01	0.64	0.18	3.6	4.0	3.4	0.7	-5.2
0.039	0.14	1.64	-4.2	0.00	74,094	######	33	37	2.30	0.24	0.03	0.20	0	-0.22	0.01	0.01	0.64	0.18	3.6	4.0	3.5	0.7	-5.2
0.04	0.15	1.65	-4.4	0.00	71,513	######	33	37	2.31	0.24	0.03	0.20	0	-0.22	0.01	0.01	0.64	0.18	3.6	4.0	3.5	0.7	-5.2
0.042	0.15	1.65	-4.5	0.00	69,107	######	33	37	2.32	0.24	0.03	0.20	0	-0.23	0.01	0.01	0.64	0.19	3.6	4.0	3.5	0.7	-5.2
0.043	**0.16**	**1.66**	**-4.7**	**0.00**	**66,857**	**######**	**33**	**37**	**2.33**	**0.24**	**0.03**	**0.20**	**0**	**-0.24**	**0.01**	**0.02**	**0.63**	**0.19**	**3.7**	**4.1**	**3.5**	**0.6**	**-5.2**
0.044	0.16	1.66	-4.8	0.00	64,749	99,099	33	37	2.34	0.25	0.03	0.20	0	-0.25	0.01	0.02	0.63	0.19	3.7	4.1	3.5	0.6	-5.2
0.046	0.17	1.67	-5.0	0.00	62,769	96,070	33	37	2.36	0.25	0.03	0.20	0	-0.26	0.01	0.02	0.63	0.19	3.7	4.1	3.5	0.6	-5.3
0.047	0.17	1.67	-5.1	0.00	60,908	93,220	33	37	2.37	0.25	0.03	0.20	0	-0.26	0.01	0.02	0.63	0.19	3.7	4.1	3.5	0.6	-5.3
0.049	0.18	1.68	-5.3	0.00	59,153	90,535	33	38	2.38	0.25	0.03	0.20	0	-0.27	0.02	0.02	0.63	0.19	3.7	4.1	3.6	0.6	-5.3
0.05	**0.18**	**1.68**	**-5.4**	**0.00**	**57,497**	**88,000**	**33**	**38**	**2.39**	**0.25**	**0.03**	**0.20**	**0**	**-0.28**	**0.02**	**0.03**	**0.63**	**0.20**	**3.8**	**4.2**	**3.6**	**0.5**	**-5.3**

- Reach limited by power budget and jitter: 50 m on OM4
  - max TJ = 0.75 UI at the input to the optical receiver CDR

Model snapshot: 25.8Gb/s, OM3, with FEC

Spreadsheet by Del Hanson, David Cunningham, Piers Dawe, David Dolfi Agilent Technologies										Rev.	3.2/3	This file		10GEPBud3_1_16a.xls			of	17-Oct-01	
Basics	Input=	**Bold**	Ts(20-80)	**21**	ps	Case: 850nm serial	**newMMF**			Attenuation=	**3.5**	dB/km		Model/format rev	3.1.16a		of	31-Oct-01	
	Q=	**4.50**	Ts(10-90)	32	ps	*Target*	Target reach	**0.08**	km	*Fiber* at	850	nm	NomSens OMA	**-9.70**	dBm		Margin	1.64	dB at
	Base Rate=	**25781**	MBd	RIN(OMA)	**-130**	dB/Hz	*and*	L_start=	**0.001**	km	C_att=	1.00	*Receive*	Refl Rx	**-12**	dB	*Answer!*	0.08 km	
Transmitter			RIN at MinER	-138.0	dB/Hz	*graph*	L_inc=	**0.008**	km	Attenuation=	3.62	dB/km	Rec_BW=	**#####**	MHz	est Rx BW	**18750**	MHz	
Wavelength Uc	**840**	nm	RIN_Coef=	**0.70**		Power Budget P=	7.70	dB	at	840	nm		c_rx	**329**	ns.MHz				
Uw (see notes)	**0.60**	nm	Det.Jitter	**4.7**	ps inc. DCD	Connections C	**1.5**	dB	Disp. min. Uo=	**1316**	nm	T_rx(10-90)	17.3	ps	Test Source ER=				
Tx pwr OMA=	**-2.00**	dBm	DCD_DJ=	**2.14**	ps TP3	Pwr.Bud.-Conn.Loss	6.2	dB	Disp. So=	**0.1028**	ps/nm^2*km	TP4 Eye	8	ps	*Test Tx*	**6.5**	dB		
Min. Ext Ratio=	3.65	dB	Effect. DJ=	0.07	(UI) ex DCD	C1=	**480**	ns.MHz	Disp. D1=	-108.41	ps/(nm.km)	Opening	(=Tx ey	TestERpe	1.98	dBo			
Worst"ave.TxPwr	**-1.0**	dBm	MPN k(OMA)	**0.3**		Reflection Noise factor	**0**	no units		RMS Baseline wander SD	**0.013**	fraction of 1/2 eye							
Ext. ratio penalty	4.01	dBo	Tx eye height	43.8%		Effective Rate	27287	MBd	(not in use)	**10**			V.E.C.P.	3.55	dBo				
Tx mask X1=	**0.3**	UI	Refl Tx	**-12**	dB	Tb_eff=	37	ps	BWm=	**2000**	MHz*km	P_BLW(no ISI)	0.01	dB	Stressed				
X2=	**0.4**	UI	ModalNoisePen	**0.3**	dB	Effective Rec Eye	0.21	UI	Eff. BWm=	######	MHz*km	P_BLW	0.01	dB	Rx sens				
Y1=	**0.25**		Tx mask top	0.2	UI														

L (km)	Patt (dB)	Ch IL (dB)	D1.L ps/nm	D2.L ps/nm	BWcd (MHz)	effBWm (MHz)	Te (ps)	Tc (ps)	Pisi central J=0, dB	P Eye corners (dB)	P_DJ central (dB)	P_DJ corners (dB)	Preflection central (dB)	Beta	SDmpn	Pmpn (dB)	Prin (dB)	Pcross central (dB)	Ptotal central (dB)	<Ptotal corners (dB)	LP Pen central (dB)	Margin (dB)	OMA central (dBm)
0.002	0.01	1.51	-0.22	0.00	1E+06	######	32	36	2.15	0.24	0.03	0.19		-1E-02	0.00	0.00		0.02	2.51	2.92	2.5	3.7	-5.5
0.001	**0.00**	**1.50**	**-0.1**	**0.00**	**#####**	**######**	**32**	**36**	**2.15**	**0.24**	**0.03**	**0.19**	**0**	**-0.01**	**0.00**	**0.00**	**0.24**	**0.06**	**2.8**	**3.2**	**2.8**	**3.4**	**-5.7**
0.009	0.03	1.53	-1.0	0.00	#####	######	32	36	2.17	0.24	0.03	0.19	0	-0.05	0.00	0.00	0.24	0.06	2.8	3.2	2.8	3.4	-5.7
0.017	0.06	1.56	-1.8	0.00	#####	######	32	37	2.21	0.24	0.03	0.19	0	-0.09	0.00	0.00	0.24	0.06	2.9	3.3	2.8	3.3	-5.8
0.025	0.09	1.59	-2.7	0.00	#####	80,972	33	37	2.28	0.24	0.03	0.19	0	-0.14	0.00	0.00	0.24	0.06	3.0	3.4	2.9	3.2	-5.8
0.033	0.12	1.62	-3.5	0.00	88,185	61,350	33	38	2.37	0.25	0.03	0.20	0	-0.18	0.01	0.00	0.24	0.06	3.1	3.5	3.0	3.1	-5.8
0.041	**0.15**	**1.65**	**-4.4**	**0.00**	**70,984**	**49,383**	**34**	**38**	**2.49**	**0.25**	**0.03**	**0.20**	**0**	**-0.23**	**0.01**	**0.00**	**0.24**	**0.06**	**3.3**	**3.7**	**3.1**	**2.9**	**-5.9**
0.048	0.18	1.68	-5.2	0.00	59,398	41,322	35	39	2.64	0.25	0.03	0.20	0	-0.27	0.01	0.01	0.24	0.06	3.5	3.9	3.3	2.7	-5.9
0.056	0.20	1.70	-6.1	0.00	51,063	35,524	36	40	2.81	0.25	0.03	0.20	0	-0.31	0.02	0.02	0.24	0.07	3.7	4.1	3.5	2.5	-5.9
0.064	0.23	1.73	-7.0	0.00	44,779	31,153	37	41	3.01	0.25	0.03	0.20	0	-0.36	0.03	0.03	0.25	0.08	3.9	4.3	3.7	2.3	-6.0
0.072	0.26	1.76	-7.8	0.00	39,873	27,739	38	42	3.24	0.25	0.03	0.20	0	-0.40	0.03	0.04	0.26	0.09	4.2	4.6	4.0	2.0	-6.0
0.08	**0.29**	**1.79**	**-8.7**	**0.00**	**35,936**	**25,000**	**40**	**43**	**3.50**	**0.25**	**0.03**	**0.20**	**0**	**-0.45**	**0.04**	**0.07**	**0.27**	**0.11**	**4.6**	**5.0**	**4.3**	**1.6**	**-6.1**

- Reach allowed by 3.6 dB vertical eye closure is 80 m on OM3
  - For a timing Q of 4.5, the p-p jitter at the input to the optical receiver CDR is 0.53 UI

Model snapshot: 25.8Gb/s, OM3, no FEC

Spreadsheet by Del Hanson, David Cunningham, Piers Dawe, David Dolfi Agilent Technologies — Rev. 3.2/3 — This file 10GEPBud3_1_16a.xls of 17-Oct-01

Basics	Input=	**Bold**		Ts(20-80)	**21**	ps	Case: 850nm serial	**newMMF**	Attenuation=	**3.5**	dB/km	Model/format rev	3.1.16a	of	31-Oct-01														
	Q=	**7.04**		Ts(10-90)	32	ps	*Target* Target reach	**0.05**	km	*Fiber* at	850	nm	NomSens OMA	**-7.80**	dBm	Margin	0.25	dB at											
	Base Rate=	**25781**	MBd	RIN(OMA)	**-130**	dB/Hz	*and* L_start=	**0.001**	km	C_att=	1.00		*Receive* Refl Rx	**-12**	dB	*Answer!*		0.05 km										
Transmitter				RIN at MinER	-138.0	dB/Hz	*graph* L_inc=	**0.005**	km	Attenuation=	3.62	dB/km	Rec_BW=	**#####**	MHz	est Rx BW	**18750**	MHz										
Wavelength Uc		**840**	nm	RIN_Coef=	**0.70**		Power Budget P=	5.80	dB	at	840	nm	c_rx	**329**	ns.MHz													
Uw (see notes)		**0.60**	nm	Det.Jitter	**4.7**	ps inc. DCD	Connections C	**1.5**	dB	Disp. min. Uo=	**1316**	nm	T_rx(10-90)	17.3	ps	Test Source ER=												
Tx pwr OMA=		**-2.00**	dBm	DCD_DJ=	**2.14**	ps TP3	Pwr.Bud.-Conn.Loss	4.3	dB	Disp. So=	**0.1028**	ps/nm^2*km	TP4 Eye	8	ps	*Test Tx*	**6.5**	dB										
Min. Ext Ratio=		3.65	dB	Effect. DJ=	0.07	(UI) ex DCD	C1=	**480**	ns.MHz	Disp. D1=	-108.41	ps/(nm.km)	Opening		(=Tx ey	TestERper	1.98	dBo										
Worst"ave.TxPwr		**-1.0**	dBm	MPN k(OMA)	**0.3**		Reflection Noise factor	**0**	no units				RMS Baseline wander SD	**0.013**	fraction of 1/2 eye													
Ext. ratio penalty		4.01	dBo	Tx eye height	43.8%		Effective Rate	27287	MBd	(not in use)	**10**					V.E.C.P.	2.72	dBo										
Tx mask X1=		**0.3**	UI	Refl Tx	**-12**	dB	Tb_eff=	37	ps	BWm=	**2000**	MHz*km	P_BLW(no ISI)	0.02	dB			Stressed											
X2=		**0.4**	UI	ModalNoisePen	**0.3**	dB	Effective Rec Eye	0.21	UI	Eff. BWm=	######	MHz*km	P_BLW	0.02	dB			Rx sens											
Y1=		**0.25**		Tx mask top	0.2	UI																							

L	Patt	Ch IL	D1.L	D2.L	BWcd	effBWm	Te	Tc	Pisi central	P Eye corners	P_DJ central	P_DJ corners	Preflection central	Beta	SDmpn	Pmpn	Prin	Pcross central	Ptotal central	<Ptotal corners	LP Pen central	Margin	OMA central
(km)	(dB)	(dB)	ps/nm	ps/nm	(MHz)	(MHz)	(ps)	(ps)	J=0, dB	(dB)	(dB)	(dB)	(dB)			(dB)	(dB)	(dB)	(dB)	(dB)	(dB)	(dB)	(dBm)
0.002	0.01	1.51	-0.22	0.00	1E+06	######	32	36	2.15	0.24	0.03	0.19		-1E-02	0.00	0.00		0.05	2.53	2.95	2.5	1.8	-4.1
0.001	**0.00**	**1.50**	**-0.1**	**0.00**	#####	######	**32**	**36**	**2.15**	**0.24**	**0.03**	**0.19**	**0**	**-0.01**	**0.00**	**0.00**	**0.65**	**0.17**	**3.3**	**3.7**	**3.3**	**1.0**	**-4.8**
0.006	0.02	1.52	-0.6	0.00	#####	######	32	36	2.16	0.24	0.03	0.19	0	-0.03	0.00	0.00	0.65	0.17	3.3	3.7	3.3	1.0	-4.8
0.011	0.04	1.54	-1.2	0.00	#####	######	32	36	2.18	0.24	0.03	0.19	0	-0.06	0.00	0.00	0.65	0.17	3.4	3.8	3.3	0.9	-4.8
0.016	0.06	1.56	-1.7	0.00	#####	######	32	37	2.20	0.24	0.03	0.19	0	-0.09	0.00	0.00	0.65	0.17	3.4	3.8	3.4	0.9	-4.8
0.021	0.07	1.57	-2.2	0.00	#####	97,087	32	37	2.24	0.24	0.03	0.19	0	-0.11	0.00	0.00	0.64	0.18	3.5	3.9	3.4	0.8	-4.9
0.026	**0.09**	**1.59**	**-2.8**	**0.00**	#####	**78,431**	**33**	**37**	**2.29**	**0.24**	**0.03**	**0.20**	**0**	**-0.14**	**0.00**	**0.00**	**0.64**	**0.18**	**3.5**	**3.9**	**3.4**	**0.8**	**-4.9**
0.03	0.11	1.61	-3.3	0.00	94,567	65,789	33	37	2.34	0.25	0.03	0.20	0	-0.17	0.01	0.00	0.63	0.18	3.6	4.0	3.5	0.7	-4.9
0.035	0.13	1.63	-3.8	0.00	81,440	56,657	34	38	2.41	0.25	0.03	0.20	0	-0.20	0.01	0.01	0.63	0.18	3.7	4.1	3.6	0.6	-4.9
0.04	0.15	1.65	-4.4	0.00	71,513	49,751	34	38	2.49	0.25	0.03	0.20	0	-0.22	0.01	0.01	0.63	0.19	3.8	4.2	3.6	0.5	-4.9
0.045	0.16	1.66	-4.9	0.00	63,744	44,346	34	39	2.58	0.25	0.03	0.20	0	-0.25	0.01	0.02	0.63	0.20	3.9	4.3	3.7	0.4	-5.0
0.05	**0.18**	**1.68**	**-5.4**	**0.00**	**57,497**	**40,000**	**35**	**39**	**2.67**	**0.25**	**0.03**	**0.20**	**0**	**-0.28**	**0.02**	**0.03**	**0.63**	**0.21**	**4.1**	**4.5**	**3.9**	**0.2**	**-5.0**

- Reach limited by power budget and jitter: 50 m on OM3
  - max TJ = 0.75 UI at the input to optical receiver CDR (‘TP4’)