Review of the 10Gigabit Ethernet Link Model

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Abstract

The theoretical model used by 10Gigabit Ethernet IEEE 802.3ae to develop the optical physical layer specifications is presented. The model calculates the penalties associated with laser-based transceivers for both singlemode (SMF) and multimode fiber (MMF). Key assumptions and limitations of the model are explained. A spreadsheet implementation of the model, used by 10Gigabit Ethernet, is reviewed.

Introduction to 10Gigabit Ethernet

10Gigabit Ethernet (IEEE 802.3ae) represents the coming together of both data communications and telecommunications. Initially, it will be a switch-to-switch interconnection for statistically multiplexing packet traffic from lower data rate (10/100/1000 Mb/s) Ethernets. Therefore, 10Gigabit Ethernet is primarily a backbone technology that is targeted at the enterprise LAN or the telecom WAN. This use of 10Gigabit Ethernet is illustrated in Figure 1, which shows various locations interconnected by a 10Gigabit Ethernet MAN. At each location the 10Gigabit Ethernet capable switch/router multiplexes the traffic from the local 10/100/1000 Ethernet LAN onto the 10Gigabit Ethernet MAN – no end station (computer) has a 10 Gb/s connection.

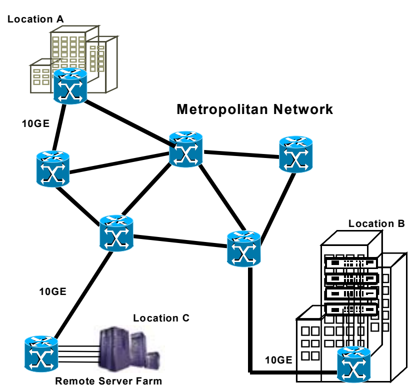

Figure 1. 10Gigabit Ethernet used as a native MAN

Since 10Gigabit Ethernet will be used both within the LAN and the WAN a relatively wide range of link types, ranges and media are included in its specification (see Table 1). 10Gigabit Ethernet will define a standard that guarantees interoperation between different vendors' implementations. Because only a slight change will be made to the medium access control (MAC) the standardization is dominated by the specification of physical layers (PHY). A major challenge addressed by the standardization effort has been the development of specifications that are friendly to directly modulated lasers – this will facilitate very cost effective implementations.

Description	Name	Comments
850 nm Serial LAN PHY	10GBASE-SR	Directly modulated VCSEL, MMF, 2-300 m
1310 nm Serial LAN PHY	10GBASE-LR	Directly modulated DFB laser, SMF, 2-10 km
1550 nm Serial LAN PHY	10GBASE-ER	Modulator, DFB laser, SMF, 2-40 km
1310 nm WWDM LAN PHY	10GBASE-LX4	Directly modulated VCSELs or DFBs, MMF (300 m) or SMF (2-10 km)
850 nm Serial WAN PHY	10GBASE-SW	Directly modulated VCSEL, MMF, 2-300 m
1310 nm Serial WAN PHY	10GBASE-LW	Directly modulated DFB laser, SMF, 2-10 km
1550 nm Serial WAN PHY	10GBASE-EW	Modulator, DFB laser, SMF, 2-40 km

Table 1 10Gigabit Ethernet Port Types

A model was developed as a tool to assist the physical layer committee of the 10Gigabit Ethernet (IEEE 802.3ae) standard to understand potential trade-offs between the various link penalties associated with laser-based backbone links. An objective for the model is for it to be uncomplicated and able to be implemented in a spreadsheet so that many users can work with it. Another objective of the model is to be applicable to both multimode fiber and singlemode fiber links. The purpose of this paper is to document the current version (3.1.16a, current in December 2001) of the model used by 10Gigabit Ethernet [1].

The 10Gigabit Ethernet model

The 10Gigabit Ethernet model is an extension of previously reported link models for LED and laser-based links [1-6]. Historically these link models were used to develop the specifications for FDDI, Fast Ethernet and Gigabit Ethernet. New features of the 10Gigabit Ethernet model are:

- The use of optical modulation amplitude (OMA) rather than average power (OMA is the difference between the power level of a one and the power level of a zero – see later);

- The inclusion of a term to correct for interactions between the various penalties;
- The inclusion of a penalty for baseline wander;
- The inclusion of a penalty to account for interferometric noise; and
- The inclusion of a term to account for polarization mode dispersion.

In the model, power penalties are calculated to account for the effects of intersymbol interference (ISI), baseline wander (BLW), modal noise (MN), mode partition noise (MPN), relative intensity noise (RIN), interferometric (reflection) noise and a term to correct for interactions between the various penalties. In addition, power penalty allocations are made for the power losses due to fiber attenuation, connectors and splices.

Application of the model
In common with earlier link models the 10Gigabit Ethernet model has been produced to aid the development of the optical specifications of the standard. Peer review and experiments in multiple laboratories validated the previous models, which formed the foundation for the 10Gigabit Ethernet model. The model is viewed to perform a reasonable worst case analysis – consistent with the Ethernet tradition. Recently, the 10Gigabit Ethernet community has begun its own testing and as expected from past experience the model seems slightly pessimistic.

It is important to note that the model is not designed for transceiver development but is an agreed framework for comparing options presented to standards bodies. The model is open to peer review within the 10Gigabit Ethernet committee. To aid the drafting of the standard the model has been designed to output many of the optical specifications.

Structure of this paper
The rest of this paper is organized as follows:

- Overview of the link model – outlines the power budget approach.
- Spreadsheet implementation of the model – describes the spreadsheet implementation with screen shots and an example graph.
- Theoretical detail – provides the detailed power penalty equations with brief descriptions.
- Conclusions.
- References.
- Appendix A – lists the input parameters of the link model.

Overview of the link model
The link model is based on a power budget calculation. Power penalties, sometimes referred to as AC penalties, are allocated for link impairments such as noise and dispersion. Power loss is also included to account for connectors and fiber attenuation. The power penalties and losses are added linearly in decibels to determine the total link penalty as a function of length. Additionally, a correction term is used to account for the interaction between penalties. Usually, the correction term is small. For this reason previous link models (Gigabit Ethernet) ignored this correction term. However, due the increase in data rate, and to be safe, 10Gigabit Ethernet included the correction.

In the model, it is assumed that the laser and fiber impulse responses are Gaussian. However, it is assumed that the optical receiver is non-equalized and has 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. These calculated rise times, fall times and bandwidths are used to determine the fiber and composite channel exit response and the ISI penalty of the optical communications link. It is assumed that rise times and fall times are equal and only the rise time is referred to throughout the rest of this paper.

It is normal for optical specifications to refer to the 20%-80% rise time. However, throughout this paper rise time refers to the 10%-90% rise time. This can be converted to a 20%-80% rise time by dividing by 1.518 (assuming Gaussian impulse response).

The relationships between the various transmit and receive optical powers in OMA and average powers are shown in Figure 2. The figure also shows how the power penalties are added within the model.

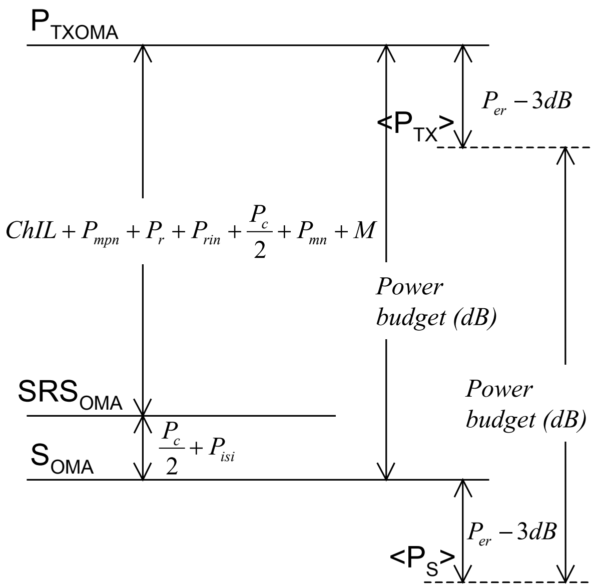

Figure 2. The 10Gigabit Ethernet power budget

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),
- $<P_{TX}>$, the average transmit power (minimum, dBm),
- $<P_s>$, 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).

From Figure 2 the following equations can be derived:

$$SRS_{OMA} = P_{TXOMA} - ChIL - P_{mpn} - P_r - P_{rin} - \frac{P_c}{2} - P_{mn} - M \qquad (1)$$

and

$$S_{OMA} = SRS_{OMA} - \frac{P_c}{2} - P_{isi} \qquad (2)$$

In the model M is given by:

$$M = P - C - P_T \qquad (3)$$

where *P* is the power budget (in dB – see Figure 2), C is the loss due to connections,

$$P_T = P_{isi} + P_{mpn} + P_r + P_{rin} + P_{mn} + P_c + Att \qquad (4)$$

and Att is the optical attenuation (in dB) of the cable.

For consistency, this paper uses the same units and dimensions as the spreadsheet implementation of the model (see Figures 3-5 and Appendix A).

Spreadsheet implementation of model

For ease of use the model is implemented as an Excel program. Within the program each physical media dependent (PMD) type is allocated one page which is populated with input parameter values relevant to a particular link case – the equations used on every page are identical. The spreadsheet implementation is openly available via the world-wide-web [1].

The spreadsheet is organized into various regions as follows:

- Columns A-X, rows 1-14 are dedicated to input parameters and calculation of various results or intermediate parameters.
- The input parameters are shown in bold text (for clarity a listing of the input parameters is given in Appendix A of this paper).
- Columns A-X, rows 15-38 are dedicated to calculating and printing the various rise times, power penalties, losses and margins as a function of link length.
- When printing a page including the above (columns A-X, rows 1-38), a graph of the results and example eye diagrams is output.
- For calculation of various intermediate results and functions a non-printable second page (columns Y-AW, rows 1-69) is included in the spreadsheet.

Figures 3-5 show how the spreadsheet appears on screen for 10GBASE-LR as an example case. In the example, the results section has been adjusted to plot results for two link lengths: 2 m and 10 km. Also, a graph of the output results for the 10GBASE-LR example case is shown in Figure 6. The units of the various input parameters and results are documented in the figures.

Basics	Input=	**Bold**			Ts(20-80)	**47.1** ps		
	Q=	**7.04**			Ts(10-90)	71 ps		
	Base Rate=	**10312.5** MBd			RIN(OMA)	**-130** dB/Hz		
Transmitter					RIN at MinER	-137.3 dB/Hz		
Wavelength	Uc	**1260** nm			RIN_Coef=	**0.70**		
Uw (see notes)		**0.20** nm			Det.Jitter	**6.0** ps inc. DCD		
Tx pwr OMA=		-3.20 dBm			DCD_DJ=	**6** ps TP3		
Min. Ext Ratio=		4.00 dB			Effect. DJ=	0.00 (UI) ex DCD		
"Worst"ave.TxPwr		**-2.55** dBm			MPN k(OMA)	**0**		
Ext. ratio penalty		3.66 dBo			Tx eye height	56.5%		
Tx mask	X1=	**0.3** UI			Refl Tx	**-12** dB		
	X2=	**0.4** UI			ModalNoisePen	**0** dB		
	Y1=	**0.25**			Tx mask top	0.2 UI		
L	Patt	Ch IL	D1.L	D2.L	BWcd	effBWm	Te	Tc
(km)	(dB)	(dB)	ps/nm	ps/nm	(MHz)	(MHz)	(ps)	(ps)
0.002	0.00	2.00	-0.01	0.00	7E+07	1.7E+08	71	83
10.00	**4.20**	**6.20**	**-64.2**	**0.13**	**14,561**	**33,333**	**80**	**91**
A	B	C	D	E	F	G	H	I

Figure 3. Columns A-I, rows 1-18 of spreadsheet

Case: 1310nm serial			**SMF**		Attenuation=		**0.4** dB/km		
Target	Target reach		**10.00** km		*Fiber*	at	1310 nm		
and	L_start=		**10.0** km			C_att=	0.27		
graph	L_inc=		**0.25** km		Attenuation=		0.42 dB/km		
	Power Budget P=		9.39 dB			at	1260 nm		
	Connections C		**2** dB		Disp. min. Uo=		**1324** nm		
	Pwr.Bud.-Conn.Loss		7.39 dB		Disp. So=		**0.093** ps/nm^2*km		
	C1=		**480** ns.MHz		Disp. D1=		-6.42 ps/(nm.km)		
Reflection Noise factor			**0.6** no units						
	Effective Rate		10993 MBd		PolMD DGDmax		**10** ps at target 10km		
	Tb_eff=		91 ps			BWm=	**1E+06** MHz*km		
	Effective Rec Eye		0.21 UI			Eff. BWm=	3.3E+05 MHz*km		
Tc	Pisi central	P Eye corners	P_DJ central	P_DJ corners	Preflection central	Beta	SDmpn	Pmpn	Prin
(ps)	J=0, dB	(dB)	(dB)	(dB)	(dB)			(dB)	(dB)
83	1.69	0.24	0.00	0.00		-9E-05	0.00	0.00	
91	**2.20**	**0.25**	**0.00**	**0.00**	**0.43**	**-0.44**	**0.00**	**0.00**	**0.23**
I	J	K	L	M	N	O	P	Q	R

Figure 4. Columns I-R, rows 1-18 of spreadsheet

Model/format rev	3.1.16a		of	31-Oct-01	
NomSens OMA	**-12.59** dBm		Margin	0.15 dB at	
Refl Rx	**-12** dB		*Answer!*		10 km
Rec_BW=	**7,725** MHz		est Rx BW	**7500** MHz	
c_rx	**329** ns.MHz				
T_rx(10-90)	42.6 ps		Test Source ER=		
TP4 Eye	19 ps		*Test Tx*	**6** dB	
Opening		(=Tx ey	TestERpen	2.23 dBo	
RMS BLW SD	**0.025**	fraction of 1/2 eye			
			V.E.C.P.	1.85	dBo
P_BLW(no ISI)	0.07 dB				Stressed
P_BLW	0.07 dB				Rx sens
Pcross central	Ptotal central	<Ptotal corners	LP Pen central	Margin	OMA central
(dB)	(dB)	(dB)	(dB)	(dB)	(dBm)
0.10	1.79	2.03	1.8	5.6	-5.4
0.19	**7.2**	**7.5**	**3.0**	**0.1**	**-10.3**
S	T	U	V	W	X

Figure 5. Columns S-X, rows 1-18 of spreadsheet

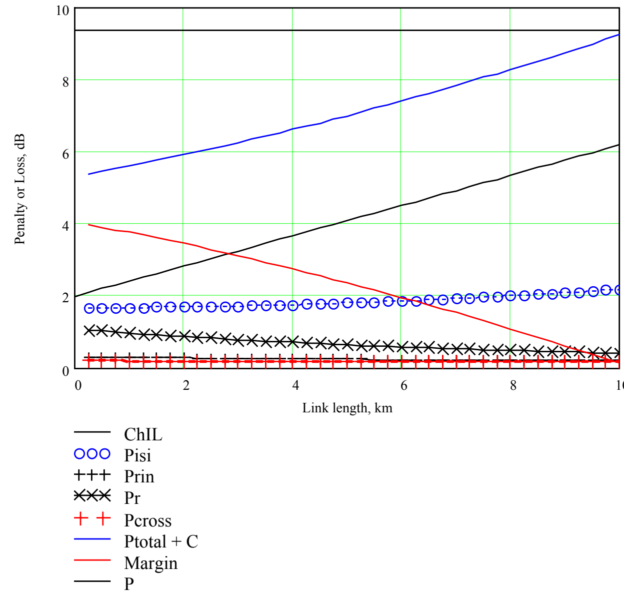

Figure 6. Example graph of spreadsheet results

The model is quite versatile, simply change the input parameters to reflect the case to be modeled. Currently, Fiber Channel has adopted the 10Gigabit Ethernet spreadsheet model as the basis for generating its 10 Gb/s specifications. In addition, the Ethernet in the First Mile (EFM), IEEE 802.3ah committee has adopted the 10Gigabit spreadsheet and will soon decide on input parameters for its 1.25 GBd link types. As EFM progresses the spreadsheet will likely evolve to include specific input parameters to account for forward error correction (FEC) and the passive couplers used for Ethernet passive optical networks (EPON).

Theoretical detail

Optical modulation amplitude (OMA)

10Gigabit Ethernet uses the optical modulation amplitude (OMA) rather than average optical power for its specifications. The relationship between average optical power and OMA is:

$$P_{av} = \frac{OMA}{2} \cdot \frac{\varepsilon + 1}{\varepsilon - 1} \qquad (5)$$

P_{av} is the optical power and ε is the laser extinction ratio; the ratio of the optical power on a "one" divided by the power on a "zero".

Risetime and bandwidth

The model converts bandwidths into 10-90% risetimes, which are combined on a sum of squares basis. Most filter responses are assumed to be Gaussian but the receiver response is assumed to be a raised cosine response.

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:

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

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]:

$$BW_{cd} = \frac{0.187}{L \cdot \sigma_\lambda} \cdot \frac{10^6}{\sqrt{D_1^2 + D_2^2}} \tag{7}$$

where

$$D_1 = \frac{S_0}{4} \cdot \left(\lambda_c - \frac{\lambda_0^4}{\lambda_c^3} \right) \tag{8}$$

and

$$D_2 = 0.7 \cdot S_0 \cdot \sigma_\lambda \tag{9}$$

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:

$$BW_{me} = \frac{BW_m}{L} \tag{10}$$

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

$$BW_{me} = \frac{L_{\max}}{3 \cdot DGD} \cdot 10^6 \tag{11}$$

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:

$$T_c = \sqrt{T_e^2 + T_r^2} \tag{12}$$

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

$$T_r = \frac{C2}{BW_r} \cdot 10^3 \tag{13}$$

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

ISI power penalty

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

$$P_{isi} = 10 \cdot \log\left(\frac{1}{2 \cdot h(0) - 1} \right) \tag{14}$$

where:

$$h(t) = \frac{1}{2} \cdot \left(\operatorname{erf}\left[\frac{2.563}{2 \cdot \sqrt{2}} \cdot \frac{(2 \cdot t + T_{eff})}{T_c} \right] - \operatorname{erf}\left[\frac{2.563}{2 \cdot \sqrt{2}} \cdot \frac{(2 \cdot t - T_{eff})}{T_c} \right] \right) \tag{15}$$

and,

$$T_{eff} = \left(\frac{1}{B \cdot 10^6} - DCD \cdot 10^{-12} \right) \cdot 10^{12} \tag{16}$$

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.

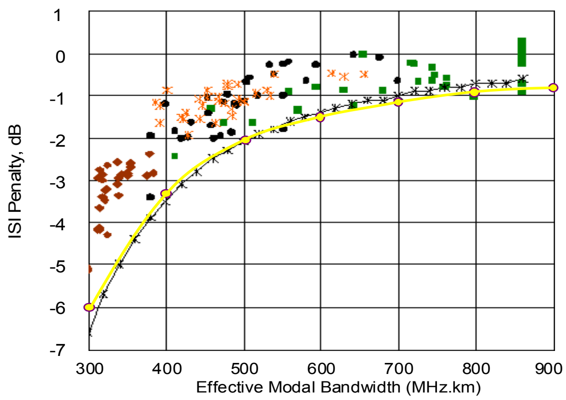

Figure 7. Measured and worst-case ISI penalty

Mode Partition Noise 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]:

$$P_{mpn} = \frac{1}{\sqrt{1-\left(Q\cdot\sigma_{mpn}\right)^2}} \qquad (17)$$

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

$$BER = \int_Q^\infty \frac{1}{\sqrt{2\pi}}\cdot\exp\left(-\frac{x^2}{2}\right)\cdot dx \qquad (18)$$

and

$$\sigma_{mpn} = \frac{k_{OMA}}{\sqrt{2}}\cdot\left\{1-\exp\left[-\left(\pi\cdot B_{eff}\cdot D\cdot L\cdot\sigma_\lambda\right)^2\right]\right\} \qquad (19)$$

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 18 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 18 is $0.5\cdot\mathrm{erfc}(Q/\sqrt{2})$.

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 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]:

$$P_\varepsilon = \frac{\varepsilon+1}{\varepsilon-1} \qquad (20)$$

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) 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:

$$P_{rin} = 10\cdot\log\left(\frac{1}{\sqrt{1-\left(\frac{Q\cdot\sigma_{rin}}{ISI_r}\right)^2}}\right) \qquad (21)$$

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:

$$\sigma_{rin}^2 = \frac{k_{rin}\cdot ISI_{test}^{\,2}\cdot 10^6}{\sqrt{\left(1/BW_{me}\right)^2+\left(1/BW_{cd}\right)^2+0.477/BW_{test}}\cdot 10^{\left(\frac{-RIN_{OMA}}{10}\right)}} \qquad (22)$$

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

$$ISI_{test} = \frac{1+O(DJ_{eff})}{2} \quad (23)$$

where the function O(x) is defined as:

$$O(x) = \mathrm{erf}\left[\frac{2.563}{2\cdot\sqrt{2}}\cdot\frac{(x+1)\cdot Teff}{T_c}\right] + \mathrm{erf}\left[\frac{2.563}{2\cdot\sqrt{2}}\cdot\frac{(1-x)\cdot Teff}{T_c}\right] - 1 \quad (24)$$

and,

$$DJ_{eff} = \frac{DJ - DCD}{T_{eff}} \quad (25)$$

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),

$$ISI_r = O(DJ_{eff}) - \frac{2\cdot R_{NF}\cdot 10^{\frac{-ChIL}{10}}\cdot GMR\cdot\sqrt{1+\varepsilon+2\cdot\varepsilon\cdot O(DJ_{eff})\cdot(\varepsilon-1)}}{(\varepsilon-1)} \quad (26)$$

$R_{NF} = 0.6$, 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 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:

$$P_r = -10\cdot\log\left[1 - \frac{2\cdot R_{NF}\cdot 10^{\frac{-ChIL}{10}}\cdot GMR\cdot\sqrt{1+\varepsilon+2\cdot\varepsilon\cdot O(DJ_{eff})\cdot(\varepsilon-1)}}{O(DJ_{eff})\cdot(\varepsilon-1)}\right] \quad (27)$$

Baseline wander 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:

$$P_{BLW} = 10\cdot\log\left(\frac{1}{\sqrt{1-\left(Q\cdot\sigma_{BLW}/ISI_{RX}\right)^2}}\right) \quad (28)$$

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

$$ISI_{RX} = \mathrm{erf}\left[\frac{2.563}{2\cdot\sqrt{2}}\cdot\frac{(W_{eff}+1)\cdot Teff}{T_{RX}}\right] + \mathrm{erf}\left[\frac{2.563}{2\cdot\sqrt{2}}\cdot\frac{(1-W_{eff})\cdot Teff}{T_{RX}}\right] - 1 \quad (29)$$

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 penalty

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

$$W_{eff} = \frac{1-2\cdot X2}{B_{eff}}\cdot 10^6 \quad (30)$$

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:

$$\mathrm{P}_{eye} = 10\cdot\log\left[\frac{1}{O(W_{eff})}\right] - P_{isi} \quad (31)$$

where T_{eff} is the effective symbol period (in ps) given by Equation 16, 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:

$$Att = L \cdot \frac{R_\lambda}{C_\lambda} \cdot \left[\left(\frac{1}{9.4 \cdot 10^{-4} \cdot \lambda_c} \right)^4 + 1.05 \right] \qquad (32)$$

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:

$$P_c = -10 \cdot \log\left[ISI_r \cdot \sqrt{1 - Q^2 \cdot \left(\sigma_{mn}{}^2 + \sigma_{mpn}{}^2 + \left\{ \left(\sigma_{BLW}{}^2 + \sigma_{rin}{}^2 \right) \Big/ ISI_r{}^2 \right\} \right)} \right] - P_{isi} - P_{mpn} - P_r - P_{rin} - P_{mn} - P_{BLW} \qquad (33)$$

Usually, P_c is less than 0.5 dB.

Conclusions
We have documented the current version of the 10Gigabit Ethernet worst-case link model. The model is an extension of the Gigabit Ethernet link model and is a simulation tool that provides a baseline for discussion on optical link specifications. To aid specification development it is designed to output many relevant specifications. Developed by contributions to and review within IEEE 802.3 it is openly available via the world-wide-web. The model is reasonably straightforward to run by simply changing the input parameters to model different cases.

However, 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.

Nevertheless, the model is the current state-of-the-art for standards-based optical specification development. It has recently been adopted by Fiber Channel and IEEE 802.3ah (EFM).

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Appendix A

Input parameters

Symbol	Description
Q	Digital signal to noise ratio.
B	Base rate or signaling speed, MBd.
λ_C	Center wavelength of the laser source, nm.
σ_λ:	Standard deviation (RMS "spectral width" of the laser spectrum, nm.
P_{TXOMA}	Transmit optical power in OMA, dBm.
ER_{min}	Minimum extinction ratio, dB.
X1	Transmit eye mask parameter, UI.
X2	Transmit eye mask parameter, UI.
Y1	Transmit eye mask parameter.
t_s	Transmit (20-80)% rise time, ps.
RIN_{OMA}	RIN relative to OMA for the laser source, dB/Hz.
k_{rin}	RIN coefficient.
DJ	Deterministic jitter at TP2, ps.
DCD	Duty cycle distortion at TP3, ps.
k_{OMA}	Mode partition noise k-factor.
R_{tx}	Transmit optical return loss (reflectance), dB.
GMR	Geometric mean of transmitter and receiver reflectance.
P_{mn}	Power penalty due to modal noise, dB.
L_{max}	Target reach, km.
L_s	Start reach, km (for graphing results).
δL	Increment of reach, km (for graphing results).
C	Loss allocated for connectors and splices, dB.

Symbol	Description
$C1$	Conversion factor; ns·MHz.
R_{NF}	Reflection noise factor.
R_λ	Actual cable attenuation in dB/km at 850 nm, 1300 nm or 1550 nm.
C_λ	Scaling factor required to calculate attenuation at a given wavelength.
λ_0	Zero dispersion wavelength, nm.
S_0	Dispersion slope parameter, ps/(nm^2·km).
DGD	Maximum differential delay due to polarization mode dispersion, ps.
BW_m	Modal bandwidth for fiber, MHz·km.
S_{OMA}	Nominal (unstressed) receiver sensitivity in OMA, dBm.
R_{rx}	Receiver optical return loss, dB.
BWr	Receiver 3 dB electrical bandwidth, MHz.
C_r	Conversion factor, ns·MHz.
σ_{BLW}	RMS baseline wander as fraction of the amplitude of the half-eye opening.
BW_{test}	Test receiver 3 dB electrical bandwidth, MHz.
ER_{test}	Test source extinction ratio, dB.

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