Annex 38A

(informative)

Optical physical media dependent link model

38A.1 Introduction

This informative annex describes the IEEE 802.3z link model for optical Physical Media Dependent (PMD) specification. The model was developed as a tool to assist IEEE 802.3z understand potential trade-offs between the various link penalties. It is an extension of previously reported models for LED-based links [1,2]. In the model power penalties are calculated to account for the effects of inter-symbol interference (ISI) [3], mode partition noise (MPN) [4], extinction ratio and relative intensity noise (RIN). In addition, a power penalty allocation is made for modal noise [5] and the power losses due to fiber attenuation, connectors and splices are considered.

The model assumes that the laser and multimode fiber impulse responses are Gaussian [2]. In addition, it is assumed that the optical receiver is non-equalized with a 3 dB electrical bandwidth of BW_r. The non-equalized receiver is assumed to have a raised cosine response [2]. The model includes expressions that convert the RMS impulse width of the laser, 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. In this annex equations for penalties or losses are in linear units unless otherwise stated.

It has been shown [6] that if h1(t) and h2(t) are positive pulses and if h3(t) = h1(t)*h2(t) (where * represents the convolution operation) then:

$$\sigma_3 = \sqrt{\sigma_1^2 + \sigma_2^2} \tag{1}$$

where σ_i is the RMS pulse width of the individual components. The 10% to 90% rise time, T_i, and the 6 dB electrical bandwidth of individual components, $BW_i(6dB)$, are related by constant conversion factors, a_i and b_i, so that:

$$\sigma_i(BW) = \frac{a_i}{BW_i(6dB)} \tag{2}$$

and

$$\sigma_i(T) = \frac{T_i}{b_i} \tag{3}$$

therefore

$$T_i = \frac{a_i \cdot b_i}{BW_i(6dB)} \tag{4}$$

Equation 1 can be generalized for an arbitrary number of components:

$$\sigma_{sys}^2 = \sum_i \sigma_i^2 \tag{5}$$

The RMS pulse widths of the individual components may therefore be used to calculate the bandwidth or the 10% to 90% rise time of the composite system if the appropriate conversion factors for each individual component are known [2]. For example the overall system rise time, T_{sys}, may be calculated using:

$$T_{sys}^2 = \sum_i \left(\frac{b_{sys}}{b_i} \cdot T_i\right)^2 = \sum_i \left(\frac{a_i \cdot b_{sys}}{BW_i(6dB)}\right)^2 = \sum_i \left(\frac{C_i}{BW_i(6dB)}\right)^2 \quad (6)$$

The Central Limit Theorem has been used to show that the composite impulse response of multimode fiber optic links tend to a Gaussian impulse [2].

38A.2 Fiber exit and channel response time

With the assumption that the fiber exit impulse response is Gaussian, equation (6) can be used to calculate the fiber 10% to 90% exit response time (T_e):

$$T_e = \sqrt{\left(\frac{C_1}{BW_m}\right)^2 + \left(\frac{C_1}{BW_{ch}}\right)^2 + T_s^{\ 2}} \quad (7)$$

where BW_m is the 3 dB optical effective modal bandwidth of the fiber link, BW_{ch} is the 3 dB optical chromatic bandwidth of the fiber link and T_s is the 10% to 90% laser rise time. It should be noted that the IEEE 802.3z specifications reference the 20%-80% laser rise time which is 1.53 times smaller than the 10%-90% laser rise time for the assumed Gaussian impulse response of the laser. Since we are assuming that the fiber has a Gaussian response, C_1=0.48.

The approximate 10% to 90% composite channel exit response time (T_c) is then:

$$T_c = \sqrt{\left(\frac{0.48}{BW_m}\right)^2 + \left(\frac{0.48}{BW_{ch}}\right)^2 + T_s^{\ 2} + \left(\frac{0.35}{BW_r}\right)^2} \quad (8)$$

for a raised cosine receiver.

38A.3 ISI penalty

The ISI penalty, P_{isi}, for a channel having a Gaussian impulse response is approximated by:

$$P_{isi} = \frac{1}{1 - 1.425 \cdot \exp\left[-1.28 \cdot \left(\frac{T}{T_c}\right)^2\right]} \quad (9)$$

where T is the baud period.

38A.4 Mode Partition Noise (MPN)

The various wavelength components of a laser output will travel at slightly different velocities through a fiber. If the power in each laser mode remained constant, then BW_{ch}, due to the time averaged optical output spectrum of the laser, would accurately account for chromatic dispersion induced ISI. However, in a multimode laser, although the total output power is constant, the power in each laser mode is not constant. As a result, power fluctuations between laser modes leads to an additional transient ISI component. This is usually referred to as mode partition noise [4]. The MPN-induced power penalty has been shown to be [4]:

$$P_{mpn} = \frac{1}{\sqrt{1-(Q \cdot \sigma_{mpn})^2}} \quad (10)$$

where the value of the digital signal to noise ratio, Q, is determined by the maximum acceptable bit error rate (BER) using [4]:

$$BER = \frac{1}{Q \cdot \sqrt{2\pi}} \cdot \exp\left(-\frac{Q^2}{2}\right) \quad (11)$$

and

$$\sigma_{mpn} = \frac{k}{\sqrt{2}} \cdot [1 - \exp[-(\pi \cdot B \cdot D \cdot L \cdot \sigma_\lambda)^2]] \quad (12)$$

where k is the laser mode partition factor ($0 \le k \le 1$), $B = \frac{1}{T}$ in ps^{-1}, D the dispersion in $\frac{ps}{km \cdot nm}$, L is the link length in km and σ_λ is the RMS width of the total laser spectrum in nanometers (nm).

38A.5 Multimode fiber chromatic bandwidth model

The chromatic dispersion of the multimode fiber link, in MHz, is [1,2]:

$$BW_{ch} = \frac{0.187}{L \cdot \sigma_\lambda} \cdot \frac{1}{\sqrt{D_1^2 + D_2^2}} \quad (13)$$

where:

$$D_1 = \frac{S_0}{4} \cdot \left(\lambda_c - \frac{\lambda_0^4}{\lambda_c^3}\right) \quad (14)$$

and

$$D_2 = S_0 \cdot \sigma_\lambda \quad (15)$$

and λ_0 is the zero dispersion wavelength, in nm, of the fiber, λ_c is the laser center wavelength, in nm, S_0 is the dispersion slope parameter at λ_0 in $\frac{ps}{km \cdot nm^2}$ and the other terms are as previously defined.

38A.6 Extinction ratio penalty

The power penalty associated with transmitting a non zero power level for a zero is [6]:

$$P_\varepsilon = \frac{1+\varepsilon}{1-\varepsilon} \quad (16)$$

where ε is the laser extinction ratio; the ratio of the optical power on “zeros” divided by the power on “ones”. In IEEE 802.3z links the extinction ratio penalty is included as part of the receiver sensitivity because it is assumed that the receiver sensitivity is measured at worst case laser extinction ratio.

38A.7 Relative Intensity Noise (RIN)

The noise variance, σ_{rin}^2, due to laser RIN can be calculated using the following equation:

$$\sigma_{rin}^2 = \alpha \cdot BW_c(6dB) \cdot 10^{\frac{RIN}{10}} \tag{17}$$

where $\alpha \approx 0.6$ for short wavelength links and $\alpha \approx 0.7$ for long wavelength links. BW_c(6dB) is the 6 dB electrical bandwidth of the link, RIN is the laser RIN in dB/Hz and α is a correction factor that accounts for the shape of the bandwidth response of the link.

The RIN induced power penalty is then:

$$P_{rin} = \frac{1}{\sqrt{1 - (Q \cdot \sigma_{rin})^2}} \tag{18}$$

Q as previously defined.

38A.8 Cable attenuation

The attenuation, in dB, of cabled optical fiber for a particular link length is modeled by the following equation where L = link length in km:

$$Attenuation = L \cdot \frac{R_\lambda}{C_\lambda} \cdot \left[\left(\frac{1}{0.94 \cdot \lambda_c}\right)^4 + 1.05\right] \tag{19}$$

The equation is based on the maximum allowable attenuation specifications for MMF, but can be applied to SMF in the 1300 nm operating region.

For 1000BASE-SX links:

R_λ = the actual cable attenuation in dB/km @ 850nm
C_λ = 3.5 dB/km

For 1000BASE-LX links:

R_λ = the actual cable attenuation in dB/km @ 1300nm for MMF or @ 1310 nm for SMF
C_λ = 1.5 dB/km

38A.9 Eye opening penalty

It is necessary to account for the eye opening penalty which results from opening the eye to a particular width to accommodate the jitter specification. An analytical relationship for the eye opening penalty at a particular T_{win}/T has been developed [1]. The analysis assumed that the shape of the analog eye is defined by a raised cosine and leads to the following relationship for L_{eye}, in dB:

$$L_{eye} = -10 \cdot Log\left(\frac{[2 \cdot \sin(\pi \cdot W_0)]}{\pi \cdot W_0 \cdot [1 - W_0^2]} - 1\right) \quad (20)$$

where, $W_0 = \frac{T_{win}}{T}$, the Window Opening Ratio,

T_{win} = Required Eye Opening, and

T = Baud Period.

38A.10 Worst case power budget, modal noise allocation and link length

The worst case power budget, P_b, is the difference between the minimum allowed laser launch power and the maximum allowed receiver sensitivity at the specified BER. If the summation of the worst case power losses and penalties is less than P_b then the link will remain within specification. Since some of the power penalties and losses vary with link length there will be a maximum link length which can be supported when all penalties and losses are set to their worst case values. When calculating the worst case link length an allocation for worst case modal noise [5] and worst case connector loss must be made.

38A.11 References

[1] ANSI T1.646-1995, Broadband ISDN-Physical Layer Specification For User-Network Interfaces, Appendix B.

[2] Gair D. Brown, “Bandwidth and Rise Time Calculations for Digital Multimode Fiber-Optic Data Links”, Journal of Lightwave Technology, VOL. 10, No. 5, May 1992, pp 672-678.

[3] James L. Gimlett and Nim K. Cheung, “Dispersion Penalty Analysis for LED/Single-Mode Fiber Transmission Systems”, Journal of Lightwave Technology, VOL., LT-4, No. 9, Sept.,1986, pp 1381-1392.

[4] Govind P. Agrawal, P. J. Anthony and T. M. Shen, “Dispersion Penalty for 1.3-µm Lightwave Systems with Multimode Semiconductor Lasers”, Journal of Lightwave Technology, VOL., 6, No. 5, May.,1988, pp 620-625.

[5] Richard J. S. Bates, Daniel M. Kuchta, Kenneth P. Jackson, “Improved Multimode Fiber Link BER Calculations due to Modal Noise and Non Self-Pulsating Laser Diodes”, Optical and Quantum Electronics, 27 (1995) pp 203-224.

[6] “Receiver Design for Optical Communication Systems” by R. G. Smith and S. D. Personick in Topics in Applied Physics, Volume 39, Semiconductor Devices for Optical Communications, Editor: H. Kressel, Published by Springer-Verlag, 1982 (ISBN 0-387-11348-7).