Dispersion penalty analysis for VSR-1 optical links*

JIA Jiu-chun**, **CHEN Hong-da**, **CHEN Xiong-bin**, and **ZHOU Yi**
State Key Lab. on Integrated Optoelectronics, Institute of Semiconductors, China Academy of Science, Beijing 100083, China

(Received 15 November 2005)

This paper presents an approach to calculate dispersion penalty for VSR-1 optical links. Based on parameters of a specific VSR-1 link, dispersion penalties are computed for various modal dispersion bandwidths respectively. The worst-case eye closure is expressed numerically by using the signal waveform at time 0, and the signal waveform is obtained in frequency domain through FFT algorithm. By this approach, the dispersion penalty is determined by the shape of transfer functions of the various components in the links. To simplify the derivation of multimode fiber link transfer function, a Gaussian form of normalized impulse response is used. This calculation approach can be used to estimate the worst-case dispersion penalty of VSR-1 links in the link budget analysis.

CLC number: TN929.11 **Document code**: A **Article ID**: 1673-1905(2006)03-0189-03

Most of intra-office interconnections are less than 300 m. The data communication within this distance is referred to Very Short Reach (VSR). To address the requirement for low-cost and high speed intra-office interconnections, several VSR optical data transmission interfaces have been developed, one of them is called VSR-1. VSR-1 uses 850-nm lasers over 12 multimode fibers at 1.25 Gbps each for distances up to 300 m. As a multimode fiber link, its performance is dependent on many parameters such as the laser, fiber or receiver characteristics, as well as the launch conditions from laser to the fiber, the optical lens, and the connectors, etc. Among these parameters, the dispersion penalty is the major limiting factor in the achievable data rate or transmission distance. Dispersion will induce pulse broadening, which affects the receiver performance in such a way that a part of the pulse energy spreads beyond the allocated bit slot and leads to Inter-Symbol Interference (ISI). Also the pulse energy within the bit slot is reduced. Such a decrease in the pulse energy reduces the SNR at the decision circuit. Since the SNR should remain constant to maintain the link performance, the receiver requires more average power to compensate the degrading effect of the dispersion. This is the origin of dispersion-induced power penalty.

This paper presents an analysis of the dispersion penalty for VSR-1 optical links. The calculation is based on the approach obtained in frequency domain. In the derivation of the calculation approach, we assume that the impulse response of the fiber link is Gaussian form. The result can be used as the reference for the link budget analysis.

* Supported by "863" Hi-Tech Research and Development Program (2005AA311030) and the National Natural Science Foundation of China (Grant No. 60502005)

** E-mail: jiuchunjia@yahoo.com.cn

Fig. 1 is the function block of VSR-1. It consists of four parts: IC converter, 12×1.25 Gbps parallel optics links, 1×12 array lasers and 1×12 detector array receivers. The VSR-1 link utilizes an array of 12 low-cost 850 nm Vertical Cavity Surface Emitting Lasers (VCSEL), operating at the Gigabit Ethernet rate of 1.25 Gbps for each, whose signals are carried over a 12-fiber ribbon for distances up to 300 m in 62.5 μm multimode fibers (MMF).

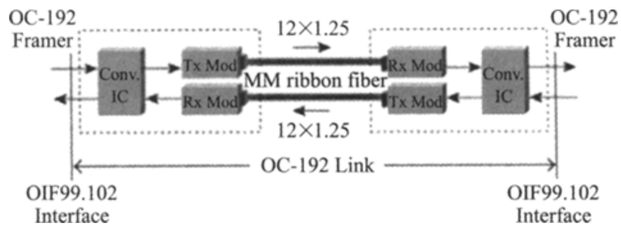

Fig. 1 The function block of VSR-1

Tab. 1 is the VSR-1 optical specifications[1], in which the link power budget and penalties for per data channel are summarized. The optical specifications leverage

Tab. 1 VSR-1 Optical Specifications

Parameters	Specifications
Fiber	62.5 μm MMF fiber
Fiber Cable Max. Attenuation	3.75 dB/km
Min. Modal Bandwidth	400 MHz · km
Link Power Budget	6.0 dB
Maximum number of connectors	4
Maximum Connector Loss (Per Connector)	0.5 dB
Minimum Operation Range	2—300 m
Unallocated Margin in Link Power Budget	0.6 dB

the Gigabit Ethernet standard and correspond to Gigabit Ethernet optical link model, except for the fiber and connector specifications, which are modified to meet the design constraints imposed by engineering parallel components. From Tab. 1 we can see that the maximum guaranteed link distance is 300 m for a system with four (0.5 dB) connectors.

Assume that the VCSEL array is modulated with a non-return-to-zero (NRZ) input signal, the frequency spectrum of the input pulse is

$$H_p(f) = \frac{\sin(\pi f/B)}{\pi f} \quad (1)$$

where B denotes the signal transmission rate.

As the link comprises an optical transmitter, a length of a multimode fiber and an optical receiver, $h_{out}(t)$ is the pulse output from the receiver given by

$$h_{out}(t) = \int_{-\infty}^{+\infty} H_p(f) H_f(f) H_r(f) \exp(i2\pi f t)\,\mathrm{d}f \quad (2)$$

where $H_f(f)$ and $H_r(f)$ are the transfer functions of the fiber and receiver respectively.

The worst case eye closure E_m can be numerically expressed as[2]

$$E_m = 2[1 - h_{out}(t_0)] = 2[1 - \int_{-\infty}^{+\infty} H_p(f) H_f(f) H_r(f) e^{i2\pi f t_0}\,\mathrm{d}f] \quad (3)$$

The dispersion penalty P_{ISI} is the needed power to re-open the eye

$$P_{ISI} = 10\log[1/(1-E_m)] = -10\log(1-E_m) \quad (4)$$

where t_0 is the sampling time.

Equation (4) indicates that if we can get the transfer functions of the fiber and receiver, the dispersion penalty can be calculated in frequency domain numerically. But the derivation of the transfer function of multimode fibers is not an easy task. Several factors have clearly been identified to influence the information-carrying capacity of multimode fiber links, namely the material dispersion (in combination with the spectrum of the exciting source), the launching conditions, as well as the mode-dependent characteristics, such as delay, attenuation, and coupling-coefficient. A comprehensive dispersion analysis to Graded-Index multimode fibers has been done[3]. Here, as an approximation, we assume that the normalized impulse of the VCSEL, multimode fiber and optical receiver is Gaussian[4], we may write

$$h_c(t) = \frac{1}{\sigma_t \sqrt{2\pi}} \exp\left(-\frac{t^2}{2\sigma_t^2}\right) \quad (5)$$

where σ_t is the RMS width of the impulse response of the link. Taking the Fourier transform of equation (5), the normalized frequency response is seen to be

$$\int_{-\infty}^{+\infty} \frac{1}{\sigma_t \sqrt{2\pi}} \exp\left(-\frac{t^2}{2\sigma_t^2}\right) \exp(i2\pi f t)\,\mathrm{d}t = \exp[2(i\pi f \sigma_t)^2] \quad (6)$$

so the E_m can be calculated as

$$E_m = 2\left[1 - \int_{-\infty}^{+\infty} \frac{\sin\left(\frac{\pi f}{B}\right)}{\pi f} \exp\left(-\frac{(2\pi f \sigma_t)^2}{2}\right) \exp(i2\pi f t_0)\,\mathrm{d}f\right] \quad (7)$$

and dispersion penalty is

$$P_{ISI} = -10\log \left\{1 - 2\left[1 - \int_{-\infty}^{+\infty} \frac{\sin\left(\frac{\pi f}{B}\right)}{\pi f} \exp\left(-\frac{(2\pi f \sigma_t)^2}{2}\right) \exp(i2\pi f t_0)\,\mathrm{d}f\right]\right\} \quad (8)$$

Suppose the RMS width of the impulse response of the VCSEL, multimode fiber and optical receiver are σ_s, σ_f and σ_r respectively, then the RMS width of the impulse response of the link σ_t is

$$\sigma_t = \sqrt{\sigma_s^2 + \sigma_f^2 + \sigma_r^2} \quad (9)$$

where σ_f is contributed by both chromatic dispersion effect σ_{fch} and inter-modal dispersion effect δ_{fm}, $\sigma_f^2 = \sigma_{fch}^2 + \delta_{fm}^2$, so, finally,

$$\sigma_t = \sqrt{\sigma_s^2 + \sigma_{fch}^2 + \sigma_{fm}^2 + \sigma_r^2} \quad (10)$$

and

$$\sigma_f^2 = \sigma_{fch}^2 + \delta_{fm}^2 = \left(\frac{C1}{BW_{ch}}\right)^2 + \left(\frac{C1}{BW_M}\right)^2 \quad (11)$$

where, BW_{ch} is chromatic bandwidth, BW_M is modal bandwidth, and $C1$ is the conversion factor. BW_{ch} is dependent on the spectrum width of the VCSEL σ_λ, the operating wavelength λ_c, the fiber zero dispersion wavelength λ_0, the fiber zero dispersion slop S_0 and the fiber length L[4],

$$BW_{ch} = \frac{0.187}{L\sigma_\lambda D_{ch}} \quad (12)$$

here, $D_{ch} = (S_0/4)(\lambda_c - \lambda_0^4/\lambda_c^3)$

Fig. 2 is the illustration of the dispersion penalty as a function of the link length for the VSR-1. Tab. 2 is the parameters specification used in the calculation. From Fig. 2 we can see that when the modal bandwidth of the fiber link is 400 MHz • km, at distance 300 m, the dispersion penalty is 1.0 dB. According to Tab. 1, if the link budget is 6 dB, except for the fiber loss, connector loss and unallocated margin, only 2.28 dB could be allocated to other penalties. In a laser based multimode fiber link, the other penalties may include Extinction Ratio Penalty associated with transmission of a non-zero power level for zero, RIN penalty, Jitter Penalty and Mode Partition Noise Penalty. From the calculation result, the sum of these penalties could not exceed 1.28 dB, otherwise, the fiber link would be failure.

Tab. 2 parameter specifications used in dispersion penalty calculation

Parameters	Specifications
Wavelength λ_c	850 nm
Line Width of VCSEL σ_λ	0.85 nm
Transmitter Rise Time (10—90%) σ_s	390 ps
Receiver Rise Time (10—90%) σ_r	350 ps
Baud Rate B	1.25 Gbps
Zero dispersion wavelength of the fiber λ_0	1 365 nm
Zero dispersion slop of the fiber S_0	0.11 ps/nm^2 • km
Conversion factor C1	480

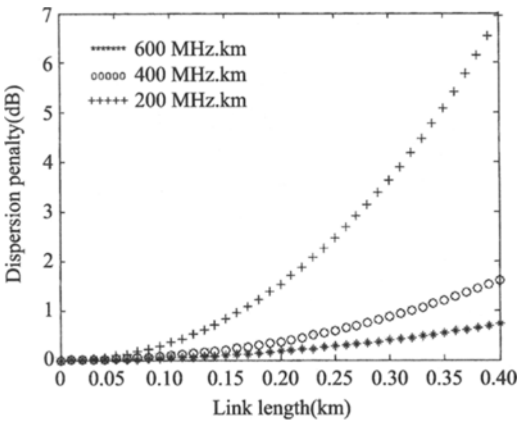

Fig. 2 Dispersion penalty vs link length

Fig. 2 also depicts the dispersion penalty for the link with modal bandwidth 200 MHz • km and 600 MHz • km. When the modal bandwidth is 600 MHz • km, the dispersion penalty increases fast.

From equation (3) and (4), we can see that the dispersion penalty is determined by the shape of the transfer functions of various components in the fiber link, such as laser, multimode fiber, connectors and optical receiver. Gaussian form impulse response is only an approximation to the multimode fiber links. The impulse response of the fiber links could be various other forms, such as 'Split-Pulse', 'Stair-Step', 'Smooth Pulse', and etc. The comparison between Gaussian form impulse response and other forms of impulse response has been carried out[5], and the conclusion from the comparison is that for distance exceeding 185 m of 500 MHz • km multimode fiber links, Gaussian performs worse than all other impulse response considered. Gaussian can be the best candidate model for worse case impulse response for 500 MHz • km fiber at distances of interest 220 m—300 m. So we believe that the dispersion penalty calculation presented in this paper can be a good prediction of the link performance for the worst case VSR-1 system.

References

[1] OIF Physical and Link Layer Working Group, *Very Short Reach (VSR) OC-192/STM-64 Interface Based on Parallel Optics: Implementation Agreement OIF-VSR4-01.0*, California, USA, 2000.

[2] J. L. Gimlett and N. K. Cheung, *Journal of Lightwave Technology*, LT-4 (1986), 1381.

[3] G. Yabre, *Journal of Lightwave Technology*, **18**(2000), 166.

[4] G. D. Brown, *Journal of Lightwave Technology*, **10**(1992), 672.

[5] IEEE802.3 document: Worst Case Impulse Responses for Various EDC Architectures.