RC22930 (W0310-043) October 7, 2003
Electrical Engineering

IBM Research Report

Statistical Analysis of the Impact of Introducing Additional Component Requirements on the Performance of 10 Gb/s LAN Links

Aleksandar Risteski[1], Petar K. Pepeljugoski[2], Bojanco Mitev[3], Boris Spasenovski[1], Tatjana Ulcar-Stavrova[1], Jeffrey A. Kash[2]

[1]Dept. of Electrical Engineering
Univ. "Sts. Kiril and Metodij"
Skopje, Macedonia

[2]IBM Research Division
Thomas J. Watson Research Center
P.O. Box 218
Yorktown Heights, NY 10598

[3]AD Makedonski Telekomunikacii
Skopje, Macedonia

Research Division
Almaden - Austin - Beijing - Haifa - India - T. J. Watson - Tokyo - Zurich

Statistical Analysis of the Impact of Introducing Additional Component Requirements on the Performance of 10 Gb/s LAN Links

Aleksandar Risteski[1], Petar K. Pepeljugoski[2], Bojanco Mitev[3], Boris Spasenovski[1], Tatjana Ulcar-Stavrova[1], Jeffrey A. Kash[2]

[1]Univ. "Sts. Kiril and Metodij", Dept. of Electrical Eng., Skopje, Macedonia

{acerist,boriss,tanjaus}@etf.ukim.edu.mk

[2]IBM T. J. Watson Research Center, Yorktown Heights, NY 10598, USA

{petarp, jeffkash}@us.ibm.com

[3]AD Makedonski Telekomunikacii, Skopje, Macedonia

bojanco.mitev@mt.com.mk

Abstract – **In this paper we analyzed the correlation between the ISI penalty and various transmitter and fiber parameters characterizing 10 Gb/s 300m long next generation multimode fiber Ethernet and Fibre Channel links. Using a large statistical sample, the analysis showed that the axial offset has detrimental effects on the performance of the link, unless additional specification parameters on the encircled flux are introduced. The introduction of additional specification parameters related to the laser encircled flux not only reduces the ISI failure rate, but also reduces the overall ISI penalty in these links by as much as 0.7 dB.**

Keywords – **10 Gb/s Ethernet, next generation multimode fiber, VCSEL, inter-symbol interference, Differential Modal Delay, encircled flux.**

Introduction

In multi-gigabit Local Area Networks (LAN), like Ethernet and Fibre Channel, Physical Media Dependent (PMD) layer solutions with short wavelength (850nm) sources over multimode fibers (MMF) historically have dominated the market due to their cost advantage over single mode fiber based solutions. This trend continued in the IEEE 802.3ae standard, also known as the 10 Gb/s Ethernet (10GbE) standard [1], which included a PMD layer for distances up to 300m over next generation 50 µm MMF. The specifications for this fiber [2], along with the corresponding measurements of the laser encircled flux (EF) [3], and fiber differential mode delay (DMD) [4] were developed by the Telecommunication Industry Association (TIA) in the same time frame as IEEE 802.3ae standard. The development and standardization of the next generation MMF and laser specifications was aided by round robin measurements and the creation of a link model [5, 6].

In these links, the performance is affected by a large number of parameters describing link components (VCSEL, fiber and receiver), as well as their interaction (launch conditions, mode mixing at the connectors). The main power penalty contributor in these links is the inter-symbol interference (ISI), mainly caused by inter-modal dispersion in the fiber. Since these links are very cost sensitive, the transceiver manufacturing results in looser mechanical tolerances affecting the launch conditions, while the fiber yield requirements affect the economically achievable fiber DMD.

All the parameters that are affecting the link performance can be divided into measurable (verifiable) parameters and design parameters (non-verifiable). The TIA has standardized a set of measurable link parameters for both the laser and fiber. The source was specified using the source EF, requiring that the EF at 4.5µm radius be less than 30% and the radius of 86% EF be smaller than 19µm. The primary specification for the fiber was the magnitude of the DMD for which the next generation MMF must pass one of six predefined DMD masks. For one mask there is an additional requirement to exceed 1500 MHz*km overfill launch bandwidth (OFLBW). In the context of this paper, the links that satisfy these criteria are referred to as TIA-compliant links.

In this paper we explore the individual and combined impact of measurable and design parameters on the link performance through their effect on the inter-symbol interference. We investigate the impact of the axial offset on the ISI correlation coefficients, average ISI and ISI failure rate for the link configuration types considered by the TIA. Our goal was to identify additional requirements for existing TIA link components that would lead to lower ISI penalty, which in turn would result in increase of the achievable link distances beyond the 300 m, either alone or in conjunction with other techniques like link equalization [7, 8].

Multimode fiber modeling and simulation approach

A complete description of the model, its simulation inputs and the result of those simulations can be found in [5, 6]. However, for the sake of completeness and to introduce the terminology, we briefly describe the link model and simulation environment. A typical block-diagram of a 10 GbE MMF link is presented in Fig. 1. As mentioned earlier, due to the need for cost effective manufacturing, there might be lateral, axial and angular offsets between the optical axis of the launched light and the fiber. The mode power distribution (MPD) among the fiber modes in the fiber depends on these offsets, as well as on the laser EF. The MPD can be determined by computing the overlap integral between the laser and fiber modes, enabling the calculation of the link transfer function and the signal at the link output.

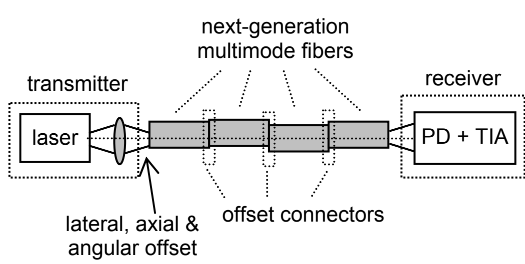

Fig. 1. A typical 10 Gb/s MMF link. The number of fibers and length of each fiber depends on the link type [6].

Here we consider the same link types as in [6]: 300 m links without connectors ("No Connections"), 300 m links preceded and followed by short 1 m fibers ("1-300-1" with two connectors, and “1-1-300-1” with three connectors), as well as “1-200-100-1” links. In these simulations, we fixed the axial offset (along the optical axis) between the laser beam waist and the fiber input face to five values (-100, -50, 0, 50 and 100 μm). Each configuration-offset pair was simulated independently and the simulation run included 40000 randomized source-fiber combinations. The transmitter characteristics differed in modal content, spectral width, spectral line spacing, center wavelength, beam waist radius, and radial and angular offset. The connections between fibers have random offsets, resulting in mode mixing, and random delays were chosen for the 19 mode groups propagating through the fiber. We used the ISI as a primary link performance measure. A link is counted as a failure if the ISI penalty exceeds its allocation in the power budget (in this case 2.5 dB). The ISI failure rate (FR) is defined as a fraction of all otherwise TIA compliant links that failed. ISI penalty is computed as $10\log_{10}(A_0/A_n)$, where A_0 and A_n are the outer and inner eye opening, respectively, in the eye diagram of the signal at the link output. We emphasize that in this context the failure indicates bit error rate (BER) below the expected performance ($BER<10^{-12}$), and not link unavailability.

Correlation between ISI penalty and link parameters

In this Section, we analyze the correlation between ISI penalty and some of the design and measurable link parameters. For this analysis, we selected a set of 10 link parameters with the highest likelihood to affect the link performance, either alone or when combined with other parameters: lateral and angular offset between the optical axes of the laser beam and the fiber; laser spot size (ω_0); radii at which the EF reaches 30% and 86% (r(EF=30%) and r(EF=86%), respectively); EF values at radii 4.5 μm and 18 μm (EF(r=4.5μm) and (EF(r=18μm), respectively); DMD Figure of Merit (FoM) in the inner (5-18 μm) and outer (0-23 μm) region, and the overfill launch bandwidth (OFLBW) of the fiber. Detailed definitions of all of these parameters can be found in [6].

Our statistical sample was comprised of 800000 randomly chosen links (four configuration types and five axial offsets, each with 40000 random links). The simulation output was a matrix with n=800000 rows and m=11 columns (10 columns for the link parameters; 1 column for the ISI penalty). The correlation coefficients are calculated in the standard manner and are given by:

$$corrcoef_{ij}(A) = \frac{C_{ij}(A)}{\sqrt{C_{ii}(A) \cdot C_{jj}(A)}} \tag{1}$$

where i,j = 1,2,…m and the corresponding covariances C_{ij} by:

$$C_{ij} = \frac{1}{n-1} \sum_{r=1}^{n} \left[(x_{ri} - \mu_i) \cdot (x_{rj} - \mu_j) \right] \tag{2}$$

where $\mu_i = \frac{1}{n} \sum_{r=1}^{n} x_{ri}$, $i = 1,2,...,m$.

In Table 1 we show the correlation coefficient between the ISI penalty and each listed link parameter. There are two columns for the correlation coefficients, one for the entire set of data, comprised of both TIA compliant and non-compliant links, and the other one only for the TIA compliant links. The highest degree of correlation exists for the parameters describing the DMD profile of the fiber, for both the TIA compliant and non-compliant links. In the other parameter groups, the correlation coefficients are lower. In the second group are some of the EF-related parameters, describing the laser source characteristics and launch conditions; this group is also indirectly affected by the parameters in the first three rows (lateral and angular offset and laser spot size), that have the lowest individual correlation coefficient in the list. Another parameter with significant influence on the ISI penalty is the fiber OFLBW. This correlation coefficient is negative, as it is expected, since higher OFLBW leads towards smaller pulse spreading in the fiber and thus lower ISI penalty.

While statistically the individual correlation coefficients are not sufficient to be adopted alone as specifying parameters, when combined provide robust specification for the link. The highest five correlation coefficients are also measurable parameters and were selected as specification parameters for the fiber and the laser [2, 6].

Table 1. ISI correlation coefficients

Parameter	ISI correlation coefficients	
	TIA-compliant links	All links
lateral offset	-0.0670	0.0987
angular offset	0.0992	0.1140
laser spot size	-0.0940	-0.1314
r(EF=30%)	-0.0003	0.1957
r(EF=86%)	0.1432	0.2746
EF(r=4,5μm)	0.0133	-0.1632
EF(r=18μm)	-0.1867	-0.2935
DMD FoM (inner)	0.6822	0.6908
DMD FoM (outer)	0.6345	0.6620
OFLBW	-0.1789	-0.1481

Impact of axial offset on ISI penalty

In some cases the axial misalignment (defocus) is intentionally introduced to either reduce the impact of the reflected light on the magnitude of the laser reflection induced intensity noise (RIIN), to achieve coupling efficiency insensitive to lateral misalignment, or to reduce the light output to meet the eye safety requirements. On Fig. 2 we show the dependence of the correlation coefficient for the measurable parameters as a function of the axial offset for the TIA compliant links. Since the correlation coefficients do not depend much on the link configuration type (they are virtually the same), only the case for "No connections" is shown. It is apparent that the correlation is smallest for zero axial offset and increases as the axial offset (defocus) is introduced in either direction.

From the fiber parameters, OFL bandwidth shows the least correlations with the ISI while the DMD based figures of merit the highest. The low correlation coefficient of the OFL is a result of the fact that the OFL bandwidth was developed for LED launches, and not for laser. The laser launches excite a limited number of fiber modes, and not necessarily the ones who contribute the most to the OFL bandwidth. As expected, the DMD figures of merit have the highest correlation coefficient because they are directly related to the effective modal bandwidth of the fiber.

The last parameter included in the comparison, the encircled flux, has low correlation coefficient indicating that it alone is not sufficient as a specification parameter for the link.

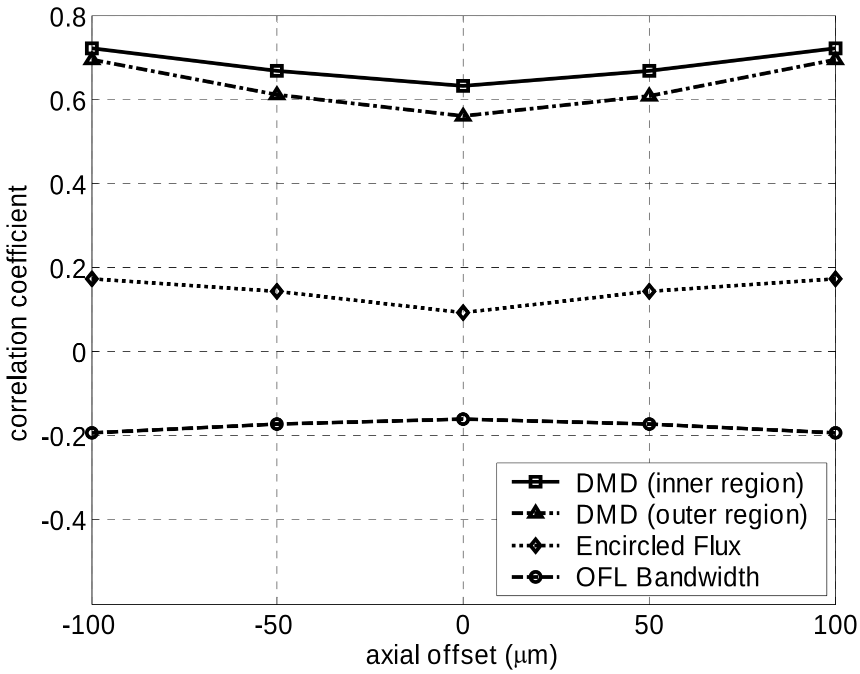

Fig. 2. ISI Correlation coefficients with measurable parameters (DMD, EF and OFL bandwidth) vs. axial offset for TIA-compliant links of type “no connections”. The correlation is smallest when there is no axial offset.

Although the TIA-compliant links have average ISI much bellow the upper limit, some links have ISI penalty higher than 2.5 dB. Those links are referred to as failure links. The ISI Failure Rate is defined as the ratio of the number of failure links and total number of TIA-compliant links. It was specified by TIA that less than 0.5% of the links should exceed the ISI FR. We examined the ISI FR as a function of the axial offset. The ISI failure rate for the entire statistical sample (“all links” shown with dot-dashed line) and TIA-compliant links (“TIA-compliant links” shown with solid line) are shown on Fig. 3.

If the axial offset exceeds 60-70 µm, the ISI FR is higher than 0.5%, but still less than 1% when the axial offset is 100 µm.

While the correlation coefficient is low for ideal focus (no axial misalignment), the failure rate is also low. In the full range of axial offsets considered, slight change (10%) in the correlation coefficient means quadrupling of the ISI failure rate from 0.2% for perfect focus to 0.8% at the edges of the interval considered. Higher defocusing intervals, usually required for improving the RIIN, coupling efficiency insensitivity to lateral offset or to achieve eye safety requirements through coupling loss, would almost certainly result not only in not meeting the encircled flux requirement, but also in links that exceed the 1% ISI failure rate.

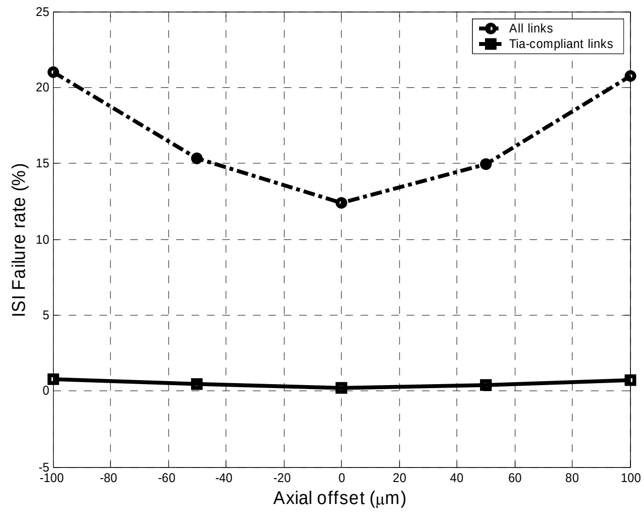

Fig. 3. ISI penalty failure rate vs. axial offset for the entire statistical sample (dashed line) and TIA-compliant links (solid line). The axial offset causes significant increase in the ISI failure rate in both curves. For TIA-compliant links the ISI failure rate is quadrupled for the highest axial offsets.

Link specification parameters and ISI penalty Failure Rate

As we mentioned before, the individual correlation coefficients for all parameters from Table 1 are insufficient to specify a robust link with low failure rate. In order to understand better their impact on the ISI failure rate, we investigated the ISI failure rate in links that are specified using only one, or a combination of two or more parameters. From the parameters we selected (EF, OFLBW and DMD), we created 8 criteria (Table

2), and calculated the ISI failure rate for each of them (Figure 4). We also defined criterions that are in addition to the TIA requirements. They are listed in Table 3.

Table 2. Criterions with partial TIA requirements

Criterion	**Link requirements**
#1	No link requirements (all links)
#2	EF only
#3	OFLBW only
#4	DMD only
#5	EF & OFLBW
#6	EF & DMD
#7	OFLBW & DMD
#8	Complete set of TIA requirements (EF & OFLBW & DMD)

Table 3. Criterions in addition to the TIA requirements

Criterion	**Link requirements as an addition to the complete set of TIA requirements**
#9	r(EF=86%)<12 μm OR r(EF=86%)>16 μm
#10	12 μm < r(EF=86%) < 16 μm
#11	13 μm < r(EF=86%) < 15 μm

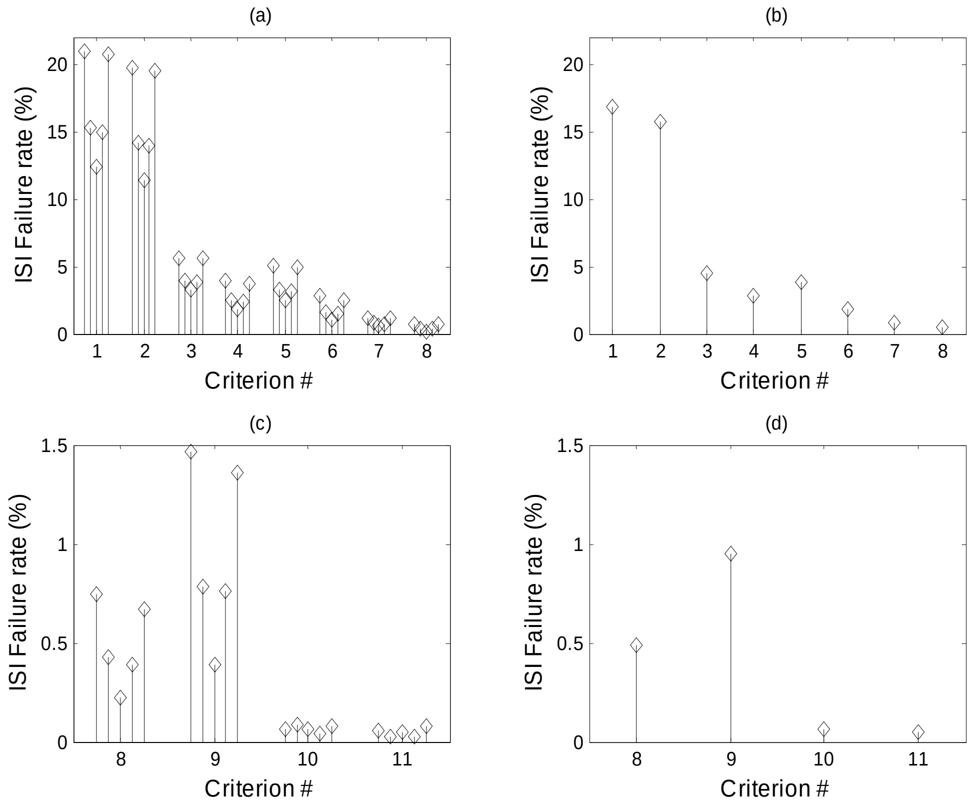

Fig. 4. ISI Failure rate vs. various criterions: (a, b) – criterions derived from a subset of TIA requirements (Table 2); (c, d) – criterions beyond TIA requirements (Table 3). (a) and (c) plot the ISI FR vs. axial offset for all criterions and (b) and (d) show the averaged ISI Failure Rate.

The stem-plots on Figure 4(a-d) show the ISI failure rates for each criterion. On Figure 4 (a, c) for each criterion we show the ISI failure rate for the same five values of the axial offset as in Figure 2 and Figure 3, shown in ascending order. Figure 4 (b, d) shows only the averaged values over all axial offsets for all criterions. Not surprisingly, the criteria without fiber specification #1 (no specification at all) and #2 (transmitter specification only) have very high failure rate (almost 20%). Introduction of only one fiber parameter as a specification (#3 and #4) significantly reduces the ISI failure rate, but this failure rate is still high. The introduction of two specifying parameters further improves the ISI failure rate. Comparing criteria #5 (EF & OFLBW), #6 (EF & DMD) and #7 (DMD & OFLBW), we concluded that #7 (DMD & OFLBW) is the best combination, while the #5 (EF & OFLBW) is the worst. The analysis done on the first 7 criteria clearly shows that the DMD is the dominant parameter affecting the ISI failure rate. It should be noted here that it alone also leads to better results than the criterion #5 (combination of two parameters: EF & OFLBW). Criterion #8, which in some instances is the complete TIA set of specifying parameters (EF, DMD, OFLBW) performs better than all previous criteria (1-7) and results in less than 1% ISI FR, and when averaged over all axial offsets, in less than 0.5%.

From the previous discussion, one may conclude that EF-related requirements do not improve much the ISI FR. However, the EF is important to reduce the IS FR to very low values, below the TIA requirement and to optimize link performance. To show its importance, we have applied the criteria shown in Table 3 to our statistical sample. Each of them has more restrictive EF requirement, in addition to the criterion #8 from Table 2.

The criterion #10 poses additional requirement that the r(EF=86%) should be within the interval between 12 and 16 μm. This interval was shown to be optimal for reducing the ISI failure rate in TIA compliant links and optimizing the launch conditions at the transmitter [9]. Criterion #9 contains only sources rejected by criteria #10. Criterion #11 is similar to #10 but further restricts the interval to [13μm, 15μm].

When criterion #9 is applied, i.e. r(EF=86%) is out of the optimal region, the ISI FR gets considerably higher values as can be observed on Figure 4d, as opposed to the case when criterion #10 is applied. This means that if the r(EF=86%) is in the optimal region, the link performance can be significantly improved. Since we show the ISI FR is lower, it means that the ISI is lower, which enables achievement of longer link distances, beyond the 300m foreseen by the standard. Further restriction of the optimal region required in criterion #11 leads to even better results than the case of criterion #10, but the number of links that are compliant to criterion #11 becomes very low. In practice, this would mean that the tolerances in manufacturing the transceiver should be very strict, which would affect the manufacturing costs. As a side benefit, the ISI Failure Rate is so low for criterions #10 and #11 that it becomes effectively insensitive of the axial offset over the entire range of offsets. This is due to fact that higher order mode excitation is avoided due to the low encircled flux.

Figure 5 shows a statistical plot of the distribution of the ISI penalty data for each criterion. The notched boxes have lines at the lower 1 percentile, median and the 99 percentile values of the ISI penalty. The horizontal line at 2.5 dB across the figure shows 2.5 dB ISI penalty allocation limit. This figure, which complements figure 4, also quantifies the effect of the introduction of more criterions. For example, we can observe that besides the reduction in the ISI failure rate to below 0.2%, the 99% value for the ISI drops by 0.7 dB from 2.5 to 1.8 dB when comparing criterions #7 (only DMD and OFLBW) and #11 (additional EF requirements included).

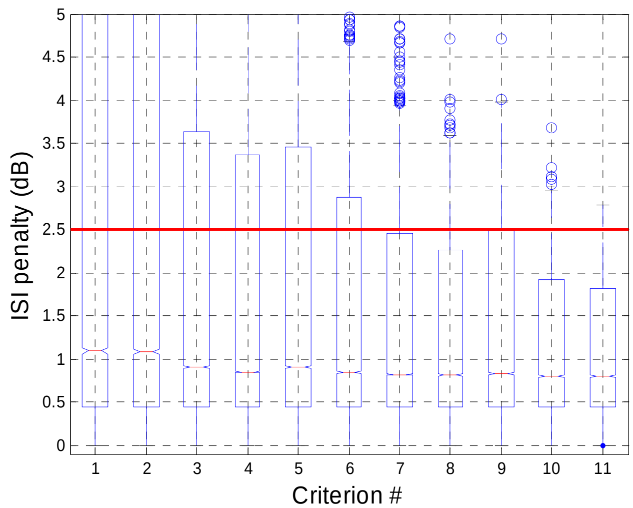

Figure 5. Statistical box-plot of the ISI penalty vs. criterion #. The boxes have lines marking the lower 1 percentile, median and 99 percentile values of the ISI penalty. The line at 2.5 dB shows the ISI penalty allocation limit.

Conclusions

In this paper we investigated the impact of various specification parameters on the ISI and ISI failure rate in 10 Gb/s LAN links over 50 µm next generation fibers, either alone or in groups of two or more. We found that in the absence of introducing additional requirements on the laser encircled flux, the introduction of intentional axial offset (defocusing) is not a desirable from link performance perspective, leading to almost quadrupling of the failure rate from ideal focus position. Restricting the radius of 86% encircled flux to 12-16 µm removes this degradation for axial offset in range [-100µm, 100μm]. Our analysis also showed that by introducing additional criterions, it is possible not only to reduce the ISI failure rate, but also to reduce the overall ISI penalty in these links by as much as 0.7 dB.

References

[1] IEEE 802.3ae 10 GbE standard (2002)

[2] "Detail specification for laser optimized, 50μm core diameter/125μm cladding diameter class Ia graded index multimode optical fibers," TIA-492AAAC (2002)

[3] "Launched Power Distribution Measurement Procedure for Graded-Index Multimode Fiber Transmitters", TIA/EIA-455-203 (2001)

[4] "Differential Mode Delay Measurement of Multimode Fiber in the Time Domain", TIA/EIA-455-220 (2001)

[5] P. Pepeljugoski, M. Hackert, J. S. Abbott, S. Swanson, S. Golowich, J. Ritger, P. Kolesar, C. Chen, J. Schlager, "Development of Laser Optimized 50 μm Multimode Fiber for Multi-gigabit Short Wavelength LANs," IEEE JLT, Vol. **21**, No. 5, 1256-1275 (2003)

[6] P. Pepeljugoski, S. Golowich, J. Ritger, P. Kolesar. A. Risteski, "Modeling and Simulation of the next generation multimode fiber," IEEE JLT, Vol. **21**, No. 5, 1242-1255 (2003)

[7] P. Pepeljugoski, J. Schaub, J. Tierno, J. Kash, S. Gowda, B. Wilson, H. Wu, A. Hajimiri, "Improved Performance of 10 Gb/s Multimode Fiber Optic Links Using Equalization", In Proc. of OFC'03 (2003)

[8] H. Wu, J. Tierno, P. Pepeljugoski, J. Schaub, S. Gowda, J. Kash,A. Hajimiri, "Differential 4-tap and 7-tap Transverse Filters in SiGe for 10Gb/s Multimode Fiber Optic Equalization", In Proc. of ISSCC'03 (2003)

[9] A. Risteski, T. Janevski, Z. Hadzi-Velkov, B. Spasenovski, D. Kuchta, P. Pepeljugoski, "Optimized laser launch conditions in 10 Gb/s links using next generation multimode fibers", submitted to OFC'04.