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Optimized Laser Launch Conditions in 10 Gb/s Links Using Next Generation Multimode Fibers

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***Abstract*—In this paper we present the dependence of the ISI penalty on various transmitter and fiber parameters characterizing 10 Gb/s Ethernet links at 850nm with 300m long next-generation multimode fiber. Statistical optimization of the launch conditions results in optimal values for the laser encircled flux (13-17µm) and lateral offset of the source (10-18µm). The analysis of the ISI correlation coefficients showed that the axial offset has detrimental effects on the performance of the link and it should be less than 60 µm.**

I. INTRODUCTION

The IEEE 802.3ae standard for 10 Gb/s Ethernet (10 GbE) [1], includes a short wavelength (850 nm) physical media dependent layer for distances up to 300 m over a 50 µm multimode fiber, popularly called the next generation fiber. Telecommunications Industry Association (TIA) developed its specifications [2], corresponding measurements procedures for the laser encircled flux (EF) [3], and fiber differential mode delay (DMD) [4]. A link model was created to aid the development and standardization of the laser and fiber specifications [5,6].

The link 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. In this paper we investigate the optimization of the launch conditions (that minimize the inter-symbol interference) in statistical manner. We explore the optimal values for the lateral offsets of the laser and the lens relative to the fiber, as well as encircled flux values, that lead to more robust 10 Gb/s links or extend achievable link distances beyond 300m.

II. LINK MODEL AND SIMULATION ENVIRONMENT

A complete description of the model and its simulation inputs can be found in [5,6]. However, for the sake of completeness we briefly describe the link model and simulation environment. A typical block-diagram of a 10 GbE MMF link is presented in Fig. 1. 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, leading to the calculation of the fiber transfer function and the signal at the link output.

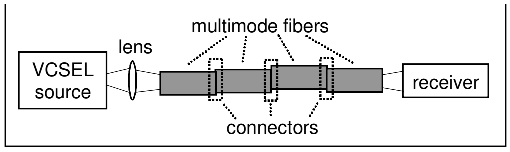

Figure 1. A typical 10 Gb/s MMF link. The number of fibers and length of each fiber depends on the link type [6].

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. The simulation runs included 40000 randomized source-fiber combinations. The transmitter characteristics differed in modal content, spectral width, spectral line spacing, center wavelength, beam waist radius, and axial, 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 considered to fail if the ISI penalty exceeds its allocation in the power budget (in this case 2.5 dB). The ISI failure rate (FR) is the fraction of all otherwise 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 performance below the expected performance (BER=1e-12), and not link unavailability.

III. LASER LAUNCH OPTIMIZATION

Once the simulation outputs were generated, we filtered the data using the selection criteria. We explored the impact of the mechanical tolerances during manufacturing that result in placement inaccuracies of the laser beam relative to the fiber axis. These included lateral offset, as well as the impact of the encircled flux on the performance on the link. In the analysis that follows, we kept the same DMD profile requirements on the fiber as in [5,6]. We considered all six standardized DMD templates for the next generation fiber. The DMD templates are denoted (x,y) where x is the maximum DMD in ps/m for launch offsets in the region 0-23 µm and y is the maximum DMD in the region 5-18 µm. We report here only the results for DMD templates #1 and #6, (0.23, 0.70) and (0.33, 0.33), respectively, for all four link types.

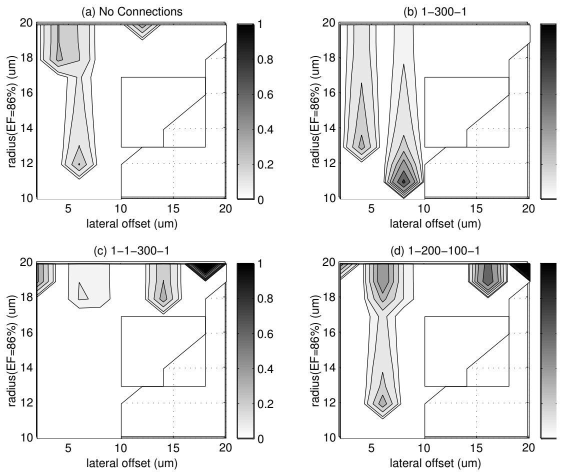

Figure 2. ISI failure rate (FR) (%) vs. lateral offset (μm) and radius (μm) of 86% encircled flux (EF) for four link types (a) "No Connections", (b) "1 -300-1", (c) "1 -1-300-1" and (d) "1 -200-100-1". DMD template is #1: (0.23,0.70). The magnitude of the ISI FR is coded in gray scale, with darker gray corresponding to higher values. The optimal values are in a rectangular region whose boundaries are between 13 and 17 μm for the radius of 86% EF and 10 and 18 μm for the lateral offset.

The remaining results are qualitatively not different from the ones reported here.

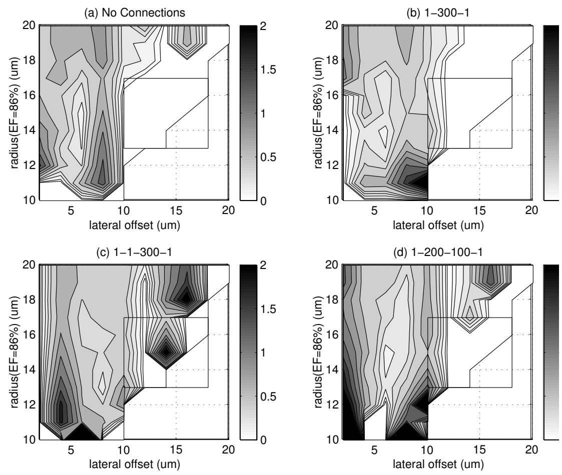

Figure 3. Same as in Fig. 2, but for DMD template #6: (0.33,0.33). The optimal values are in same regions as in Fig. 2. The "hot spot" that is present within the optimal region (c) is a result of a small number of samples in the bin.

Figures 2 and 3 show contour plots of ISI FR as a function of lateral offset and radius of 86% EF. The magnitude of the ISI FR is coded in gray scale, with darker gray corresponding to higher failure rate. This representation gives insight into the impact of both the lateral offset and the encircled flux on the link performance. These figures suggest that the optimal values for the lateral offset are between 10 and 18 μm, and between 13 and 17 μm for the radius of the 86% EF. We placed a rectangle on Figures 2 and 3 showing the boundaries for the optimal region. Further increases in the upper limit for the lateral offset can lead to lower coupling efficiency.

As the radius of the EF gets closer to 20 μm, "hot spots" appear with increased probability of link failure, since more power is launched into higher order modes. Similarly, very small 86% EF radius values (close to 10 μm) are more likely to generate higher failure rates. A slight "hot spot" with FR above 1% is observable for 14.5μm lateral offset and 15 μm 86% EF (e.g. Fig. 3 (c)). This hot spot is due to the fact that at the particular bin there are only 43 links, and only 1 link has exceeded the ISI allocation by only 0.2 dB. Therefore, the optimal launch conditions are valid in this region.

Our results are consistent with the previous approaches [7] that have shown the benefits of lateral offset launch for 1 Gb /s links. However, the results presented in this paper are more general, since the laser encircled flux is also optimized and the launch is not restricted to single mode fiber launch. Measurements performed during the development of this fiber confirm these simulations [8], showing 0.7 to 1.0 dB improvement in the ISI penalty.

We also investigated the influence of the number of laser transversal modes on the ISI FR. For this purpose, we considered typical 10 Gb/s VCSELs with 2 and 3 transversal modes (i.e. 2 and 3 spectral lines). The transversal mode spacing is randomly chosen in the interval 0.3-0.5 nm, while keeping the RMS spectral width to be less then 0.35 nm. The relative power in each spectral line is also random.

Figures 4 and 5 explore the influence of the number of

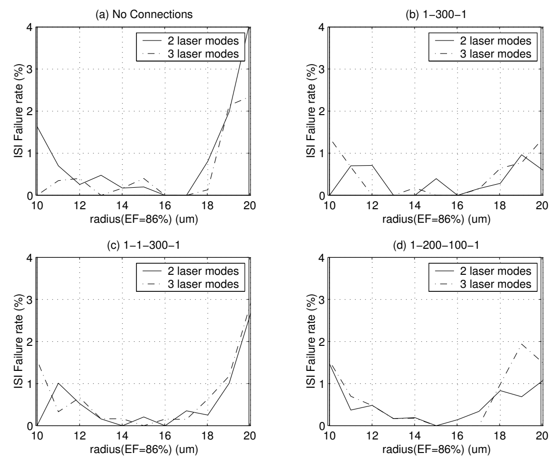

Figure 4. ISI ISI FR (%) vs. radius (μm) of 86% EF for 2-moded (solid line) and 3-moded (dashed line) lasers and for four link types as defined in Fig. 2. DMD template is #1: (0.23,0.70). The optimal values for the radius of 86% EF (between 13 and 17 μm) remain the same

laser modes on the ISI failure rate for the same DMD templates as above. It can be noticed that ISI FR is minimized for EF in the same regions as in the previous case, but for two-moded lasers there are instances when the 1% FR threshold is greatly exceeded. These are typically cases when the radius of 86% encircled flux is very small or very large. The three-moded lasers perform better and are within the 1% FR threshold for all 4 configurations and 6 DMD templates. This may be attributed to the fact that two mode lasers are more prone to pulse splitting.

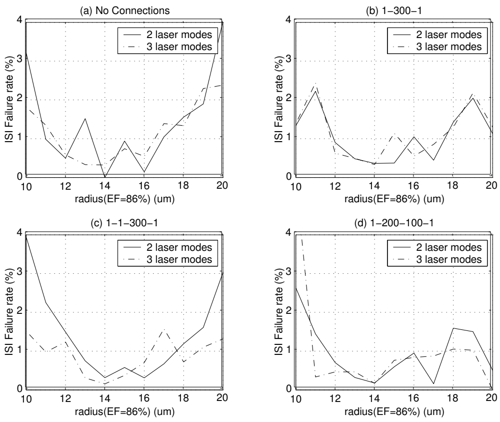

Figure 5. Same as Fig. 4, but for DMD template #6: (0.33,0.33). The 1% ISI FR threshold is exceeded when the radius of 86% encircled flux is very small or very large, especially for two-moded lasers

IV. 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:

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

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

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

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.

TABLE I.
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

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].

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. 6 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.

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. 7. 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.

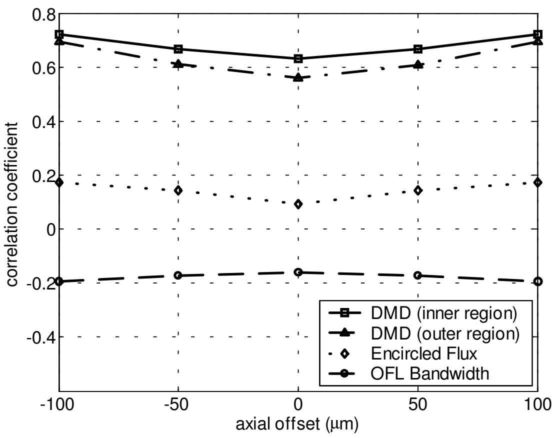

Figure 6. ISI Correlation coefficients with measurable parameters (DMD, EF and OFL bandwidth) vs. axial offset for TIA-compliant links of type "no connections". The correlation is smallest when there is no axial offset

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.

V. CONCLUSION

Statistical optimizations of the launch conditions in 300 m long 10 Gb/s links using 50 µm next generation fiber, show that encircled flux values between 13 and 17 µm, and lateral offsets between 10 and 18 µm result in reduced level of ISI FR. It was also shown that 3-moded VCSELs lead to lower ISI FR than 2-moded VCSELs. Since the width of the rectangular region of optimal values is larger than the normal manufacturing placement tolerances, these results may be used to design and manufacture transmitter optical subassemblies with built-in offset that could improve the link performance and robustness, as well as improve achievable distances.

We also investigated the impact of various specification parameters on the ISI failure rate. We found that 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.

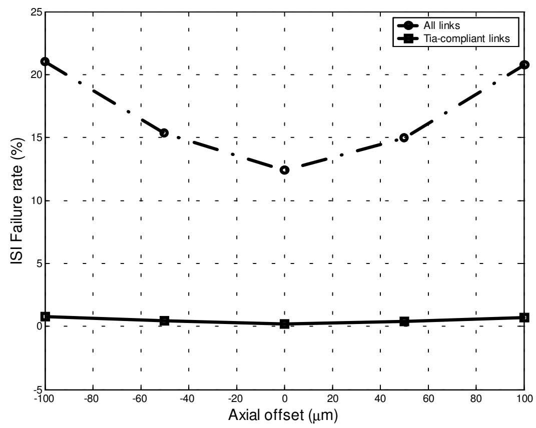

Figure 7. ISI penalty failure rate vs. axial offset for the entire statistical sample (dashed line) and TIA-compliant links (solid line). The axial offset causes significant increase in the ISI failure rate in both curves. For TIA-compliant links the ISI failure rate is quadrupled for the highest axial offsets

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