Parameter Influence on the Performances of 10 Gb/s Ethernet Optical Link with Multimode Fibers and Vcsel's

Bojanco Mitev[1], Aleksandar Risteski[2], Boris Spasenovski[2], Tatjana Ulcar-Stavrova[2], Petar Pepeljugoski[3]

[1]AD Makedonski Telekomunikacii – Skopje, Orce Nikolov b.b, 1000 Skopje, bojanco.mitev@mt.com.mk

[2]Faculty of Electrical Engineering – Skopje, Karpos II, b.b. P.O.Box 574, 1000 Skopje, {acerist,boriss,tanjaus}@etf.ukim.edu.mk

[3]IBM T. J. Watson Research Center, P.O.Box 218, Yorktown Heights, NY 10598, USA, petarp@us.ibm.com

Abstract – In this paper, we present the analysis on the correlation between Inter-Symbol Interference (ISI) Penalty, being considered as quality parameter for the performances of the 10 Gb/s Ethernet optical link, and relevant parameters characterizing the link. We found the Differential Mode Delay (DMD) profile of the fiber to be the crucial parameter, thus we have analyzed the dependence of ISI Penalty on DMD. We have also performed analysis on the influence of axial offset to the ISI Failure Rate and correlation coefficients.

Key words - 10 Gb/s Ethernet link, next-generation multimode fiber, VCSEL, Inter-Symbol Interference, correlation coefficients, ISI Failure Rate etc.

1. Introduction

With the announcement of the IEEE 802.3ae 10Gb/s Ethernet standard in June 2002 [1], an optical link with a wavelength of 850nm was anticipated. In order to achieve a link length of 300m, a "next-generation" multimode fiber [2] should be used as a transport medium. Cost-efficient multimode laser diode of VCSEL (Vertical Cavity Surface Emitting Laser) type is used in the transmitter. The link performances depend on many parameters that represent the laser, fiber or receiver characteristics, as well as the launch conditions from the laser to the fiber, the optical lens, the optical connectors, etc.

The Inter-Symbol Interference (ISI) Penalty is used to measure the quality of the link. If ISI Penalty has values less than 2.5dB, then the bit error rate will be lower than 10^{-12}. The unsatisfactoriness of this ISI criterion doesn't cause link dysfunction, but a bit error rate greater than 10^{-12}.

According to the IEEE and TIA (Telecommunications Industry Association) criteria, if for an optical link the measured Encircled Flux (EF) at radius 4.5μm is less than 30% and at radius 18μm EF is greater than 86%, while measured Differential Modal Delay (DMD) of the fiber satisfies one of the six predefined DMD profiles, and yet the Overfill Launch Bandwidth (OFLBW) of the fiber is greater than 1.5GHz*km, then with a high probability is expected that the link ISI Penalty will be less than 2.5dB. The links that satisfy these criteria are called TIA compliant links. Some TIA compliant links, although satisfy all these criteria, may still generate ISI Penalty greater than 2.5dB.

The goal of this paper is to show the dependency between ISI Penalty and each of the relevant parameters that characterize the optical link: radial, axial and tilt offset, the laser spot size, the laser modal structure, the EF at different radii, the radii at which the EF gets predefined values, the links configuration, the fiber DMD profiles, the OFLBW, etc.

We aimed to determine which parameter contributes highest ISI Penalty increase, which means the parameter that is mostly correlated with ISI Penalty.

When the most influential parameters are determined, it should be concluded the dependency between each of them and ISI Penalty. With an adequate parameter control and optimization of the launch conditions from the laser to the fiber, the link performances will be improved, and will be possible to outrun the standard link length of 300m.

2. Models and Simulations

The 10Gb/s Ethernet link model is shown on Figure 1. It is 300m long, and consists of an optical source (multimode VCSEL that emits light at 850nm), next generation multimode fibers with effective modal bandwidth higher than 2000MHz*km, and an optical receiver. The light is launched from the transmitter into the first fiber through a lens. As a consequence of the non-ideal mechanical alignment, a radial, axial and tilt offsets appear. The fibers through the link are connected with optical connectors, which introduce only radial offset.

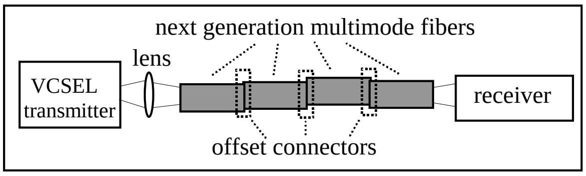


Figure 1. Link model

According to the link models and results presented in [3], [4], [5], four link configurations are simulated (according TIA): “no connections” – 300m fiber without connectors, “1-300-1”, “1-1-300-1” and “1-200-100-1”, where the numbers show the fiber length in meters, and the lines correspond to the connectors. Here, the results are shown for each link configuration as a function of the axial offset (z_offset), which has the following values: -100μm, -50μm, 0μm, +50μm and +100μm.

We have simulated 20×40000=800000 randomly chosen source, fiber and link configuration combinations, in order to get a real view of the link behavior for different circumstances. 2000 different VCSEL sources, 5000 DMD fiber profiles that represent the mode delay in the fiber, and 1000 different combinations of radial offsets in the connectors through the link, are used.

The link simulations, the performance calculations and other analyses are done in MATLAB, while for result presentation MATLAB and MS EXCEL are used.

3. Results

3.1 Computing the Correlation Coefficients

In order to execute the statistical computations of the parameter correlations, the existing MATLAB functions cov(A) and corrcoef(A) are used. For a given matrix A, where each row is an observation, and each column a variable, corrcoef(A) is a matrix of correlation coefficients. If the original matrix A has n rows and m columns, the dimensions of the obtained matrix of correlation coefficients are $m \times m$, which means that the number of rows and columns in the new matrix is the same as the number of columns in the original matrix. The matrix of correlation coefficients contains values that are normalized measure of the strength of the linear relationship between two variables. Uncorrelated data results in a correlation coefficient of 0, while equivalent or the same data sets have a maximum correlation coefficient of 1. As the value of a given element is greater than 0 and closer to 1, the correlation of the variables in the columns that form that element is greater. The positive correlation between two variables means that the increase of the first variable influences the second variable increase, while the negative correlation means that if the first variable gets higher values, the second variable values will decrease.

First, the covariances C_{ij} are calculated. The covariance represents the relationship between the variable in the column *i*, with those in the column *j*, in the original matrix, and is given with the following relation:

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

where

$$\mu_i = \frac{1}{n}\sum_{r=1}^{n} x_{ri}\ ,\ i=1,2,...,m\ ,\ j=1,2,...,m\ . \qquad (2)$$

n and *m* are the number of rows and columns in the original matrix A, respectively. The element computation of the matrix of correlation coefficients is simple after getting the covariances C_{ij}, using the following relation:

$$corrcoef_{ij}\left(A\right)=\frac{C_{ij}\left(A\right)}{\sqrt{C_{ii}\left(A\right)\cdot C_{jj}\left(A\right)}} \qquad (3)$$

3.2 Correlation Coefficients between ISI Penalty and the Link Parameters

In this part, an analysis of the correlations between ISI Penalty and the other characteristic system parameters is given, for all link configurations and axial offsets. Two cases are considered: an average for all 800000 links and average only for the TIA compliant links. The correlation coefficients are shown in Table 1. Both analyses show that ISI Penalty is most correlated with the fiber DMD related parameters, which means that the fiber profile has greatest influence of ISI Penalty. The DMD Figure of Merits (FoM) parameters: FoM(11), FoM(12), FoM(13), FoM(14) and FoM(15) describe the fiber quality in the following radial ranges 5–16μm, 5–17μm, 5–18μm, 0–18μm and 0–23μm, respectively. The indices 11, 12, 13, 14 and 15 are arbitrarily chosen. The other parameters influence the ISI Penalty at various extent, and according to their influence, they have greater or smaller ISI correlation coefficients. The EF at radius 18μm and the radius where the EF gets 86%, are parameters that have second influence, right after the fiber profile influence. The parameters EF at radius 4.5μm and the radius where the EF gets 30% have smaller influence to ISI Penalty, but its influence is important especially when analyzing all links. Other parameter that shows significant influence to ISI Penalty is the OFLBW. From these conclusions it is absolutely clear why the TIA criterion contains the parameters that represent the DMD profile, EF and OFLBW.

Table 1. Correlation coefficients between ISI Penalty and some relevant parameters

Parameter	Correlation coefficients with ISI Penalty	
	TIA links	**All links**
radial offset	-0.0670	0.0987
axial offset	0.0992	0.1140
laser spot size	-0.0940	-0.1314
radius (EF=30%)	-0.0003	0.1957
radius (EF=86%)	0.1432	0.2746
EF (radius=4,5µm)	0.0133	-0.1632
EF (radius=18µm)	-0.1867	-0.2935
DMD FoM(11)	0.6368	0.6672
DMD FoM(12)	0.6631	0.6881
DMD FoM(13)	0.6822	0.6908
DMD FoM(14)	0.6736	0.6844
DMD FoM(15)	0.6345	0.6620
OFLBW	-0.1789	-0.1481

3.3 ISI Penalty Dependence on the Fiber DMD Profile

In this part it is analyzed the ISI Penalty dependency from the parameter DMD FoM(15), which is a relative parameter that defines the fiber profile in the whole intersection from 0–23µm, for different link configurations and axial offsets. The analyses are done for all 20×40000 links and for the TIA compliant links. On Figure 2 it is illustrated the ISI Penalty distribution from FoM(15) for all links with link configuration “no connections” and zero axial offset. The ISI Penalty values are given in dB. We have chosen the parameter FoM(15) for analysis, because it represents the whole fiber intersection. In that way, real view for the ISI Penalty dependency, for the whole fiber width, can be obtained. From Figure 2 it can be noticed that in the range 0<FoM(15)<1, the distribution of the maximum ISI Penalty magnitudes for the links of all matrices has non-linear form, and in this interval the links has greatest density, as it can be seen in Figure 3. In the interval in the range 1<FoM(15)<2.5 ISI Penalty has almost constant distribution of its maximum values. In the interval 2.5<FoM(15)<4 there is a small number of links, which ISI Penalty values are relatively huge. For the results given in Figure 2, the links with ISI Penalty<2.5dB and FoM(15)<1 are declared as “good”.

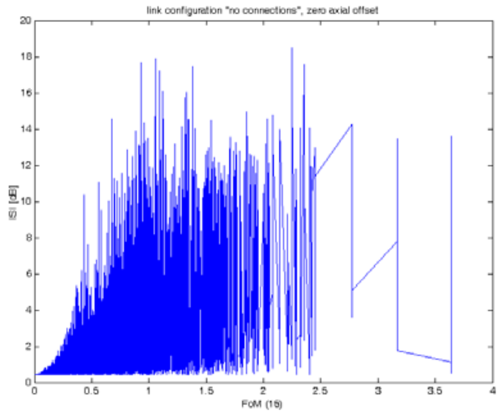


Figure 2. ISI Penalty vs. FoM(15) for all links with link configuration “no connections” and zero axial offset

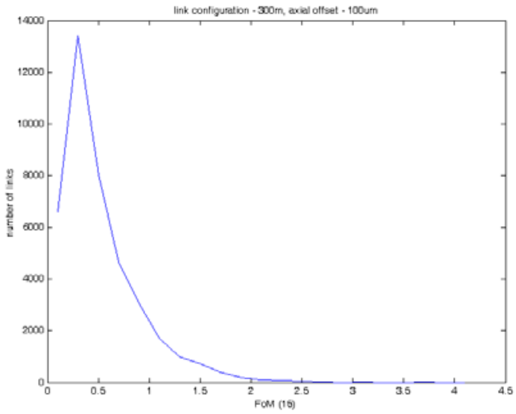


Figure 3. Link number distribution from FoM(15) for all links

In Figure 4 it is given the ISI Penalty vs. FoM(15) dependency for the TIA compliant links. It can be noticed that the forms given on Figure 4 have similarity with the forms given on Figure 2. The difference with the previous figures is that ISI Penalty has significantly lower values, and its distribution is up to FoM(15)=0.8, because of the DMD compliance. The distribution of the maximum ISI Penalty magnitudes in the range 0<FoM(15)<0.5 has growing tendency, while in the range 0.5<FoM(15)<0.8 the distribution is almost flat. The links that satisfy the condition ISI Penalty<2.5dB are declared as “good” links, since all the links satisfy the condition FoM(15)<1. If we compare the maximum ISI Penalty values, it can be concluded that the values given in Figure 2 reach almost 20dB, and for other link configurations and axial offsets reach 30dB. The TIA compliant links shown in Figure 4 has maximum ISI Penalty values of 3.25dB, while for other configurations and offsets the maximum ISI Penalty values are lower than 4.77dB. It would be perfect if the TIA compliant links has maximum ISI Penalty values lower than 2.5dB.

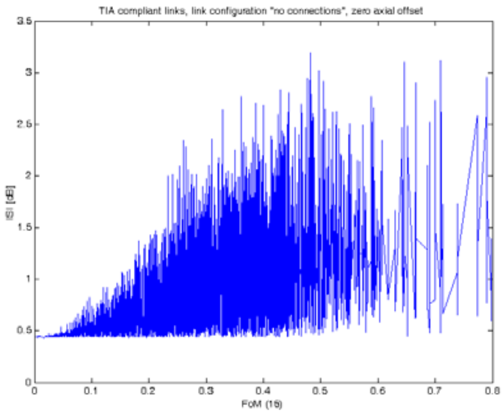


Figure 4. ISI Penalty vs. FoM(15) for TIA compliant links with link configuration "no connections" and zero axial offset

3.4 ISI Failure Rate

If we separate those links that generate ISI Penalty values grower than 2.5dB, then the percentage of the "bad" links, from ISI Penalty point of view, can be determined. The relation between these "bad" links and all analyzed links defines the ISI Failure Rate – ISI FR. On Figure 5 it is given the dependency of ISI FR vs. the axial offset (z_offset). It can be seen that lowest failures have the links with zero axial offset, and if the axial offset is increased in positive or negative direction, the ISI FR increases. Considering that all links are analyzed, without defining any condition that should be satisfied, the obtained ISI FR values in the range 17-24% are expected. If we separate only the links that satisfy the TIA conditions, and from these links we separate the links that generate ISI Penalty values greater than 2.5dB, then ISI FR gets significantly lower values, between 0.2 and 0.8% (Figure 6). These values are the best indicator why TIA has chosen these links parameters (EF, DMD fiber profile and OFLBW) that should be used as a criterion to evaluate the link performances. It is certified that only a small number of the TIA compliant links have ISI Penalty>2.5dB. From Figure 6 it can be seen that lowest ISI FR values have the links without axial offset.

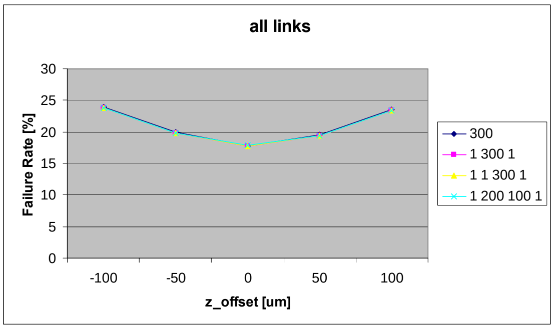


Figure 5. FR vs. axial offset for all links

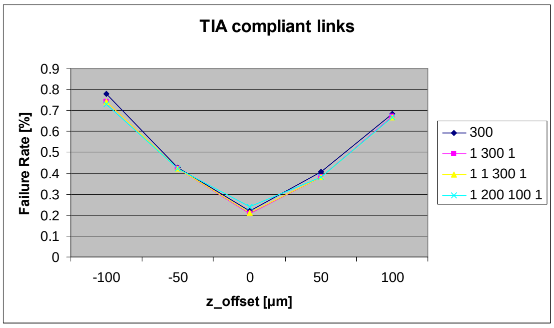
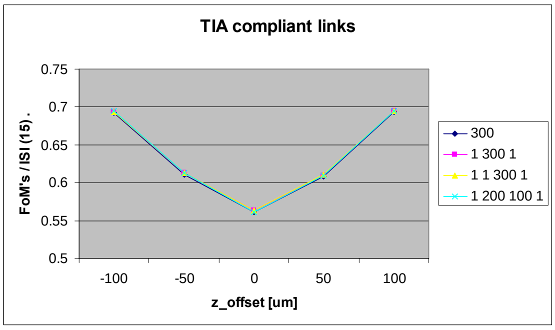


Figure 6. FR vs. axial offset for the TIA compliant links

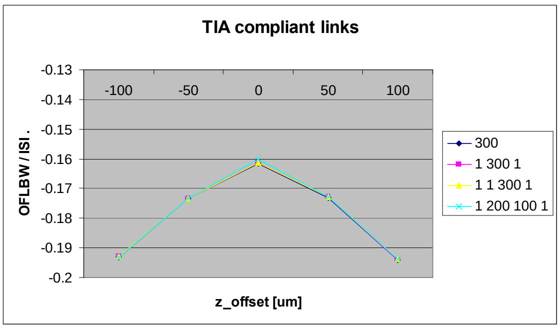
3.5 Dependence of Correlation Coefficients on Axial Offset

Next, an analysis between the correlation coefficients and the axial offset is done. In Figure 7 it is illustrated the dependency of the correlation coefficients for ISI Penalty with the two parameters: DMD FoM(15) and OFLBW, separately, for the TIA compliant links. From Figure 7a) it can be concluded that the curves, that represent the dependency of the ISI Penalty and FoM(15) correlations from the axial offset, have similar shape as ISI FR given in Figure 6. Each correlation coefficient has positive value. The lowest values exist when the axial offset is absent, and highest values when the axial offset is +/-100µm. The positive correlation means that if the DMD FoM(15) value increases, then ISI Penalty grows, too. Higher correlation between ISI Penalty and FoM(15) when the axial offset is grower, can be explained with the fact that, if the fiber is excited with light with bigger diameter (because the fiber beginning moves away from the beam focal plain), the fiber profile has grower impact to the system performances, which produces higher correlations between FoM(11,12,13,14,15) and ISI Penalty.

The negative correlation between ISI Penalty and OFLBW shows that if the system bandwidth grows, the ISI Penalty value decreases.



a) coefficients between ISI Penalty and DMD FoM(15);



b) coefficients between ISI Penalty and OFLBW

Figure 7. Dependency of the correlation coefficients vs. the axial offset and different link configurations, for the TIA compliant links

The curves for the correlations between the other parameters and ISI Penalty are not illustrated here. The curve shapes that show the correlations between ISI Penalty and the parameters r(EF=30%) and EF(r=4,5μm), separately, are very similar. The correlations between ISI Penalty and r(EF=30%) have negative values for the links that have no axial offset, while with the offset growing the correlations pass in the positive axis part. The correlations between ISI Penalty and EF(r=4.5μm) have positive values for the links without axial offset, and fall to the negative values when the axial offset grows.

The correlation between ISI Penalty and r(EF=86%) is positive, while there is negative correlation dependency between ISI Penalty and EF(r=18μm). Minimal correlation coefficients (according to their absolute values) are obtained for the links that have no axial offset.

Conclusions

The detailed sight of ISI Penalty correlation, as a main measure of the 10 Gb/s Ethernet link performances, with the parameters that describe the system components, can be useful in order to explain the “hot spot” appearance, where ISI Penalty gets very high values. These regions should be avoided for link exploitation, or we should stop their appearance with a determined control and optimization of the light launch from the laser into the fiber.

References

[1] IEEE 802.3ae 10 GbE standard, June 2002

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

[3] A. Risteski, et al. “Comparison of methods for modeling the next generation multimode fiber”, in 2002 Proc. IASTED CSN’2002 Conf., Malaga Spain, 2002

[4] P. Pepeljugoski et al, “Development of Laser Optimized 50μm Multimode Fiber for Multi-gigabit Short Wavelength LANs”, IEEE Journal Of Lightwave Technology, May 2003

[5] P. Pepeljugoski et al, “Modeling and Simulation of the Next Generation Multimode Fiber, IEEE Journal of Lightwave Technology, May 2003