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Interferometric Noise Penalty on 10 Gb/s LAN Links

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Abstract: The interferometric noise penalty in 10 Gb/s Ethernet LAN links is assessed as a function of receiver and transmitter reflection coefficients and other link parameters. Robust link operation was experimentally observed and theoretically confirmed with 12 dB return loss for both the receiver and transmitter, and 4 dB extinction ratio.

Introduction

In an optical communications network, the received optical signal can be corrupted by any of a number of parasitic optical signals falling within the receiver passband. In addition to the linear crosstalk, beating of the signal and parasitic light from optical interference produces an interferometric noise (IN) component. For high-speed LAN single-mode fiber links, IN from successive reflections at the ends of a link generally dominates. The analysis is simplified by the absence of a multitude of interspersed optical elements and/or WDM channels. In telecommunication networks, the return loss from any interface, including the receiver, is generally better than 20 dB. However, in the LAN environment, where less expensive components are used, typically the return loss from the receiver is 12 dB. In this paper we examine the penalties due to IN in the 10 Gb/s Ethernet environment. Our theoretical approach is similar to that outlined in /Legg/, but here we also take into account signal degradation and actual power penalties in the link. The link penalty due to IN will impose limits upon the receiver and transmitter reflection coefficients in conjunction with the extinction ratio of the modulated light /1-3/.

IN Penalty Calculations

The resultant received light waveform $P_{rx}(t)$ is given by:

$$\begin{aligned} P_{rx}(t) = {} & P(t) + A^2 R_{Rx} R_{Tx} P(t-T) \\ & + 2\sqrt{P(t)\hat{e}(t)} \cdot \sqrt{A^2 R_{Rx} R_{Tx} P(t-T)\hat{e}(t-T)} \\ & \times \cos[\omega T + \phi(t) - \phi(t-T)] \end{aligned}$$

where $T = 2l/c$ is the fiber link round-trip time; R_{Rx}, R_{Tx} are reflection coefficients at the receiving and transmitting ends of the link; $A = e^{-\alpha l}$ is the single-pass link attenuation; $\hat{e}$ is the light polarization unit vector; ω is the optical carrier frequency; and ϕ is the carrier phase. IN arises from random fluctuations in the third mixing term dependent upon the relative phases and polarizations of the interfering light. For time delays T much greater than the laser coherence time τ_c, a condition which is generally satisfied, the IN is driven by the laser phase noise /1/. The relative polarizations drift comparatively slowly with changing environmental conditions; the worst-case IN occurs for aligned polarizations. Similar variations in the round-trip delay T may also introduce a low bandwidth IN drift.

Under these conditions and ignoring laser RIN, P_{rx} for a given $P(t)$ and $P(t-T)$ is a function of the single random variable $\Delta\phi = [\omega T + \phi(t) - \phi(t-T)]$, which for $T >> \tau_c$ is effectively distributed uniformly over the interval $[0, 2\pi]$ /4,5/. The probability density function $f(P_{rx})$ is easily derived as:

$$f(P_{rx}) = \frac{1}{\pi} \times \left| \frac{\partial(\Delta\phi)}{\partial P_{rx}} \right|$$

and yields a familiar bounded distribution. The ultimate probability density function (pdf) for the receiver photocurrent is the convolution of $f(P_{rx})$ with the Gaussian distribution of the detector thermal noise.

The impact of intersymbol interference (ISI) is included in an approximate worst-case manner by calculating the BER with $P(t)$ respectively reduced for a 1-bit (P_1) and increased for a 0-bit (P_0) by ISI, while interfering bits $P(t-T)$ are left unaffected by ISI. Explicitly, considering synchronous signal and interfering data bits, and equal probability of each of the four possible combinations of signal and interfering bits:

$$\begin{aligned} BER \approx {} & \frac{1}{4} \mathrm{P}_e\left[P(t) = P_1 - \delta/2, P(t-T) = P_1\right] \\ & + \frac{1}{4} \mathrm{P}_e\left[P(t) = P_1 - \delta/2, P(t-T) = P_0\right] \\ & + \frac{1}{4} \mathrm{P}_e\left[P(t) = P_0 + \delta/2, P(t-T) = P_1\right] \\ & + \frac{1}{4} \mathrm{P}_e\left[P(t) = P_0 + \delta/2, P(t-T) = P_0\right] \end{aligned}$$

for a symmetric optical eye closure δ. The probabilities of error P_e are evaluated by integrating the photocurrent pdf with respect to the decision threshold in the usual manner. The threshold settings have not been optimized in the calculations or the measurements, consistent with 10 Gb/s Ethernet receiver designs.

Experimental Set-up and Results

A fiber Mach-Zehnder interferometer illustrated in Figure 1 was used to experimentally measure the IN penalties under different conditions. A jumper cable within one arm of the

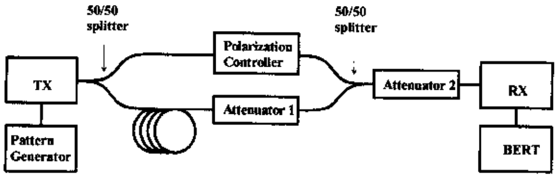

Figure 1: Mach-Zehnder interferometer setup used to measure interferometric noise penalty

interferometer provided a relative delay T much greater than the coherence time of the isolated DFB laser (1310 nm) directly modulated at 10.3125 Gb/s. Different combinations of link length, receiver return loss, and transmitter return loss were simulated by varying the attenuation $A^2R_{Rx}R_{Tx}$ within the delay arm. A polarization controller enabled the relative polarizations of the light from the two interferometer arms to be set. The BERT sampling time and decision threshold were set and subsequently held fixed by performing an eye-centering operation at an intermediate signal amplitude and with the interferometer delay arm blocked.

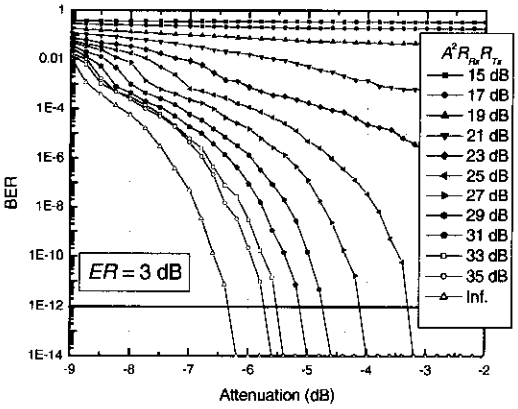

Figure 2: BER measurements for aligned polarizations (3 dB extinction ratio)

Worst-case BER measurements for aligned polarizations are shown as a function of the received signal amplitude in Figure 2 for an extinction ratio (*ER*) of 3 dB. BER floors form at very strong interference levels. The IN penalty is extracted from the family of BER curves. Worst-case IN penalties (at BER = 10^{-12}) for the particular case of $R_{Rx} = R_{Tx} = -12$ dB are given in Figures 3 and 4 as a function of link length ($A = 0.5$ dB/km) for links with and without the maximum 2 dB of allowed connector losses. Positive agreement is observed between measurements and calculations. Calculated penalties are with an eye closure of 1 dB due to ISI in line with the experimental conditions. Also plotted is the remaining power budget for the preliminary 10 Gigabit Ethernet link budget. A positive margin is maintained in all instances with larger margins for shorter links. At the extreme limit of a 10 km link with 2 dB connector losses, the worst-case IN penalty is only a fraction of a dB. Absence of an appreciable IN penalty was confirmed for orthogonal polarizations.

Conclusions

Components used in the LAN environment are cost sensitive and it is therefore crucial that they not be overspecified. We demonstrate that maximum receiver and transmitter return losses of 12 dB, combined with extinction ratios greater than 3 dB, are sufficient to control the IN penalty at reasonable levels and maintain robust link operation over link lengths up to 10 km. For added margins and more robust links, a minimum transmitter extinction ratio of ~4 dB should be used.

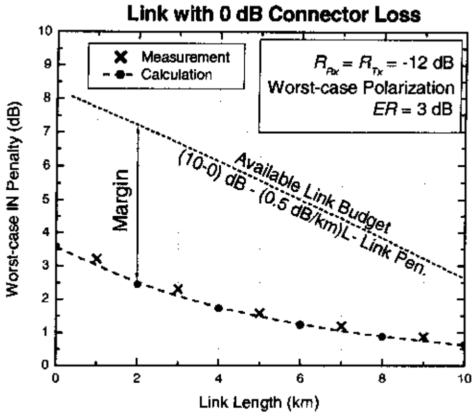

Figure 3: Worst-case IN penalties and link margin for link with 0 dB connector loss. Note large margin for all distance objectives.

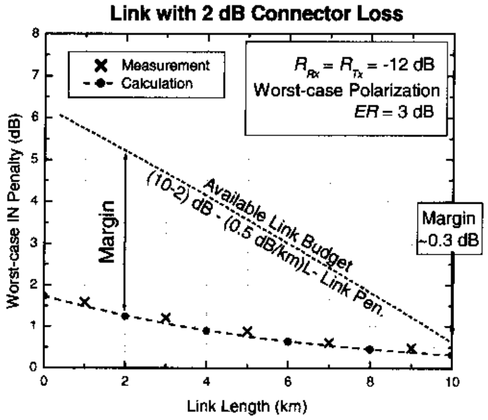

Figure 4: Worst-case IN penalties and link margin for extreme link with 2 dB connector loss. Note positive margin maintained for all distance objectives.

References

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