Accurate Statistical Performance Evaluation of EDC Techniques on 10 Gb/s Multimode Fiber Links

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***Abstract*—We perform a statistical investigation (based on the Cambridge 108-fiber set) of the performance limits of different electronic dispersion compensation (EDC) techniques in terms of their robustness to modal dispersion, considering the impact of connection offsets in 10GBASE-LRM (long reach multimode) systems with connection offsets. We also investigate the effectiveness of an accurate and fast analytical method to take into account any amount of intersymbol interference based on Gaussian quadrature rules, thus allowing a thorough statistical investigation of the performance of different EDC techniques.**

***Keywords*—Multimode fiber links, intersymbol interference (ISI), decision feedback equalizer (DFE), maximum likelihood sequence detection (MLSD), electronic dispersion compensation (EDC), optical fiber communication systems, 10GBASE-LRM, optical fiber LAN**

I. Introduction

Interest in electronic dispersion compensation (EDC) techniques, such as combined feed-forward and decision-feedback equalization, has grown significantly in last years as a result of the standardization activities of the IEEE 802.3aq task force, which developed the 10GBASE-LRM standard for 10 Gb/s Ethernet over fiber-distributed-data-interface (FDDI)-grade legacy silica multimode fibers (MMF) [1]. A comprehensive investigation of the full set of worst-case performance MMF links is mandatory because of the considerable variability in the installed fiber population, due to variations in the refractive-index profile [2]. Moreover, since statistical analysis is an essential complement to the emerging experimental results [3], efficient analytical methods to evaluate error performance are highly desirable. This work emphasizes the baseband approach and gives a statistical investigation of the performance limits of different EDC techniques in terms of their robustness to modal dispersion, considering the impact of connection offsets and further investigating the benefits of the optimal maximum-likelihood sequence detection (MLSD) strategy for a MMF link over lengths up to 500 m. Indeed, the channel impulse response of 10 Gb/s communication links over FDDI-grade legacy MMF spans several bit times, making performance evaluation computationally too time consuming when performed by means of the exhaustive method used in the literature [4], [5], where worst-case statistical analysis is usually performed by using pseudorandom binary sequence (PRBS) generators. In this work we extend the results presented in [6], showing that using a PRBS could be misleading if the channel memory is not properly accounted for by the PRBS length, and also establish the effectiveness of the method based on the Gaussian quadrature rules (GQR) technique [7] to take into account any amount of intersymbol interference (ISI) for evaluating the performance of standard EDC techniques in 10GBASE-LRM. The accuracy of the GQR method is checked against the results obtained through both the exhaustive method and standard Monte Carlo simulations, whose computational cost grows exponentially with the ISI length, in contrast with the almost linear growth observed with the GQR method.

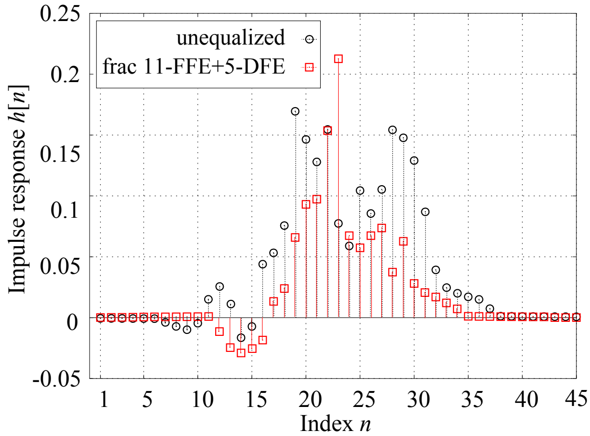

Fig. 1. Discrete-time characteristic of another representative MMF link.

II. Fiber Channel Model

The fiber output is given by the superposition of the modal power coefficients carried by each mode group; every condition that modifies the energy distribution among the launched modes will generate accordingly different modal impulse responses. The adopted model and parameters of the end-to-end fiber follow the typical link in the draft standard [1], with two offset connectors near the transmitter end and a worst-case axis offset of 7 µm [8]. Fig. 1 shows the equivalent discrete time channel characteristic of a 400 m MMF link with an illustrative fiber taken from the 108-Cambridge fiber database [9], before and after a feedforward equalizer (FFE) with 11 fractionally-spaced taps combined with a 5-taps decision feedback equalizer (DFE), dimensioned according to the minimum mean square error criterion. Each channel in the Cambridge database is uniquely identified by a number (98, in our case) indicating the refractive index profile of the fiber and a launch offset expressed in microns (17 µm, in our case). Fig. 1 illustrates that MMF links suffer from a large amount

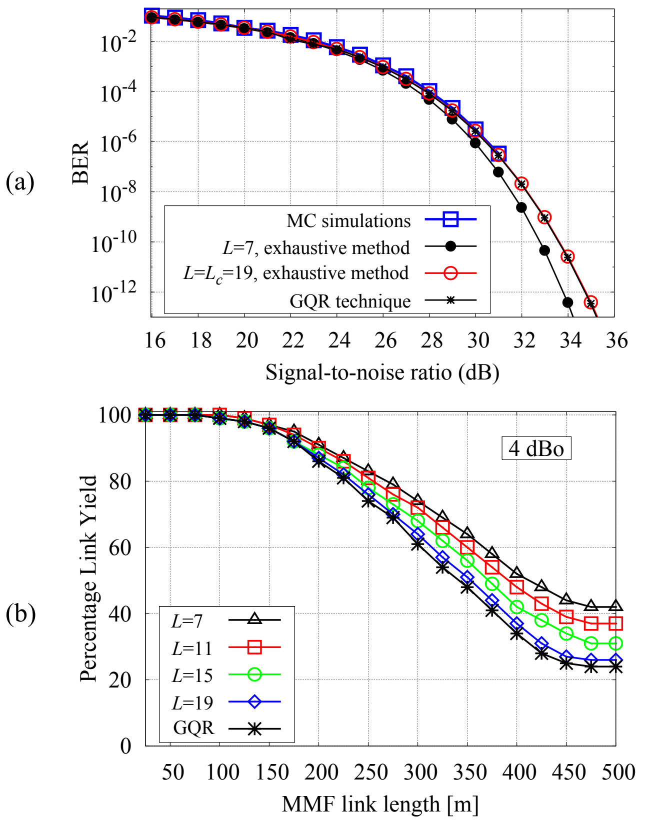

Fig. 2. (a) Performance comparison using different BER computation methods. (b) Yield curves with 17 µm offset launch and fractionally-spaced 11-FFE+5-DFE, considering increasing values of the number L of interferers for a reference penalty of 4 dBo. The GQR curve is approached for $L \geq 21$ (curves for these values of L are not shown to avoid clutter).

of amplitude distortion; the link impulse response results in severe ISI, spanning approximately $L_c = 25$ bit periods (both pre-cursors and post-cursors), whereas the channel memory L_c reduces to ~ 19 after equalization.

III. Numerical Results

The statistical investigation on the performance of different EDC techniques in terms of their robustness to modal dispersion is performed by considering a reference bit-error rate (BER) of 10^{-12}, such that Monte Carlo (MC) simulations are infeasible and analytical methods have to be used. The exhaustive method is one approach to compute the error probability that yields an exact result. Fig. 2(a) shows the performance in terms of bit error rate (BER), computed using both the exhaustive method accounting for different numbers L of interfering symbols and the GQR method, based on the computation of the ISI moments [10, p. 284], in the case of the channel in Fig. 1. In this case, the number of symbols involved in the ISI induced by DMD is $L_c \approx 19$, hence the computation of the error probability is exact only for $L = L_c$; in Fig. 2(a) we also show the BER curve obtained by accounting only for $L = 7$ interferers. Standard MC simulations were also performed for further validation of the results. When using $L = 7$, the penalty is ~ 0.37 dB at a BER of 10^{-4} and increases to ~ 1 dB at 10^{-12}, which is the standard reference BER. Hence, the error performance analysis of an MMF link could be misleading if a PRBS of not sufficient length is employed. Indeed, to account for $n-1$ interferers, a PRBS of length greater than or equal to $2^n - 1$ is needed.

In order to investigate the accuracy of the GQR method, we compare the results with those obtained through the time-consuming exhaustive method by accounting for an increasing number L of interferers by means of PRBSs of length $2^{L+1}-1$. In the following, the dispersion penalty is defined as the increase in the received optical power (given in dBo) necessary to achieve a BER of 10^{-12} with respect to a back-to-back transmission [5]. In Fig. 2(b) we report the performance of a fractionally-spaced 11-FFE combined with a 5-DFE in terms of percentage yield, giving the ratio of links whose dispersion penalty is below a given value (4 dBo). The yield curves are computed as a function of the MMF link length (from 25 m to 500 m in 25 m steps). It turns out that the curves for $L \geq 21$ coincide with the curve labeled GQR. This means that $L = 21$ is the minimum number of interferers to be used for all the population of MMF fibers and for all link lengths to converge to the exact result, which is directly obtained through the GQR method. In principle, one could alternatively estimate the channel memory L_c of every fiber of the 108-Cambridge fiber database, for every radial offsets of the SMF launch (17 µm, 20 µm, 23 µm) and for every link distance, and then compute the BER by using a PRBS of appropriate length for each different case. Hence, it reads clear that a rigorous statistical analysis using the exhaustive method is exceedingly time-consuming compared to the fast and accurate GQR method.

The results confirm that the length L of the considered ISI pattern has a non-negligible impact on percentage yield curves for a given reference value of the dispersion penalty. Indeed, the percentage difference between the curve for $L = 7$ and that for $L = 21$ (curve labeled GQR) is equal to ~ 18% for a link length of 400 m and an allocated margin of 4 dBo, which represents a realistic ISI power-penalty criterion [4]. Given the excellent agreement between the limiting curves obtained by the expensive exhaustive method for increasing values of L and the efficient GQR, the comprehensive EDC statistical investigation was based on the GQR technique.

Along with standard techniques such as combined FFE and DFE, we also investigate the performance of the optimal MLSD strategy, which provides the ultimate bound achievable through electronic processing and thus a benchmark for assessing the relative performance of simpler strategies. The performance of a MLSD receiver is evaluated by using the classical union bound based on the exact branch metrics, thus providing a tight upper bound to the BER. This ultimate bound provided by the MLSD technique is explored under two different constraints on the sampling rate, since oversampling is a possible way to guarantee sufficient statistics. Then, we statistically compare the performance of both standard equalizers and MLSD receiver in terms of the coverage curve, giving the percentage of fibers featuring a penalty less than a prescribed value (in dB), and in terms of percentage yield. In a practical implementation, the number of equalizer taps and trellis states for the MLSD receiver should be properly chosen depending on the channel memory L_c. However, since the purpose of this work is a statistical investigation of the performance limits of different techniques in terms of their robustness to modal dispersion, in order to get the asymptotically

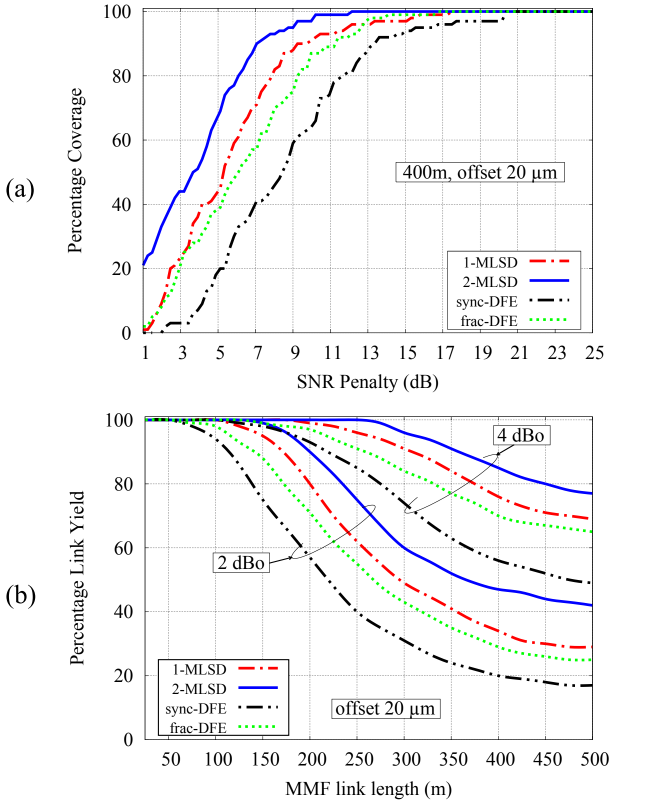

Fig. 3. (a) Coverage curves for a 400 m MMF link with 20 µm offset launch, (b) Yield curves with 20 µm offset launch and two system margins.

best performance for the FFE+DFE structures, an exceedingly high number of taps for both the feedforward and feedback filters were used.

In Fig. 3(a) the percentage coverage of different receiver structures is shown in the case of a 400 m long link with a 20 µm offset launch: the synchronous MLSD receiver (curve labeled 1-MLSD) does fairly better than a synchronous FFE combined with a DFE (curve labeled sync-DFE), but no significant improvement is observed when using a fractionally spaced FFE (curve labeled frac-DFE). However, performance is significantly improved by means of oversampled MLSD (curve labeled 2-MLSD), exhibiting an impressive robustness to ISI. This result is confirmed also in Fig. 3(b), which shows the percentage yield for 20 µm offset launch. Two different system margins are assumed as references, 4 dB (2 dBo) and 8 dB (4 dBo). The maximum dispersion penalty is typically allocated during the design process. The curves confirm that a fractionally-spaced FFE performs better than its synchronous counterpart, and that the improvement achieved by synchronous MLSD is no more than ~ 5% at a link length of 300 m. However, the improvement increases to ~ 20% (at a link length of 300 m), in the case of MLSD with 2 samples per bit period processed at each trellis step. A more comprehensive evaluation and comparison of the effectiveness of different EDC techniques in 10GBASE-LRM is reported in [6], which also includes a more detailed discussion of the MMF channel model and the simulation setup employed in the present analysis.

IV. Conclusions

The effectiveness of the GQR analytical method to correctly take into account any amount of ISI for evaluating the performance of standard EDC techniques has been established. It has been shown that the common use of a PRBS to evaluate system performance could be misleading when the channel memory is not properly accounted for by the PRBS length. The proposed analytical approach is found to be accurate and computationally efficient even when the number of interfering terms is very large. Using the GQR technique, we have also provided a comparison of different strategies aimed at increasing the tolerance of MMF systems to DMD. The investigation reveals that the fractionally-spaced FFE+DFE equalization structure is very effective in 10GBASE-LRM, since it gives a performance that is relatively close to the MLSD receiver with one sample per bit period. Oversampled MSLD is the optimum receiver for an ISI and Gaussian noise limited transmission channel such as the one under consideration. However, regarding the digital signal processing (DSP) implementation complexity, the MLSD solution grows exponentially with the memory length, while the FFE+DFE approach only linearly [10]. Since the MMF channel memory L_c strongly depends on the length of the link and can easily exceed $L_c = 20$, an MLSD receiver would require a so high number of states to become unpractical even for off-line processing, and thus it is completely unreasonable for an actual DSP design. We then conclude that the fractionally-spaced FFE+DFE equalization approach is a good choice for an MMF link, due to its good balancing between performance and complexity.

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