Maximizing 425G SWDM VCSEL-MMF Systems Reach Through Variable Rate per λ

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Abstract: We demonstrate the maximization of reach for 425G SWDM systems based on VCSEL-MMF links through *variable rate* solutions, reaching up to >100 m for 99% of tested links.

1. Introduction

In data center interconnects (DCI), the most common solution for short reach links (∼ hundreds of meters) relies on multi-mode fibers (MMF) coupled with transceivers based on directly modulated vertical cavity surface emitting lasers (VCSEL). Indeed, compared to single mode systems, VCSEL-MMF represents a significant cost-effective solution particularly thanks to cheap components, simplified laser-fiber coupling due to the larger MMF core, reduced power consumption and higher system reliability [1]. However, following the ever increasing demand of throughput (>100 Gbps) to keep up with modern technologies requirements, new challenges are posed to upgrade the next generation DCI, which are mainly limited by opto-electronic devices' bandwidth, modal dispersion (MD) and chromatic dispersion (CD) [2]. Thus, possible solutions to increase system throughput and maximum reach, include the deployment of broader bandwidth MMFs and the introduction of short wavelength division multiplexing (SWDM), where multiple wavelengths (λs) per fiber are used together with equalization [3].

In [4], a comprehensive statistical analysis was performed on a four λs SWDM system based on PAM-4 VCSEL-MMF links operating at 100 Gbps/λ net bit rate over a large dataset of OM3 and OM4 fibers. The study investigates the performance of three different equalizers: feed-forward equalizer (FFE), decision feedback equalizer (DFE) and maximum-likelihood sequence estimation (MLSE) equalizer. The authors showed that, an aggregated throughput of 400 Gbps was feasible for 99% of the simulated links reaching ∼60 m and ∼80 m, respectively for OM3 and OM4, implementing MLSE-based equalization. Nevertheless, maximum reach performance was different over the four λs, with shorter distances achieved by longer wavelengths, actually limiting the maximum reach of the overall SWDM system.

In this paper, we propose a variable rate (VR) approach for SWDM VCSEL-MMF systems, in contrast with the fixed rate (FR) solution adopted in [4], consisting in the optimization of the bit rate per λ. With this method, an equalization of the performance over the four λs is obtained together with a significant improvement in the system maximum reach. The study is carried out for the family of VCSELs considered in [4] (*Vendor 1*), and extended to two more families (*Vendor 2* and *Vendor 3*), over both OM3 and OM4 MMF fibers (same datasets used in [4]).

Results show significant increase in maximum reach when the VR approach is exploited, with increments up to 33%. In particular, transmissions beyond 100 m are demonstrated for 99% of simulated OM4 links in case of MLSE equalizer using VCSELs supplied by *Vendor 2* and *Vendor 3*.

2. Methodology: the Variable Rate strategy

Initially, we consider the same PAM-4 $4\lambda \times 100$ Gbps/λ SWDM VCSEL-MMF system of [4] (*fixed rate*), analyzed for 20233 MMFs (16467 OM3 and 3766 OM4) coupled with 8 VCSELs from *Vendor 1*. A soft forward error correction (FEC) code KP4-FEC with 6.25% overhead, resulting in 106.25 Gbps raw bit rate (R_B), and a target bit error rate (BER) of $BER_T = 2 \cdot 10^{-4}$ are assumed. To determine transfer functions for all VCSELs coupled with all MMF fibers, following the approach presented in [5], the spectral and spatial characterizations of all sources has been performed in our laboratory [4]. Afterwards, the statistical study to evaluate the maximum reach (L_{MAX}) is carried out for all fibers and VCSELs combinations through a system-level numerical simulator. Like in [4], the four SWDM λs are 850 nm, 880 nm, 910 nm and 940 nm, and three different equalizers, i.e. FFE, DFE and MLSE, are considered.

Now our goal is to extract an analytical relationship between maximum reach and bit-rate from simulated data. Having defined the maximum reach as the distance guaranteed by 99% of analyzed cases, we extract from results the 1% of worst performing VCSEL-MMF links (shortest length). This process is applied independently on each wavelength, equalizer and fiber type. It results in 1317 and 301 cases, respectively for OM3 and OM4.

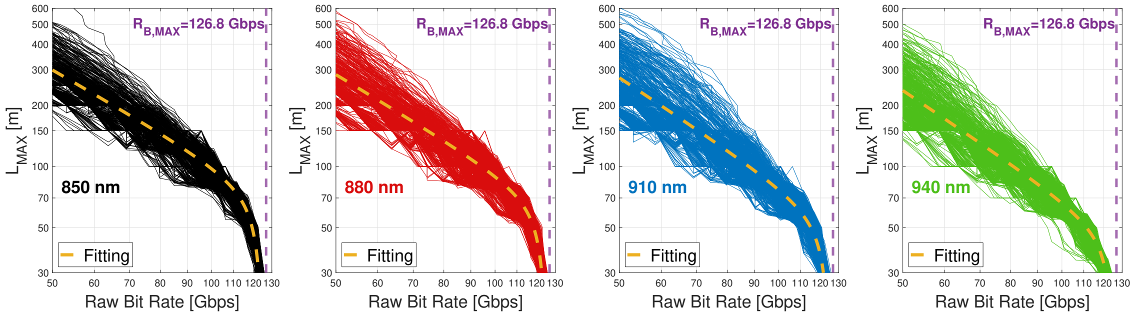

Fig. 1. Maximum reach vs raw bit rate at BER_T for the 1% VCSEL-MMF links with shortest length in case of OM3 fibers coupled with *Vendor 1* lasers and MLSE equalizer for the four SWDM λs.

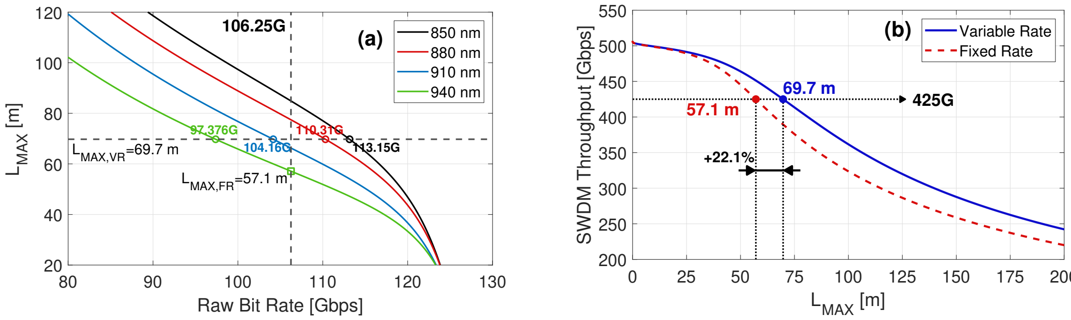

Fig. 2. (a) Fitted curves of L_{MAX} vs R_B for the four λs and (b) estimated SWDM throughput vs maximum reach for fixed rate (FR) and variable rate (VR) for *Vendor 1* VCSELs, OM3 and MLSE.

Consequently, we analyze the system performance for these extracted cases at different raw bit rate values, from 50 Gbps up to $\sim$130 Gbps. Fig. 1 reports the maximum reaches vs related raw bit rate curves obtained for all λs at the target BER in case of OM3 fibers and MLSE equalizer.

For each wavelength we then fit these data with the function in Eq. (1):

$$y = mx + n + \frac{p}{x - log_{10}(R_{B,MAX})}, \qquad \text{where } x = log_{10}(R_B) \text{ and } y = log_{10}(L_{MAX}), \tag{1}$$

a weighted combination of a linear behavior with a vertical asymptotic bound, related to the maximum achievable raw bit rate $R_{B,MAX}$ in back-to-back. The choice of the fitting function comes from observation of Fig. 1, but it is also supported by the knowledge of the channels analyzed. If the vertical bound is given by the transceiver setup, the linear behaviour captures the combination of modal and chromatic dispersion present in the channel. $R_{B,MAX}$ changes with the three equalizers and is 115.7G, 121.2G and 126.8G, respectively for FFE, DFE and MLSE. m, n and p are the free coefficients determined through MSE fitting procedure. In Fig. 1, the fitted curves are plotted as yellow dashed lines.

Fig. 2(a) reports fitting results for OM3 and MLSE equalizer zooming around the region of interest for the 425G SWDM application. Cutting vertically the fitted curves at 106.25G fixed rate per λ, it is possible to estimate the maximum reach on all 4 λs. It is clear that the maximum achievable length of the overall SWDM system, operating at $4 \times 106.25\text{G} = 425\text{G}$ raw bit rate, is limited to $L_{MAX,FR}$=57.1 m by the channel at 940 nm.

We propose a novel approach that remove the constraint of keeping the same bit rate on all wavelengths. At any length, we sum up the maximum bit rate on each wavelength and we obtain the maximum throughput of the SWDM for that reach. This is reported as the blue solid line curve in Fig. 2(b). As a reference we also report the maximum throughput based on the FR approach. In this specific case, we observe an estimated increment of 22% in maximum reach (from 57.1 m to 69.7 m) of the SWDM at 425G when the VR solution is considered against the FR approach. Going back to Fig. 2(a), reading the crossings at $L_{MAX,VR}$=69.7 m, we determine the four raw bit-rates (summing to 425G) to be employed in the VR case (values reported as colored labels). Interestingly, Fig. 2(b) provides a comprehensive characterization of maximum SWDM throughput for a wide range of link lengths. There is always a clear advantage in using the novel VR strategy with respect to the standard FR.

The same procedure is performed on both OM3 and OM4 fibers for all the three equalizers and it is extended to the other two families of VCSELs supplied by *Vendor 2* and *Vendor 3*. Therefore, different optimized rates are obtained depending on vendor, fiber type, equalizer and channel wavelength.

3. Validation of the Variable Rate approach through statistical simulations

Results obtained in previous section are predictions based on fitted curves. To verify the correctness and effectiveness of the proposed VR strategy, we validate them through statistical simulations over the whole dataset of fibers. In Fig. 3, we compare the maximum reach obtained from the statistical analysis exploiting VR strategy

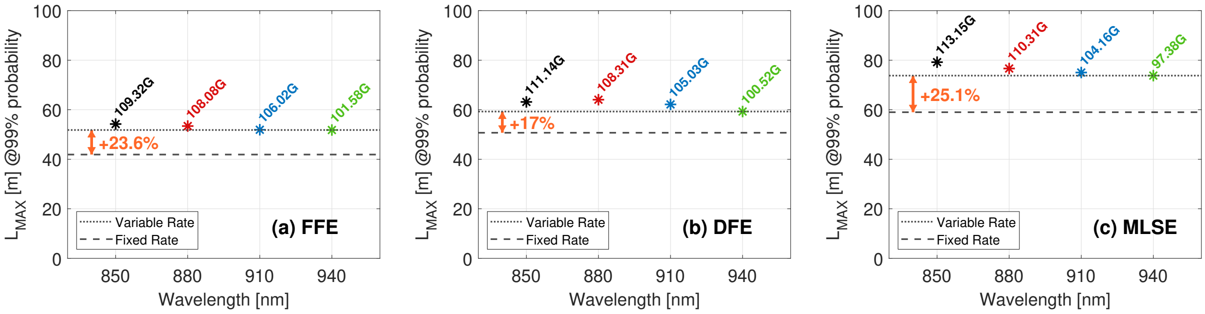

Fig. 3. Maximum reach at 99% probability resulting from the validation of the proposed variable bit rate strategy for *Vendor 1* VCSELs and OM3 fibers in case of: (a) FFE, (b) DFE and (c) MLSE.

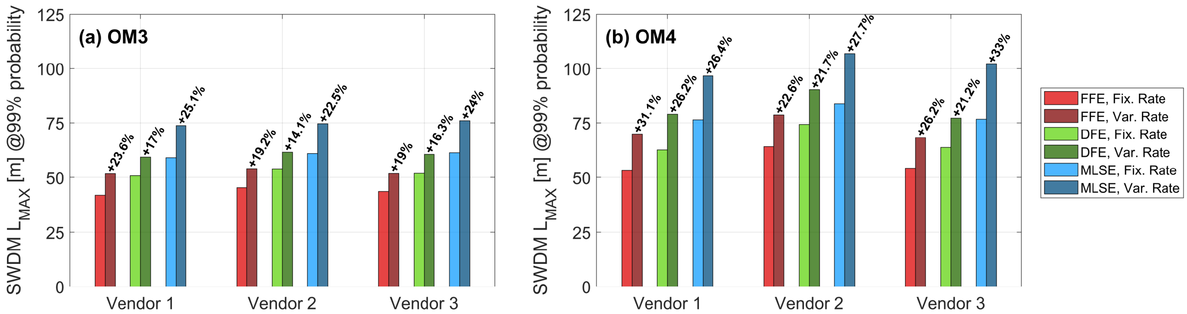

Fig. 4. Comparison of the SWDM maximum reach at 99% probability between fixed rate and variable rate strategies for all vendors and equalizers in case of: (a) OM3 and (b) OM4.

for the three equalizers in case of *Vendor 1* and OM3. Performance of single wavelengths with the corresponding different raw bit rates are shown in the figure. We can notice an equalization of maximum reaches achieved by each wavelength. As a reference, in Fig. 3 we also show the maximum reach for standard FR (dashed line). As expected from the predictions, improved maximum reaches are achieved when the VR is applied, with an increment of 23.6%, 17% and 25.1% for FFE, DFE and MLSE, respectively.

To demonstrate that our approach can be generalized to any source type, we extend our study to other two families of VCSELs. We obtained samples from other vendors and we proceeded with the full spectral and spatial characterization in our lab [4]. Then we perform maximum reach analysis both using FR and VR approaches. Fig. 4 summarizes the resulting SWDM system maximum reach for all equalizers, vendors and fiber types, comparing the performance of FR and VR strategies. Thanks to the VR solution, for all vendors we are able to achieve ∼75 m at 99% probability using MLSE over OM3, with more than 22% of increase compared to FR. Using OM4 and MLSE, transmissions above 100 m are possible employing VCSELs produced by *Vendor 2* and *Vendor 3*. Only *Vendor 1* falls short by a few meters. These results show that with today's available VCSEL technology, the 100 m barrier can be broken by a SWDM systems carrying 425G (400G net).

4. Conclusions

A variable rate approach is proposed to increase the maximum reach of 425G SWDM systems based on VCSEL-MMF short reach links. Bit-rate adaptation on a wavelength basis, in contrast to fixed rate strategies, where the maximum achievable length is limited by the longest wavelength proved to be advantageous. Our results show the effectiveness of the proposed solution, analyzed for a large data set of MMFs (both OM3 and OM4) and for three families of VCSELs supplied by different vendors. Maximum reach improvement varies based on equalization methods, but it always surpasses 14%. Remarkably, transmissions beyond 100 m were demonstrated for 99% of OM4 links in combination with lasers of two of the three vendors using MLSE-based equalizer.

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