Power Optimization for Datacenter Optical Transmitters

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Abstract: Power allocation is investigated for a non-repeated/non-amplified datacenter network scenario. A mathematical model is constructed for the optical eye amplitude in a power constrained case, and the effectiveness of the model is demonstrated experimentally.

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1. Introduction

Mega datacenters are fundamental for an increasing number of services. These include cloud-based data storage, high performance computing, video streaming etc. Thus resulting in a relevant energy footprint, with an estimated energy consumption in the United States of 70 billion kWh in 2014, approximately 1.8% of the total national electricity consumption [1], estimated to reach 13% of the world energy consumption by 2030 [2]. Of those, approximately 15% (more than 10 billion kWh in 2014) consumed by the network equipment [3]. Many efforts, are directed to lower the power requirement of the physical level network components [4]. Most studies, however, focuses on the efficiency of the overall network architecture, or at improving individual optical components.

Here beginning with the assumption of limited total available power, we analyze how different power allocation strategies affect the performance of an externally modulated intensity modulated direct detection (IM-DD) link. We first define the mathematical transmitter model and estimate the link performance. We then compare the analytical results with the experimental bit error rate (BER) measurements. The optimal power allocation is found to be of 2/3 of the power to the laser source and 1/3 to the electrical data signal.

2. Model and measurements

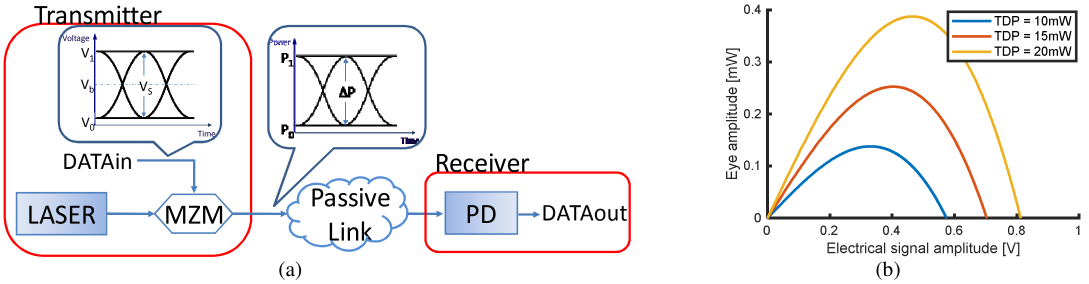
Fig.1(a) sketches the network scenario. The transmitter, is composed of a laser source externally modulated by a Mach-Zehnder modulator (MZM), connected through a passive optical link to the receiver. The power dissipated by the link equals the electrical power dissipated by the laser plus the power required to drive the modulator. A laser wall-plug efficiency of η=20% is assumed, the MZM half wave voltage (V_π), insertion loss (IL), and input impedance (Z) are 5V, 6dB, and 30Ω, respectively. The amplitude ΔP of the optical modulated signal (see Fig. 1(a)), defined as the power difference between the logic zero (P_0) and one (P_1), can be calculated, neglecting noise contributions as in Eq. 1, where P_{laser} is the wall plug power dissipated by the laser, V_0 and V_1 are, respectively, the digital zero and one electrical amplitudes, assumed bipolar (i.e. V_0=-V_1), and V_b is the modulator bias voltage.

$$\Delta P = P_1 - P_0 = 10^{IL/10}\eta P_{laser}\left(\cos\left(\frac{2\pi(V_1+V_b)}{V_\pi}\right)-\cos\left(\frac{2\pi(V_0+V_b)}{V_\pi}\right)\right) \qquad (1)$$

The bias voltage, which maximizes the MZM electro-optical conversion, is found by maximizing the derivative of the MZM transfer function with respect to V_b. The point of maximum slope corresponds to the MZM quadrature point (V_b=V_π/2). Using the small signal approximation, and defining V_s=|V_1-V_0 |≪V_π, Eq. 1 can be written as:

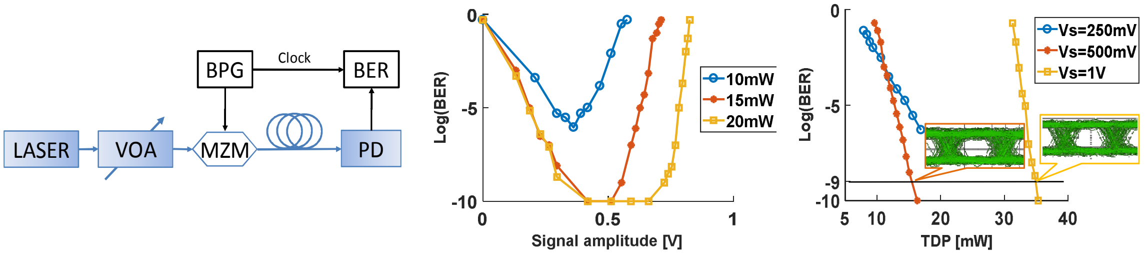
$$\Delta P = kP_{laser}\left[\frac{2\pi V_s}{V_\pi}\right] \longrightarrow \Delta P = kP_{laser}\left[\frac{2\pi\sqrt{Z(P_{tot}-P_{laser})}}{V_\pi}\right] \qquad (2)$$

where $k=\eta 10^{IL/10}$. P_{tot}=P_{laser}+P_s is the total available power, and P_s=V_s^2/Z. From Eq. 2, the ΔP is linearly proportional both to the laser power and the electrical signal amplitude. Therefore, to double ΔP, it is possible either to double P_{laser}, or V_s, leading in the second case to a four-fold increase in the signal power required. Maximizing



(a) (b)

Fig. 1: (a) Network scenario considered in the model, MZM: Mach-Zehnder modulator, PD: photodetector. (b) Simulation of the optical eye diagram amplitude as a function of the electrical signal amplitude for different TDP levels (total dissipated power).



(a) (b) (c)

Fig. 2: (a) Test optical link, VOA: variable optical attenuator, BPG: bit pattern generator, BER: bit error rate tester. (b) measured BER as a function of the electrical driving voltage for different TDP values.(c) Measured BER different values of the driving signal amplitude.

Eq. 2 with respect to P_{laser}, the optimal strategy for low available power condition is to allocate 2/3 of P_{tot} to the laser and 1/3 to the electrical data signal. It's important to notice that the modulator parameters do not affect the power allocation strategy. Fig. 1(b) shows the simulated eye amplitude as a function of V_s for different values of the total dissipated power (TDP). As shown, if V_s is small, the optical eye amplitude is also small; negligible modulation dept, almost all the power is allocated to the optical source. As V_s increases, ΔP also increases, even if with a reduced extinction ratio (ER). The maximum ΔP is reached for $V_s = \sqrt{ZP_{tot}/3}$. Further increasing V_s results in an increase of the optical ER, however, the consequent reduction of the laser power leads to a reduction of ΔP.

If the small signal approximation doesn't hold, more power must be allocated to the laser source. As a limit, as the optimal electrical signal reaches $V_s=V_\pi$, the total amount of excess power must be allocated to the laser.

To validate the theoretical model, a 10 Gb/s optical link has been tested (Fig. 2(a)). The link operates at a wavelength of 1550 nm, the MZM has a V_π=5 V, IL=6 dB, and $V_b=V_\pi/2$. A bit pattern generator (BPG) drives the MZM with a signal amplitude between 0.2 V_{pp} to 2 V_{pp}. The laser optical power was varies through a variable optical attenuator. At the receiver, a 12.5 GHz bandwidth photodetector is directly connected to the BER analyzer. Fig. 2(b) reports the BER measurements as a function of the driving voltage for three different total available power levels (10mW, 15mW, and 20mW), the optical power has been varied consequently. When the whole power is allocated to the laser (0 V signal amplitude), the optical eye diagram is completely closed (absence of modulation). BER=0.5. The same happens when the total power is allocated to the electrical signal; in this case the laser power is zero and no optical signal is present. Increasing the driving voltage from zero, the eye diagram rapidly opens and consequently the BER drops. When the power allocated to the electrical signal reaches 1/3 of the total available power, ΔP reaches its maximum and consequently the BER reaches its minimum. For the 10mW the minimum BER (equal to 4e-6) is reached for an electrical signal amplitude of 0.37 mV. In this case, the total allocated power is not sufficient to meet the receiver sensitivity and for this reason error free operation is not reached. Also, for the 15mW and 20mW cases it is possible to see that as the minimum of the measurable BER (1e-10 for our instrument) is reached for approximately 60% of the maximum voltage swing, thus demonstrating the theoretical prediction.

From a different perspective, Fig. 2(c) shows the BER measurements performed with a constant signal amplitude, for the cases of 250mV, 500mV, and 1V. With 1V (yellow curve), the error free (EF) condition is reached at approximately TDP = 37mW where P_s=33 mW and P_{laser}=4 mW. Reducing P_s to 500mV (orange curve), EF can be reached with a TDP of approximately 16mW, where P_s=8mW and P_{laser}=8mW. The insets of Fig.2(c) show the 10mV amplitude eye diagrams at BER=1e-9 where the reduced modulation depth is associated with the reduced driving voltage that fully recovered by the increased laser power.

3. Conclusions

In this paper, the power allocation for an energy constrained optical link has been reported. The model predicts that an optimized link allocates 2/3 of the power to the laser source and 1/3 of the power to the electrical data signal. The theoretical model has been compared with experimental BER measurements performed on a 10 Gb/s link.

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4. References

[1] Shehabi, A., et al. (2016). United States Data Center Energy Usage Report:. LBNL Report #: LBNL-1005775.
[2] Andrae, ASG, and Edler, T. "On global electricity usage of communication technology: trends to 2030." *Challenges* 6.1 (2015): 117-157.
[3] Greenberg, A., et al. "The cost of a cloud: research problems in data center networks." ACM SIGCOMM Vol. 39, no. 1 p. 68-73 (2008).
[4] Hiraki, T, et al. "Heterogeneously integrated iii–v/Si MOS capacitor Mach–Zehnder modulator." Nature Photonics 11.8 (2017): 482.