Energy Efficiency Analysis of Linear Photonic Neurons

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We present a universal analytical apparatus for energy efficiency analysis applicable to multi-wavelength or coherent N-to-1 linear photonic neuron configurations, concluding to guidelines for energy efficiency increase and foreseeing performance of only few fJ/MAC.
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1. Introduction

The rise of the neuromorphic photonics as a novel platform for artificial neural networks brings a promise of orders-of-magnitude computational yield increase, owing to high clock rates at which multiply-accumulate (MAC) operations are performed [1]-[3]. Herein, we present analytical expressions for linear neuron power consumption and energy efficiency, concluding to existence of the optimal data-rate and foreseeing performance of only few fJ/MAC.

2. Towards fJ/MAC Photonic Neuron Operation

Total electrical power given in mW, P_{el}, consumed by an N-to-1 linear photonic neuron shown in Fig. 1(a), is governed by the neuron configuration and employed active devices:

$$P_{el} = P_R/\eta_{wp} \times 10^{\alpha[dB]/10} + N(P_X + P_W)\,, \qquad (1)$$

where the first term describes the laser power consumption (accounting for its wall-plug efficiency, η_{wp}) which provides enough optical power to compensate the losses along the optical path, α, and meet the PD sensitivity requirements, P_R. The second term of (1) accounts for the power consumption of the input signal modulators, P_X, and weights, P_W.
Energy efficiency, η_E, is defined as the ratio of the throughput $T = NB$ and P_{el}, with B denoting data-rate, whereas energy per MAC can be found as $E_{MAC} = 1/\eta_E$. Having determined the empirical dependence of P_R on B, namely, $P_R = c_1(B/1\ GHz)^{c_2}$, where c_1 = 11.6 nW and c_2 = 2.82 [4], we choose a global parameter design space with the following ranges: $N \in [8,128]$, $\alpha \in [6,30]$ dB, $P_X + P_W \in [0.1,50]$ mW, and $P_R \in [-25,20]$ dBm, assuming η_{wp} = 10% and we investigate η_E and E_{MAC}.
Increase in P_R and/or α raises P_{el}, as Fig. 1(b) confirms, through the first term of (1). Same holds true for increase in N and/or $P_X + P_W$ through the second term of (1), which additionally raises the plateau in Fig. 1(b), visible for low P_R and α. Unlike with throughput, increasing B does not guarantee increase in η_E, as Fig. 1(c) reveals, owing to B appearing in both numerator and denominator of η_E, yielding an optimal value B_{opt} Depending on remaining parameters, plateau $\eta_E^{max} = \eta_E(B_{opt})$ may appear in attainable data-rates range, of up to 100 Gb/s, demanding the optimization of α and $P_X + P_W$ for raising of the efficiency. A more detailed insight in η_E plateauing is given in Figs. 1(d)-(e), where α has negligible impact on η_E for $B < B_{opt}$. We find that, for the explored parameter design-space, η_E reaches 0.2 PMAC/s/W and E_{MAC} comes down to 5 pJ/MAC.

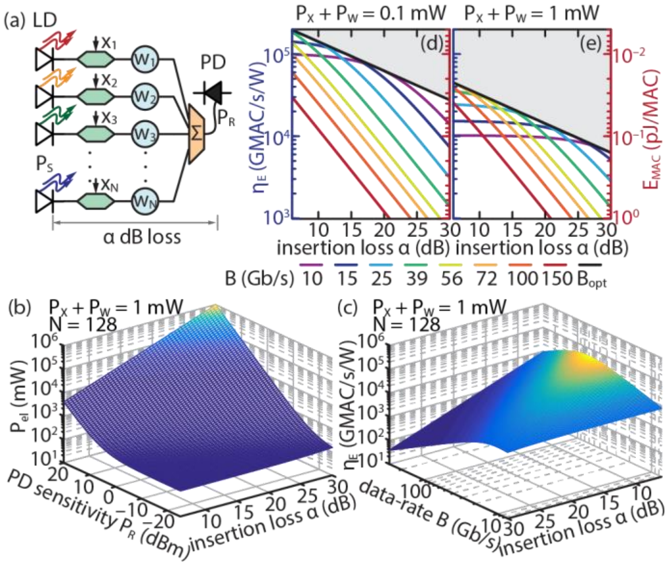

Fig. 1 (a) Generic N-to-1 linear photonic neuron with inputs x_i and weights w_i. (b) Consumed electrical power and (c) energy efficiency, both for N = 128 and $P_X + P_W$ = 1 mW. (d), (e) Energy efficiency for $B \in$ [10,150] Gbps for $P_X + P_W$ of (d) 0.1 mW and (e) 1 mW.

3. Conclusion

We presented a universal analytical framework for determining the energy efficiency of linear photonic neurons, suitable for both multiwavelength and coherent architectures. We showed the plateau of energy efficiency and identified the existence of optimal data-rate. On the road towards fJ/MAC performance, we highlight the need to reduce optical losses and modulator power consumption and increase laser wall-plug efficiency.

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