Optical and Electrical Interconnect Partition Length Based on Chip-to-Chip Bandwidth Maximization

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***Abstract*—The lengths beyond which board-level optical waveguides are capable of transferring a larger number of bits per second than electrical interconnects are found for various technology generations. As technology scales from the 130-nm technology node to the 45-nm technology node, the partition length falls from 29 to 8.3 cm due to seven times larger driver-switching frequency and 40% finer waveguide pitches.**

***Index Terms*—Data rate, electrical interconnects, off-chip wiring, optical interconnects, technology forecasting, waveguides.**

I. INTRODUCTION

WHILE OPTICAL interconnection has found mainstream application in fiber-optics telecommunications, it is still unclear at which technology generation optics will be used for on-chip or chip-to-chip communication in complementary metal–oxide–semiconductor microelectronic systems. Optics can potentially improve interconnection in terms of energy dissipation, latency, and/or bandwidth. Energy dissipation of optical interconnects can be smaller than that of electrical interconnects with a voltage swing of 1 V [1]. However, reducing the voltage swing of electrical interconnects can make the energy dissipation of electrical and optical interconnects comparable while their signal-to-noise ratios are roughly equal [2]. Also, although latency of optical interconnects may be somewhat smaller for long distances [3], the improvement that optics can offer in terms of latency is not significant. This is because 1) latency is limited by time-of-flight (ToF), which is the latency dictated by the speed of light, and 2) relatively wide and thick electrical wires available at the board-level (30 to 100 μm) can offer latencies close to ToF [2]. Although energy dissipation and latency issues do not provide compelling motivation for using optical interconnects, bandwidth, however, can be substantially larger in optical interconnects than in electrical interconnects, and thus, represents a major motivation for using optics for chip-to-chip or even on-chip interconnection [4]. Svensson has concluded in [2] that the models used for bandwidth of electrical interconnects in [4] are too conservative, and for a case study of 10-cm-long interconnects he has shown that optical and electrical interconnects have comparable aggregate bandwidths. However, any comparison between optical and electrical interconnects is strongly length-dependent. Advocating or opposing the use of optics for all chip-to-chip or on-chip interconnects, therefore, should be avoided. Instead, optical and electrical interconnects should be compared based on the identification of lengths beyond which optical interconnects can outperform electrical interconnects. Also, it has been assumed in both [2] and [4] that wire bandwidth is proportional to cross-sectional area, which is only true for wires with circular or square cross-sections. Due to skin effect, electrons flow at the surface of a wire, and at high frequencies wire resistance becomes inversely proportional to its perimeter. Bandwidth of a wire is, therefore, proportional to the square of the perimeter, not the cross-sectional area. The assumption that wire bandwidth is proportional to its cross-sectional area using the relationship between perimeter and area of a circle or square [2], [4] can be a source of error in calculating the bandwidth of wires with rectangular cross section.

In this letter, a partition length is identified that illustrates the length beyond which optical waveguides can offer a larger aggregate interchip bandwidth in comparison to electrical interconnects when constrained by a fixed routing area using a corrected expression for wire bandwidth. In this analysis, it is assumed that optical drivers and receivers eventually will mature and become comparable with their electrical counterparts in terms of power, size, and cost. The comparison, therefore, emphasizes the interconnect media, or "wires versus waveguides," rather than the interface circuits. Since initial opportunities to use optical interconnects appear to be more promising for chip-to-chip interconnection rather than on-chip interconnection, only board-level interconnects are considered in this letter.

II. ELECTRICAL INTERCONNECTS

Board-level wires usually operate in the resistance–inductance–capacitance (RLC) regime, where skin effect limits the bandwidth as

$$B_{\text{elect}} = \frac{B_0 P^2}{kl^2} \tag{1}$$

where B_0 is a constant determined by the conductor material, P is the cross-sectional perimeter, l is the wire length, and k is a factor between 60–120 depending on the height of "eye opening" that is desired in the signal eye diagram. B_0 is 1.846×10^{18} (b/s) for copper, and k is chosen equal to 120, a sufficiently large value corresponding to the case that there is no need for equalization. Equation (1) is derived in the Appendix .

Because of proximity effect, electrons flow mostly through the lower and upper regions of wires that are close to ground

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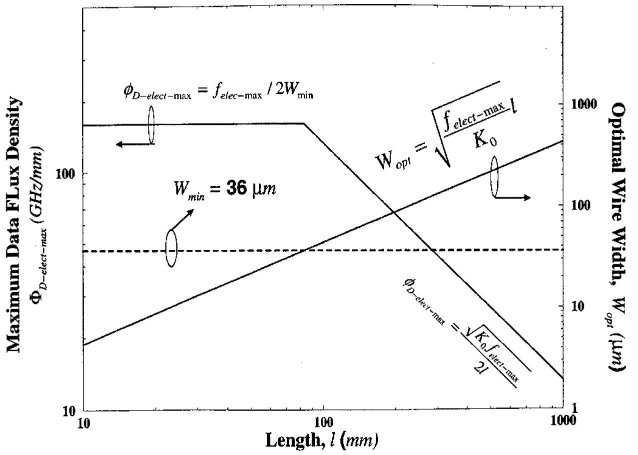

Fig. 1. Maximum data flux density and optimal wire width versus interconnect length for the 45-nm technology node. The dashed line shows the minimum linewidth available on-board as projected by the ITRS [5].

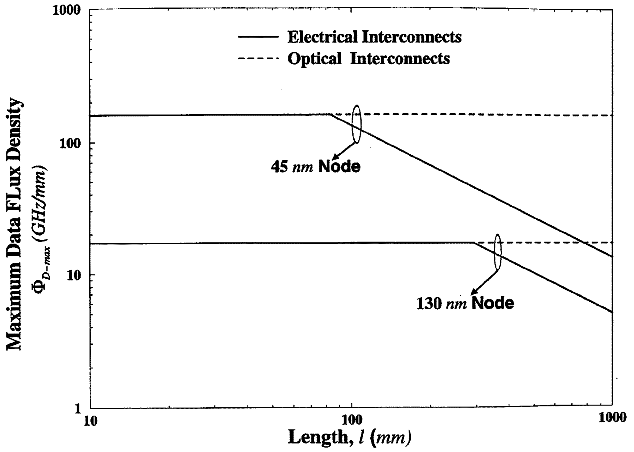

Fig. 2. Maximum data flux density for electrical and optical interconnects implemented in 130- and 45-nm technology nodes. Performance of optical waveguides is length independent [4], [6].

planes . Hence, the effective perimeter of a wire can be taken as $2W$, and (1) can be written as

$$B_{\text{elect}} = \frac{K_0 W^2}{l^2} \tag{2}$$

where $K_0 \equiv 4B_0/k = 6.152 \times 10^{16}$. Assuming that the spacings between interconnects are equal to their widths, data flux density, which is bandwidth per unit width of an interconnect, is

$$\phi_{D-\text{elect}} \equiv \frac{B_{\text{elect}}}{p} = \frac{K_0 W}{2l^2} \tag{3}$$

where p is interconnect pitch. Equation (3) shows that data flux density increases linearly with increasing wire width. Assuming that interconnect bandwidth is proportional to cross-sectional area is misleading because it results in a data flux density independent of wire width.

Equation (3) suggests that on-board electrical interconnects should be made as wide as possible to maximize the aggregate bandwidth. The maximum frequency that a driver can switch, however, introduces a limit on maximum wire width. From (2), the optimal wire width, therefore, is the width at which interconnect bandwidth becomes equal to the maximum frequency that the driver can switch $f_{\text{elect}-\max}$

$$W_{\text{opt}} = l\sqrt{\frac{f_{\text{elect}-\max}}{K_0}}. \tag{4}$$

By substituting (4) into (3), the maximum data flux density that electrical interconnects can offer is, therefore,

$$\phi_{D-\text{elect}-\max} = \frac{\sqrt{K_0 f_{\text{elect}-\max}}}{2l}. \tag{5}$$

To estimate the maximum data flux density, we assume that $f_{\text{elect}-\max}$ will be equal to the International Technology Roadmap for Semiconductors (ITRS) [5] projections for the chip-to-board clock frequency. Fig. 1 shows the maximum data flux density and the optimal wire width versus interconnect length at the 45-nm technology node. Fig. 1 shows that as interconnect length decreases, the optimal wire width decreases, and in this manner, data flux density increases. The wire width, however, is limited by the minimum linewidth available at the board level $W_{\min}$ (36 μm projected by the ITRS for the 45-nm technology node), implying that a minimum length exists below which data flux density remains constant. Hence, the maximum data flux density attainable by electrical interconnects is independent of length for short interconnects that are minimum linewidth-limited and inversely proportional to length for longer interconnects.

III. OPTICAL INTERCONNECTS

While bandwidth of an electrical interconnect is determined by its length and cross-sectional dimensions, the bandwidth of a typical board-level waveguide is, in practice, independent of its physical dimensions, and is determined by the driver and receiver [4], [6]. In this way, the maximum data flux density is

$$\phi_{D-\text{optic}} = \frac{f_{\text{opt}-\max}}{p_{\text{opt}}} \tag{6}$$

where $f_{\text{opt}-\max}$ is the maximum frequency at which optical drivers and receivers can switch, and p_{opt} is the pitch of optical waveguides. Although optical wavelength and waveguide technology influence optical crosstalk and, hence, the minimum value of p_{opt}, p_{opt} is tentatively set to $2W_{\min}$. The maximum data flux density for optical interconnects, therefore, is

$$\phi_{D-\text{optic}-\max} = \frac{f_{\text{opt}-\max}}{2W_{\min}}. \tag{7}$$

Fig. 2 illustrates data flux density for both electrical and optical interconnects at 130- and 45-nm technology nodes. It can be seen that, in contrast to electrical interconnect technology, the data flux density of optical interconnects is always minimum linewidth-limited and is independent of length.

IV. PARTITION LENGTH BETWEEN ELECTRICAL AND OPTICAL INTERCONNECTS

Although $f_{\text{opt}-\max}$ and $f_{\text{elec}-\max}$ can be different, they cannot be completely unrelated, since an optical driver is driven by an electrical driver and an optical receiver feeds an electrical driver. In this analysis, the maximum switching frequencies for optical and electrical transceivers are assumed to be equal. A small modification would be necessary if these two frequencies are different.

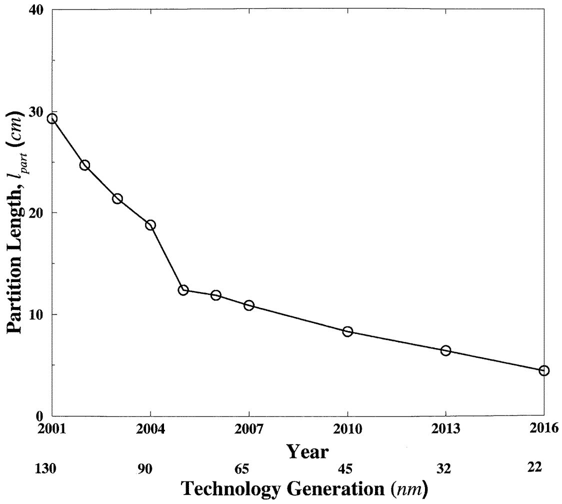

Fig. 3. Partition length between optical and electrical interconnects for different generations of technology.

By comparing (5) and (7), a partition length for electrical and optical interconnects can be found as

$$l_{\text{part}} = W_{\text{min}} \sqrt{\frac{K_0}{f_{\text{max}}}} \tag{8}$$

which shows the interconnect length beyond which optical waveguides offer a larger data flux density compared to electrical interconnects. Fig. 3 plots the partition length for different ITRS [5] technology nodes. From Fig. 2, it is evident that the data flux density of optical waveguides is constant and larger than that of electrical interconnects for interconnects longer than l_{part}. As technology advances, the partition length decreases due to decreases in available board-level linewidth and increases in clock frequency. For instance, the partition length decreases from 29 cm at the 130 nm to 8.3 cm at the 45 nm because of seven times larger driver switching frequencies and 40% smaller linewidth.

By pushing the board-level technology and achieving minimum linewidths smaller than those the ITRS has projected, smaller partition lengths can be attained and optical waveguides outperform electrical interconnects to an even greater extent. Fig. 4 plots the partition length versus minimum board-level linewidth for five different maximum switching frequencies. From Fig. 4, it can be seen that if linewidths on the order of 10 μm are available, it would be better to replace virtually all on-board wires with optical waveguides.

V. CONCLUSION

For the first time, the impact of interconnect length and minimum linewidth at the board level are highlighted in comparing board-level optical and electrical interconnects. Unlike previous publications that totally ruled out or advocated replacing electrical interconnects with optical waveguides, it is shown that a partition length exists beyond which optical interconnects can outperform electrical interconnects in terms of aggregate bandwidth when constrained by a fixed routing area. The partition length is determined by the maximum switching frequency of drivers and the minimum linewidth available at the board level.

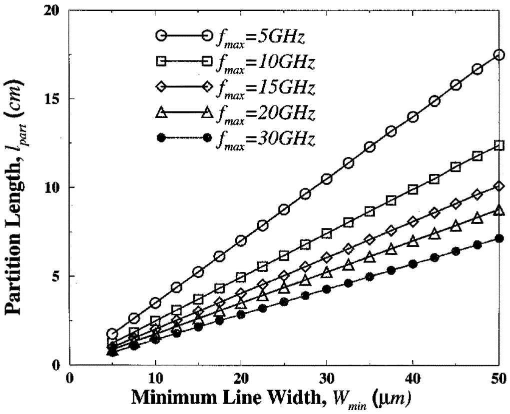

Fig. 4. Partition length between optical and electrical interconnects versus minimum available board-level linewidth.

APPENDIX

The transfer function of a transmission line in the Laplace domain can be written as [7]

$$\frac{V(x=l)}{V_{\text{in}}} = \exp(-sl\sqrt{LC})\exp\left(\frac{-l\sqrt{s}R_{\text{sk}}}{2Z_0}\right) \tag{9}$$

where Z_0 is the line's characteristic impedance, and L and C are the line's inductance and capacitance per unit length, respectively. $R_{\text{sk}} = \sqrt{\rho\mu}/P$ is the skin effect resistance [7], where μ is the magnetic permeability and ρ is metal resistivity. The step response of a transmission line can be obtained as

$$f(t) = \text{erfc}\sqrt{\frac{\beta}{(t - l\sqrt{LC})}} \tag{10}$$

for $t \geq l\sqrt{LC}$, and zero for $t < l\sqrt{LC}$, where erfc() is the complementary error function, and $\beta \equiv (\mu\rho/16Z_0^2)(l/P)^2$. Equation (10) shows that the signal rise time at the end of the transmission line, which determines the opening dimension in the eye diagram [2], is determined by β. Hence, the interconnect bit rate limit can be written as $B = 1/k\beta$, where k determines the amplitude of signal at the receiver, and is typically chosen between 60 and 120 that correspond to signal amplitudes of $0.85V_{\text{in}}$ and $0.90V_{\text{in}}$, respectively.

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