Some physical considerations on digital optical computing

Haldun M. Ozaktas*

Department of Electrical Engineering, Bilkent University
06533 Bilkent, Ankara, Turkey

Joseph W. Goodman

Department of Electrical Engineering, Stanford University
Stanford, CA 94305, USA

ABSTRACT

Since optical communication is preferable for establishing connections exceeding a certain critical length, for large system sizes the beneficial use of normally conducting wires for the shortest connections becomes an edge effect and can be ignored. This suggests that the performance and cost of an all optical computer might not be much inferior to an optimal hybrid alternative. We argue that for applications for which high bit repetition rates are useful despite large propagation delays, it might make sense to contemplate the construction of an optical digital computer.

1. INTRODUCTION

The possibility of an optical digital computer has attracted considerable attention. Despite the vast literature on devices, systems, architectures and algorithms,[2] there has been considerable discomfort as to its usefulness as compared to other approaches. Switching energy arguments on power-delay diagrams, such as in references 3 and 4 have resulted in the digital optical computer being mostly viewed as an esoteric curiosity. In the 1980's, interest in "optical computing" shifted towards "optical interconnections."[5] This led to the notion of the hybrid optoelectronic computer. Nevertheless, the assumptions underlying the negative arguments have not remained unchallenged and optical computing research has been accelerating. In this work we explore some issues relating to the potential usefulness of an optical digital computer and try to identify the conditions under which it would make sense to consider it as an alternative to existing approaches. We fully realize that such studies can never be definitive and that our arguments unavoidably rest on floating ground. We nevertheless present the following with the hope that it will provide a seed for further investigations.[1]

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*The first author is presently on leave with the Applied Optics Group, Physics Institute, University of Erlangen-Nürnberg, Staudtstr. 7/B2, W-8520 Erlangen, FRG.

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A digital computer can be viewed as a collection of switching elements interconnected according to a certain graph. The switching elements often rely on electronic interaction. Usually, this is true even of so called "optical switches," since in most optical switches, photons interact indirectly via electrons. On the other hand, communication among the elements is often established via photons, even in fully electronic computers. The question is whether conductors are used to confine the wave fields. Thus, we define an all optical computer to be one which does not employ conducting materials for the purpose of guiding signals among its switching elements. The all optical computer, as defined, is a special case of hybrid optoelectronic computers which employ both conducting wires and optical communication for this purpose.

2. CONNECTIVITY MODEL

Consider a simple model computing system consisting of N elements laid out on an e dimensional ($e = 2$ or 3) regular cartesian grid with $N^{1/e}$ elements along an edge, with an average of k connections per element. We will use the parameter $0 \leq p \leq 1$, known as the Rent exponent, to quantify the connectivity of our layouts. Rent's rule states that kN'^p connections emanate from a group of N' elements with k connections each.[6,7] An equivalent measure of connectivity is the *fractal dimension of information flow* $n = 1/(1-p)$. We speak of systems with large values of p as *highly interconnected.* The larger p is, the greater the fraction of longer connections in our system.

We characterize our processing systems with 3 parameters: i.) The number of elements N. ii.) The bit repetition rate B along the connections. iii.) The inverse delay $S = 1/\tau$ across the linear extent of the system. We will investigate how much we can increase S for given N and B.

3. WIRING TECHNOLOGIES

By nature, normal conductors are lossy so that the energy per transmitted bit must increase with increasing line length.[8] As a simple model, we take the energy per bit for a line of length ℓ as $E_n = \gamma\ell$ where $\gamma \simeq 100\,\mathrm{fJ/mm}$ (reference 9). We have assumed that an unterminated line is charged up to $1\,\mathrm{V}$. Optical interconnections rely only on dielectric inhomogenieties for confinement so that they suffer little line loss compared to normal conductors. For this very reason however, some coupling and radiation losses are unavoidable. Thus, the energy for optical interconnections are large but roughly independent of connection length, for the length scales involved in a computing environment. As a direct outcome of such observations, it is well understood that normal conductors are better for shorter connections whereas optics is better for longer ones.[6]

4. LOWER BOUNDS ON SYSTEM SIZE

Minimizing global propagation delays is equivalent to minimizing system linear extent. Two major physical considerations lead to lower bounds on system size: i.) Wireability requirements. ii.) Heat removal requirements. Wireability requirements dictate that the system linear extent $\mathcal{L}$ grow $\propto N^q$ for $e = 2$ dimensional systems and $\propto N^{q/2}$ for $e = 3$ dimensional systems where

$q = \max(p, (e-1)/e)$ (references 6 and 10). If we assume constant power dissipation per element, heat removal requirements dictate that the system linear extent grow as $\mathcal{L} \propto N^{1/2}$, since the surface area of both 2 dimensional and 3 dimensional systems grow as the square of their linear extent. Since $p \leq 1$, we conclude that (unless $p = 1$) with increasing N, the linear extent of 3 dimensional systems will become limited by heat removal considerations.

Given that there are upper limits to device speed, the best we can do to construct ever powerful computing systems is to make them 3 dimensional and of an ever increasing number of elements N. Thus, heat removal will be the major factor determining how densely we can pack the elements of our system. This means that employing layouts with larger Rent exponents will not result in greater system size and delay. This suggests that highly interconnected approaches, which offer greater functional flexibility, will be preferred in future large scale systems.

5. OPTIMAL HYBRID PARTITIONING

Minimization of system size and propagation delay is possible with a hybrid layout, involving both normally conducting and optical interconnections.[8,11] Let us consider an $e = 3$ dimensional system with $N = 10^6$, $k = 5$ and $p = 0.8$ operated at $B = 10\,\text{Gbit/sec}$. Let the optical communication energy be $E_o = 1\,\text{pJ}$ and the electrical energy be $\gamma = 100\,\text{fJ/mm}$ per unit length. Let us be capable of removing $Q = 10\,\text{W/cm}^2$ of power per unit cross section of our system. (Note that the power we can remove from the system is proportional to its cross sectional area, and not to its volume.[8,14]) It is now possible to show that employing an optimal hybrid combination of normal conductors and optics results in a system with linear extent $\mathcal{L} \simeq 0.5\,\text{m}$ (reference 1). Any other than the optimal mix of optics and normal conductors will result in a larger linear extent.

We would now like to determine how worse off we are if we make *all* connections optically. In this case, we obtain a system linear extent of 0.7 m and power dissipation only twice as much as the optimal hybrid system. (It is also possible to show that making all connections electrical would result in a system linear extent in excess of 3 m.)

If the disparity between 0.5 m and 0.7 m is not considered significant, we might as well make all connections optically. This might simplify the design and construction of our system. It should not be surprising that the all optically connected system is almost as good as the optimal hybrid system in terms of size, delay and power. After all, in our example the beneficial use of conductors for the shortest connections is an edge effect and can be neglected.

6. AN ARGUMENT FOR OPTICAL DIGITAL COMPUTING

What does our all optically connected system look like at this point? An array of N electrical switches with sources/modulators at their outputs and detectors at their inputs. This system already qualifies as an all optical digital computer according to our definition, since it does not utilize any conductive wiring for communication among its elements. However, we can do even better by replacing the discrete detector-electrical switch-source/modulator combinations by their integrated versions. We will speak of an integrated version of such a combination as an optical switch. A self-electro-optic effect device[12] (SEED) is an example of such a device. Such an integrated replacement can only reduce the overall energy consumption. Notice that there is no distinction between the optical communication energy and the optical switching energy, as the optical communication energy was that required for the optical modulator and detector, which we have now merged together to be the optical switch.

It is possible to show that the disparity between the size of the optimal hybrid system and the all optical system decreases with increasing B and p (reference 1). It is also necessary for N to be large for the validity of our analysis. Thus, in general, when N, B and p are large, an all optical system is almost as good as the optimal hybrid system.

We already argued that future 3 dimensional computing systems of ever increasing numbers of elements will tend to employ large values of p. If, in addition, we *assume* that large values of B are employed, we see that the conditions stated at the end of the previous paragraph coincide with the trend in constructing ever more powerful computing systems.

We should note that with increasing system size and delays, some algorithms may have a tendency to be bottlenecked by communication latencies, so that working with a high bit repetition rate B may not be of any utility. Thus, there may be a tendency to operate at slower rates with increasing N. This would invalidate our argument in many ways[1,8,13] so that for such systems, an all optical computer would probably not be useful.

The vision of the digital optical computer emerging from our considerations is as follows. It will be large ($N \sim 10^7$-10^8 and $\mathcal{L} > 1\,\mathrm{m}$), highly interconnected, operated at very large repetition rates (multi Gbit/sec) and due to its size exhibit large speed of light limited delays between its distant elements ($\sim 10\,\mathrm{nsec}$). Its bisection-bandwidth product (the rate at which we can transfer information from one half of the system to the other) might be of the order of 10^{16} bit/sec. It will be suitable for situations in which a large repetition rate is useful despite large propagation delays.

7. CONCLUSION

To build ever more powerful processing systems, we must increase the number of elements N. If the bit repetition rate B along the connections of our system is large, heat removal considerations tend to dominate wireability considerations for 3 dimensional systems, suggesting that highly interconnected approaches may be preferred to increase parallelism and functional flexibility. For such systems, the fraction of connections with lengths greater than the energy breakeven between normally conducting and optical interconnections will be large, so that we might as well make all connections optically. Thus, if large values of B are useful despite large propagation delays, it might be meaningful to consider the construction of an all optical digital computer.

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