1. Introduction

Growth in the volume of Internet traffic increases the need for carriers to maximize the utilization of the telecommunications infrastructure. Packet switching provides traffic grooming at a sub-wavelength level and this is a significant factor in ensuring maximum utilization of network resources. In today’s network, electronic routers provide this sub-wavelength grooming. To date, electronic routers have kept up with the demands of traffic growth. However, there is some concern in the research community that the achievable capacity of the network will eventually be limited by traffic bottlenecks in electronic routers. Also of concern to some researchers is the growth in power consumption and the anticipated large footprint of future high-capacity electronic routers.

Possible solutions to the scaling and power dissipation problems in electronic routers include replacing the electronic routers with all-optical packet switches (OPS), in which optical packets are buffered and routed in optical form [1]-[3]. A key challenge in finding a technically feasible solution to optical packet switching is the lack of an adequate optical buffering technology. However, a recent surge of new research in the area of slow light [4]-[7] has opened up the possibility of improved optical buffer performance.

In this paper we investigate the scaling properties of optical packet switches and compare optical buffers and high-speed optical cross connects with electronic buffers and high-speed electronic cross connects. The basis of our comparison is the power dissipation and physical size of optical components with the projected power dissipation and size of electronic components. Our analysis is based on aggressive but plausible estimates of optical and electronic device performance, projected out to around 2020. Our broad conclusion is that electronic technologies are likely to remain as integral components of future high-capacity buffers.

2. Petabit-per-Second Routers

To provide a concrete set of comparisons, we focus here on routers with throughputs of 1 Pb/s (10^15 b/s). Where feasible, we have based our projections on fundamental limitations using device physics considerations. For example, our projections of slow light buffers are based on new insights into the fundamental physical limitations and scaling properties of slow-light optical delay lines. In general, this gives an optimistic view of the capabilities as it ignores some non-ideal behaviour. However, we show that the loss in waveguide devices is a key parameter. Because there is no easily-determined fundamental limitation on loss in waveguides, we base our calculations on expected best experimental results. Our estimates of future performance of CMOS devices and circuits are based on the 2005 International Technology Roadmap for Semiconductors [8].

Conventional high-capacity electronic routers employ around 250 ms of buffering on each port [9]. If a 1-Pb/s router has 250 ms of buffer on each port (with 25,000 ports, each at a line rate of 40 Gb/s), the buffer size for each port would be 10 Gb and the total capacity of all buffers in the router would be 250 Tb. Buffers of this size can, in principle, be accommodated using electronic RAM, but they are impractical in delay line buffers. Recently, it has been shown that when there is a large number of TCP sessions running simultaneously on each wavelength, the size of buffers on routers buffering can be reduced significantly [9]. Using paced TCP, the buffer capacity could be reduced to around 10 packets per port [9] or around 2.5 µs, at 40 Gb/s. This could open up new opportunities for delay line optical buffering.

3. Optical Buffers and Electronic Buffers

We compare the characteristics of optical buffers and embedded dynamic RAM (eDRAM) in SiCMOS. Projections for sub-20-nm feature size CMOS [8] call for eDRAM with read/write energies of 4x10^-17 J/bit and read/write cycle times of 0.2 ns. The projected cell area is 0.0075 µm². For comparison, an ideal slow light waveguide with zero dispersion has a cell area about 1 µm, which is about three orders of magnitude larger. With an array area efficiency of
60% [8], the projected storage density of eDRAM is approximately 100 Tb/m$^2$, which is 500 times larger than the storage density of an ideal slow light delay line (200 Gb/m$^2$) [10]. When dispersion in slow light waveguides is taken into account [11], the storage density in CMOS is more than 5000 times larger. It is clear that on the basis of chip area alone, optical delay lines are not competitive with electronic buffers.

Waveguide loss is a key limitation on the capacity of optical buffers. Losses can, in general, be overcome using optical gain, but optical gain requires the expenditure of energy and leads to additional power dissipation. In addition, optical gain introduces spontaneous emission noise which degrades the signal quality. We have developed a model of the dissipated energy per bit of stored data in a lossy delay line buffer, and the maximum achievable capacity of a delay line [10]. This model has then been used to compare the energy per bit and the associated power dissipation of optically-amplified slow light optical buffers, fiber buffers, and SiCMOS eDRAM buffers. The energy per bit and the power dissipation for the delay line buffers scales approximately as the square of the buffer capacity. For buffers with capacities above a few hundred packets, the power dissipation in the slow light buffers can be quite large – more than tens of kW. We conclude that optical technologies may have a role for small buffers, but the small size of electronic buffers is a key advantage of this technology [10]. Optical buffers may be practical for OPS application if the buffer capacity is small (< 1 kByte/port). However, if larger buffers are needed, electronic technologies will be mandatory. In general, electronic memory technology offers significant advantages over the projected best possible performance of slow-light optical buffers.

4. Cross Connects

To clarify the relative advantages of different switch technologies, we have compared the properties of cross connects using arrayed-waveguide gratings (AWG’s) with tuneable wavelength converters (TWC’s), semiconductor optical amplifier (SOA) gate arrays, and electronic cross connects. SOA gate arrays will not scale to the sizes needed for large routers. However, AWG-based wavelength-routed cross connects provide low-power switching when combined with optical or O/E/O wavelength converters. We estimate that the power consumption in all-electronic cross connects may be larger than in all-optical cross-connects and O/E/O cross connects. A key difficulty in building all-optical AWG-based cross connects is the lack of technology for all-optical wavelength conversion. Our calculations in this paper have assumed that viable wavelength converters will emerge, but even if this happens, wavelength converters based on O/E/O conversions might be more competitive. Finally, it needs to be pointed out that large cross connects will never become a reality without small, low power interconnects that can be easily interfaced to optical and electronic chips. Even if very small and very low power interconnects become a reality, the management of the tens of thousands of interconnects is likely to cause significant difficulties.

5. Conclusions

We have investigated the power and space requirements of future high-capacity routers and have compared the scaling properties of optical and electronic buffers and cross connects. Our analysis is based on aggressive but plausible estimates of optical and electronic device performance, projected out to around 2020. Our broad conclusion is that both optical and electronic technologies will be integral components of future high-capacity routers. Given that there are very sound reasons for including at least some electronics in the cross connects and the buffers, there does not appear to be a compelling case for moving towards all-optical router technology. We believe that future high-capacity routers will employ optoelectronic packet switching rather than pure optical packet switching.

References