Designing Multisocket Systems with Silicon Photonics

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Research Project

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Abstract

To fuel an increasing need for parallel performance, system designers have resulted to using multiple sockets to provide more hardware parallelism. These multisocket systems have limited off-chip bandwidth due to their electrical interconnect which is both power and pin limited. Current systems often use of a *Non-Uniform Memory Architecture* (NUMA) to get the most system memory bandwidth from limited off-chip bandwidth. A NUMA system complicates the work of a performance programmer or operating system, because they must maintain data locality to maintain performance.

Silicon photonics is an emerging technology that promises great off-chip bandwidth density and energy efficiency when compared to electrical signaling. With this abundance of bandwidth, it will be possible to build a relatively flat, high bandwidth memory interconnect. Because this interconnect has uniform bandwidth, NUMA optimizations will be unnecessary, which increases performance programmer productivity.

If the penalties to making a multi-socket system are negated by the use of silicon photonics, there is less incentive to integrate, and economic incentives to disintegrate. In this thesis, we present this scalable and coherent multi-socket design along with discussing the tradeoffs facing an architect when incorporating silicon photonics technology.

Chapter 1

Introduction

Given the difficulties of scaling uniprocessor performance further, most commercial microprocessor manufacturers have instead used increased transistor densities to integrate multiple processor cores on one die [1]. These manycore systems will require increasing memory bandwidth at reasonable energy consumption if they are to deliver improvements in application performance. Otherwise these systems may be grossly underutilized [27].

When the desired number of cores cannot fit on a die that is economical to manufacture, they are spread across multiple sockets. To feed many cores spread across multiple sockets will require even more memory bandwidth. Each socket will have its own attached DRAM, but in a shared memory machine it must be made accessible to the other sockets within the system. This interconnect must have an on-chip portion that connects all of the cores within a socket in addition to an off-chip portion that connects all the sockets within the system.

Current multisocket systems often have their off-chip bandwidth constrained by power and pin limitations [14, 18, 23]. As more cores are integrated into a die within a socket, they will need even more bandwidth, and this bottleneck will become more troublesome as it is unlikely off-chip electrical bandwidth will be able to keep up. The energy required to send a bit between sockets is not scaling down very quickly because the sockets are not getting much closer physically, and the materials used for traces is not getting significantly less resistive or capacitive. Even if off-chip electrical signaling becomes sufficiently more energy efficient, pin bandwidth could become the next limiting factor. Off-chip signaling rates and die sizes are not growing fast enough to provide enough pin bandwidth to meet the growing demand.

A socket's limited off-chip bandwidth must be divided up between links to its own locally attached DRAM and inter-socket links to reach remote DRAM attached to other sockets (Figure 1.1). If all of the bandwidth is allocated to the locally attached DRAM, the system will have the maximum memory bandwidth possible, but it will be disjoint. In contrast, if all of the bandwidth is allocated to the inter-socket links, the system will have no memory bandwidth but great inter-core bandwidth. If the two are balanced uniformly such that each socket receives an equal amount of bandwidth from every part of memory (remote or local) the system will have a *Uniform Memory Architecture* (UMA), and if they are balanced non-uniformly, the system will have a *Non-Uniform Memory Architecture* (NUMA).

Systems trying to get the most system memory bandwidth while coping with off-chip bandwidth scarcity will be pushed towards a NUMA design. This is true independent of the off-chip network topology, because each inter-socket link occupies bandwidth at two sockets, while a link to DRAM

only occupies bandwidth at one socket. Any bandwidth taken away from the inter-socket links, can be turned into twice the bandwidth for the links to DRAM. This encourages system designers to skew the bandwidth allocations in favor of locally attached DRAM instead of reaching other sockets, to maximize system memory bandwidth.

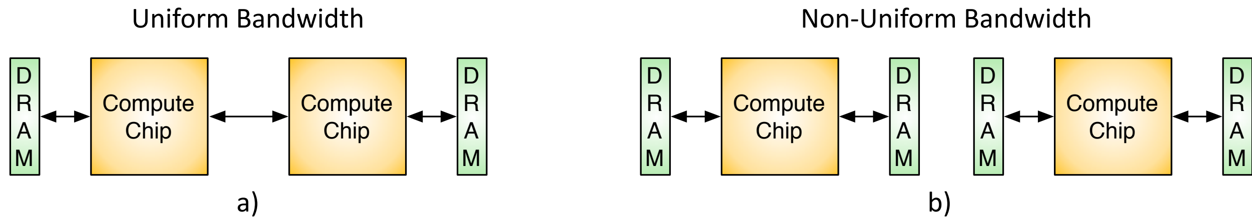

Figure 1.1: Motivation for NUMA

A NUMA design imposes additional complexity on the performance programmer, as it is crucial that data is co-located with the computation using it. This careful mapping is yet another optimization performance programmers must consider [27], but if the memory system was flat (uniform) it would be unnecessary, increasing their productivity. Some multiprogrammed workloads, such as virtual machines running within a datacenter, will also benefit from the scheduling flexibility that bandwidth uniformity provides. When scheduling jobs, a job could be run on the first available core independent of where the data it needs resides. Furthermore, some workloads exhibit poor spatial locality so it is difficult to spread the data across sockets effectively. If a new technology provided an abundance of bandwidth, it would be worthwhile to allocate it uniformly to increase programmer productivity and make the system more flexible.

In this work, we leverage silicon photonics to design high and uniform bandwidth multi-socket memory interconnects. We present a general network design that can be used to make systems of varying sizes, and to provide shared memory which makes the system more usable, we discuss how to reasonably implement coherency on top of the network. Because of the nature of the design, it has much less incentive to integrate, which opens the door to chip disintegration for cost savings. Overall, multi-socket interconnects are an interesting place to explore applications of current research in silicon photonics because of its emphasis on off-chip communication.

Chapter 2

Photonic Technology Introduction

Over the last few decades, the scale at which optical technology has been adopted for communication has been steadily decreasing. Optical communication was first used for long distance telecommunications, because its high endpoint costs were amortized over very long links. As processing technologies have improved, the cost (delay, space, energy, dollars . . .) of the endpoints have decreased, which in turn has decreased the distance at which optical communication is advantageous. Continued technology advances along with increased integration have enabled silicon photonics, which decreases the feasible distance down to the inter-chip and even intra-chip level.

2.1 Technology Overview

In recent years, silicon photonics has been shown to be an increasingly desirable technology for system interconnects because of its potential for higher bandwidth density, greater energy efficiency, and lower latency. The technology is still immature with many competing implementation proposals, so projected performance on these important metrics varies significantly. To ground the results of our study, we select a particular monolithically integrated silicon photonics technology [4], but the overall approach should be applicable to the other current proposals because much of it is based on general technology insights.

Figure 2.1 shows a basic link is comprised of: a light source, a modulator, a waveguide, and a photodetector. The modulator encodes the signal by absorbing or not absorbing light as it passes by it through the silicon waveguide. At the other end of the waveguide, the photodetector senses the changes in light and decodes the signal. The electro-optical and opto-electrical conversions at the endpoints introduce a latency and energy cost that needs to be amortized beyond a minimum distance to be advantageous to electrical.

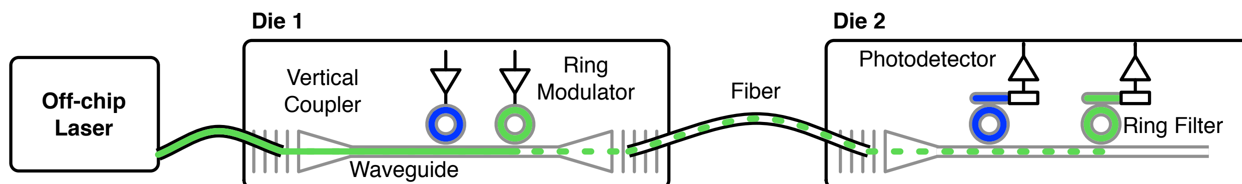

Figure 2.1: An inter-socket photonic link

The selected technology provides Dense Wave Division Multiplexing (DWDM) which contributes to its high bandwidth density (bits/second/ μm). DWDM allows light from different wavelengths to share the same waveguide with minimal interference, which allows multiple logical links to share the same physical media without time multiplexing. This is enabled by putting rings which resonate with a narrow frequency of light onto the waveguide, such that when the light resonates with a ring, it is pulled off the waveguide into the ring. We can use these rings along with charge injection to make a ring modulator [11, 20, 21]. Applying a charge to a ring shifts the ring's resonant frequency so a particular wavelength can be absorbed or not absorbed to modulate the light.

A filter can also be made by using these resonant rings [21, 26], and the selected technology uses two cascaded rings to get additional frequency selectivity (Double Ring Filter). Since the photodetectors are sensitive to a wide range of light frequencies, a double ring filter is placed between the photodetector and the waveguide so only the correct wavelength gets through the filter and strikes the photodetector. These resonant rings are sensitive to a variety of environmental factors and manufacturing variations, but these can be combated by thermally tuning the rings with in-plane heaters.

The selected technology is monolithically integrated, and it utilizes a current CMOS manufacturing process which makes it much more realizable since it leverages a great deal of manufacturing hardware investment and knowledge. Other photonic proposals may be better suited for transmitting light, but they use materials or steps not currently part of a standard CMOS process making them more cost prohibitive to implement [3, 11, 15].

The light used by the system is generated by an off-chip laser because conventional CMOS processes are poorly suited for laser fabrication. This light is brought on chip through a fiber and then a coupler into the waveguide. On-chip light travels through poly-Si, which can be made into a usable waveguide (Figure 2.2) by placing it on top of shallow trench isolation (STI) and etching an air gap underneath it [10]. The air gap helps to improve the cladding on the bottom of the waveguide, because the STI is too thin on its own. The air gap does take up silicon area, so when possible multiple waveguides should share one to amortize the overhead. A great advantage of photonics is that once the signal has been encoded optically, that light can be guided through through couplers and a fiber to another chip's waveguide without retransmission (Figure 2.1), enabling links that operate seamlessly across long distances.

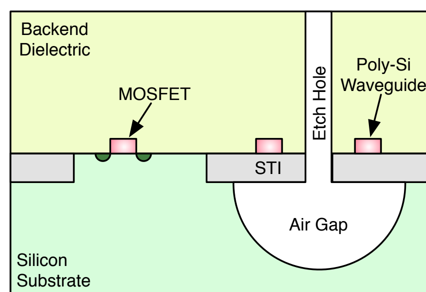

Figure 2.2: Cross section of an on-chip waveguide

2.2 Performance

Looking forward to when this silicon photonic proposal might be fully realizable, we compare it against a projected optimally repeated electric wire in a 22nm process and Tables 2.1, 2.2, and 2.3 give a summary of the comparison. Based on preliminary results and device projections, the silicon photonic proposal assumes a signaling rate of 10Gbps (faster could be possible) and squeezes in 64 wavelengths per direction [21], meaning a single link (fiber or waveguide) has 80GB/s of bidirectional bandwidth.

Table 2.1: Approximate energy costs per bit

Quantity	Electric (fJ)	Photonic (fJ)	Ratio
On-Chip Model	$50\frac{fJ}{mm}$	150[1]	
Off-Chip Model	5000	150	
Local On-Chip Wire (1 μm)	0.05	150	0.00033
Intermediate On-Chip Wire (1mm)	50	150	0.33
Global On-Chip Wire (10mm)	500	150	3.33
Off-Chip Trace (40mm)	5000	150	33.33
Chip-to-Chip Link (40mm off-chip, 10mm on-chip)	5500	150	33.67

Table 2.2: Approximate latency costs per bit

Quantity	Electric (ps)	Photonic (ps)	Ratio
On-Chip Model	$100\frac{ps}{mm}$	$200 + 10\frac{ps}{mm}$	
Off-Chip Model	$50 + 5\frac{ps}{mm}$	$200 + 5\frac{ps}{mm}$	
Local On-Chip Wire (1 μm)	0.1	200.01	0.0005
Intermediate On-Chip Wire (1mm)	100	210	0.48
Global On-Chip Wire (10mm)	1000	300	3.33
Off-Chip Trace (40mm)	250	400	0.63
Chip-to-Chip Link (40mm off-chip, 10mm on-chip)	1250	700	1.79

Table 2.3: Approximate bandwidth densities per bit. Photonic values sum the bandwidth of both directions

	Electric (Gb/s/ μm)	Photonic (Gb/s/ μm)	Ratio
On-Chip	5	320	64.0
Off-Chip	0.2	26	130.0

[1] $100\frac{fJ}{b}$ (modulator) + $50\frac{fJ}{b}$ (receiver) + $80uW$ (power to thermally tune rings) + optical power

2.2.1 Power

Energy efficiency ($\frac{bits/sec}{W} = \frac{bits}{J}$), especially off-chip, has been listed as one of the strongest advantages of the selected photonic technology. It is important to fully explore the three ways it expends power:

- *Encoding/Decoding* power is consumed at the endpoints and it includes electrical circuits to serialize/deserialize the signal from the native system clock to the transmission rate as well as the power consumed by charge injection to modulate the signal. This power is insensitive to distance, is mostly dynamic, and the values quoted in Table 2.1 are for 100% utilization.

- *Light Generation* power is burned by the laser to produce the light used for communication. This power is constant, independent of utilization. It is difficult to dynamically adjust laser power. To generate laser light more efficiently, the same laser is used for multiple links, so unless all of the links are inactive, it is hard to scale back. It is important to note that the light generation power is the amount of electrical power required to produce the *laser power* (light intensity) the system needs. Light generation power is often overlooked, and most of the prior work has not added it to the power total with the justification that it is off chip and thus does not contribute to power density hotspots on the processor [25]. Keeping with convention, for most of this work laser power will be presented separately, because laser light generation is an orthogonal area of research, so converting it to electrical power might be misleading. However, when calculating the total power for a system, a conservative estimate of future laser efficiency of 25% is used. This power is strongly dependent on how much loss the path has, and Section 2.3 will present more details about this.

- *Thermal Tuning* power is burned up by heaters to control the ring's resonant frequency for process variation. The observed sensitivity is $1\mu W$/ring/K and the needed control range is 20K, so each ring will burn $20\mu W$.

In summary, using a silicon photonic link purely on-chip will not be significantly advantageous with regards to energy, unless it travels a substantial distance ($> 3mm$), however off-chip it could be more than an order of magnitude more efficient.

2.2.2 Latency

Most of the latency for a silicon photonic link is at the endpoints, since light propagates rapidly. The endpoint latency is a consequence of serializing and deserializing the data from the native clock rate to the transmission rate of 10 Gbps. Table 2.2 shows that photonics only has lower latency than electrical beyond $2.2mm$ on-chip. As mentioned earlier, the photonic links can go inter-chip without retransmission, so in those cases the latency gap between electric and photonic is further reduced.

2.2.3 Area

On-chip waveguides are larger than wires and they have a wider pitch. The air gaps makes the waveguides effectively wider because no circuits can be placed over them. Even though waveguides take up more area than wires, there is so much more bandwidth per waveguide from DWDM and bidirectional communication that it still obtains a large bandwidth density advantage (Table 2.3).

Off-chip this advantage becomes more significant because they have comparable pitches, with the same data rates, but a single fiber contains 64 links in each direction while an electrical pin only implements a single link in one direction.

2.3 Laser Power

Every optical component introduces some amount of loss to the signal, increasing the laser power needed to ensure sufficient light reaches every photodetector. As mentioned, in 2.2.1, light generation power is significant, and it is directly proportional to laser power. We define the *optical critical path* as the path with the greatest loss between the light source and the last photodetector. Along the optical critical path, the laser power required to overcome losses tends to grow exponentially rather than linearly, so a reasonable design can quickly become unreasonable when scaled up. The network layout and size can contribute greatly to loss, so careful physical layout design is essential to save power.

Using Figure 2.3, we can trace out an example optical critical path and show where the losses come from. Table 2.4 is included to give sense of the relative magnitudes, since the absolute values could change as the technology matures. The optical critical path starts at the laser, and ends at the last photodetector (the one attached to the filter for the green wavelength). Traveling any distance, the light experiences some loss, which is negligible for off-chip fibers and significant for on-chip waveguides. To go from from off-chip to on-chip or vice versa, the light travels through a coupler, which incurs loss substantial enough that links which span more than two chips may be untenable. Once the light has been brought on-chip, it typically is fanned out through splitters to make all of the needed links. When the waveguide crosses another waveguide, it also incurs loss because all waveguides are routed in the same plane with this technology. Crossing losses can be significant, because often multiple waveguides are routed parallel to each other, so a crossing actually results in many crossings.

There are a variety of losses caused by the resonant rings. When light passes by a filter tuned for another wavelength, it experiences *through loss* (Filter to through node). When it passes through the intended filter and reaches the photodetector, it experiences *drop loss* (Filter to drop node). *Modulator insertion loss* is incurred when a wavelength of light passes by a modulator tuned for that frequency that is currently inactive.

Another important consideration is the non-linearity limit imposed by the Poly-Si waveguide. As the combined power of the light inside a waveguide grows, there is a non-linear increase in the amount of light that escapes. To combat that loss, more laser power is used which results in even more loss, so its best to keep the total power for a waveguide within reasonable limits. Normally how many wavelengths can be put into a waveguide is set by the frequency selectivity of the photonic components used, but the number of wavelengths used per waveguide may also be set by the path loss which determines the power required per wavelength and thus the number of wavelengths that can fit under the non-linearity limit. The designs presented later in this study were made to have low loss, and they should be able to carry 64 wavelengths per direction without issue.

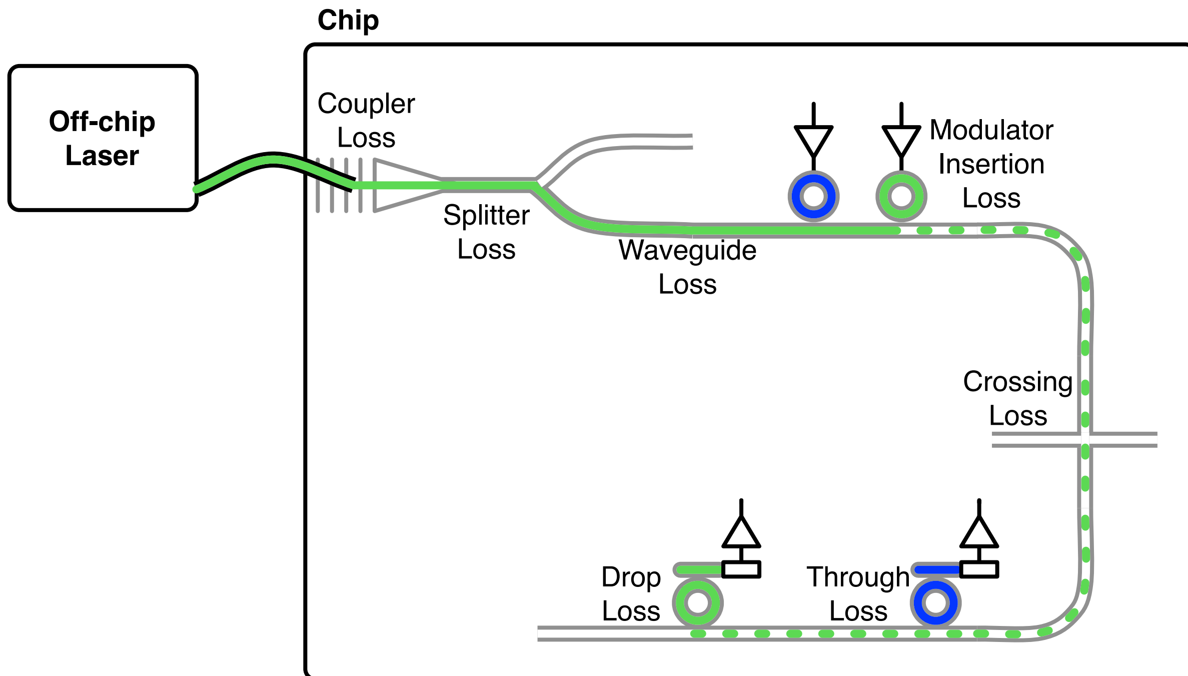

Figure 2.3: Photonic link with with losses labelled for the green wavelength

Table 2.4: Optical Power Costs [4]

Component	Loss (dB)
Coupler	1.0
Splitter	0.2
Non-Linearity	1.0
Filter (to through node)	0.01
Modulator Insertion	0.5
Waveguide Crossing	0.05
Waveguide (per cm)	1.0
Optical Fiber (per cm)	0.000005
Filter (to drop node)	1.5
Photodetector	0.1

2.4 Design Implications

As shown by Tables 2.1 & 2.3, the selected photonics technology can provide a tremendous amount of off-chip bandwidth, because of its energy efficiency and bandwidth density advantages. Replacing the electrical inter-socket links with photonic ones will enable much more bandwidth to each socket. Used in conjunction with an electrical on-chip network, it could still result in dramatically higher system bandwidth.

Even though entirely on-chip photonic links do not hold much of an advantage over electrical on-chip links, if photonics is used for the off-chip network, it makes sense to continue seamlessly on-chip because the conversions costs will have already been paid. By using these seamless links, off-chip networks and on-chip networks are flattened into one domain. To get the most from this flat network will require co-design of the on-chip and off-chip networks.

In this thesis, the connection between a memory controller and a DRAM module is assumed to be electrical. Future work could investigate a photonic link between a memory controller and DRAM, and doing so should not change the results of this study.

Chapter 3

Design of a Photonic Multisocket System

Section 2 shows that silicon photonics has great potential, and in this section we present a network designed to take full advantage of it. When designing a system known to be multi-socket, it is important to consider the off-chip network in addition to the on-chip network, and co-designing the on-chip and off-chip networks makes best use of seamless photonic links.

3.1 System Assumptions

To provide structure for the rest of this study, we make some assumptions about the target system. There are a variety of architectures that could take advantage of the transistor gains from Moore's law, but to achieve high computational throughput on a workload without high arithmetic intensity, they will all require high memory bandwidth. For this work, we envision a system comprised of many simple in-order cores, but some of the higher level results should still be applicable to other architectures.

To ground our design with real numbers (Table 3.1), we assume in a 22 nm process with 400 mm^2 of silicon, it will be possible to fit 256 cores running at 2.5GHz [4]. Each of these cores will include 4-way SIMD with Fused Multiply Accumulate (FMAC), giving the the system a total of 5 TFLOPS of peak performance. The amount of memory bandwidth needed to adequately supply this system will depend on the arithmetic intensity of the target workload, but the frequently desired ratio of one byte of memory bandwidth per one flop will support many desired workloads, which will equate to 5 TBps of memory bandwidth for the system [27]. This bandwidth will be supplied by 16 memory controllers, and each of these memory controllers may be attached to multiple physical DRAM channels, but from the point of view of the rest of the system, each memory controller is a single endpoint of arbitration and contention. We also assume that this system will be implemented over four sockets, so each socket will have one quarter of the cores and memory controllers. We assume a shared-memory system, where photonics is used to connect processor to memory controllers, not cores to cores.

	Baseline Socket	Max Configuration
Sockets	1	4
Cores	64	256
Clock Rate	2.5 GHz	2.5 GHz
Total Silicon Area	$100\,\text{mm}^2$	$400\,\text{mm}^2$
Memory Bandwidth	1.25 TBps	5 TBps
Memory Controllers	4	16

Table 3.1: Target system assumptions

3.2 Topology Insights

A network designer must balance the needs of the target workload with what the technology allows. The assumed workload for this system will need high bandwidth to feed many functional units, but this bandwidth must be provided uniformly (equally by all memory controllers) to simplify programming and to increase portability. Memory latency must be keep moderately low since the cores are mostly scalar, so they are incapable of cheaply tolerating too much memory latency. By Little's Law, the amount of data in flight is proportional to the product of latency and bandwidth. If the memory latency is increased, additional area will need to be dedicated to holding and tracking the increased amount of data in flight, which will make the simple cores more expensive.

A low-diameter, high-radix network will achieve these goals, and it will map well to the selected silicon photonics technology proposal. Low-diameter networks are known for low latency due to their low hop count, as well as having more uniform latency because there is less variance in path length [8]. This low hop count also results in more uniform bandwidth because there are less hops for links to get congested by other traffic on the network. To reach the same number of endpoints, a lower-diameter network must compensate with a higher radix. With a constant bandwidth per endpoint, increases in radix result in decreased bandwidth per link, which can be problematic as it will increase the serialization latency.

A common challenge with implementing low-diameter, high-radix networks in electrical technologies is that the links tend to become longer, and as a consequence, consume a significant amount of power. The selected photonic technology, however, is mostly distance insensitive with respect to latency and power. Another challenge with implementing these global links is that when mapped to a physical substrate, the bisection bandwidth required is high. This can be troublesome to route off-chip, but fortunately the selected photonic technology provides great off-chip bandwidth density. In contrast, if this network was implemented electrically, the bisection bandwidth would be constrained by the electrical pins, limiting the total network bandwidth. This would encourage the network designer to use a higher-diameter, lower-radix network to reduce the demand for bisection bandwidth which will also reduce the demand for off-chip bandwidth, at the price of longer and less uniform latencies and less uniform bandwidths.

Our design takes the low-diameter, high-radix network to the extreme, by using a simple fully-connected network (Figure 3.1a) as a starting point. Each network endpoint (core or memory controller), will have a high-radix switch with a photonic link for every possible endpoint. A single photonic hop minimizes latency while maximizing bandwidth uniformity. A one-hop topology will become a limiting factor as the design is scaled up to higher numbers of endpoints, since it will also increase the radix. Increasing the radix will hurt performance because the serialization latency will

grow as the links get narrower, and the power and area for the electrical switch will grow as its radix does. For the intended design scale of a single-board, compelling systems might be possible utilizing the selected photonic technology without taking up an unreasonable amount of area or power.

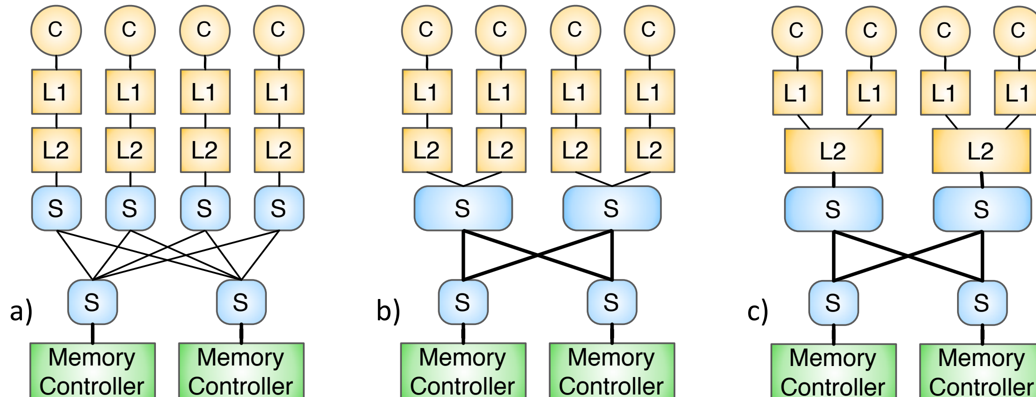

Figure 3.1: Topological benefits of concentration. a: Fully-connected network b: Fully-connected network with core concentration c: Fully-connected network with core concentration done by a shared cache

3.2.1 Concentration

Taking the simple initial design of a fully connected topology between individual cores and memory controllers and scaling it to meet the target system parameters will result in poor performance. The effective radix is high because there are so many memory controllers and cores, making each core–memory controller link so narrow (for the target system: $\frac{1}{16}^{th}$ of a core's bandwidth) that the serialization latency is significant. It is also statistically harder for a simple core to have enough memory request parallelism to keep all of those links busy simultaneously, leaving many of them underutilized. Low utilization is worrisome because static power constitutes a large fraction of a photonic link's power, but this can be avoided by using *concentration* to share links to increase utilization [8].

By grouping cores into *clusters* (Figure 3.1b), concentration widens the links to the memory controllers, which drastically cuts down on serialization latency. Since each cluster contains multiple cores, within in a cluster it is statistically easier to generate enough memory request parallelism to obtain higher utilization. Concentration combines the switches and links at the core side of the network to reduce the effective radix of the network. This has the desired effect of improving serialization latency, but it could also be used to build larger networks with the same serialization latency.

Since the cores within a cluster will be physically near each other as they share the same photonic cluster–memory links, they could also share their last level cache (Figure 3.1c). There are architectural benefits of sharing a cache, and current caches have been built with 8-way sharing [17]. These short links between cores and caches, and caches and the local switch should electrical, since it is too short of a distance for photonics to be advantageous. For the rest of our designs we

assume 8–core clusters, which obtains the benefits of concentration without overly burdening the cluster interconnect, but clusters of 2–16 cores should also be feasible.

3.2.2 Off-Chip Connections

With multi-socket systems it is desirable if the same chip can be used by simply varying the number connected together (even if only powers of two), because it will increase the volume of that part, lowering its cost. This scalable reusability is difficult to obtain while providing the goal of uniform memory bandwidth. As shown in Figure 3.2a, if the connections between clusters and memory controllers are made on-chip, that bandwidth is fixed because we want to reuse the same chip in all systems. Using that chip to build systems with a variable number of sockets populated will require some bandwidth (on-chip or off-chip) be turned off to keep the bandwidth allocation between the memory controllers on-chip and the memory controllers in other sockets uniform. If every connection is made off-chip (Figure 3.2b), the bandwidth allocations can be changed off-chip without modifying the chip.

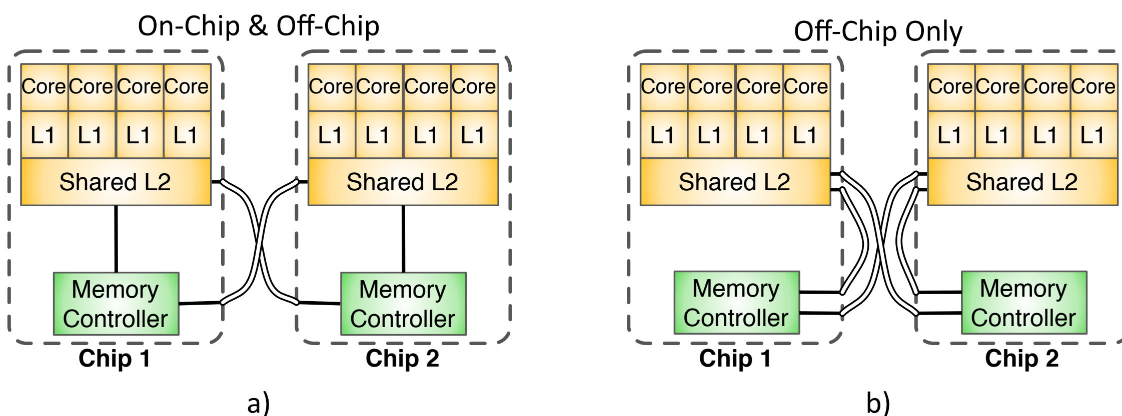

Figure 3.2: Topological benefits of all connections off-chip

To implement this, each cluster will have enough links to support the maximum number of memory controllers in the largest possible system, and the memory controllers will have enough links to support the maximum number of clusters in the largest possible system. In a fully populated system, all of these links will be connected one to one. If the system has only half of its sockets populated, there will be two links between each cluster and each memory controller. These links could be ganged together to make a single logical link of twice the bandwidth, or they could be kept separate to allow for greater memory request parallelism. In the case of a single socket system, the off-chip fibers are looped back.

It might seem that routing all traffic off-chip is wasteful when some of it could be done purely on-chip, but with photonics this penalty is greatly reduced. Most of the latency and on-chip energy cost of a photonic link is at the endpoints, so whether the link is purely on-chip or not only affects optical power. Depending on what the optical critical path loss is, this change in optical power may be truly negligible. This is in contrast to electrical off-chip links which consume sufficiently more energy and area such that an efficient design will never send data off-chip unless forced. Taking advantage of the off-chip bandwidth density, energy efficiency, and distance insensitivity of photonic

links, for the flexibility it provides and for the uniformity it maintains, the benefits of making all connections off-chip outweigh the small light generation power increase.

3.3 Packaging

To package the topology into a physical design will require more innovation. Because all of the cluster–memory controller connections are off-chip, each chip will have two types of fibers: those originating at clusters and those originating at memory controllers. Somehow off-chip, all of these fibers must be appropriately attached. To keep the fibers more organized, they can be grouped into *ribbons*, which simplifies assembly. As the number of sockets in the system grows, the number of ribbons that must be attached could be become unreasonable, because the topology is fully connected, so each socket must a have a ribbon to every socket (including itself). Figure 3.3a shows this for the four socket case.

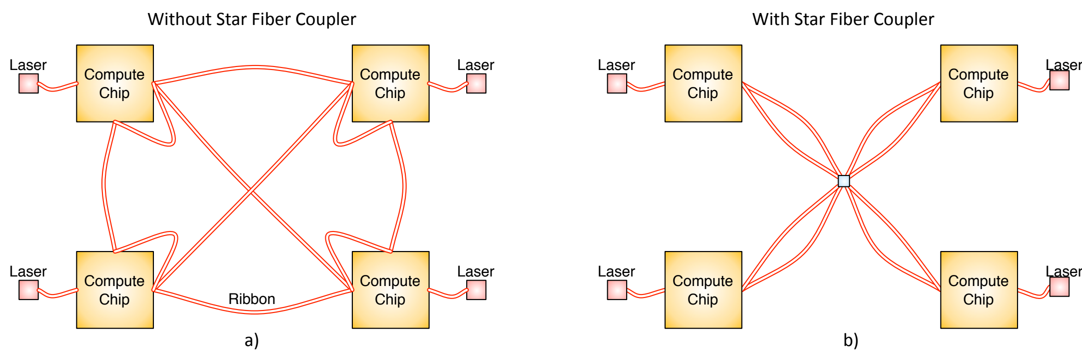

Figure 3.3: Comparison of with/without star fiber coupler

A *star fiber coupler* provides the needed all-to-all connectivity while greatly simplifying the fiber routing (Figure 3.3b). The star fiber coupler acts as a hub chip, so independent of system size, each socket only needs to attach two ribbons (one from its clusters and one from its memory controllers) to the coupler, and it will create the all-to-all connections. As shown in Figure 3.4, all of the cluster ribbons attach to one side of the coupler, and all of the memory controller ribbons attach to the other side. The ribbons from both sides come in orthogonal to each other so each ribbon crosses every other ribbon. In the example shown, four ribbons of four fibers come in each side, so effectively it is as if there is a fiber between every socket including itself (one fiber gets looped back).

The star fiber coupler can be generalized to support cases when there are more fibers than sockets or when multiple fibers are destined for each socket. It is a completely passive device, whose only purpose is to precisely hold ribbons such that their fibers can be efficiently coupled. The star fiber coupler should be comparably inexpensive, and along with some of the ribbons, are the only things to change between different system sizes.

To lay the system out on a board, the compute dies that contain the clusters and memory controllers are placed around the star fiber coupler as shown in Figure 3.5a. Each of the compute dies is surrounded by its own locally attached DRAM to reduce the distance for the electrical links between them. The memory controllers are evenly spaced around the edge of the die to provide

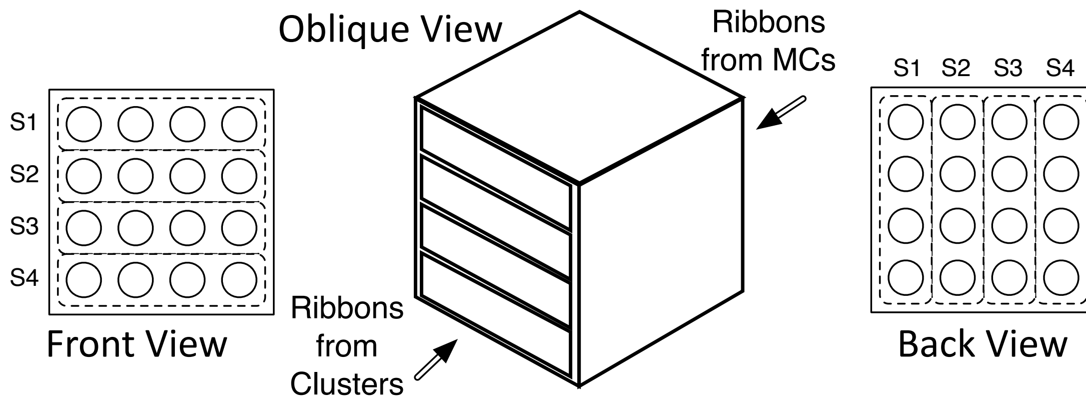

Figure 3.4: Schematic of star fiber coupler

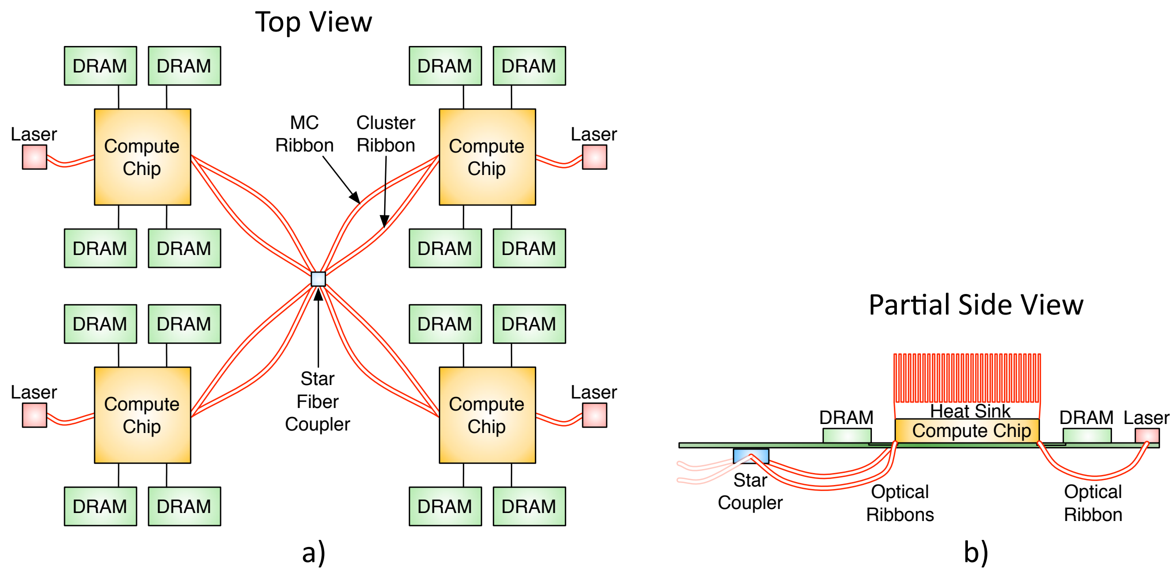

Figure 3.5: System layout

the easiest exposure for wiring to DRAM. By using photonics for inter-socket links, only a small amount of area needs to be dedicated to the fibers, leaving the rest of the pin area for connecting to DRAM or attaching to power and ground. The ribbons are attached only at the endpoints by vertical couplers and the ribbons will float freely beneath the board (Figure 3.5b), so they can avoid the heat sinks of the compute dies. A more dense board layout might reduce ribbon lengths, but it could significantly complicate the much more costly electrical signaling to DRAM or increase the power density. Extra distance in the ribbon is tolerable since the additional optical power loss and the increase in delay are both negligible.

3.4 Die Layout

The layout of the photonic components on-chip is crucial because it can greatly affect the optical power. Without careful design, the loss along the optical critical path quickly becomes so great that the laser power becomes unreasonable. Essentially the designer's job is to take all of the logical links, map those to wavelengths, and then map those to appropriate waveguides. The following sections highlight the optimizations used to make an efficient layout, such as the 64 core die layout in Figure 3.6.

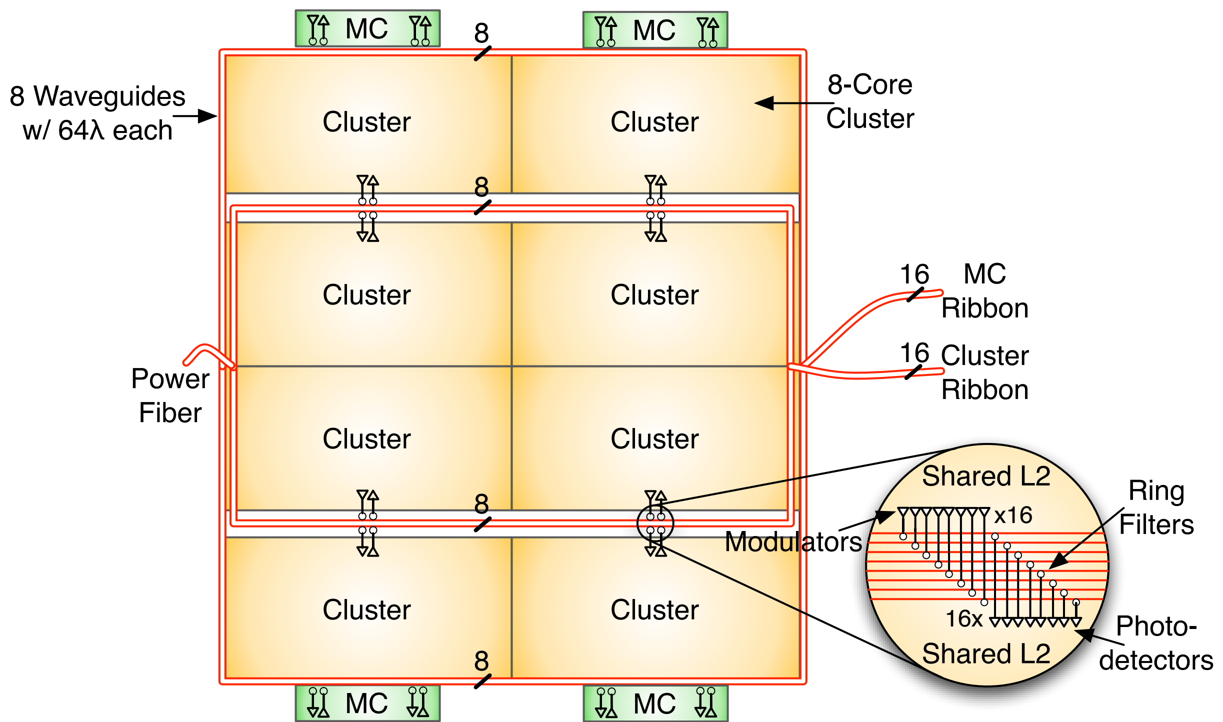

Figure 3.6: Die layout for 64 core die designed to support a 256 core system

3.4.1 Nested-U Waveguide Layout

Laying out the waveguides in a *nested-U* configuration as shown in Figure 3.6 can help combat two sometimes avoidable sources of optical loss: waveguide length and crossing loss. By bringing the power fiber in on one side and the inter-socket ribbons on the other, the waveguide distance is minimized while still reaching all the needed endpoints. The nested-U layout guarantees the the waveguide distance is less than or equal to the length of the chip plus the width of the chip. A single crossing doesn't contribute too much loss, but quite often waveguides are routed in parallel so a crossing will intersect multiple waveguides and then the losses multiply. Nesting the waveguides removes all crossings, since they always go around each other.

3.4.2 Cluster Striping Across Waveguides

With the nested-U waveguide layout, a waveguide from the power fiber to the inter-socket ribbon actually passes by more than one cluster. To load a waveguide with wavelengths from only one cluster exclusively is wasteful, because later on those wavelengths will need to be mixed for the inter-socket fibers. Striping a cluster's wavelengths across all the waveguides that pass by reduces the need to mix wavelengths later on.

In the example in Figure 3.6, eight waveguides pass four clusters. If each cluster put all of its wavelengths on two waveguides, somehow the wavelengths will need to be shuffled around such that they map appropriately to the four fibers that go between each socket. A device like the one presented in Section 4.2.1 could accomplish the needed mixing, but with striping it is often unnecessary.

3.5 Evaluation

As mentioned in Section 3.1, the network presented is designed to support 4 sockets of 64 cores, for a total of 256 cores. As an early evaluation of feasibility, we analyze its interconnect performance using conservative overestimates (Table 3.2). The system at theoretical peak can provide each core with the desired 1 byte : FLOP, for a total of 5 TBps of memory bandwidth.

Table 3.2: Overestimates for Quad Socket Interconnect for 256 Cores Total

Quantity	Value
Total Power	9.77W
Latency	1ns
Area (per socket)	$4.2\,\text{mm}^2$

Figure 3.7 shows a breakdown of where the power is consumed in the interconnect. For our analysis we use the impractical 100% utilization to show what the peak power could be. With 0% utilization, the encoding/decoding power will scale down to about half of what it is at peak utilization, but the rest of the interconnect power is static and will not change based on activity. The encoding/decoding power is directly related to the number of photonic endpoints, and with a constant number of cores it will scale directly with the amount of offered bandwidth per core. Light generation power is burned in off chip lasers so it adds to the system wall power but not

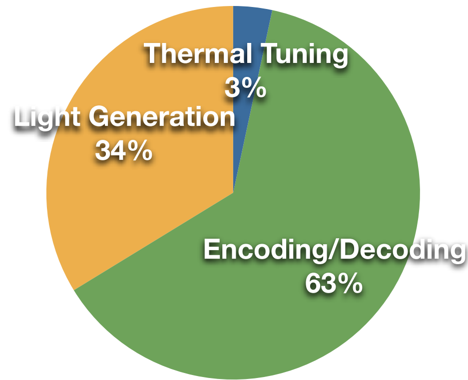

Figure 3.7: Breakdown of network power consumption for 256 core system with 64 cores per die

to the compute die's power density. For comparison, we converted laser power to light generation power assuming a conservative laser efficiency of 25%. Thermal tuning power is set by the number of rings which is also directly proportional to the number of photonic endpoints. This power is continuously burned, but it is not a large overall contributor (Figure 3.7).

The latency will depend on how far apart the sockets are placed, but if the off-chip fiber is under 11cm, the latency will be under 1ns (2-3 cycles for out target clock of 2.5GHz). This latency is actually quite good when it is put in context with other steps in memory operations such as L2 cache access latencies or DRAM access latencies. For our target system, the serialization latency will be 16 cycles for a 64B cache line, so in 18-19 cycles a cache line could move from a memory controller to a cluster's cache.

The area was grossly overestimated to give generous gaps between photonic components and the transistors around them. The area in Table 3.2 is per die, and in our target system each is $100\,\text{mm}^2$, so that is only 4.2% overhead.

Integrating a new technology will have its costs, and they will have to be justified by dramatic performance improvements. Fortunately, the photonic network presented here will make some other parts of the system cheaper or easier to design. For example, since all inter-socket communication will be carried over fibers, this will dramatically reduce the number of traces that need to be routed on the printed circuit boards (PCB). This will make the PCB easier to design, cheaper to manufacture, and it will leave more space for other signals. Routing all inter-socket data through fibers will also mean that there will be less pins coming out of the socket, allowing for a smaller and cheaper package to be used. The increase in delay or energy for an increase in fiber length is marginal, which will give the system designer more flexibility in where they place sockets. In summary, using photonics simplifies much of the rest of the system, which will hopefully lessen the cost of adopting a new technology.

Chapter 4

Die Size Exploration

The design presented in Section 3 can be generalized to handle greater numbers of cores or even different die sizes. Since all connectivity is off-chip and we leverage the distance insensitivity of photonics, there is less motivation to integrate and an economic incentive to disintegrate.

4.1 Incentives for Disintegration

Disintegration may be able to reduce the cost of the system (relative to another made with the same template). Smaller dies could reduce costs by:

- *Increased yield.* Figure 4.1 shows the relative costs of manufacturing $400\,\mathrm{mm}^2$ of silicon as one whole die or many smaller dies. Although the combined cost of the smaller dies is always cheaper due to increased yield, most of the gain can be had by splitting the die four ways to get a $\approx 3\times$ cost advantage. Figure 4.1 is from a simple model [12] that only takes into account parameters for area and defect densities. In the real world there will also be fixed costs (packaging, assembly, and test) per die that will make the systems with the smallest dies less desirable, but there still will be significant advantage to using multiple moderately smaller dies rather than a single large die.

- *Better binning.* Since the dies are smaller they can be binned on a finer granularity to reduce the impact of process variation. Within a small die, the probability of there being high process variance is reduced, allowing a greater number of high performance dies to be sold.

- *Greater design reuse.* As mentioned previously, being able to use the same die in systems of different sizes allows for greater amortization of non-recurring engineering (NRE) costs over the increased manufacturing volume. Smaller dies are easier to reuse because they support a greater variety of system sizes.

Smaller dies could also make system design easier. With smaller dies, possibly spread farther apart, the board-level power density of the system is reduced making cooling easier. It will be even easier to interface to adjacent electrically connected DRAM with smaller dies, since there will be less memory surrounding each die.

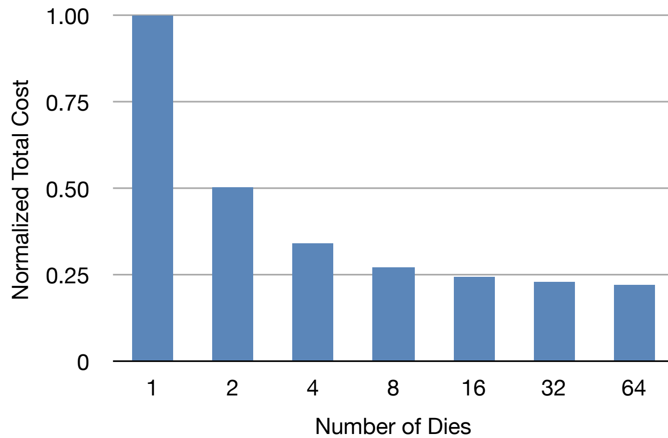

Figure 4.1: Relative total costs for 400 mm^2 of total silicon area

4.2 Scaling the Design

The design presented in Section 3 can scale to some other sizes, but in this section we describe two further photonic structures that increase the feasible range of designs.

4.2.1 Mixer

DWDM allows multiple logical links to share the same waveguide, but when a link needs to cross to another waveguide a *mixer* can be used. For each waveguide on one side, all of its wavelengths are evenly and disjointly distributed across the waveguides on the other side. It is a bidirectional component, and Figure 4.2 shows a simplified case, where two wavelengths from one waveguide are separated onto two waveguides. It is possible to extend this design to handle multiple waveguides per input group, so a NxN mixer (k wide) mixes N groups of k waveguides each. With this abstract notation, a wide range of components can be classified as mixers, and many of these special cases have already appeared in various other photonic designs [6, 24, 28].

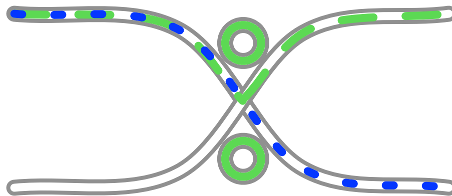

Figure 4.2: Simplified 2x2 mixer (1 wide). Only one waveguide's wavelengths shown for simplicity.

To take the system from Section 3.4 from 256 cores total to 1024 cores total (still 64 cores per socket) will require two 2x2 mixers (8-wide) placed where the inter-socket ribbons attach to the on-chip waveguides (Figure 4.3). To reach 1024 cores with 64 core dies (100 mm^2), there are 16

sockets so each inter-socket link has only 1 fiber. Scaling in this manner keeps the bandwidth per core constant, but it does come from a greater number of memory controllers. The input groups to the mixers correspond to the groups of waveguides on the die. Without striping, the mixers would have to have more input groups.

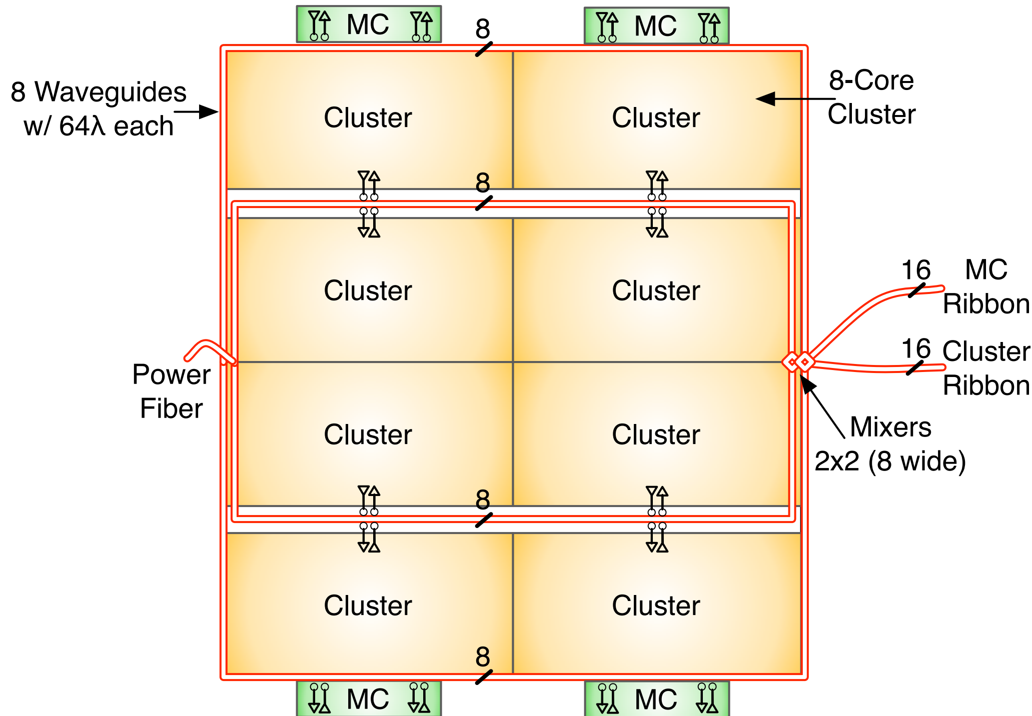

Figure 4.3: Die layout for 64 core die designed to support a 1024 core system

4.2.2 Add-Drop Multiplexer

When there are more dies in the system than waveguides on a die (this often happens with small dies), an *add-drop multiplexer* (ADM) can be used to fan out the wavelengths of one waveguide onto multiple underloaded waveguides. This component is bidirectional, so from one direction it looks like a splitter but from the other it looks like an aggregator. As shown in Figure 4.4 this can be done without crossings. Alternatively the die layout could simply under-fill the waveguides on-chip, but this wastes area and the optical loss through the ADM is low.

4.3 Evaluation

Using the generalized design template, we explore a range of possible systems with maximum capacities of 64 – 1024 cores built from 4 – 64 dies. We keep the cluster size the same (8 cores), the ratio of memory controllers to cores the same (1:16), and the same core density (0.64 cores/ mm^2). Table 4.1 shows what additional components (mixers or ADMs) are required to build systems of various sizes. There are tradeoffs when designing the base building block (die) for the system,

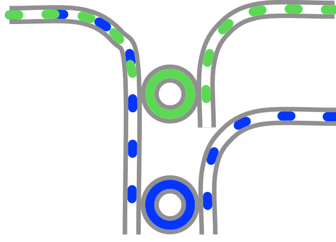

Figure 4.4: Simplified Add-Drop Multiplexer with two wavelengths per waveguide

both in terms of how big it is and how many other blocks it expects. If the maximum system size is designed too small, it will not be able to scale to larger systems without penalties, but if it is designed too large, the functionality needed for larger systems will waste area and raise cost when used in smaller systems. Some places where this tradeoff becomes apparent are: off-chip bandwidth, off-chip link organization, and coherency. For our particular family of designs, how populated the system is does not noticeably affect performance once the die size and the maximum system size have been set.

Table 4.1: Additional component requirements (mixers and ADMs) per die to scale the system size. The fanout degree for the ADM is on the top line, while the mixer degree is the bottom line.

	64 cores/system	128 cores/system	256 cores/system	512 cores/system	1024 cores/system
16 cores/die		2x	4x	8x	16x
32 cores/die			2x2 (4 wide)	2x 2x2 (4 wide)	4x 2x2 (4 wide)
64 cores/die					2x2 (8 wide)
128 cores/die					
256 cores/die					

4.3.1 Power

Since we keep the bandwidth per core constant, the encoding/decoding power remains constant at 24mW per core, whether we scale the number of cores or the number of dies to implement them (Figure 4.5). Since some of the higher core count designs use additional rings for filters in the interconnect (in ADM's and mixers), they will have slightly higher thermal tuning power but it is still negligible. These additional components will have a much larger impact with increased loss on the optical critical path which will increase the light generation power significantly.

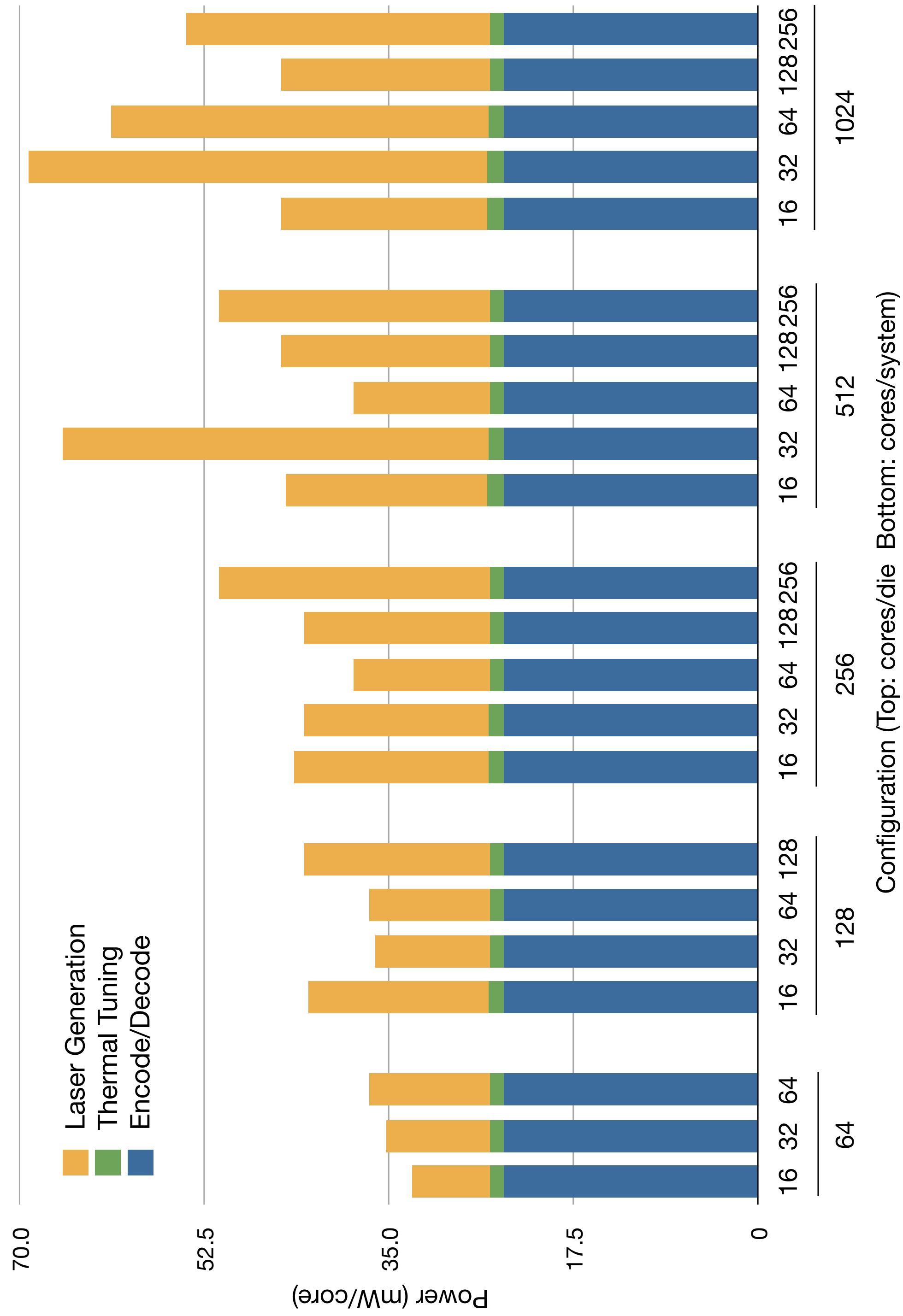

Figure 4.5: Total power per core

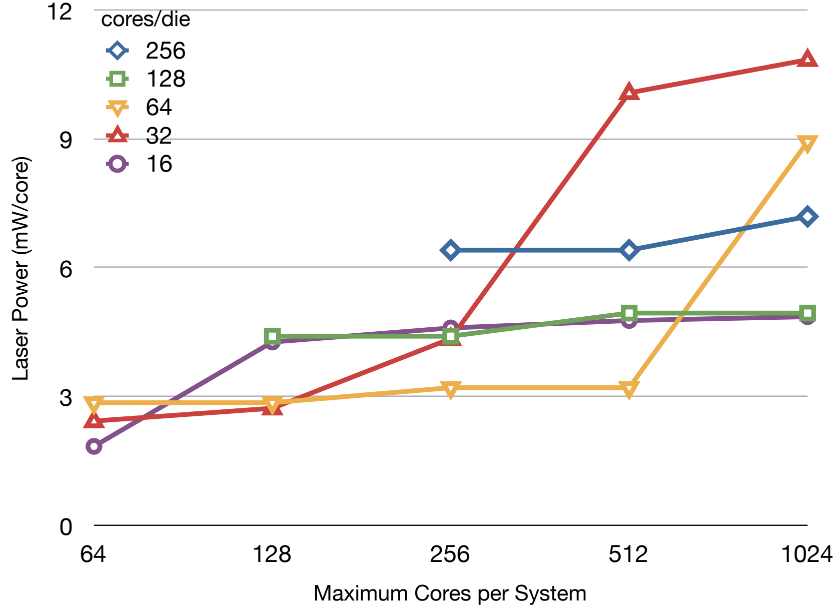

Figure 4.6: Laser power per core

Figure 4.6 shows the laser power required for fully populated systems as a function of die size and maximum system size. Systems that are not fully populated require the same laser power per core except for when only 1 or 2 sockets are populated and the star coupler is not needed. For all die sizes, as the maximum supported system size is increased, the required optical power is also increased, as expected. The rate at which it increases can fluctuate significantly because as the system size increases, some components (mixers, ADMs, star fiber couplers) are added to the interconnect and the loss rates of these components varies. A more interesting trend is that smaller systems are more efficiently constructed from smaller dies, as is visible on the pareto-optimal curve (underside of the graph). This appears to indicate that systems with a moderate number of sockets perform best because of the fan-out costs associated with making the all to all connectivity. With our selected technology, smaller dies have an advantage of shorter waveguides (less loss) as shown by the line for 16 cores per die.

4.3.2 Latency

Surprisingly latency does not get much worse when breaking sockets apart into smaller ones, even if electrical links are used off chip. As visible back in Table 2.2, both technologies get faster off chip after a minimum distance has been traversed to make up for the conversion delay. Once the overhead of getting onto a fiber is paid, the signal can travel 8cm in a clock cycle of our baseline system, so within less than a few cycles, everything is reachable by everything else on board. The only time link latency is worrisome is when trying to route a signal for a long distance electrically with a normal repeated wire on-chip, but this does not happen in our design since all long links are done photonically. Even with systems larger than the one in Section 3.1, the latency will not

get much bigger. With the largest conceivable board layouts, the link latency will still be less than 2ns, which will be dwarfed by the serialization latency.

4.3.3 Area

In general our photonic interconnect fits well within an area budget as shown in Figure 4.7. These are for die designs that are capable of supporting up to a maximum of 1024 cores in the system. Since our technology is using projected values, these overheads could change, but we are pessimistic in our assumptions about sizing, which results in over-estimates for area. Smaller dies use less area for the interconnect, because more of it is off chip and they are small enough that it is still possible to put many or all of the waveguides over the same air trenches. Although this suggests less wasted area is another reason smaller dies will be more cost-effective, the most important result is that using smaller dies is no worse than using larger ones, with respect to area overhead.

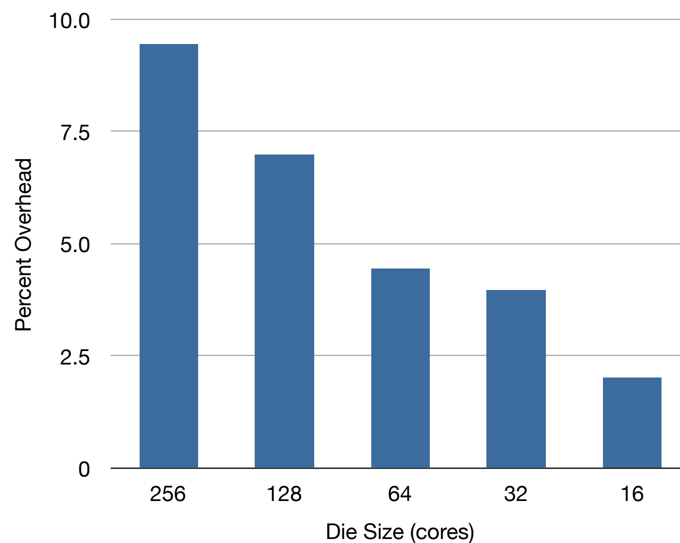

Figure 4.7: Percentage die area taken by photonic network (not including switch area)

4.3.4 Discussion

The main lesson is that there is a tradeoff between integration and disintegration. The models may not be able to fully capture all of the penalties of having many small dies, but dies smaller than the ones currently used may be feasible to make systems with a moderate number of sockets.

Historically systems have been built out of dies as large as is reasonable to manufacture because of the interconnect penalties of traversing socket boundaries. This sometimes results in paying a significant premium to fabricate larger monolithic dies. The photonic network template presented could reduce the barrier to multi-socket designs, enabling a new system design methodology of picking a die size that is cheapest to manufacture, and then using as many dies as needed to build the desired system.

Chapter 5

Related Work

The work of Batten et al. [4], identified the potential for monolithic silicon photonics for making an interconnection network to connect DRAM to processing cores. We used their technology assumptions and baseline machine as a starting point for our work. Our work differs in that it adds the contributions of using multi-socket systems as a way to reduce cost and considering coherence much more closely. Much of the other related work focusses on the on-chip network for a single chip and does not consider anything off-chip [7, 13, 16, 22, 24].

Kirman et al. presented a photonic on-chip interconnect in [16]. Their architecture attempted to utilize each interconnection topology for the range of distances it was best at. They subdivided a CMP into four blocks and those four blocks were connected by a photonic ring topology. Within a block electrical interconnects were used at a distance where they were advantageous to optical. Our network topologies were influenced by this, but we have made a more ambitious design that uses a more optimistic photonic technology.

Shacham et al. present a photonic NoC for a multiprocessor system that uses photonic switches built from crossings and resonant rings [24]. To set up a link, an electric control signal must travel ahead in parallel to the path to set up the switches. This enables them to get higher bandwidth utilization on their links than a point to point system like what was presented in this paper, but at the cost of path set up latency and the possibility of network contention. As a consequence of the set up requirements, they get the best performance from lightly contested bulk transfers.

Joshi et al. present a low-diameter photonic Clos network and compare it to electrical alternatives [13]. Their low-diameter network is motivated by the same desire of this work to provide uniform bandwidth while taking advantage of the distance insensitivity of photonic links. Unlike this work, their Clos network is able to utilize path diversity, but this would be harder to implement for the multisocket case because there are more endpoints to connect.

Phastlane [7] intends to bring the benefits of photonics to a dimension ordered mesh network. Since light propagates quickly, they allow a packet to sometimes travel multiple hops in a single cycle. Unlike [24], they set up each hop with an optical control signal that travels in parallel to the data payload. When there is contention, the packet will travel less hops in a cycle and is stored in an electrical buffer. If the buffer is full, the packet is dropped, and the sender is notified. Of the photonic proposals, Phastlane is the only one to consider not providing reliable transmission at the link layer.

Firefly [22] presents a hierarchical NoC. Similar to [16], it subdivides the chip into clusters, and within a cluster it uses electrical links and between clusters it uses photonic links. The photonic

links use a crossbar, but to prevent the need for global arbitration they break it up into multiple logical crossbars.

Proximity interconnect [9] is an interesting technology that is trying to solve many of the same problems our photonic socket-level interconnect is. It places dies very close together and uses capacitive coupling to transmit data without actual wire contacts. By doing so, it is able to obtain pitches and bandwidths comparable to on-chip wires. They have aspirations similar to ours for its use whether it be making small dies to reduce cost or combining large dies to approach wafer scale integration. Photonics, especially with DWDM should be able to achieve even higher bandwidths and is a little more robust of a technology since the exact relative alignment of two dies does not matter as much.

Three dimensional die stacking is another technology with the same motivation, but it could be used in conjunction with a photonic interconnect like in Corona [25]. They place their photonic network on its own die to give them more area and let them use better photonic materials which allows them to build more complicated networks. They use a large serpentine crossbar which has orders of magnitude more components than our networks and would be infeasible with our monolithically integrated photonics technology. As such, they burn significantly more laser power than our design for comparable bandwidth, but it is hard to accurately make this comparison since they are using a different photonic technology.

Chapter 6

Conclusion

In this work, we present design techniques that produce a general network template that can be scaled to handle varying numbers of cores and sockets. To scale our network design to even larger core counts will probably require moving to a multi-hop network.

Chip disintegration may seem counterintuitive for performance reasons, but with our photonic network, the performance degradation is made small enough that the cost incentives out weigh it. This could allow for a re-thinking of the design process where systems are built out of the appropriate number of the most economically sized die.

Due to the current state of silicon photonic research, multi-socket memory interconnects are a great application. In the near horizon, photonics provides great advantages over electrical at the scale of on-board/off-chip. To optimize these multi-socket systems, photonics should be used to communicate directly with DRAM, which will remove the last bit of wasteful off-chip electrical signaling. Further advances, such as efficient integrated lasers, will enable photonics research to continue to decrease the scale at which optical communication is advantageous, possibly opening up the chip micro-architecture as the next interesting application.

Appendix A

Coherence Considerations

To make this system more realizable it will need a coherency scheme (protocol and hardware implementation) to turn the network into a memory interconnect, which is something past designs have not given much consideration to. Especially for the general architecture presented in this paper, it is essential that the coherency scheme achieve the same goals of reusability and scalability. We want the same design to be able to handle different binary amounts of populated sockets in the system without unreasonable overheard. Our system uses shared memory, and coherency is maintained amongst all caches by a two level protocol corresponding to within and between clusters.

A.1 Intra-Cluster Coherence

Within a cluster, each core has its own private L1 cache and they all communicate through a shared L2 cache. The L2 cache is not inclusive of the L1s, but it does store duplicates of the tags. We envision using this with a protocol similar to what was described in Piranha [2]. This protocol will be responsible for keeping the caches within each cluster coherent, and requests that it cannot handle will be passed up to the next level coherency protocol.

A.2 Inter-Cluster Coherence

To maintain coherence between clusters we use a 4–hop MESI directory protocol. From the point of view of the directory, all caches in a cluster are lumped together and treated as one. We position a directory by every memory controller so it can intercept requests to memory and take the appropriate protocol actions. A directory is only responsible for the memory locations its associated memory controller provides. The protocol uses 4 hops because there is no core to core network, so all inter–core traffic must be routed through the memory controller.

To make the directory small enough to fit on chip rather than off-chip DRAM, we use a reverse tagged directory implemented with a Content Addressable Memory (CAM). For every cache line it is responsible for, the directory contains a duplicate of the cache tag and a few bits of protocol state. We reduce the associativity required for the directory by implementing it with many small CAMs where each one corresponds to a cache set. When a request is being looked up, only the CAM corresponding to the request's set needs to be examined. A cache tag's location in the reverse directory implicitly identifies the location of its owner. Because all the caches in the system are set associative, this puts a limit on the number of possible cache lines that could hold a block, namely

Nk if the system has N clusters and each one is k-way set associative. If this associativity is still too high, multiple CAM arrays could be used which will still be faster and cheaper than going to a direct mapped directory implemented by off-chip DRAM.

Although photonics provides great bandwidth which might tempt one to snoop, the energy cost at the endpoints to do associative lookups for every message at every cluster in the system will be prohibitive, especially as it scales. With snooping, for a given protocol miss (like a write miss), rather than searching the state of one cluster and the home directory, every cluster will need to be searched. This will also require a broadcast mechanism, which our current network topology does not provide. It could be possible to design it, but our topology was designed to minimally meet our goals and our coherency protocol works well without it. The bandwidth savings a directory protocol provides will also help the system scale to higher core counts and conserve energy.

A.3 Reusability

To support a variable number of populated sockets the way memory addresses are interleaved can be leveraged. For a given die size, if the number of populated sockets is doubled, the number of cache lines double, however the number of sets per cache that can address a particular memory controller get halved, so the number of possible locations a directory needs to be concerned with stays the same. The only thing that changes is the implicit addressing of clusters to tags in the reverse directory.

A.4 Directory Implementation Feasibility

To prove the feasibility of such a technique, we present a rough model of what reverse tagged directories would cost by scaling [5] down to 22 nm. To stress our design, we target the maximum size system our network targeted: 1024 cores over 1600 mm^2 of silicon. The target system uses a 48-bit physical address. Each cluster has 4MB of L2 cache that is 8-way set associative.

To implement the CAMs efficiently, we use a pre-computation based CAM [19] with a Half-NOR cell size of 0.34 μm^2 and a NAND cell size of 0.3695 μm^2. For the CAM arrays alone, this would take 50.531 mm^2, so rounding up generously for extra decode and control logic, this could be implemented in 80 mm^2 which is only 5% of the total silicon area.

The power required is harder to estimate due to its dependence on workload and coherence traffic. In 45 nm[5] each search took $0.14\frac{fJ}{bit}$, so including decode overheads and pessimistic energy scaling $0.1\frac{fJ}{bit}$ might be possible in 22 nm. Assuming the wildly high coherence activity rate of each core needing to access the directory once every five instructions results in 0.786W total. This amount will almost surely be drowned out by static power of the SRAMs included to hold the CAMs' state. The dynamic search power makes up such a small portion of the directory's power because the cache set partitioning makes the relative activity factor of any CAM cell quite low.

The latency of the directory itself should be quite tolerable. Even without much speed improvement from process technology and accounting for controller overhead, it should be possible to get a search done in under a nanosecond [5]. This should clearly win by more than an order of magnitude compared to off-chip DRAM. Overall we believe we could make an effective coherence mechanism utilizing reverse tagged directories built from on-chip CAMs.

Bibliography

[1] Krste Asanovic et al. The landscape of parallel computing research: A view from berkeley. Technical report, U.C. Berkeley, 2006.

[2] L. Barroso, K. Gharachorloo, R. McNamara, and A Nowatzyk et al. Piranha: A scalable architecture based on single-chip multiprocessing. *ISCA*, Jan 2000.

[3] T. Barwicz et al. Silicon photonics for compact, energy-efficient interconnects. *Journal of Optical Networking*, 6(1):63–73, 2007.

[4] C Batten, A Joshi, J Orcutt, A Khilo, B Moss, Charles Holzwarth, Milo s Popovic, Hanqing Li, Henry Smith, Judy Hoyt, Franz Kartner, Rajeev Ram, Vladimir Stojanovic, and Krste Asanovic. Building manycore processor-to-dram networks with monolithic silicon photonics. *High Performance Interconnects*, Jan 2008.

[5] Scott Beamer and Mehmet Akgul. Design of a low power content addressable memory (cam). *EE 241 Final Project*, May 2009.

[6] M. Brière, B. Girodias, Y. Bouchebaba, G. Nicolescu, F. Mieyeville, F. Gaffiot, and I. O'Connor. System level assessment of an optical noc in an mpsoc platform. In *DATE '07: Proceedings of the conference on Design, automation and test in Europe*, pages 1084–1089, San Jose, CA, USA, 2007. EDA Consortium.

[7] MJ Cianchetti, JC Kerekes, and DH Albonesi. Phastlane: a rapid transit optical routing network. *ISCA*, 36, 2009.

[8] William James Dally and Brian Towles. *Principles and Practices of Interconnection Networks*. Morgan Kaufmann, 1st edition, 2004.

[9] R Drost, R Hopkins, R Ho, and I Sutherland. Proximity communication. *IEEE Journal of Solid-State Circuits*, 39(9):1529 – 1535, Sep 2004.

[10] C. Holzwarth et al. Localized substrate removal technique enabling strong-connement microphotonics in bulk si cmos processes. *Conf. on Lasers and Electro-Optics*, 2008.

[11] C. Gunn. CMOS photonics for high-speed interconnects. *IEEE Micro*, 26(2):58–66, Mar-Apr 2006.

[12] J. Hennessy and D. Patterson. *Computer Architecture: A Quantitative Approach*. Morgan Kaufmann, 4th edition, 2007.

[13] A Joshi, C Batten, Y Kwon, S Beamer, Imran Shamim, Krste Asanovic, and Vladimir Stojanovic. Silicon-photonic clos networks for global on-chip communication. *NOCS*, 3, Jan 2009.

[14] Ron Kalla. Power7: Ibm's next generation power microprocessor. *A Symposium on High Performance Chips*, 21, 2009.

[15] L. Kimerling et al. Electronic-photonic integrated circuits on the CMOS platform. *Proceedings of the SPIE*, 6125, Mar 2006.

[16] N Kirman, M Kirman, R Dokania, and J Martinez. Leveraging optical technology in future bus-based chip multiprocessors. *IEEE Micro*, 27(6), Jan 2006.

[17] Poonacha Kongetira, Kathirgamar Aingaran, and Kunle Olukotun. Niagara: A 32-way multithreaded sparc processor. *IEEE Micro*, page 9, Apr 2005.

[18] Sailesh Kottapalli and Jeff Baxter. Nhm-ex cpu architecture. *A Symposium on High Performance Chips*, 21, 2009.

[19] Chi-Sheng Lin, Jui-Chuan Chang, and Bin-Da Liu. A low-power precomputation-based fully parallel content-addressable memory. *JSSC*, 38(4):654– 662, 2003.

[20] M. Lipson. Compact electro-optic modulators on a silicon chip. *Journal of Selected Topics in Quantum Electronics*, 12(6):1520–1526, Nov-Dec 2006.

[21] J. Orcutt et al. Demonstration of an electronic photonic integrated circuit in a commercial scaled bulk cmos process. *Conf. on Lasers and Electro-Optics*, 2008.

[22] Y Pan, P Kumar, J Kim, G Memik, Y Zhang, and A Choudhary. Firefly: illuminating future network-on-chip with nanophotonics. *ISCA*, 36, 2009.

[23] Sanjay Patel, Stephen Phillips, and Allan Strong. Sun's next-generation multi-threaded processor - rainbow falls. *A Symposium on High Performance Chips*, 21, 2009.

[24] A Shacham, B Lee, A Biberman, and K Bergman. Photonic noc for dma communications in chip multiprocessors. *IEEE Symposium High-Performance Interconnects*, 15, Jan 2007.

[25] D Vantrease, R Schreiber, M Monchiero, and M McLaren. Corona: System implications of emerging nanophotonic technology. *ISCA*, Jan 2008.

[26] M. Watts et al. Design, fabrication, and characterization of a free spectral range doubled ring-resonator filter. *Conf. on Lasers and Electro-Optics*, 1:269–272, May 2005.

[27] Samuel Webb Williams, Andrew Waterman, and David Patterson. Roofline: An insightful visual performance model for floating-point programs and multicore architectures. Technical Report UCB/EECS-2008-134, EECS Department, University of California, Berkeley, Oct 2008.

[28] Lei Zhang, Mei Yang, Yingtao Jiang, Emma Regentova, and Enyue Lu. Generalized wavelength routed optical micronetwork in network-on-chip. In *Proceedings of the 18th IASTED International Conference Parallel and Distributed Computing Systems*, 2006.