2015 IEEE 23rd Annual Symposium on High-Performance Interconnects

OWN: Optical and Wireless Network-on-Chip for Kilo-core Architectures

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***Abstract*—As technology scaling is already enabling the integration of tens of hundreds of cores on a single chip, kilo-core chip multiprocessors (CMPs) are expected to be available within a decade. However, metallic-based on-chip interconnects may not scale to support kilo-core architectures due to increased hop count, high power dissipation, and increased latency. Emerging technologies such as silicon-photonics and wireless interconnects are under serious consideration as they show promising results for power-efficient, low-latency, and scalable on-chip interconnects. However, photonic technology suffers from scalability issues due to high component cost and complex arbitration while wireless technology lacks sufficient bandwidth for on-chip communication. In this paper, we propose an architecture called Optical-Wireless Network-on-Chip (OWN) that leverages the advantages of wireless and photonic technologies while circumventing the disadvantages of these two emerging technologies. Kilo-core OWN is designed such that one-hop photonic interconnect is used up to 64 cores (called a cluster). For communication beyond a cluster, one-hop wireless interconnect is proposed to enhance scalability. Both wireless and photonic bandwidths are efficiently shared using time division multiplexing (TDM). Moreover, packets routed across technologies are guaranteed to be deadlock-free. Our area results indicate that OWN requires 34% more area than hybrid-wireless architectures and 35.5% less area than photonic architectures. The energy/bit for OWN is 30.36% less than wireless and 13.99% more than photonic architecture. OWN demonstrates higher saturation throughput when compared to wired, wireless, and photonic technologies for synthetic network traffic.**

I. INTRODUCTION

The International Technology Roadmap for Semiconductors (ITRS) predicts that complementary metal-oxide semiconductor (CMOS) feature size will shrink to 11 nm by 2020 [1]. As a result, billions of transistors will allow computer architects to accommodate hundreds or even thousands of cores on a single chip without altering the current chip dimensions [2]. However, global wire delays and energy costs do not scale with CMOS technology. Based on ITRS predictions, traditional metal interconnects may not be able to support kilo-core chip multiprocessors (CMPs) due to power and performance limitations. Consequently, emerging technologies such as wireless and photonics could provide adequate bandwidth within the power budget for network-on-chips (NoCs) in future CMPs.

On-chip silicon-photonic interconnects offer low-latency ($\sim$ps), low power consumption ($\sim$0.25pJ/bit), and high-bandwidth ($\sim$40Gbps) [3], [4], [5], [6] making it suitable for on-chip communication. However, optical-only architectures have drawbacks for kilo-core designs. Optical-only NoCs using crossbars do not scale well for large number of cores due to significant area and power overhead. For example, a 64×64 crossbar using photonics will require 448 modulators, 7 waveguides and 28224 photodetectors using single-writer-multiple-reader (SWMR). If we scale to 1024×1024, then we will need approximately 7168 modulators, 112 waveguides, and 7.3 million photodetectors which is prohibitive and not easily scalable. Additionally, optical-only NoCs suffer from high optical power losses (insertion loss) due to long snakelike waveguides and crossovers (splitters). For example, a 64×64 and a 1024×1024 optical crossbar has an insertion loss of approximately 11.2064 and 35.3024 dB/wavelength respectively. Therefore, crossbar-based architectures such as Corona [3], decomposed crossbar based architectures such as Firefly [4] and 3D-NoC suffer from scalability issues for large core counts. Multi-hop networks with smaller crossbars such as Clos-based networks could be better suited for scaling the core counts; however they suffer from higher latency due to multiple hops. While all prior architectures have been proposed for lower cores (64-256), ATAC is the only optical architecture that has been proposed for 1024 cores. ATAC reduces the hardware cost by designing electrical hubs for smaller cores (16) and broadcasting flits to all destinations from the hub. Therefore, ATAC suffers from both high power (broadcasting, electrical hub) and delay.

On-chip radio-frequency (RF)/wireless NoCs have been proposed in [2], [7], [8] for scaling to large core counts. WiNoC offers several advantages, such as CMOS compatibility, distance-independent communication, multicasting, and broadcasting which help to lower power consumption by reducing hop count. Frequency division multiplexing (FDM), time division multiplexing (TDM), and space division multiplexing (SDM) can be combined to increase the overall wireless bandwidth. However, wireless technology suffers from several disadvantages, such as (1) higher transceiver area and energy/bit and (2) lower wireless bandwidth at 60 GHz frequency. Therefore, several wireless architectures are designed as a two-tier hybrid wireless architecture where wireless is used to connect subnets (a group of cores) and each subnet is

978-1-4673-9160-3/15 $31.00 © 2015 IEEE
DOI 10.1109/HOTI.2015.14

connected using wired mesh or fully connected networks [8], [9], [2]. Among all the wireless architectures, only WCube has been proposed for 1024-cores by increasing the size of the subnets to 64. This forces all 64 cores to share a single wireless transmitter which causes hot-spots. Moreover, the wireless communication is multi-hop as the subnets are arranged as a hypercube. Further, the frequency spectrum cannot be reused due to the nature of frequency sharing among different subnets.

In this paper, we uniquely combine two emerging technologies namely optics and wireless to design a scalable architecture called Optical-Wireless Network-on-Chip (OWN). We propose to design decomposed crossbars for clusters of 64 cores where 16 routers share optical bandwidth and enhance locality. This allows OWN to maximize the efficiency of lasers (as these are always on), reduce latency (while waiting for tokens) and reduce insertion losses (shorter waveguides). Wireless technology is utilized to interconnect the clusters wherein we reduce the hop count, improve performance and economically utilize the wireless bandwidth. The combined impact is that we can build kilo-core architecture using a maximum of three-hops for any-to-any core communication. Our results indicate that OWN consumes 30.36% less energy, and improves throughput by 8% over wireless architectures and obtains 35.5% less area than optical architectures.

II. RELATED WORK

In this section, we briefly discuss prior work relevant to our proposed architecture. Early NoC architectures have been predominantly two-dimensional mesh, torus and concentrated mesh (CMesh) topologies [10]. As metallic NoCs faced limitations, emerging technologies were proposed to overcome the drawbacks of traditional NoCs. One of the earliest wireless NoC architecture proposed is WCube [2]. WCube extends the CMesh architecture using wireless routers for every group of 16 routers, and wireless is used only for long distance communication. The frequency spectrum of operation is 100-500 GHz and an energy of 4.5 pJ/bit was proposed for wireless link. WCube uses polyimide on top of silicon to reduce the substrate loss and amplitude shift keying (ASK) as the modulation scheme. Other architectures such as WiNoC [8] and iWISE [9] use wired technology for smaller groups/sets of routers and wireless for longer distance using on-off keying (OOK) modulation. Wireless channels are shared using tokens by combining time division multiplexing (TDM) and frequency division multiplexing (FDM). There has been considerable interest in using photonics for NoCs and early optical NoCs mostly use global photonic crossbar and wavelength division multiplexing (WDM) [11], [3], [4], [12]. Some architectures use electrical networks for local communication. One such architecture, ATAC [12] implements a global optical crossbar to connect the hubs using SWMR where each hub is placed at the center of an isolated 16-core electrical mesh block. It uses off-chip laser as the light source and requires buffering and arbitration at the receiving hub. As compared to several proposed architectures that use emerging technologies, OWN combines both photonic and wireless technology within the same architecture for the first time.

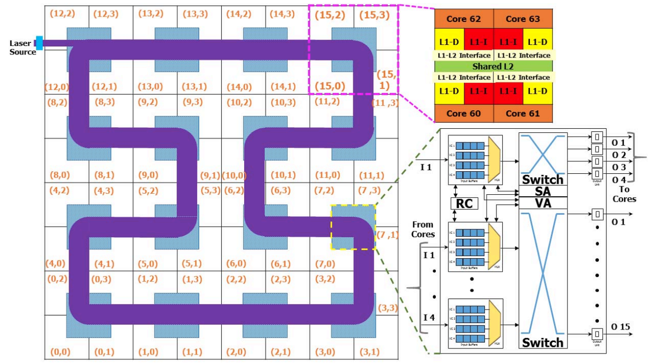

Fig. 1. shows the 64-Core OWN architecture, connected by 16×16 optical crossbar with inset showing a tile and the proposed optical router.

III. THE PROPOSED ARCHITECTURE: OWN

This section explains the proposed OWN architecture. First, we describe the design of 64-core OWN architecture using optical technology. Second, the 64-core OWN will be used as the basic building block for designing 1024-core using wireless technology. Third, we explain the routing mechanism with examples. Fourth, as the 1024-core architecture using wireless technology is prone to deadlocks, we will propose techniques to ensure deadlock freedom.

A. 64-Core OWN architecture: Cluster

The OWN architecture is a tile-based architecture with each tile consisting of four processing cores and their private L1 instruction and data caches, a shared L2 cache and a network interface or router. The inner components of a tile are shown in Figure 1 for the four cores connected to router 15 (upper-right-most tile). Each tile is located within a *cluster*, which consists of 16 such tiles (64 cores). The tiles inside a cluster are represented by two coordinates (r, c) where r is the number of the tile or the router and c identifies one of the four cores in that tile. These tiles are connected by a 16 × 16 optical crossbar which is the snake-like optical waveguide and takes one hop for core-to-core communication, as shown in Figure 1. We propose multiple-write-single-read (MWSR) scheme with arbitration wherein each tile is assigned dedicated wavelength(s) to receive messages from the remaining 15 tiles. On the other hand, SWMR scheme requires high laser power as one router writes to its assigned channel and all the remaining routers can read by peeling off a portion of the wavelengths [4]. We chose MWSR over SWMR to reduce the laser power consumption, however the power consumption can be reduced even in SWMR by tuning only the intended receiver [4]. The tradeoff in using MWSR is increased latency since each router must wait to grab the token before writing to a specific channel. As there are 16 routers inside the cluster and communication between the routers require only one hop, we argue that this latency will not dramatically affect the performance. So, any one of the 15 tiles of 64-core OWN architecture can write to the other tiles such that all the 16 tiles can read at the same time in their assigned wavelength(s). Thus, each cluster requires two waveguides. For example, core (0, 3) wants to send a packet to core (15, 2). Router 0 will wait for the token to modulate the wavelength(s) assigned to router 15. Having the token, router

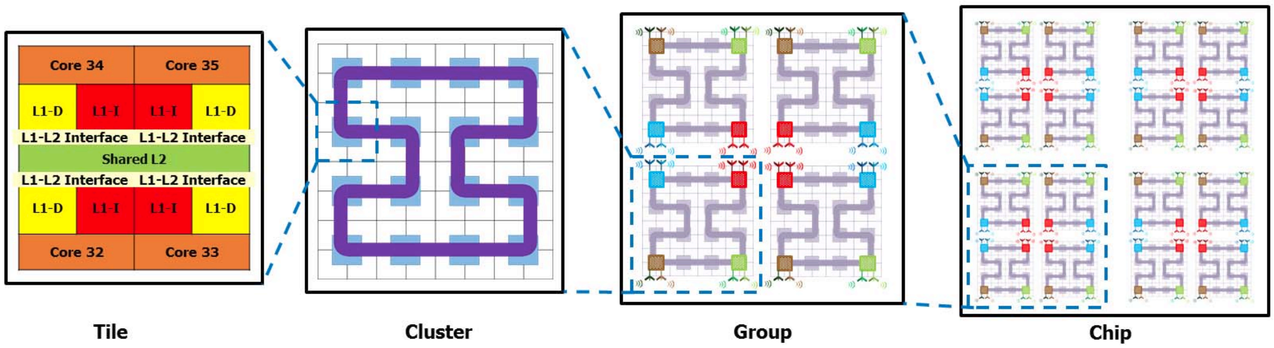

Fig. 2. The basic building block is a tile; sixteen tiles form a cluster; four clusters form a group and four groups form the 1024-core OWN architecture.

0 will modulate the appropriate wavelength(s) to router 15 as shown in Figure 1. In addition, an arbitration waveguide is used to arbitrate between multiple routers wanting to transmit to the same receiver, so that signal integrity is maintained.

B. *1024-core OWN architecture: Cluster and Group*

The building blocks of 1024-core OWN architecture is shown in Figure 2. As explained before, sixteen tiles form a cluster, four clusters form a group, and four groups form the 1024-core OWN architecture. Intra-cluster communication is implemented using optical interconnects. Inter-cluster or intra-group and inter-group communication is facilitated using wireless interconnects. Starting at the top level, as we have four groups, twelve ($^4P_2$) unidirectional frequency channels are required for inter-group communication. Unique pairs of frequency channels are assigned for communication between each pair of groups. So, each group needs three frequency channels to send packets to the rest of the group (horizontal, vertical, and diagonal group). Each cluster inside a group is assigned three transmitter antennas matched at those frequencies employing TDM. This ensures that only one of the four clusters inside the group can send data using the shared channel to a destination group at a time. Similarly, each cluster has three receiver antennas tuned at the frequencies of other groups, but we implement it as a multicast due to lack of wireless bandwidth. All four clusters can receive messages from a sender at the same time and then decide whether to keep or discard the packet. Inside a group, the four clusters are connected using a 32 Gbps frequency channel. This frequency channel is shared by the four clusters of a group where only one of them can write but all of them can receive simultaneously. Therefore, each cluster of a group will have four transceivers: one for intra-group communication, and three for inter-group communication.

The four corner routers of each cluster (Figure 1) is chosen for the on-chip wireless communication. The complete architecture for 1024-core is shown on Figure 3. The red transceivers connected with the routers A, B, C, and D indicate the intra-group wireless communications between the clusters of group 0, 1, 2, and 3 respectively. Only the routers for the intra-group communications contain the transmitter and the receiver both tuned to the same frequency. For example, the intra-group wireless routers A, B, C, and D have transceivers tuned to frequency channels F00, F11, F22 and F33 respectively. Routers for the inter-group communication contain a

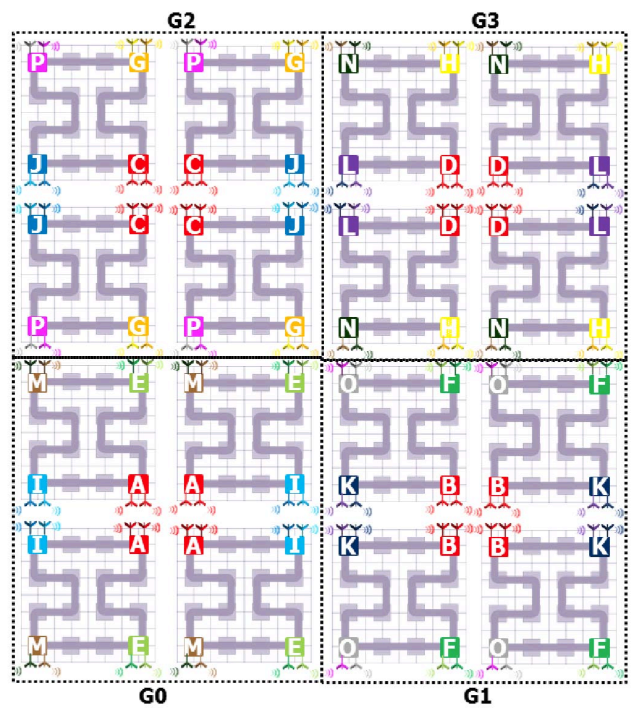

Fig. 3. Kilo-Core OWN architecture. Routers with same letter share a frequency channel and Fxy represent a wireless channel to send packets from group x to group y. For example, Routers A, B, C, D share the intra-group wireless channel F00, F11, F22, F33 respectively. Routers E, F, G, H require four inter-group wireless channels F01, F10, F23, F32 respectively to communicate with the horizontal group. Routers I, J, K, L require four inter-group wireless channels F02, F20, F13, F31 respectively to communicate with the vertical group. Routers M, N, O, P require four inter-group wireless channels F03, F30, F12, F21 respectively to communicate with the diagonal group.

transmitter tuned to the frequency assigned to that group for communicating with the other groups and a receiver tuned to the frequency of the sender group. For example, each of the four inter-group wireless routers E of group 0 in Figure 3 contain a transmitter tuned to frequency F01 and a receiver tuned to frequency F10. Similarly, for communicating with the diagonal groups, each router P of group 2 contains a transmitter tuned to frequency F21 and a receiver tuned to the transmitting frequency of group 1, F12. From Figure 3, it can

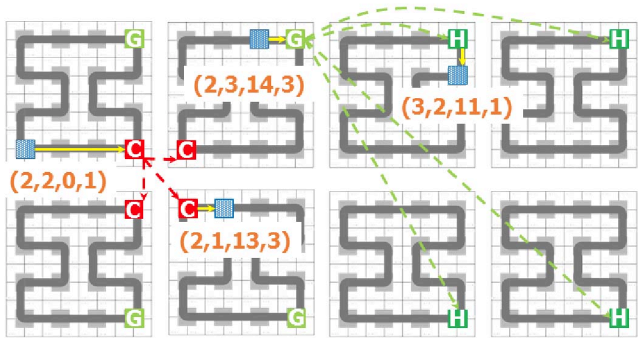

Fig. 4. Intra-cluster Intra-group and Inter-group transmission on 1024-core OWN architecture. The dotted lines represent wireless link where the solid lines represent optical link. Routers of the same letter share same frequency channel.

be seen that only the frequency channels assigned for the intra-group communications can be reused employing SDM. This replaces the need of four intra-group frequency channels F00, F11, F22, and F33 with only one wireless channel, F0. Hence, we require a total of thirteen, 32 Gbps frequency channels for the proposed OWN architecture, more details on the wireless technology is explained in Section 4.

C. Intra-Group and Inter-Group Communication

Consider Figure 4 for the detailed communication pattern. Each core in 1024-core OWN is identified by a 4-digit co-ordinates with *group*, *cluster*, *router*, and *core* number. It is represented as (g, cs, r, c) where g is group, cs is cluster, r is router, and c is core number. The total number of cores in OWN is $g \times cs \times r \times c$, where 0 $\leq$ g $\leq$ 3, 0 $\leq$ cs $\leq$ 3, 0 $\leq$ r $\leq$ 15 and 0 $\leq$ c $\leq$ 3. For example, core (2, 2, 0, 1) is in group 2, cluster 2 (top-left inside a group), and at the first tile (router 0). If it wants to send packet to core (2, 1, 13, 3), then it is an intra-group communication. The packet from the source router will be sent to the right-most corner router (2, 2, 3), using optical link when it has the token to write. Once the packet arrives at the router (2, 2, 3), the router will wait for the intra-group frequency channel, F0. Once it has the right to transmit, router (2, 2, 3) will broadcast the packet to the other three routers residing in the three clusters of group 2 who are assigned the intra-group wireless frequency. Only the router (2, 1, 12) at the destination cluster will accept the packet and the remaining two routers will discard the packet. Then router (2, 1, 12) will send the packet to the destination router (2, 1, 13) over the optical link when it has the token to write to the wavelengths assigned to (2, 1, 13). This will require three hops - one optical, one wireless and one optical. Let's consider inter-group wireless communication between horizontal groups with source core (2, 3, 14, 3) and destination core (3, 2, 11, 1). The source core (2, 3, 14, 3) will insert the packet to the router (2, 3, 14). This will send the packet to (2, 3, 15) using optical link after receiving the token. Router (2, 3, 15) will contend for the wireless channel F23 with the three other routers (G) in that group. Once it has the permission to use the channel F23, the packet will be broadcasted to all the four routers (H) of group 3 in the four different clusters. Only the router (3, 2, 15) at the destination cluster will accept the packet. It will then send the packet optically to the destination router (3, 2, 11). This communication will also take three hops. So, the minimum hop count is one (optical, intra-cluster) and the maximum hop count is three (optical-wireless-optical, inter-cluster) for 1024-core OWN architecture. The lower diameter of OWN contributes to lower energy and latency. Another underlying advantage of OWN is scalability. In this architecture, we have reused the intra-group frequency. By restricting the antenna beamwidth, inter-group horizontal and vertical wireless links can be reused employing SDM. Moreover, for very large number of cores, diagonal wireless channel can be reused where we might not need to restrict the antenna beamwidth. This can be a future work.

D. Deadlock Free Routing

There are two types of communication in OWN architecture: intra-cluster (optical) and inter-cluster (wireless). *Both these types of communication in isolation does not create deadlocks, however when these two communication are taken together, then deadlocks are likely to occur*. From Figure 5(a), A, B, C, and D are four packets where A, C are intra-group and B, D are inter-group packets. Packet A originates at router (2, 2, 15), takes the optical link to (2, 2, 3) and reaches intra-group wireless-network-router (2, 3, 0), and then arrives the destination (2, 3, 15) via optical link where it exits the network. Similarly, travel path of packet C is: (3, 2, 15)-optical link-(3, 2, 3)-intra-group wireless link-(3, 0, 15)-optical link-(3, 0, 3). Inter-group packet B originates at router (2, 3, 0), via optical link reaches (2, 3, 15), takes inter-group-horizontal wireless link to (3, 2, 15), and then arrives the destination (3, 2, 3) via optical link where it exits the network. Similarly, the travel path of the other inter-group packet D is: (3, 0, 15)-optical link-(3, 0, 3)-inter-group horizontal wireless link-(2, 2, 15)-optical link-(2, 2, 3). All the packets require three hops to reach their respective destination router from the source router. Either A, C or B, D alone does not create any deadlock, but simultaneous transmission of A, B, C, and D creates circular dependency. Another case of deadlock that includes inter-group vertical and horizontal wireless communication with intra-group wireless communication is shown on Figure 5(b).

There are different types of deadlock avoidance techniques such as distance class or dateline class [13]. To avoid deadlocks, in this paper, we have followed a form of dateline class. Each router of OWN has 4 virtual channels (VCs) associated with each input port. We restrict the VC allocation for each type of communication. Both intra-cluster and intra-group transmission use VC0 only. Rest of the VCs, VC1, VC2 and VC3 are assigned to the flits requiring inter-group horizontal, vertical and diagonal transmission respectively. These VC assignments are followed throughout the lifetime of the packet in the network. Due to this restricted VC allocation, input buffers will not be utilized completely and might contribute to the increase in latency and decrease in throughput. The proposed deadlock avoidance ensures that all packets reach their intended destination.

IV. Technology: Wireless and Optical

In this section, we discuss the technology used to implement the proposed architecture. Except for wireless and optical sections, bulk 45 nm LVT technology is used for all the other electrical components like wire link, router.

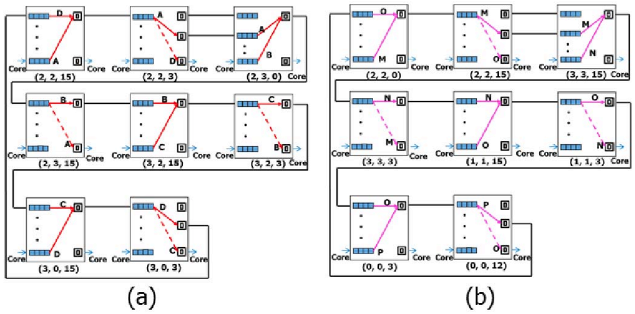

Fig. 5. Possible deadlock scenarios in a 1024-core OWN. Deadlock creation between groups using (a) inter-group-horizontal wireless link and (b) inter-group horizontal and vertical wireless link;

TABLE I. OPTICAL DEVICE PARAMETERS [19], [20], [21].

Parameter	Value
Waveguide Pitch	4um
Ring Resonator Diameter	12um
Wavelengths/Waveguide	64
Waveguide Loss	1.0 dB/cm
Pass-by Ring Resonator Loss	0.0001 dB
Photo-detector Loss	1.0 dB
Splitter Loss	0.2 dB
Modulation Loss	1.0 dB
Demodulation Loss	1.0 dB
Receiver Sensitivity	-17dBm
Laser Efficiency	15%
Ring Heating Power	26uW/ring
Ring Modulating Power	500uW/ring
Ring Modulation Frequency	10GHz

A. *Wireless Technology*

Although continuing progresses in CMOS technology has made the higher frequency operation in mm-wave possible, thereby reducing the antenna size to a scale suitable for on-chip implementation, low gains due to low Si substrate resistivity is one of the challenges of wireless communication [14]. In our design, monopole antenna is considered. Because, monopole antennas radiate horizontally in all the directions which is necessary for broadcasting or multicasting. Additionally, monopole's ground separates the substrate from the antenna, reducing the substrate's effects on the antenna and enhancing radiation efficiency. The antennas are fabricated at the top most layer of the chip. To enclose the chip a nonmetallic ceramic cover can be used, which can help also the thermal insulation and reduce multi-path and dispersion concerns.

In our design, each wireless channel has a bandwidth of 32 Gbps. Since we have 16 wirelessly communicating pairs, 16 wireless channels are required. The distances between different types of communicating antennas are different. As shown in Figure 3, the intra-group antennas have lowest distances while the inter-group-diagonal antennas have highest distances. Required transmission power can be varied in accordance to the distance covered which allow reuse of a frequency channel on the same chip without interference [9]. The maximum distance between the intra-group wireless transceivers is around 1.77 mm (assuming router-router spacing 1.25 mm with 0.625 mm spacing between the side cores to the edge of the chip). The minimum distance between intra-group wireless routers located in two different groups is around 8.75 mm. Hence, *the minimum separation between intra-group antennas of different groups is almost five times the maximum radiating distance of an intra-group transmitter*. Hence, only one frequency channel can be used for all the intra-group wireless communications i.e. F00, F11, F22, and F33 can be replaced by one wireless channel say F0. Due to the application of SDM in our design, the total number of wireless channels required will be reduced from 16 to 13. So, in total approximately 416 Gbps wireless bandwidth is required which is achievable [2]. For modulation, OOK is chosen due to low power consumption nature. Thus, each wireless link require three pairs of transmitter and receiver with each transmitting at ~10.7 Gbps [9].

Today mm-wave circuits are already being implemented at 65 nm or smaller CMOS technology nodes in many fabrication facilities [15], [16], [17]. With the advances of CMOS technology and scaling, higher frequency of operation with lower power and area requirement may be possible. From our simulations, the foot print of transmitter antenna is 0.42 mm2 and receiver antenna is 0.20 mm2 at 65 nm technology. Based on current trends in fabrication, wireless link power efficiency could possibly reach about 1 pJ/bit [7] which we have also considered in our paper. Moreover, application of the double-gate MOSFETs (FinFETs) may lower the threshold voltage of the transistor which will help to reduce the supply voltage and as a result power dissipation. Additionally, a power reduction of three times may be projected for RF wireless transceivers built using 22 nm technology, thanks to smaller passives, improvements in nano-materials and transistor off-currents, and lower losses in ultra-thin Si devices that can be transfer printed onto high-resistivity carrier substrates. With this admittedly optimistic outlook, we believe we can reach and even drop below 1pJ/bit efficiency for wireless links to be used in the above implementation.

B. *Photonics Technology*

Optical transmission requires the presence of optical waveguide and ring modulators. Each waveguide contains 64 wavelengths. Our proposed architecture OWN applies WDM to communicate via the optical waveguide. The modulators can modulate the wavelengths at 10 Gbps using electro-modulation [18]. Since except the optical waveguide all the on-chip components are electrical in nature, we need electrical-to-optical and optical-to-electrical converters at both side of the optical transmission line. To convert the electrical signal to optical signal, photodiodes can be used and to convert the optical signal to electrical signal, photodetectors and cascaded amplifiers can be used. The technological parameters used in this paper are shown in Table I.

V. PERFORMANCE EVALUATION

To evaluate the performance, we have compared the proposed architecture OWN with CMesh [10], WCube [2] and ATAC [12] architectures. We have used Dsent v. 0.91 [22] to calculate the area and power of the wired links and routers. To simulate network performance for different types of synthetic traffic patterns such as uniform (UN), bit-reversal (BR), complement (COMP), matrix transpose (MT), perfect shuffle (PS),

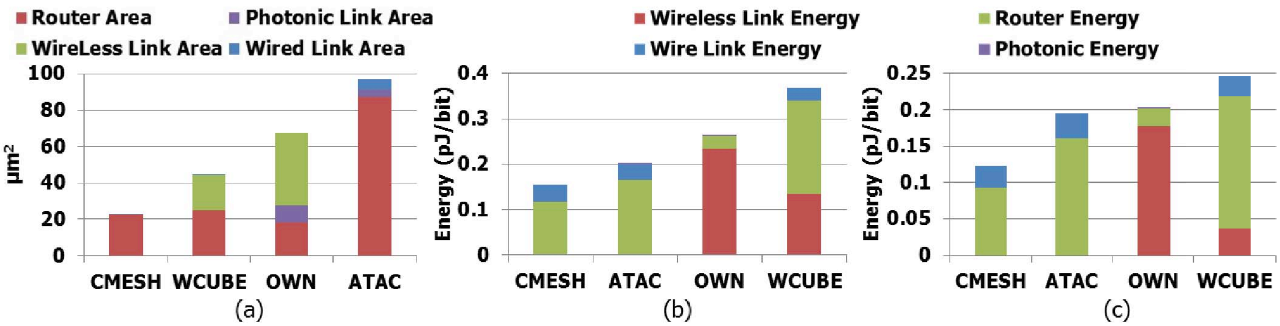

Fig. 6. Area and energy comparison between different topologies. (a) Topology layout area. (b) Energy per bit for uniform traffic pattern. and (c) Energy per bit for perfect shuffle traffic pattern. This energy calculation includes leakage power loss.

and neighbor (NBR), we have used a cycle accurate simulator [23] keeping the clock period same for all the networks. In order for a fair comparison between different topologies, we have kept the bisection bandwidth same for all the architectures by adding appropriate delay. In case of ATAC and OWN, the architectures are not completely symmetric. We believe for fairness, bisection bandwidth of the wired links for ATAC and bisection bandwidth of the optical links for OWN should also be considered while calculating the overall bisection bandwidth of the architecture.

A. Area

Area of an architecture consists of link (wired, wireless, and optical) area, and router area. As shown in Figure 6(a), ATAC acquires the highest area which is 35.5% higher than OWN whereas WCube and CMesh acquires 34.14% and 66.53% less area respectively compared to OWN. CMesh and OWN both have 256 routers with core concentration of 4, ATAC has 1024 routers with core concentration of 1, and WCube has 256 routers with core concentration of 4 and 16 wireless routers connected with 4 other routers. The main reason of ATACs area being highest is the use of very large number of routers. Another fact contributing to the large router area can be the high radix of the hubs. During the area calculation of ATAC, instead of calculating the hub area for 67×2 RADIX, we have split the switch into two 4×1 and 63×1, and then added the corresponding area. Although WCube has higher number of routers in total than OWN, OWN has 4x transmitter antennas than WCube. Because of this, OWN requires more area than WCube. As photonic link area consists of the power, data and arbitration waveguide area, it is higher than the traditional wire link area. Since ATAC and OWN contain photonic link, it has contributed to their area more than the wired link in CMesh and WCube.

B. Energy

While calculating the wired link energy consumption, we have multiplied the number of times each wired link traversed collected from the cycle accurate simulation to the corresponding wired link energy found using Dsent. In case of ATAC, since the receiver hub broadcast the flits to all the cores under that hub, we have multiplied the energy consumption of one hub to core link by 16. For wireless link, we have assumed a fixed 1 pJ for each bit transmission for both WCube and OWN. Although WCube used 4.5 pJ/bit in their paper, we think this is a technology based parameter and for fairness, all the wireless topologies have the same wireless energy cost. During the calculation of optical link energy consumption, we have considered the worst case scenario. Table I lists the parameters value used. For OWN we have also included the arbitration energy consumption. While calculating the router energy consumption we have divided the buffer power with the number of buffers and crossbar power with the radix since Dsent gives the total buffer and crossbar power.

Figure 6(b, c) shows the energy per bit comparison for uniform and perfect shuffle traffic patterns (other patterns have been omitted due to space restrictions). For both cases, WCube consumes less wire energy since it uses wireless for distant transmission. On the other hand, CMesh has higher wire link energy than WCube. As ATAC uses wired mesh from source router to the hub and broadcasting at the receiving end, wired link energy is higher. OWN consumes lowest router energy. This is due to the lower radix of the split router and moreover, OWN requires only three hops. Further, increasing the router radix decreases the energy consumed when compared to using multiple router traversals [24]. WCube has a higher radix than CMesh which is why it dissipates higher energy compared to CMesh. ATAC has the highest number of routers among the four but still it consumes less router energy than WCube. This is because WCube shares a single router with 64-cores whereas ATAC shares the router with only 16-cores. From the Figure 6(b, c), we can see that the majority percentage of OWNs energy is wireless link energy. WCube has lower wireless link energy requirement than OWN as it employs wireless only for distant packets where OWN uses wireless for all the inter-cluster transmission whether they are neighbor or not. Figure 6(b, c) shows that OWN costs 23.2% higher energy/bit than ATAC and 40.2% less energy/bit than WCube for uniform traffic and only 3% higher energy/bit than ATAC and 21.2% lower energy/bit than WCube for perfect shuffle traffic. The energy overhead of OWN is mostly because of wireless link. The reduction of energy per bit of WCube from uniform to perfect shuffle is due to the use of lower wireless link which is also true for OWN. However, the wireless energy per bit requirement is technology dependent and as advances in technology is made, OWN will greatly benefit due to the reduction of this parameter in terms of energy consumption over the other architectures compared.

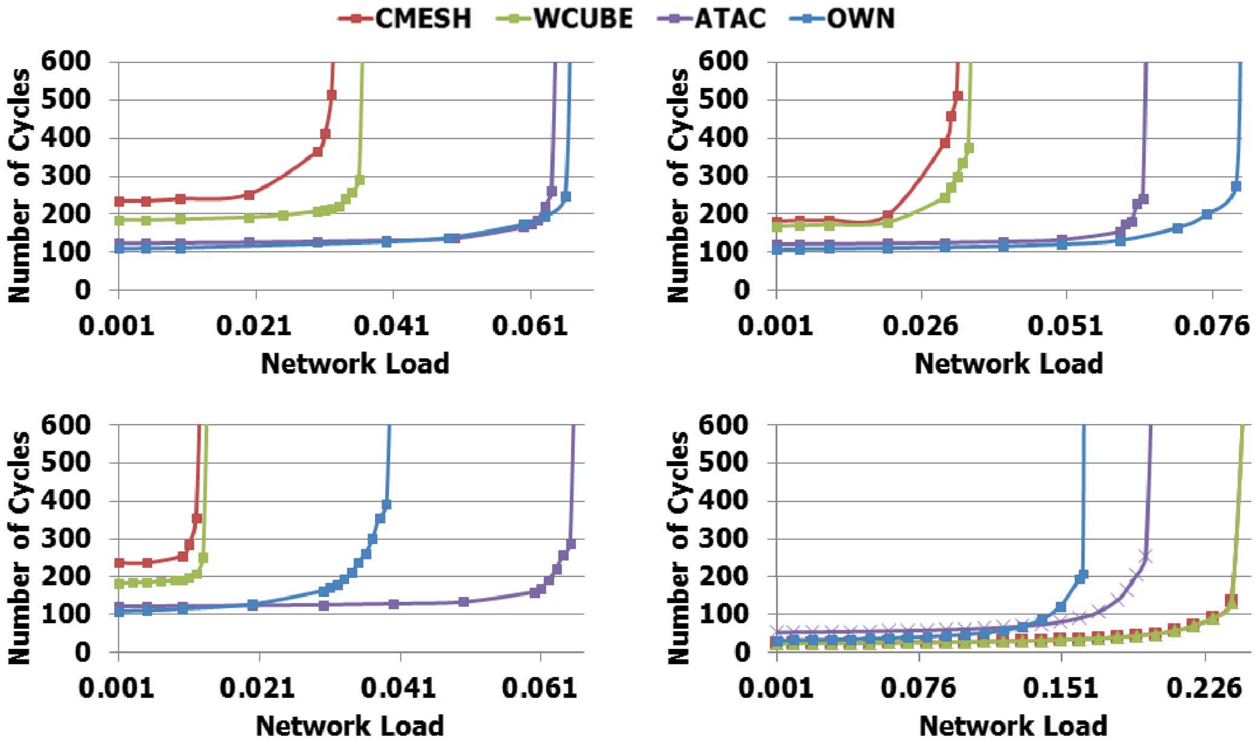

Fig. 7. Latency shown as Network Load vs. Number of Cycles for various types of synthetic traffic. (Top-left) Uniform, (Top-right) Bit-reversal, (Bottom-left) Matrix transpose and (Bottom-right) Neighbor

C. Saturation Throughput and Latency

In this section, we briefly discuss the latency and saturation throughput of OWN compared to CMesh, WCube and ATAC. WCube is an extension of CMesh and takes wireless link to transmit packets requiring higher wired hops. To provide the best performance, we have optimized the distance where to take the wireless link instead of wired link during simulation. We have counted the number of wired and wireless hop required for each pair of source and destination cores, and varied the difference between them to find out the best position to take the wireless link. To imitate ATAC as closely as possible, we have subtracted the buffer and crossbar delay for the flits travelling from the destination hub to the cores to represent the broadcast scheme. For fairness, we have kept the same number of VC and buffer for all the architectures. Figure 7 shows the latency for the traffic types UN, BR, MT and NBR as a measure of number of cycles in response to a varied network load. For the uniform and bit-reversal traffic shown in Figure 7 (top-left and top-right), OWN performs the best. This is because OWN requires only three hops to transmit to any part of the network. ATAC requires higher number of hops than OWN but lesser than CMesh and WCube. Since WCube uses wireless for distant source-destination pairs, it performs better than CMesh. For matrix transpose traffic, ATAC performs best whereas for neighbor traffic OWN shows the worst performance as shown in Figure 7 (bottom-left and bottom-right). In case of neighbor traffic, the source and destination cores are close to each other and this is why CMesh and WCube perform better than the rest. Since OWN requires token to send packet every time, its performance is affected.

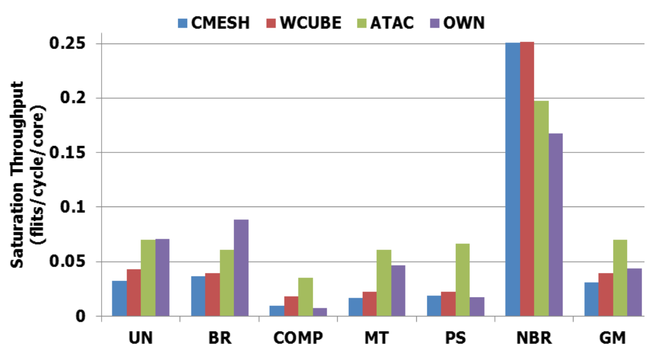

Fig. 8. Saturation throughput for various types of synthetic traffic pattern

ATAC shares a hub with 16 routers which are connected using wired mesh topology. So, the packets only need to wait for using the global optical channel and the received packets are broadcast to all the hubs. For matrix transpose, source row and column are interchanged to form the destination. As OWN requires token for every transmission which ATAC does not need, ATAC performs better than OWN. Figure 8 shows the saturation throughput for various synthetic traffic types where GM represent the geometric mean. Although ATAC has highest saturation throughput, OWN out performs WCube and CMesh by 8% and 28% respectively.

VI. Conclusions

The proposed OWN architecture has integrated two disruptive technologies: wireless and photonic. OWN requires less area than state-of-the-art optical architecture ATAC but higher area than state-of-the-art wireless architecture WCube. With advances in CMOS technology, the transceivers and photonic link area may reduce which will benefit OWN. In terms of energy per bit, OWN consumes more energy for transmitting each bit than ATAC and less than WCube. It is mostly because of the comparatively higher wireless energy. Since photonic link consumes low energy, the combination of wireless with photonics will balance the overall energy cost. As wireless technology progresses, the decrease in wireless energy per bit will reduce the energy overhead of OWN. In case of latency and throughput, OWN has higher saturation throughput than the CMesh and WCube but lower than ATAC. It shows lower latency than all the comparable topologies for some traffic patterns. The true advantage of wireless is the flexibility is creating dynamic connections between clusters. On-demand connections can be easily designed using wireless technology rather than hard-wired waveguides using optics which will allow OWN architecture to scale to large core counts with comparable performance and reduced energy per bit. This flexibility of using wireless technology for diverse traffic patterns will be explored in the future.

Acknowledgment

This research was supported by the US National Science Foundation (NSF) awards CNS-1547034, ECCS-1342702, CCF-1547035, CCF-1547036, CCF-1054339 (CAREER), ECCS-1129010, CCF-1318981, ECCS-1342657, and CCF-1420718. We would like to thank all the anonymous reviewers for their valuable comments on the paper.

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