A Novel Optical Mesh Network-on-Chip for Gigascale Systems-on-Chip

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***Abstract*—Nanoscale CMOS technologies are posing new network-on-chip (NoC) concepts to gigascale system-on-chip (SoCs). However, electronic network on chip designs face several problems like energy consumption, bandwidth and latency. Optical NoC (ONoC) promises to solve these problems. The advances in nanoscale photonic technology make ONoCs possible. This paper proposes a new non-blocking optical router, OXY, and uses it to build a 2D mesh ONoC. OXY based optical mesh NoC fully utilizes the properties of XY routing in 2D networks, and significantly reduce the number of microring resonators required for ONoCs. We compared OXY based optical mesh NoC with three other schemes in number of microring resonators, loss and energy consumption. The results show that OXY based optical mesh NoC achieves the best in all the comparisons. We simulated 2D optical mesh ONoC based on OXY, and showed the end-to-end delay and throughput under different traffic loads and network sizes.**

I. INTRODUCTION

As the scale of the transistors enters nanometer regime, the number of transistors on a single chip increases to billions or even larger numbers. Traditional on-chip communication techniques for systems-on-chip (SoCs) face several issues, such as poor scalability, limited bandwidth, low utilization, and so on. Networks-on-chip (NoCs) promise to relieve these issues by modern communication and networking theories [1][2]. Many NoCs have been proposed, such as ASNoC [3], Nostrum [4], Æthereal [5], and etc. However, as semiconductor technologies continually scale the feature sizes down and the on-chip communications required by new applications increases, the conventional metallic interconnect is becoming the bottleneck of NoC performance with limited bandwidth, long delay, and high power consumption. Therefore, electronic NoC will not satisfy the bandwidth and latency requirements within the power consumption budget of future gigascale SoCs [6][7][8].

Optical NoC (ONoC) is based on optical routers and interconnects, and is a promising candidate to overcome these limitations. Before applied to NoC, optical interconnect has found applications in multicomputer systems, on-board inter-chip interconnect, and switching fabrics in Internet routers. When applied to nanoscale gigabit systems, changes should be made accordingly. Mesh topology is widely used for electronic NoCs for its simple layout. It consists of a grid of horizontal and vertical links with nodes placed at their intersections. The regular topology of mesh is suitable for minimal routing algorithms. Router is the basic unit to build an interconnect network. Several optical on-chip routers, which are based on microring resonators [8], are proposed in literature. λ-router is proposed in [9], which uses N wavelengths and multiple basic 2x2 switching elements to realize NxN non-blocking switching function. Another non-blocking router is proposed in [10]. It is based on a 2x2 switching element to implement a 4x4 router. Since typical 2D NoCs use 5x5 routers, the 4x4 router is augmented by extra ports for local injection and ejection. It is an improvement over the previous design [11]. The improved router architecture optimizes the architecture and solves the blocking issue.

Both of the routers in [10][11] are demonstrated in the networks using XY routing. In XY routing, each packet is routed first in X dimension until it reach the node, which is in the same column with the destination, and then along the perpendicular Y dimension to the destination. XY routing is a minimal path routing algorithm and is free of deadlock and livelock. In addition, it is a low-complexity distributed routing algorithm without any routing table. These features make XY routing algorithm particularly suitable for NoCs, which require low latency and low cost at the same time. Many practical systems have been using it [12], and it has also been favored by many NoC studies [13] [14][15][16].

In this paper, we propose a new router, OXY (Optical XY routing) router, for ONoCs using XY routing algorithm. With OXY, an optical mesh NoC is built up. Compared with other schemes, OXY based optical mesh NoC requires the least number of microring resonators, consumes the least power, and has the lowest optical power loss. It has been designed to take advantages of the properties of XY routing. To save power and reduce optical power loss, the microring resonators are active only when packets need to make turns.

II. OXY ROUTER ARCHITECTURE

Optical routers are the key components of an ONoC. They implement the routing and flow control functions. An optical router switches packets from an input port to an output port

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using a switching fabric, which is composed of multiple basic switching elements. We proposed a new optical router, OXY, for ONoCs based on XY routing algorithm, as is shown in Figure 1. It consists of a switching fabric and a control unit which uses electrical signals to configure the switching fabric according to the routing requirement of each packet. The control unit is built from traditional CMOS transistors and uses electrical signals to power on and off each microring resonators. The control units of all the OXY routers in an ONoC use an electronic network to setup and maintain optical paths.

The switching fabric is built up by microring resonators (MRs), which have the same on-state and off-state resonance wavelengths, λ_{on} and λ_{off}. The optical signals just use one wavelength which equals to λ_{on}. The on-off state change of MR will guide the optical signals to different ports. The switching fabric implements a 5x5 switching function, which uses only 12 microring resonators and 6 waveguides. We can also replace the last resonator on the waveguide for the injection port with a Y-branch. Although this reduces the number of resonators and saves power, more loss will be encountered by packets which exist from the east port. Compared with the crossbar, OXY uses not only the basic 1x2 switching elements with the crossing waveguide structure, but also those with the parallel waveguide structure to reduce the waveguide crossing insertion loss. Furthermore, the internal structure of the switching fabric is designed to minimize waveguide crossings.

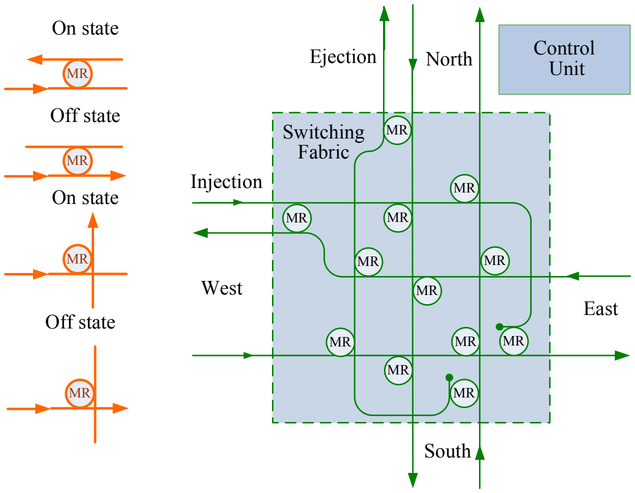


Figure 1. OXY architecture

OXY architecture has an excellent feature. Regardless of the network size, the maximum power to route a packet through an optical mesh NoC based on OXY is a constant number. As we will see in the following section, the constant number is very small and close to the average power consumption. Hence, OXY based optical mesh NoC can scale to large size without worrying about energy increase. The feature is designed by avoiding any resonator switching activity for routing packets between the two horizontal ports and the two vertical ports in the OXY architecture. The design makes that at most three OXY routers need to power on one resonator each for any packet in a network of any size.

For ONoCs using XY routing algorithm, OXY router is strictly non-blocking. This can be proved by listing all the possible cases. For example, when a packet is injected from the injection port to the east port, it will not block packets from west to south, west to north, south to north, or north to south.

III. OPTICAL MESH NOC

A. *Network architecture*

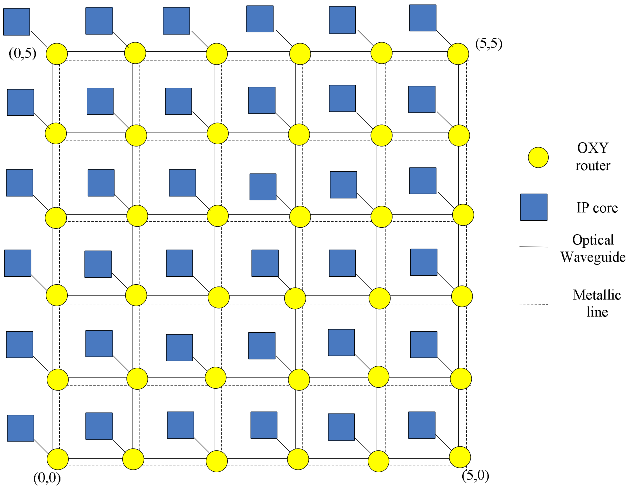


Figure 2. OXY based 6x6 mesh ONoC

With OXY, we build a mesh ONoC, as is shown in Figure 2. The ONoC consists of two overlapped networks, an optical network for large payload packets and an electronic network for control packets and small payload packets. Payload packets carry data and processor instructions, while control packets carry the network control information. The electronic network connects the control units of all the OXY routers in the same topology as the optical network. In general, the topologies of the two networks can be different. For example, torus can be used for the optical network by adding a waveguide to each pair of end routers. The optical and metallic interconnects are all bidirectional. While the optical interconnects are 1-bit wide on each direction, metallic interconnects are 32-bit wide on each direction.

B. *COMPARISON AND ANALYSIS*

We compared the mesh ONoC built from different optical router architectures including OXY, λ-router, crossbar, and the router proposed in [11], which is referred to as CR for clarity. We compared and analyzed three main aspects, including the power consumptions, optical power insertion losses, and areas in terms of the numbers of microring resonators. Since regular 2D mesh topology requires 5x5 routers and the λ-router architecture prefers the even number of input and output ports, a 6x6 λ-router is used in the comparison with one pair of idle input and output ports.

The number of microring resonators used by an optical mesh NoC decides its area cost along with its floorplan.

Lower number of resonators indicates a lower chip cost by reducing die size and increasing yield. We compared the numbers of resonator required to build a 9x9 optical mesh NoC by the four optical router architectures in Table I. OXY uses the lowest number of resonators, 972, which is 52% less than the full-connected crossbar. λ-router requires the highest number of resonators mainly due to the multistage switching structure. Crossbar has the second largest number of resonators. CR also requires a relative large number of resonators because of the additional accessing point blocks to implement the 5x5 switching function.

Power consumption is a critical aspect of ONoC design. For high-performance computing, low power consumption can reduce the cost related with packing, cooling solution, and system integration. ONoCs consume power in three ways. First, ONoC interfaces consume power to generate, modulate, and detect optical signals. Second, optical routers consume power to route packets. Third, the networked control units of an ONoC consume power to communicate and process routing information. We are concentrated on the second item and assume the four schemes use the same networked control units and network interfaces for XY routing algorithm. λ-router uses passive switching fabric but requires extra units for wavelength selection or conversion. Due to incomplete information, we could not compare the power consumption of λ-router with other routers.

Due to the asymmetrical architecture of an optical router, a packet taking different input and output ports will require different amount of power to route it. To better measure the power efficiency of the optical routers, we analyzed the average power consumption of a router in the 9x9 mesh ONoC. The average power consumption E is calculated using the equation (1). M is the total number of paths in a network. E_i is the power consumed on the *i-th* path when the bandwidth is B. R_i is the number of routers on the *i-th* path.

$$E = (\sum_{i=1}^{M} \frac{E_i}{R_i})/(M \times B) \qquad (1)$$

We assume a moderate bandwidth of 12.5Gbps for each path in the network. An optical router needs to power on and off its microring resonators to route packets. In the on state, a microring resonator needs a DC current and consumes less than 20μW [17]. In the off-state, no power will be consumed by a microring resonator, if we ignore the small bias voltages to mitigate process variations. The power consumption of a resonator is expected to decrease with the continual improvement of its material and structure.

The comparison results show that OXY based optical mesh NoC has the lowest average power consumption, 0.69fJ/bit, which is 57% less than the crossbar. A further analysis shows that the maximum power consumption of OXY in the network is also 0.69fJ/bit. This coincidence is due to most packets in a network based on OXY needs the same amount of power to route and the limited precision of the two numbers hide the small difference. Regardless the size of a network, OXY has a constant maximum power consumption, thanks to the optimized architecture. This can be proved as follows. According to the architecture, OXY does not need to power on any resonator for a packet traveling along a column or row. OXY only powers on one resonator when a packet enters a network from an injection port, turns from a row to a column, or exits the network from an ejection port. In the worst case, at most three resonators are powered on to route a packet in a network based on OXY, and this number does not change with the network size. This feature allows an optical network based on OXY scales without worrying the power consumed by the additional routers on a longer path. Compared with other optical routers, OXY-based ONoC scales better than other schemes.

TABLE I. COMPARISONS OF VARIOUS SCHEMS

	Crossbar	***CR***	***λ-router***	***OXY***
Number of resonators	2025	1782	2430	972
Power comsumption(fJ/bit)	1.60	1.42	/	0.69

Optical power loss of an ONoC decides its feasibility as well as the power consumption. In our comparison, we considered two major sources of optical power losses, the waveguide crossing insertion loss and microring resonator insertion loss. The waveguide crossing insertion loss is 0.12dB per crossing [18], and the microring resonator insertion loss is 0.5dB [19]. First, we consider the loss insider a single router. We compared the maximum loss, minimum loss, and average loss of all possible cases (Table II). OXY has 28% less minimum loss, 27% less average loss, and 33% less maximum loss than the crossbar. We also compared the average loss of the longest paths in the 9x9 mesh ONoC. OXY based optical mesh NoC has the lowest loss in this comparison, while the crossbar-based scheme has the highest loss. OXY based optical mesh NoC has 51% less average longest path loss than the crossbar based scheme. The detail of calculation is omitted due to space limitation.

TABLE II. LOSS ANALYSIS(dB)

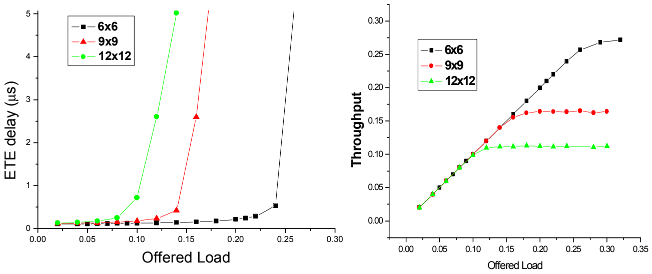
	Average	***MAX***	***MIN***	***Path loss***
Crossbar	0.98	1.46	0.50	16.66
CR	0.99	1.60	0.60	17.47
λ-router	0.92	1.10	0.60	13.87
OXY	0.72	0.98	0.36	8.22

IV. SIMULATION RESULTS

In this section, we will evaluate the network performance of the proposed 2D optical mesh ONoC based on OXY and XY routing algorithm. In the ONoC, processors generate packets independently and at time intervals following a negative exponential distribution. We used the uniform traffic pattern, i.e. each processor sends packets to all other processors with the same probability. The ONoC is simulated using a network simulator, OPNET [20].

The performance of the ONoC is measured in terms of end-to-end (ETE) delay and throughput. The ETE delay is the average time between processors generate packets and the packets reach destinations. It is the sum of the connection-oriented path-setup time and the time used to transmit optical packets. The throughput of the ONoC is normalized under a given offered load. We simulated three network sizes and use the 128-byte, 4-byte, 4-byte size for data, path-setup and acknowledge packets respectively.

The performance of ETE delay with 3 different mesh sizes, 6×6, 9×9, and 12×12, are compared in Figure 3 (a). It is obvious that larger network suffer from more serious degradation in performance. In details, 12×12 mesh saturates when the offered load is merely 0.1, while the saturation point of the smallest 6×6 mesh is over 0.24. The mesh network with larger sizes generates more packets at certain range of time, which means that for the same value of the offered load, larger network is more heavily loaded, so an earlier saturation point is encountered. Similar conclusion can also be drawn from Figure 3(b), which shows the performance of throughput with three different mesh sizes.



(a)ETE delay

(b) Throughput

Figure 3. Network performance with three mesh sizes

V. CONCLUION

We proposed a novel optical router, OXY, for ONoCs which use XY routing algorithm. A mesh ONoC is built from OXY routers. Various schemes of mesh ONoC are compared, and the comparison results show that OXY-based ONoC has the lowest power consumption and losses and requires the smallest area. OXY can guarantee the maximum power to route a packet through a network to be a small constant number, regardless of the network size. Furthermore, the maximum power consumption is very close to the average power consumption. We simulated three mesh ONoCs based on OXY and XY routing algorithm, and showed the end-to-end delay and network throughput under different traffic loads and network sizes.

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REFERENCES

[1] L. Benini, G. De Micheli, “Networks on chip: A new paradigm for systems on chip design”, *Design, Automation and Test in Europe Conference and Exhibition*, 2002

[2] M. Sgroi, M. Sheets, A. Mihal, K. Keutzer, S. Malik, J. Rabaey, A. Sangiovanni-Vincentelli, “Addressing the system-on-a-chip interconnect woes through communication-based design”, *Design Automation Conference*, 2001

[3] J. Xu, W. Wolf, J. Henkel, and S. Chakradhar, “A Design Methodology for Application-Specific Networks-on-Chip”, *ACM Transactions on Embedded Computing Systems*, July 2006.

[4] S. Kumar, A. Jantsch, J.P. Soininen, M. Forsell, M. Millberg, J. Öberg, K. Tiensyrjä, and A. Hemani, “A network on chip architecture and design methodology”, *IEEE Computer Society Annual Symposium on VLSI*, 2002.

[5] K. Goossens, J. Dielissen, A. Radulescu, “Æthereal network on chip: Concepts, architectures and implementations”, *IEEE Design Test Comput*, Vol.22, No.5, pp414–421. 2005.

[6] M. Briere, E. Drouard, et al, “Heterogeneous modeling of an optical network-on-chip with SystemC”, *In Proceedings of 16th IEEE International Workshop on Rapid System Prototyping*, 2005

[7] J. Fujikata, K. Nishi, A. Gomyo, et al, “LSI On-Chip Optical Interconnection with Si Nano-Opticals”, *IEICE Transactions on Electronics*, Vol.91-C, No.2, pp131-137, 2008

[8] A. Driessen, D. H. Geuzebroek, E.J. Klein, “Optical network components based on microring resonators”, *In proc. of 8th International Conference on Transparent Optical Networks*, pp. 210-215, 2006

[9] M. Briere, B. Girodias, et al, “System Level Assessment of an Optical NoC in an MPSoC Platform”, *Design, Automation & Test in Europe Conference & Exhibition*, 2007.

[10] A. Shacham, B.G. Lee, A. Biberman, K. Bergman, L.P. Carloni, “Optical NoC for DMA Communications in Chip Multiprocessors”, *Hot Interconnects*, 2007

[11] A. Shacham, K. Bergman, L. P. Carloni, “On the Design of a Optical Network-on-Chip”, *In proc. of First International Symposium on on-Chip*, pp53-64, 2007

[12] W. Dally and B. Towles, “Principles and Practices of Interconnection Networks”, *Morgan-Kaufmann Press*, 2004

[13] M. Majer, C. Bobda, A. Ahmadinia, J. Teich, “Packet Routing in Dynamically Changing Networks on Chip”, *in proc. of 19th IEEE International Symposium on Parallel and Distributed Processing*, 2005

[14] J. Hu and R. Marculescu, “Energy-aware mapping for tile-based NoC architectures under performance constraints”, *In Proc. ASP-DAC*, pp233-239, 2003.

[15] G. Michelogiannakis, D. Pnevmatikatos, M. Katevenis, “Approaching Ideal NoC Latency with Pre-Configured Routes”, *in proc. of First International Symposium on network on chip*, pp.153-162, 2007

[16] J. Xu, W. Wolf, S. Chakradhar, and J. Henkel, “H.264 HDTV Decoder Using Application-Specific Networks-on-Chip”, *IEEE International Conference on Multimedia and Expo*, July 2005.

[17] Q. Xu, S. Manipatruni, B. Schmidt, J. Shakya, M. Lipson, “12.5 Gbit/s carrier injection-based silicon microring silicon modulators”, *Optics Express*, Vol.15, No.2, pp430–436, 2007

[18] A. W. Poon, F. Xu, X. Luo, “Cascaded active silicon microresonator array cross-connect circuits for WDM networks-on-chip”, *in Proc. SPIE.* Vol.6898, 2008

[19] S. Xiao, M. H. Khan, H. Shen, and M. Qi, "Multiple-channel silicon micro-resonator based filters for WDM applications," *Optics Express*, vol. 15, pp. 7489-7498, 2007.

[20] Opnet. *www.opnet.com*