

HOG-NoC: Hybrid Optical-Electronic Mesh-based Grouped NoC

Xinxin Yue, Fen Ge, Ning Wu, Gaizhen Yan

Abstract—Hybrid optical-electronic NoC (HONoC) are recently considered as a promising solution to construct the low diameter and high energy efficiency network by introducing nano-photonics technologies. The traditional fully covered HONoC provides both electrical and optical links to all the nodes. Although extremely high bandwidth can be provided, large scale optical links necessitate too many wavelengths and moriorings, thus resulting in large static power. This over provision of bandwidth leads to ultra-low energy efficiency of the whole network. To solve the problem, we proposed hybrid optical-electronic mesh-based grouped NoC (HOG-NoC). HOG-NoC first interconnects the nodes with electrical mesh network, and then groups all the nodes into clusters. Each cluster has one optical interface. The optical nodes are further divided into four groups to decrease the utilized wavelengths and moriorings. Experiments showed that, compared to E-Mesh with 64 nodes under random traffic pattern, HOG-NoC improved throughput by 25.7%, decreased latency by 75% and reduced energy consumption by 12.9%.

Index Terms—HOG-NoC, hybrid NoC, Mesh-based, Grouped

I. INTRODUCTION

With the development of the integrated circuit technique, the number of available transistors on a single chip is increasing larger and larger. As a consequence, more and more cores are integrated on the chip [1]-[2], which leads to the result that traditional interconnection no longer satisfies the communication requirement of multiprocessor System-on-Chip (MPSoC), because of critical issues such as poor scalability, limited bandwidth, the difficulty of parallelism communication and crosstalk [3]. Network-on-Chip (NoC) emerges as a new on-chip communication system to relieve these issues of MPSoC by using modern communication and network theories, which use routers as key component, providing better performance.

However, large scale NoC may need long wires for global interconnects to reduce network diameter [4]. But long wires will no longer satisfy the communication needs because as

semiconductor technologies continually shrink feature sizes and the frequency of the cores are increasing to gigahertz frequency range, metallic interconnects gradually become the bottleneck of NoC performance due to the limited bandwidth, long delay, large area, and high power dissipation [5]. In fact, 256-node Electrical Mesh NoC in 22nm CMOS technology has exceeded the allocated network power budget by an order of magnitude [6].

With the maturity of integrated silicon-compatible nano-photonics technologies, Optical Network-on-Chip (ONoC) are getting focused. ONoCs utilize light as the signal propagation medium of the network, which are tending to provide high bandwidth, low latency, low power and low electro-magnetic interference [7]. Moreover, wavelength division multiplexing (WDM), which enables many wavelengths to transmit data on a single waveguide, expands bandwidth largely. However, optical interconnects also have constrains. Firstly, wavelength number are limited because WDM technology is not mature enough, the most advanced dense wavelength division multiplexing enable limited wavelengths to work together, which constrains the scale of ONoC. Secondly, static energy consumption in ONoC is large and too many optical nodes will consume a large amount of energy [8]. What's worse, small hops communication in ONoC, such as one hop communication, may consume more power and delay than ENoC, and also occupy the bandwidth of optical link. For instance, all optical NoC Amon proposed by Werner et al. [9] and QuT proposed by Hamedani et al. [10] although get better scalability by grouping, still fully covered optical nodes bring large static power consumption and provide no electrical connection for neighbored nodes, which leads to larger delay.

As a result, electronic interconnect will perform better in short-distance communication while optical interconnect fits for long distance communication. Make full use of the advantages of both electronic network and optical network will be a wise choice, that is, constructing a HONoC is promising to bring up with a better performance in delay, throughput and power consumption. In this way, optical links take the place of long wires in traditional NoC to provide better performance with lower energy loss.

Li et al. [5] has proposed a Hierarchical Cluster-based Optical NoC architecture HCONoC, in which optical interconnects are made up with many levels of cluster. In this architecture, neighbor nodes in different cluster will have to go optical layer although very close physically, bringing larger delay and energy consumption. Ye et al. [11] has proposed a Torus-based Hierarchical ONoC THOE, in which optical interconnect uses circuit switch to transmit data. Circuit switch need network to set up a path before transmission and tear down after transmission, which will

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impose large delay due to these two procedures are performed in electronic network, while the optical transmission procedure cost little delay. As a consequence, circuit switch fits for the case only when the packet is large, such as 1KB size and even more, which is uncommon in on-chip communication. Vantrease et al. [12] designed Corona for 256 nodes, in which cores are divided into 64 four-core cluster and they are connected with all-optical high-bandwidth DWDM crossbar. But critical difficulties occur when expanding the scale because wavelengths utilized at the same time are limited.

The existing network has promoted the development of hybrid network, but problems exist. Firstly, cluster-based electrical network did a bad job in neighbor communication because of unconnection. Secondly, circuit switching costs too much time to set up and tear down the path, which means high frequency and small data communications will suffer from this. Thirdly, global wavelength division optical crossbar limits the scale of the network.

Based on the above observation, we proposed a hybrid mesh-based NoC for MPSoC, which is called HOG-NoC. It is composed of an electrical interconnection layer and an optical layer where WDM is utilized, and we connect each layer with TSV (through-silicon via) [13]. We design the electrical interconnection layer as normal 2D mesh architecture, for the sake of providing electrical connection for any two neighbored nodes. In order to decrease the utilized wavelengths and moriorings, we divide the optical nodes into four groups. Besides, to deliver global communication and local communication in optical link and electronic link, respectively, we give out our routing algorithm to determine the routing path for each packet.

The rest of this paper is organized as follows. Section II describes proposed architecture and optimization. Section III introduces the routing mechanism. Experimental results of HOG-NoC will be compared with other NoCs in section IV. Section V is the conclusion of this paper.

II. ARCHITECTURE OF THE PROPOSED HOG-NOC

A. Proposed Architecture

The proposed hybrid optical-electronic architecture is shown in Fig. 1. It consists of three layers: Electric Die, Electro-Optical Transceiver Die and Optical Die, as shown in Fig. 1(a). The Optical Die consists of waveguide for delivering packets in light and optical router which is made up with passive micro-rings for routing packets during transmission. And each optical node is allocated with a particular wavelength λ_n for routing address. The Underneath layer is an Electro-Optical Die, which is composed of modulators and Photo-detectors for conversion between electrical and optical signal. The bottom layer is an electrical Mesh layer, in which main components are processor elements and electrical routers, as shown in Fig. 1(c), closed to heat sink for better thermal dissipation. Each Die is connected with TSVs for data transmission, as shown in Fig. 1(b).

In order to reduce optical nodes number and provide optical connection for each electrical node, we place an optical node every two hops in both X and Y direction. But traditional even distribution of optical nodes doesn't serve

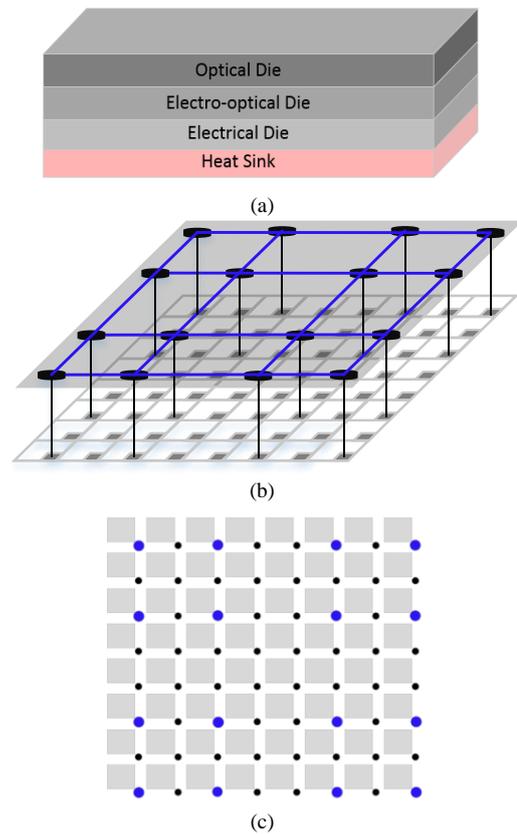


Fig. 1 Architecture of proposed HONoC.

- (a) The Architecture
- (b) 3D connection of electrical layer and optical layer
- (c) Topology of electrical layer

well for edge electrical nodes because not all edge nodes can access optical nodes within one hop while edge nodes are more likely need to access optical nodes. In order to improve this problem, we firstly divide electrical nodes into four sub-meshes and optical nodes are placed close to the edge of network to serve for long-hops packets better within a sub-mesh with even number of nodes (such as a sub-mesh with 4×4 or 6×6 nodes). Within a sub-mesh with odd number of nodes (such as a sub-mesh with 5×5 nodes or 7×7 nodes), optical nodes are distributed in the center of each sub-mesh for fairness. Optical nodes distribution of a 8×8 network is shown as Fig. 1(c).

For each packet, it can choose to go electrical interconnect or optical interconnect for less delay or less energy consumption. When it goes optical layer, the source optical node will modulate data in the same wavelength with destination, then with the resonance of micro-rings in optical router, light with packet data will route toward destination optical node directly in a MWSR crossbar.

B. The Design of Optical Interconnection

With the scale of network increasing larger, more optical nodes and wavelengths are needed in the optical layer, in order that each optical node can be addressed when routing. But the number of wavelengths utilized in optical interconnect are limited because laser technology is not mature enough. On the other hand, power consumption of laser sources accounts for a large proportion in total power consumption in optical layer. Laser power is determined by

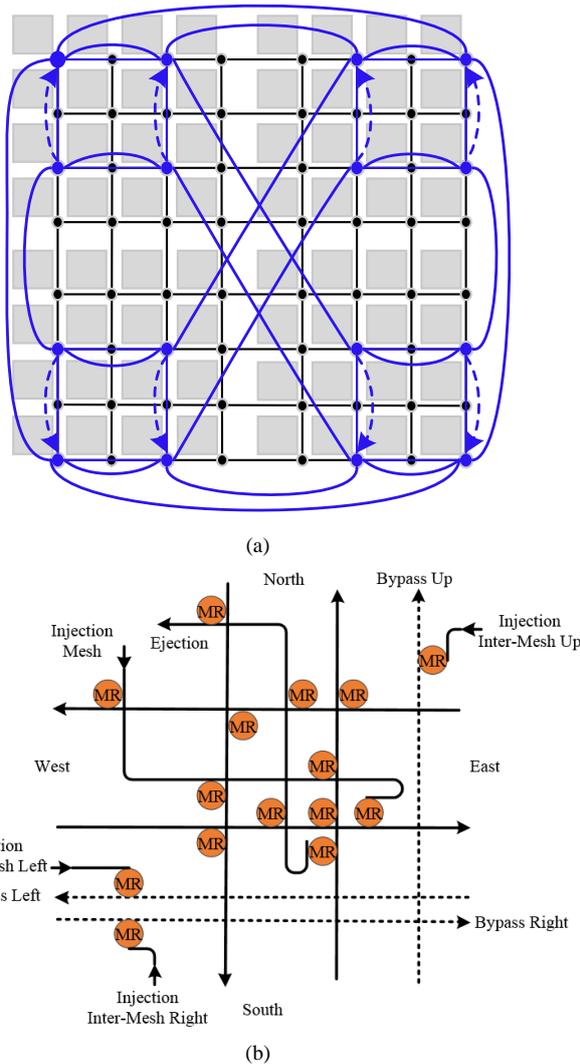


Fig. 2 Architecture of HOG-NoC
(a) The architecture (b) Optical router of HOG-NoC

the biggest insertion loss in the network, which is proportional to diameter of the network.

In order to reduce wavelength utilization and shorten diameter of the network, we separated optical nodes into four groups and each group is a sub-mesh, as shown in Fig. 2(a). In this occasion, number of optical nodes need to be $a \times a \times 4$ ($a \geq 2$). Within a sub-mesh, each optical node is assigned with a unique wavelength for addressing, and each node is connected with Mesh links, which are represented as straight lines within the sub-mesh in Fig. 2(a). Besides Mesh links, there are three bypass links alongside each node, and they are connected to the other three sub-meshes separately. In Fig. 2(a), bypass links are represented as curves within the sub-mesh and lines between different sub-meshes, and bidirectional bypass links are represented as solid lines while unidirectional bypass links are represented as dotted lines. In this way, communication between optical nodes within a sub-mesh starts at an Injection Mesh port and transfers with inner-mesh links through X-Y static routing algorithm. And for optical nodes distributed in different sub-meshes, communication will starts at an inner-mesh injection Mesh port and continues through bypass inter-mesh waveguides, which converge with Mesh links at destination sub-mesh. After that, X-Y static routing algorithm will be carried on for

addressing target optical node. The optical router used in HOG-NoC left up sub-mesh is shown as Fig. 2(b), and mirror structure will be used in other sub-meshes. Because of no conflict between inner-mesh and inter-mesh links, the four sub-meshes share the same wavelength sets to reduce wavelength utilization to 1/4, and by return this reduce large number of microrings and increases the scalability of the network greatly, especially when scale of network is large. On the other hand, since optical links have provided pretty large bandwidth for the network comparing with E-Mesh, we decrease the number of virtual channels of electrical routers in electrical layer of HOG-NoC to reduce redundant energy consumption of electrical buffers.

Anyway, conflicts happen in optical interconnect of HOG-NoC when many source optical nodes are sending to one destination node. In order to avoid conflicts, an all-optical MWSR is used as CN (Control Network).

III. ROUTING MECHANISM

For each packet generated, two paths can be selected toward destination including electrical path and optical path. In order to decrease power consumption of the network, route selection should be determined by power consumption calculation of different paths.

Assuming network scale is $m \times m$, and each node is identified as N_i . For a packet transferred from source node n_s to destination node n_d , the Manhattan Distance L between N_s and N_d can be calculated as equation (1).

$$L = |n_d \% m - n_s \% m| + |n_d / m - n_s / m| + 1 \quad (1)$$

If the packet is routing in electrical layer, power dissipation from N_s to N_d can be evaluated as equation (2) where P_r and P_l are power dissipation of electrical router and global link transmit 1-bit data, respectively, and L_p is packet length.

$$P_E = (P_r \times L + P_l \times (L - 1)) \times L_p \quad (2)$$

If the packet is transmitted in optical layer, routing path contains both electrical and optical path. Total power dissipation can be expressed as equation (3), where P_{Ep} and P_{Op} are power dissipation of electrical part and optical part.

$$P_O = P_{Ep} + P_{Op} \quad (3)$$

Power consumption of electrical part can be evaluated as equation (4) where L_s is Manhattan Distance between N_s and closest optical node, and N_d is Manhattan Distance between N_d and closest optical node.

$$P_{Ep} = ((P_r + P_l) \times (L_s + L_p + 2)) \times L_p \quad (4)$$

Power consumption of optical part can be evaluated as equation (4) where P_{EO} and P_{OE} are power dissipation of electro-optical and optical-electronic conversion for 1-bit data.

$$P_{Op} = (P_{OE} + P_{EO}) \times L_p \quad (5)$$

When $P_E < P_O$, the packet will be transmitted in electrical layer with X-Y static routing algorithm. Otherwise if $P_E > P_O$, the packet will be sent to closest optical node. Then packet will be injected into optical waveguide for propagation through one particular injection Mesh port according to destination sub-mesh. If destination node shares the same sub-mesh with source node, Injection Mesh port will be used. Otherwise, Injection Inter-Mesh Left, Injection Inter-Mesh

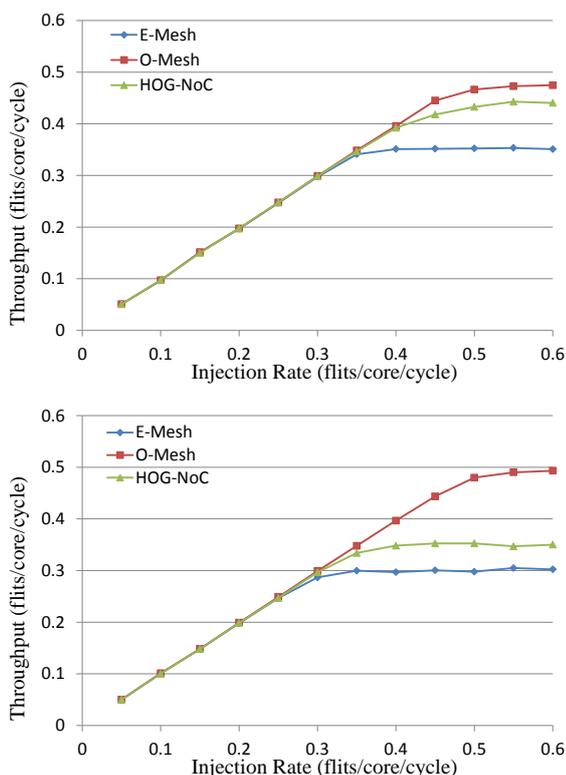


Fig. 3 Throughput comparison for 64 nodes and 100 nodes under Random traffic pattern

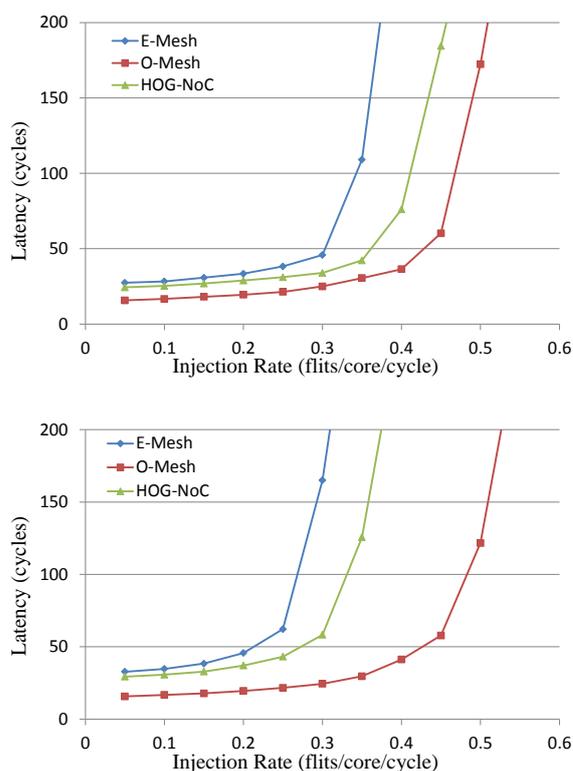


Fig. 5 Latency comparison for 64 nodes and 100 nodes under Random traffic pattern

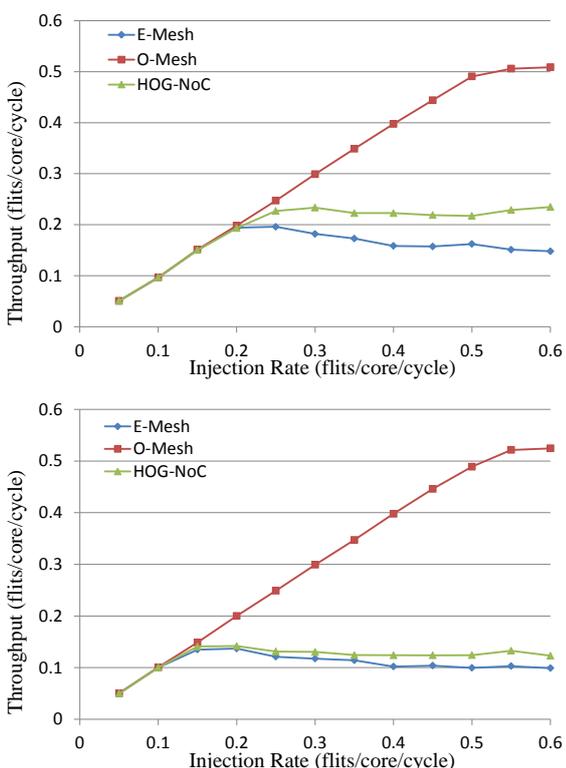


Fig. 4 Throughput comparison for 64 nodes and 100 nodes under Transpose1 traffic pattern

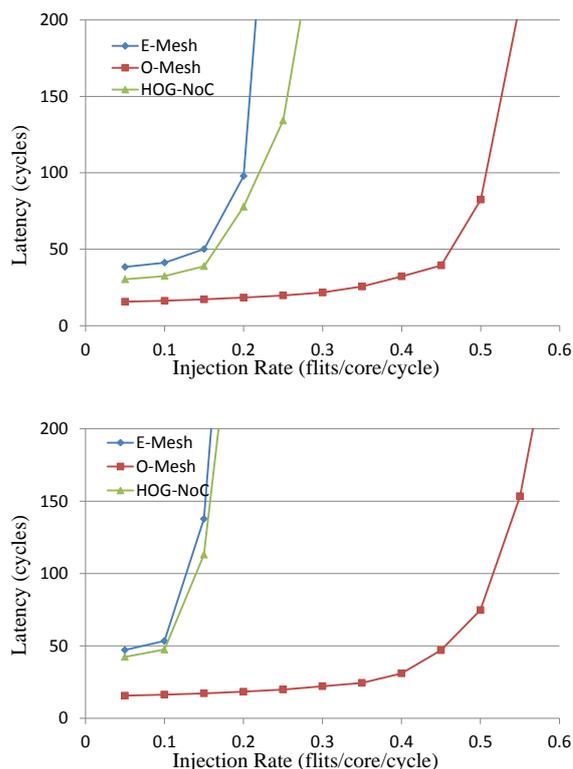


Fig. 6 Latency comparison for 64 nodes and 100 nodes under Transpose1 traffic pattern

Right and Injection Inter-Mesh up ports will be used according to destination location. After optical transmission, again X-Y static routing algorithm will be used for targeting destination.

In this way, routing choice is considered basing on power consumption calculation in each route. But when workload is

heavy, more situations should be considered to promote performance of the network. Optimizing routing mechanism to promote performance is left as future work.

IV. EXPERIMENT AND RESULT

In order to evaluate the throughput, delay and energy of HOG-NoC, we implemented three networks including

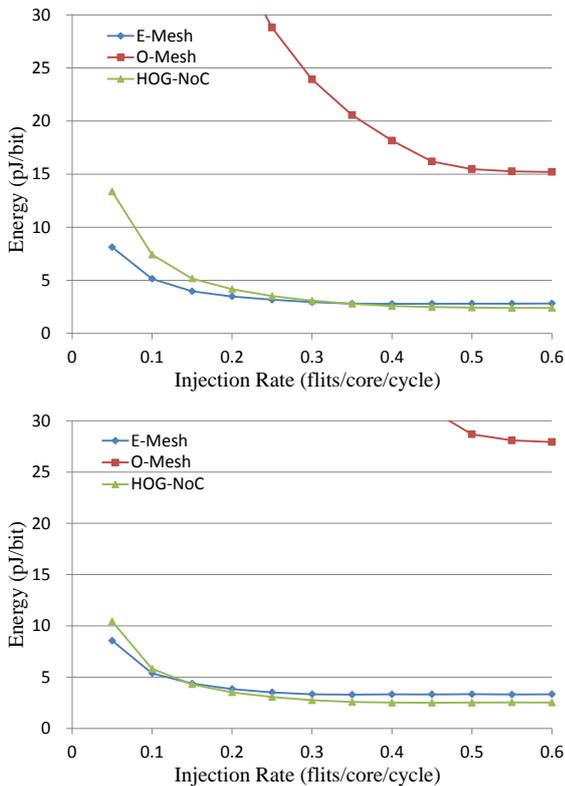


Fig. 7 Energy comparison for 64 nodes and 100 nodes under Random traffic pattern

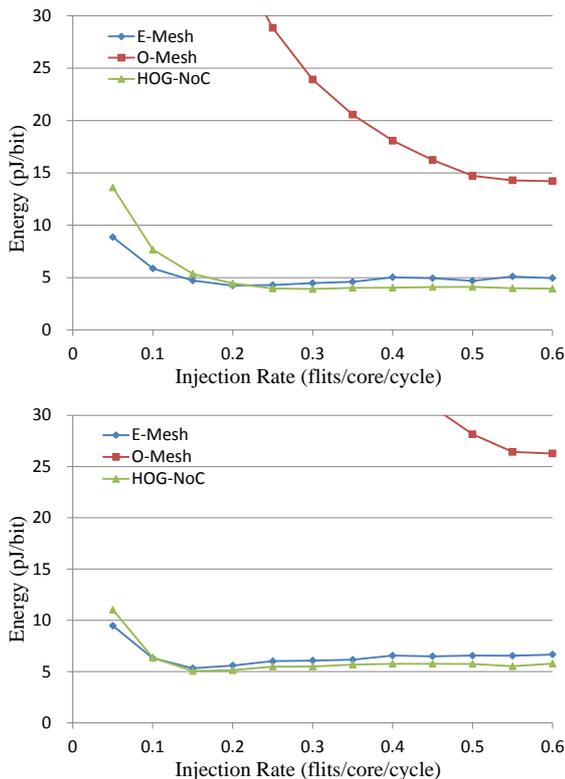


Fig. 8 Energy comparison for 64 nodes and 100 nodes under Transpose1 traffic pattern

E-Mesh, O-Mesh and our hybrid optical-electronic HOG-NoC for 64 nodes and 100 nodes under both random traffic pattern and transpose1 traffic pattern in cycle-accurate NoC simulation environment JADE [14]. In the experiment, packet size was set as 128 bits and energy evaluation was based on 45nm DESENT [15] power model.

A. Throughput

Throughput results comparison of three networks is shown in Fig. 3 and Fig. 4. Under Random traffic pattern, E-Mesh, O-Mesh and HOG-NoC get saturated at injection rate of 0.35, 0.5 and 0.45 for 64 nodes and get saturated at injection rate of 0.3, 0.5 and 0.35 for 100 nodes, respectively. Under Transpose1 traffic pattern, E-Mesh, O-Mesh and HOG-NoC get saturated at injection rate of 0.2, 0.5 and 0.25 for 64 nodes and get saturated at injection rate of 0.15, 0.5 and 0.15 for 100 nodes, respectively. Compared with E-Mesh, HOG-NoC improved saturated throughput by 25.7% and 16.55% for 64 nodes and 100 nodes under Random traffic pattern, and improved saturated throughput by 16.9% and 4.4% for 64 nodes and 100 nodes under Transpose1 traffic pattern. O-Mesh had the best throughput because of all-optical interconnect provides extra-high bandwidth.

B. Latency

Latency results comparison is shown in Fig. 5 and Fig. 6. It can be seen that, saturated latency of proposed HOG-NoC has been reduced by 75% and 64% for 64 nodes and 100 nodes under Random traffic pattern and by 69% and 18% for 64 nodes and 100 nodes under Transpose1 traffic pattern compared to E-Mesh. Injection rate for 100-cycle latency of HOG-NoC has been extended by about 20% and 22% for 64 nodes and 100 nodes under Random traffic pattern and by about 6% and 18% for 64 nodes and 100 nodes under Transpose1 traffic pattern compared with E-Mesh. Latency of O-Mesh keeps lower than the other two networks because of direct optical link connection for each node.

C. Energy Efficiency

Energy efficiency comparison results are shown in Fig. 7 and Fig. 8. Compared with E-Mesh and O-Mesh, HOG-NoC reduces per-bit energy consumption by 12.9% and 84% for 64 nodes and by 22.6% and 91% for 100 nodes under Random traffic pattern when network gets saturated, respectively. Under Transpose1 traffic pattern, HOG-NoC reduces per-bit energy consumption by 8% and 86% for 64 nodes and by 5% and 94% for 100 nodes compared with E-Mesh and O-Mesh. Energy efficiency of HOG-NoC is smaller than E-Mesh when injection rate is light, because static power consumption accounts for large proportion in total power consumption of optical layer.

Although O-Mesh shows better throughput and delay, per-bit energy consumption is extremely high than HOG-NoC, because O-Mesh has bigger network diameter and a pretty larger number of micro-rings caused by more wavelengths occupation. As a result, energy efficiency of O-Mesh is unaffordable for chips.

D. Area

In HOG-NoC, we introduce an additional optical layer for better performance compared to E-Mesh. As a result, in electrical layer electrical routers connected with optical layer will introduce another port for data transmission with optical routers, which increases area cost of the network. Since optical layer has provided pretty high bandwidth, we decrease the number of virtual channels of electrical router for reducing energy cost and area cost, which amortizes the area cost caused by additional port of electrical routers. DSENT evaluation shows that area cost of electrical routers

was reduced by 33% because of decreased virtual channels. With the maturity of 3D integrating technology, optical layer can be integrated as a single layer above electrical layer, which will not introduce additional area cost.

V. CONCLUSION

In this paper, we proposed hybrid optical-electronic Network-on-Chip HOG-NoC. Experiment shows that HOG-NoC improved throughput by 25.7% and 16.55%, and reduced latency by 75% and 64% at most compared to E-Mesh for 64 nodes and 100 nodes under Random traffic pattern, respectively. And HOG-NoC reduced energy consumption by 12.9% and 84% for 64 nodes, by 22.6% and 91% for 100 nodes under Random traffic pattern compared with E-Mesh and O-Mesh when get saturated. As a conclusion, HOG-NoC provides better performance with lower energy cost comparing with E-Mesh, which only introduces one optical layer with 3D integrating overhead.

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