Power Allocation Method for TDM-Based Optical Network on Chip

Zhengyu Wang, Huaxi Gu, Yintang Yang, and Bixia Zhang

***Abstract*— Optical Network on Chip has emerged as a high-efficiency interconnection for the future generation of many-core system-on-chips because of its high bandwidth, low interference, and low power consumption. However, only a few papers discuss the allocation of laser power to each node. The even distribution method of laser power ignores the difference of communication requests for each node. In this letter, we first discuss the design of a power waveguide and how to guide light for each source node. Then, a method to allocate optical power to each node is proposed. The method is based on time division multiplexing. By considering the communication requests, the new method can save 92% and 92.8% of the total laser power, respectively, in an 8 × 8 mesh compared with even distribution method under uniform and matrix transpose traffic.**

***Index Terms*— Laser, optical network on chip, optical power allocation, time division multiplex (TDM).**

I. Introduction

With the increasing cores integrated into a single chip, traditional electrical network on chip (ENoC) cannot meet the high bandwidth and low energy consumption requirements of SoCs. ENoC can barely overcome problems, such as EMI and high power. The development of optical devices, such as optical switches, makes optical network on chip (ONoC) a promising substitute. Shacham *et al.* [1] were the first to present a hybrid ONoC, which was composed of an electrical control network and optical data transmission network. A few other ONoCs have also been proposed, such as Corona [2] and Firefly [3]. Considering the indirect Si bandgap, there are no high efficiency laser sources in Si. Therefore, all these architectures utilize an external laser to provide optical power to the source nodes. Light from an off-chip laser source is carried by an optical fiber and arrives perpendicular to the chip's surface, where a vertical coupler steers the light into an on-chip waveguide (called the power waveguide) [4]. The power waveguide carries the light passing from a series of source nodes. An S-shaped power waveguide was utilized in [3],

Manuscript received January 5, 2013; revised March 31, 2013; accepted April 8, 2013. Date of publication April 12, 2013; date of current version May 7, 2013. This work was supported in part by the National Science Foundation of China under Grants 60803038 and 61070046, in part by the special fund from the State Key Lab under Grant ISN1104001, in part by the Fundamental Research Funds for the Central Universities under Grant K5051301003, and in part by the 111 Project under Grant B08038.

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Digital Object Identifier 10.1109/LPT.2013.2257718

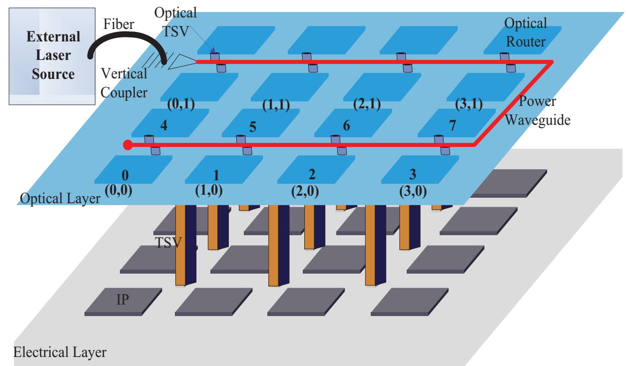

Fig. 1. 3-D floorplan of an optical ONoC.

but the authors did not describe how they allocated laser power. To the best of our knowledge, only a few studies explain in detail how a power waveguide connects or how much power is provided to each source node. We first provide the power waveguide design in this letter. After that, we discuss how we allocate laser power to each node. Finally, a conclusion is drawn and a discussion concerning some problems is presented.

II. Power Waveguide Design

Figure 1 gives a schematic of the 3D architecture of ONoC. The electrical layer contains IP cores and electrical routers (these routers are omitted for clarity). The optical layer includes optical routers connected through waveguides (not shown in the figure). The power waveguide is placed on the optical layer, which guides the light from the external laser into the chip. The light is dropped onto the optical layer through an optical TSV. The design of the optical TSV is provided in Fig. 2(a). An optical TSV is utilized as the power divider in this study. The micro-resonator can be utilized to drop a fraction of power from the power waveguide by controlling the applied voltage [7], [8]. Figure 2(b) provides the design of the optical router. The optical router comprises micro-resonators and waveguides. Micro-resonator 1, which is near the injection port, is the micro-resonator of the optical TSV. When the source has a communication request, it turns the micro-resonator 1 to the on state. Thus, a fraction of light is dropped from the power waveguide in layer 2 to the source node in layer 1 (optical layer). Then, the source node modulates the dropped light for communication with the destination (modulator and detector are omitted for clarity).

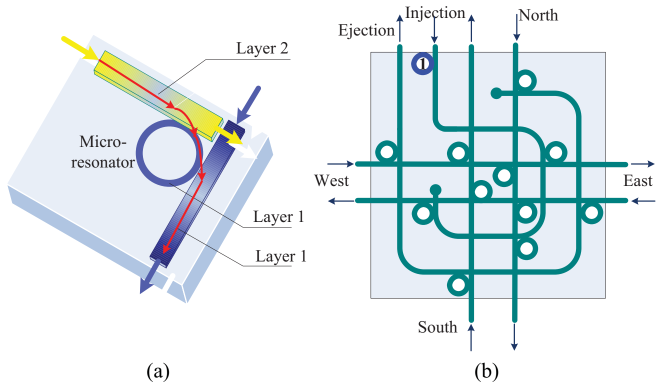

Fig. 2. (a) Optical TSV [5], [6]. (b) Optical router.

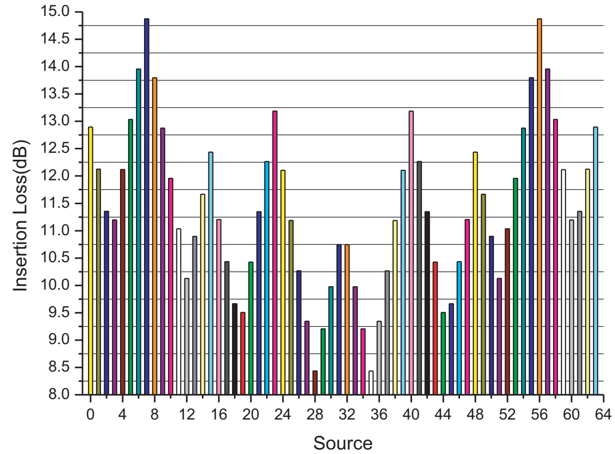

Fig. 3. Maximum insertion loss of each node.

TABLE I
INSERTION LOSS OF DIFFERENT COMPONENTS [10]

Component	Loss Parameter
Waveguide Crossing	0.15 dB
Waveguide Bend	0.005 dB/90^0
Drop Into a Ring	0.5 dB
Pass By a Ring	0.005 dB

III. ALLOCATION OF LASER POWER

Laser power determines the network size and number of wavelengths that can be utilized as stated in [9]. Considering that optical signals experience insertion loss along the path from the modulator to the detector, the provided optical power should counteract the loss and ensure correct detection of the signal at the detector side. The power required by the source node to communicate is determined by (1) [9]

$$P^s_{laser} - S \geq IL^s_{\max} + 10\log n \tag{1}$$

where P^s_{laser} is the required laser power of node s, S is the sensitivity of the detector assumed to be -20 dBm [6], and n is the total number of utilized wavelengths. P^s_{laser} is calculated in dB in (1). We discuss in this letter the minimum laser power a network should provide and how to allocate the power to each node. We consider only the low limit of P^s_{laser} for (1). The maximum insertion loss of node s, $IL^s_{\max}$, is calculated by (2) as follows:

$$IL^s_{\max} = \max\left(IL_{sd}\right) \;\; for\ d \neq s,\ \ d \in [0, N) \tag{2}$$

where N is the total number of nodes in the network, and IL_{sd} is the insertion loss the signal experiences from source s to destination d. Insertion loss includes waveguide bending loss, crossing loss, and losses caused by micro-resonator. The parameters of these losses are listed in Table I [10].

The traditional method distributes power equally to each node. The allocated power to each node is the power required by the node whose $IL^s_{\max}$ is the largest among all the nodes in the network. The maximum of $IL^s_{\max}$, $MaxIL$, can be obtained by (3)

$$MaxIL = \max\left(IL^s_{\max}\right) \;\; s \in [0, N). \tag{3}$$

An 8×8 mesh is utilized as an example. The XY-routing algorithm is applied. In XY-routing, the packet should first be transmitted in the X dimension until it reaches the node that has the same coordinate of X with the destination node. Then, the packet passes through the Y dimension to the destination. With the parameters indicated in Table I and Equation (2) and (3), $MaxIL$ is obtained. Its value is 14.875 dB. The total laser power is 19.6644 mW when only one wavelength ($n = 1$) is utilized. We believe that this situation involves a waste of power considering that even distribution of power does not consider the difference in the communication requests of each node. Figure 3 shows the $IL^s_{\max}$ of each node in the 8×8 mesh. The values of $IL^s_{\max}$ are significantly different, thus rendering P^s_{laser} different, too. Hence, the provision of same amounts of power to each node is unnecessary. Power can be saved by allocating each node the power it requires.

Table II lists the destination node for the source node when $IL^s_{\max}$ is attained. Table II shows that $1 \to 63$ and $2 \to 63$ both experience maximum insertion loss, and they have the same destination node (63). This occurrence is impossible in real communication scenario because a node cannot receive data simultaneously from different nodes. We refer to this condition as destination collision. If we provided node 1 and node 2 the power calculated by (1), the actual power they require would still be lower than the power we provided because they cannot experience maximum insertion loss simultaneously. The same condition applies to source collision, such as when communication requests are from the same source, for example $1 \to 63$ and $1 \to 3$. Two communication pairs with overlapped paths cannot coexist simultaneously too. Two paths overlap when the paths utilize the same link and packets are transmitted in the same direction. For example, in the communication from source 0 to destination 2, the links $0 \to 1$ and $1 \to 2$ are reserved. Communication from source 1 to destination 3 reserves the links $1 \to 2$ and $2 \to 3$. Both paths share link $1 \to 2$. However, link $1 \to 2$ can only be reserved by one of the paths. Therefore, the two communication pairs cannot coexist. We refer to this condition as path collision. Total laser power is further lowered by considering these collision situations. Every node should know how much power it requires and how much power is left in the power waveguide to decide the ratio of power to be dropped when light passes through.

TABLE II
SOURCE AND DESTINATION COMMUNICATION PAIRS WITH MAXIMUM INSERTION LOSS

Source	Destination
0, 1, 2, 8, 9, 10, 11, 16, 17, 18, 24, 25, 26, 27, 28, 29, 30, 31	63
3, 4, 5, 6, 7, 12, 13, 14, 15, 19, 20, 21, 22, 23	56
32, 33, 34, 35, 40, 41, 42, 43, 44, 48, 49, 50, 51, 56, 57, 58, 59, 60	7
36, 37, 38, 39, 45, 46, 47, 52, 53, 54, 55, 61, 62, 63	0

That is, every node should have global information on which combinations of communication pairs' the network operates each time. However, obtaining global information requires network support and may consume too much network resources. Although global information can be obtained, the real-time computation of the ratio the node obtains is time consuming. Therefore, we utilize the time division multiplex (TDM) communication paradigm. We apply TDM communication in power allocation. The communication pairs' combination in each slot is fixed and determined in advance in TDM. Hence, the ratio can be calculated off-line and stored in a table. The source can refer to the table to obtain the ratio before communication. This is a practical method to allocate optical laser power.

The TDM based method can be expressed by an optimization model. Our optimization model has two objectives. One is to minimize the total time slot number, and the other is to minimize the total laser power a network should provide.

The number of total time slots for the network is closely related to network end-to-end delay performance. Too many time slots means that communication requests would have to wait longer to obtain a slot and complete communication. Hence, the total number of time slots should be minimized. The first objective is addressed by (4). If different communication requests are allocated in the same slot, the total number of required time slots would be different. The ith allocation method allocates all communication requests to N_i slots. Even if the total slots number of ith and jth allocation method are the same ($N_i = N_j$), the communication requests in each slot for these two allocation methods may be different.

Given that the laser power allocated to each slot is different, we should guarantee that the slot that requires maximum laser power is provided such. Low maximum laser power means low network-provided power. The second objective of our optimization model is addressed by (5). The maximum laser power $P^i_{\max}$ for the ith allocation method is calculated by (6) where IL_{sd} is the insertion loss between source s and destination d, and C^{ij}_{sd} signifies whether there is communication between source s and destination d in slot j for the ith allocation method (expressed by (7)). Source, destination, and path collision are expressed as the constraints of the model by (8), (9), and (10). P^{ij}_{sd} is the set of links in the path when node s communicates with node d at slot j for the ith allocation method. We assume that $L_{i,j}$ represents the link from node i to node j. For the 4th allocation method in slot 2, source 1 communicates with destination 3. The elements of $P^{4,2}_{1,3}$ are $L_{1,2}$ and $L_{2,3}$

$$N_{slot} = \min N_i \quad i \in Z^+ \tag{4}$$

$$\min \quad P^i_{\max} \tag{5}$$

$$\begin{cases} P^i_{\max} = \max\limits_{j\in[0,N_i)} \left(10^{0.1S} \times n \times \sum_s \sum_d 10^{0.1 C^{ij}_{sd} IL_{sd}}\right) \\ s, d \in [0, N) \; s \neq d \end{cases} \tag{6}$$

where

$$C^{ij}_{sd} = \begin{cases} 1, & \text{if source } s \text{ has communication with destination } d \text{ in slot } j \text{ for the ith allocation method} \\ 0, & \text{else} \end{cases} \tag{7}$$

$$\sum_s^{C^{ij}_{sd}} \leq 1 \quad s \neq d \tag{8}$$

$$\sum_d^{C^{ij}_{sd}} \leq 1 \quad d \neq s \tag{9}$$

$$\bigcap_{s,d} P^{ij}_{sd} = \emptyset \quad s, d \in [0, N) \; s \neq d. \tag{10}$$

Considering that sensitivity and the number of wavelengths are fixed, we can neglect these constant parts. The second objective can now be addressed by (11) by taking logarithm of (6). Equation (11) simplifies the solution of the model

$$\min_i \left(\max_{j\in[0,N_i)} \left(\sum_s \sum_d C^{ij}_{sd} IL_{sd} \right) \right). \tag{11}$$

IV. EXPERIMENTATIONS RESULTS

The laser power allocation problem is an NP problem, while the search space of problem increases with the exponential of the network size. We employ a genetic algorithm to solve the above model. Our primary target is to reduce the total laser power. Therefore, we turn the first objective (4) as a restriction and assume that N_{slot} is not larger than 200 in accordance with the results we obtained in [11]. The result of the model provides the communication pairs in each slot. Calculating the ratio of power the node drops from the power waveguide becomes easy with this information. We again regard the 8 × 8 mesh as an example. The routing algorithm is still XY-routing. One of the traffic patterns we analyze is uniform, in which the node sends data to other nodes equally. The other pattern is matrix transpose, in which the node i sends data to node (N-i-1). Figures 4 and 5 provide the result. We only list communication pairs in slot 0 and slot 1 for brevity. The total slots of uniform traffic and matrix transpose are 186 and 4, respectively. The values of total optical power are 1.61307 mW and 1.40939 mW when the number of wavelengths is 1 ($n = 1$). These values are far less than 19.6644 mW, the value obtained by the equal division of laser power. The method proposed in this letter can be realized easily. Two devices are needed. One is an optical TSV, which has been proposed by [5], [6] and can be utilized as a power divider. The other is a slot table, which can be fabricated by an electrical buffer. Each node in original TDM system has a local

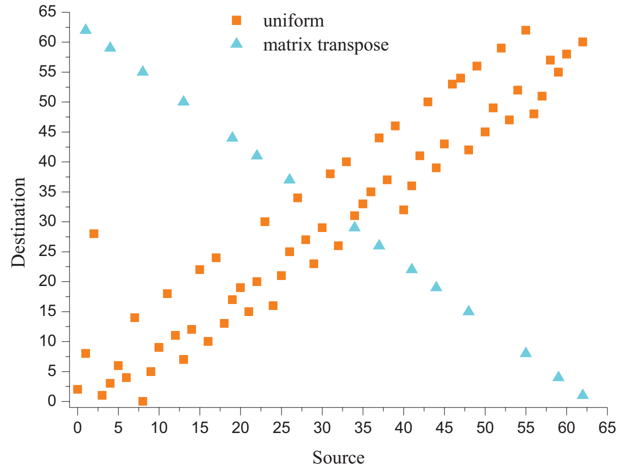

Fig. 4. Communication pairs of slot 0.

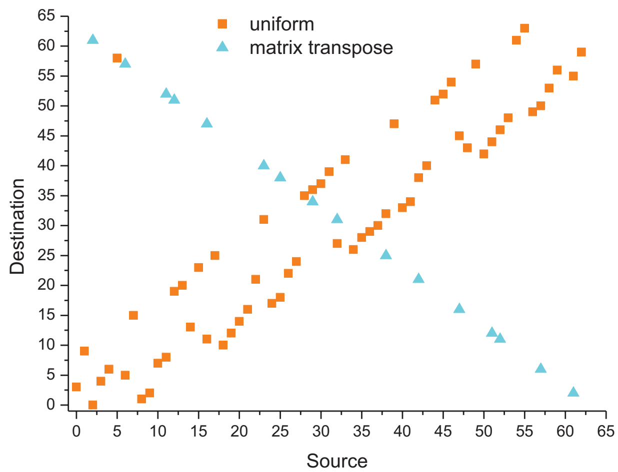

Fig. 5. Communication pairs of slot 1.

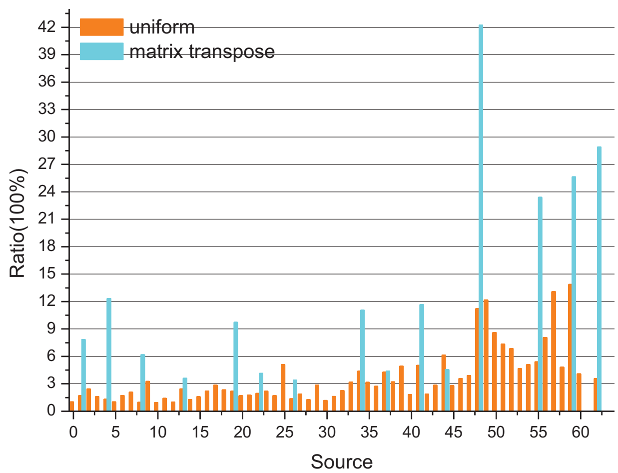

Fig. 6. Ratio of each source node in slot 0.

slot table, which contains the item of the slot and destination. We add a new item, ratio, to the local slot table. The node refers to the slot table to obtain the ratio at the beginning of the time slot. The node controls the micro-resonator of the optical TSV by changing the applied voltage of the micro-resonator to obtain the required ratio of power from

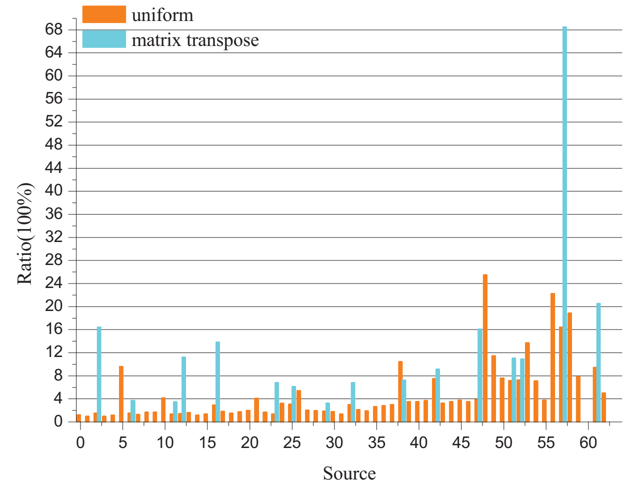

Fig. 7. Ratio of each source node in slot 1.

the power waveguide for communication with the destination in the time slot. Figures 6 and 7 provide the ratio of power every node receives in slots 0 and 1.

V. Conclusion

This letter analyzes the optical power a laser should provide for communication and proposes a method to design a power waveguide that allocates power to each source. However, numerous opening problems need to be solved. For example, the ring resonator's sensitivity to temperature [12] may further influence the ratio.

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