Accelerating Lightpath Setup Via Broadcasting in Binary-Tree Waveguide in Optical NoCs

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***Abstract*—In this paper, we propose a binary-tree waveguide connected Optical-Network-on-Chip (ONoC) to accelerate the establishment of the lightpath. By broadcasting the control data in the proposed power-efficient binary-tree waveguide, the maximal hops for establishing lightpath is reduced to two. With extensive simulations and analysis, we demonstrate that the proposed ONoC significantly reduces the setup time, and then the packet latency.**

I. Introduction

As billions of transistors are integrated into one die [1], researchers have embraced the manycore architecture [2]–[4], posing a challenge to the on-chip communication. Hence, NoC is proposed as a promising communication subsystem to provide high parallelism and reduce power dissipation [5].

The delay, as well as the power consumption, of the copper interconnect degrades significantly with the improvement of VLSI technology [6]. To address that problem, researchers try to transmit photons as opposed to electrons through CMOS-compatible waveguides [7].

Merging the advantages of NoC and optical communication, ONoC is proposed as the future on-chip interconnect structure with great prospects from researchers [7]–[10]. In general, ONoC consists of arranged optical routers and incident optical interconnect.

More specifically, optical interconnect, as an example shown in Fig. 1, consists of four basic optical components: a modulator [13], a waveguide [15], a photo-detector [16], and a laser [14]. Optical router mainly consists of an optical switch and a routing/control logic [9]. The on-chip wavelength switching is based on a CMOS-compatible component, namely the microresonator [17], coupling optical signals with the resonance wavelength and allowing other wavelengths to pass through. Note that, we could change the resonance wavelength by powering on and off the microresonator, so that there are on-state and off-state resonance wavelengths correspondingly.

So far, researchers have put lot of efforts on optimizing switches, such as reducing the number of microresonators and waveguide crossovers [10] [12]. The routing/control logic, however, is not well-studied. Through the simulations discussed in Sec. III, we could find that the lightpath establishment contributes more than 40% to the packet latency.

The high latency for establishing the lightpath is mainly introduced by the serial processing of the control data by routers on the xy-routing path. Traditional optical networks adopt this strategy due to the fact that they are initially designed for the wide area network, where nodes usually have a distance of several kilometers (or longer). In the ONoC, however, nodes are very close, so that the proposed ONoC enables the broadcast of control data by exploiting the Y-branch waveguide [19], [21], [22] and the regularity of xy routing [18]. Our contributions are summarized below in two technical areas:

1) We present a binary-tree waveguide, consisting of cascaded asymmetric Y-branch waveguides, with a very high power efficiency (low power loss).
2) We exploit the regularity of xy-routing to broadcast the control data in the binary-tree waveguides, so that the setup time is significantly reduced.

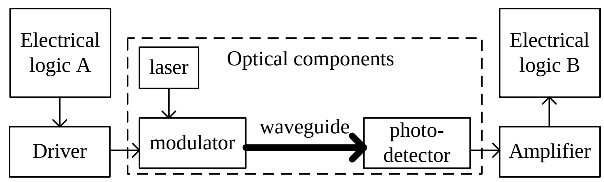


Fig. 1. The diagram of the on-chip optical interconnect.

The rest of this paper is organized as follows: Sec. II shows the proposed router architecture and detailed design issues; Sec. III shows the experimental results; Sec. IV concludes this paper.

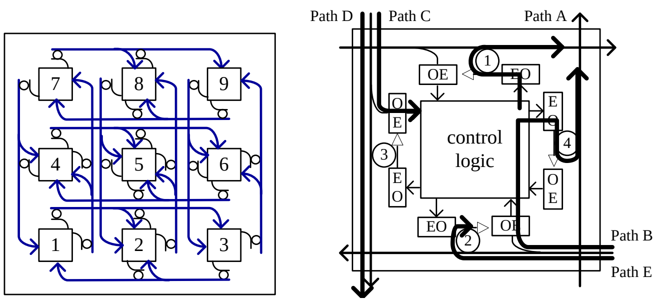
II. The Proposed Optical NoC

In this section, we first discuss the network topology, router architecture, as well as the procedure to establish/release the lightpath, and then discuss the design issues about the proposed binary-tree waveguide.

A. Network Topology

As shown in Fig. 2, a 3×3 ONoC is shown on the left side, and the detailed router architecture is shown on the right. The optical switches, and corresponding microresonators, are omitted for simplicity since optimizing switches is not our objective. As shown in Fig. 2(a), the cores in each row and column are connected by a binary tree waveguide in both positive and negative directions. The positive direction refers to left→right and south→north, and the negative direction refers to the opposite ones.

The binary tree waveguide bifurcates at each node that not at network boundaries, and the two branches all connect with the node. More specifically, one branch connecting with the input port of current node is utilized to receive data from parents, the other branch connecting with the output port is utilized to send data to children. Particularly, as shown in Fig. 2(b), the router receives packet from the binary-tree waveguide via an O/E converter. To send a packet, the router first converts the packet to optical signals through the E/O converter, and then couples them to the binary-tree waveguide via a microresonator.



(a) 3×3 network (b) router architecture

Fig. 2. Overview of the proposed ONoC and detailed router architecture. (cycles denote microresonators, and triangles represent terminators.)

As we previously mentioned, the binary tree waveguide is utilized to accelerate the lightpath setup, which mainly involves the five following steps:

1) Determine the relative position of current node,
2) Configure the control logic,
3) Configure the optical switch,
4) If it is the turning node, forward the control data,
5) If it is the destination, send ack back.

At the first step, we are interested in that whether the current router is the source, turning, destination or irrelevant node. A node is irrelevant, if it does not reside on the xy-routing path, but receives the control data broadcasted in the binary-tree waveguide. The router does nothing if it is an irrelevant node.

At the source node, we turn on the microresonator at the selected $output$. Consider an example shown in Fig. 2(b), when $east$ is selected, we turn on the microresonator 1, thus the control data is sent to the east neighbor through the $Path\ A$.

At the turning node, we turn on the microresonator at the selected $output$, as well as the one on the original direction of the control data. For example, as shown in Fig. 2(b), the control data to $west$ is expected to turn to $north$. Hence, to forward the control data via $Path\ B$, we turn on the microresonator 4 at the selected $output$. We also turn on the microresonator 2 on the original direction $west$ to avoid the incorrect release discussed later.

At the destination node, we turn on the microresonator on the original direction of the control data. For example, as shown in Fig. 2(b), the control data is sent to the control logic via the $Path\ C$. To avoid the incorrect release, as in the turning node, we should turn on the microresonator 3 on the original direction $south$.

At other nodes residing on the xy-routing path, we turn off the microresonator at the selected $output$. For example, as shown in Fig. 2(b), to transmit the control data through the $Path\ D$, the microresonator 3 is turned off.

The optical switch configuration is utilized to establish a lightpath (not shown in this paper) for transmitting the $payload$ and ack data.The detailed configuration is shown in the literature [10] [12].

After the configuration, the router should forward the control data through the selected $output$ if it is the turning node. Otherwise, if it is the destination, it sends back the ack signal through the established lightpath to the source for starting the transmission.

To release the lightpaths, the source node sends the $release$ data to the destination. Unlike the control data, the $release$ data cannot be received by irrelevant routers since we have turned on corresponding microresonators in the turning and destination nodes. For example, the $release$ data to the $west$ reaches the turning node shown in Fig.2(b). Since microresonator 2 has been turned on, the $release$ data cannot further spread in the west direction, but is coupled to a terminator through the $Path\ E$. At the destination node, the situation is same.

B. Binary-tree Waveguide Design

The key component of the proposed ONoC is the Y-branch waveguide, which is widely utilized to realize 1×N optical splitters [19] [20]. In their technical scenarios, the Y-branch waveguide is expected to be symmetric with low excess power loss. Hence, each branch will get 50% input power if the excess power loss is omitted. However, the symmetric Y-branch leads to an asymmetric binary-tree waveguide with a very poor power efficiency. For example, the i^{th} level branch will get $1/2^i$ input optical power.

To address that problem, we adopt the asymmetric Y-branch waveguide [21], [22], which has a high extinction ratio with a very low excess power loss. If the physical parameters (such as materials, bending radius, and the length of arms) are fixed, the extinction ratio between two branches is a function of the wavelength. In other words, if the wavelength is fixed, we could adjust the extinction ratio by changing the physical parameters.

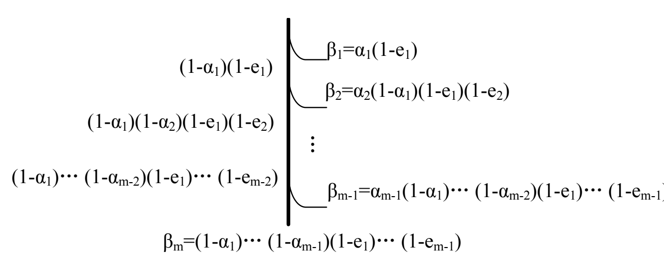


Fig. 3. Asymmetrically optical splitting.

As shown in Fig. 3, we assume that the excess power loss per Y-branch is e_i, thus $(1-e_i)$ effective input power is split into two branches. Particularly, we assume that the i^{th} level branch splits α_i of the effective input power to the coupled router, and splits $(1-\alpha_i)$ to the stem branch for further spreading. The objective is to minimize the difference between the optical power coupled to different routers. Mathematically, the problem is formulated as a NLP problem as shown in (1), where m is the number of leaves. Note that, The binary-tree waveguide design is utilized to direct the fabrication, and the extinction ratios are fixed once the chip is taped out.

$$Min \quad variance = \frac{1}{m}\sum_{i=1}^{m}(\beta_i - \overline{\beta})^2$$

$$s.t. \quad \begin{cases} \beta_i = \alpha_i \prod_{k=1}^{i-1}(1-\alpha_k)(1-e_k), 1 \le i \le m-1 \\ \beta_m = \prod_{k=1}^{m-1}(1-\alpha_k)(1-e_k) \\ \overline{\beta} = \frac{1}{m}\sum_{i=1}^{m}\beta_i \\ 0 < \alpha_i < 1 \end{cases} \tag{1}$$

Another design issue is how many Y-branches could be cascaded to form a binary-tree waveguide. Generally, we say a binary-tree waveguide is acceptable if its power loss is smaller than a predefined threshold. Now, we consider the following example. With the results of the above NLP problem, we calculate the power loss as shown in (2), where m is the number of leaves.

$$power\_loss = -10\lg\sum_{i=1}^{m}\beta_i \tag{2}$$

Example Consider a m-leaves binary-tree waveguide, we assume the excess power loss at each branch is 0.2 or 0.3 dB according to the different physical parameters [21], [22]. [1] For the binary-tree waveguides, with 1 to 16 leaves, we plot their results in Fig. 4. According to these results, we find that the proposed binary-tree waveguide is quite power efficient. For example, with the 0.2(0.3)dB excess power loss Y-branch, the total power loss is 0.45(0.67)dB and 0.89(1.35)dB for the 4-leaves and 8-leaves binary-tree waveguides respectively. If we define the threshold as 2dB, maximally 15(11) Y-branches with 0.2(0.3)dB excess power loss could be cascaded.

According to the law of conservation of energy, the input power (introduced by lasers) of the binary-tree waveguide is multiplied by the number of leaves, and this is inevitable for all techniques supporting broadcast or multicast. However, since the sensitivity of the photo-detector (-7.4dBm [16]) and the power efficiency of the binary-tree waveguide are both high enough, the power increase for broadcasting the control data is negligible.

[1]Actually, the excess power loss at different branch is different, but we assign a same value to all branches for both simplicity and the fact that there is no available function to describe it [21], [22].

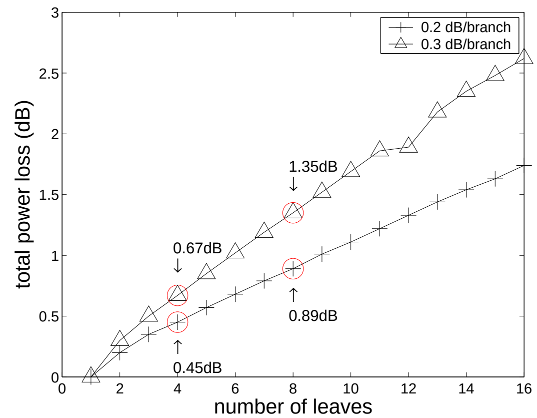


Fig. 4. The total power loss of binary-tree waveguide.

III. Experimental Results

In this section, we will show the performance of the proposed ONoC in term of packet latency through simulations with a cycle accurate ONoC simulator. This simulator, consisting of optical routers with coupled waveguides, realizes the optical circuit switching for both traditional and proposed ONoC. For the $control$ data, optical routers have three stages: receive, route, and forward. The previous two stages are same for both optical routers, while the forward stage is different. Through the established lightpath, the $payload$ data, as well as the ack data, is transmitted between the source and the destination.

In each simulation we utilize 1,000 cycles to warm up the simulator, and require five successive converged samples to terminate the simulation. The sample period is also assumed as 1,000 cycles, and a sample is considered as converged if its average packet latency differs with that of the proceeding sample within 5ps. The detailed models and parameters relating to the calculation of packet latency are discussed in the following.

As shown in (3), the packet latency is mainly composed of the setup time, and the time for transmitting $payload$, ack, and $release$ data. In particular, as shown in (4), the transmitting time is determined by the packet distance (H hops), waveguide length per hop (L), data size ($L_{<data\_type>}$), waveguide infractive index (n), light speed in vacuum (c), the O/E and E/O conversion delay ($t_{eo}+t_{oe}$). Note that the $< data\_type >$ in (4) should be replaced by $payload$, ack, and $release$.

$$t = t_{setup} + t_{payload} + 2 \cdot t_{ack} + t_{release} \tag{3}$$

$$t_{<data\_type>} = (H \cdot L \cdot L_{<data\_type>}) \cdot n/c + t_{eo} + t_{oe} \tag{4}$$

For the traditional ONoC, as shown in (5), the setup time consists of the blocking time (t_b), routing time (t_{rt}), the O/E and E/O conversion delay ($t_{eo}+t_{oe}$), as well as the propagation delay of control data (t_p). Particularly, $t_p = (L \cdot L_{ctrl}) \cdot n/c$,

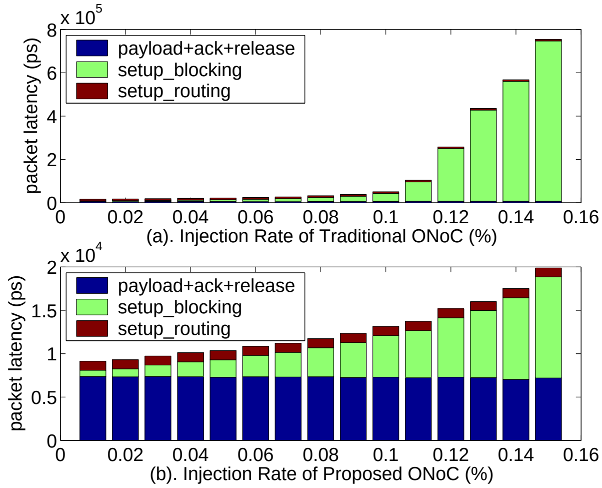


Fig. 5. Simulation results.

where L is the length of waveguide, L_{ctrl} is the size of control data. For the proposed ONoC, as shown in (6), the main difference is the number of routing and conversion delay. Particularly, $k = 0$ if the source and destination are in the same row or column, otherwise $k = 1$.

$$t_{setup} = t_b + (H+1) \cdot t_{rt} + H \cdot (t_{eo} + t_{oe} + t_p) \quad (5)$$

$$t^{'}_{setup} = t_b + t_{rt} + (1+k) \cdot (t_{rt} + t_{eo} + t_{oe}) + \frac{L_{ctrl} \cdot H \cdot L \cdot n}{c} \quad (6)$$

In this experiment, we assume a 16×16 network with a uniform traffic pattern. The t_{eo} is about 200ps [13], t_{oe} is about 140ps [16], and t_{rt} is about 250ps. Besides, as estimated in [6], the refractive index n is about 1.7. We assume the chip size is $1cm \times 1cm$, then the waveguide length L is maximally $\frac{1}{15}$cm.

Fig. 5(a) shows the simulation results in the traditional ONoC, while Fig. 5(b) shows the results in the proposed network. Particularly, we separately show the latency introduced by different data type. More specifically, for the $setup$ latency, we further consider the latency caused by the routing (including the O/E and E/O conversion delay, as well as the propagation delay of the control data), and that solely caused by blocking. According to these results, proposed ONoC significantly reduces the packet latency (more than 90%) compared to the traditional ONoC. In the traditional ONoC, the setup time dominates the packet latency. As the increase of injection rate, more than 99% packet latency is introduced by the setup time. In the proposed ONoC, the setup time is significantly reduced by broadcasting the control data. Furthermore, the possibility of blocking is also largely reduced.

Another experiment, which is omitted due to the limited space, shows that the proposed ONoC consumes larger energy than the traditional one. This is mainly incurred by the broadcasting in the proposed binary-tree waveguide. However, the proposed ONoC is still very power efficient compared with the electrical NoC (about 80% reduction), which consumes several nano-joule per packet [11].

IV. Conclusion

In this paper, we proposed a new ONoC to address the problem that transmitting the control data, for establishing the lightpath, becomes the bottleneck of ONoC. The proposed network exploits the asymmetric Y-branch waveguide and the regularity of xy routing to enable the broadcast of the control data both in horizontal and vertical binary-tree waveguides. As a consequence, only one extra routing delay, as well as a group of O/E and E/O conversion delay, is introduced into the lightpath establishment at the turning node. Furthermore, we show that the proposed binary-waveguide is power efficient enough to be implemented on current and future large-scale ONoC. Finally, we demonstrate that the proposed ONoC significantly reduces the packet latency through simulations.

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