A Universal Method for Constructing N-port Non-blocking Optical Router Based on 2×2 Optical Switch

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Abstract— We propose a universal method for constructing N-port non-blocking optical router fully based on 2×2 optical switches. The proposed optical router has fewer optical switches and lower power-consumption.

1. INTRODUCTION

With CMP continuously requiring more communication bandwidth, metallic-based electrical network-on-chip (NoC) gradually becomes the bottleneck for improving the performance of CMP due to its high power consumption, limited bandwidth and long latency [1]. Photonic NoC is considered as a potential solution to overcome the limitations of its electrical counterpart. Many topologies for photonic NoCs have been widely studied, such as Mesh, Torus, Crossbar, Fat-Tree and Clos. The optical router is located at each node of photonic NoC and connects the local processing core with other processing cores. Several nonblocking optical routers have been proposed or even demonstrated [2–5], which are not scalable. High-radix non-blocking optical routers have potential applications in the future on-chip optical interconnects, such as Cluster-Mesh and Clos photonic NoCs. We also propose a general guideline for designing the N-port non-blocking optical router based on MR optical switches [5]. Although MR optical switch or M-Z optical switch can manipulate two optical links simultaneously, most reported optical routers fully or partly utilize them as 1×2 optical switches. In this paper, we propose a universal method for constructing the N-port non-blocking optical router, in which all optical switches behave as 2×2 optical switches.

2. GUIDELINES FOR CONSTRUCTING N-PORT NON-BLOCKING OPTICAL ROUTER

Figure 1 shows the schematics of the M-Z optical switch, the MR optical switch with two parallel waveguides and the MR optical switch with two cross waveguides. Note that the MR optical switch with two parallel waveguides is rearranged so that two input ports are located at one side and two output ports are located at the other side. All three optical switches can be abstracted as a simplified 2×2 optical switch and the details in the dotted box do not affect our discussion on the construction method. One 2×2 optical switch can manipulate two optical links simultaneously.

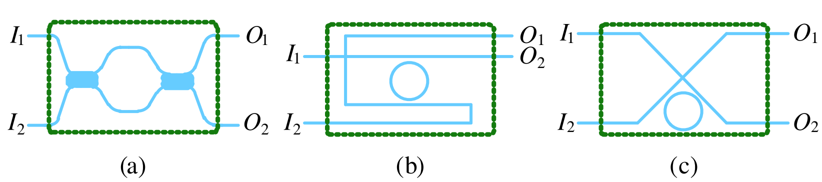


Figure 1: Schematic of (a) M-Z optical switches, (b) the MR optical switch with two parallel waveguides, (c) the MR optical switch with two cross waveguides.

Compared to 1×2 optical switch, 2×2 optical switch manipulate two optical links simultaneously. (see Fig. 2(b)). One 2×2 optical switch can realize the functions of two 1×2 optical switches. If the N-port non-blocking optical router is constructed by 2×2 optical switches, the number of the used optical switches can be reduced by half.

Any N-port non-blocking optical router for photonic NoC must obey the following rules, which have been adopted in the reported optical routers. (1) Communication from the input to the output for the same port is not required. (2) N-port optical router should be non-blocking in order to avoid link contentions. (3) For an N-port non-blocking optical router, light injected into the input of one port must be able to be guided to any output of the other $(N-1)$ ports.

According to the guidelines mentioned above, if the N-port non-blocking optical router is constructed by 2×2 optical switches, $N(N-2)/2$ optical switches are required if N is an even number

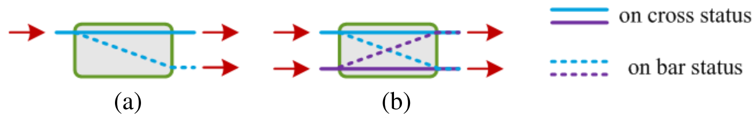


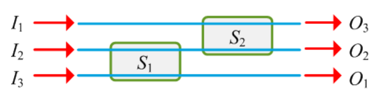
Figure 2: (a) 1×2 optical switch and (b) 2×2 optical switch.

and at least $(N-1)^2/2$ optical switches are required if N is an odd number. N waveguides are required. Since the number of the used optical switches is dependent on the parity of N, we firstly introduce the simplest two optical routers when N is an odd and even number, respectively, and then introduce the expanding method from the $(N-2)$-port non-blocking optical router to the N-port non-blocking optical router. It should be noted that the expanding method for the N-port non-blocking optical router does not depend on the parity of N although the start point is different when N is an odd or even number.

Table 1 shows the schematics of the 3- and 4-port optical routers. The 3-port optical router has two routing states and the 4-port optical router has nine routing states. To demonstrate their non-blocking routing, all of the possible cases are listed in the Table 1. Clearly, the 3- and 4-port optical routers are non-blocking and their optical links obey the aforementioned rules.

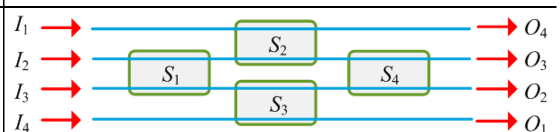
Table 1: Schematics of the 3- and 4-port optical routers and their routing tables.

3-port optical router



State	Optical links	S_1	S_2
1	$I_1 \to O_2$, $I_2 \to O_3$, $I_3 \to O_1$	Cross	Bar
2	$I_1 \to O_3$, $I_2 \to O_1$, $I_3 \to O_2$	Bar	Cross

4-port optical router



State	Optical links	S_1	S_2	S_3	S_4
1	$I_1 \to O_2$, $I_2 \to O_3$, $I_3 \to O_4$, $I_4 \to O_1$	Cross	Cross	Bar	Cross
2	$I_1 \to O_3$, $I_2 \to O_4$, $I_3 \to O_1$, $I_4 \to O_2$	Bar	Cross	Cross	Bar
3	$I_1 \to O_4$, $I_2 \to O_1$, $I_3 \to O_2$, $I_4 \to O_3$	Cross	Bar	Cross	Cross
4	$I_1 \to O_2$, $I_2 \to O_1$, $I_3 \to O_4$, $I_4 \to O_3$	Cross	Cross	Cross	Cross
5	$I_1 \to O_2$, $I_2 \to O_4$, $I_3 \to O_1$, $I_4 \to O_2$	Bar	Cross	Cross	Cross
6	$I_1 \to O_3$, $I_2 \to O_4$, $I_3 \to O_2$, $I_4 \to O_1$	Bar	Cross	Bar	Bar
7	$I_1 \to O_3$, $I_2 \to O_1$, $I_3 \to O_4$, $I_4 \to O_2$	Cross	Cross	Cross	Bar
8	$I_1 \to O_4$, $I_2 \to O_3$, $I_3 \to O_2$, $I_4 \to O_1$	Bar	Bar	Bar	Bar
9	$I_1 \to O_4$, $I_2 \to O_3$, $I_3 \to O_1$, $I_4 \to O_2$	Bar	Bar	Cross	Bar

Figure 3 illustrates the expanding method from the $(N-2)$-port optical router to the N-port optical router. Two waveguides and $2(N-2)$ optical switches are added to the $(N-2)$-port optical router. When N is an odd number, the 5-, 7-,..., $(N-2)$- and N-port optical routers can be constructed successively based on the 3-port optical router by the expanding method. When N is an even number, 6-, 8-, ..., (N-2)- and N-port optical routers can be constructed successively based on the 4-port optical router by the expanding method.

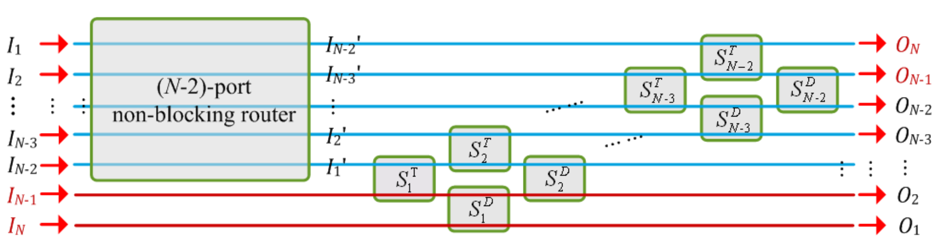


Figure 3: Expanding method from the $(N-2)$-port non-blocking optical router to the N-port non-blocking optical router.

Following the expanding method, the 5-port optical router can be constructed by adding two waveguides and six optical switches (S_3, S_4, S_5, S_6, S_7, S_8) to the 3-port optical router and the 6-port optical router can be constructed by adding two waveguides and eight optical switches (S_5,

S_6, S_7, S_8,S_9, S_{10}, S_{11}, S_{12}) to the 4-port optical router (see Figs. 4(a) and 4(b)). The 5-port optical router has 44 routing states and the 6-port optical router has 265 routing states. In order to check whether blocking occurs or not, we exhaust all optical links in each routing state and find that the 5- and 6-port optical routers are non-blocking. The 5- and 6-port optical routers have 8 and 12 optical switches respectively, which 50% less than the reported optical routers based on MR optical switches [28–32].

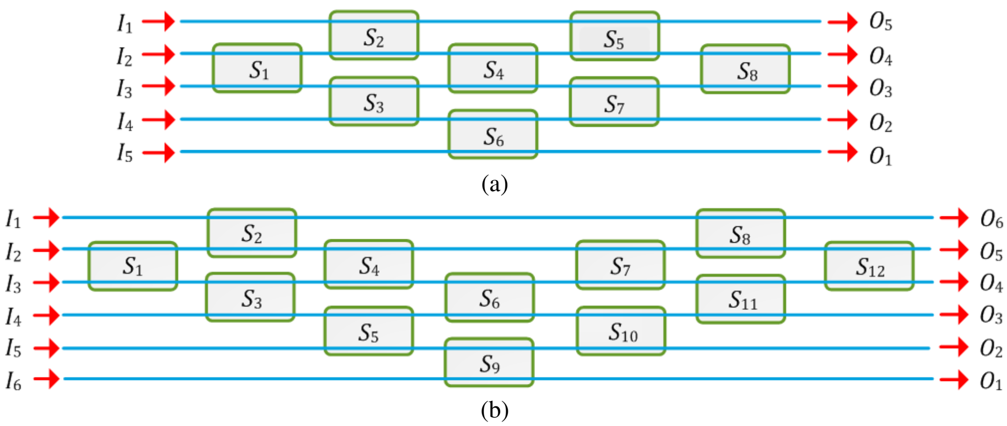


Figure 4: Schematics of the 5- and 6-port non-blocking optical routers.

Since all input ports are arranged on one side and all output ports are arranged on the other side for the reported optical router based on M-Z optical switch [24], we can compare the proposed optical router with it directly. Since the input and output for one specific port of the reported optical routers based on MR optical switches are arranged in the same physical address [25–31], we replace all 2×2 optical switches in the proposed optical routers by MR optical switches and arrange their input and output for one specific port in the same physical address. To facilitate expression, we define the propagation losses of the 2×2 optical switch on the "cross" and "bar" statuses as X_c and X_b respectively, the propagation loss of the waveguide cross as Y, the tuning power consumption of a 2×2 optical switch as P. The average power consumption of the proposed 5-port optical router is at least 28% less than the reported 5-port optical routers. All optical routers have small difference in average insertion loss and worst-case insertion loss. We can conclude that fully adopting 2×2 optical switches in the optical router can reduce its average power consumption and footprint without sacrificing its insertion loss. Tables 2 and 3 show the comparisons of the proposed 4- and 5-port optical routers with the reported 4- and 5-port optical routers.

Table 2: Comparison of the proposed 4-port optical router with the reported 4-port optical routers [6–9].

		Columbia [6]	**HKUST [7]**	**ISCAS-Ji [8]**	**IBM [9]**	**This work**
Switch		8	8	8	6	4
Average loss	MR	$\frac{24X_c+8X_b+40Y}{12}$	$\frac{24X_c+8X_b+32Y}{12}$	$\frac{24X_c+8X_b+24Y}{12}$		$\frac{16X_c+8X_b+36Y}{12}$
	M-Z				$\frac{21X_c+7X_b+32Y}{12}$	$\frac{16X_c+8X_b}{12}$
Worst-case loss	MR	$2X_c+X_b+4Y$	$2X_c+X_b+4Y$	$2X_c+X_b+2Y$		$2X_c+X_b+4Y$
	M-Z				$2X_c+X_b+4Y$	$2X_c+X_b$
Power /state		$24P/9$	$24P/9$	$24P/9$	$20P/9$	$16P/9$

The number of the optical switches used by an optical router decides its footprint. The 4- and

Table 3: Comparison of the proposed 5-port optical router with the reported 5-port optical routers [2–5].

	HKUST-Poon [2]	HKUST-Gu [3]	ISCAS-Ji [4]	ISCAS-Min [5]	This work
Switch	20	16	16	15	8
Average loss	$\frac{60X_c+20X_b+90Y}{20}$	$\frac{58X_c+16X_b+61Y}{20}$	$\frac{59X_c+16X_b+68Y}{20}$	$\frac{60X_c+15X_b+60Y}{20}$	$\frac{48X_c+16X_b+80Y}{20}$
Worst-case loss	$6X_c+X_b+9Y$	$4X_c+X_b+6Y$	$4X_c+X_b+4Y$	$4X_c+X_b+4Y$	$4X_c+X_b+6Y$
Power /state	$176P/44$	$176P/44$	$176P/44$	$165P/44$	$119P/44$

5-port optical routers constructed by this method use 4 and 8 optical switches respectively, which is about 50% less than the reported optical routers based on MR optical switches and more than 30% less than the reported optical router based on M-Z optical switches.

Power consumption is one critical point for designing photonic NoC. To establish different optical links will require different power consumption for the optical routers. To characterize the power efficiency of the optical routers, we get the average power consumption per routing state by the statistics method. We assume that each routing state occurs with equal probability. 4-port optical router has 9 routing states, each of which comprises four independent links, and 5-port optical router has 44 routing states, each of which comprises five independent links. As shown in Tables 2 and 3, the average power consumption of the proposed 4-port optical router is at least 20% less than the reported 4-port optical routers and the average power consumption of the proposed 5-port optical router is at least 28% less than the reported 5-port optical routers.

Insertion loss is another critical point for designing photonic NoC. Different optical links of an optical router may have different insertion losses. The 4-port non-blocking optical router has 12 optical links and the 5-port non-blocking optical router has 20 optical links. Tables 2 and 3 show the comparisons in average insertion loss and worst-case insertion loss between the proposed 4- and 5-port optical routers and the reported 4- and 5-port optical routers. We find that all optical routers have small difference in average insertion loss and worst-case insertion loss.

Based on the above analysis, we can conclude that fully adopting 2×2 optical switches in the optical router can reduce its average power consumption and footprint without sacrificing its insertion loss.

3. CONCLUSION

We propose a universal method for constructing N-port non-blocking optical router for photonic networks-on-chip, in which all MR optical switches or M-Z optical switches behave as 2×2 optical switch. The optical router constructed by this method has the lowest average power consumption and requires the least theoretical optical switches, in which the number of the optical switches is reduced about 50% compared to the reported optical routers based on MR optical switches and more than 30% compared to the reported optical routers based on M-Z optical switches, and therefore is more compact in footprint.

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