On-Chip Wavelength-Routed Photonic Networks with Comb Switches

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Abstract

In this paper we propose to use comb switches to simplify Banyan-type on-chip wavelength-routed passive photonic networks constructed by micro-ring resonator (MRR)-based optical switches. Compared with general wavelength-routed optical networks, the number of MRRs used in the simplified network is significantly reduced.

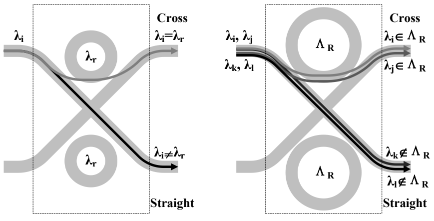
I. INTRODUCTION

Photonic Network-on-Chips (NoCs) have been proposed as a promising solution to interconnect a large number of processing cores. The heart of a photonic NoC is the on-chip photonic interconnection network which is composed of silicon waveguides and optical switches [1]. Micro-ring resonator (MRR)-based optical switches are typically preferred due to its ultra-compact size (3-10μm diameter), simple-mode resonances and ease of phase matching between the MRR and the coupled waveguides [1]. Fig. 1(a) shows the operation of a 2×2 MRR-based optical switch. The incident light is only coupled through the switch on the cross direction (i.e., dropped) if the incident wavelength λ_i satisfies

$$m_i \lambda_i = n_{eff} L \qquad (1)$$

where m_i is an integer number, L is the cavity of the ring, and n_{eff} is the effective index of the optical mode.

For any given L, there exist a set of λ satisfying Eqn. (1) corresponding to different integer m. Fig. 1(b) illustrates the 2×2 MRR-based comb switch [2-4] which is designed based on this principle. A comb switch can drop off lights with the set of wavelengths that satisfy Eqn. (1) to another waveguide while passing through lights with all other wavelengths. The size of the MRR in a comb switch shall be carefully chosen such that the desired set of wavelengths can be dropped.



(a) (b)

Fig. 1. MRR-based 2×2 switch (a) and 2×2 comb switch (b).

In recent years, a number of MRR-based wavelength-routed optical NoC architectures have been proposed. The λ-router [5] is constructed by cascading MRR-based switches to form a Banyan network. But this router architecture is only applicable to networks with even-numbered input/output ports. This parity problem is later solved by the generalized wavelength-routed optical network (WRON) [6]. The generic passive router [7] is similar to WRON in topology but excludes self-communications. Another passive optical router is the oblivious bidirectional 5×5 cross-grid wavelength router [8], which is compact in size. But the high design complexity makes it difficult to be extended to construct a larger sized network. The passive optical routers listed above are non-blocking. Most of these wavelength-routed optical networks are isomorphic in topology, which is Banyan-type. In [9], another cascaded $N \times N$ wavelength-routed network is proposed, which, unfortunately, is an incomplete crossbar as not all input signals can be routed to any of the outputs. The 4×4 64-wavelength optical crossbar proposed in [10] can route 16 different wavelengths. However, this design is actually blocking.

In this paper we propose to use comb switches to simplify Banyan-type wavelength-routed passive photonic networks. Without loss of generality, we use WRON [6] to describe this process. The analytical result shows that the number of MRRs needed is reduce by O($N^{1/2}$) after the simplification.

II. TRANSFORM THE BASIC NETWORK TO THE RECURSIVE NETWORK

A. Passive wavelength routing optical networks

An N-WRON has N inputs and N outputs that can be used to interconnect N nodes [6]. Inside an N-WRON there are N stages of MRR switches, with the MRRs at each stage sharing a distinct resonance wavelength. The number of MRRs in an N-WRON is

$$S_{WRON} = N^2 - N. \qquad (2)$$

According to the routing scheme in [6], a unique input wavelength can be determined for communication between an input and an output. Totally N input wavelengths are needed for realizing the communication of any permutation of all inputs and outputs. Besides, multicasting/broadcasting and many-to-one communication can be supported on an N-WRON with wavelength-division multiplexing. That is to say, any input can communicate with all N outputs simultaneously with N wavelengths. Totally N^2 simultaneous communications between N inputs to N outputs are supported on an N-WRON without confliction. Fig. 2 shows the structure of 9-WRON. In the network, totally there are 72 MRRs, assigned to nine stages according to the resonance wavelengths. Correspondingly, nine input wavelengths are needed in support of communication between any input and any output.

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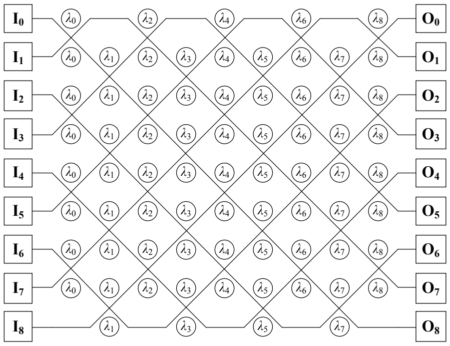
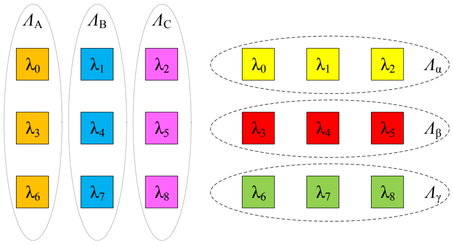


Fig. 2. 9-WRON.

B. *Transformation of WRON into Recursive Structure*

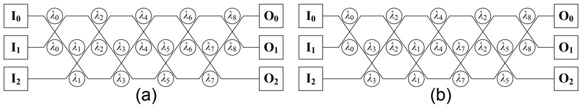
An N^2-WRON requires N^2 input wavelengths. These N^2 wavelengths can be arranged into an $N \times N$ 2D matrix. Then from each dimension the matrix can be partitioned to N subsets with N wavelengths in each subset. Fig. 3 shows the wavelength partitions of 3^2 wavelengths from two dimensions.



(a) (b)

Fig. 3. Wavelengths partitioning in a 9×9 WRON.

Two types of $N \times N$ Redundant WRONs (RDWRONs) [6] can be built by adopting the wavelengths in each column as an input wavelength group (Type I RDWRON) and the wavelengths in each row as an input wavelength group (Type II RDWRON), respectively. There are N^2 stages of MRR switches in an $N \times N$ RDWRON. Fig. 4 shows these two types of RDWRONs. Tab. I presents the routing wavelength assignments for 3×3 Type I and II RDWRONs.



(a) (b)

Fig. 4. (a) 3×3 Type I RDWRON. (b) 3×3 Type II RDWRON.

TABLE I
ROUTING WAVELENGTHS ASSIGNMENT OF 3×3 TYPE I & II RDWRON.

Λ	TYPE I RDWRON			TYPE II RDWRON		
	O_0	O_1	O_2	O_0	O_1	O_2
I_0	$\lambda_1,\lambda_4,\lambda_7$	$\lambda_0,\lambda_3,\lambda_6$	$\lambda_2,\lambda_5,\lambda_8$	$\lambda_3,\lambda_4,\lambda_5$	$\lambda_0,\lambda_1,\lambda_2$	$\lambda_6,\lambda_7,\lambda_8$
I_1	$\lambda_2,\lambda_5,\lambda_8$	$\lambda_1,\lambda_4,\lambda_7$	$\lambda_0,\lambda_3,\lambda_6$	$\lambda_6,\lambda_7,\lambda_8$	$\lambda_3,\lambda_4,\lambda_5$	$\lambda_0,\lambda_1,\lambda_2$
I_2	$\lambda_0,\lambda_3,\lambda_6$	$\lambda_2,\lambda_5,\lambda_8$	$\lambda_1,\lambda_4,\lambda_7$	$\lambda_0,\lambda_1,\lambda_2$	$\lambda_6,\lambda_7,\lambda_8$	$\lambda_3,\lambda_4,\lambda_5$

The $N \times N$ recursive WRON (N-RCWRON) can be constructed by interconnecting N Type I RDWRONs and N Type II RDWRONs. A unique input wavelength can be derived to route between an input and an output in an RCWRON. The structure of 9-RCWRON is shown in Fig. 5. The total number of MRRs in an N-RCWRON is

$$S_{RCWRON} = 2N^2 - 2N^{3/2} \tag{3}$$

Similarly, all other isomorphic networks of WRONs can be transformed to RCWRON-like structures.

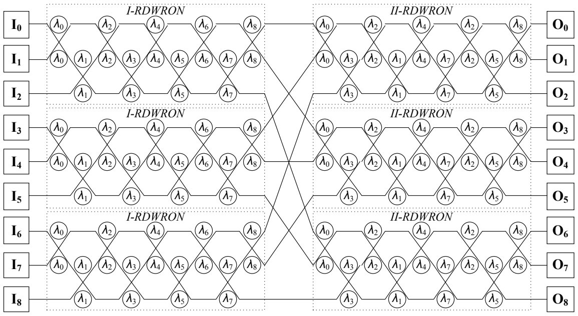


Fig. 5. 9-RCWRON.

III. WRON WITH COMB SWITCHES

The structure of an RCWRON can be simplified using comb switches. In general, according to the partitions (as shown in Fig. 3) of N^2 wavelengths, for each wavelength set Λ, a comb switch can be designed to only resonate the wavelengths in Λ by properly selecting its cavity length L_{comb} as

$$\begin{cases} \Lambda = \{\lambda_i \mid i = 1, \dots, N\} \\ n_{eff} L_{comb} = m_1 \lambda_1 = \cdots = m_N \lambda_N \quad m_1, \dots, m_N \in \boldsymbol{I} \end{cases}$$

By replacing the stages of MRRs with resonance wavelengths in a wavelength set by the corresponding comb switch in a Type I/Type II RDWRON, a Type I/Type II RDWRON with comb switches (shortened as RDWRON-CS) can be constructed. Further an $N \times N$ RCWRON with comb switches (shortened as WRON-CS) can be constructed by using N pairs of Type I and Type II RDWRON-CS. An $N \times N$ WRON-CS has exactly the same functions as the same size RCWRON yet using much less number of MRRs.

For the example in Fig. 3, the following 3 wavelength sets for each of the two wavelengths partitions can be defined:

Λ_A:	$\lambda_0,\lambda_3,\lambda_6$	Λ_α:	$\lambda_0,\lambda_1,\lambda_2$
Λ_B:	$\lambda_1,\lambda_4,\lambda_7$	Λ_β:	$\lambda_3,\lambda_4,\lambda_5$
Λ_C:	$\lambda_2,\lambda_5,\lambda_8$	Λ_γ:	$\lambda_6,\lambda_7,\lambda_8$

Fig. 6 presents the 9×9 WRON-CS comprised of Type I and Type II RDWRON-CS. And its routing wavelength assignment is shown in Tab. II.

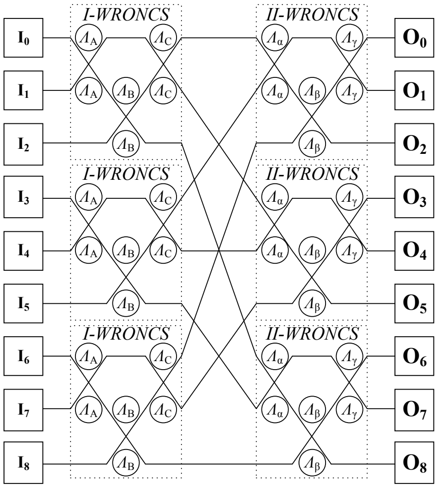


Fig. 6. 9×9 WRON-CS.

TABLE II
9×9 RCWRON WAVELENGTH ROUTING TABLE

Λ	O_0	O_1	O_2	O_3	O_4	O_5	O_6	O_7	O_8
I_0	λ_4	λ_1	λ_7	λ_3	λ_0	λ_6	λ_5	λ_2	λ_8
I_1	λ_5	λ_2	λ_8	λ_4	λ_1	λ_7	λ_3	λ_0	λ_6
I_2	λ_3	λ_0	λ_6	λ_5	λ_2	λ_8	λ_4	λ_1	λ_7
I_3	λ_7	λ_4	λ_1	λ_6	λ_3	λ_0	λ_8	λ_5	λ_2
I_4	λ_8	λ_5	λ_2	λ_7	λ_4	λ_1	λ_6	λ_3	λ_0
I_5	λ_6	λ_3	λ_0	λ_8	λ_5	λ_2	λ_7	λ_4	λ_1
I_6	λ_1	λ_7	λ_4	λ_0	λ_6	λ_3	λ_2	λ_8	λ_5
I_7	λ_2	λ_8	λ_5	λ_1	λ_7	λ_4	λ_0	λ_6	λ_3
I_8	λ_0	λ_6	λ_3	λ_2	λ_8	λ_5	λ_1	λ_7	λ_4

The total number of MRRs used in an $N \times N$ WRON-CS is

$$S_{CRON} = 2N^{3/2} - 2N \tag{4}$$

Tab. III shows the comparison of the number of MRRs used in different sized networks. From Eqns. (2) and (4), it can be seen that compared with an $N \times N$ WRON, the number of MRRs in an $N \times N$ WRON-CS is reduced by $O(N^{1/2})$ using comb switches.

Following the same process, other wavelength-routed optical networks isomorphic to WRONs can be simplified using comb switches.

TABLE III
COMPARISON OF NUMBER OF MRRS IN DIFFERENT NETWORKS

MRR Number	Network Size					
	9×9	16×16	25×25	36×36	49×49	64×64
WRON	72	240	600	1260	2352	4032
RCWRON	108	384	1000	2160	4116	7168
WRON-CS	36	96	200	360	588	896

IV. TRANSMISSION POWER LOSS

To evaluate the optical power loss experienced in the WRON-CS, the power loss parameters given in [11] are adopted: each MRR has a drop-loss of 1.5dB and a through-loss of 0.01dB, and the crossing-loss is 0.05dB. Therefore, for a given input-output pair $I_i \rightarrow O_j$ the total power loss on the routing path can be estimated by:

$$P_{loss}=1.5\times N_{drop}+0.01\times N_{through}+0.05\times N_{crossing}. \tag{5}$$

Tab. IV shows the minimum, maximum, and average N_{drop}, $N_{through}$, $N_{crossing}$, and total power loss among all routing paths for 9×9 WRON-CS.

TABLE IV
TRANSMISSION POWER LOSS IN

	Min.	Avg.	Max.
N_{drop}	0	1.33	2
$N_{through}$	2	5.88	8
$N_{crossing}$	0	2.04	4
P_{loss} (dB)	0.08	2.16	3.24

V. CONCLUSIONS

In this paper, we propose to use MRR-based comb switches to simplify Banyan-type on-chip wavelength-routed photonic network structures. The analysis shows that the total number of MRRs in an $N \times N$ network is reduced by $O(N^{1/2})$ after the simplification. This will help reduce the cost and fabrication complexity of on-chip photonic interconnection networks. Our future work includes design and prototyping of a WRON-CS or its isomorphic network.

ACKNOWLEDGEMENT

This work was supported in part by the National Science Foundation under grant no. CNS-1126688.

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