Computers and Electrical Engineering xxx (2009) xxx–xxx

Contents lists available at ScienceDirect

Computers and Electrical Engineering

journal homepage: www.elsevier.com/locate/compeleceng

Architectures and routing schemes for optical network-on-chips

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ARTICLE INFO

Available online xxxx

Keywords:
Network-on-chip (NoC)
Optical switch
Wavelength routed optical network (WRON)
Recursive wavelength routed optical network (RCWRON)

ABSTRACT

As indicated in the latest version of ITRS roadmap, optical wiring is a viable interconnect technology for future SoC/SiC/SiP designs that can provide broad band data transfer rates unmatchable by the existing metal/low-*k* dielectric interconnects. In this paper, we present an interconnection architecture, referred as the wavelength routed optical network (WRON), suitable to build on-chip optical micro-networks. The routing scheme for WRON, using any two of the three routing parameters (the source node address, the destination node address, and the routing wavelength), is generalized in this paper. With WRON as the primitive platform, we further propose a new recursive architecture, the recursive wavelength routed optical network (RCWRON), and it serves as the basis of a redundant architecture, the redundant wavelength routed optical network (RDWRON). The routing schemes for RCWRON and RDWRON are also detailed in this paper.

1. Introduction

The international technology roadmap for semiconductors (ITRS) [18] has predicted that by 2010, high performance system-on-chips (SoCs) will grow to two billion transistors running at a frequency of 10 GHz. With a communication-centric design style, network-on-chip (NoC) [2] was proposed as a new paradigm of SoC to meet the distinctive challenges of providing functionally correct, reliable operation of interacting SoC components. The continuously shrinking feature sizes, higher clock frequencies, and the simultaneous growth in complexity have made electrical interconnects a formidable task [5,6,14]. Current interconnect (metal/dielectric) is not sufficient to meet such requirements.

Two important issues come out. (1) Material and signal front: optics (optical signal) to replace metal (electrical signal) based interconnection (signal). Looking further into the future, optical wiring could significantly raise the performance limits hindered by metal/dielectric interconnects [9]. Optical fibres are capable of carrying encoded optical data in terabits per second while maintaining near speed-of-light limited transit latencies [16]. Moreover, the power consumed by optical interconnect is almost independent of the interconnect length [7], and is much less compared with electrical interconnect (around 1/10 in general) [19]. (2) Architecture front: it is inevitable that network-on-chip (NoC) will replace the traditional SoC architecture. An NoC system is composed of a large number of processing units communicating to other units through an interconnection network. This interconnection network plays an important role in achieving high performance, scalability, power efficiency, and fault-tolerance.

These two issues when combined lead to optical network-on-chip (ONoC). ONoC has been considered to enabling high bandwidth and low contention routing of data [16] using wavelength division multiplexing (WDM)-enabled optical waveguides [14]. Here optical switch [12] and waveguides [1] are used in ONoC to realize the same function as a conventional electrical router but with routing based on wavelength and with no need for an arbiter [17].

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0045-7906/$ - see front matter
doi:10.1016/j.compeleceng.2008.09.010

In [4], a micronetwork architecture based on wavelength routing is suggested for on-chip optical networks. This architecture has been generalized in this paper [4] and the routing scheme for this architecture is also developed. Based on WRON, we present a new redundant architecture, the redundant wavelength routed optical network (RDWRON), with higher degree of fault-tolerance capability. Next we further develop a new recursive architecture, the recursive wavelength routed optical network (RCWRON) based on the RDWRON, and provide the routing schemes for both RDWRON and RCWRON.

The rest of the paper is organized as follows. Section 2 introduces the operating mechanism of basic optical switches. Section 3 presents the basic structure of the WRON, and Section 4 details the routing scheme of WRON. In Section 5, we present the RDWRON as the basic building block to construct the RCWRON. Section 6 presents the structure of RCWRON, followed by its routing scheme shown in Section 7. Section 8 concludes the paper with suggestions for future exploration.

2. Basic optical switches

An optical switch is a resonating structure, and is most commonly used in "add-drop" filters [14] (named so because of their capacity to add or subtract a signal from a waveguide based on its wavelength). As shown in Fig. 1, one switch is composed of one or more identical microdisks evanescently side-coupled to signal waveguides [3]. The electromagnetic field is propagated within the structure only for modes corresponding to specific wavelengths, where these resonant wavelength values are determined by geometric and structural parameters (substrate and microdisk material index, thickness and radius of microdisk) [11].

The basic function of an optical switch can be viewed as a wavelength-controlled switch. The operation of the switch depends on the wavelength of the signal entering at one of the inputs of the bidirectional add-drop filter, w_p. Each filter is associated with a resonant wavelength, e.g., w_i for the switch shown in Fig. 1. For any input signal from w_p, the signal will propagate to both filters. If $w_p = w_i$ (tolerance is of the order of a few nanometer, depending on the coupling strength between the disk and the waveguide), w_p passes through the switch on the same direction as the input signal (referred as the "straight" function); if $w_p \neq w_i$, the signal will pass through the switch on the cross direction (referred as the "across" function), as shown in Fig. 2. Noticeably, the input and output of the optical switch are reversible. However, to avoid conflicts

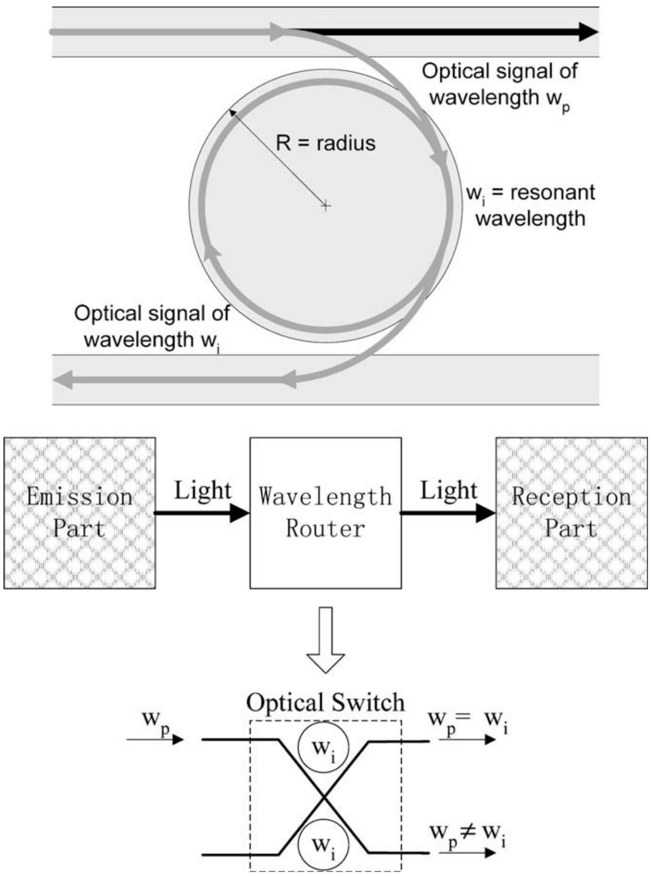

Fig. 1. Structure of the optical switch [14].

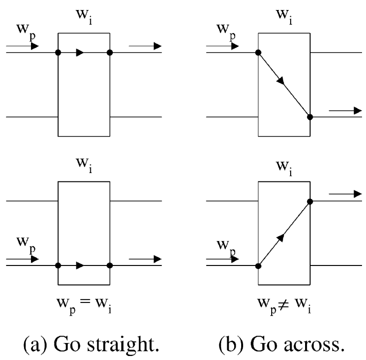

Fig. 2. Basic functions of the optical switch.

inside the optical switch (caused by the signals sent in opposite directions), it is not allowed to let inputs at opposite directions come to an optical switch simultaneously.

The advantages of such structures lie in the possibility of building highly complex, dense and passive on-chip switching networks. One application of this device is in optical crossbar networks. More elaborate $N \times N$ switching networks have been reported in [11], although their functionalities are subject to be verified experimentally. The optical switch shown in Fig. 1 can be used to build highly complex, dense and passive on-chip switching networks, as exemplified it can be applied to build 4×4 ONoC [14]. However, across the literature, there has been no general discussion of the network properties of the ONoC. In light of this special case of ONoC structure shown in [14], here we attempt to develop a generalized $N \times N$ (where N represents the number of input/output nodes) optical interconnection network suitable for ONoC. Following the same naming convention as adopted in [14], we shall name this network structure as wavelength routed optical network (WRON).

3. Basic structures of on-chip wavelength routed optical network

The generalized WRON is composed of input/output nodes and multiple stages of optical switches. In WRON, the number of stages is found equal to the number of input/output nodes, except for the case when only two input/output nodes are present. At any stage, all the optical switches within it share the same resonating wavelength.

The structure of an N-input/output WRON, hereafter denoted as N-WRON, is dependent on the value of N. Basically, there are two types of WRON.

3.1. WRON Type I

WRON type I has the following properties.

- When N is an odd number (i.e., there are odd-numbered input/output nodes), there are $(N-1)/2$ switches in each of N stages.
- When N is an even number, there are $N/2$ switches in each of the odd-numbered stages, and $(N/2)-1$ switches in each of the even-numbered stages.

Lemma 1. *The number of optical switches in an N-WRON is* $\frac{N\times(N-1)}{2}$.

Proof. When N is even, the number of optical switches is

$$\frac{N}{2}\times\frac{N}{2}+\left(\frac{N}{2}-1\right)\times\frac{N}{2}=\frac{N\times(N-1)}{2}.$$

When N is odd, the number of optical switches is

$$\frac{N-1}{2}\times N=\frac{N\times(N-1)}{2}. \qquad \square$$

As an example, the structure of type I 4-WRON and 5-WRON are shown in Fig. 3a and b, respectively.

In a type I WRON, all ports (nodes) in the network are labelled as follows.

- Denote the pth source node of an N-WRON as S_p, and the qth destination node as D_q.
- When n is an odd number, label the first and the second output ports (input ports) of the mth switch at the nth stage as $O(2m-1,n)$ and $O(2m,n)$ ($I(2m-1,n)$ and $I(2m,n)$), respectively.

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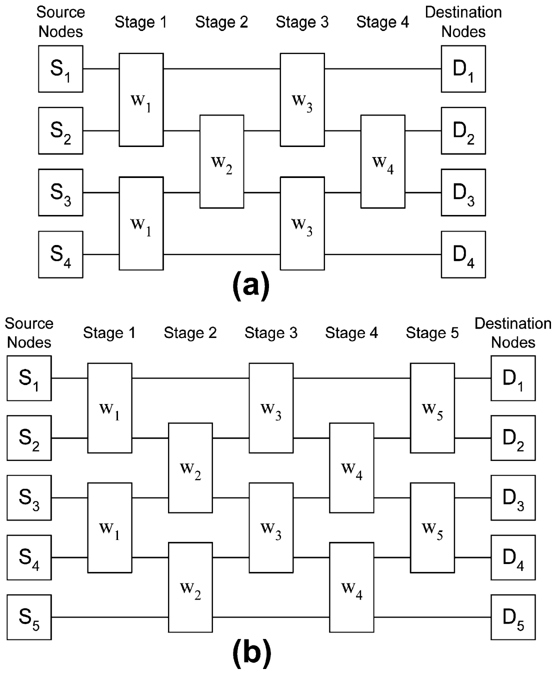

Fig. 3. (a) Type I 4-WRON and (b) Type I 5-WRON.

- When n is an even number, label the first and the second output ports (input ports) of the mth switch at the nth stage as $O(2m,n)$ and $O(2m+1,n)$ ($I(2m,n)$ and $I(2m+1,n)$), respectively.

The connection of all optical switches of an N-WRON can be clearly described by an $N \times (N+1)$ connection matrix. In the connection matrix, only the output ports of the switches in the prior stage or the source nodes connected to the input ports of the switches in the current stage or the destination nodes need to be considered.

Except the entries in the last column, any of the remaining entries in the connection matrix, denoted as $C(i,j)$, is the index of the output port (or source node) that the ith input port at the jth stage connects to. The kth entry in the $(N+1)$th column in the connection matrix specifies the output port which connects to destination node D_k. When there is no port connection, $C(i,j)$ is set to zero. This zero value also indicates a logical link that will bypass the jth stage's switches (i.e., a link that crosses two stages).

The connection matrix can be constructed as follows:

Case 1: (When N is an even number)

$$C(i,j) = \begin{cases} S_i & \text{when} \quad j = 1, \\ 0 & \text{when} \quad j = 2p \quad \& \quad 1 < j \leqslant N \quad \& \quad i = 1, \\ 0 & \text{when} \quad j = 2p \quad \& \quad 1 < j \leqslant N \quad \& \quad i = N, \\ O(i,j-2) & \text{when} \quad j = 2p+1 \quad \& \quad 1 < j \leqslant N+1 \quad \& \quad i = 1, \\ O(i,j-2) & \text{when} \quad j = 2p+1 \quad \& \quad 1 < j \leqslant N+1 \quad \& \quad i = N, \\ O(i,j-1) & \text{when} \quad j > 1 \quad \& \quad 1 < i < N. \end{cases}$$

Case 2: (When N is an odd number)

$$C(i,j) = \begin{cases} S_i & \text{when} \quad j = 1 \quad \& \quad i < N, \\ S_N & \text{when} \quad j = 2 \quad \& \quad i = N, \\ 0 & \text{when} \quad j = 2p \quad \& \quad 1 < j < N \quad \& \quad i = 1, \\ O(i,j-2) & \text{when} \quad j = 2p \quad \& \quad 2 < j \leqslant N+1 \quad \& \quad i = N, \\ O(i,j-2) & \text{when} \quad j = 2p+1 \quad \& \quad 1 < j < N \quad \& \quad i = 1, \\ 0 & \text{when} \quad j = 2p+1 \quad \& \quad 1 \leqslant j \leqslant N \quad \& \quad i = N, \\ O(i,j-1) & \textit{when} \quad j = N+1 \quad \& \quad i = 1, \\ O(i,j-1) & \textit{when} \quad j > 1 \quad \& \quad 1 < i < N. \end{cases}$$

As an example, the connection matrix of type I 4-WRON shown in Fig. 3a is given as

$$\left\{\begin{matrix} S_1 & 0 & O(1,1) & 0 & O(1,3) \\ S_2 & O(2,1) & O(2,2) & O(2,3) & O(2,4) \\ S_3 & O(3,1) & O(3,2) & O(3,3) & O(3,4) \\ S_4 & 0 & O(4,1) & 0 & O(4,3) \end{matrix}\right\}.$$

The connection matrix of the type I 5-WRON shown in Fig. 3b is given as

$$\left\{\begin{matrix} S_1 & 0 & O(1,1) & 0 & O(1,3) & O(1,5) \\ S_2 & O(2,1) & O(2,2) & O(2,3) & O(2,4) & O(2,5) \\ S_3 & O(3,1) & O(3,2) & O(3,3) & O(3,4) & O(3,5) \\ S_4 & O(4,1) & O(4,2) & O(4,3) & O(4,4) & O(4,5) \\ 0 & S_5 & 0 & O(5,2) & 0 & O(5,4) \end{matrix}\right\}.$$

3.2. WRON Type II

WRON type II has the following properties.

- When N is an odd number, there are $(N-1)/2$ switches in each of the N stages.
- When N is an even number, there are $(N/2)-1$ switches in each of the odd-numbered stages, and $N/2$ switches in each of the even-numbered stages.

As an example, the structure of type II 4-WRON and 5-WRON are shown in 4a and 4b, respectively.
Following the same notation, the connection matrix of type II WRON can be constructed as follows:

Case 1: (When N is an even number)

$$C(i,j) = \begin{cases} S_i & \text{when} \quad j=1 & \& \quad 1<i<N, \\ S_i & \text{when} \quad j=2 & \& \quad i=1 \text{ or } N, \\ 0 & \text{when} \quad j=2p+1 & \& \quad 1\leqslant j<N & \& \quad i=1, \\ 0 & \text{when} \quad j=2p+1 & \& \quad 1\leqslant j<N & \& \quad i=N, \\ O(i,j-2) & \text{when} \quad j=2p & \& \quad 2<j\leqslant N & \& \quad i=1, \\ O(i,j-2) & \text{when} \quad j=2p & \& \quad 2<j\leqslant N & \& \quad i=N, \\ O(i,j-1) & \text{when} \quad 1<j\leqslant N & \& \quad 1<i<N, \\ O(i,N) & \text{when} \quad j=N+1. \end{cases}$$

Case 2: (When N is an odd number)

$$C(i,j) = \begin{cases} S_i & \text{when} \quad j=1 & \& \quad 1<i\leqslant N, \\ S_1 & \text{when} \quad j=2 & \& \quad i=1, \\ 0 & \text{when} \quad j=2p & \& \quad 1<j<N & \& \quad i=N, \\ O(i,j-2) & \text{when} \quad j=2p & \& \quad 2<j\leqslant N+1 & \& \quad i=1, \\ O(i,j-2) & \text{when} \quad j=2p+1 & \& \quad 1<j\leqslant N & \& \quad i=N, \\ 0 & \text{when} \quad j=2p+1 & \& \quad 1\leqslant j\leqslant N & \& \quad i=1, \\ O(i,j-1) & when \quad 1<j\leqslant N & \& \quad 1<i<N, \\ O(i,j-1) & when \quad j=N+1 & \& \quad 1<i\leqslant N. \end{cases}$$

As an example, the connection matrix of the type II 4-WRON shown in Fig. 4a is given as

$$\left\{\begin{matrix} 0 & S_1 & 0 & O(1,2) & O(1,4) \\ S_2 & O(2,1) & O(2,2) & O(2,3) & O(2,4) \\ S_3 & O(3,1) & O(3,2) & O(3,3) & O(3,4) \\ 0 & S_4 & 0 & O(4,2) & O(4,4) \end{matrix}\right\}.$$

The connection matrix of the type II 5-WRON shown in Fig. 4b is given as

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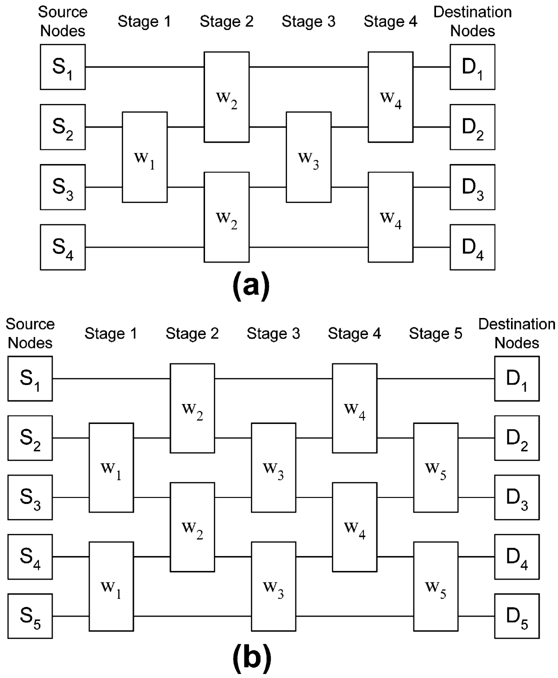

Fig. 4. (a) Type II 4-WRON and (b) Type II 5-WRON.

$$\left\{\begin{array}{cccccc} 0 & S_1 & 0 & O(1,2) & 0 & O(1,4) \\ S_2 & O(2,1) & O(2,2) & O(2,3) & O(2,4) & O(2,5) \\ S_3 & O(3,1) & O(3,2) & O(3,3) & O(3,4) & O(3,5) \\ S_4 & O(4,1) & O(4,2) & O(4,3) & O(4,4) & O(4,5) \\ S_5 & 0 & O(5,1) & 0 & O(5,3) & O(5,5) \end{array}\right\}$$

Type I WRON and type II WRON are closely related. When N is even, swapping the input and output nodes of a type I WRON will convert it to a type II WRON. When N is odd, rearranging the input and output nodes of type I WRON in a reversed order will convert it to a type II WRON. Therefore, the structure of types I and II WRON are isomorphic to each other, and the routing problems of type II WRON can be solved using the same solution to type I WRON combined with a simple linear numeric transform. In the following, we shall focus our study on type I WRONs only.

4. Routing scheme of WRON and its system organization

4.1. Routing scheme

In WRON, each routing path P_i is associated with a tri-tuple $\langle S, D, W \rangle$, where S denotes the source node address, D denotes the destination node address, and W is the assigned routing wavelength for the data transmission. All the wavelength assignments of a 4-WRON (Fig. 3a) are tabulated in Table 1. For instance, to send data from source node S_1 to destination node D_3, only wavelength w_1 can be used. From the same table one can see that by using four different wavelengths, S_1 can reach four destinations using the same wavelength; different sources can reach different destinations in a non-blocked fashion. Table 2 shows the wavelengths assignment for a 5-WRON (Fig. 3b).

In general, for an N-WRON, given any two of the three parameters (S, D, or W), the routing path is uniquely determined and the last parameter can be derived from the two known parameters as follows.

Table 1
The wavelength assignment of 4-WRON.

W	D_1	D_2	D_3	D_4
S_1	w_2	w_3	w_1	w_4
S_2	w_3	w_4	w_2	w_1
S_3	w_1	w_2	w_4	w_3
S_4	w_4	w_1	w_3	w_2

Proposition 1. *For an N-WRON, given the source node address S and the routing wavelength W, the destination node address D can be uniquely determined as*

$$D = f_D(N,S,W) = \begin{cases} 1 - D^* & \text{if } D^* \leqslant 0, \\ D^* & \text{if } 0 < D^* \leqslant N, \\ 2 \times N + 1 - D^* & \text{if } D^* > N, \end{cases} \tag{1}$$

where $D_* = S + (N - 2W + 1) \times (-1)^S$.

Proposition 2. *For an N-WRON, given the destination node address D and the routing wavelength W, the source node address S can be uniquely determined as*

$$S = f_S(N,D,W) = \begin{cases} 1 - S^* & \text{if } S^* \leqslant 0, \\ S^* & \text{if } 0 < S^* \leqslant N, \\ 2 \times N + 1 - S^* & \text{if } S^* > N, \end{cases} \tag{2}$$

where $S_* = D + (N - 2W + 1) \times (-1)^{N+D}$.

Proposition 3. *For an N-WRON, given the source node address S and the destination node address D, the routing wavelength W can be uniquely determined as*

$$W = f_W(N,S,D), \tag{3}$$

where

$$W = f_W(N,S,D) = \begin{cases} \frac{N+1+S-D}{2} & \text{when} \quad S = 2s \quad \& \quad D = 2d+1, \\ \frac{-N+S+D}{2} & \text{when} \quad S = 2s \quad \& \quad D = 2d \quad \& \quad S+D > N, \\ \frac{N+S+D}{2} & \text{when} \quad S = 2s \quad \& \quad D = 2d \quad \& \quad S+D \leqslant N, \\ \frac{N+1-S+D}{2} & \text{when} \quad S = 2s+1 \quad \& \quad D = 2d, \\ \frac{3N+2-S-D}{2} & \text{when} \quad S = 2s+1 \quad \& \quad D = 2d+1 \quad \& \quad S+D \geqslant N+2, \\ \frac{N+2-S-D}{2} & \text{when} \quad S = 2s+1 \quad \& \quad D = 2d+1 \quad \& \quad S+D < N+2, \end{cases}$$

when N is an even number, and

$$W = f_W(N,S,D) = \begin{cases} \frac{N+1+S-D}{2} & \text{when} \quad S = 2s \quad \& \quad D = 2d, \\ \frac{-N+S+D}{2} & \text{when} \quad S = 2s \quad \& \quad D = 2d+1 \quad \& \quad S+D > N, \\ \frac{N+S+D}{2} & \text{when} \quad S = 2s \quad \& \quad D = 2d+1 \quad \& \quad S+D \leqslant N, \\ \frac{N+1-S+D}{2} & \text{when} \quad S = 2s+1 \quad \& \quad D = 2d+1, \\ \frac{3N+2-S-D}{2} & \text{when} \quad S = 2s+1 \quad \& \quad D = 2d \quad \& \quad S+D \geqslant N+2, \\ \frac{N+2-S-D}{2} & \text{when} \quad S = 2s+1 \quad \& \quad D = 2d \quad \& \quad S+D < N+2, \end{cases}$$

when N is an odd number.

The proofs of Propositions 1–3 are given in Appendix I.

From the above propositions, one can see that in a WRON, any pair of source and destination nodes can be routed without experiencing a conflict when using a unique routing wavelength.

For example, in 4-WRON (Table 1), source nodes S_1, S_2, S_3 and S_4 can simultaneously communicate with the same destination node D_1, provided routing wavelength w_2, w_3, w_1 and w_4, are used. The only constraint applied to the routing in a WRON is that bidirectional communication between the same pair of nodes can not be possibly realized. The reason is quite simple, the wavelength used by routing from a source node to a destination node and the wavelength by routing on the reverse direction will be the same. The optical signals with the same wavelength but on opposite directions will cause interference inside an optical switch. This constraint must be observed by the communication protocol applicable to ONoC.

Table 2
The wavelength assignment of 5-WRON.

W	D_1	D_2	D_3	D_4	D_5
S_1	w_3	w_2	w_4	w_1	w_5
S_2	w_4	w_3	w_5	w_2	w_1
S_3	w_2	w_1	w_3	w_5	w_4
S_4	w_5	w_4	w_1	w_3	w_2
S_5	w_1	w_5	w_2	w_4	w_3

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4.2. System organization

To illustrate the system organization of a WRON, a 4-WRON is shown in Fig. 5 [15]. Here, there are a total of eight processing elements that are connected by a 4-WRON. Each processing element is directly connected to a transmitter block which enables the electro-optical conversion. Each transmitter core consists of laser(s) [10], drivers and a serializer, and each core has a receiver block [8,13] which enables the opto-electronic conversion. This opto-electronic unit features a PIN photodiode (conversion of flow of photons into photocurrent), a transimpedance amplifier (TIA), a decision circuit (digital signal regeneration) and a deserializer (DES) [3].

5. 2-D redundant optical network

As shown in Section 4, a WRON is capable of routing any permutation of a set of input and output nodes given enough wavelengths. However, as WRON is not a recursive structure, a large WRON cannot be built by connecting WRONs in smaller sizes. For example, a 6-WRON can not be directly obtained from connecting multiple 3, 4 or 5 WRONs.

Based on basic WRON structure introduced above, in what follows, we propose a new recursive structure, the two-dimensional recursive wavelength routed optical network (2-D RCWRON), and this 2-D RDWRON serves as the basic building block to build 2-D RCWRON. The construction and the routing scheme of RDWRON will be introduced in detail followed by the introduction of the RCWRON in the next section.

There are two basic units, the inverse connector (IC) and WRON, to construct a RDWRON.

5.1. Inverse connector IC

The function of an IC is to switch the input signal to specialized output port according to a fixed inverse function. We denote an IC with N source/destination nodes as N-IC, and its structure is shown in Fig. 6.

Lemma 2. *For an N-IC, if the address of a source node is S, the address of its destination node D is* $D = N + 1 - S$.

5.2. Construction of 2-D redundant optical network

The 2-D redundant wavelength routed optical network (RDWRON) is the basic building block to construct a 2-D RCWRON. A RDWRON with N input/output nodes is constructed by connecting N N-WRON and N-1 N-IC alternatively as shown in Fig. 7. Wavelengths in different stages in the RDWRON are preset as $1, 2, \ldots, N^2$ from the first stage of the first N-WRON to the last stage of the last N-WRON.

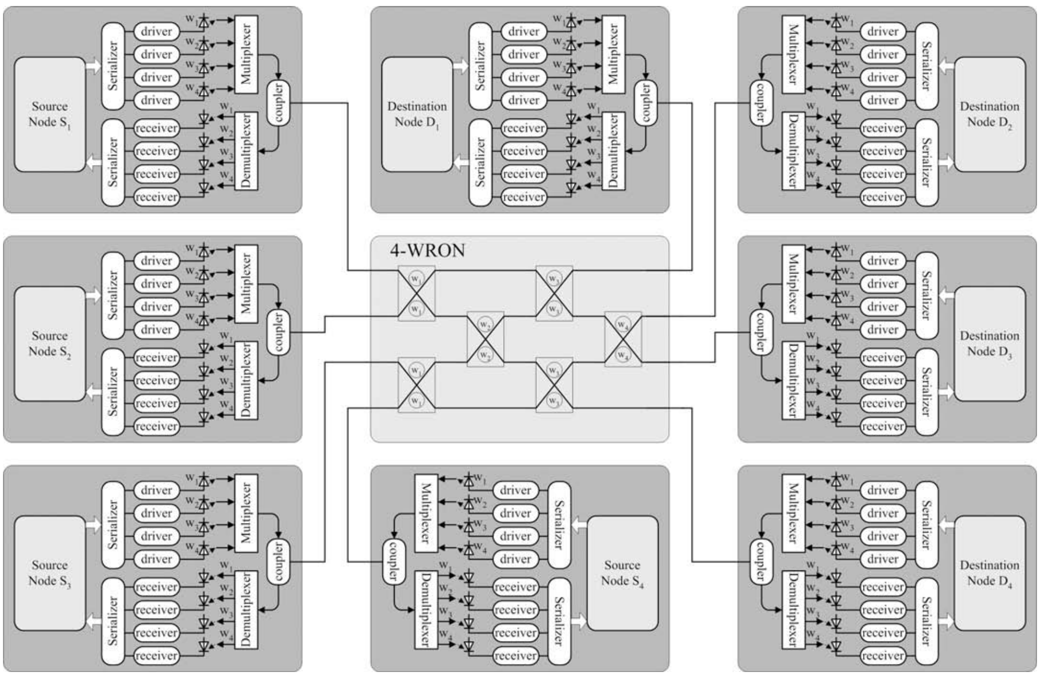


Fig. 5. System organization of a 4-WRON.

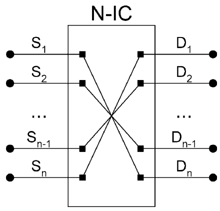


Fig. 6. Structure of an N/Ic

We denote 2-D RDWRON with N input/output nodes as N^2-RDWRON. Fig. 8 shows the structures of 3^2-RDWRON and 4^2-RDWRON.

Lemma 3. *The total number of switches in one 2-D N^2-RDWRON is* $O_{RDWRON} = N \times \frac{N\times(N-1)}{2} = \frac{N^2(N-1)}{2}$.

5.3. Features of 2-D RDWRON

The 2-D RDWRON has the following features:

- A set of different wavelengths can be used so that of the same source and destination pair, there are multiple routing paths.
- Different source nodes can use the same set of wavelengths to reach different destination nodes. These different wavelengths can be used to all source nodes to share the same property.

For an N^2-RDWRON with N inputs/outputs and N^2 different wavelengths, all these N^2 wavelengths can be segmented into N subsets $\{W_1, W_2, \ldots, W_N\}$ in which each subset W_i ($i = 1,2,\ldots,N$) has exactly N different wavelengths and $W_i \cap W_j = \Phi$, for all $i \neq j$. Then,

(a) For each source node S_j, any wavelength in the same subset W_i can lead to the same destination.
(b) For all source nodes, the partitions of N^2 wavelengths into N subsets are same (refer to Table 3). When the partition is derived, it can be applied to all source nodes in which (a) will be satisfied.
(c) For each source node, different subsets can be used to route to different destination nodes. Hence by using all N subsets, all N destination nodes can be reached from any source node.

The routing scheme of N^2-RDWRON can be solved according to the following propositions.

Proposition 4. *For an N^2-RDWRON, given the source node address S and the routing wavelength w, the destination node address D can be derived as*

$$D = f_D(N, S, w_0),$$

where $w_0 = \mathrm{mod}(w - 1, N) + 1$ *and f_D is defined in Eq. (1).*

Proposition 5. *For an N^2-RDWRON, given the destination node address D and the routing wavelength w, the source node address S can be derived as*

$$S = f_S(N, D, w_0),$$

where $w_0 = \mathrm{mod}(w - 1, N) + 1$ *and f_S is defined in Eq. (2).*

Proposition 6. *For an N^2-RDWRON, a set of different routing wavelengths can be used in routing from one source node to one destination node. Denote the set of different wavelengths of the N^2-RDWRON as W, given the RDWRON size N, the source node address S and the destination node address D, W can be derived as*

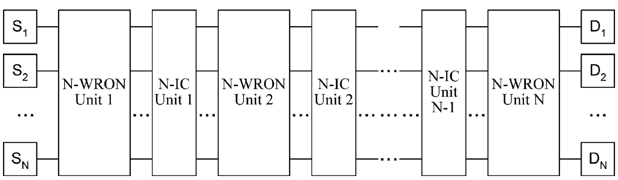
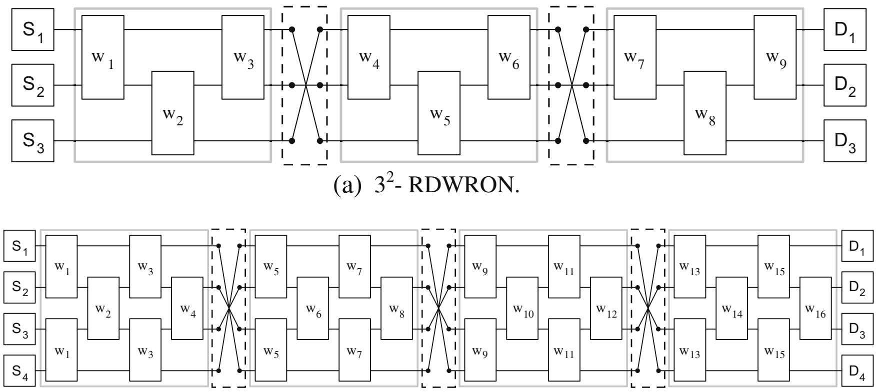


Fig. 7. Structure of N^2-RDWRON.



(a) 3^2- RDWRON.

(b) 4^2-RDWRON.

Fig. 8. Examples of N^2-RDWRON.

Table 3
The routing wavelengths assignment of 3^2-RCWRON.

W	D_1			D_2			D_3		
S_1	w_2	w_5	w_8	w_1	w_4	w_7	w_3	w_6	w_9
S_2	w_3	w_6	w_9	w_2	w_5	w_8	w_1	w_4	w_7
S_3	w_1	w_4	w_7	w_3	w_6	w_9	w_2	w_5	w_8

$$W = \{w, w+N, w+2N, \ldots, w+(N-2)N, w+(N-1)N\} = \{w+(k-1)N \mid k = 1, 2, \ldots, N\},$$

where $w = f_w(N,S,D)$ and f_w is defined in Eq. (3).

The proofs of Propositions 4–6 are given in Appendix II.
The wavelength assignment of 3^2-RDWRON is shown in Table 3.

5.4. Level2 RDWRON

The wavelength selection for a RDWRON is not unique. In the following, another type of RDWRON will be introduced. We name it *Level*2 RDWRON which will be used in the construction of RCWRON. Correspondingly, we denote the RDWRON introduced before as *Level*1 RDWRON in which wavelengths setting in the optical switches are in sequence.

The wavelength presetting at the kth stage in *Level*2 RDWRON is w_k, where $w_k = i + (j-1) \times N$ and

$$\begin{cases} j = \mathrm{mod}(k-1, N) + 1, \\ i = \lfloor \frac{k-1}{N} \rfloor. \end{cases}$$

The following propositions can be derived for solving the routing scheme of *Level*2 RDWRON.

Proposition 7. *In Level2 N^2-RDWRON, given the source node address S and the routing wavelength w, the destination node address D can be derived as follows:*

$$D = f_D(N, S, w_0),$$

where $w_0 = \lfloor \frac{w-1}{N} \rfloor$ and f_D is defined in Eq. (1).

Proposition 8. *In the Level2 N^2-RDWRON, given the destination node address D and the routing wavelength w, the source node address S can be derived as follows:*

$$S = f_S(N, D, w_0),$$

where $w_0 = \lfloor \frac{w-1}{N} \rfloor$ and f_S is defined in Eq. (2).

Proposition 9. *In the Level2 N^2-RDWRON, given the source node address S and the destination node address D, the routing wavelength set W can be derived as follows:*

$$W = \{(w-1)N+1, (w-1)N+2, \ldots, (w-1)N+(N-1), wN\},$$

where $w = f_w(N,S,D)$ and f_w is defined in Eq. (3).

Please cite this article in press as: Zhang L et al. Architectures and routing schemes for optical network-on-chips. Comput Electr Eng (2009), doi:10.1016/j.compeleceng.2008.09.010

6. Structure of 2-D recursive optical network

6.1. Construction of 2-D RCWRON

A 2-D RCWRON can be constructed by connecting multiple RDWRONs. In specific, a 2-D RCWRON has two subnetworks, each composed of N N^2-RDWRONs. The RDWRONs in the first and second level are *Level*1 RDWRONs and *Level*2 RDWRONs, respectively. The wavelength selections for RDWRONs in different levels are different.

Each N^2-RDWRON in a 2-D RCWRON has N inputs/outputs and N^2 stages. Totally a N^2-RCWRON has N^2 inputs/outputs. Hence, we denote the RCWRON with N^2 inputs/outputs as N^2-RCWRON ($N > 2$). Fig. 9 shows the structure of an N^2-RCWRON ($N > 2$).

The connection principle of N^2-RCWRON is explained as follows. The ith output node of the jth N^2-RDWRON is connected to the jth input node of ith N^2-RDWRON in the second level.

One may notice that the structure of an N^2-RCWRON is not unique. The basic rule is that each *Level*1 RDWRON must have a connection to each *Level*2 RDWRON, and vice versa.

Lemma 4. *The total number of switches in one 2-D N^2-RCWRON is*

$$O_{RCWRON} = 2 \times N \times \frac{N^2(N-1)}{2} = \frac{2N^3(N-1)}{2}.$$

6.2. Fault-tolerance capability

Compared with the WRON, a distinct advantage of RCWRON is attributed to its fault-tolerance capability. As shown in Fig. 9, an N^2-RCWRON is composed of $2N$ RDWRONs, which are independent from each other. When one path fails, the faulty RDWRON can be easily identified by checking the sub-path in different levels of subnetworks. By abandoning the faulty RDWRON and the input/output nodes connected by the faulty RDWRON, the rest of the RCWRON can still operate normally.

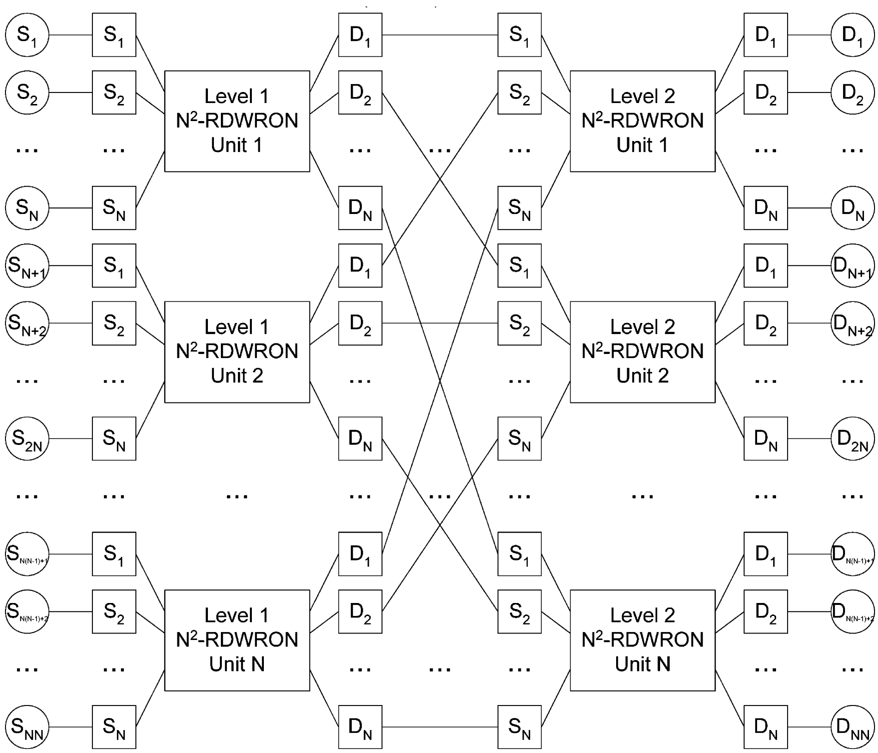


Fig. 9. Structure of N^2-RCWRON.

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7. Routing scheme of 2-D RCWRON

The key idea of the routing scheme for the 2-D RCWRON is to decompose the routing path into two parts, each corresponding to the sub-paths in two subnetworks, respectively, and then solve the routing problem in each RDWRON.

In the following, we will first present the rules of assigning routing wavelengths before we describe the routing scheme.

7.1. Routing wavelength assignment

N^2 different wavelengths can be partitioned into two disjoint subsets $W^{(1)}$ and $W^{(2)}$. For all *Level*1 RDWRONs, their assigned routing wavelengths are exclusively from $W^{(2)}$ as, while for all *Level*2 RDWRONs, assign wavelength subsets in $W^{(1)}$ as their routing wavelengths.

For any routing path P in RCWRON with assigned wavelength w, the path can be decomposed into two segments, P_1 and P_2, where P_1 is the routing path in the first subnetwork (i.e., *Level*1 RDWRONs) and P_2 is the routing path in the second subnetwork (i.e., *Level*2 RDWRONs). For P_1, the routing wavelength w must be in one of the subsets in the Partition 2, denoted as $W^{(2)}$. And for P_2, the routing wavelength w must be in one of the subsets in the Partition 1, denoted as $W^{(1)}$. The following lemmas elaborate how to determine such w.

Lemma 5. *Given a set W with N^2 different elements, there exist at least two different ways to partition W into N subsets*

$$\boldsymbol{W} = W^{(1)} = \bigcup_{m=1,2,\dots,N} W_m^{(1)} \quad \text{and} \quad \boldsymbol{W} = W^{(2)} = \bigcup_{n=1,2,\dots,N} W_n^{(2)},$$

where each subset has N elements such that for any two different subsets $W_m^{(1)} \subset W^{(1)}$, $W_n^{(2)} \subset W^{(2)}$ ($m, n = 1,2,\dots,N$), there is one and only one common element, i.e.,

$$w_{mn} = W_m^{(1)} \cap W_n^{(2)}.$$

Lemma 6. *There are totally N^2 different combinations of $W_m^{(1)}$ and $W_n^{(2)}$, where $W_m^{(1)} \subset W^{(1)}$, $W_n^{(2)} \subset W^{(2)}$ ($m, n = 1,2,\dots,N$). All N^2 common elements for the N^2 combinations of $W_m^{(1)}$ and $W_n^{(2)}$ are different from each other and these common elements compose the N^2 different elements of set W.*

Lemmas 5 and 6 can be proved as follows.

Proof. Assume that $W = \{w_t, t = 1,2,\dots,N^2\}$, then an $N \times N$ matrix M can be generated as

$$M(i,j) = w_t, \quad \text{if } t = (i-1) \times N + j, \ \ 1 \leqslant i,j \leqslant N,$$

where i and j denote the row and column number in M, respectively.

The two partitions of W can be obtained as follows:

$$\boldsymbol{W} = W^{(1)} = \bigcup_{m=1,2,\dots,N} W_m^{(1)} = \bigcup_{m=1,2,\dots,N} \{M(m,j) | j = 1,2,\dots,N\}$$

and

$$\boldsymbol{W} = W^{(2)} = \bigcup_{n=1,2,\dots,N} W_n^{(2)} = \bigcup_{n=1,2,\dots,N} \{M(i,n) | i = 1,2,\dots,N\}.$$

It is easy to see that the subset $W_m^{(1)}$ in $W^{(1)}$ and the subset $W_n^{(2)}$ in $W^{(2)}$ correspond to the mth row and the nth column in M, respectively. The mth row and the nth column in M must intersect at the element $M(m,n) = w_t$, where $t = (m-1) \times N + n$, which corresponds to that subsets $W_m^{(1)}$ and $W_n^{(2)}$ must have one and only one common element $w_{mn} = W_m^{(1)} \cap W_n^{(2)} = w_t$.

Conversely, each element in M, $M(m,n) = w_t$, is uniquely identified by its coordinate (m, n), which corresponds to the common element of the unique combination of $\{W_m^{(1)}, W_n^{(2)}\}$.

Hence, Lemmas 5 and 6 hold. □

One of the simplest ways to partition set $\boldsymbol{W} = \{1,2,\dots,N^2\}$ into two different subset groups which satisfy Lemmas 5 and 6 are

Partition 1:

$$\boldsymbol{W} = \bigcup_{m=1,2,\dots,N} W_m^{(1)} = \bigcup_{m=1,2,\dots,N} \{(m-1) \times N + i | i = 1,2,\dots,N\}.$$

Partition 2:

$$\boldsymbol{W} = \bigcup_{n=1,2,\dots,N} W_n^{(2)} = \bigcup_{n=1,2,\dots,N} \{n + (j-1) \times N | j = 1,2,\dots,N\}.$$

It is easy to verify that Partitions 1 and 2 are just the redundant routing wavelength subsets of *Level*2 and *Level*1 RDWRONs, respectively. According to Lemma 5, $W_m^{(1)}$ and $W_n^{(2)}$ have one and only one common element $w = W_m^{(1)} \cap W_n^{(2)}$. Then w is the only wavelength which can be used to route for path P.

7.2. Routing scheme for RCWRON

The following notations are used in our discussion.

S ($1 \leqslant S \leqslant N^2$): the source node address of an N^2-RCWRON.
D ($1 \leqslant D \leqslant N^2$): the destination node address of an N^2-RCWRON.
S_1 ($1 \leqslant S_1 \leqslant N$): the source node address of *Level*1 RDWRON.
D_1 ($1 \leqslant D_1 \leqslant N$) the destination node address of *Level*1 RDWRON.
S_2 ($1 \leqslant S_2 \leqslant N$): the source node address of *Level*2 RDWRON
D_2 ($1 \leqslant D_2 \leqslant N$): the destination node address of *Level*2 RDWRON.
D_M ($1 \leqslant D_M \leqslant N^2$): the destination node address in the subnetwork composed of all *Level*1 RDWRONs.
S_M ($1 \leqslant S_M \leqslant N^2$): the source node address in the subnetwork composed of all *Level*2 RDWRONs.
w ($w \in \boldsymbol{W}$): the routing wavelength for the whole N^2-RCWRON for a given S and D.
w_1 ($w_1 \in \boldsymbol{W}$): the minimum routing wavelength of *Level*1 RDWRON for a given S_1 and D_1.
w_2 ($w_2 \in \boldsymbol{W}$): the minimum routing wavelength of *Level*2 RDWRON for a given S_2 and D_2.

According to the structure of RCWRON, we can obtain following equations:

$$\begin{cases} S_1 = \mathrm{mod}(S-1,N)+1, \\ S_2 = \mathrm{mod}(S_M-1,N)+1, \\ D_1 = \mathrm{mod}(D_M-1,N)+1, \\ D_2 = \mathrm{mod}(D-1,N)+1, \\ D_M = \lfloor \frac{S-1}{N} \rfloor \times N + D_1, \\ S_M = D_1 \times N + \lfloor \frac{S-1}{N} \rfloor. \end{cases} \tag{4}$$

According to Propositions 3 and 6, and Lemmas 5 and 6, we can obtain the following equation:

$$w = w_1 + (w_2 - 1) \times N. \tag{5}$$

Based on Eqs. (1)–(5), we can derive the following equations:

$$\begin{cases} S_1 = \mathrm{mod}(S-1,N)+1, \\ S_2 = \lfloor \frac{S-1}{N} \rfloor, \\ D_1 = \mathrm{mod}(D-1,N)+1, \\ D_2 = \lfloor \frac{D-1}{N} \rfloor, \\ w_1 = \mathrm{mod}(w-1,N)+1, \\ w_2 = \lfloor \frac{w-1}{N} \rfloor \end{cases} \tag{6}$$

and

$$\begin{cases} D_1 = f_D(N,S_1,w_1), \\ D_2 = f_D(N,S_2,w_2), \\ S_1 = f_S(N,D_1,w_1), \\ S_2 = f_S(N,D_2,w_2), \\ w_1 = f_W(N,S_1,D_1), \\ w_2 = f_W(N,S_2,D_2). \end{cases} \tag{7}$$

Then we have the following results for determining the routes in N^2-RCWRON.

Proposition 10. *For an N^2-RCWRON, given the source node address S and routing wavelength w, the destination node address D can be derived as*

$$D = D_2 + (D_1 - 1) \times N,$$

where

$$\begin{cases} S_1 = \mathrm{mod}(S-1,N)+1, \\ S_2 = \lfloor \frac{S-1}{N} \rfloor, \\ w_1 = \mathrm{mod}(w-1,N)+1, \\ w_2 = \lfloor \frac{w-1}{N} \rfloor, \\ D_1 = f_D(N,S_1,w_1), \\ D_2 = f_D(N,S_2,w_2), \end{cases}$$

The function f_D in Proposition 10 is given by Eq. (1).

Proposition 11. *For an N^2-RCWRON, given the source node address S and the routing wavelength w, the destination node address D can be derived as*

$$S = S_1 + (S_2 - 1) \times N,$$

where

$$\begin{cases} D_2 = \mathrm{mod}(D-1, N) + 1, \\ D_1 = \lfloor \frac{D-1}{N} \rfloor, \\ w_1 = \mathrm{mod}(w-1, N) + 1, \\ w_2 = \lfloor \frac{w-1}{N} \rfloor, \\ S_1 = f_S(N, D_1, w_1), \\ S_2 = f_S(N, D_2, w_2). \end{cases}$$

The function f_S in Proposition 11 is given by Eq. (2).

Based on the discussion in the previous subsection, the routing wavelength for N^2-RCWRON can be derived as follows.

Proposition 12. *For an N^2-RCWRON, given the source node address S and the destination node address D, the routing wavelength w can be derived as*

$$w = W_1 \cap W_2 = w_1 + (w_2 - 1) \times N,$$

where

$$\begin{cases} w_1 = f_w(N, S_1, D_1), \\ w_2 = f_w(N, S_2, D_2), \\ W_1 = \{w_1, w_1 + N, w_1 + 2N, \ldots, w_1 + (N-2)N, w_1 + (N-1)N\}, \\ W_2 = \{(w_2 - 1)N + 1, (w_2 - 1)N + 2, \ldots, (w_2 - 1)N + (N-1), w_2 N\} \end{cases}$$

and

$$\begin{cases} S_1 = \mathrm{mod}(S-1, N) + 1, \\ S_2 = \lfloor \frac{S-1}{N} \rfloor, \\ D_2 = \mathrm{mod}(D-1, N) + 1, \\ D_1 = \lfloor \frac{D-1}{N} \rfloor. \end{cases}$$

The function f_w in Proposition 12 is given by Eq. (3).

7.3. One routing example

Here we use 4^2-RCWRON as an example to illustrate the routing scheme. Fig. 10 shows the structure of *Level*1 4^2-RDWRON and *Level*2 4^2-RDWRON. The structure of the 4^2-RCWRON is shown in Fig. 11.

The routing wavelength assignment for *Level*1 and *Level*2 RDWRON are shown in Tables 4 and 5, respectively. The routing wavelength assignment for the whole 4^2-RCWRON is given in Table 6.

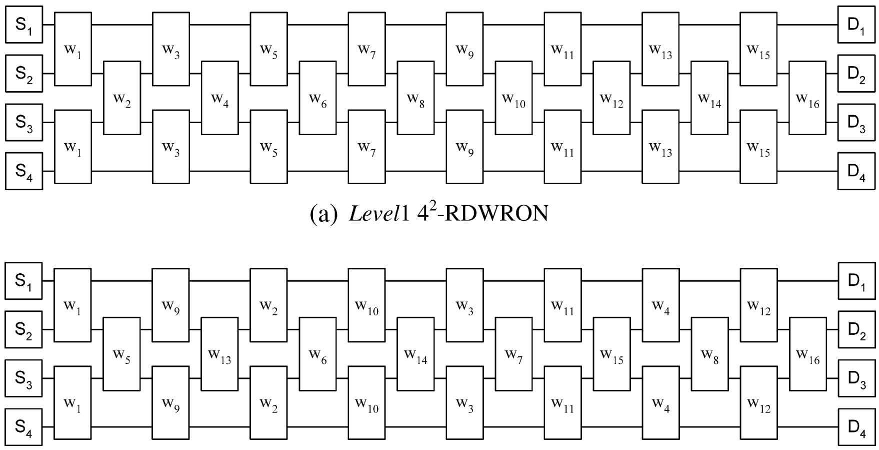
8. Conclusion

In this paper, we presented a generalized wavelength routed optical micronetwork architecture WRON, and generalized its routing scheme. Based on WRON, we proposed a new 2-D recursive wavelength routed optical network, an on-chip interconnection network suitable for ONoC. We first introduced the structure of the 2-D RDWRON and its routing scheme. Then we showed how to construct 2-D RCWRON using 2-D RDWRONs. The routing scheme for 2-D RCWRON is derived based on the routing scheme for 2-D RDWRON.

The major advantage of the proposed 2-D RCWRON over the WRON is its fault-tolerance capability at a relatively high construction cost. Our future work includes the study of alternative interconnection network structures which balance between the construction cost and the fault-tolerance capability.

Appendix I. Proof of Propositions 1–3

For the convenience of proof, we represent the WRON using a diagonal grid structure, and expand it to a Tri-network structure by adding two virtual WRONs at both sides of the original WRON. We denote the original WRON as the *Real WRON*,



(a) *Level*1 4^2-RDWRON

(b) *Level*2 4^2-RDWRON

Fig. 10. Structures of 4^2-RDWRON.

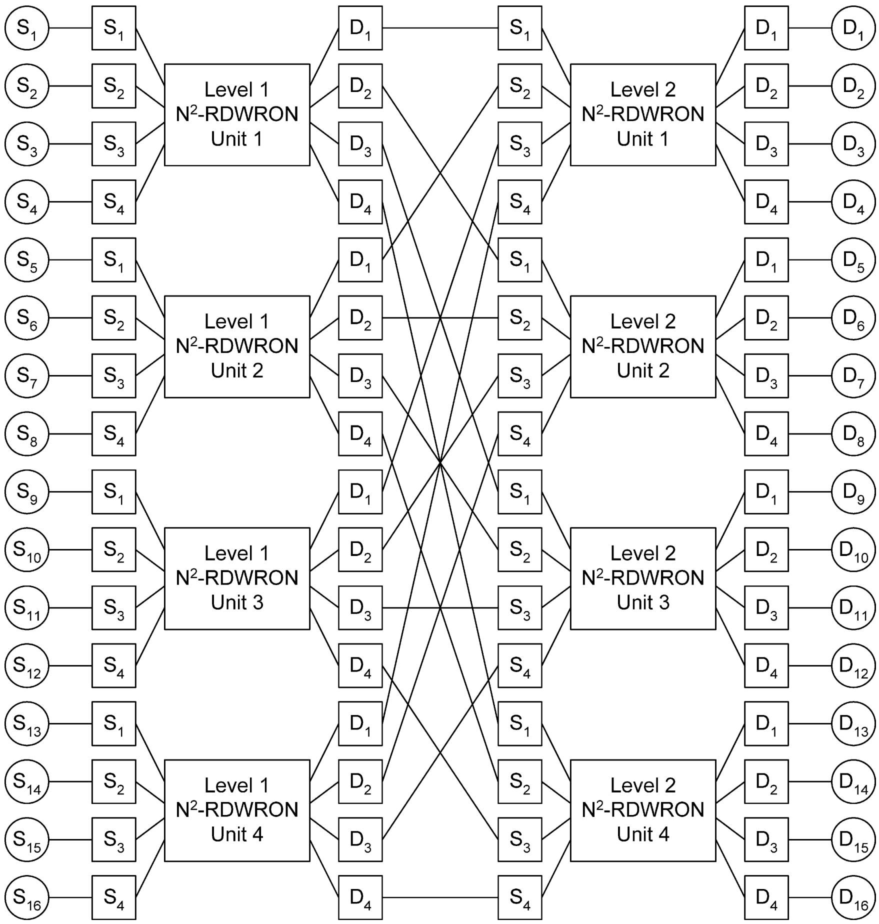


Fig. 11. Structure of 4^2-RCWRON.

the virtual network close to the first (last) source node of the *Real WRON* as the *Negative WRON* (*Positive WRON*). The Tri-network structure of $N = 4$ is shown in Fig. 12.

Each optical switch in the Tri-network is indicated by the coordinate (C,R) according to Rule 1.

Table 4
Routing wavelengths for *Level*1 4^2-RDWRON.

w	D_1				D_2				D_3				D_4			
S_1	w_1	w_5	w_9	w_{13}	w_4	w_8	w_{12}	w_{16}	w_2	w_6	w_{10}	w_{14}	w_3	w_7	w_{11}	w_{15}
S_2	w_4	w_8	w_{12}	w_{16}	w_3	w_7	w_{11}	w_{15}	w_1	w_5	w_9	w_{13}	w_2	w_6	w_{10}	w_{14}
S_3	w_2	w_6	w_{10}	w_{14}	w_1	w_5	w_9	w_{13}	w_3	w_7	w_{11}	w_{15}	w_4	w_8	w_{12}	w_{16}
S_4	w_3	w_7	w_{11}	w_{15}	w_2	w_6	w_{10}	w_{14}	w_4	w_8	w_{12}	w_{16}	w_1	w_5	w_9	w_{13}

Table 5
Routing wavelengths for *Level*2 4^2-RDWRON.

w	D_1				D_2				D_3				D_4			
S_1	w_1	w_2	w_3	w_4	w_{13}	w_{14}	w_{15}	w_{16}	w_5	w_6	w_7	w_8	w_9	w_{10}	w_{11}	w_{12}
S_2	w_{13}	w_{14}	w_{15}	w_{16}	w_9	w_{10}	w_{11}	w_{12}	w_1	w_2	w_3	w_4	w_5	w_6	w_7	w_8
S_3	w_5	w_6	w_7	w_8	w_1	w_2	w_3	w_4	w_9	w_{10}	w_{11}	w_{12}	w_{13}	w_{14}	w_{15}	w_{16}
S_4	w_9	w_{10}	w_{11}	w_{12}	w_5	w_6	w_7	w_8	w_{13}	w_{14}	w_{15}	w_{16}	w_1	w_2	w_3	w_4

Table 6
Routing wavelengths of $4^2 \times 4^2$ RCWRON.

Wavelength	Destination	*Level*2 Unit 1				*Level*2 Unit 2				*Level*2 Unit 3				*Level*2 Unit 4			
Source	w	D_1	D_2	D_3	D_4	D_1	D_2	D_3	D_4	D_1	D_2	D_3	D_4	D_1	D_2	D_3	D_4
*Level*1 Unit 1	S_1	w_1	w_{13}	w_5	w_9	w_4	w_{16}	w_8	w_{12}	w_2	w_{14}	w_6	w_{10}	w_3	w_{15}	w_7	w_{11}
	S_2	w_4	w_{16}	w_8	w_{12}	w_3	w_{15}	w_7	w_{11}	w_1	w_{13}	w_5	w_9	w_2	w_{14}	w_6	w_{10}
	S_3	w_2	w_{14}	w_6	w_{10}	w_1	w_{13}	w_5	w_9	w_3	w_{15}	w_7	w_{11}	w_4	w_{16}	w_8	w_{12}
	S_4	w_3	w_{15}	w_7	w_{11}	w_2	w_{14}	w_6	w_{10}	w_4	w_{16}	w_8	w_{12}	w_1	w_{13}	w_5	w_9
*Level*1 Unit 2	S_1	w_{13}	w_9	w_1	w_5	w_{16}	w_{12}	w_4	w_8	w_{14}	w_{10}	w_2	w_6	w_{15}	w_{11}	w_3	w_7
	S_2	w_{16}	w_{12}	w_4	w_8	w_{15}	w_{11}	w_3	w_7	w_{13}	w_9	w_1	w_5	w_{14}	w_{10}	w_2	w_6
	S_3	w_{14}	w_{10}	w_2	w_6	w_{13}	w_9	w_1	w_5	w_{15}	w_{11}	w_3	w_7	w_{16}	w_{12}	w_4	w_8
	S_4	w_{15}	w_{11}	w_3	w_7	w_{14}	w_{10}	w_2	w_6	w_{16}	w_{12}	w_4	w_8	w_{13}	w_9	w_1	w_5
*Level*1 Unit 3	S_1	w_5	w_1	w_9	w_{13}	w_8	w_4	w_{12}	w_{16}	w_6	w_2	w_{10}	w_{14}	w_7	w_3	w_{11}	w_{15}
	S_2	w_8	w_4	w_{12}	w_{16}	w_7	w_3	w_{11}	w_{15}	w_5	w_1	w_9	w_{13}	w_6	w_2	w_{10}	w_{14}
	S_3	w_6	w_2	w_{10}	w_{14}	w_5	w_1	w_9	w_{13}	w_7	w_3	w_{11}	w_{15}	w_8	w_4	w_{12}	w_{16}
	S_4	w_7	w_3	w_{11}	w_{15}	w_6	w_2	w_{10}	w_{14}	w_8	w_4	w_{12}	w_{16}	w_5	w_1	w_9	w_{13}
Level 1 Unit 4	S_1	w_9	w_5	w_{13}	w_1	w_{12}	w_8	w_{16}	w_4	w_{10}	w_6	w_{14}	w_2	w_{11}	w_7	w_{15}	w_3
	S_2	w_{12}	w_8	w_{16}	w_4	w_{11}	w_7	w_{15}	w_3	w_9	w_5	w_{13}	w_1	w_{10}	w_6	w_{14}	w_2
	S_3	w_{10}	w_6	w_{14}	w_2	w_9	w_5	w_{13}	w_1	w_{11}	w_7	w_{15}	w_3	w_{12}	w_8	w_{16}	w_4
	S_4	w_{11}	w_7	w_{15}	w_3	w_{10}	w_6	w_{14}	w_2	w_{12}	w_8	w_{16}	w_4	w_9	w_5	w_{13}	w_1

Rule 1: In the *Real WRON*, when j is odd, the coordinate of the ith switch in the jth stage is $(j, 2*i-1)$; when j is even, the coordinate of the ith switch in the jth stage is $(j, 2*i)$. In the *Negative WRON*, when j is odd, the coordinate of the ith switch in the jth stage is $(j, 2*i-1-N)$; when j is even, the coordinate of the ith switch in the jth stage is $(j, 2*i-N)$. In the *Positive WRON*, when j is odd, the coordinate of the ith switch in the jth stage is $(j, 2*i-1+N)$; when j is even, the coordinate of the ith switch in the jth stage is $(j, 2*i+N)$.
Rule 2: At the up and bottom boundaries of the *Real WRON*, there are many *Peak Nodes* as marked in Fig. 12. In the *Real WRON*, the coordinates of the *Peak Node* is indicated as (C,R), where C is the stage number of the *Peak Node* and R equals to 0 (N) when the *Peak Node* is connected to the first (last) switch in the stage.
Rule 3: When the routing path reaches the *Peak Nodes* in the network, if the horizontal coordinate C of the *Peak Nodes* is same as the wavelength assigned to the path, the path will change its routing direction and return to the *Real WRON*. Otherwise, the routing path will keep its direction and move forward into one of the virtual WRONs. According to Rule 3, in solving the routing scheme, we shall try to avoid the trouble arose by the veer of the routing path at some of the *Peak Nodes*. All source and destination node addresses in the Tri-network are numbered following Rule 4.
Rule 4: Every destination node address indicated in the Tri-network is the virtual destination address D_*. When the routing follows Rule 1, a routing path will reach the virtual destination node D_*. The relationship between the virtual addresses D_* and its corresponding real address D is shown below

$$D = \begin{cases} 1 - D^* & \text{when} \quad D^* \leqslant 0, \\ D^* & \text{when} \quad 0 < D^* \leqslant N, \\ 2 \times N + 1 - D^* & \text{when} \quad D^* > N. \end{cases}$$

Similar to the source node, the relationship between the virtual addresses of source node $S*$ in the Tri-network and its corresponding real source address S is shown below

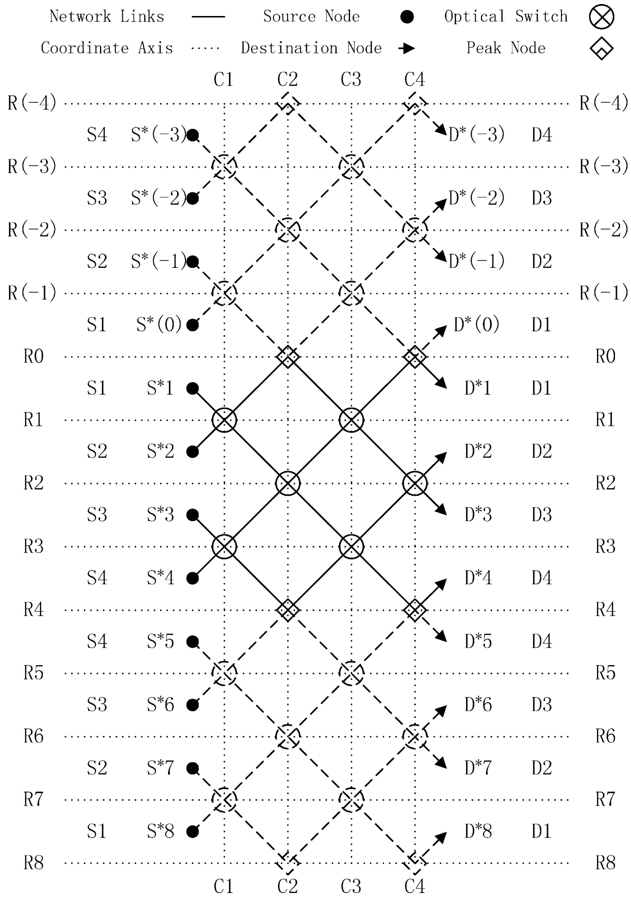


Fig. 12. Structure of the Tri-network for a 4×4 WRON.

$$S = \begin{cases} 1 - S^* & \text{when} \quad S^* \leqslant 0, \\ S^* & \text{when} \quad 0 < S^* \leqslant N, \\ 2 \times N + 1 - S^* & \text{when} \quad S^* > N. \end{cases}$$

For the ease of understanding, we have the following definitions.

Definition 1 (*Start node*). The *start node* is the first node on the routing path following the source node. It can be a switch node or a *peak node*.

Assume the source address for a routing path is S, then:

The coordinate of the *start node* is $(1, S-1)$ if S is even, or $(1, S)$ if S is odd.

Definition 2 (*Reflection node*). The *reflection node* is the specified *node* in a routing path whose horizontal coordinate is same as the wavelength assigned to the path. The routing path will change its direction in the *reflection node*. There are two kinds of *reflection nodes*: *reflection peak node* and *reflection switch node*. In any routing path there is one and only one *reflection node*.

Definition 3 (*Inherent slope*). The *inherent slope* is the slope of the routing path starting from the source node to the *reflection node*.

Assume the source address for a routing path is S, then:

The *inherent slope* is -1 if S is even, or 1 if S is odd.

Definition 4 (*Acquired slope*). The *acquired slope* is the slope of the routing path from the *reflection node* to the destination node. Obviously it is the opposite value of the *inherent slope*.

Assume the source address for a routing path is S, then:

The *acquired slop*e is 1 if S is even, or -1 if S is odd.

Please cite this article in press as: Zhang L et al. Architectures and routing schemes for optical network-on-chips. Comput Electr Eng (2009), doi:10.1016/j.compeleceng.2008.09.010

Definition 5 (*End node*). The *end node* is the last node on the routing path before the destination node. It can be a switch node or a *peak node*.

Given an *end node* with the coordinate of (N,R), if the *acquired slope* is 1, the destination node address is $R+1$; if the *acquired slope* is -1, the destination node address is R.

In the following proof, we denote the coordinate of a node as (c,r) where r denote the vertical coordinate and c denote the horizontal coordinate.

Proof of Proposition 1. In an N-WRON, given the source node address S and the routing wavelength W, the destination address D can be derived by the following procedure.

- When N is Even

  Case 1: When S is even

  The coordinate of the *start node* is $(1,S-1)$. The *inherent slope* is -1. The function of the routing path before the *reflection node* is $(r-(S-1))+(c-1)=0$, i.e., $r=S-c$.Given the routing wavelength W, let $c=W$, then $r=c-W$. Hence the coordinate of the *reflection node* is $(S-W,W)$.Hence the function of the routing path after the *reflection node* is $(r-(S-W))-(c-W)=0$, i.e., $r=S+c-2\times W$.The vertical coordinate of the *end node* is N, hence the horizontal coordinate of the *end node* is $r=S+N-2\times W$. Then the virtual address D_* of the destination node is

  $$D* = S + (N - 2W + 1).$$

  Case 2: When S is odd

  By the procedure similar to case 1, when S is odd, the virtual address of the destination node can be derived as

  $$D^* = S - (N - 2W + 1).$$

  In summary, $D_* = S + (N - 2W + 1) \times (-1)^S$.
- When N is odd:

  By the same way as in case 1, when N is odd, the virtual address $D*$ of the destination node can be derived as

  $$D^* = S + (N - 2W + 1) \times (-1)^S. \qquad \square$$

Proof of Proposition 2

- When N is even

  Case 1: When D is even: Similar to the cases in Appendix I, the virtual address of the source node can be derived as

  $$S^* = D + (N - 2W + 1).$$

  Case 2: When D is odd: The virtual address of the source node can be derived as

  $$S^* = D - (N - 2W + 1).$$

  In summary, $S^* = D - (N - 2W + 1) \times (-1)^{N+D}$.
- When N is odd: The virtual address of the destination node can be derived as $S* = D - (N - 2W + 1) \times (-1)^{N+D}$. $\square$

Proof of Proposition 3. For an N-WRON, given the source node address S and the destination node address D, the routing wavelength W can be derived based on S as follows. The major problem in deriving W is that sometimes we should not use the real address D but the virtual address D_* in computing the correct wavelength W.

- When N is even: Assume N is even, as shown in Fig. 12. When S and D have different parities, the destination node of the routing path is in the *Real WRON*, i.e., $D_* = D$.

  Case 1: When S is even

  When D is odd, $D_* = D$. The coordinate of the *start node* is $(1,S-1)$, the *inherent slope* is -1. The function of the path before the *reflection node* is $r-S+c=0$.The coordinate of the *end node* is $(N,D-1)$. The *acquired slope* is 1. The function of the routing path after the *reflection node* is $r-(D-1)=c-N$, i.e., $r-D-1+N+c=0$.Assume the *reflection node* is in (c_0,r_0), then

  $$\begin{cases} r_0 + c_0 - S = 0 \\ r_0 - c_0 - D + N + 1 = 0 \end{cases} \Rightarrow c_0 = \frac{N+S-D+1}{2} \Rightarrow W = \frac{N+1+S-D}{2}.$$

- When D is even, the destination node is in the *Virtual WRON*, i.e., $D_* \neq D$. There have two possibilities: $D_* > N$ or $D_* \leqslant 0$. Hence the routing wavelength W for the path from source node S to destination node D should be

  $$W = \frac{N+1+S-D*}{2},$$

where

$$\begin{cases} D* = 2 \times N + 1 - D & \text{when} \quad D* > N, \\ D* = 1 - D & \text{when} \quad D* \leqslant 0. \end{cases}$$

Then we have

$$\begin{cases} W_1 = \frac{N+1+S-(2\times N+1-D)}{2} = \frac{S+D-N}{2}, \\ W_2 = \frac{N+1+S-(1-D)}{2} = \frac{S+D+N}{2}. \end{cases}$$

The wavelength W should be greater than 0 and less than N, hence we have the following expressions:

$$\begin{cases} W_1 = \frac{S+D-N}{2} \\ 0 < W_1 \leqslant N \end{cases} \Rightarrow N < (S+D) \leqslant 3N \Rightarrow (S+D) > N,$$

$$\begin{cases} W_2 = \frac{S+D+N}{2} \\ 0 < W_2 \leqslant N \end{cases} \Rightarrow -N < (S+D) \leqslant N \Rightarrow (S+D) \leqslant N.$$

Then $W = W_1$ when $S + D > N$ and $W = W_2$ when $S + D \leqslant N$.
Case 2: When S is odd: It can be derived similarly to case 1, when D is even

$$W = \frac{N+1-S+D}{2}.$$

When D is odd

$$\begin{cases} W = \frac{-S-D+3\times N+2}{2} & \text{when} \quad S+D \geqslant N+2, \\ W = \frac{-S-D+N+2}{2} & \text{when} \quad S+D < N+2. \end{cases}$$

- When N is odd: When S and D have same parities, the destination node of the routing path is in the *Real WRON*, i.e., $D_* = D$.

  Case 1: When S is even: Similar to the last case, when D is even

$$W = \frac{N+1+S-D}{2}.$$

When D is odd

$$\begin{cases} W = \frac{S+D-N}{2} & \text{when} \quad S+D > N, \\ W = \frac{S+D+N}{2} & \text{when} \quad S+D \leqslant N. \end{cases}$$

  Case 2: When S is odd: Similar to the case 1, when D is odd,

$$W = \frac{N+1-S+D}{2}.$$

When D is even

$$\begin{cases} W = \frac{-S-D+3\times N+2}{2} & \text{when} \quad S+D \geqslant N+2, \\ W = \frac{-S-D+N+2}{2} & \text{when} \quad S+D < N+2. \end{cases} \qquad \square$$

Appendix II. Proof of Propositions 4–6

All rules and definitions used here are same as in Appendix I.

1. Step 1. Consider the topology structure of the WRON as shown in Fig. 13. Each switch is indicated by its coordinate (c, r) uniquely in the network as introduced in [20]. When the routing wavelength w assigned to the routing path is different to all the wavelengths preset in the WRON, we refer this situation as the "*The N-WRON is irrelative to the wavelength w*". When the N-WRON is irrelative to the wavelength, the relationship between the address of the source node S and the address of the destination node address D can be derived as $D = N - S + 1$.
2. Step 2. When an N-WRON is connected with an inverse connector (IC), there are two types of connections between IC and N-WRON as shown in Fig. 14. Given the size of IC N, the address of source node S, when the N-WRON is irrelative to the wavelength, the destination node address is derived as: $D = N + 1 - S$. The routing truth of the subnet shown in Fig. 14 is given by

$$\begin{cases} m = N + 1 - s \\ d = N + 1 - m \end{cases} \Rightarrow d = s.$$

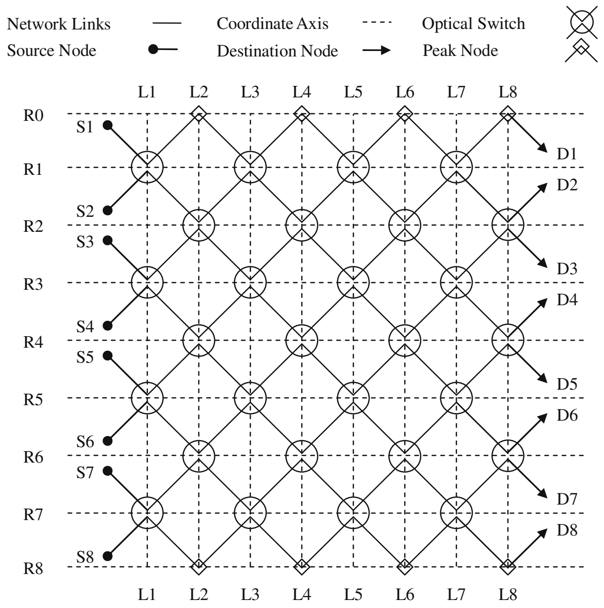


Fig. 13. Structure of 8-WRON.

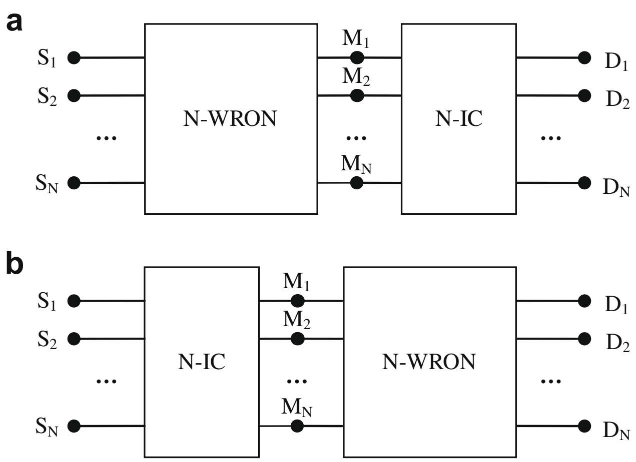


Fig. 14. Two type of connections between IC and WRON.

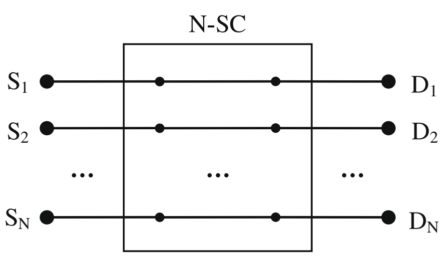


Fig. 15. Straight connection block.

Hence both subnetworks shown in Fig. 14 can be substituted as the straight connection (SC) block (Fig. 15). Note that the integration of any number of *N*-SCs is equal to one *N*-SC and the integration of *N*-SC to other network (WRON) is equal to that network (WRON).

3. Step 3. Given any N^2-RDWRON and a wavelength w assigned to a special routing path, we can easily transform the RDWRON to a WRON by the following way. In the N^2-RDWRON, there are N N-WRON and N-1 IC blocks. Assume that

$$k = \left\lfloor \frac{w-1}{N} \right\rfloor, \quad w_0 = \mathrm{mod}(w-1, N) + 1.$$

Then the wavelength w exists only in the $(k + 1)$th N-WRON, i.e., all other $k - 1$ N-WRONs are irrelative to the wavelength w. For the ith N-WRON, $0 < i < k$, in the N^2-RDWRON, it can be integrated with the ith IC to an N-SC; for the jth N-WRON, $k < j \leqslant N$, in the N^2-RDWRON, it can be integrated with the $(j - 1)$th IC to an N-SC too. Then the N^2-RDWRON is composed only of SCs and WRONs which can be treated as WRON merely. This process is shown in Fig. 16. Hence, the routing scheme of N^2-RDWRON is almost same as that of N-WRON. The derivations of the destination address and the source address for N^2-RDWRON are same as those for N-WRON. In deriving the routing wavelength, we can treat the N^2-RDWRON as N different N-WRON and calculate them separately. We summarize the routing scheme of RDWRON as follows. For an N^2-RDWRON, given the source node address S and the routing wavelength w, the destination node address D can be derived as follows:

$$D = f_D(N, S, w_0),$$

where $w_0 = \mathrm{mod}(w - 1, N) + 1$, and f_D is the function defined in Eq. (1). For an N^2-RDWRON, given the destination node address D and the routing wavelength w, the source node address S can be derived as following:

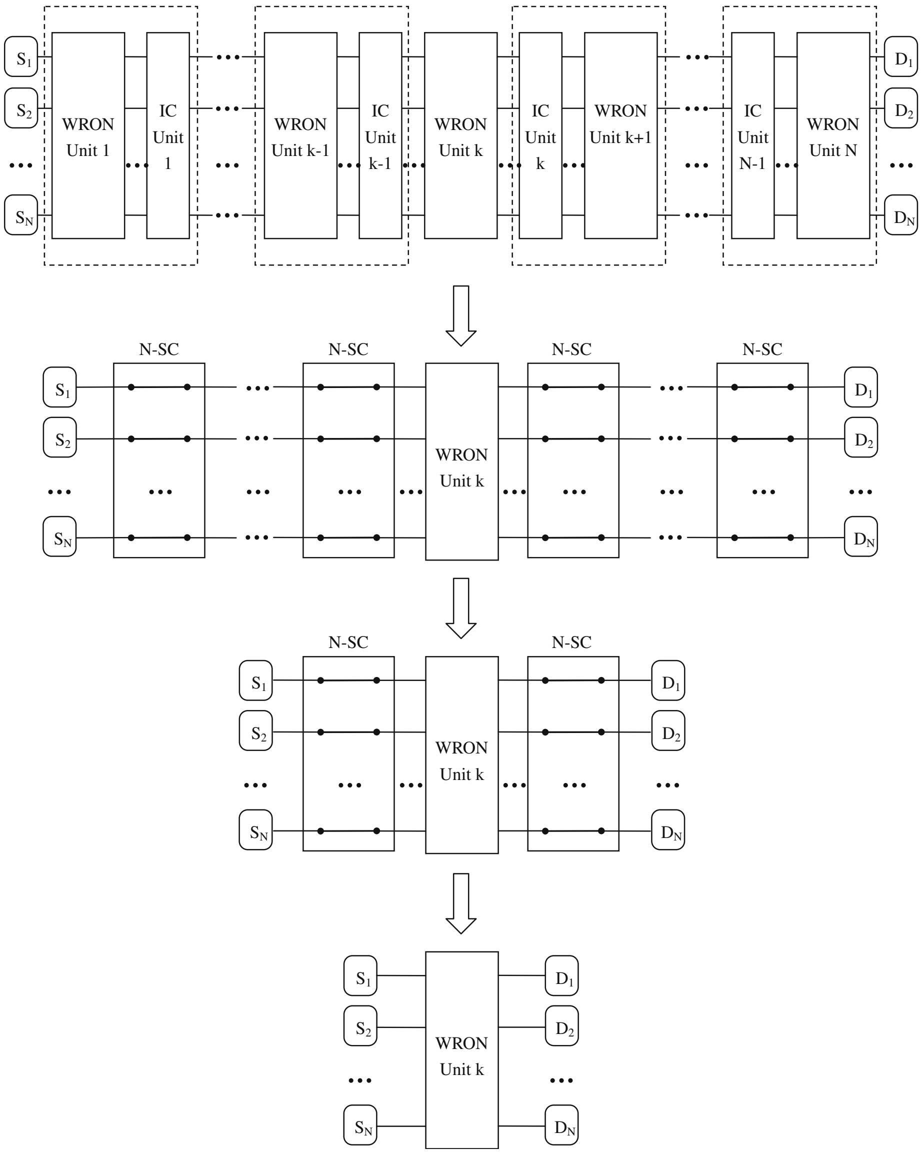


Fig. 16. Transform N^2-RDWRON to N-WRON.

$$S = f_S(N, D, w_0),$$

where $w_0 = \mathrm{mod}(w-1, N) + 1$, and f_D is the function defined in Eq. (2). In an N^2-RDWRON, a set of different routing wavelengths can be used in routing from one source node to one destination node. Denote the set of different wavelengths of the N^2-RDWRON as W, given the RDWRON size N, the source node address S and the destination node address D, W can be derived as:

$$\begin{aligned} W &= \{w, w+N, w+2N, \ldots, w+(N-2)N, w+(N-1)N\} \\ &= \{w+(k-1)N \mid k = 1, 2, \ldots, N\} \end{aligned}$$

where $w = f_w(N, S, D)$, and f_D is the function defined in Eq. (3).

Hence, Propositions 4–6 hold.

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