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GENERALIZED WAVELENGTH ROUTED OPTICAL MICRONETWORK IN NETWORK-ON-CHIP

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ABSTRACT
The wavelength routed optical network (WRON) [1] is a promising optical interconnection architecture that can be integrated into a System-on-Chip (SoC) to replace traditional wire-connected on-chip micro-networks which pose severe bandwidth limitations on future super large SoC chips. In this paper, we present the architecture of WRON and generalize the routing schemes based on source address, destination address and the routing wavelength.

KEY WORDS
Optical switch, Network-on-Chip, wavelength routed optical network (WRON)

1. Introduction

The International Technology Roadmap for Semiconductors (ITRS) [2] has predicted that by 2010, high performance SoC will count up to two billion transistors per chip and work with clock frequencies of the order of 10GHz. As a new paradigm of SoC, with a communication-centric design style, Network-on-Chip (NoC) [3] was proposed to meet the distinctive challenges of providing functionally correct, reliable operation of interacting SoC components. A 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 in an NoC system [4].

The continuously shrinking feature sizes, higher clock frequencies [5] and the simultaneous growth in complexity have made electrical interconnects a formidable task [5]. Integrated optical interconnect [6] is a promising solution to alleviate some of the more pressing issues involved in moving volumes of data between processing units in NoC. As such, an Optical Network-on-Chip (ONoC) has been considered to enabling high bandwidth and low contention routing of data using Wavelength Division Multiplexing (WDM)-enabled [7] optical waveguides [5]. In specific, optical switch [7] and waveguides [8] 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 [9].

In this paper, we present a generalized wavelength routed optical micronetwork architecture that is particularly suitable for ONoC. And the routing algorithms for this architecture are developed.

The rest of the paper is organized as follows. Section II introduces the operating mechanism of basic optical switches. Section III presents the basic structure of the WRON, and Section IV studies the routing schemes of WRON. Section V 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 [3] (named because of their capacity to add or subtract a signal from a waveguide based on its wavelength). As shown in Fig. 1, it is composed of one or more identical microdisks evanescently side-coupled to signal waveguides. 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).

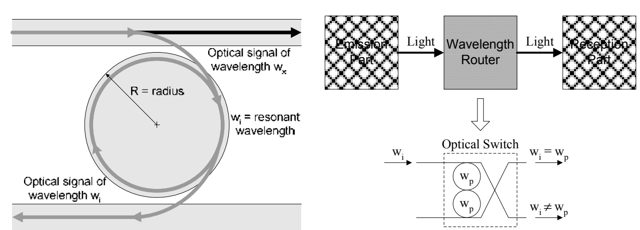
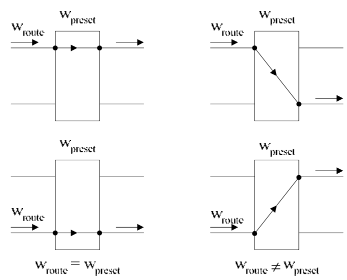


Figure 1. Structure of the Optical Switch

The basic function of an optical switch can be viewed as a wavelength-controlled switch. If the wavelength of an optical signal passing through a waveguide in proximity to the resonator does not correspond to the resonant wavelength, then the electromagnetic field continues to propagate along the waveguide but not through the structure. If, however, the signal wavelength is close enough to the resonant wavelength (tolerance is of the order of a few nanometer, depending on the coupling strength between the disk and the waveguide [5]), the electromagnetic field propagates around the structure and then out along the second waveguide.

Switching is performed based on the physical properties of the signal. A fairly obvious application of this device is in optical crossbar networks. More elaborate $N \times N$ switching networks have been reported in [6], although their functionalities are subject to be verified experimentally. The advantages of such structures lie in the possibility of building highly complex, dense and passive on-chip switching networks [5]. 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_i. Each filter is associated with a resonant wavelength, e.g., w_1 for the switch shown in Fig. 1. For any input signal from w_i , the signal will propagate to both filters. If $w_i = w_1$, w_i passes through the switch on the same direction as the input signal (referred as the "straight" function); if $w_i \neq w_1$, the signal will pass through the switch on the cross direction (referred as the "across" function), as shown in Fig. 2.



(a) Go straight. (b) Go across.
Figure 2. Basic Functions of the Optical Switch

The optical switch shown in Fig. 1 can be used to build highly complex, dense and passive on-chip switching networks, as exemplified in a 4×4 ONoC [5] built upon this type of optical switch. However, across the literature, there has been no general discussion of the network properties of the ONoC. In light of the ONoC structure proposed in [5], 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 in [5], we shall name it 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 the input/output nodes, except for the case when only 2 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.

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

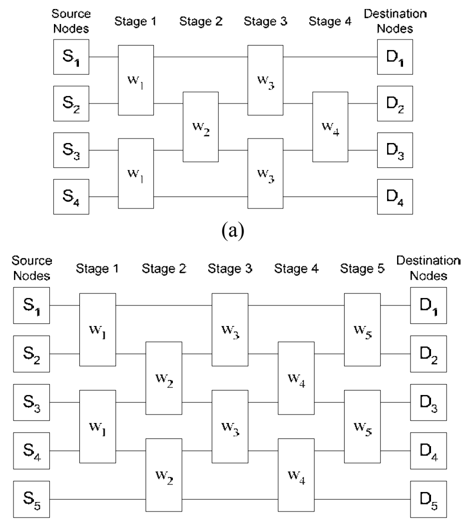
Proof: When N is even, the number of optical switches is

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

When N is odd, the number of optical switches is

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

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



(b)

Figure 3. (a) Type I 4-WRON, (b) Type I 5-WRON.

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

- ♦ Denote the p^{th} source node of an N-WRON as S_p, and the q^{th} destination node as D_q.
- ♦ When N is an odd number, label the first and the second output ports (input ports) of the m^{th} switch at the n^{th} stage as $O(2m\text{-}1,n)$ and $O(2m,n)$ ($I(2m\text{-}1,n)$ and $I(2m,n)$), respectively.
- ♦ When N is an even number, label the first and the second output ports (input ports) of the m^{th} switch at the n^{th} stage as $O(2m,n)$ and $O(2m+1,n)$ ($I(2m\text{-}1,n)$ and $I(2m,n)$), 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, it only needs to consider the ports (nodes) of the prior stage connected to the current input ports of the switches or the destination nodes.

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 i$^{\text{th}}$ input port at the j^{th} stage connects to. The k^{th} entry in the $(N+1)^{\text{th}}$ 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 j^{th} 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)

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

Case 2. (When *N* is an odd number)

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

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

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

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

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

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 Fig. 4(a) and (b) respectively.

Following the same denotation, the connection matrix of type II WRON can be constructed as follows:

Case 1. (When *N* is an even number)

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

Case 2. (When *N* is an odd number)

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

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

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

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

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

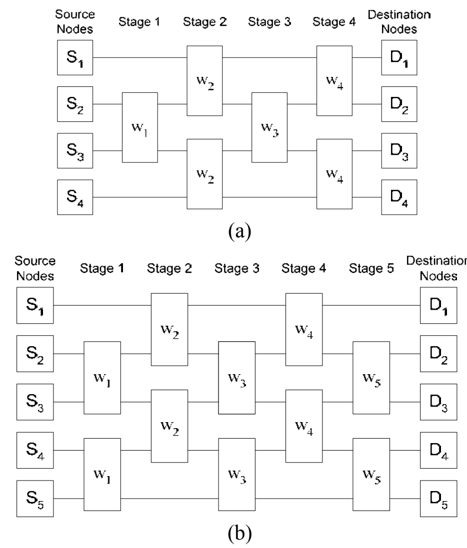


Figure 4. (a) Type II 4-WRON, (b) Type II 5-WRON.

It can be observed that the relation between type I WRON and type II WRON as follows. 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 reversed order will convert it to a type II WRON. Therefore, the structure of type I and II WRON are isomorphic to each other. Hence in the following, we shall focus our study on the type I WRON. Due to the bidirectional conversion and the isomorphism between type I and II WRON, the routing problems of type II WRON can be solved using the same solutions of type I WRON combined with the basic linear numeric transform.

4. Routing Scheme of WRON

In WRON, each routing path P_i is associated with a tri-tuple $<S,D,W>$, where *S* denotes the address of the source node, *D* denotes the address of the destination node, and *W* is the assigned routing wavelength for the data transmission. All the wavelength assignments of a 4-WRON (Fig. 3(a)) are tabulated in Tab. 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 and using the same wavelength; different sources can reach different destinations without confliction. Tab. 2 shows the wavelengths assignment of 5-WRON (Fig. 3(b)).

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

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

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

- Given a source node address S and a destination node address D, there is a unique routing wavelength W can be used for the transmission. (See Proposition 1)
- Given the source node address S and the routing wavelength W, the destination node address D is uniquely defined. (See Proposition 2)
- Given the destination node address D and the routing wavelength W, the source node address S is uniquely defined. (See Proposition 3)

A routing scheme thus can be readily derived according to the Propositions 1-3.

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

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

(1)

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

The proof of Proposition 1 is given in Appendix I.

Proposition 2. For an N-WRON, given the destination node address D and the routing wavelength W, the source node address S can be derived by

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

(2)

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

The proof of Proposition 2 is shown in Appendix II.

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 by

$$W = f_W(N,S,D)$$

(3)

where

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

when N is an even number, and

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

when N is an odd number.

The proof of Proposition 3 is given in Appendix III.

5. Conclusion

Due to its advantage in architecture, design simplicity, timing, and other physical aspects, optical interconnection network is considered as a promising solution for NoC systems. In this paper, we generalized the basic structure and the construction scheme of Wavelength Routed Optical Network (WRON). We also generalized the routing scheme of WRON and proposed solutions for routing problems based on the two of the three parameters source node address, destination node address, and routing wavelength. Future work includes study of fault-tolerance variant of the WRON.

Appendix

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 WRON at both sides of the original WRON. We denote the original WRON as the *Real WRON*, 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. 5.

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

Rule 1. In the *Real WRON*, when j is odd, the coordinate of the i^{th} switch in the j^{th} stage is (j,2*i-1); when j is even, the coordinate of the i^{th} switch in the j^{th} stage is (j,2*i).

In the *Negative WRON*, when j is odd, the coordinate of the i^{th} switch in the j^{th} stage is (j,2*i-1-N); when j is even, the coordinate of the i^{th} switch in the j^{th} stage is (j,2*i-N).

In the *Positive WRON*, when j is odd, the coordinate of the i^{th} switch in the j^{th} stage is (j,2*i-1+N); when j is even, the coordinate of the i^{th} switch in the j^{th} 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. 5. *Peak Nodes* to the shortcut connection in the original WRON structure.

In the *Real WRON*, the coordinates of the *Peak Node* is indicated as (C,R), where C is the stage number of the *Peak Nod* 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 WRON.

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 the some of the *Peak Nodes*.

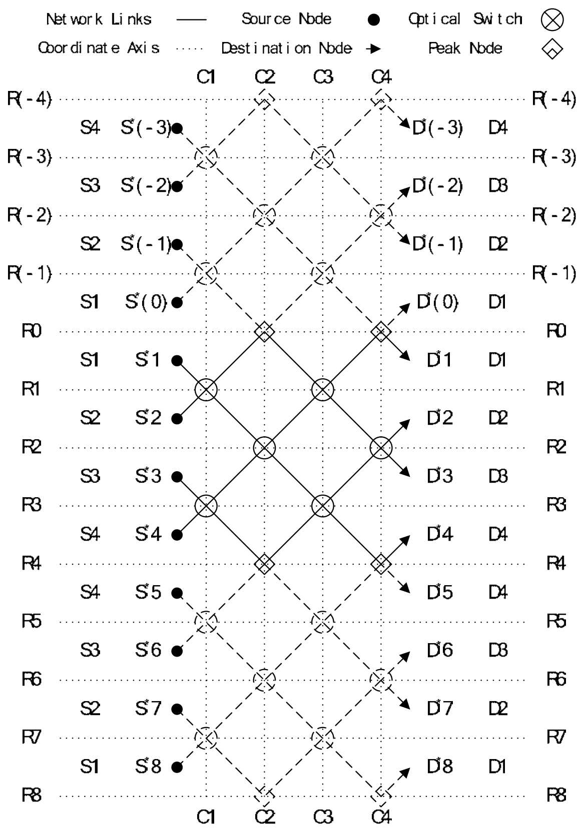


Figure 5. Structure of the Tri-network for a 4×4 WRON

All source and destination node addresses in the Tri-network are numbered following Rule 4.

Rule 4. Every destination nodes address indicated in the Tri-network is the virtual destination address *D**. When routing follows Rule 1, a routing path will reach the virtual destination node *D**. The relationship between the virtual addresses *D** the real address *D* it corresponding to is shown below.

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

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

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

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:

If *S* is even, the coordinate of the *start node* is (1,*S*-1).

If *S* is odd, the coordinate of the *start node* is (1,*S*).

Definition 2. (Reflection Node):

The *reflection node* is the specified *node* in a routing path whose horizontal coordinate is same to 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:

If *S* is even, then the *inherent slope* is -1.

If *S* is odd, then the *inherent slope* is 1.

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:

If *S* is even, then the *acquired slop*e is 1.

If *S* is odd, then the *acquired slope* is -1.

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*.

Now we can start to proof. 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.

I. 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.

1. 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×*W*

The vertical coordinate of the *end node* is *N*, hence the horizontal coordinate of the *end node* is *r*=*S*+*N*-2×*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, $D^*=S+(N\text{-}2W+1)\times(-1)^S$.

2. 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

$D^*=S+(N-2W+1)\times(-1)^S$. ■

II. Proof of Proposition 2

1. 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 be derived as

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

In summary, $S^*=D+(N-2W+1)\times(-1)^{N+D}$.

2. When N is odd:

The virtual address of the destination node be derived as

$S^*=D+(N-2W+1)\times(-1)^{N+D}$. ■

III. 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 use not the real address D but the virtual address D^* in computing the correct wavelength W.

1. When N is Even

Assume N is even, as shown in Fig. 5. 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 $(1, S\text{-}1)$, the *inherent slope* is -1. The function of the path before the *reflection node* is $r\text{-}S\text{+}c=0$.

The coordinate of the *end node* is $(N,D\text{-}1)$. The *acquire slope* is 1. The function of the routing path after the *reflection node* is $r\text{-}(D\text{-}1)=c\text{-}N$, i.e., $r\text{-}D\text{-}1\text{+}N\text{+}c=0$.

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 of is in the *Virtual WRON*, i.e., $D^*\neq D$. There have two possibilities: $D^*>N$ or $D^*\leq 0$. 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

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

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:

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

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

Then $W=W_1$ when $S+D>N$ and $W=W_2$ when $S+D\leq N$.

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,

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

2. 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

Similarly to the last case, when D is even,

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

When D is odd,

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

Case 2. When S is odd

Similarly to the case 1, when D is odd,

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

When D is even,

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

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