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ORIGINAL PAPER

A routing algorithm for reducing optical loss in photonic Networks-on-Chip

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Abstract Photonic Network-on-Chips is a new generation of Network-on-Chips and has been proposed as a novel solution for the communication infrastructure of chip multiprocessors as well as a different solution to eliminate limitations of Network-on-Chips. Photonic Network-on-Chips has important properties such as increasing communication bandwidth, lowering transmission latency, and lowering power consumption. These networks have some challenges such as routing for transfering photonic data over photonic layer. In this paper, we propose a new routing algorithm in which we use turning models, circuit-switching method, different traffic patterns such as Random, Paratec, Madbench, Bitreverse, Cactus, and Tornado to reduce optical loss to photonic layer. To do this, we have also considered non-blocking five-port router and 2-D Mesh topology. The new proposed routing algorithm can choose different source and destination nodes through selecting the path with the lowest optical loss. So to evaluate optical loss in different paths, we have considered best-case loss path, average-case, and worst-case. This was because we can use best-case loss path in order to transfer photonic data over photonic layer. In the end, proposed routing algorithm with turning models and different traffic patterns shows some improvements of optical loss in photonic layer and notably reduce this factor compared to the other XY dimension-order routing algorithm with 5 ports router.

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1 Introduction

In the last few years, many researchers have pointed out the limitations of the current networks and have proposed as a viable solution data center networks based on optical interconnects. Data center networks based on optical interconnects are interdisciplinary fields, which encompasses such as computer networks, computer architecture, hardware design, optical networks, and optical devices [37].

Data centers are experiencing an exponential increase in the amount of network traffic they have to sustain due to cloud computing and several emerging web applications. To face this network load, large data centers are required with thousands of servers interconnected with high bandwidth switches. Current data center networks, based on electronic packet switches, consume excessive power to handle the increased communication bandwidth of emerging applications. Optical interconnects have gained attention recently as a promising solution offering high throughput, low latency, and reduced energy consumption compared to current networks based on commodity switches [36].

A major design paradigm shift is currently impacting high-performance microprocessors as critical technologies are simultaneously converging on fundamental performance limits. Essentially, the scaling in transistor speeds and integration densities can no longer drive the expected congruent multiples in computation performance. Accelerated local processing frequencies have clearly reached a point of diminishing returns: further increases in speed lead to tighter bounds on the logic coherently accessed on chip and the associated power dissipation is exacerbated in an exponential fashion. Clearly, within the next few years, performance gains will come from increases in the number of processor cores per chip, leading to the emergence of a key bottleneck: the global intrachip communications infrastructure. Perhaps the most daunting challenge to future systems is to realize the enormous bandwidths capacities and stringent latency requirements when interconnecting a large number of processing cores in a power-efficient fashion. Low latency, high data-rate, on-chip interconnection networks have therefore become a key to relieving one of the main bottlenecks to chip multiprocessor (CMP) system performance. Significant research activity has recently focused on intrachip global communication using packet-switched micronetworks. These so-called Networks-on-Chip (NoC) are made of carefully engineered links and represent a shared medium that is highly scalable and can provide enough bandwidth to replace many traditional bus-based and/or point-to-point links [13].

However, with a fixed upper limit to the total chip power dissipation and the communications infrastructure emerging as a major power consumer, performance-per-watt is becoming the most critical design metric for the scaling of NoCs and CMPs. It is not clear how electronic NoCs will continue to satisfy future communication bandwidths and latency requirements within the power dissipation budget. Photonic interconnection networks offer a potentially disruptive technology solution with fundamentally low power dissipation that remains independent of capacity while providing ultra-high throughputs and minimal access latencies. One of the main drivers for considering photonic NoCs is the expected reduction in power expended on intrachip communications. The key power saving rises from the fact that once a photonic path is established, the data are transmitted end-to-end without the need for repeating, regeneration, or buffering. In electronic NoCs, on the other hand, messages are buffered, regenerated, and then transmitted on the inter-router links several times en route to their destination [13].

In this case, NoC plays an important role in the intra-chip multiprocessor-core interconnection. However, as the number of the processor core and the local clock frequency increases in the CMP, larger communication bandwidth of the NoC is required to realize the communication among the processor cores. By increasing required communication bandwidth, power consumption and transmission latency become the bottleneck of the traditional electronic NoC [5]. Photonic Network-on-Chip (PNoC), which has larger communication bandwidth, lower transmission latency, and lower power consumption, has been proposed recently [1,5]. Photonic Network-on-Chip is based on photonic technology and use silicon-based optical interconnects and routers which are compatible with CMOS technology [6,7]. Also, its performance can be increased noticeably by using Wavelength-Division Multiplexing (WDM) method [8]. In addition, since waveguides are independent of distance and data rate per bit does not impact power consumption in waveguides and photonic switches, power consumption in such network is desirable [9]. During the recent years, different designs of photonic networks have been proposed and most of them possess significant improvement compared to their electric counterparts [10]. Photonic routers serve as one of the key components of PNoCs, and they are considered important when defining performance and cost parameters such as optical loss, power dissipation, and throughput [11].

Based on the two basic switching elements such as waveguides and microring resonators, Crux [12] optical router was developed. Crux router uses 12 microresonators to implement the strictly non-blocking 5*5 routing function required by the dimension-order routing algorithm. Crux includes a switching fabric and control unit. The routers have five bidirectional ports such as Injection/Ejection, East, South, West, and North. The Injection/Ejection port is connected to a local processor core through an Optical/Electronic (O/E) interface. These five ports are aligned to their intended directions, and the input and output of each port are also properly aligned to ensure that no extra crossing or waveguide bending is required when multiple routers are connected to form Mesh-based PNoCs. Crux takes the advantages of the parallel switching element to minimize optical loss. Unlike the optimized crossbar in which optical signals travel in one dimension, Crux can passively route them and does not require to power on any microresonator. Only when optical signals use the Injection/Ejection port or make a turn from one dimension to the other, routers need to power on one microresonator. In Crux, the maximum number of waveguide crossings between the ports is five. Moreover, regardless of the network size, the Mesh-based PNoCs based on Crux only need to power on at most three microresonators to inject, turn, and eject an optical signal between any pair of processor cores, Crux is non-blocking. Figure 1 shows Crux optical router.

In this paper, we propose a new routing algorithm which uses turning models [30,31], circuit-switching method [1], and different traffic patterns such as Random, Paratec, Madbench, Bitreverse, Cactus, and Tornado [28,29] to reduce optical loss over photonic layer. To do this, we have also considered non-blocking five-port Crux router [12] and 2-D Mesh topology. Generally, different traffic patterns can choose source and destination nodes and then determine the path between them with circuit-switching and turning mod-

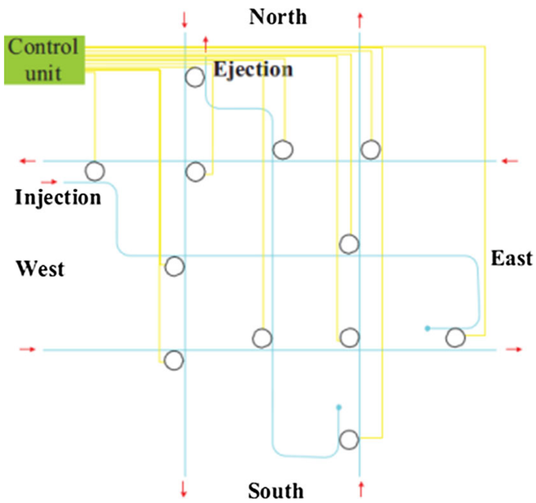

Fig. 1 Crux router; *blue lines* are waveguides and *circles* are microring resonator [12]

els. After evaluating optical loss at each path, we compared this factor values and called them best-case loss, average-case loss, and worst-case loss. To transfer photonic data, we chose the path with the lowest loss (best-case loss). Later, we compared proposed approach with XY dimension-order routing algorithm to show the improvement of this factor.

The rest of the paper is as follows: Sect. 2 reviews some proposed routing algorithms which are used to reduce optical loss to 2-D Mesh topology in PNoCs. Section 3 is dedicated to the PNoCs topology used in this paper and illustration of the basic and demand components in photonic networks; furthermore, we will describe new approach too. In Sect. 4, simulation results are evaluated and compared with XY dimension-order routing algorithm. In the end, Sect. 5 includes concluding remarks and further research.

2 Related works

Since the introduction of photonic Network-on-Chips as an effective solution by Shacham et al. [13], we have reviewed some approaches which are presented about routing and Loss.

Xie et al. [7,12] proposed that the non-blocking five-port Crux router switching function of Crux is reduced for XY routing only in Mesh or Torus-based topology. XY routing is a low complexity distributed without any routing table. Each packet is routed first in X dimension until it reaches the node in the same column with the destination, and then along the perpendicular Y dimension to the destination. XY routing algorithm with Crux router is used to reduce optical loss.

Gu et al. [14] proposed that Cygnus non-blocking five-port optic router with high performance, high cost, and low power that uses XY routing algorithm to transfer optic data at the path with low loss.

Ye et al. [15] use 8*8 Mesh-based photonic Network-on-chip and different non-blocking 5 ports routers such as Crux with XY non-blocking routing algorithm to transfer photonic data on photonic layer then evaluate optical loss factor. The simulation result was 0.64 (dB).

Gu et al. [16] proposed a novel optical Mesh Network-on-Chip (ONoC) with a new non-blocking optical router, OXY, and used it to build a 2-D Mesh ONoC, XY routing algorithm to evaluate loss and energy consumption.

Hatamirad et al. [11] proposed loss-aware router design, which can use dimension-ordered routing algorithms in PNoCs. Router structure is four ports, and the XY routing algorithm can be used. They reduced parallel switch element which are not useful to routing and try to achieve low loss.

Ji et al. [17] designed five-port optical router for photonic Networks-on-Chip based on microring resonators tuned through the thermo-optic effect. The characteristics of the microring resonator-based switching element are investigated to achieve balance performance in its two output ports. This design is fabricated on the SOI platform using standard CMOS processing. They tried to reduce waveguide crossing and XY routing algorithm to achieve low loss.

Shacham et al. [18] reviewed the hybrid electronic/photonic NoC and improve non-blocking photonic switch and then estimate the optical loss. Also, they use XY routing algorithm to transfer data from source to destination nodes.
After reviewing some common related works, in Sect. 3, we will explain basic and important concepts which are practical in our approach.

3 Basic concepts and proposed approach

3.1 Network architecture

One of the attributes of photonic communication is buffers that cannot be implemented for photonic Network-on-Chip [13]. Therefore, unlike traditional chips using packet switching methods, circuit-switching is used in photonic interconnections [1]. Different solutions have been proposed for implementing circuit-switching method in this network.

For example, one of the methods is to use photonic signal with different wavelengths for transmitting data, in which each packet uses its path based on the signal's waveguide. The advantage of this method is sending different data simultaneously using different rates. On the other hand, high cost and power loss of having different laser source are disadvantages of the mentioned method [6,19–22].Another method for implementing photonic communication is making use of electrical control circuits. These circuits are used as an arbitrator. If we compare two methods, disadvantage of the second method is its increased power loss. The electrical-optical structure known as a hybrid structure is used in PNoCs [6,23]. A photonic circuit-switching-enabled chip is com-

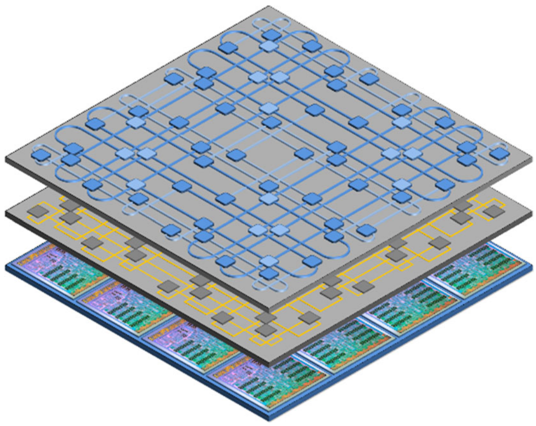

Fig. 2 3 layer photonic plane [24]

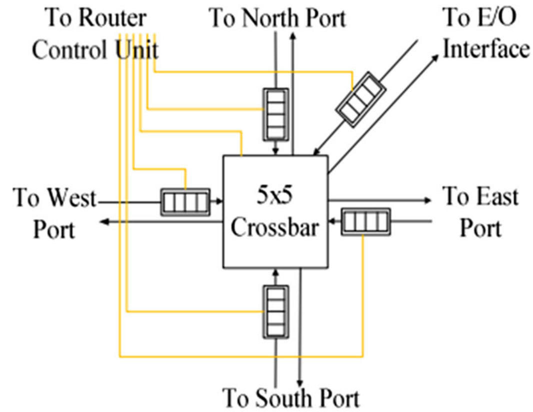

Fig. 3 Electronic switching fabric [25]

posed of three logical layers: a processing layer, electronic control plane, and a photonic data plane. The processing plane is where the processing nodes sit and act as the sources and sinks for all communications (bottom). The top most layers, the photonic data plane, provide high-speed WDM-enabled optical links between each pair of communicating processors. However, the photonic plane cannot be adjusted all-optically and the photonic devices need to be preconfigured before any optical data can be transmitted. For this reason, an electronic control plane is provided for the purposes of configuration (middle). Figure 2 shows a plane topology [24].

3.2 Photonic Networks-on-Chip basic elements

PNoCs have some basic components which are key roles to implementation. In this subsection, we will review these elements.

3.2.1 Components of electrical parts

Electrical parts are composed of wired communication and an electrical router. This router acts as both a controller and an arbitrator. Communications between electronic and optical domains are facilitated by the O/E interface, which handles serialization, deserialization, and O/E conversions. The 5x5 electronic switching fabrics are composed of five input buffers and a 5x5 crossbar. Four ports are connected to local processor cores, and one is connected to the O/E interface. The 5x5 non-blocking crossbar allows five concurrent transactions if there is no contention for the same output port. Figure 3 shows electronic switching fabric [25].

3.2.2 Components of photonic parts

Waveguide carries photonic messages. Modulators are devices that convert electrical signal to optical ones. Detectors are used at the end of an optical communication link and convert optical signal back to electrical. Microring resonator (MRR) is used for deciding between continuations of changing data paths on waveguides. On the other hand, MRR can transfer photonic waves with specific resonance frequencies from one wave to another. MRR has two states, namely On state to transfer the signal and Off state [11]. Parallel switching element (PSE) and crossing switching element (CSE) are two basic elements in PNoCs used in photonic routers. A PSE is composed of one MRR and two waveguides. In this structure, waveguide is parallel to MRR. A CSE is like PSE, but in this structure MRR location is the crossing of waveguide. Generally, we have 4 ports including input, drop, through, and add. When MRR is in On state, the signal changes its paths and will be forwarded to the drop; otherwise the signal will continue its path and will be forwarded to the through port. Figure 4 shows these structures. Sometimes, these ports have id numbers, too. Id number of the input port 1, drop port 2, through port 3, and add port is 4 [26].

3.3 Topology and turning models

3.3.1 Topology structure

Topology is a very noticeable factor in the design of photonic Network-on-Chip because design of a router depends upon it. Different topologies are proposed in the literature for the design of PNoC such as Mesh and Torus. Some researchers have also proposed topologies suitable for an application or an application area. In this paper, we will focus on non-blocking 2-D Mesh topology due to its simplicity and regularity. Figure 5 shows this topology structure.

In Fig. 5, orange rectangle is Processing Element (PE) and column is numbered 1, 1 to M, 1 and 1, N to M, N. Green circle is 5*5 non-blocking Crux router [12]. Flashes are waveguides to transfer photonic data.

The topology of choice in our design reflects the characteristics of entire system—a chip multiprocessor (CMP), where

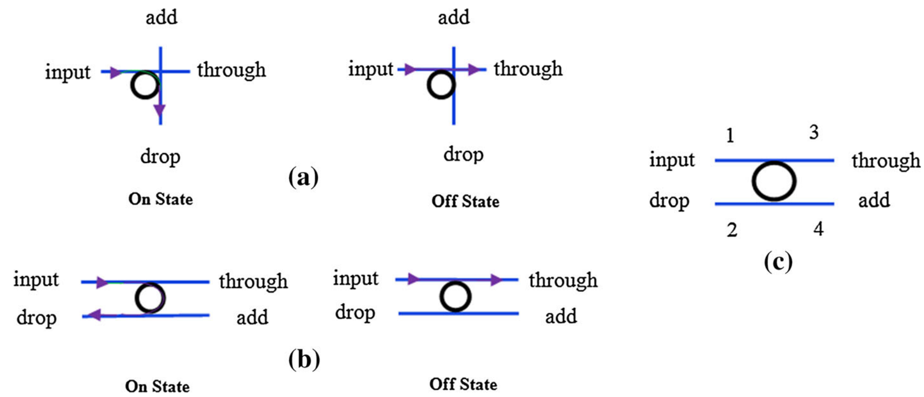

Fig. 4 CSE (**a**) and PSE (**b**) structures, PSE with id numbers (**c**)

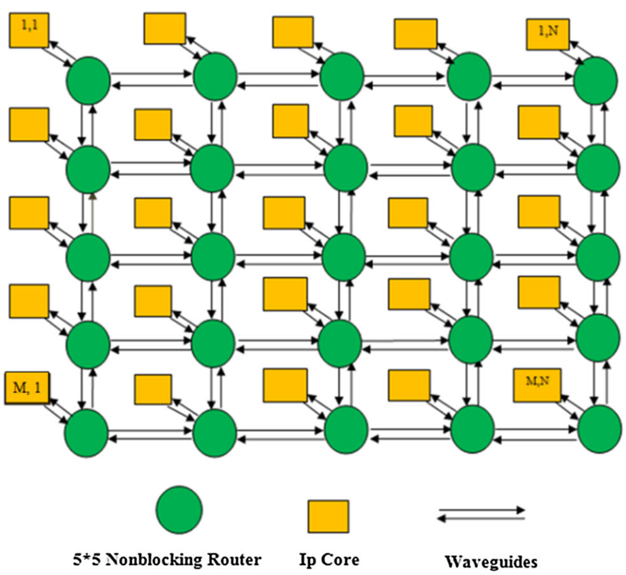

Fig. 5 The structure of 2-D Mesh topology

a number of homogeneous processing cores are integrated as tiles on a single die. The communication requirements of a CMP are best served by a 2-D regular topology such as a Mesh or a Torus. These topologies match well the planar, regular layout of the CMP and the application-based nature of the traffic. Any program running on the CMP may generate a different traffic pattern. Two-dimensional order topologies are the most suitable for the construction of the hybrid network. The same reasons that made them popular in electronic NoCs, namely their felicity to handle a large variety of workloads and their good layout compatibility with tiled CMP chip, still apply in the photonic case. Further, high-radix switches are very difficult to build with photonic switching elements so the low-radix switches the building blocks of Mesh or Torus networks are a better fit. Topological means can also be employed to overcome the lack of buffering in photonics [13].

A key advantage of photonic implementations of Meshes and Torus is related to the nature of the guided waves. When two waveguides intersect at a right angle, as they do many times in Mesh and Torus networks, the waves continue propagating in their original direction and the crosstalk is negligible. This property enables the construction of the photonic NoC in a single layer, above the metal stack, thus reducing the fabric [1]. The 2-D Mesh topology has some attractive characteristics including a modular design, short interconnecting wires, and simple dimension-order routing algorithm such as XY [34].

The modeled electronic networks include the Mesh and Torus topology. Torus offers a lower network diameter compared to Meshes at the expense of having longer links [18]. The Mesh topology is used as a baseline comparison. In contrast with other exotic electronic network topologies, the Mesh is simple to implement due to its use of relatively low-radix switches in a regular 2-D planar layout [35]. After reviewing the reason for the choice of 2-D non-blocking Mesh topology, Subsect. 3.3.2 turning models are described.

3.3.2 Turning models

In 2-D Mesh topology, a photonic signal can travel in one of four directions of router such as North, South, West, and East. A turn means that signal changes its direction of travel. Accordingly, we have four turning models like West-first, North-last, Negative-first, and Odd-even. In these turning models, we can delete one direction in each clockwise or counterclockwise direction and delete direction in odd or even columns.

All the turning models are deadlock-free. It means that turning models eliminate set of turns needed to achieve deadlock freedom while retaining some path diversity and potential for adaptivity. With dimension-order routing algorithm, only four possible turns are permitted for the eight turns available in a two-dimensional Mesh. Turn model routing increases the flexibility of the algorithm by allowing six out of eight turns. Only one turn from each cycle is eliminated [30]. In Fig. 6, four possible turning models are illustrated.

The West-first algorithm (Fig. 6a) is shown in addition to eliminating the North to West turn (counterclockwise); the South to West turn (clockwise) is eliminated [30]. In other

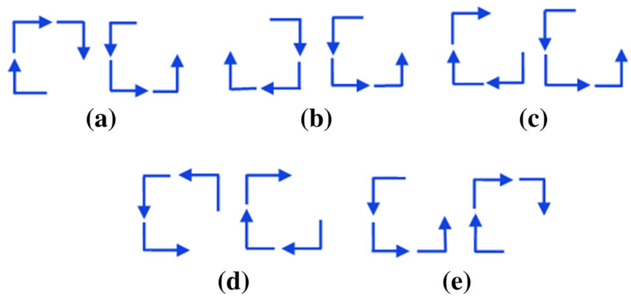

Fig. 6 West-first (**a**), North-last (**b**), Negative-first (**c**), Odd-even an even column (**d**), odd-even an odd column (**e**)

words, a photonic data must first travel in the West port before traveling in any other port or direction.

The North-last (Fig. 6b) eliminates both the North to West turn (counterclockwise) and North to East turns (clockwise) [30]. Unless a photonic data turn North, no further turns are permitted. In the other words, the North turn must be made last.

The Negative-first (Fig. 6c) removes turns from North to West (counterclockwise) and East to South (clockwise). A photonic data travel in the negative directions (West and South) before it is permitted to travel in positive direction (East to North) [30].

The Odd-even turn model routing (Fig. 6d, e) eliminates a set of two turns depending on whether the current node is in an odd or even column. For example, photonic data are traversing a node in an even column turns from East to North and from North to West are prohibited. When photonic data traversing an odd column node turns from East to South and from South to West are prohibited. With this set of restrictions, the Odd-even turn model is deadlock-free provided 180° turns are disallowed [31].

More sophisticated algorithms are realized using routing tables at each hop which store the outgoing link a packet should take to reach a particular destination, by accessing routing information at each hop (rather than all at the source) [30]. In source routing, the information about the whole path from the source to the destination is pre-computed and provided in packet headers by the participation of routers on the path. With source routing, all routing decision are made inside the source core before injecting any packet in the network. For this reason, each source contains lists or tables that contain complete route information to reach all other resources in the network. Source routing is not perhaps suitable for dynamic networks where network size and topology are changing [33].

Compared source routing, node-based routing requires smaller routing tables at each node. Each routing table needs to store only the routing information to select the next hop for each destination rather than the entire path. When multiple outputs are included per destination, node-based routing supports some adaptivity. Node-based routing tables can also be programmable [30].

Turning algorithms have the same turning models at the Network-on-Chip and photonic network-on-Chip. West-first, Negative-first, and Odd-even turning models pseudo-code are presented as follows [32]; the North-last algorithm is written as pseudo-code used at our simulation.

Algorithm 1: West-first [32]

```
if at destination then
  arrive
else if destination in same column then
    if destination is North then
      go North
    else
      go South
    end if
else if destination in same row then
   if destination is East then
     go East
   else
     go West
   end if
else if destination is West then
   go West
else if destination is North then
   go North or East
else if destination is south then
   go South or East
end if
```

Algorithm 2: North-last

```
if at destination then
  arrive
else if destination in same column then
    if destination is North then
      go North
    else
      go South
    end if
else if destination in same row then
    if destination is East then
      go East
    else
      go West
    end if
 else if destination is West then
    go North or East
 else if destination is North then
   go South
end if
```

Algorithm 3: Negative-first [32]

```
if at destination then
   arrive
else if destination in same column then
   if destination is North then
      go North
   else
      go South
   end if
else if destination in same row then
   if destination is East then
      go East
   else
      go West
   end if
else if destination is North East then
   go North or East
else if destination is North West then
   go West
else if destination is South East then
   go South
else if destination is South West then
   go South or West
end if
```

Algorithm 4: Odd-even [32]

```
Valid_Directions = 0
if at destination then
  arrive
else if destination in same column then
   if destination is North then
      Valid_Directions ⟵ (Valid_Direction U North)
else
      Valid_Directions ⟵ (Valid_Direction U South)
end if
else if destination is East then
  if destination in same row then
      Valid_Directions ⟵ (Valid_Direction U East)
else
  if this column is Odd then
     if destination is North then
      Valid_Directions ⟵ (Valid_Direction U North)
else
      Valid_Directions ⟵ (Valid_Direction U South)
     end if
end if
if destination is Odd or more than one column away then
    Valid_Directions ⟵ (Valid_Direction U East)
     end if
  end if
else
     Valid_Directions ⟵ (Valid_Direction U West)
    if this column is even and destination is not in the same row then
        if destination is North then
           Valid_Directions ⟵ (Valid_Direction U North)
        else
            Valid_Directions ⟵ (Valid_Direction U South)
end if
```

After reviewing network and topology structure, some electrical and photonic elements and turning models, we have described proposed routing algorithm clearly.

In this paper, we have proposed a new routing algorithm, which can lead us to evaluate optical loss in different paths between source and destination nodes and choose a suitable path to transfer optical data over photonic layer. In our approach, we used non-blocking M*N 2-D Mesh topology, 5*5 non-blocking Crux router [12], turning models [30,31], circuit-switching method [1], and different traffic patterns [28,29]. Phases of proposed approach are given as follows:

Marking columns: First, we should mark columns in M*N 2-D Mesh topology which are shown in Fig. 5. We can consider source and destination nodes at the same or different rows and columns. Considering the type of different traffic patterns to determine the source and destination nodes, proposed routing algorithm is used to achieve 3 different paths between these nodes and evaluate the optical loss at each path.

Routing at each router: Traffic patterns [28,29] determine the source and destination nodes over photonic layer. Routing algorithm was run in each photonic 5*5 non-blocking Crux router [12], which is on the path between these nodes. Prohibited clockwise and counterclockwise turning models [30,31] in each router are considered.

Turning model running and circuit-switching: Allowed ports and direction are chosen to go to other router hop by hop. At the same time, along with turning models, we use circuit-switching method [1] to reserve routers and paths. It means our algorithm is repeated at each router in order to achieve the destination node and reserve the path between source and destination nodes with circuit-switching.

Transferring photonic data: After the reservation of the paths, photonic data are sent from source to destination nodes.

The goal of the proposed approach: We want to choose a suitable path between different paths to transfer our optical data. To do this, we considered optical loss factor. It means each path has the least optical loss than the other paths. This path is suitable to transfer optical data. The optical loss is one of the important factors at PNoCs.

Evaluating optical loss: We know that some optical elements such as waveguide crossing loss, waveguide bending loss (bending 90°), and microring resonator in On and Off states are effective factors in optical loss. After reserving the path, we should evaluate the optical loss in each router. Then, these values are added together and considered optical loss in one path. We repeat this method to achieve optical loss in path2 and path3. In the end, having compared these values in the 3 paths, we will be able to choose the path with the least optical loss (best-case loss path) to transfer optical data.

Examples of the proposed approach: In each turning model [30,31] and different traffic patterns [28,29], we

Table 1 Routing Algorithm Pseudo-codes

Routing Algorithm Phases	Pseudo-codes	Comments
Phase 1	Assign values of M, N	Dimension of topology
Phase 2	Determine source and destination nodes	With running each traffic patterns algorithm
Phase 3	Running each turning model algorithm at each router	To locate suitable port
Phase 4	Running circuit-switching simultaneous phase 3	For reserve path between each router
Phase 5	Repeat phase 2 and phase 3 again	–
Phase 6	Path reservation end	When receive destination node
Phase 7	Repeat phase 3 to phase 6	For each other two paths
Phase 8	Evaluate optical Loss at each router	Each router at each paths
Phase 9	Evaluate optical Loss at each path	Summing optical Loss values which are gain phase 8
Phase 10	Compare values of phase 9 to determine low optical loss	Which is called best-case loss
Phase 11	Choose best-case loss path to transfer optical data	–

considered sixteen statuses (sixteen source and destination nodes). For example, twelve statuses are in different rows and columns and four statuses are in the same rows or columns. Notice that when our source and destination nodes are in the same rows and columns, best-case loss, average-case loss, and worst-case loss values are the same. In the end, we want to evaluate and show how much improvement has been made in the amount of optical loss in our PNoC comparing our approach results with other algorithm such as XY dimension-order routing algorithm. For this reason, after evaluation of best-case loss, average-case loss, and worst-case loss for each status, sixteen best-case losses are added, sixteen average-case losses are added, and sixteen worst-case losses are added too. Finally, the subtract values of worst-case and best-case is optical loss improvement at each turning model. After describing proposed algorithm clearly, Table 1 shows pseudo-code phases.

In this section, we reviewed basic concepts and proposed approach phases. In Sect. 4, experimental results are explained.

4 Experimental results

In this section, the simulation is done to achieve low optical loss in paths between source and destination nodes.

4.1 Simulation environment

In this paper, we have used CLAP [26] and MATLAB in order to evaluate the functionality of photonic Networks-on-Chip such as optical loss. However, the primary value of some parameters and physical components must be set.

Simulation makes it possible to access different scenarios with various network sizes. The basic components and other important simulation configuration have been mentioned in Tables 2, 3, 4, 5.

Table 2 Simulation configuration

Simulation parameters	Values
Message size	1024 Bits
Max packet size	32 Bits
Laser power	10 db/m

Table 3 Symbols and parameters of 5*5 Crux router

Parameters	Symbols
Port i	P_i
Port j	P_j
Injection port	In
Ejection port	Eje
North port	N
South port	S
West port	W
East port	E

4.2 Optical loss

One of the analyzed parameters in this paper is optical loss, which has been evaluated for different Mesh networks sizes. For example, network size ranges from 2*2 to 8*8. We tested for 8*8 network size. The simulation is based on the primary data which is listed in Tables 2 and 5 to achieve optical loss. We mentioned our proposed algorithm in Sect. 3 completely. This section shows how this variable for different statuses can be evaluated. Equation (1) is our proposed equation, which is used in simulation to measure optical loss in each router for different paths.

Table 4 Parameters and symbols of optical loss

Parameters	Symbols
Optical Loss in Router (x,y) from port i to port j	$L_{(Pi,Pj)}R(x,y)$
Router (x,y)	R(x,y)
Switch Loss in port i to port j	Switching (P_i, P_j)
Chip size (cm^2)	C_S
Network Size	M*N

Table 5 Parameters and symbols of optical Loss

Parameters	Symbol	Values
Loss in waveguide crossing	L_{WC}	0.15 dB [27]
Loss in waveguide bending	L_{WB}	0.005 dB/90° [27]
Loss in MRR when On state and optical data drop into MRR	L_{DRon}	0.5 dB [27]
Loss in MRR when Off state and optical data pass by MRR	L_{PRoff}	0.005 dB [27]

$$L^{R(x,y)}_{(P_i,P_j)} = \sum\nolimits_i^j \text{Switching}(P_i, P_j)$$
$$\text{Switching}(P_i, P_j) = L_{WC} * L_{WB} * L_{DRon} * L_{PRoff} \quad (1)$$

In Eq. (1), $L_{(Pi,Pj)}R(x,y)$ is optical loss in router (x,y) from port i to port j, Switching (P_i, P_j) is switch loss in port i to port j; this variable is evaluated with multiplication of L_{WC} which is waveguide crossing loss, L_{WB} is waveguide bending loss, L_{DRon} is loss in MRR when On state and optical data drop into MRR and L_{PRoff} is loss in MRR when Off state and optical data pass by MRR. We evaluate four turning models [30, 31] with different traffic patterns such as Random, Paratec, Madbench, Bitreverse, Cactus, and Tornado [28,29].

In this section, we have presented some sample of our simulation results such as Odd-even and West-first turning models [30,31] with Random traffic pattern [28,29]. On the other hand, we can analyze the improvement in optical loss, an Odd-even, and West-first turning models. The results of mentioned turning model are shown; West-first turning model has less optical loss than Odd-even turning model when traffic pattern is Random. Figures 7 and 8 show these results.

Figures 9 and Table 6 show our optical loss results with four turning models [30,31] and different traffic patterns such as Random, Paratec, Madbench, Bitreverse, Cactus and Tornado [28,29]. The results of our simulation are presented in Table 6. The comparison of all the results shows that West-first turning model has the lowest optical loss percentage in different traffic patterns. If we compare our results with similar routing algorithms such as XY dimension-order routing algorithm with Crux router [12], XY achieves 64% optical loss [15]. It means that our proposed approach is aware of loss compared with XY dimension-order routing algorithm.

Table 6, shows that West-first turning model [30] with Madbench, Bitreverse, Random, Tornado, Cactus, and Paratec traffic patterns [28,29] has the lowest optical loss percentage compared with other turning models. Also, it shows that Paratec traffic pattern holds the highest optical loss percentage compared with other traffic patterns. This depends on the location of the nodes either they are in the edge or inside

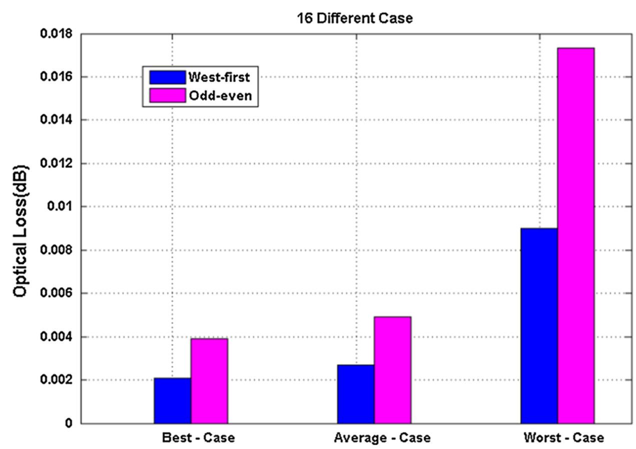

Fig. 7 Optical loss at West-first and Odd-even turning models

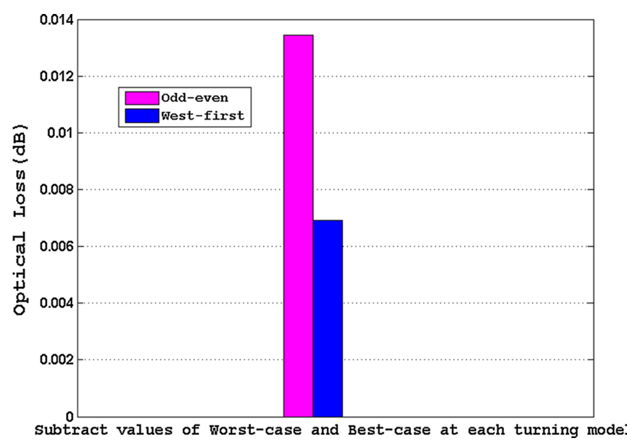

Fig. 8 Subtract optical loss values between worst-case loss and best-case loss

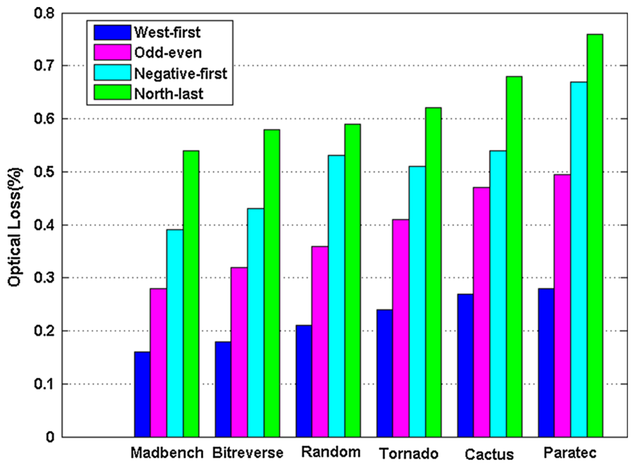

Fig. 9 Optical loss percentage with four turning models and different traffic patterns

Table 6 Comparing optical loss (%)

Optical Loss (%)	Madbench	Bitreverse	Random	Tornado	Cactus	Paratec
West-first	0.17	0.18	0.20	0.23	0.27	0.28
Odd-even	0.28	0.32	0.35	0.41	0.48	0.50
Negative-first	0.39	0.43	0.53	0.51	0.54	0.67
North-last	0.55	0.57	0.59	0.62	0.67	0.77

the topology. It also depends on our turning models clockwise and counterclockwise prohibited turn [30,31]. At traffic patterns, it can depend on their algorithm steps and which mechanisms are used or how nodes are determined and their communications [28,29].

5 Conclusions and further research

It can be observed that the non-blocking 2-D Mesh topology and proposed routing algorithm have used four turning models [30,31], circuit-switching method [1], different traffic patterns such as Random, Paratec, Madbench, Bitreverse, Cactus, Tornado [28,29] and non-blocking five-port Crux router [12]. A significant improvement can be achieved in optical loss. As mentioned in related works, some methods and approaches try to reduce optical loss in photonic Network-on-Chip with XY dimension-order routing algorithm and design new structure of routers having low number of waveguides, microring resonators, and bending degrees. However, in this paper, we proposed a new routing algorithm which is independent of the router structure and can be used to access various paths between different source and destination nodes. It can also select the best path with the lowest optical loss to transfer optical data over photonic layer. Finally, we have evaluated and compared our simulation results with XY dimension-order routing algorithm. This shows that our proposed approach is better than XY dimension-order routing algorithm and improves optical loss values in PNoCs. It can be claimed that the proposed routing algorithm is aware of loss but the other routing algorithms are not. As a further research, our algorithm can be tested for:

- Different non-blocking 5*5 optical routers
- Different traffic patterns

The goal of this evaluation is to show how turning models with different assumptions can access low optical loss.

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