PAPER An Optimization Algorithm to Build Low Congestion Multi-Ring Topology for Optical Network-on-Chip*

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SUMMARY Ring-based topology is popular for optical network-onchip. However, the network congestion is serious for ring topology, especially when optical circuit-switching is employed. In this paper, we proposed an algorithm to build a low congestion multi-ring architecture for optical network-on-chip without additional wavelength or scheduling overhead. A network congestion model is established with new network congestion factor defined. An algorithm is developed to optimize the low congestion multi-ring topology. Finally, a case study is shown and the simulation results by OPNET verify the superiority over the traditional ONoC architecture.

key words: optical interconnect, NoC, architecture, congestion

1. Introduction

Progresses in silicon nanophotonics have made optical network-on-chip (ONoC) a promising alternative to electronic network-on-chip (ENoC) owing to its many advantages such as high bandwidth, high signal propagation speed, low energy consumption and electromagnetic interference [1]-[4]. Several ONoC architectures have been proposed for future multicore microprocessors, such as Mesh [5], Corona [6], RONoC [7] and PHENIC [8]. In which, due to its low complexity, the ring topology is frequently considered. However, many architectures of ONoC employ optical circuit-switching (OCS) [9] due to the lack of optical buffer and process modules. Some OCS based ONoC architectures suffer from low throughput and high latency since the high congestion probability. When the path is occupied by a communication pair, any link of this path cannot be used by other pairs of communication nodes. As a consequence, path-setup packet of others communication pairs will be blocked if its path is overlapped with the occupied path, which brings about a high congestion probability.

Some architectures are proposed to solve the high congestion probability. For instance, Corona [6] is a fully-

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connected photonic crossbar with Multi-Write-Single-Read implementation, which employs token-based arbitration mechanism. Corona can alleviate congestion problem by providing more optical resources. It needs $O(N^2)$ modulators/transmitters. Hence, the complexity and cost will limit the scalability of Corona. ORB [10] and ORNoC [11] are also proposed to decrease the blocking by exploiting wavelength division multi-placing (WDM) and wavelength assignment. The scalability of network is still a problem because the number of available wavelengths is limited.

In this paper, we propose an optimization algorithm to build low congestion multi-ring architecture for ONoC. This optimization algorithm employs multiple independent rings to build the architecture. The network congestion factor is defined by the occupation probability of the links in the multi-ring. The optimization algorithm is constructed to select the multi-ring with the minimal network congestion factor. A 16-node multi-ring network architecture is built as a case study. The architecture is simulated with OPNET to evaluate the performance of our algorithm.

2. Related Work

Based on the silicon photonic technologies, different onchip optical network architectures have been proposed. Gu et al. [5] presented a mesh topology. Mesh has been regarded as a popular NoC solution for many-core processors. Many researches focused on the routing algorithm of mesh to avoid deadlock, livelock and to improve the performance of network. Due to the simplicity, deadlock-freedom and livelock-freedom, most ONoC usually deploy the deterministic routing algorithms. Gu et al. [5] presented the xy routing algorithm. It routes packets first along x dimension and then along y dimension. It cannot balance the traffic and maintain the performance with OCS-based ONoC under high traffic load. As a result, the adaptive routing is needed. In case of adaptive routing algorithm, it must be deadlock-free and livelock-free. The representative adaptive routing is the routing algorithm based turn model [19], [20]. These algorithms are deadlock-free by restricting the minimum number of turns. The basic idea of Odd-Even routing algorithms is to limit the turns to certain direction [21]–[23]. The improvement of network performance is less significant by changing the employed routing algorithm of ONoC. Vantrease et al. [6] proposed a crossbar, in which a waveguide for data transfer is shared by multiple writers and a single reader. Gu et al. [7] proposed a reconfigurable archi-

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tecture for application-specific optical network-on-chip. It configures the connections by altering the states of different groups of microring resonators. Pasricha et al. [10] proposed a clustered architecture with local electronic buses and a global optical ring connecting local domains. The optical configuration requires that each wavelength must be statically assigned to a given optical network interface, limiting the achievable parallelism. Le Beux et al. [11] presented an optical ring NoC (ORNoC) for both 2-D and 3-D architecture. In ORNoC, a wavelength can be reused in a waveguide such that it can also support multiple transactions to improve the performance.

3. The Optimization Algorithm

Algorithm 1 Network Congestion Factor Computation Algorithm

Input: ring-group set *G*, including N_{group} ring-groups, and each ringgroup includes N_{link} links and N_{ring} rings, t_{ij} represents the number of the ring that connected to the communication node pair (n_i, n_j) in g_k , communication demand matrix *B*, b_{ij} represents the communication demand between communication node pair (n_i, n_j)

Output: the network congestion factor of ring-group g_k , labeled as P_k

1: Begin

- 2: Create matrices *p*[*N*_{*link*}] and *t*[*N*_{*link*}], N represents the number of nodes in network, variables *i*, *j*, initialize them as 0
- 3: for each ring-group do
- 4: **for** each $l \in [1, N_{link}]$ **do**
- 5: **for** each $i, j \in l$ **do** //*i*, *j* represents the nodes in ring where link *l* located
- $6: \qquad p_l = p_l + b_{ij}/2t_{ij}$
- 7: end for
- 8: $p_l = p_l / C_H^2 / / H$ represents the number of node pairs on ring where link *l* located
- 9: end for
- 10: end for
- 11: for each $l \in [1, N_{link}]$ do
- $12: \quad A_k = A_k + p_l$
- 13: end for
- 14: $A_k = A_k / N_{link}$ //compute the average link occupancy probability
- 15: for each $l \in [1, N_{link}]$ do
- 16: $V_k = V_k + (p_l A_k)(p_l A_k)$
- 17: **end for**
- V_k = V_k/N_{link} //compute the variance of link occupancy probability in ring-group
- 19: $P_k = \alpha E_k + (1 \alpha)F_k //\alpha$ is an adjustable parameter, E_k and F_k represents the serial number of A_k and V_k respectively
- 20: End

The multi-ring topology includes N_{ring} isolated rings. Each ring may connect all nodes or partial nodes. A ringgroup is identified as a combination of different multiple isolated rings. All the cores can be connected with other cores by at least one ring in each ring-group. Therefore, the packets will not be transferred between rings during transmission which avoids the use of sophisticated router and simplifies the architecture. For instance, as Fig. 1 shows, a multi-ring topology consists of multiple rings. In Fig. 1, the combination of ring (a), ring (b) and ring (c) is a multi-ring topology. We can see that this multi-ring consists of three rings, ring (a), ring (b) and ring (c). Each ring in multi-ring topology is



Fig. 1 A ring-group. Ring (a), (b), (c) are independent with each other.

independent. That is to say the ring (a), ring (b) and ring (c) are independent. Independence means that the ring-to-ring transfer is not allowed. For example, when a data is transmitting in ring (a), then this data cannot be transferred to ring (b) or ring (c). A multi-ring is identified as a combination of different multiple independent rings. There are two paths between Core 1 and Core 4, two paths between Core 2 and Core 7, only one path between Core 1 and Core 2.

Considering the features presented above, there are plenty of ring-groups can build up an ONoC architecture. Hence, the network congestion factor should be defined to help to achieve the optimized ring-group. In the subsection, network congestion factor computation model is developed, and the optimization algorithm of building low-congestion multi-ring is introduced in detail.

3.1 Network Congestion Factor Computation Model

For an ONoC architecture consisting of N_{core} cores, the N_{core} -order matrix B is used to denote the communication demands of cores, and $b_{i,j}$ represents the communication demand from node n_i to node n_j , $0 \le i, j \le N_{core}$. In order to describe the congestion condition in the OCS-based ONoC accurately, the l - th link occupancy rate p_l is used to compute the network congestion factor P_k . P_k is defined as the network congestion metric of multi-ring, in which, k present the serial number of the multi-ring. p_l is defined as the link occupancy rate metric of link, in which, l present the serial number of the link of multi-ring. If the serial number of a link in multi-ring is l, then, we will say the link is the l-th link. Assume that g_k represents k - th ring-group and consists of N_{ring} rings. G represents a set of ring-group, including N_{group} ring-groups $g_1, g_2, g_3, \ldots, g_{N_{group}}$. The number of ring which connects the communication node pair (n_i, n_j) in ring-group g_k is $t_{i,j}$. Because of the bidirectional communication characteristic of the optical waveguide, the number of paths of the communication node pair (n_i, n_j) is $2t_{i,j}$. The node pair (n_i, n_i) selects the path by equal probability in communication. It can be found that the probability of $(n_i,$ n_i) bring to each link on $2t_{i,i}$ paths is $b_{i,i}/2t_{i,i}$. The link occupancy rate p_l is the sum of the occupancy probabilities of all the communication node pairs to the link, as follows:

$$p_l = \frac{\sum_i \sum_j \frac{b_{i,j}}{2t_{i,j}}}{C_H^2}.$$
(1)

In Eq. (1), C is the symbol of combination. A combination is an un-ordered collection of distinct elements, usually of a prescribed size and taken from a given set.

 $C_H^2 = \frac{H!}{2!(H-2)!}$. *H* represents the number of nodes in the ring where the link is located, *i* and *j* represent the different node number on the ring. Supposing that there are N_{link} links in g_k , according to Eq. (1), N_{link} link occupancy rates can be calculated. The average link occupancy rate of g_k can be calculated as follows:

$$A_k = \frac{\sum_{l=1}^{N_{link}} p_l}{N_{link}}.$$
(2)

According to Eq. (2), average link occupancy rates $A_1, A_2, \ldots, A_{N_{group}}$ of ring-groups $g_1, g_2, \ldots, g_{N_{group}}$ in *G* can be calculated and sorted in ascending order to get the serial number $E_1, E_2, \ldots, E_{N_{group}}$. Further, there may be a link occupancy rate p_l that is much higher than the others, which is not expected. The variances of N_{link} link occupancy rates need to be considered either, as follows:

$$V_k = \frac{\sum_{o=1}^{N_{link}} (p_o - A_k)^2}{N_{link}}.$$
(3)

According to Eq. (3), variances $V_1, V_2, \ldots, V_{N_{group}}$ of ring-groups in *G* can be calculated and sorted in ascending order to get the serial number $F_1, F_2, \ldots, F_{N_{group}}$. The "serial number" means "1, 2, 3, ..., N_{group} ". For example, there are 5 variances $V_1 = 31, V_2 = 23, V_3 = 50, V_4 = 11, V_5 = 21$. Then we sort the 5 variances in ascending order, and get the serial number $F_1 = 4, F_2 = 3, F_3 = 5, F_4 = 1, F_5 = 2$. The "serial number" of average link occupancy rates is the same way.

The network congestion factor P_k can be calculated, as follows:

$$P_k = \alpha E_k + (1 - \alpha) F_k. \tag{4}$$

In Eq. (4), α is an adjustable parameter with a default value of 0.5. According to Eq. (4), N_{group} network congestion factors of ring-groups in *G* can be calculated. The algorithm for the computation of network congestion factor is shown in Algorithm 1.

3.2 No-Cross-Ring (NCR) Detection

No-cross-ring detection for a ring-group is achieved by an corresponding N_{core} -order matrix D. $d_{i,j}$ is the value of the *i*-th row and the *j*-th column of the matrix D. If node n_i and node n_j in the multi-ring network can be connected together through a ring, $d_{i,j}$ is equal to 1, otherwise $d_{i,j}$ is equal to 0. When all the values of the matrix D are 1, all the cores can be connected with other cores by at least one ring. That means the ring-group satisfies the NCR.

3.3 Algorithm to Build Low-Congestion Multi-Ring

In this algorithm, we mitigate link competition by selecting the ring-group with minimal network congestion factor in the set of ring groups and updating constantly. In order to obtain satisfactory ring-group g, the times of updates Tand N_{ring} are adjustable parameter. All ring-group have the same number of rings, which is N_{ring} . In this section, we present details of the optimization algorithm for building low-congestion multi-ring topology. It should be explained that the proposed method is a general method for all the special-purpose chips. The method is used to get optimized topology before fabrication.

The pseudo-code of the optimization algorithm is illustrated in Algorithm 2, which optimizes the network congestion factor defined in Sect. 2. The first generation of ringgroup q_0 is initialized by setting every bit value of q_0 to 0 or 1 randomly. The algorithm updates the set of ring-group G constantly to obtain the optimized multi-ring. In order to maintain the low complexity of ring topology and avoid the use of sophisticated router, all the cores can communicate with each other through one ring without transferring from one ring to another. To accomplish this objective, each ringgroup needs to satisfy the no-cross-ring (NCR) detection, and the network congestion factor of each ring-group is calculated. The ring-group q_n with the smallest network congestion factor is selected. For the purpose of getting more potential multi-ring topologies, set G is updated by using the ring-group q_n to get the new generation of G. Specifically, multiple ring-groups are generated by the cross exchange and recombination of the rings in ring-group g_n . Then the lines 4–7 of the algorithm 2 are executed and G is updated. We can adjust T until get the satisfying ring-group. The best ring-group found at the last times G is taken as the output of the algorithm.

Algorithm 2 Low-Congestion Architecture Design

- **Input:** Packet injection rate matrix B, B is a N_{core} -order matrix, N_{core} is the number of nodes in network
- **Output:** The ring-group g_{min} with the minimal network congestion factor 1: **Begin**
- 2: Create a set of ring-group G_0 , including N_{group} ring-groups, ring-group is labelled as g_k
- 3: for each $n \in [1,T]$ do
- 4: for each $k \in [0, N_{group} 1]$ do
- 5: Judge all the nodes of ring-group g_k can communicate without transferring from one ring to another
- 6: If not satisfied, recreate ring-group g_k
- 7: end for
- 8: **for** each $k \in [0, N_{group}] 1$ **do**
- 9: Compute P_k of g_k
- 10: **end for**
- 11: Sort ring-groups from small to large according to P_k
- 12: Choose the ring-group with the minimal network congestion factor, labeled as g_n
- 13: Update G_n according to g_n
- 14: end for
- 15: End

Please note that only one ring-group is selected as the final topology of the chip after executing all steps of the optimization algorithm. In the process of the optimization algorithm, there are multiple ring-groups.



Fig. 2 A 16-node topology developed by proposed method. $N_{ring} = 6$

4. Case Study and Analysis

4.1 Case Study

Non-uniform traffic patterns are frequently used in the most applications [12]. Therefore, in this paper, we are interested in the performance of non-uniform traffic pattern. Based on the proposed algorithm, a 16-node multi-ring is achieved, in which the transpose traffic pattern is selected as the communication demand matrix of the 16 nodes.

4.1.1 Multi-Ring Architecture

The 6-ring architecture is shown in Fig. 2. There are 16 nodes in the network. The 16 nodes correspond to 16 spokes. If the node can communicate with other nodes through some ring, the intersection of the ring and spoke corresponded with the node is denoted with a dot. Different nodes are connected together via rings with different color. For example, the innermost brown ring connects nodes 6, 7, 8, 10, 11, 12 together. At the same time, the outermost red ring connects nodes 0, 1, 2, 3, 4, 5, 7, 8, 11, 12, 13, 15 together. The node 7 and node 8 communicate only through the brown and red rings. That is because there are only these two rings include the node 7 and node 8 simultaneously.

To observe the optimized multi-ring we design the optimization algorithm based on the network congestion factor computation model. All the communication node pairs have nearly the same number of communication paths. The node pair (n_1, n_4) and node pair (n_7, n_8) have two paths to communicate. The other communication node pairs have three paths to communicate. Hence the link resources are almost averaged between different communication pairs to decrease the congestion. In the meanwhile, multiple paths of node pair can provide more chance to achieve the transmission of signals for communication pair.

In order to verify the effectiveness of the proposed optimization algorithm clearly, two algorithms are employed to obtain multi-rings for the same network traffic demand in Sect. 3.2.1.

4.1.2 Communication Mechanism

We propose an adaptive routing algorithm for the proposed multi-ring architecture in this section. The routing algorithm is deadlock free by employing an existing switching mechanism [18]. Furthermore, the 16-node multi-ring in Fig. 2 is taken as an example to illustrate how the routing algorithm works.

For a multi-ring with N_{core} nodes, if a node needs to communicate with the other node, the first thing to do is to check the number of rings that contain the two nodes simultaneously. All the rings are labeled as available rings. Once we've obtained a list of available rings, only one available ring is picked out by considering the traffic conditions of all available rings. Before continuing, we need to explain what the traffic condition is. The number of packets that passing through the ring is defined as the traffic distribution of the



Fig. 3 The hardware implementation of the multi-ring interface.

network. When there is more than one available ring, packets will select the ring with smaller traffic condition. In this selected ring, there are two directions to transfer the data. The hop counts of two directions between two nodes are computed and the direction with less hop count is selected. The output port is computed and the routing algorithm is finished.

Communication between node 2 and node 13 in Fig. 2 is taken as an example to illustrate how the routing algorithm works. Node 2 is assumed to communicate with node 13. We can see that the two nodes are contained by three rings simultaneously, red ring, dark purple ring and green ring. Assuming that the traffic condition of the red ring is 6, the traffic condition of dark purple ring is 4 and the traffic condition of the green ring is 2. The green ring is picked out and then the direction is determined. If the packet is sent in a clockwise direction, it will need 7 hops to get to the destination node. Yet, if the packet is sent in a counterclockwise direction, it will only need 3 hops to go to the destination node. Thus, the counterclockwise direction is selected to send the packet.

4.1.3 Hardware Implementation

In this section, we introduce the hardware implementation of multi-ring. In the proposed multi-ring architecture, each core has an multi-ring interface to cope with inter-core communications, which can be viewed as a simplified replacement of traditional optical router. Figure 3 illustrates the multi-ring interface, which consists of three modules, namely, IP core, interface, and ring buses. The interface is composed of the control unit, the EO/OE unit and the optical switch. The EO/OE unit and the optical switch are co-designed in Ref. [5]. In the Fig. 3, the solid blue lines represent the optical waveguide, the solid yellow lines represent the electric wire, and the black dashed line means electric control wire. The control unit decides the routing and controls the micro-ring in the EO/OE unit and the optical switch. A core only has one transmitter, and it can transmit only one signal at one time. For a core in multi-ring, if it has N_{ring} rings to communicate with others, there will be N_{ring} ring buses to build the interface.

4.2 Results and Discussion Performance Evaluation

In this section, the performance of multi-ring developed by our method is evaluated. We compare it with multi-ring developed by the randomized algorithm, multi-ring developed by genetic algorithm, mesh with xy routing algorithm and mesh with Odd-Even routing algorithm to verify the effectiveness of the proposed optimization algorithm. Two algorithms are carried out to obtain two multi-rings based on the network congestion factor computation model we establish in Sect. 2.1. We also compare the hardware overhead of multi-ring topology with mesh to demonstrate the simplicity of multi-ring architecture.

4.2.1 Performance Evaluation

We build a network simulator for multi-ring based on OP-NET and compare this multi-ring with mesh employed xy routing algorithm [5], mesh employed Odd-Even routing algorithm [22] and two multi-rings developed by randomized algorithm and genetic algorithm on 16-node, 25-node, and 36-node ONoC in terms of latency and throughput. Three multi-rings have the same number of links for a fair comparison. For the genetic algorithm, the representation (permutation encoding) of a multi-ring is the same with the proposed optimization method, in which each ring of multi-ring will be represented as a binary array. The length of this binary array is N_{core} . Value 0 or 1 represents that if this ring includes this core or not. The crossover probability is set to be 0.1. The crossover location is determined by rolling around mechanism. The mutation probability is set to be 0.01. The selection theme is achieved by selecting the multi-ring with the minimal network congestion factor, which is computed by the network congestion factor computation in Sect. 3.1.

Figure 4 (a) (b) (c) and (g) (h) (i) shows the ETE delay vs. offered load on the 16-node, 25-node and 36-node network-on-chips with different topology when the packet sizes are 1024 bits and 2048 bits. In both of 1024 bits and 2048 bits packet sizes of different topologies, multirings achieve lower latency under heavy loads than that of two kinds of mesh networks. The performance improvement of multi-rings is mainly brought by more link resource and lower congestion probability. The multi-ring developed by the proposed optimization algorithm outperforms multiring developed by the randomized algorithm. The multiring developed by the proposed optimization algorithm has a very similar performance compared with the multi-ring developed by the genetic algorithm. This is because, by using congestion optimization model and heuristic computation. The proposed algorithm and genetic algorithm can obtain multi-ring with more effective links than multi-ring developed by the randomized algorithm. According to the Fig. 4 (a) (b) (c) and (g) (h) (i), we can proof the effectiveness of the proposed optimization algorithm. On the other hand, in the terms of different size of network, multi-ring developed by the proposed method outperforms two kinds



Fig. 4 The ETE delay vs. offered load when the packet size is 1024 bits in (a) 16-node network, (b) 25-node network, (c) 36-node network. The throughput vs. offered load when the packet size is 1024 bits in (d) 16-node network, (e) 25-node network, (f) 36-node network. The ETE delay vs. offered load when the packet size is 2048 bits in (g) 16-node network, (h) 25-node network, (i) 36-node network, The throughput vs. offered load when the packet size is 2048 bits in (j) 16-node network, (k) 25-node network, (l) 36-node network, (l) 36-node network, (l) 36-node network, (l) 36-node network.

of mesh topologies and multi-ring developed by the randomized algorithm and multi-ring developed by the genetic algorithm. It can be observed that the performance of the multi-ring developed by genetic algorithm degrades with the number of the network nodes increasing. The main reason is that the crossover and the mutation method in GA are inefficient for development of the multi-ring with the increasing of the network scale. Figure 4 (d) (e) (f) and (j) (k) (l) shows the Throughput vs. offered load on the 16-node, 25-node and 36-node network-on-chips with different topology when the packet sizes are 1024 bits and 2048 bits. In both of 1024 bits and 2048 bits packet sizes of different topologies, all kinds of topologies have the similar performance under low offered load. However, with the growth of the offered load, multi-ring keeps high throughput and has a large satura-

Router	Crossbar	Cygnus	[14]	[15]	Crux	[17]	Multi-ring
N _{router}	16	16	12	18	12	8	$1+N_{ring}$
Nnetwork	256	256	192	288	192	128	72

 Table 1
 The number of micro-ring of the different switches.

tion throughput, but the two kinds of mesh topologies are strongly influenced by the serious contention. The multiring developed by the proposed optimization algorithm has a higher saturation throughput than multi-ring developed by the randomized algorithm, while it has a very similar saturation throughput compare with multi-ring developed by genetic algorithm in the 16-node network. When the network scales, the multi-ring developed by the proposed optimization algorithm outperforms multi-ring developed by the genetic algorithm.

4.2.2 Multi-Ring Interface Overhead

In this section, we evaluate the optical switches of multi-ring with other popular optical switches. In the multi-ring architecture, each IP core has a bidirectional interface to communicate with the other cores, which have proposed in Ref. [3]. When an IP core has one ring to communicate with other IP cores, the interface of this core has 2 micro-rings. When an IP core has two rings to communicate with other IP cores, the interface of this core need to employ one more microrings and one more waveguide so as to add an extra ring to communicate. That means that the interface of this core has 3 micro-rings. The number of micro-rings of different cores can be calculated in this way. When an IP core has N_{ring} rings to communicate with other IP cores, the interface of this core has N_{ring} +1 micro-rings. Thus, according to comparing the number of micro-rings in different network with different optical switches, crossbar, cygnus [13], crux [16], switches from [14], [15] and [17]. From the table in Table 1, we can see that the number of micro-ring optical switches of multi-ring is less than that in other optical switches. We can come to a conclusion that the multi-ring can avoid the use of sophisticated router.

5. Conclusion

An optimization algorithm to build low congestion multiring topology for ONoC is proposed. Unlike the previous method which alleviate congestion by using multiple wavelength simultaneously, our algorithm based on the network congestion model, to explore available low congestion multi-ring. Thereby this optimization algorithm can achieve the simplicity, scalability and flexibility. Simulation results show the proposed algorithm has a lower latency and higher saturation throughput.

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