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A multi-wavelength communication strategy for 2D-mesh Network-on-Chip

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Abstract: 2D-mesh is widely used in Network-on-Chip as its regular topology and simple layout match the two-dimensional VLSI layout well. Further more, the optical circuit switching (OCS) is introduced to provide higher bandwidth and lower power consumption. However, the undesirable property of OCS is the coarse granularity of resource reservation. It leads to a high blocking ratio and degrades the performance. This paper proposes a multi-wavelength communication strategy and an optical router to solve this problem. The simulation results show that the strategy improves the performance in terms of end-to-end delay and throughput.

Keywords: Network-on-Chip, 2D-mesh, multi-wavelength, path-shared

Classification: Fiber optics, Microwave photonics, Optical interconnection, Photonic signal processing, Photonic integration and systems

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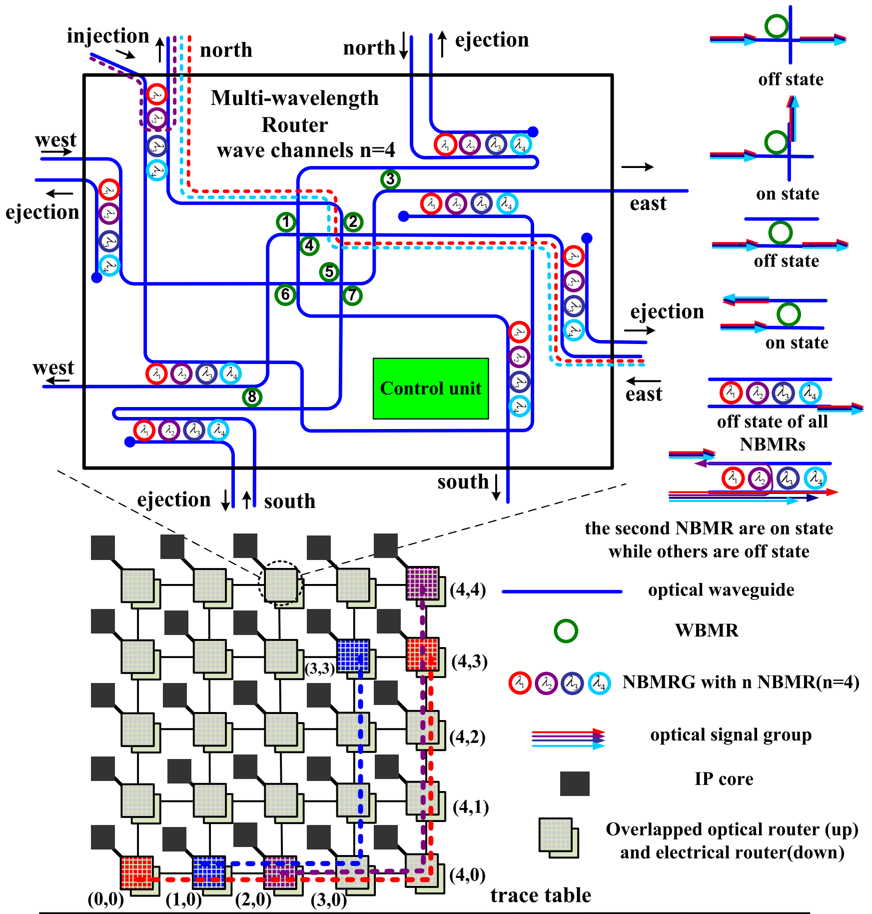
1 Introduction

Network-on-Chip (NoC) is introduced into the realm of chip design to solve the issues which traditional bus-based on-chip communication techniques for Systems-on-Chip (SoC) have to face [1]. Various architectures have been proposed for NoC. Among these architectures, 2D-mesh is widely used for its regular structure and simple layout [2]. Meanwhile, the optical interconnection draws attention because of high bandwidth and low power consumption. As the optical circuit switching is a relatively mature technique, it is widely employed in optical NoC [3]. However, the drawback of this connection based approach is its low bandwidth utilization. Once a path has been reserved for a connection, it cannot be reused by others. Moreover, the limited path diversity of 2D-mesh makes the contention serious. These issues lead to a higher blocking ratio and degrade the whole performance of the 2D-mesh optical NoC. A multi-wavelength communication strategy is proposed to solve these problems. It realizes several connections share a path at the same time. In addition, an optical router is designed to support the path-shared strategy.



trace table

Packet ID	Input port	Wavelength required by setup	Wavelength required by ACK	source	destination	critical path flag
1157	W	1	4	(0,0)	(4,3)	1
2768	W	2	null	(2,0)	(4,4)	0

Fig. 1. The architecture of 5 × 5 2D-mesh optical NoC with 4 wavelengths

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2 The multi-wavelength communication strategy

2.1 Network architecture

A 2D-mesh optical NoC is shown in Fig. 1. It comprises two overlapped networks, an optical network for data transmission and an electronic network for control. The links are arranged in the horizontal and vertical directions, while the routers are placed at the intersections with local IP core connected. The addresses of the nodes are labeled by coordinates (x, y). A same address is shared by the local IP core and two overlapped routers. The XY routing is applied because of simplicity and deadlock freedom. For any pair of source and destination, there is a deterministic path between them. Since the 2D-mesh optical NoC traditionally introduces single wavelength, a connection has to reserve every link it traverses. This coarse granularity of reservation makes the resource efficiency low and the block ratio high.

To insure better bandwidth utilization, a multi-wavelength path-shared strategy is proposed. For example, the connection from $(0, 0)$ to $(4, 3)$ can share path with the connection from $(2, 0)$ to $(4, 4)$ by employing different wavelengths. In some cases, two connections cannot share path since the optical router is only able to separate the signal which arrives at the destination. For example, the connection from $(0, 0)$ to $(4, 3)$ cannot share path with the connection from $(1, 0)$ to $(3, 3)$ even part of overlapped path exists. Additionally, the strategies to allocate wavelengths and avoid wavelength collision are also important. To eliminate too much control information overhead, the local distributed method is adopted by these strategies in the stages of setup packet processing and ACK packet processing. Each output of the electrical router maintains a trace table, as is shown in Fig. 1, which records the information for the path-shared judgment.

2.2 The communication process

As the optical circuit switching is employed, before data transmission, a setup packet with a required wavelength is sent to reserve the path through the electronic network. At each hop, the node checks whether the output port has been occupied by other setup packets. If the output port is free, this setup packet occupies the output port and its information is recorded in the corresponding trace table. Its wavelength number is registered in the item *wavelength required by setup*, the *wavelength required by ACK* is set to null and the *critical path flag* is set to 1. However, when the setup packet is blocked, other than waiting for the release of the output port, the path-shared judgment will be invoked. The path information of the setup packet is compared with the critical path in the corresponding trace table. Since more setup packets sharing path means higher bandwidth utilization, the algorithm of path-shared judgment should make full use of the properties of the XY routing algorithm and the optical router, as is shown in Table I.

If the packet is permitted to share the path, the wavelength allocation is then applied to check the corresponding trace table. In case the wavelength required by the setup packet has been registered already, an idle wavelength

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is assigned. Thus the setup packet is truly blocked only in the cases of failing in the path-shared judgment or lacking idle wavelengths. As a new entity is registered in the trace table, to insure all the entities in the trace table can share the path, the node should decide whether it needs to change the critical path flag. If there is no turn in the previous critical path, the new entity becomes the critical path.

Table I. The algorithm of path-shared judgement

Procedure DIRECTION_JUDGE (C_s,C_d)

input : one dimensional coordinate of the source: C_s
one dimensional coordinate of the destination: C_d
output : dir (propagation direction along the X dimension or the Y dimension)

begin
if C_d=C_s then **return** dir = zero
else if $C_d > C_s$ then **return** dir = positive
else if $C_d < C_s$ then **return** dir = negative
end

Procedure PATH-SHARED JUDGMENT (Path I,Path J)

input : Path I (the critical path) : source (x_{si}, y_{si}), destination(x_{di}, y_{di})
Path J (the setup packet) : source (x_{sj}, y_{sj}), destination(x_{dj}, y_{dj})
output : P_{share} (result of the path-shared judgment): p/f (permit/forbid)

begin /*calculate the dir of the path I and path J at first*/
X_i=DIRECTION_JUDGE(x_{si}, x_{di}) Y_i=DIRECTION_JUDGE(y_{si}, y_{di})
X_j=DIRECTION_JUDGE(x_{sj}, x_{dj}) Y_j=DIRECTION_JUDGE(y_{sj}, y_{dj})
G_i=(x_{di}, y_{si}) G_j=(x_{dj}, y_{sj}) /*the inflection point of path I and path J*/
case 1 : Y_i = zero **then**
  if (x_{di}, y_{di}) is the intermediate node of the path J **then** $P_{share} \leftarrow$ p
  else $P_{share} \leftarrow$ f
case 2 : X_i = zero **then**
  if (x_{si}, y_{si}) is the intermediate node of the path J **then** $P_{share} \leftarrow$ p
  else $P_{share} \leftarrow$ f
default :
  if G_j =G_i and X_j = X_i and Y_j = Y_i
  then $P_{share} \leftarrow$ p
  else if Y_j =zero **then**
    if (x_{dj}, y_{dj}) is the intermediate node of the path I **then** $P_{share} \leftarrow$ p
    else $P_{share} \leftarrow$ f
  else if X_j =zero **then**
    if (x_{sj}, y_{sj}) is the intermediate node of the path I **then** $P_{share} \leftarrow$ p
    else $P_{share} \leftarrow$ f
  else $P_{share} \leftarrow$ f
end

It is worthwhile to note that the wavelength allocation in the setup processing only solves the competition of current router but cannot avoid wavelength conflict along the shared path. For example, assume that the connection 1 from $(4,1)$ to $(4,4)$ has reserved the path with wavelength λ_1. Then the connection 2 from $(2,0)$ to $(4,3)$ sends its setup packet with initial wavelength λ_1. This packet is blocked at node $(4,1)$ and then an idle wavelength λ_2 is reallocated. In this case, the connection 3 from $(0,0)$ to $(4,0)$ can re-

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serve the path with λ_2 successfully because the connection 2 reserves its part of path from $(2, 0)$ to $(4, 1)$ with λ_1. However, as the wavelength allocated at the destination is the final determined communication wavelength. The connection 2 will also use λ_2 to transmit data. This collision can be settled in the ACK packet processing. When the setup packet arrives at the destination, an ACK packet is sent back to the source through the electronic network with the wavelength number allocated at the destination. At each hop, the wavelength collision check is implemented. If the wavelength required by the ACK packet is not recorded in the corresponding trace table, the wavelength is registered and then the packet is forwarded. Otherwise, the ACK packet is blocked until the wavelength is released.

Finally, after the data propagates through the optical network, a teardown packet is sent to the destination to release the resources.

3 The multi-wavelength router for path-shared strategy

Considering the existing multi-wavelength router [4] cannot support the proposed strategy. A new multi-wavelength router is designed, as is shown in Fig. 1. The switching fabric of the new router consists of optical waveguides and two types of microring resonators, the Wide-Band Microring Resonator (WBMR) [5] and Narrow-Band Microring Resonator (NBMR). These resonators are actively set to be in an off-state or on-state by the control unit. The WBMR has a relatively small free spectral range (FSR). Thus it can switch on and off a large number of wavelength channels simultaneously. But the bandwidth of the NBMR is limited. One NBMR can only switch a specific wavelength. Several different NBMRs form a group and act as a filter in the switch. Further more, the communication wavelengths are decided by the number of distinct NBMRs. An example shown in Fig. 1 illustrates the working principle of the router. Assume that two signals λ_1 and λ_4 share the same path from east to north. They first encounter a NBMR group at the east input port. Since all the NBMRs are in off-state, the signals pass by them directly. At the WBMR labeled number 2, these two signals shift into another waveguide because this WBMR is in on-state. The NBMR group at north output port has no effect on these two signals because the corresponding NBMRs are in off state. However, as the injection signal λ_2 need to be transmitted to north simultaneously, the NBMR with resonant wavelength λ_2 is set to on-state in this group.

The switching fabric contains 4 ejection ports which facilitate the IP core to receive optical signals from the network. Additionally, the switching fabric is strictly non-blocking which can be proved by enumerating all the possible communication cases.

4 Performance evaluation

We evaluate the performance of the path-shared strategy by OPNET. The spatial distribution of the traffic is uniform while the time interval of two continuous packets generated by the IP core follows a negative exponential

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distribution. Additionally, the bandwidth of the optical link is 12.5G per wave channel. The optical data packets are set at 1024 bits and other packets including the setup packet, the ACK packet, and the teardown packet are set at 32 bits. The performance is evaluated in terms of end-to-end (ETE) delay and throughput. Moreover, the offered load is normalized under the maximum injection rate and the throughput is normalized under a given offered load. Fig. 2 shows the performance of the 8×8 2D-mesh optical NoC with different configurations. When the 2D-mesh optical NoC introduces single wavelength, the saturation point is merely 0.16. It means a higher blocking probability in mesh topology. However, the performance is improved even with two wave channels introduced. The saturation point shifts to 0.18, which indicates that the path-shared strategy can help to reduce the blocking ratio. The saturation point becomes higher with the number of wavelength increasing.

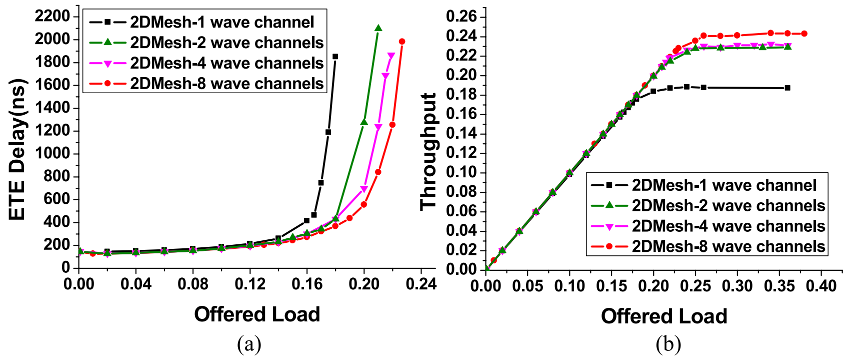

Fig. 2. ETE delay (a) and throughput (b) of the 2D-mesh optical NoC with different wave channels

5 Conclusion

This paper proposes a multi-wavelength communication strategy and an optical router for the 2D-mesh optical NoC. The communication strategy realizes the path-shared communication with less control cost while the optical router utilizes the WBMRs and NBMRs to guide the optical signals or separate a specific wavelength signal. The simulation results show that the multi-wavelength path-shared communication strategy could reduce the blocking ratio in mesh topology effectively even with a few wave channels.

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