A Learning-Based Thermal-Sensitive Routing for Power Optimization of Optical NoCs

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***Abstract*—Optical networks-on-chip (NoCs) have been proposed as an emerging on-chip communication architecture for chip multiprocessors with large core counts. However, due to thermo-optic effects, silicon photonic devices used in optical NoCs suffer from significant thermal-induced optical power loss. To tackle this problem, in this work, we propose a learning-based thermal-aware routing algorithm to find optimal shortest paths with the minimum estimated thermal-induced optical power loss according to runtime on-chip temperature distributions. Network simulations of a 3D 8x8x2 torus-based optical NoC show that the learning-based thermal-aware routing algorithm is able to learn the runtime on-chip temperature information quickly and find an optimal path with the minimum estimated thermal-induced optical power loss for every communication pair.**

***Index Terms*—Optical network-on-chip, chip multiprocessor, thermo-optic effect, temperature sensitivity.**

I. Introduction

Network-on-chip (NoC) architectures have been widely proposed as a new generation of on-chip communication architectures, which could scale better than on-chip shared buses and ad-hoc networks as the number of cores increases [1]. However, due to the limitations of traditional electronic interconnects in power efficiency and bandwidth density, as well as issues of high-frequency crosstalk noise and parasitic capacitance in deep-submicron integrated circuit design, there are still bandwidth, power efficiency and reliability bottlenecks in traditional NoCs based on electronic interconnects.

With the booming developments in nanoscale silicon photonic technologies for short-haul communications, silicon photonics based optical interconnects are emerging as a promising new approach to moving on-chip data at high speeds and low power. Compared to traditional electronic interconnects, optical interconnects can enable significantly increased bandwidth density, low power consumption, and low latency. By integrating optical interconnects in NoC architectures, optical NoCs can overcome many of the most serious on-chip communication issues [2], [3]. Most of the prior works on optical NoCs are based on silicon photonic devices including optical waveguides and silicon microresonators. However, as a result of thermo-optic effects, wavelength-selective silicon photonic devices such as microresonators, which are widely used in optical NoCs, suffer from temperature-dependent wavelength shifts [4]. The thermal related wavelength mismatch could cause significant additional optical power loss. An investigation of related thermal issues shows that if we take the thermal regulation power into account, optical interconnects may not have advantages in power efficiency as compared with their electrical counterparts [5].

In order to mitigate thermal effects in optical NoCs, runtime thermal management techniques such as OS-based workload migration and DVFS (dynamic voltage and frequency scaling) have been proposed to reduce the on-chip temperature gradients [6]. Due to the limitations of these thermal management techniques, device-level thermal compensation techniques are still in need. Thermal tuning by local microheaters is one such device-level solution, however, it is relatively slow and power inefficient [7]. Additionally, athermal microresonators have been demonstrated by applying proper polymer materials [8]. However, there are still compatibility issues when implementing athermal microresonators with CMOS technology. Furthermore, some efforts have been made to overcome the thermal challenges in optical NoCs from system-level perspectives. In [9], the authors proposed a thermal-aware methodology to design optical NoCs with distributed CMOS-compatible VCSELs, based on steady-state thermal simulations and SNR (signal-to-noise ratio) analysis. In [10], the authors systematically modeled thermal effects in optical NoCs and proposed several low-temperature-sensitivity techniques. In [11], a system-level proactive thread migration technique and a device-level thermal island framework were proposed to alleviate the thermal issues in optical NoCs.

Adaptive routing which takes account of on-chip temperature variations is another way to improve the reliability of optical NoCs in presence of temperature variations. In work [12], a fault-tolerant routing was proposed to route packets away from hot regions, and through cooler regions, to their destinations. In work [13], a thermal-aware fault-tolerant routing mechanism that exploits path diversity was proposed to perform adaptive routing in a hybrid optical-electronic NoC in presence of on-chip thermal variations. Q-learning based adaptive routing algorithms take advantages of Q-learning technique to optimize the routing decisions according to runtime network state [14], [15]. Several adaptive routing algorithms based on Q-learning have been proposed for electronic NoCs. In work [14], a Q-learning based adaptive routing was proposed to reduce the latency in traditional electronic NoCs. In work [15], a hierarchical Q-learning based deflection routing algorithm was proposed for a mesh-based electronic NoC to improve the performance in presence of faults.

To further tackle the thermal issue in optical NoC designs, in this work, we propose a learning-based thermal-aware routing algorithm to find optimal paths with the minimum estimated thermal-induced optical power loss according to runtime on-chip temperature distributions. The rest of the paper is organized as follows. In Section II, the learning-based thermal-aware routing algorithm is presented. In Section III, we show simulation results and comparisons in terms of thermal-induced optical power loss and energy efficiency. Last, Section IV concludes this work.

II. A Thermal-Aware Routing Algorithm for Power Optimization

For mesh or torus-based NoCs, the traditional dimension-order routing is a low-complexity deterministic routing algorithm. However, due to the deterministic feature, the traditional dimension-order routing cannot avoid bad paths with significant thermal-induced optical power loss in the presence of on-chip temperature variations. In this section, we propose a learning-based thermal-aware routing algorithm to find optimal paths with the minimum estimated thermal-induced optical power loss according to runtime on-chip temperature distributions.

A. Thermal-induced optical power loss

As a result of the thermo-optic effect, material refractive index is temperature dependent and follows Equation (1), where n_0 is the refractive index at room temperature, dn/dT is the thermo-optic coefficient of the material, and ΔT is the temperature variation.

$$n = n_0 + \frac{dn}{dT}\Delta T \tag{1}$$

The thermo-optic effect will cause changes in the device characteristics. As shown in Equation (2), the resonant wavelength of a single-microresonator basic optical switching element shifts approximately linearly with temperature T, where λ_0 is the resonant wavelength at room temperature T_0, and ρ is defined as the temperature-dependent wavelength shift of the basic optical switching element.

$$\lambda = \lambda_0 + \rho(T - T_0) \tag{2}$$

Temperature variations across the chip will result in wavelength mismatches between the laser wavelength and the resonant wavelengths of intermediate switching elements in the path. As shown in Equation (3), the wavelength mismatch results in additional optical power loss (in dB) in switching. 2δ is the 3-dB bandwidth of the basic optical switching element, κ^2 is the fraction of power coupling between the waveguide and the ring, and κ_p^2 is the power loss per round-trip of the ring [16].

$$L = 10log((\frac{2\kappa^2 + \kappa_p^2}{2\kappa^2})^2 \cdot (1 + \frac{(\lambda_{VCSEL} - \lambda)^2}{\delta^2}) \tag{3}$$

B. L-value

In traditional Q-routing based electronic NoCs, Q-values represent the latency of alternative paths, and the Q-learning technique is performed to learn network congestions for latency optimization [14]. In this work, we target optical NoCs in presence of temperature variations, and focus on the optimization of thermal-induced optical power loss.

We assume the optical NoC is circuit switching, in which an optical path is reserved before payload transmission. For each packet to be sent, a setup packet is routed in the control network. The routing algorithm decides how the setup packet selects a path. We use the Q-learning technique to learn the runtime on-chip temperature information and find an optimal shortest path with the minimum estimated optical power loss. For each source-destination communication pair, we first find shortest paths as alternative paths, then they are provided to be learnt by the proposed learning-based thermal-aware routing algorithm. This ensures that the proposed routing can achieve the power optimization at little sacrifice of network performance.

Each node in the optical NoC keeps an L-table which stores L-values. The L-values represent the estimated thermal-induced optical power loss of alternative paths. Each node learns the state of the network by receiving L-values from neighboring nodes. When a node receives updated L-values from its neighboring nodes, it updates its local L-table. For a packet to be sent from the source node s to the destination node d, assume that its setup packet just went by the node x and is currently at node y. Assume that $N(y)$ is the set of feasible next nodes found along the shortest path, we define $L_y(n,d)$ as the L-value representing the estimated thermal-induced optical power loss from any feasible next node $n \epsilon N(y)$ to the destination. As shown in Equation (4), the neighboring node $z \epsilon N(y)$ which is with the minimum estimated thermal-induced optical power loss will be selected as the next node.

$$L_y\left(z,d\right) = \min_{n \epsilon N(y)} L_y(n,d) \tag{4}$$

As soon as node y forwards the setup packet to the next node z, node y will send a L-value $L_x\left(y,d\right)_{min}$ back to its previous node x, which indicates the minimum estimated thermal-induced optical power loss from the node y to the node d. As shown in Equation (5), $L_x\left(y,d\right)_{min}$ is equal to the sum of two quantities, where $L_y(z,d)$ is the minimum estimated thermal-induced optical power loss from node z to the destination, and l_y is the thermal-induced optical power loss at the node y.

$$L_x\left(y,d\right)_{min} = L_y\left(z,d\right) + l_y \tag{5}$$

The thermal-induced energy consumption for packet transmission in optical NoC includes the energy consumed by O/E interfaces which is dominated by the thermal-induced optical power loss in path. For a packet sent from the source node s, when it passes through an intermediate node i towards the destination, we define $l(i)$ as the optical power loss inserted by the node i. $l(i)$ is sensitive to the temperature in the node i which determines the resonant wavelength of the optical switching element. By adding up the optical power loss inserted by each node in the path, we get the total optical power loss in the path and then we can calculate the required energy consumption for the transmission.

Assume that node x and node y are two intermediate nodes in the path, we define $L(x, y)$ as the optical power loss from node x to node y. We divide the estimated optical power loss of the whole path from the source node s to the destination node d into three parts: (1) the optical power loss from the source node s to the node x, $L_y(s, x)$, where y is the current node; (2) $l(y)$, which is the optical power loss inserted in the node y; (3) $L_y(z, d)$, which is the estimated optical power loss from the node z to the destination node d.

So when the setup packet is in the node y, it can estimate the total optical power loss $L(s, d)$ in the whole path as Equation (6) where the N is the set of passing nodes from node s to node d, and y is the current node.

$$L(s, d) = \sum_{i \epsilon N} l_i = L_y(s, x) + l(y) + L_y(z, d) \tag{6}$$

C. L-table

Table I shows an example of the L-table in node y, with address (1,1) in a 3x3 mesh network. The L-table has three fields: the state-space, the action-space and the L-value field. The state-space stores the address information of the current node, the source node, the destination node, and feasible next nodes found by shortest-path routing. The action space stores the output ports in the current node towards each feasible next node. In mesh or torus-based optical NoC, the feasible output ports are within the following cases: left, right, up, down and local directions. For example, for a setup packet that is routed from the source node with address (0,0) to the destination node with address (2,2) in the 3x3 mesh network, when the setup packet is currently in the node y with address (1,1), feasible output ports includes the Up output port towards the neighbouring node with address (1,2), and the East output port towards the neighboring node with address (2,1). The L-value field is the estimated optical power loss from the next node to the destination. In the proposed learning-based thermal-aware routing, each node utilizes the L-values to estimate the total thermal-induced optical power loss in alternative path, and then dynamically makes routing decisions to find optimal paths with the minimum estimated thermal-induced optical power loss.

D. The proposed routing algorithm

Algorithm 1 presents the procedure of path selection in the proposed learning-based thermal-aware outing. For a setup packet $p(s, d)$ that is routed from the source node s to the destination node d, assume that it is currently at an intermediate node y. The routing unit at the node y first gets a set of valid output ports ($Set_{output-port}$) along shortest paths, which guarantees that alternative paths found are shortest and the

TABLE I: An example of L-table

State-Space				Action-Space		L-value L(z,d)	
y Cur	d Dest	z Next		a Output-Port		L(z,d) Optical Loss	
(1,1)	(2,1)	(2,1)	-	East	-	Var	-
(1,1)	(1,2)	(1,2)	-	Up	-	Var	-
(1,1)	(2,2)	(1,2)	(2,1)	Up	East	Var	Var

Var *means the value stored in the table.*

proposed routing can achieve the power optimization at little sacrifice of network performance. Then the optimal selection function selects an optimal output port from $Set_{output-port}$ with the minimum estimated thermal-induced optical power loss towards the destination node. Algorithm 2 shows how the optimal selection function decides the optimal output port. In detail, if the size of $Set_{output-port}$ is only one, it just returns the only valid output port. If the size of $Set_{output-port}$ is two, it compares the estimated thermal-induced optical power loss according to L-values stored in the L-table, and returns the output port with less estimated thermal-induced optical power loss towards the destination node. After the current node forwards the setup packet $p(s, d)$ to the next node through the selected output port, it sends back a learning packet which contains the L-value to the previous node. Upon receiving the learning packet, the previous node updates the corresponding L-value in local L-table.

Algorithm 1 The proposed learning-based thermal-aware routing algorithm

1: Receive $p(s, d)$ at current node y
2: Get $Set_{output-port}$ along the shortest paths
3: Select an optimal output-port from $Set_{output-port}$ by the Optimal Selection function
4: Send $p(s, d)$ to the next node through the selected optimal output port
5: Send a learning packet back to the previous node
6: Update the L-table after receive the learning packet

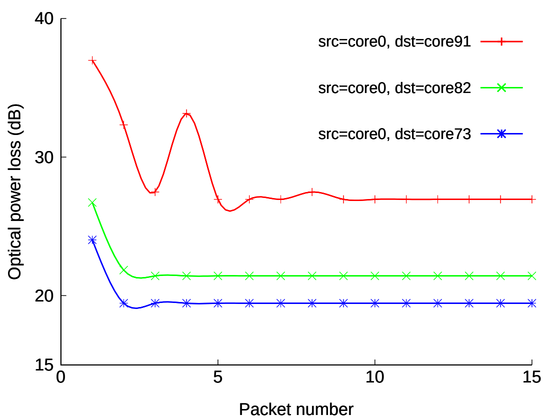

Fig. 1: The convergence of thermal-induced optical power loss optimization by the proposed routing

Algorithm 2 The Optimal Selection Function

$Dest\_id \leftarrow Get_{D}est()$
if $Dest\_id = local\_router\_id$ **then**
    return the direction to Processor
end if
if $Size_{Output-Port} = 1$ **then**
    return the Output-Port
end if
if $Size_{Output-Port} = 2$ **then**
    $Loss\_Neighbor1_{est} \leftarrow L\text{-}table(Neighbor1, d)$
    $Loss\_Neighbor2_{est} \leftarrow L\text{-}table(Neighbor2, d)$
    if $Loss\_Neighbor1_{est} <= Loss\_Neighbor2_{est}$ **then**
        return Neighbor1
    else if $Loss\_Neighbor1_{est} > Loss\_Neighbor2_{est}$ **then**
        return Neighbor2
    end if
end if

III. Simulation results and comparisons

We developed a SystemC-based cycle-accurate network simulator for a 3D 8x8x2 torus-based optical NoC with the proposed learning-based thermal-aware routing algorithm. Network simulations were conducted under several synthetic traffic patterns as well as a set of real applications. For each real application, we used traffic information to simulate the on-chip temperature distributions with McPAT [17] and HotSpot [18]. We assumed 40Gbps data-link bandwidth for the optical NoC. The electronic control network operates at 1.25GHz with 32-bit wide bidirectional metallic interconnects. In order to show the efficiency of the proposed learning-based thermal-aware routing algorithm, we used a matched 3D 8x8x2 torus-based optical NoC with the traditional XYZ routing as a baseline for comparisons.

A. The convergence of the proposed routing algorithm

In order to show the convergence of the proposed learning-based thermal-aware routing algorithm, we simulated a 3D 8x8x2 torus-based optical NoC with the proposed routing algorithm under uniform traffic. A random temperature distribution was applied during the simulation, and we assumed that the on-chip temperature was within the range of [55^oC, 85^oC]. We assumed the 3-dB bandwidth of the basic optical switching element is 1.24nm. Figure 1 shows the convergence of thermal-induced optical power loss optimization for delivering packets from node 0 to node 91, from node 0 to node 82, and from node 0 to node 73. It is shown that for packets belongs to the same source-destination communication pair, the thermal-induced optical power loss in path varies before the proposed routing algorithm reaches the state of convergence. After learning the network with a certain number of packets, the proposed learning-based routing algorithm reaches the state of convergence, which means that it finds the optimal path with optimized thermal-induced optical power loss. For packets sent from node 0 to node 91, it finds the optimal path after learning five packets, and the optimal path is with optical power loss of 26.9dB. For packets sent from node 0 to node 73, it finds an optimal path with optical power loss of about 19.5dB. If we assume a smaller 3-dB bandwidth, the optimization of optical power loss would be more significant. It can be observed from Figure 1 that it needs to learn less packets to find the optimal path for a shorter path.

TABLE II: Energy Efficiency of O/E Interface

O/E interface component	Energy efficiency in 45nm (pJ/bit)
VCSEL driver [21]	0.1125
Photodetector [22]	0.0003
TIA-LA circuit [21]	0.3375
Serializer [23]	0.16
Deserializer [23]	0.128

B. Thermal-induced optical power loss and energy efficiency

In the following, we present more simulation results and comparisons in terms of thermal-induced optical power loss and energy efficiency, under several synthetic traffic patterns as well as a set of real applications. The power consumed in optical domain includes the power consumed by turning on microresonators in optical routers and the power consumed by optical/electronic (O/E) interfaces for O/E conversions. We assume the power consumption for turning on an microresonator is $20\mu W$ [19]. The thermal-induced optical power loss inserted by an microresonator follows Equation (3), where we assume the 3-dB bandwidth is 1.24nm. We assume to use VCSEL as the off-chip laser source [20]. Table II summarizes the energy efficiency of main components in O/E interface except for the VCSEL laser. Since the electronic part of the proposed optical NoC is in 45nm, we scale all the related power consumption linearly to 45nm.

1) Synthetic traffic patterns: We simulated a 3D 8x8x2 torus-based optical NoC with the proposed learning-based thermal-aware routing algorithm under a set of synthetic traffic patterns. A matched 3D 8x8x2 torus-based optical NoC with the traditional XYZ routing was simulated as a baseline for comparisons. During the simulations, we applied random on-chip temperature distributions within the range of [55^oC, 85^oC].

Figure 2 shows the comparison of the average thermal-induced optical power loss of all packets under each synthetic traffic pattern. It is shown that on average of the four synthetic traffic patterns, the proposed learning-based thermal-aware routing reduces the average thermal-induced optical power loss by 14.3% as compared to the traditional XYZ routing.

Figure 3 shows the comparison of the normalized average thermal-induced optical energy efficiency of all packets under each synthetic traffic pattern. It is shown that the proposed learning-based thermal-aware routing reduces the average thermal-induced optical energy consumption significantly than the XYZ routing. On average of the four synthetic traffic patterns, it reduces the average thermal-induced optical energy consumption by 76.1% as compared to the XYZ routing. If we assume a smaller 3-dB bandwidth, the improvement of optical power loss would be more significant. It could be observed that the proposed routing algorithm has a greater optimization space for traffic patterns with more long-distance traffic (e.g. Bitreverse) than the uniform traffic.

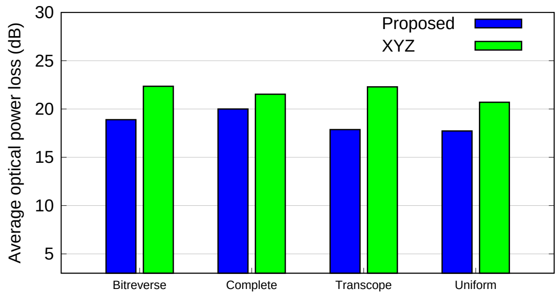

Fig. 2: The average thermal-induced optical power loss under synthetic traffic patterns, with random temperature distributions

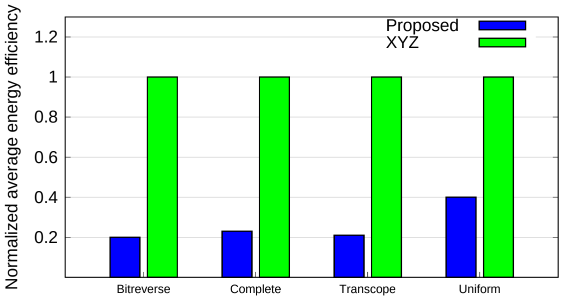

Fig. 3: The average thermal-induced optical energy efficiency under synthetic traffic patterns

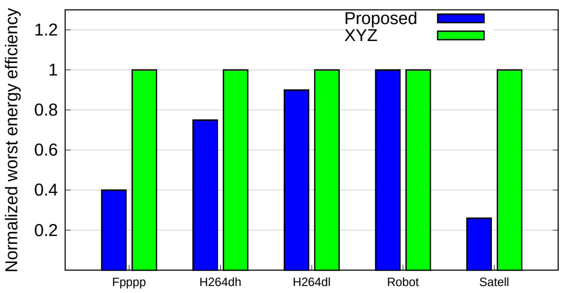

Fig. 4: The worst-case thermal-induced optical energy efficiency under real applications

2) Real applications: In addition to the synthetic traffic patterns, we also simulated the 3D 8x8x2 torus-based optical NoC with the proposed learning-based thermal-aware routing under a set of real applications. A matched 3D 8x8x2 torus-based optical NoC with the traditional XYZ routing was simulated as a baseline for comparisons. For each real application, we

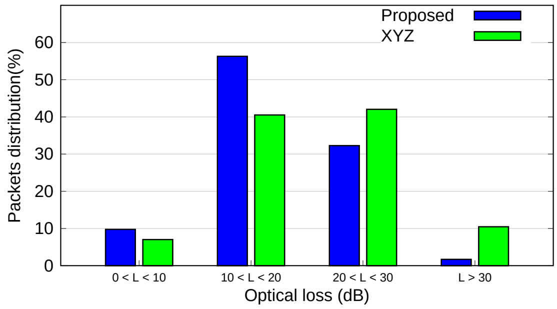

Fig. 5: The loss distribution of the SATELL application

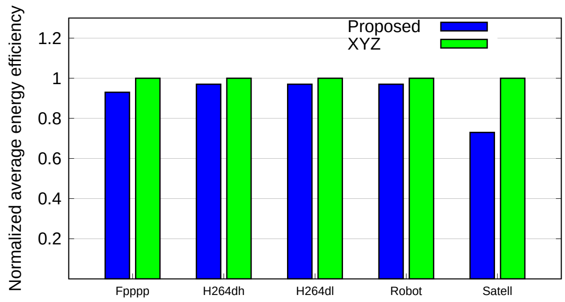

Fig. 6: The average thermal-induced optical energy efficiency under real applications

used traffic information to simulate the on-chip temperature distribution with HotSpot [18] and McPAT [17].

Figure 4 shows the comparisons of the normalized worst-case thermal-induced optical energy efficiency among all packets in each real application. It shows that on average of the five real applications, the proposed learning-based thermal-aware routing reduces the worst-case energy consumption by 33.8% as compared to the traditional XYZ routing. For applications with more long-distance traffic (e.g. the SATELL application), the proposed routing algorithm has a greater space for optimization, and thus it could achieve more significant improvements. This can be further illustrated by Figure 5, which shows the loss distribution of the SATELL application. It is shown that the loss distribution is shifted to the low-loss regions by using the proposed learning-based thermal-aware routing. With the traditional XYZ routing, 10.1% of packets are with more than 30dB loss. If using the proposed routing, only 1.7% of packets are with more than 30dB loss.

Figure 6 shows that on average of the five real applications, the proposed learning-based thermal-aware routing reduces the average thermal-induced optical energy consumption by 8.6% as compared to the traditional XYZ routing. For applications with more long-distance traffic, e.g. the SATELL application, the proposed routing reduces the average thermal-induced optical energy consumption by 27.2% as compared to the XYZ routing. We could conclude that the proposed routing has a greater space for optimization for long-distance traffic as compared to short-distance traffic. If we assume a smaller

3-dB bandwidth, the improvement of optical power loss would be more significant.

Since the proposed learning-based thermal-aware routing finds the optimal path from shortest paths, it achieves the power optimization at little sacrifice of network performance. This can be illustrated by Figure 7, which shows the comparisons of normalized network performance under each real application. Here the network performance is measured in terms of the application end-to-end (ETE) delay. It is shown that on average of the five real applications, the application ETE delay increases by 0.25% as compared to the traditional XYZ routing.

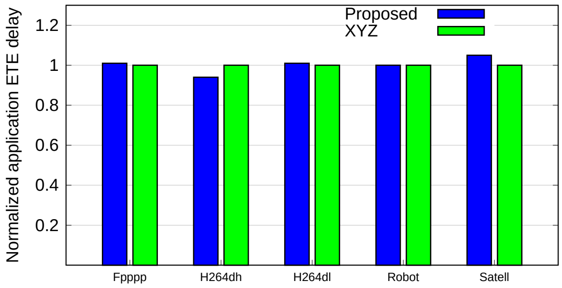

Fig. 7: The normalized performance under real applications

IV. Conclusions

To tackle the thermal issues in optical NoC designs, we proposed a learning-based thermal-aware routing algorithm to find optimal paths with the minimum estimated thermal-induced optical power loss according to runtime on-chip temperature distributions. We applied the proposed learning-based thermal-aware routing algorithm to a 3D 8x8x2 torus-based optical NoC. Simulation results show that for a set of four synthetic traffic patterns, the average thermal-induced optical energy consumption is reduced by 76.1% as compared to the XYZ routing. For a set of five real applications, the worst-case thermal-induced energy consumption is reduced by 33.8% on average as compared to the XYZ routing, while the average thermal-induced energy consumption is reduced by 8.6% as compared to the XYZ routing.

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