LETTER

Collaborative thermal- and traffic-aware adaptive routing scheme for 3D network-on-chip systems

Lili Shen^{1, 2, a)}, Ning Wu¹, Gaizhen Yan³, and Fen Ge¹

Abstract Due to the stacking dies and unequal cooling efficiency of different layers, 3D NoC-based systems suffer severe thermal issues. Adaptive routing can alleviate the thermal issues, but current routing algorithms either suffer from the thermal balance or traffic congestion. This paper proposed a collaborative thermal- and traffic-aware adaptive routing (CTTAR) scheme, which considers the traffic and temperature information together and avoids the packets transferring to congested region. Experiments show that, there is 19.4% to 48.4% system performance improvement compared with other routing algorithms under the same thermal limit.

Keywords: 3D NoC, adaptive routing, thermal-aware, dynamic buffer adjustment

Classification: Integrated circuits (memory, logic, analog, RF, sensor)

1. Introduction

With the advance in the semiconductor technology, the Network-on-Chip (NoC) as an efficient solution for multi-core chips has attracted wide attention [1, 2]. In recent years, the 3D network-on-chip is proposing to cope with the complicated on-chip interconnection issues by applying die stacking technology [3]. However, because of the die stacking and unequal cooling efficiency of different layers, the power density becomes higher and the heat dissipation path becomes longer in 3D NoC-based systems which lead to more serious thermal issues [4, 5, 6, 7]. The thermal issues may degrade the system performance and cause lower reliability of the system. In order to tackle the thermal issues in 3D NoC-based systems, dynamic thermal management [8, 9, 10, 11, 12, 13] and adaptive routing strategy [14, 15, 16, 17, 18, 19] have been proposed.

Although the dynamic thermal management approaches can regulate the system temperature, they also result in significant performance impact and high computation complexity. By contrast, adaptive routing strategy can deliver the packets through alternative paths from source to the destination to balance the thermal distribution. Chen et.al [20] presented a adaptive routing algorithm (TAABR) to select

minimal path or beltway path achieving a balanced distribution of the temperature and traffic in 3D NoC systems. The TAABR provided multiple routing paths and balanced the system temperature by balancing the traffic distribution. However, because the TAABR only considers traffic information when delivering the packets, it may through the regions which will be the potential hotspot. Kuo et.al [21] proposed a proactive routing algorithm (PTB³R). A novel index, Mean Time to Throttle (MITT), was proposed to solve thermal issue. However, the MITT information only represents the previous traffic information instead of the current traffic information. Therefore, the PTB³R is hard to tackle network congestions and may degrade the system performance.

As described above, the current routing algorithms are facing with the traffic congestion or thermal balance problem. The reason is that the temperature is a long-term accumulation of energy consumption [22], which represents the historical traffic information not current traffic situation. Due to this asynchrony of thermal and traffic information, the packets could be delivered to the more hotter or more traffic congested regions.

In order to synchronize the network traffic and thermal information, we present a collaborative thermal-aware adaptive routing (CTTAR) scheme. Due to system hotspots result from switching excessive packets, the CTTAR first adopts the dynamic buffer adjustment, which can constrain the routing resource around the overheated regions to slow down the rate of temperature increment according to the predicted thermal information. In this way, the dynamic buffer adjustment can reduce heat production and diffusion because the routers in overheat region switch fewer packets. We turn the overheated regions into congested regions. Afterward, the CTTAR adopts efficient adaptive routing algorithm providing higher path diversity to achieve traffic balance in the thermal control period.

2. Proposed collaborative thermal-aware adaptive routing (CTTAR)

Due to the 3D NoC-based systems still face with the traffic load or thermal issue, we present a collaborative thermal- and traffic-aware adaptive routing (CTTAR) scheme considering the temperature and traffic information together. The CTTAR consists of two steps:

(1) Dynamic buffer adjustment.

In this part, we make the dynamic buffer adjustment of

¹ College of Electronic and Information Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China

² Jincheng College, Nanjing University of Aeronautics and Astronautics, Nanjing 211156, China

³ School of Electrical and Electronic Engineering, Anhui Science and Technology University, Chuzhou 233100, China

^{a)} shirely_ivy@163.com

every NoC node which has higher temperature to aggravate the traffic load around the hot node and turns the thermal issue into the network traffic issue.

(2) Efficient adaptive routing algorithm.

In this part, we present an efficient adaptive routing algorithm to increase alternative paths and control the distribution of the network traffic to enhance the routing performance.

2.1 Dynamic buffer adjustment

As mentioned before, because of the asynchrony of thermal and traffic information, it is need to synchronize the network traffic and thermal information to achieve a thermal and traffic balance. Dynamic buffer adjustment worsens the traffic information around the hot node to transfer the temperature of the NoC node into the traffic load. In [23], Lee et.al defined the Rate of Temperature Increment (RTI) to make a buffer adjustment for the NoC node. By using the thermal prediction mode [24], the RTI is derived as:

$$RTI = T(t + \Delta t_s) - T(t) \quad (1)$$

Where $T(t)$ is the current temperature, Δt_s is the sampling time and $T(t + \Delta t_s)$ is the predicted temperature from [24]. In [23], the length of buffer will be adjusted when the NoC node has large RTI value comparing neighbour NoC nodes. However, the large RTI value can not mean high temperature. So the 3D NoC-based system may still face with the unbalance of the network traffic and thermal information after the buffer adjustment. In order to solve this issue, we should take the current temperature into account when we make a buffer adjustment for the overheated NoC node. By using the thermal prediction mode [24], the current temperature can be predicted as

$$\begin{aligned} T(t + \Delta t) &= T(t) + \Delta T \\ &= T(t) + RTI \\ &= T(t) + (T(t) - T(t - \Delta t)) \cdot e^{-(\Delta t/RC)} \end{aligned} \quad (2)$$

Where C is the thermal capacitance and R is the thermal resistance. By using this equation, we take the current temperature and the historical temperature into account. The NoC node with high temperature has high probability to become overheated.

In Fig. 1, there are two adjacent NoC nodes and A is a hot node. We apply a queueing analysis in this paper, the service rate of upstream node relies on the full probability of the input buffer in the downstream node. The switching activities of A will be blocked when the input buffer of B from node A is full. The larger full probability of the input buffer of B is, the lower effective service rate of A might be. According to the Fourier's Law, the lower service rate of NoC nodes can lead lower power consumption and lower temperature. Therefore, it can be proved that traffic block can help to reduce the system temperature. It is necessary to reduce the output buffer length of hot node A to increase the full probability of the input buffer of B. On the other hand, the longer input buffer length of A can lead to larger average waiting time based on the queueing theory. Therefore, increasing input buffer length of the hot node A can aggravate the traffic load around A. So it is necessary to decrease the output buffer length and increase input buffer length of the

Fig. 1 An example between two adjacent nodes for demonstration

Fig. 2 The flow chart of the dynamic buffer adjustment

hot node to turn the thermal issue into the traffic load issue.

In 3D NoC systems, every node has up, down, north, south, west and east neighbour nodes and every node has different temperature value. Therefore, if the temperature of the node is higher than that of most neighboring nodes, the buffer length of the NoC node will be adjusted. Fig. 2 shows the flow chart of the dynamic buffer adjustment.

In this part, we make the dynamic adjustment by increasing the length of input buffer or decreasing the length of output buffer of the hot node. The maximum buffer length L_{max} depends largely on the NoC router design. The larger L_{max} , the larger system saturation throughput. On the other hand, the L_{min} can be equal to zero in fact. However, if L_{min} equals to zero, it may lead to a lot of packets blocked around the hot node. Therefore, to take all this into account, we set the L_{max} to 8 flits and the L_{min} to 1 flit.

2.2 Efficient adaptive routing algorithm

After dynamic buffer adjustment, the overheated NoC nodes turned into the congested nodes and the thermal and traffic information are synchronized. Hence, efficient adaptive routing algorithm can keep the packets far away from the overheated NoC nodes. The proposed adaptive routing algorithm uses turn model analysis to enhance routing performance under congested situation.

The Odd-Even (OE) turn model was presented in [25, 26]. The OE turn model prohibited and permitted turns

Fig. 3 Proposed intra-layer turn models

Fig. 4 The illustration of the prohibited vertical turns (a) up-xy; (b) xy-down

depending on the routed packets in even or odd columns. We would like to present an efficient adaptive routing algorithm which is an extension of OE turn model. The proposed routing algorithm transforms the turn restrictions into intra-layer turn and inter-layer turn models.

2.2.1 The intra-layer turn model

The bottom layer is placed near the heatsink, and the Z coordinate of the bottom layer is defined 0. All the layers are divided into four groups according to the remainder after dividing by 4. The turn restrictions in intra-layer are defined basing on the remainder and the rows and the columns being odd or even. The Intra-layer Turn Model is illustrated in Fig. 3.

- (1) In layers where $Z\%4=0$, “East-first” turns in even rows and “West-last” turns in odd rows are prohibited to prevent deadlock.
- (2) In layers where $Z\%4=1$, “South-first” turns in even Columns and “North-last” turns in odd columns are prohibited to prevent deadlock.
- (3) In layers where $Z\%4=2$, “West-first” turns in even rows and “East-last” turns in odd rows are prohibited to prevent deadlock.
- (4) In layers where $Z\%4=3$, “North-first” turns in even columns and “South-last” turns in odd columns are prohibited to prevent deadlock.

2.2.2 The inter-layer turn model

The prohibited Inter-layer Turn Model is illustrated in Fig. 4.

- (1) In even layers, up-xy turns are forbidden for all packets at any NoC nodes.
- (2) In odd layers, xy-down turns are forbidden for all packets at any NoC nodes.

Algorithm 1 in Fig. 5 details the routing algorithm for 3D NoC systems. Line 4, Line 9 and Line 15 mean that Intra-layer turn models are applied to implement lateral plane routing. Line 6 to Line 11 forbid up-xy turns in even layers

Algorithm 1: Adaptive routing algorithm

Input: $Src (s_x, s_y, s_z); Dest (d_x, d_y, d_z); Cur (c_x, c_y, c_z)$

Output: $Avail_dirs$

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1   $Avail\_dirs \leftarrow \Phi$ ;
2   $e_x = d_x - c_x; e_y = d_y - c_y; e_z = d_z - c_z$ ;
3  IF ( $e_z == 0$ ) THEN
4    Add lateral directions to  $Avail\_dirs$  ELSE
6  IF ( $e_z > 0$ ) THEN
7    IF ( $(c_z \% 2 != 1 \parallel (e_x == 0 \ \&\& \ e_z == 0) \parallel (e_z != 1))$ ) THEN
8      Add Up to  $Avail\_dirs$ 
9    ELSE IF ( $(c_z \% 2 == 1 \parallel c_z == s_z)$ ) THEN
10     Add lateral directions to  $Avail\_dirs$ 
11    END IF
12  IF ( $e_z < 0$ ) THEN
13    Add Down to  $Avail\_dirs$ 
14    IF  $c_z \% 2 == 0$  THEN
15      Add lateral directions to  $Avail\_dirs$ 
16    END IF
17  END IF
18 END IF

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Fig. 5 Proposed adaptive routing algorithm

and Line 12 to Line 17 forbid xy-down turns in odd layers.

The proposed adaptive routing algorithm is deadlock-free. In order to prove it, it is need to show that there is no cycle on every plane and the transmission between the layers will not create cycles. In intra-layers, Intra-layer turn models can guarantee deadlock freeness [27]. In inter layers, packets travelling upward can not enter a even layer and packets travelling in an odd layer can not move down from this layer. It means that there is no packets travelling to form cycle between layers.

3. Experiments

3.1 Performance evaluation

In order to evaluate the proposed algorithm, simulations are conducted using the thermal-traffic co-simulation environment AccessNoxim [28], which integrates the Noxim [29] and the Hotspot [30] to simulate the thermal and traffic behavior in 3D NoC systems. The network topology is set as $8 \times 8 \times 4$, and the length of router buffer is 8 flits without any virtual channel. In addition, the packet length is distributed between 2 to 8 flits randomly. To evaluate the performance, we adopt uniform random and transpose-1 traffic patterns in the experiments. For the sake of fairness, we set the same packet injection rate in this work.

In order to analyze the equilibrium results of temperature and traffic distribution, we first adopt the TAAR that was proposed in [16] as the base method of the experiments, then we adopted other three different routing algorithms: TAABR [20], PTDBA [23] and the proposed CTTAR in the experiments.

The normalized standard deviation of temperature and traffic distribution under uniform random and transpose-1 traffic patterns are shown in Fig. 6. Although the TTABR provided multiple routing paths, the similar network traffic makes the traffic and temperature distribution of TTABR and TAAR almost the same. The PTDBA adjusts the buffer length to aggravate the traffic congestion of the hot nodes

(a) uniform random

(b) transpose-1

Fig. 6 Comparison of the standard deviation of temperature and traffic distribution under (a) uniform random and (b) transpose-1

according to the temperature increasing rate of the nodes. However, the large temperature increasing rate can not mean high temperature, which results in unbalanced traffic distribution. The proposed CTTAR can unsynchronize the network traffic and thermal information by adjusting buffer length. Besides, efficient adaptive routing algorithm can keep the packets far away from the overheated NoC nodes. Therefore, the proposed CTTAR can achieve balanced temperature and traffic distribution.

Fig. 7 shows the transient maximum temperature under the four different routing schemes. As can be seen from the figure, all routing schemes can maintain the peak temperature below the hard thermal limit, 100°C. The temperature of PTDBA and the proposed CTTAR is little higher than the TAAR and TAABR, because PTDBA and the proposed CTTAR adopt the dynamic buffer adjustment. The transient maximum temperature of the PTDBA is higher than the proposed CTTAR because the PTDBA easily lead to traffic congestion which further increase the temperature.

The throughput under four different routing algorithms adopting two different traffic patterns is shown in Fig. 8. Compared with the other three routing algorithms, the CTTAR can deliver packets avoiding overheated and congested region and improve throughput by 19.4% to 48.4%.

3.2 Area cost

The proposed CTTAR introduces two additional modules: dynamic buffer adjustment and adaptive routing strategy. Although the proposed CTTAR can improve throughput,

(a) uniform random

(b) transpose-1

Fig. 7 The transient maximum temperature under

(a) uniform random and (b) transpose-1

Fig. 8 Throughput comparison using different routing algorithms

hardware overhead needs to be considered. Table I shows the area cost, which is based on TSMC 90nm CMOS technology. Compared with TAAR, TAABR and PTDBA, the proposed CTTAR has an area overhead of 2.2% under UMC 90-nm technology which can be considered negligible.

Table I Area cost comparison of different schemes

	Routing Scheme			
	TAAR	TAABR	PTDBA	CTTAR
Area (μm^2)	213451	213842	216782	218332

4. Conclusion

This paper proposed a collaborative thermal- and traffic-aware adaptive routing scheme for 3D NoC-based system. The proposed CTTAR adjusts the input buffer length firstly to transfer the temperature issue to traffic issue, then it adopts adaptive routing algorithm to deliver packets avoiding overheated and congested region. Results confirm that the proposed CTTAR scheme is effective for 3D NoC-based systems. Comparing to the TAAR, TAABR and PTDBA, the proposed CTTAR can improve the system performance 19.4% to 48.4% under the same thermal limit.

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