Adaptive Thermal and Traffic Balanced Routing Algorithm for 3D NoC

Zhiping Wu, Ning Wu, Lei Zhou, and Hao Xiao

Abstract—**With the size's increase of 3D Network-on-Chip (NoC) and the improvement of communication requirements, heat dissipation and traffic congestion are gradually becoming the main problems of 3D NoC research. In this paper, we transform the structure of the traditional 3D NoC router, monitor, analysis the network status and share it through multicast communication mechanism. In the end, we propose a global traffic-statistics-based Adaptive Thermal and Traffic Balanced Routing algorithm (ATTBR). The routing algorithm chooses regional avoidance routing strategy when the temperature is too high and uses traffic-balance routing strategy when the temperature is low. Experiment results show that, in the 4×4×4 3D Mesh, under the uniform traffic distribution in random conditions, our routing algorithm can reduce 4.32% temperature variation compared to Non-Heat-Radiation-ZXY routing algorithm (NHR-ZXY) and reduce the 85.83% variance of each sublayer's traffic compared to Downwards routing algorithm.**

Index Terms—**Network on-chip, traffic statistics, thermal and traffic balance**

I. INTRODUCTION

THE 3D Network-on-Chip (NoC) is an effective solution for the global interconnection and communication problems of complex SoC design, it has the advantage of high bandwidth, high performance and low power consumption compared to the general design approach. The key factors determining its performance are the design of routers and routing mechanism[1]. With the continuous decrease of system chip area and feature size and development of communication requirements, heat dissipation and congestion problems on chip become unavailable neglected. These problems are fundamentally traffic distribution problems, traffic being concentrated in the position that heat dissipate poorly will produce a hot spot, concentrated in fewer traffic link will cause congestion problems. Therefore, the use of appropriate routing algorithms to achieve thermal and traffic balance becomes an important issue of NoC routing mechanism design.

The key point of achieving 3D NoC heat balance is to avoid hot spots. The common method currently is vertically downward routing algorithm, the data packets route to the layer closest to the cooling sublayer from vertical direction and then routes horizontally to the node under the destination node. In the end, the packets route directly to the destination node. However, the vertical downward traffic routing algorithm focus the traffic on the bottom layer, it is likely to cause traffic congestion, results in a greater delay. Daneshtalab proposed the AntNet routing algorithm, making the packet distribute in the network evenly to reduce the possibility of hot spots[2]. An-Yeu Wu and his teammates continuously make a variety of routing policies (TTAR, TLAR, VTBR, TTMRA and TTABR) with their own 3D NoC design thermal and traffic mutual coupling simulation collaborative platform[3]-[9]. As their points are established on the researches on the method for avoiding hot spots, and to optimize the routing algorithm step by step. However, those routing algorithms only choose routing path based on the temperature and the flow rate near the current node and it haven't taken advantage of entire network status.

Moreover, for the traffic balance problem, under uniform random communication condition, when the traffic is small, common ZXY routing algorithm can balance traffic to a certain extent. But if there is a large amount of traffic in the area away from the heat sink, hot spot may occurs. Ahmed proposed a improvement way of the original forward XYZ routing algorithm (Look-ahead-XYZ)[10], which chooses the minimum traffic path according to the traffic around current node so that the traffic of the links in each floor is equal. However, the most important point is the equalization among each floor, the traffic congestion could be caused in a single floor as the traffic is too large.

In this paper, we adopt the 3D-Mesh topology as a prototype. Considering the lack of the traditional routing algorithms to avoid hot spots and to balance traffic distribution, basing on the structure of the traditional 3D NoC router, we add traffic statistics and analysis module and design the network status sharing policy which is based on multicast communication to release analysis results, and then realize the adaptive traffic-thermal balanced routing algorithm based on the analysis results. When the temperature is too high or too low, we choose heat balance priority and traffic balance priority routing strategy respectively.

The main contents are as follows, Chapter 2 describes the design of the network status sharing policy, Chapter 3

Manuscript received July 2 2014; revised August 5, 2014. This work was supported by the National Natural Science Foundation of China under Grant (No.61376025, No.61106018), the Industry-academic Joint Technological Innovations Fund Project of Jiangsu under Grant (No.BY2013003-11), the Funding of Jiangsu Innovation Program for Graduate Education under Grant (No.KYLX_0273), the Fundamental Research Funds for the Central Universities, and the Natural Science Foundation of Jiangsu Province of China (No.BK20140834).

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introduces the adaptive traffic-thermal balanced routing algorithm, in Chapter 4, the routing algorithm will be compared with other routing algorithms, and the experiment results will be given. Chapter 5 is the conclusion.

II. NETWORK STATUS SHARING POLICY

A. Router structure design

To ensure the balance of traffic between different sublayer, the traffic conditions of sublayers in the entire 3D NoC should be monitored. The traditional method is using a global network monitor. However, this method consumes a large count of hardware and has high difficulty in crafts, so we can transform router's structure and add a traffic statistics mode to achieve network traffic monitoring.

Moreover, in order to ensure that all nodes in the network traffic can be informed of the current network status and take appropriate routing policy, we need a global sharing mechanism, it will notify the global traffic condition to all nodes through the network. Since the problem of the amount of data and network size, the traditional unicast mode will greatly increase the transmission burden of communication links, so we choose the multicast mode to share traffic state in the network. Under multicast mode, the header flit contains the node address of the multicast group members, it accesses each multicast group member in some way in the course of transmission and copies data in the current network interface to each destination node, then the data is eventually supplied to all destination nodes. This method only sends data once and each destination node can get it. Therefore, we add a packet information cache module and the arbitrate module in the router.

The router architecture is shown in Figure 1.

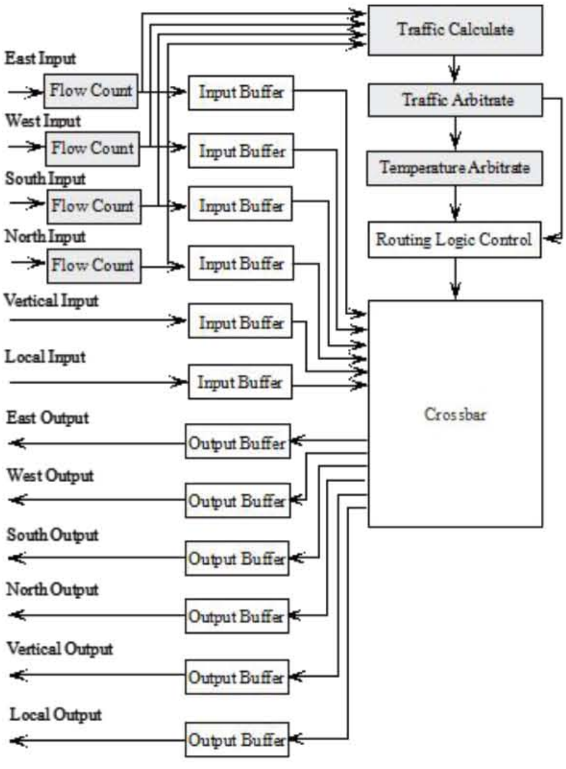

Fig. 1. Router architecture

B. Head flit structure

Packets have two kinds, packet header microchip and packet payload microchip, the length of microchip in this paper is designed to 32bits. When the microchip transfers in the same sublayer, the traffic should only be counted at the first time it enters, therefore some bits must be retained for the flag of sublayer's number. As shown in Fig. 2, in head flit, the 30-31 bits indicate packet mode, the packet is a multicast packet or data traffic statistics packet when it is 10 or 01, otherwise it is a general packet. The 28-29 bits indicate current layer number, the 22-27 bits are the number of source node and the 16-21 bits are the number of destination node, the packet length is saved in 12-15 bits and the 0-11 bits in the data packet carry traffic information when it is a traffic statistics package, these bits are 0 in general.

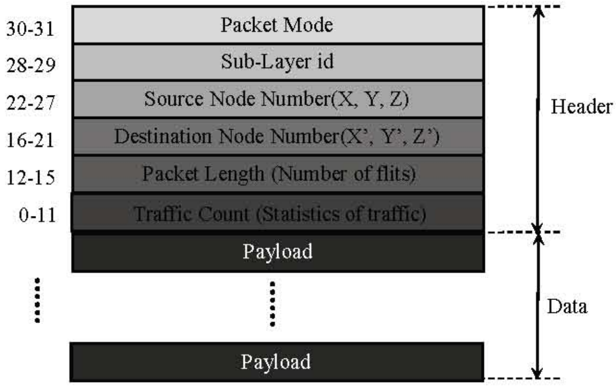

Fig. 2. Flit structure

When a traffic statistics packet is transmitted to a router, it will be unpacked and checked the number of Traffic_Count, then the traffic arbitrate module calculates the average traffic of these nodes. Finally, the average value will be refilled in the packet. Since the number of passed node is related to its identifier, the traffic count can be calculated as the formula below.The N_i indicates the number of current node.

$$Traffic = (T_{packet} + T_{local})/(16 - Ni\,\%\,16) \quad (1)$$

C. Traffic statistics mechanism

The traffic statistics mechanism consists of two main parts, the first is traffic statistics in horizontal ports of routers, the second is traffic statistics for each horizontal sublayer and judgment for choosing sublayer to route.

When the microchip outputs form a horizontal port, the router detecting layer number first. If the binary value of the layer number is equal to current sublayer's number, it means that the microchip enters the sublayer from the other node, so we don't count it; if the binary value of the layer number and current sublayer's number are not the same, it indicates that the microchip enters the sublayer the first time, the traffic should be counted, and the binary value of the layer number should be changed to current sublayer's number.

For the statistics of traffic information, we need to find a appropriate routing path for transmitting statistics results. In the horizontal direction, due to the transmission need of data packets, it is easy to produce deadlock. In this paper, refer to Hamiltonian path mode, the routing model is able to avoid a deadlock occurs. Statistical data packet starts from the router with the highest number in each layer, then accumulating traffic sequentially through all routers and aggregating to the router with the smallest number routers in each layer. The results of each layer will be routed vertically downward to the No.0 router for the statistical traffic node to compare. After comparison, the analysis result will be sent back to each router. The routing number sequence and routing path are shown in Fig. 3.

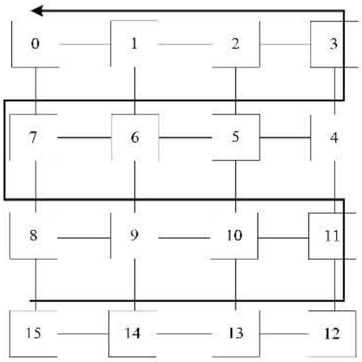

Fig. 3. Horizontal path routing traffic statistics

As the routers are communicating through network, they require multiple cycles to collect traffic information together, therefore we take a certain time interval to complete it. For the network of 4×4×4 in this paper, considering the calculation in each router, it need at least 33 cycles to collect all the traffic information to node 0, while sending multicast traffic also at least requires 18 cycles. This paper will adopt 100 cycles as time interval. Moreover, in order to ensure the accuracy of traffic statistics, it takes a longer time for collecting and we pause once every 1000 cycles. When the router receives the judgment, it starts a new round of traffic statistics.

D. *Muticast routing mechanism*

Statistical nodes need to send the results to all nodes through multicast mode. In this paper, the transmission of data from source node to destination node adopts ZXY dimension order routing algorithm. When a packet arrives at a router, check the destination address of multicast packet head microchip that if it is the same as current router address. If so, transmitting data through ZXY dimension order routing algorithm, otherwise, sending a copy of the packet to the local port of the current node, then unpacking the packet to IP core connected with the local interface.

At the same time, the destination address of the packet should be modified to the next destination address, the packet continues to be transmitted to the next destination node according to the ZXY dimension order routing algorithm until it is sent to all nodes in the multicast group members. In multicast mode, we also use Hamiltonian path mode and the routing path of the traffic in the horizontal direction is opposite to the former one.

The process of the entire routing mechanism is shown in Fig. 4. When the router receives multicast packet head microchip, making a choice on the direction of forwarding packets according to the received header information and transmitting request from output port in that direction, in case of the permit to use the port, the packets will be transmitted to the port.

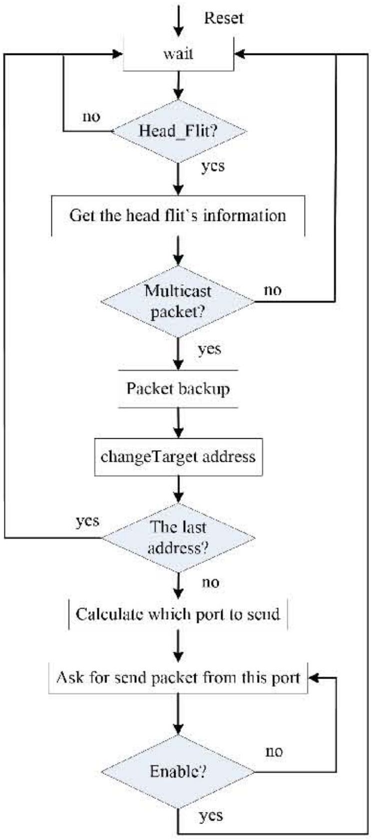

Fig. 4. Multicast routing mechanism

III. ADAPTIVE THERMAL AND TRAFFIC ROUTING ALGORITHM

As a 3D NoC network with heat sink layer, cooling effect is much better at the sublayer close to the heat sink than one away from it. If traffic distributions are large and roughly same among each sublayer, the temperature rises rapidly at the sublayer away from the heat sink and probably forming hot zone, the traffic concentrated near the heat sink layer would also cause uneven traffic within the system, creating local congestion. Hence, we need to find a dynamic thermal management routing mechanism in order to achieve both thermal and traffic balance.

Most dynamic thermal managements in routing algorithms are currently based on a single power or temperature change threshold what is used as a selection base on the routing switch. However, in the actual simulation process, we found that the routing policy repeatedly switched frequently within a predetermined time because of the determination method with a single threshold value, as a result, affecting the stability of the routing results. Therefore, our algorithm uses a method of double threshold, the low temperature change threshold T_d and a high temperature threshold T_u, which are selected 10K and 20K.

In this paper, we use an adaptive thermal and traffic balanced routing algorithm. At first, using the default traffic balanced routing algorithm. If the temperature is higher than temperature threshold T_u, using regional avoidance routing algorithm and routing in a lower temperature sublayer closer to the destination node. If the temperature is lower than temperature threshold T_d, changing to traffic balanced routing algorithm to select the corresponding sublayer according to the network status. Specific routing mode is shown in Fig. 5 and Fig. 6, S indicates the source node, D is the destination node, M1, M2 are intermediate nodes, the traffic of M1 is smaller than that in M2, the traffic is smallest at the bottom sublayer in Fig. 5.

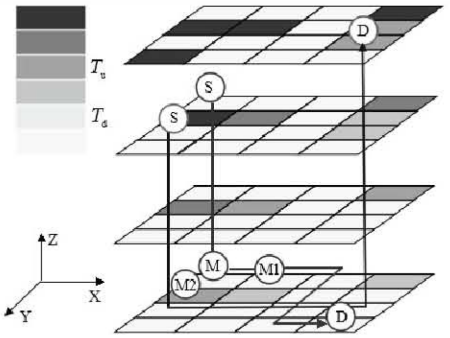

Fig. 5. Traffic balanced routing algorithm

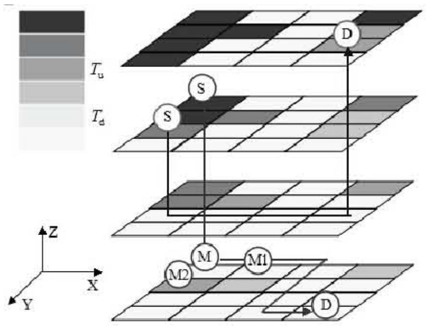

Fig. 6. Regional avoidance routing algorithm

Therefore, we can use some parameters to build the routing algorithm pseudo-code for describing the entire routing algorithm. The pseudo-code of this routing algorithm is shown in Fig. 7.

```
Temperature_Aware_Route()
Input: Current Node($x_c, y_c, z_c$)
       Destination Node($x_s, y_s, z_s$)
       Current Node Temperature $T_c$
       Temperature threshold $T_d, T_u$
       Flow of four outputs $F_e, F_s, F_w, F_n$,
Output: Next Node
$H\_xdist = x_s - x_c$;  $H\_ydist = y_s - y_c$;  $V\_dist = z_s - z_c$
if ($T_c > T_u$)
    transfer down to the node which is cool than $T_u$;
else if ($T_c < T_d$)
    check the traffic sian;
    transfer vertically to the sub-layer the traffic is smallest;
if ($H\_xdist > 0$ and $H\_ydist > 0$)
    transfer to one of $F_e$ and $F_n$ that the traffic is smaller;
else if ($H\_xdist > 0$ and $H\_ydist < 0$)
    transfer to one of $F_e$ and $F_s$ that the traffic is smaller;
else if ($H\_xdist < 0$ and $H\_ydist < 0$)
    transfer to one of $F_w$ and $F_s$ that the traffic is smaller;
else if ($H\_xdist < 0$ and $H\_ydist > 0$)
    transfer to one of $F_w$ and $F_n$ that the traffic is smaller;
else if ($V\_dist \mathrel{!}= 0$)
    transfer vertically to the Destination Node;
end
```

Fig. 7. Pseudo-code of routing algorithm

The definitions of parameters are as follow, the coordinate of the current node (xc, yc, zc), the coordinate of the destination node (xs , ys, zs), current node ' s temperature Tc, the temperatures of the nodes around current node Te, Tw, Tn, Ts, the traffic of four horizontal output ports Fe, Fw, Fn, Fs.

IV. EXPERIMENT RESULTS

The proposed adaptive thermal and traffic balanced routing algorithm (ATTBR) is improved based on vertically downward routing and NHR-ZXY routing. Therefore, we select these two common routing algorithms for comparing. In the network which size is 4×4×4, we set the simulation frequency of 100MHz and the simulation time 1 million cycles, then use random uniform pattern to test temperature change distribution and traffic distribution.

The temperature change distribution of this routing algorithm at injection rate of 0.3 flit/node/cycle are shown in Fig. 8. The four figures are layer 3, layer 2, layer 1, layer 0 in sequence.

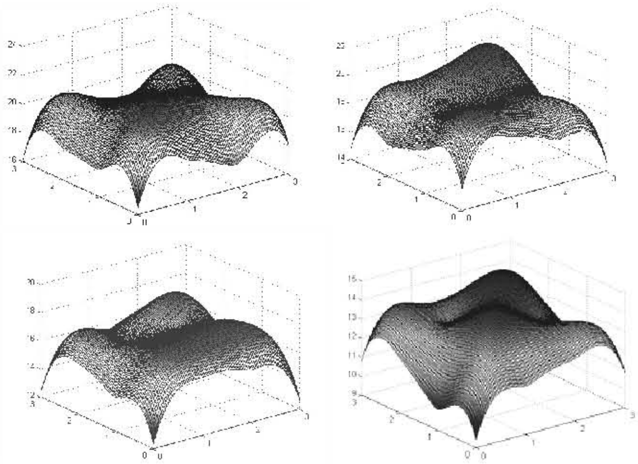

Fig. 8. Temperature distribution of each sublayer

As the Fig. 8 shows, the highest and lowest temperatures change in layer 3 are 22K and 16K, those in layers 2 are 20K and 14K, those in layer 1 are 18K and 12K and in layer 0 are 14K and 9K. Although the regional internal temperature is not exactly the same among the sublayers, the distribution is still relatively uniform and the gap between the highest and lowest temperatures is not more than six degrees.

Then we set the injection rate of 0.06 flit/node/cycle and test these routing algorithms.

TABLE I
TEMPERATURE CHANGE IN EACH SUBLAYER

	Layer	Non-balanced	Temperature balanced algorithm	
		Downward	NHR-ZXY	ATTBR
Temperature (K)	L3	3.4769	4.0042	3.7131
	L2	3.2170	3.6715	3.3584
	L1	3.0134	3.4066	3.0223
	L0	3.3185	2.5946	2.9925
	Average	3.26	3.42	3.27

As shown in Table I, NHR-ZXY and ATTBR algorithm are both concerned with with temperature balance except Downward algorithm . Comparing ATTBR to NHR-ZXY routing algorithm, it reduces the mean temperature change by 4.32% within the simulation time, thereby ATTBR could be better able to dissipate heat for 3D NoC.

TABLE II
TRAFFIC IN EACH SUBLAYER

	Layer	Non-balanced	Traffic balanced algorithm	
		NHR-ZXY	Downward	ATTBR
Traffic (flit/cycle)	L3	3.2601	3.85×10^{-4}	1.6320
	L2	3.2588	3.98×10^{-4}	2.3452
	L1	3.2455	3.17×10^{-4}	3.1234
	L0	3.2494	10.3247	6.0563
	Variance	3.81×10^{-5}	19.98	2.83

As shown in Table II, Downward and ATTBR algorithm are both concerned with with traffic balance except NHR-ZXY algorithm. Comparing ATTBR to Downward routing algorithm, the traffic variance reduction has been reduced by 85.84%, ATTBR could be more capable of 3D NoC traffic balance at uniform traffic distribution mode.

Based on the analysis above, ATTBR routing algorithm can take both the thermal and traffic equalization into account.

V. CONCLUSION

In this paper, we transform the traditional 3D NoC architecture, through traffic monitoring and network status sharing, realizing a routing algorithm ATTBR (Adaptive Thermal and Traffic Balanced Routing) based on global traffic statistics. The routing algorithm uses traffic-balance priorities routing strategy in high temperature and use heat balanced routing strategy in low temperature. Experiment results show that in the 3D Mesh NoC topology which size is 4×4×4, at the uniform traffic distribution in random conditions, the thermal-traffic balanced routing algorithm can reduce the temperature change by 4.32% compared to NHR-ZXY routing algorithm and reduce 85.83% variance of the traffic values among each sublayer compared to vertically downwards routing algorithm. Therefore it can take both thermal and traffic equalization into account.

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