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Adaptive Routing Algorithms based Fault-tolerant in 3D NOC

***Mohammad Trik**[1,2]**, Fardin Mohammadi Darvandi**[1,2] **,Kumarth nazari**[3]
[1,2]Young Researchers and Elite Club, Sardasht Branch, Islamic Azad University, Sardasht, Iran
[1,2]Young Researchers and Elite Club, Urmia Branch, Islamic Azad University, Urmia, Iran
[3] Applied Science Training Center of Justice Kermanshah, Kermanshah,Iran
*Author for Correspondence

Abstract-*In traditional congestionaware techniques, congestion is measured at a router level and delivered to other routers, either local or non-local.In this work, we present an efficient fully adaptive fault-tolerant routing algorithm for 3D Network-on-Chip (3D NoC). The presented approach is discussed in both two-dimensional (2D) and three-dimensional (3D) mesh networks. To collect and propagate the congestion information of different clusters, a distributed approach is presented. Instead of rerouting packets around the fault regions when fault occurs, our proposed algorithm applies a fault detection scheme which can get the fault information one hop away in advance, and it combines the fault information when doing the path computation. This algorithm can deal with multi faults in the 3D NoC architecture. Simulation results show that our proposed routing algorithm can achieve lower latency, energy consumption and higher packet arrival rate compared with other traditional routing algorithms in various network applications.*

Keywords: *fault-tolerant,routing algorithm,adaptive,3D NoC*

I. Introduction

System-on-chip (SoC) design is moving towards the integration of tens or hundreds of intellectual property (IP) blocks on a single chip. As chip integration grows, the on-chip communication becomes a performance bottleneck in high performance multi-processor systems-on-chip (MPSoCs). As the increasing number of processing element integrated on a chip, Three-Dimensional Network-on-Chip (3D NoC) which combines the benefits of short vertical interconnects of 3D ICs and the scalability of NoC has emerged to be a promising solution for on-chip interconnection [1][2]. NoC interconnects implemented with deep submicron semiconductor technology, running at GHz clock frequencies are prone to failures [3]. The regular tile-based network-on-chip (NoC) architecture has been proposed as a solution to meet the performance and design productivity requirements of the complex on-chip communication infrastructure [1]. A NoC provides an infrastructure for better modularity, scalability, fault-tolerant and higher bandwidth compared with traditional approaches [1]. When making a routing decision, the algorithm considers routing distance, network traffic condition, diversity of the path selection, and the fault information simultaneously, which makes a comprehensive judgment according to the network state. It enables the integration of a large number of IP cores into a chip [1–3]. However, a planar chip fabrication technology is facing new challenges in the deep submicron regime [4, 5]. By the usage of global interconnects in two-dimensional (2D) designs, wire delay and power consumption increase

significantly. To overcome these limitations, technology is moving rapidly towards the concept of
three-dimensional integrated circuits (3D ICs), where multiple active silicon layers are vertically stacked. Three-dimensional technology overcomes the limited floorplanning choices of 2D designs and allows each layer to be instantiated with a different technology [6]. The major advantages of 3D NoCs are the considerable reduction on the average wire length and wire delay, resulting in lower power consumption and higher performance [4, 7–9]. Congestion occurs frequently in NoCs when the packets' demands exceed the capacity of network resources. Congestion may lead to the increased transmission delay, and thus limiting the performance of NoCs. Efficient routing algorithms can address this issue by routing packets through less congested areas and flattening traffic over the network. Routing algorithms are classified as deterministic and adaptive algorithms. The simplest deterministic routing method is dimension-order routing, which is known as XY or YX algorithm. Implementations of deterministic routing algorithms are simple but they are not able to balance the load across the links in a non-uniform or bursty traffic[3]. Adaptive routing has been used in interconnection networks to improve network performance and to tolerate link or router failures. In adaptive routing algorithms, a packet can traverse from a source to a destination through multiple paths. Specifically, adaptive routing

algorithms can be used to avoid congestion by adapting the routing decision to the network status. Adaptive routing algorithms can be either partially adaptive or fully adaptive. In partially adaptive routing algorithms, packets are limited to choose among some shortest paths, whereas in fully adaptive methods, packets are allowed to take any minimal paths available between the source and destination pair [10]. The process of gathering and transmitting traffic information is performed through a distributed propagation mechanism. In this work, we consider 2D and 3D mesh topologies with wormhole switching technique. In a 2D mesh network, each router has five input/output ports whereas in a 3D mesh network, each router includes seven input/output ports, a natural extension from a 5-port 2D router by adding two ports to make connections to the upper and lower layers [12]. There are some other types of 3D routers such as the hybrid router [13] and MIRA [6]; however, since router efficiency is out of the concept of this paper, we have chosen a simple 7-port router. The remainder of this paper is organised as follows: In Section 2, the related work is given. In Section 3, the fully adaptive routing algorithm in 3D NoCs is introduced. Sections 4 and 5 discuss the region-based NoC for 2D and 3D mesh networks. The results are reported in Section 6 while the summary and conclusion are given in the last section.

II. Related work

Recent researches have paid much attention to NoC routing algorithms. Many kinds of routing algorithms including deterministic routing such as Dimension-Order Routing [5], and adaptive routing such as odd-even [6], turn model [7] in 2D and 4NP-first [8] in 3D. Several methods are presented in the realm of 2D NoCs in order to balance the traffic load over the network. The drawbacks of this method are that it results in long routing distance and it can only tolerant limited number of faults; The third is resending fault message [8], which resends the message that can't reach the destination. This method also introduces redundant packets and additional virtual channel are needed. In this paper, we propose a fully adaptive fault-tolerant routing algorithm for 3D NoC, which can overcome the drawbacks of the traditional routing methods and ensure both reliability and high performance.

III. DESIGN ALGORITHMS

The routing algorithm is composed of two parts: vertical node assignment in inter-layer routing and 2D fully adaptive routing algorithm in intra-layer routing. In the algorithm, packets are firstly routed towards the destination layer through inter-layer routing, and the transmission in 2D layers is using intra-layer routing. There are two assumptions in our model: first, the links connecting to the local PE are always non-faulty; second, if one direction of the bidirectional link is fault, the whole link is considered as faulty.

We employ a fault detection mechanism that each router transfers the faulty information on its horizontal links to the four 2D neighbors [10], through which the local router is informed of the link status in each direction of the four 2D neighbors. The fault information is represented in a 4-bit signal, with "1" representing "in good condition", and "0" as "faulty". For each 3D router, it is also aware of its local fault information of the vertical links. When doing path computation, the faulty information of each neighbor node is taken into consideration. The router can select a route that bypasses the faulty part while ensuring short transmission distance. This algorithm considers local traffic condition in decision making in which each router compares the congestion condition in the instance input buffers of the neighbouring routers. Another routing algorithm based on local congestion is presented in [16]. This algorithm allows packets to be routed through more output channels at each router but the routing decision is made based on local congestion information.

A. Routing algorithms based on non-local congestion

The DBAR method [17] only considers the congestion value of the routers that are located in axes. These routers should be located in the shortest path between a source and destination. As the network size increases, the congestion information of faraway routers becomes unreliable and may result in wrong decisions. A well-known method, named regional congestion awareness (RCA), is proposed in [18] to utilise non-local congestion information in the routing decision. In the RCA method, in order to provide global congestion information, the locally computed congestion value of a router is combined with those global signals propagated from the downstream routers and the newly aggregated value is transmitted to the upstream routers and so on. The main drawback of RCA is that the same congestion value may be used for the comparison purposes regardless of the destination position. It implies that the routing decision is affected by the congestion values of some routers which are resided outside of the minimal region from the source to the destination. DAR [11] has addressed the shortcoming of RCA by considering only the routers which are located between the source and the destination. However, the mechanism of distributing the information is more complex than RCA. Moreover, the congestion information is less frequently updated, which may result in routing decision based on un-updated data. Different realisations of cluster-based topology for 2D mesh networks are discussed in [19]. However, the emphasis of this paper is on the network and cluster sizes rather than a suitable routing algorithm. The presented method in [20] is another cluster-based approach with static short-cut channels to reduce the packets' latency. The complexity and overhead of the algorithm are the main weakness points of it. In CATRA [21], the passing probability of packets through the intermediate routers was calculated and based on this knowledge, clusters with the shape of trapezoids were formed. CATRA performs well in 2D mesh networks, but because of its specific structure, scalability is limited when moving to 3D networks.

B. Routing algorithms based on fuzzy logics and artificial intelligence algorithms

Different attempts were made to exploit fuzzy logic and machine learning approaches into NoCs. The presented fuzzy-based routing algorithm in [22] relies on local congestion information but the routing decision is more accurate and validated than DyXY. The idea behind these algorithms is to avoid rigid boundaries on the congestion values by employing the fuzzy logic mechanism. Fuzzy controllers compensate for ambiguities in a data by giving a level of confidence rather than declaring the data simply true or false.

DuQAR [23] and HARAQ [24] are two approaches based on Q-learning models. In these methods, the network condition is learned at run time and then this knowledge is utilised in the routing decision. In DuQAR, only the shortest paths can be used and each router maintains a Q-table to store the estimated latencies from the source to each destination router while in HARAQ, both minimal and non-minimal paths are utilised and Q-tables maintain the estimated latencies from the source to each destination region. As packets move within the network, Q-tables incorporate more global information. In addition to routing algorithms which directly affect the performance of the network, there are some other attempts trying to collect the profiling information [25] or model the traffic dynamics in many-core systems [26]. These series of works help to optimise NoCs for more realistic models of network traffic. Some other works focus on deflection routings which naturally leads to a better load balance than wormhole routings [27, 28]. However, in deflection routings flits should be reordered at destinations to form the original packet.

C. Routing algorithms in 3D mesh networks

Although there are many congestion-aware routing algorithms presented in 2D NoCs, there are a few presented methods in 3D NoCs. MAR [29] is a partially adaptive routing algorithm in 3D networks based on the Hamiltonian path. It is a simple approach which provides adaptivity without using virtual channels. An extension of turn models from 2D to 3D network is done in 4N-First and 4P-First methods [30]. These algorithms are also partially adaptive routing algorithms and do not require any virtual channels. The planar-adaptive routing algorithm [31] is a well-known method presented in the realm of interconnection networks. This algorithm requires one, three and two virtual channels along the X, Y and Z dimensions, respectively. The adaptivity of this method is limited to a fully adaptive routing algorithm inside a sequence of 2D planes. In this paper, we present a region-based routing algorithm on a 2D and 3D mesh networks. In these approaches, the network is partitioned into a group of clusters. The clusters are connected to each other via a light weight clustering network to distribute the congestion information. This network is built upon the mesh network where the data packets are propagated. The routing decision relies on the congestion level at the neighbouring clusters rather than local information. To implement these methods, a fully adaptive routing algorithm is needed in 2D and 3D NoCs. For this purpose, we use a traditional method, DyXY, as an underlying fully adaptive routing algorithm for 2D NoCs. However, due to the lack of fully adaptive method in a 3D NoCs, a novel algorithm is presented in this paper. This algorithm requires two, two and four virtual channels along the X, Y and Z dimensions, respectively.

A. Fault-tolerant Inter-layer Routing

The node containing a TSV for vertical transmission is called vertical node. Since not every node is designed as a vertical node in the topology with limited quantity of TSVs, we must assign a proper vertical node for the packets which have to traverse multi-layers. We design a dynamic vertical node selection method, in which the destination vertical node in each layer is adaptively selected according to the source and destination node in every routing decision. We use S and D to represent the source node and destination node respectively, and their 3D coordinates are defined by S(xS, yS, zS) and D(xD, yD, zD). V means the set of vertical nodes vi, where i = 1, 2, … N. D' denotes the corresponding destination in the same layer with S, and D'' means the corresponding destination in the adjacent layer to S's layer. There are two cases in this algorithm. (Case-1) D and S are in adjacent layers: if there are more than one vi in the shortest path area from S to D', the algorithm will randomly select one vi in the shortest path area; otherwise, it will select the vi which has the minimum distance between the S and D'. (Case-2) D and S are not in adjacent layers: if there are more than one vi in the shortest path area from S to D', the algorithm will select the vi nearest to S in the shortest path area; otherwise, select the vi which has the minimum distance between S and D'. If the vertical link of the selected vertical node is fault, the algorithm will reselect another vertical node using the current selected vertical node as the source node.

B. Fault-tolerant Intra-layer Routing

The intra-layer routing is a 2D fully adaptive routing algorithm, in which the route of the next hop is determined by distance, traffic state, path diversity, and fault status of the neighbors together. It also includes livelock avoidance and deadlock recovery schemes. We denote C, D and Ci as the current node, destination node and the neighbor node in direction i (North, South, East, West in 2D) respectively, and use an objective function

$$fi = \alpha li + \beta si, i = 1,2,3,4 \quad (1)$$

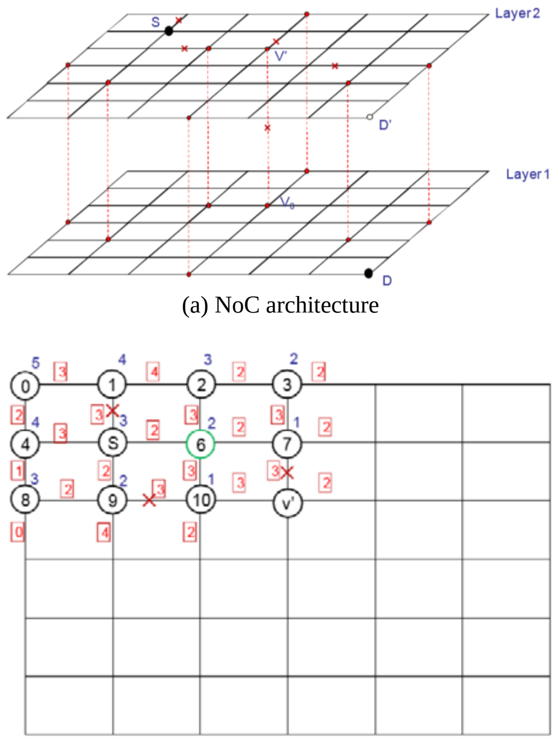
to evaluate the routing condition of each neighbor node, where li denotes the distance (number of hops) from Ci to D, and si denotes each current traffic state in direction i, and α and β represent the weights for the two objectives. Each objective is normalized to the average value of the current node. The node Ci with the maximum function value will be selected as the next transmitting node on the routing path. The parameters α and β are used to regulate the preference towards each objective. If there are more than one candidate neighbor nodes, we will make decisions according to its path diversity. Diversity (di) is defined as the number of shortest path from the current node to the destination node [8]. In this case, the neighbor with high diversity will be selected.

The fault information of the neighbor nodes is input to the current router, which has an impact on each parameter of the function. We use nni, nsi, nei, and nwi to denote the faulty status of the North, South, East, and West links for the neighbor in direction i. There are two cases:

- If the direct neighbor links (ns1, nn2, nw3, and ne4) are faulty, the corresponding li is set to be ∞.
- If other links of each neighbor node are faulty, li and di are changed according to the locations of the faulty links. If there are still shortest paths to avoid faulty from C to D, li remains unchanged. If there is no shortest path from C to D by considering the faulty, li is recalculated by constructing a shortest path from C to D to bypass the faulty links. If one of the shortest path links is faulty, di is reduced to 1/2 of the original value; if all links on the shortest path direction are faulty, di is reduced to 0.

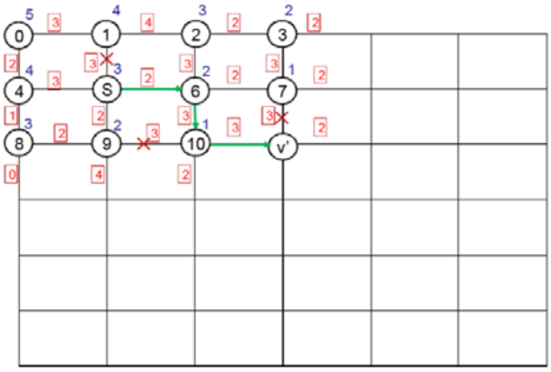
To avoid livelock, we use a small amount of state in packet to record the number of times the packet has been misrouted (Nm). Once Nm reaches a threshold N0, no more misrouting is allowed [5]. The utilization of traffic state to make routing decisions decreases the probability of deadlock occurrence. When deadlock happens, we use a deadlock recovery scheme DISHA [12] to handle the problem. In this case, each router is equipped with an extra flit buffer to store the header flit of one of the deadlock engaged packets.

An example of the proposed routing algorithm is shown in Fig. 1. A packet is injected in S and is going to D which is in a different layer. The nodes with vertical links are vertical nodes, and faulty links are remarked. The algorithm firstly assigns a vertical node v' for a transmission to the layer 1 through interlayer routing algorithm.

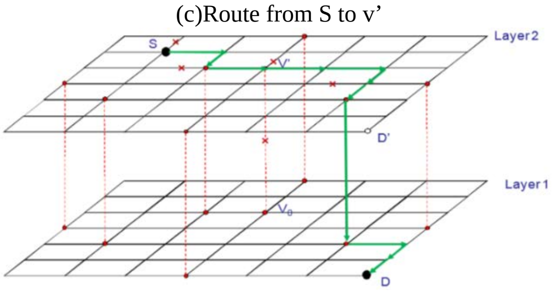


(a) NoC architecture

(b) First step from S to v'



(c)Route from S to v'



(d) Final route from S to D

Fig. 1. Example of the routing algorithm in 2 layers

Since there are more than one vi in the shortest path area from S to D', the algorithm will randomly select one vi (v') in the shortest path area (Fig.1 (a)). The transmission from S to v' is using intra-layer routing algorithm. In Fig.1 (b), the number above each node is minimum distance (li), and the value on each edge is the free buffer size (si). We set $\alpha = 0.7$, $\beta = 0.3$, and the buffer size is 4. Firstly, C = S, l0 = 3, s0 = 4, and d0 = 3. We calculate the function value of each neighbor node. Since ns1 is faulty, l1 is set to ∞. From the results, we can find our proposed algorithm can achieve high transmission efficiency while ensuring the network reliability. By comparing with the detour methods, our proposed algorithm can improve the network latency and packets arrival rate. When the fault rate becomes larger, our proposed method is superior to others. However, the energy consumption is worse than other algorithms, because the fault detection module and route computation are more complex, which consume the energy largely.

IV. CONCLUSIONS

In this paper, we proposed a fault-tolerant adaptive routing algorithm for 3D NoC. The algorithm used a novel vertical node selection method to adaptively assign a proper vertical node for vertical transmission and a fully adaptive 2D routing algorithm in which transmission distance, traffic state, route diversity, and neighbor fault information are considered comprehensively. One of the contributions of this work is to show that the performance can be improved if the routing decisions are made based on regional traffic condition. We discussed the region-based approach in both 2D and 3D mesh networks and utilised fully adaptive routing algorithms in both networks. Therefore, pockets can be routed using all the shortest paths without any routing restriction.By comparing with other routing algorithms using the reconfigurable methods, our proposed algorithm achieved better performance on considering the network latency, and packets arrival rate at the expense of energy consumption.

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