

A Fuzzy-Based Power-Aware Routing Algorithm for Network on Chip

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Abstract— Network-on-chip (NoC) is being proposed as a scalable and reusable communication platform for future embedded systems platforms. In this paper a novel routing algorithm for avoiding congested areas using a fuzzy-based routing decision is proposed. The routing path is established by minimizing a cost which is calculated by fuzzy controller and considers the power consumption and free slots input buffer of the neighbor cores. The proposed routing scheme can effectively regulate power distribution to meet power balance requirement and avoid hotspot with low hardware overhead.

Keywords— Network on chip, Routing, Fuzzy Controller, Power-aware, Congestion

I. Introduction

A possible approach for coping with the limiting factor in future system-on-chip (SoC) designs is to use an on-chip interconnection network instead of ad hoc global wiring [1]. Network on Chips are emerging as a solution to the existing interconnection architecture constraints due to the following characteristics; (i) energy efficiency and reliability; (ii) scalability of bandwidth when compared to traditional bus architecture; (iii) reusability; (iv) distributed routing algorithm [2,3]

The tile-based NoC architecture is known as a suitable solution for overcoming communication problems in future VLSI circuits. Network on chip is a solution for communication architecture of future SoCs that are composed of switches and IP cores where each core can be SoC, an IP, a DSP, etc Figure1 shows a mesh NoC consists of 16 cores. Each core connected to a router by a local network interface. Each router is connected to its neighbours through a bidirectional link. In fact, the trend of technology leads us to applications which need NoC architecture with numerous IP Cores. Cores communicate with each other by sending packet via network therefore. The performance of NoC largely depends on the underlying routing techniques, which chooses a path for a packet and decides the routing behaviors of the switches. The important concerns of research are design of low cost, high-performance, reliable and flexible on chip router and also develop deadlock-free and livelock free adaptive routing algorithms, and the design of contention and congestion-aware selection schemes.

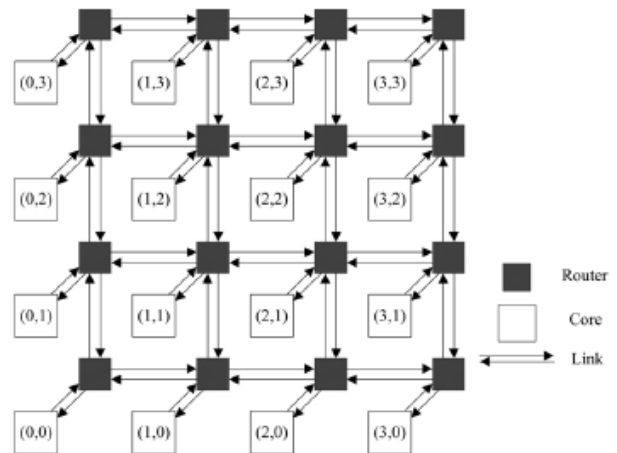


Figure1. Block diagram of 4*4 mesh-based NoC

Routing algorithm can be generally classified as deterministic and adaptive routing. In the former models, the path between the source and the destination of a packet is determined by the source and the destination themselves and the current traffic status of the network is not considered and it benefits from its simplicity in router design, however it is likely to suffer from throughput degradation when the packet injection rate increases. In adaptive routing the path between the source and the destination is determined node by node depending on the network status as the packet moves toward the destination. Adaptive routing algorithms use information about the state of the network to make routing decision. As shown in Fig.2 first a routing function computed the set of admissible output channels toward which the packet can be forwarded to reach the destination. Then a selection function is used to select one output channel from the set of admissible output channels depending on dynamic network conditions such as the presence of faulty or congested channels [7].

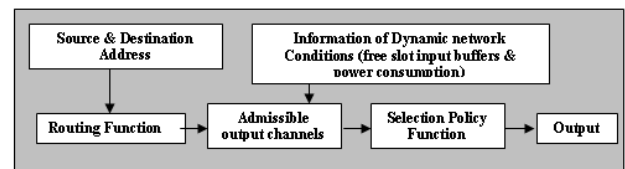


Figure2. Adaptive Routing Algorithm

Power is a critical issue in interconnection network driven by power-related design constraints such as power

distribution optimization and thermal Protection design. In this work we present an on chip fuzzy routing algorithm that the route is determined by minimum cost which is calculated by fuzzy controller and considering the free slots input buffer and power consumption of the neighbouring cores as shown in figure3. A distributed run-time mechanism estimates the power dissipation of the router and shares this information among adjacent routers. Using the algorithm the router selects one of the shortest paths by balancing the power consumption across all its neighbours and avoiding routing packets to congested node.

In this paper we propose an adaptive routing algorithm in which the link cost are dynamically assigned using a fuzzy system. The traffic is routed to nodes which are less congested and have lower power consumption. So this proposed routing scheme which dynamically monitors packet routing and ensures that there will be balanced power distribution over the network and remove possible congestion. The routing scheme combines a power model and odd-even routing [4] which is distributed and each router routes the packet through the destination considering the cost value which is calculated by fuzzy controller therefore the router selects one of the shortest paths with lowest power consumption and non-congested node. The rest of the paper is organized as follows. Section2 reviews the related routing algorithms. In Section 3, the power model is described. Section4 describes fuzzy logic control. Section5 discusses router architecture. Section6 explains the proposed routing. Section 7 discusses our experimental result and section 8 concludes the work.

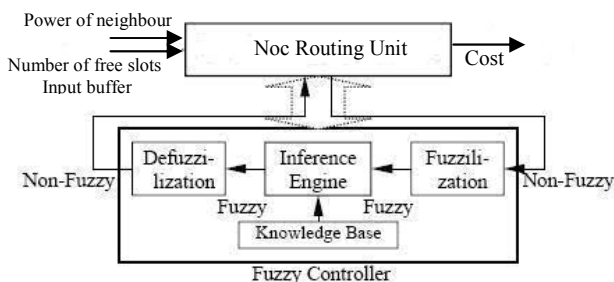


Figure3 .fuzzy Controller

II. Related works

In [4] a routing algorithm called odd-even was proposed based on turn model [6]. It restricts some locations where turn can be taken so that deadlock can be avoided. In comparison with previous methods, the degree of routing adaptiveness provided by the model is more even for different source destination pairs. A routing scheme called DyAD was proposed in [5] this algorithm is the combination of a deterministic routing algorithm called OE_fixed and adaptive routing algorithms called odd-even as proposed in [4]. This router can switch between these two routing modes based on the network's congestion conditions. Another adaptive routing named DyXY along with an analytical model based on queuing theory for a 2D mesh has been proposed [8]. The authors claim that DyXY

ensured deadlock-free and livelock-free routing and it can achieve better performance compared with static XY routing and odd-even routing. In [7] authors have presented a novel Selection strategy called NoP that can be coupled with any adaptive routing algorithm the proposed selection strategy is based on the concept of neighbors-on-path the aim of which is to exploit the situation of indecision occurring when the routing function returns several admissible output channels. In [12] the paper investigates the impact of input selections and presents a novel contention-aware input selection (CAIS) technique for NoC that improves the routing efficiency. When there are contentions of multiple input channels competing for the same output channel, CAIS decides which input channel obtain the access depending on the contention level of the upstream switches, which in turn removes possible network congestion.

III. Power model

In an interconnection network power is dissipated when flits traverse routers and links. As shown in figure4(a), flits flow through an interconnection networks with stream of operations in a typical router without Virtual-channel .(1) buffer write, (2) routing, (3) switch arbitration,(4)buffer read, (5) switch traversal and (6) link traversal. But compared to other operations, the power consumption of arbitration and routing logic is negligible.[13] thus a simplified router operation for power estimation is derived.(1) buffer write, (2) buffer read, (3) switch traversal and (4) link traversal as shown in figure 4(b).

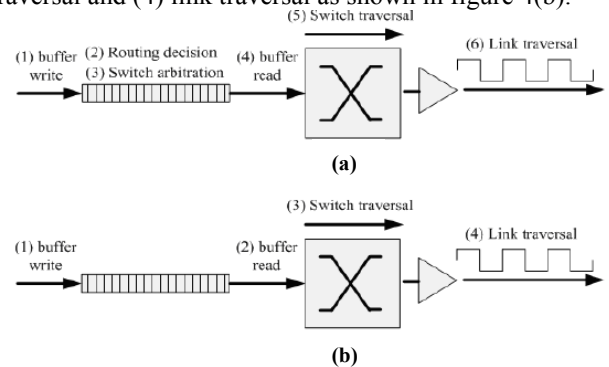


Figure4. Router operations for on-chip power estimation

In routers, power consumption is highly correlated with the switching activity of the arriving flits at the boundaries of each functional block, as demonstrated in [9]. Hence capturing aggregated switching activities at the edge of each functional block is sufficient for on-line power estimation. We thus propose a switching activity based approach for modelling the average power consumption of each operation in figure (3) b. The power model has been used as described in [10] which is explained as follows:

Input buffers: in a router, buffers read and write are the two operations that trigger dynamic power dissipation in input buffers. The average power consumption for read (P_{buff_rd}) and (P_{buff_wr}) operations over time T can be

approximately estimated based on four variables: number of read operation operations N_{buff_rd} number of write operations N_{buff_wr} and aggregated switching activities of each read (write) operation, $S(i)_{buff_rd}$ $S(i)_{buff_wr}$ As follows:

$$P_{buff_rd} = \left(C_{buff_rd} \times \sum_{i=1}^{N_{buff_rd}} S(i)_{buff_rd} \right) / T$$

$$P_{buff_wr} = \left(C_{buff_wr} \times \sum_{i=1}^{N_{buff_wr}} S(i)_{buff_wr} \right) / T$$

C_{buff_wr}, C_{buff_rd} is power coefficient of buffer write (read) operation.

Crossbar switch: the crossbar switch relays flits from input buffers to output ports. The boundary switching activities of the crossbar switch $S(i)_{crossbar}$ and the number of switch traversal operations $N_{crossbar}$ are used to model power consumption in a crossbar switch as follows:

$$P_{crossbar} = \left(C_{crossbar} \times \sum_{i=1}^{N_{crossbar}} S(i)_{crossbar} \right) / T$$

$C_{crossbar}$ Is power coefficient of switch traversal.

Links: The power consumption of link circuitry is similarly modelled based on input switching activity, $S(i)_{link}$ and the number of link traversal operations, N_{link} :

$$P_{link} = \left(C_{link} \times \sum_{i=1}^{N_{link}} S(i)_{link} \right) / T$$

C_{link} Is power coefficient of link traversal.

The total router power consumption in figure3 (b) is thus estimated as:

$$P_{total} = P_{buff_rd} + P_{buff_wr} + P_{crossbar} + P_{link}$$

The aggregated switching activity parameters in the different functions are not independent. Switching activity is the hamming distance between adjacent flits, which changes when either flit data change or when the flit sequence shuffled. In the operation sequence shown in figure 3 (b), $S_{buff_wr} \equiv S_{crossbar} \equiv S_{link}$. The router power model can now be simplified as follows:

$$P_{total} = C_1 \times \sum_{i=1}^{N_{flit_wr}} S(i)_{buff_wr} + C_2 \times \sum_{i=1}^{N_{flit_rd}} S(i)_{buff_rd}$$

Where N_{flit_wr} (N_{flit_rd}) is the number of flits entering (leaving) this router during time T.

Only two aggregate switching activity parameters S_{buff_wr} and S_{buff_rd} need to be captured on line.

The router power model is simplified as follows:

$$P_{total} = \left(C_1 \times \overline{S_{buff_wr}} \times N_{flit_wr} + C_2 \times \overline{S_{buff_rd}} \times N_{flit_rd} \right) / T$$

And

$$P_{total} = (W_{wr} \times N_{flit_wr} + W_{rd} \times N_{flit_rd}) / T$$

Where W_{wr}, W_{rd} is the power weight of write (read) operation, which mainly depends on the technology adopted in the design, the design itself, and it is a little influenced by applications.

Iv. Fuzzy Logic Control

A fuzzy control system [11] is a rule based system which a set of so-called fuzzy rules represents a control decision mechanism to adjust the effects of certain causes coming from the system. The aim of the fuzzy control system is normally to substitute for or replace a skilled human operator with a fuzzy rule based system. Specifically, based on the current state of a network an inference engine equipped with a fuzzy rule base determines an online decision to adjust the system behaviour in order to guarantee that it is optimal in some certain senses. The design process of a fuzzy control system consists of a series steps. The first step in fuzzy control is to define the input variables and the control variables. The input variables may be crisp or fuzzy. Each variable must be quantified; for instance, the variable temperature may be quantified as cold, warm or hot. Each quantification of the variable is assigned a membership function.

Once these membership functions have been quantified for each quantification of the input and control variables, a fuzzy rule base must be design, this rule base determines what control action take place under what input conditions. The rules are written in an if-then format. an implication formula is used to evaluate the individual if-then rules in the rule base. A composition rule is used to aggregate the rule results to yield a fuzzy output set. In the proposed fuzzy system, Mamdani minimum inference method [14] was used as the fuzzy inference method. A defuzzification method is then applied to the fuzzy control action to produce a crisp control action. We use center of gravity as defuzzification method.

V. Router Architecture

Our router has five ports, one is used for its local and the other are used for communication with others ports. Each input port has a controller and an input buffer. We use wormhole method for the switching because first, it requires smaller buffers as compared to the store-and-forward switching scheme. Second, network latency becomes relatively insensitive to path. After receiving the packet header, the routing unit determine which outputs can be used for routing a packet and then the arbiter request for a grant to inject the packet to a proper output. In adaptive routing, if the set of output channels determine by the router contains at least two non-reserved output channels, the router have to choose one of them by a

selection policy. The switch has a routing table for a $n \times n$ 2D mesh. This table has four rows and $(n \times n) - 1$ columns. Each row is one of directions and each column shows the cost which is calculated by fuzzy controller. Each router estimates its own power consumption and number of free slots in input buffers then this estimation is used for update the neighbours routing.

VI. Proposed Routing Algorithm

This routing algorithm, routes packets to the destination by using a routing table, which is based on fuzzy controller in 2D, mesh NoC. This routing table is filled by a cost which is calculated by free slot input buffer and power of neighbours with a fuzzy controller. We use minimal adaptive odd-even routing algorithm [4]. The deadlock free and livelock free features of this algorithm are incorporated by limiting a packet to traverse the network only by one of the shortest paths. Design of a fuzzy control routing system consists of series steps:

Step1: Define the input and output variables, respectively power of neighbours and free slot input buffers as inputs and cost as the output.

Step2: Each variable quantified, for instance the power quantified as low, middle and high. Each quantifications of the variable is assigned a membership function as shown in figure 5 and 6. Membership function for cost is chosen to be singletons.

Step3: A fuzzy rule base designed. These rule bases determine what action take place under what input conditions. The rules are written in if-then formats as shown in table 1.

Step4: a defuzzification method is applied to the fuzzy control action to produce a crisp cost. We use one of the famous defuzzification method "center of gravity" to produce a crisp output.

Step5: The port with lowest cost is selected to route packet.

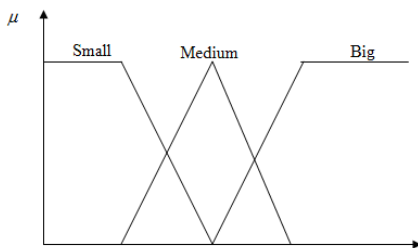


Figure5. Membership Function for free slots input buffer

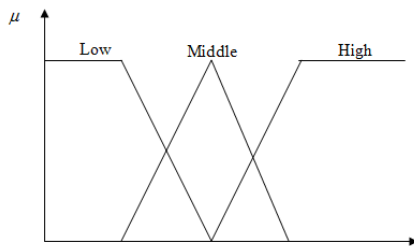


Figure5. Membership Function for power

Table 1: Rule Base for fuzzy based approach for adaptive Routing

Power Buffer	Low	Middle	High
Small	Very Low	Low	Medium
Medium	Low	Medium	High
Big	Medium	High	Very Low

VII. Comparison Analysis

To compare performance of the proposed method we implemented three other routing algorithms. These three algorithms include DyAD, XY, and Odd-Even. A NoC simulator is developed and written in Systemc which can calculate the average delay and the total energy for the packet transmission. We have used the 4×4 mesh configuration for the NoC. Each simulation was run for a warm-up period of 1000 cycles, it was executed for 10000 cycles.

A. Evaluation under Random Traffic

In the uniform traffic, each core sends a packet to every other core with an equal probability. Table 2 shows the comparison of these algorithms.

Routing algorithm	Sent packet	Average delay(cycle)	Average throughput	Max Delay (cycle)	Total energy
XY	2182	12.01	0.090	59	2.32479 e-05
DyAD	2229	12.93	0.092	88	2.40735 e-05
Odd-even	2187	12.14	0.091	98	2.31302 e-05

Table 2: Performance of different algorithms in uniform traffic

As shown, XY routing algorithm performs better than others. Since the XY algorithm is non-adaptive, it embodies global long-term information about the uniform traffic pattern [6]. The adaptive algorithms, on the other hand select channels based on local short-term information. This type of decision benefits only the packets in the immediate future, which tend to interfere with other packets [5].

B. Evaluation under First Transpose Traffic

For $n \times n$ mesh, under the first transpose traffic model, each core at (i, j) position can send its packet to the core at $(n-i-1, n-j-1)$ position. As shown it is observed that a XY routing performs badly due to its deterministic characteristic.

Table 3: Performance of different algorithms in transpose traffic

Routing algorithm	Sent packet	Average delay	Average throughput	Max delay	Total energy
XY	2171	11.80	0.080	122	2.12704e-05
DyAD	2181	11.68	0.082	105	2.21281e-05
Odd-even	2201	9.68	0.082	63	2.15902e-05

Table 4: Comparison of different routing algorithms characteristic

Routing mechanism	Hardware Overhead	Power Distribution	QoS guarantee
XY	low	low	-
Odd-even	medium	low	-
DyAD	high	medium	Low
Proposed algorithm	medium	high	High

As shown in table4 our proposed approach has better advantages than other routing algorithms in NoC. Obviously, using fuzzy controller guarantees QoS and distributes power consumption better than traditional algorithms. In average case, using proposed algorithm has spectacular outcome in three mentioned parameters.

VI. CONCLUSIONS

Routing in Network on Chip using a fuzzy system was proposed in this paper. The proposed fuzzy system showed better system performance when compared to other routing algorithm. As the load on the NoC increased the weights associated with composite metric had to be changed so as to attain better performance whereas the fuzzy system was able to match best performance of the composite metric under different loads. The comparisons showed that this proposed routing algorithm achieved a better power balancing and it has less delay than those of the others with less hardware overhead.

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