High-Level Modeling of a Novel Reconfigurable Network-on-Chip Router

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Abstract. This paper presents a novel router architecture for implementing a Reconfigurable Network-on-Chip (RNoC) at high level design using SystemC language. RNoC is an adaptive NoC-based system-on-chip providing a dynamic reconfigurable communication mechanism. By adding a virtual port – named Routing Modification port – into the conventional router architecture, the network router will be able to route communication data flexibly whenever the target routing path is blocked, by unwanted defects or intently by a software programme to meet the requirements of applications. The proposed architecture has been modeled in SystemC, simulated and verified within a 2D mesh 5×5 network platform. The static XY routing algorithm has been used in the normal communication mode while the West-First algorithm with a proposed prohibited router surrounding technique has been applied in the reconfiguration mode. Experimental results are also reported to compare the performance of the network architecture in different operation modes.

1 Introduction

The Network-on-Chip (NoC) paradigm has been known as an emerging design methodology for billion-transistor System-on-Chip thanks to many advantages: high throughput, scalability and flexibility, power management efficiency, etc. [1]. In NoC based systems, a hundred of processing cores (i.e., Intellectual Properties or IPs) have been integrated into a single system to meet the demand of applications. This leads to many challenges in system design. One of these challenges is how to make the system adaptive to the need of target applications at a specific time or adaptive to the faults appeared during the operation. It means that the system should be able to be reconfigured at run-time.

As the communication is decoupled from the computation in NoC-based systems, the design of network infrastructure and protocol should be considered to increase the systems' flexibility and reconfigurability. In [2], a reconfigurable NoC infrastructure was developed to make the system interconnection more flexible. This work aims at providing a reconfigurable interconnection architecture for FPGA implementation. The work presented in [3] introduced a reconfigurable mechanism for NoC architectures to provide fault tolerance. The uLBDR (Universal Logic-Based Distributed Routing) is proposed as an efficient logic-based mechanism to adapt to irregular topologies for 2D mesh networks. The main advantage of this proposal is the flexibility in routing communication information. However, it is obvious that we need more hardware resources for implementing the network routers. The work, presented in [4], proposed a hybrid communication reconfigurable NoC architecture. By using special wrappers surrounded the network routers, the network topology can be modified to adapt the requirements of applications. In another work [5], Lan *et al.* proposed a router architecture allowing each communication channel to be dynamically self-reconfigured to transmit data in either direction in order to better utilize on-chip hardware resources (therefore, enhance the performance of on-chip communication). The disadvantage of this proposal is that it leads to the complexity of routing algorithms.

In this paper, we present a novel reconfigurable router architecture for 2D mesh NoC implementation. The network router is able to route communication data flexibly thanks to a virtual port – named Routing Modification (RM) port. With this design, the network router is dynamically reconfigured whenever the target routing path is blocked, by unwanted defects or intently by a software programme to meet the requirements of applications. The proposed network router is then used to build a 2D mesh 5×5 Reconfigurable Network-on-Chip (RNoC) platform for validation purpose. All the platform has been modeled and verified at high level using SystemC, a C/C++ library for hardware modeling. The static XY routing algorithm has been used in the normal communication mode while the West-First algorithm with a proposed prohibited router surrounding technique has been applied in the reconfiguration mode.

The remaining part of the paper is organized as follows. Section 2 presents the proposed reconfiguration solution which allows modifying routing information to adapt real situations of the network. In Section 3, we present the proposed reconfigurable router architecture, which is used to build the RNoC. The simulation and experimental results of a 2D mesh 5×5 RNoC are given in Section 4. Finally, conclusions will be provided in Section 5.

2 Proposed Reconfiguration Solution for NoCs

Many NoC architectures have been developed by research groups in universities and industries. However, the most dominant topologies used in those NoC architectures are 2D mesh/torus because of semiconductor implementation. In our work, we focus on 2D mesh NoC architectures with source, deterministic routing. The target NoC architecture has been presented in [6].

In 2D mesh NoC architectures, the static XY routing algorithms route communication data following straight routing segments and routing corner [7]. A routing corner appears when the routing path changes the direction from X to Y. When there is a prohibited router on the routing path, the communication data has to be routed around the prohibited router. It means that the related routers must be reconfigured to change the routing path to avoid the prohibited router. In this situation, depending on the position of the prohibited router and the destination router, the routing path should be modified in different strategies in order to ensure that the communication data will reach to the destination router with a minimum cost. By exploring the 2D mesh NoC architectures, we can divide the reconfiguration strategy into 3 cases:

Case 1: The prohibited router appears at the middle of a straight segment of the routing path (see Figure 1(a)). In this case, the routing path has to be changed at the router before the prohibited router to avoid the prohibited router. The main principle is the communication data is routed to the left or the right routers instead of the prohibited router (the West-First routing algorithm is preferred in our experiment). Then the communication data will be forwarded by two hops with the same direction as the old routing path (normal routing path) before it is given back to the old routing path. In this case, we need two more hops in the new routing path (one to avoid the old routing path and one to come back to the old routing path). The router before the prohibited router must be reconfigured to add and update the routing information for 5 related hops (one hop needs to be updated, two hope need to be added, and the middle one and the last one can be kept). The old routing path is depicted as dot line and the new routing path (reconfigured routing path) is depicted as continuous line.

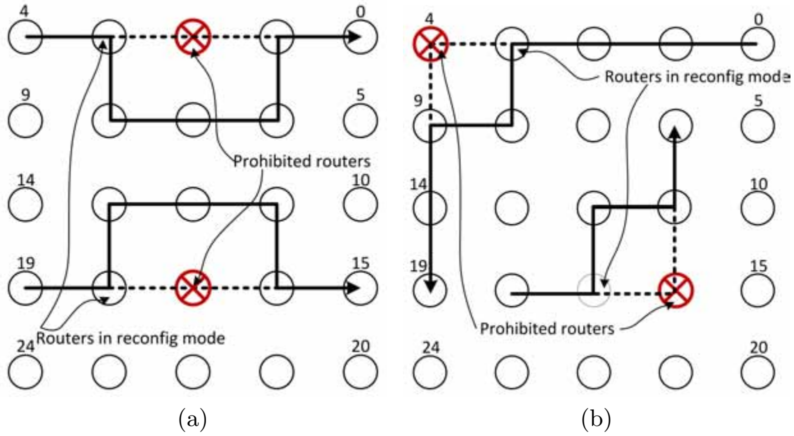


Fig. 1. Update the routing path when the prohibited router appears: at the middle of a straight segment of the routing path (a) or at the corner of the routing path (b).

Case 2: The prohibited router appears at the corner of the routing path. The routing path is also changed to avoid the prohibited router as depicted in Figure 1(b). The dot line describes the old routing path and the continuous line describes the new (reconfigured) routing path. However, in this case there are only three routers affected by the reconfiguration to establish the new routing path, even if the routing corner appears at the corner of network architecture.

The router placed before the prohibited router must be reconfigured to change the routing information for three hops in corresponding to three related routers.

Case 3: The prohibited router appears just before or just after the corner of the routing path. Figure 2(a) illustrates the case that the prohibited router appears before the corner of the routing path and Figure 2(b) illustrates the case that the prohibited router appears after the corner of the routing path. Similar to the two cases above, the routing path is also changed to avoid the prohibited router. However, in this case there are four routers affected by the reconfiguration to establish the new routing path. The West-First routing algorithm is also preferred in changing the routing direction. The router before the prohibited router has to be reconfigured to change the routing information for four hops (if the prohibited router appears before the corner of the routing path) or five hops (if the prohibited router appears after the corner of the routing path). In the case 3a, one hop needs to be updated, one hop needs to be added, and two last ones can be kept). In the case 3b, one hop needs to be updated, two hops need to be added, the middle one and the last one can be kept.

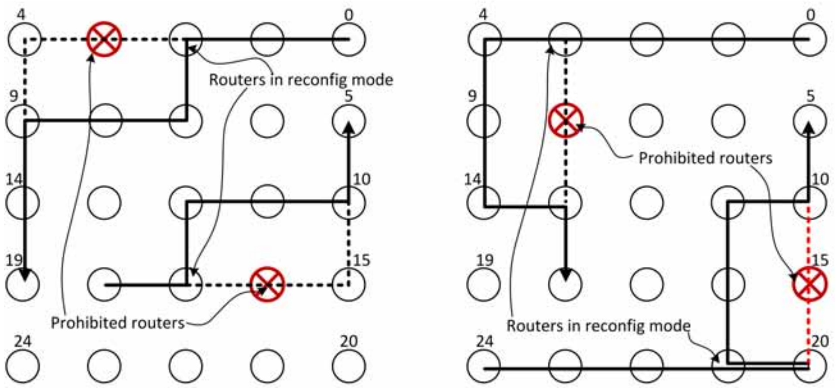


Fig. 2. Update the routing path when the prohibited router appears just before or just after the corner of the routing path.

There is a special case, when the destination router is prohibited (the destination router becomes the prohibited router). The communication data cannot reach to its destination and therefore should be deleted to increase network load. This is also considered in our proposal.

With deterministic, source routing NoC architectures, the routing information is stored in "Path-to-Target" field of the header flit [6]. Therefore, to change the routing path the network router should be able to update/modify the routing information in "Path-to-Target" field. That's why we have proposed a novel router architecture for reconfigurable NoCs as presented in the next section.

3 Reconfigurable Router Architecture

In this work, we propose a novel architecture for the network router used in reconfigurable Network-on-Chips, depicted in Figure 3. The proposed reconfigurable network router is composed of five INPORT modules, five OUTPUT modules, and a virtual Routing Modification (RM) port. Four INPORT/OUTPORT pairs are connected to four neighbour routers and the remaining pair (local INPORT/OUTPORT) is connected to the nearest IP core. The virtual RM port is used for reconfiguration purpose. These modules are connected together through two signals matrix for two virtual channels. The local INPORT has a signal vector to indicate the status of OUTPORT modules; and the local OUTPORT has four flag signals to inform the status of INPORT modules.

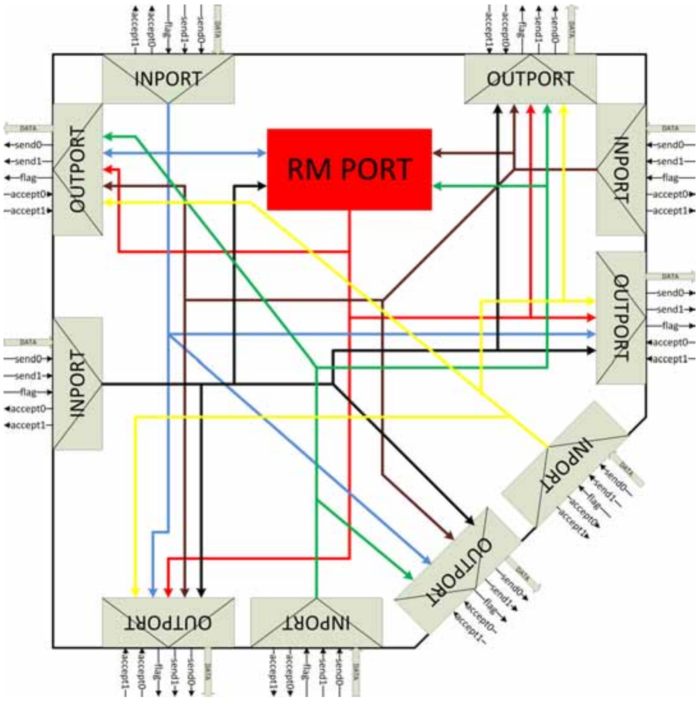


Fig. 3. The proposed reconfigurable network router.

There are two operation modes of the router: normal mode and reconfig mode. In normal mode, a data packet is received at INPORT and will be sent to next router through the target OUTPORT for all flits in the packet. In reconfig mode, INPORT received a header flit, but it cannot be sent to selected OUTPORT because the selected OUTPORT is blocked. Therefore, the INPORT changes its operation mode, then sends header flit to the RM port and waits for the response from the RM port. At the RM port, the routing information ("Part-to-Target" field) of the header flit will be changed so that the header flit is sent to a new OUTPORT; the RM port sends a command back to the INPORT to control the sending of the body flits of the packet (these flits will be routed to the new OUTPORT instead of the previously selected OUTPORT).

The detail of INPORT structure is shown in Figure 4. This work supports communication with two virtual channels (0 and 1), so that INPORT has sub-blocks corresponding virtual channels: RouteVC0 & RouteVC1, sendacc0 & sendacc1. The VC_Demux sub-block is used to receive flit and give routing information at "Path-to-Target" field in normal mode. When the selected OUTPORT is blocked, the Prohibited Control sub-block detects and sets the mode of INPORT into reconfig mode. When a cell is prohibited, this sub-block receives status flag from LOCAL port and then it prohibits the OUTPORT module which is connected to it.

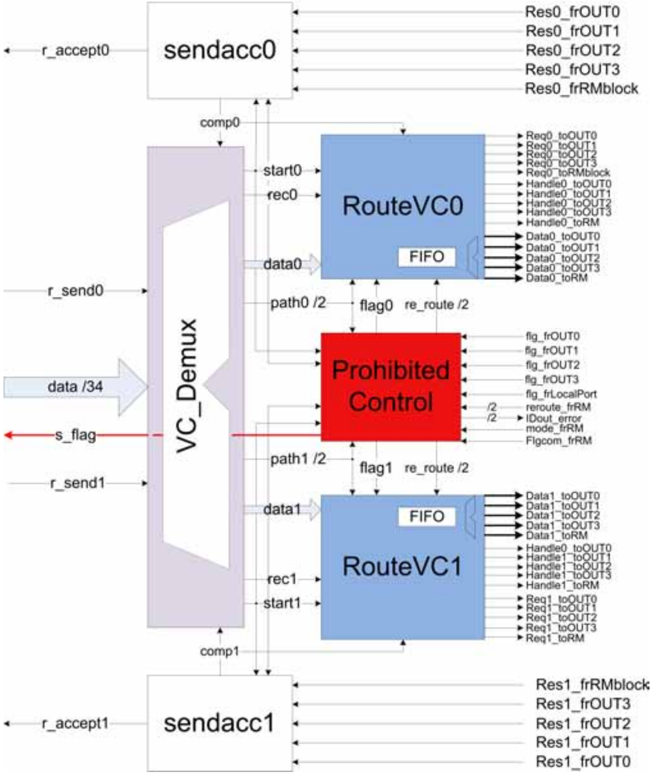


Fig. 4. Micro-architecture of INPORT modules.

OUTPORT module has eight sub-blocks and supports two virtual channels as described in Figure 5. There are three pair sub-blocks supporting two virtual channels, such as: Arbiter0 & Arbiter1, Forward0 & Forward1, and MuxVC0 & MuxVC1.

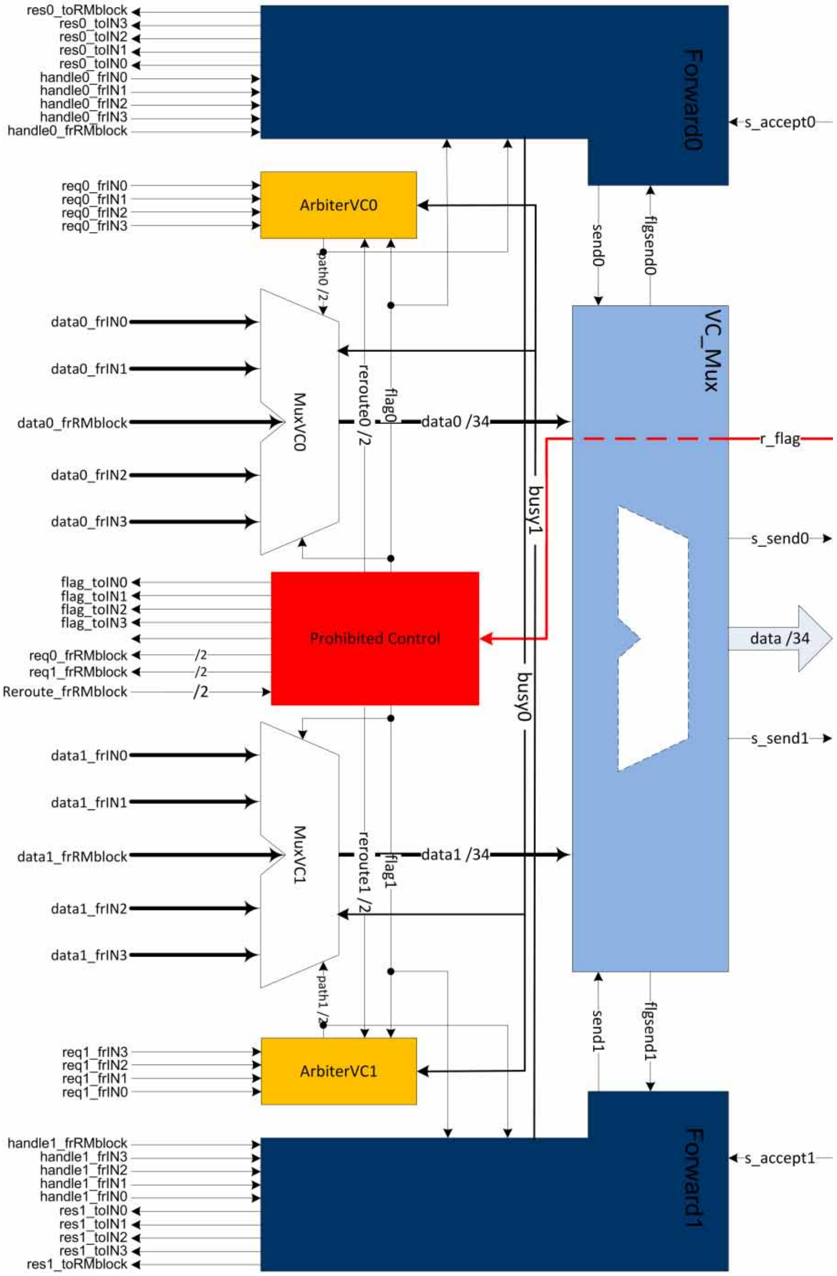


Fig. 5. Micro-architecture of OUTPORT modules.

The VC-Mux sub-block is used to combine two virtual channels and to send data to next router. At the Arbiter sub-blocks, we use First In-First Served (FIFS) mechanism when there are more than one request from INPORT blocks. The OUTPORT goes into reconfig mode when it receives a request from RM port, and then the Prohibited Control sub-block actives flag to control other sub-blocks in reconfig mode. At reconfig mode, the OUTPORT receives header flit from RM port and command to forward other flits of data packet. If RM port only sends header flit, the response of OUTPORT is changed to INPORT which is indicated from RM port.

The architecture of the virtual RM port is shown in Figure 6. In this virtual port, two sub-blocks, Receiver0 and Receiver1, are used to receive flits from INPORT modules and two sub-blocks, Sender0 & Sender1, send flits to OUTPORT modules for virtual channels 0 & 1, respectively. The Controller sub-block is used to control the sub-blocks in RM port and receives request from INPORT modules. The process which is used to change routing information in "Path-to-Target" field and selected new OUTPORT is implemented in the Update sub-block. In the Update sub-block, we use small sub-block to check the status of OUTPORT modules in router. The checking results are used to select a possible OUTPORT to forward data into previous router in the new routing path.

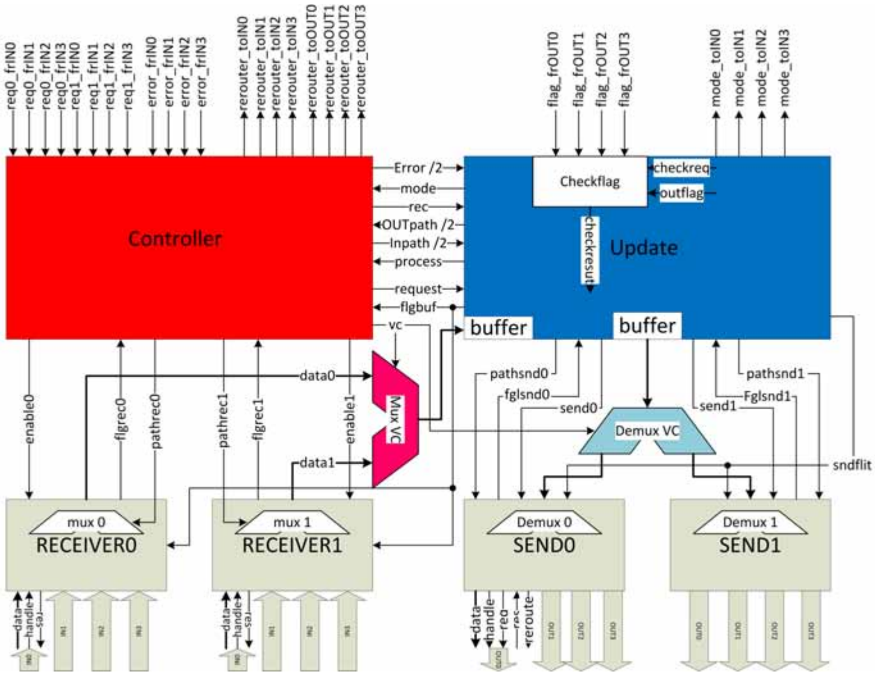


Fig. 6. Architecture of the virtual Routing Modification (RM) port.

In this work, the RM port is equivalent to a virtual port, it only use one buffer for two virtual channels.

4 Simulation and experimental results

The simulated platform is configured in 2D mesh topology with 5×5 network size. We use complement communication pattern and source static XY routing algorithm to generate data packet and inject into network from stimulating IP cores [8]. When RNoC is simulated, we control it to change prohibited cell (obtain router and IP core) and network load is injected into network. After simulating RNoC, the evaluation is executed to compute network latency and average throughput.

The operation of INPORT modules is shown in Figure 7 and the flowchart describes operation of OUTPORT in Figure 8.

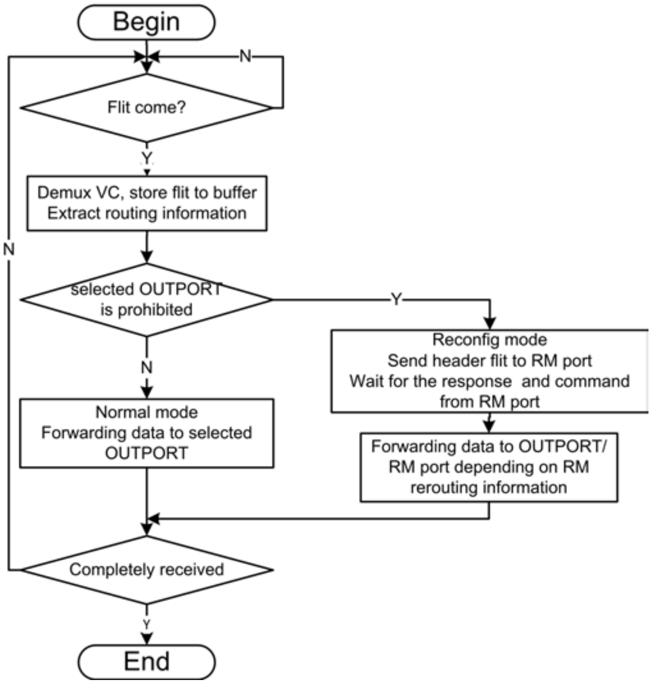

Begin
N
Flit come?
Y
Demux VC, store flit to buffer
Extract routing information
N
selected OUTPORT is prohibited
Y
Reconfig mode
Send header flit to RM port
Wait for the response and command from RM port
N
Normal mode
Forwarding data to selected OUTPORT
Forwarding data to OUTPORT/ RM port depending on RM rerouting information
Completely received
Y
End

Fig. 7. Operation flowchart of INPORT.

The reconfig mode is started at INPORT and is processed at RM port in the router. When the corresponding OUTPORT is blocked, the Prohibited Controller sub-block release an active mode flag and controls other sub-block in the reconfig mode. The header flit is forwarded to RM port, after INPORT waits until the RM port completely processes the header flit. If 'mode_frRM' signal is not active, INPORT will forward other flits of packet to a new OUTPORT that is selected from RM port.

At OUTPORT module, the reconfig mode is started when it is requested from RM port, the Prohibited Controller controls other sub-block of OUTPORT module. If 'mode_frRM' is not active, the OUTPORT interrupts response for RM port and then the RM port informs the INPORT to send other body flit of packet.

The RM port is active when there are any requests from INPORT modules. The RM port receives data flit similar OUTPORT mechanism and stores it into receiver buffer. Base on routing the current information routing in "Path-to-Target" field, the ID of INPORT, and the ID of the error OUTPORT, the Update sub-block decides a new corresponding OUTPORT and modifies routing information. After completing the process for header flit, RM port sends the header flit to OUTPORT and a command to INPORT to ask the INPORT to go into reconfig mode. In the normal mode, the RM port is not used; the data packets will be transferred from INPORT through OUTPORT modules.

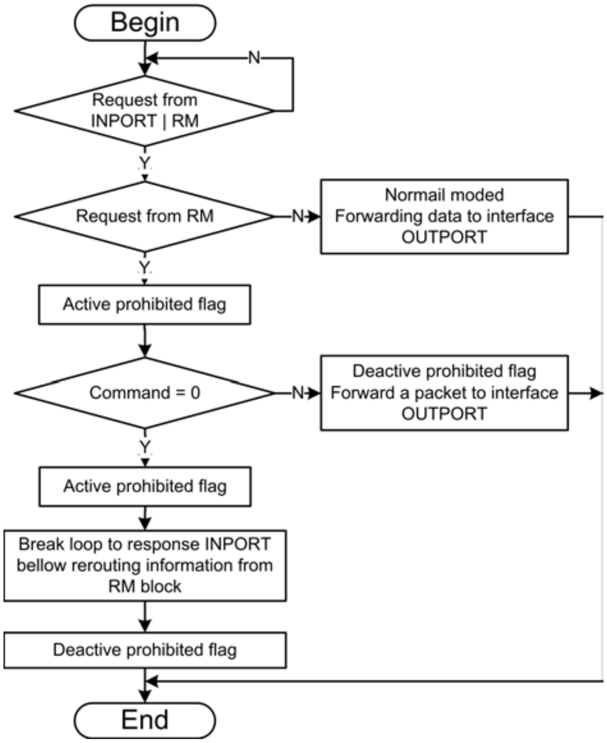
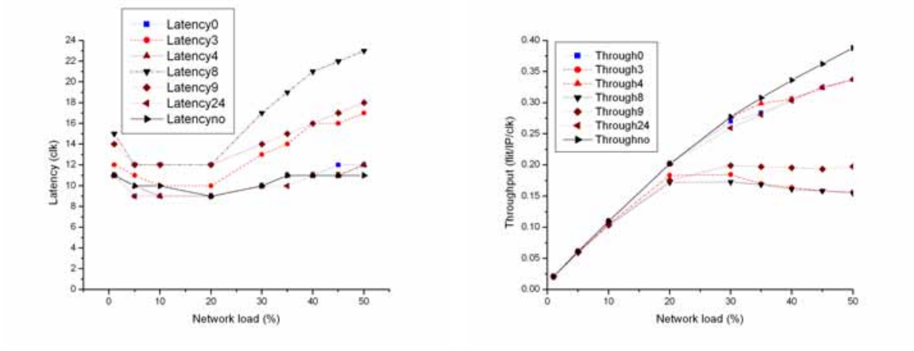

Begin
N
Request from INPORT | RM
Y
Request from RM
N
Normail moded Forwarding data to interface OUTPORT
Y
Active prohibited flag
Command = 0
N
Deactive prohibited flag Forward a packet to interface OUTPORT
Y
Active prohibited flag
Break loop to response INPORT bellow rerouting information from RM block
Deactive prohibited flag
End

Fig. 8. Operation flowchart of OUTPORT.

To show the difference between normal mode and reconfig mode of the proposed RNoC, we compare the communication performance in terms of latency and throughput of these modes with different positions of prohibited node. Figure 9(a)(a) shows the relationship between the network latency and the network load with normal mode (*latencyno*) and different reconfig modes. In the figure, the latency of normal mode is lowest and the latency of reconfig mode in which the 8^{th} router is prohibited (see Figure1(a) for router location) is highest. In fact, when the 8^{th} router is prohibited, four directions will be blocked. As a result, many packets are blocked in routing path; thus there are many routing paths which are reconfigured.

The communication throughput in corresponding with the network load is presented in Figure 9(b)(b). We can see that when the network load is small enough, the throughput in reconfig mode is similar to the throughput of normal mode. When a prohibited router is located at the network boundary, the throughput is slightly reduced. In the worst case, the throughput saturates at 0.15*flit/IP core/clk* when network load is equal to 30%.



(a)

(b)

Fig. 9. The network latency in corresponding with the network load (a) and the network throughput in corresponding with the network load (b).

5 Conclusions

We have presented the routing method and the design of a reconfigurable router which can be used for implementing a reconfigurable Network-on-Chip (RNoC). The design has been modeled at high level using SystemC. By adding a virtual Routing Modification port (RM port) into the router architecture, the network router is able to route communication data flexibly whenever the target routing path is blocked to meet the requirements of reconfiguration or to adapt the working situation caused by unwanted defects. The proposed architecture has been simulated and verified within 2D mesh 5×5 network platform. In this verification platform, the static XY routing algorithm has been used in the normal communication mode while the West-First algorithm and a proposed prohibited router surrounding technique have been applied in the reconfig mode.

Acknowledgment

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References

1. L. Benini and G. De Michel, "Networks on chips: A new SoC paradigm," *IEEE Computer Journal*, vol. 35, no. 1, pp. 70–78, January 2002.
2. C. Bobda, A. Ahmadinia, M. Majer, J. Teich, S. Fekete, and J. van der Veen, "DyNoC: A dynamic infrastructure for communication in dynamically reconfugurable devices," in *Proceedings of the International Conference on Field Programmable Logic and Applications*, 2005, pp. 153–158.
3. S. Rodrigo, J. Flich, A. Roca, S. Medardoni, D. Bertozzi, J. Camacho, F. Silla, and J. Duato, "Addressing manufacturing challenges with cost-efficient fault tolerant routing," in *Proceedings of the Fourth ACM/IEEE International Symposium on Networks-on-Chip (NOCS)*, 2010, pp. 25–32.
4. L. Zheng, C. Jueping, D. Ming, Y. Lei, and L. Zan, "Hybrid communication reconfigurable network on chip for MPSoC," in *Proceedings of the 24th IEEE International Conference on Advanced Information Networking and Applications (AINA)*, 2010, pp. 356–361.
5. Y.-C. Lan, H.-A. Lin, S.-H. Lo, Y. H. Hu, and S.-J. Chen, "A bidirectional NoC (BiNoC) architecture with dynamic self-reconfigurable channel," *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems*, vol. 30, no. 3, pp. 427–440, 2011.
6. N.-K. Dang, T.-V. Le-Van, and X.-T. Tran, "FPGA implementation of a low latency and high throughput network-on-chip router architecture," in *The 2011 IEICE International Conference on Integrated Circuits and Devices in Vietnam (ICDV)*. IEICE, August 2011, pp. 112–116.
7. C. Glass and N. L.M., "The turn model for adaptive routing," *Journal of the Association for Computing Machinery*, vol. 41, pp. 875–902, 1994.
8. T.-V. Le-Van, X.-T. Tran, and D.-T. Ngo, "Simulation and performance evaluation of a network-on-chip architecture based on SystemC," in *Proceedings of the 5th International Conference on Advanced Technologies for Communications*, Hanoi, Vietnam, October 2012, pp. 170–175.