A QoS-Enabled Optical-Electronic Networks-on-Chip

Guoming Nie, Ning Wu, Fen Ge, and Gaizhen Yan

***Abstract*—Photonic on silicon is recently envisioned as a promising technology to solve the power and latency problem in large scale Networks-on-Chip (NoCs). However, its inability in storing and processing data makes it unsuitable to directly be implemented like traditional buffered NoCs. Hybrid optical-electronic networks (HOE-NoC) solve the problem by introducing circuit switching technologies. Anyway, the optical bandwidth for an individual flow highly depends on the path setup process. Path setup between neighbored nodes is easier than the one between the nodes far from each other. But in HOE-NoC, optical links usually delivers large and long distance traffic. Therefore, without quality-of-service (QoS) management, there would be severe unfairness problem among individual flows. This paper is motivated to develop a QoS-Enabled hybrid optical-electronic network-on-chip, in which, each flow get fair bandwidth allocation. Experiments show that, compared to the network without QoS mechanism, the proposed network has excellent fairness guarantee under hotspot traffic pattern.**

***Index Terms*—circuit switched, hybrid optical-electronic network, quality-of-service**

I. Introduction

With the development of integrated circuits technology, the scale of Multi-Processors System-on-Chip (MPSoC) is increasing rapidly, which facing more and more challenges such as power consumption and throughput limit. Network-on-chip has been presented as a promising interconnection method to provide high performance, low power consumption and small area overhead [1, 2]. However, with the amount of data increasing rapidly, traditional Electronic NoCs (ENoCs) have encountered various bottlenecks, such as communication bandwidth, power consumption and transmission delay [3, 4]. Recently, optical network has been proposed as a promising interconnection way, which can improve the bandwidth and reduce power consumption [5]. However, because of the inability in storing and processing data, directly implementing optical NoCs like traditional buffered ENoCs might compromise the ultra-fast propagation of the optical signal.

There are two main different technologies in recent optical NoC research. The first class is based on circuit switching [6]. When transmit payload data in optical network, it needs to reserve path before sending data. What’s more, the reserved path is torn down after the transmission of control packets sent in electronic control network. Therefore, this kind of technology is also called Hybrid Optical-Electronic Networks-on-Chip (HOE-NoC). The second class is based on wavelength division multiplexed (WDM) technologies [7], in which, different flows can be directly transmitted from the source and destination without the necessity for path reserving. This class is also called full optical NoC (ONoC).

Although compared with full ONoC, the performance of HoE-NoC is limited by path setup and tear down process, HoE-NoC still has several appealing features. First of all, HoE-NoC utilizes wide-band ring resonators, thus having better thermal stability and saving the power for thermal tuning. Secondly, HoE-NoC shows excellent performance in large data and bursty traffic delivery. Anyway, in HoE-NoC, the optical link bandwidth that an individual flow gets highly depends on the path setup process. Path setup between neighbored nodes is easier than the one far from each other. But in HOE-NoC, optical links usually deliver large and long distance traffic. Therefore, without quality-of-service (QoS) management, there would be severe unfairness among individual flows.

Quality-of-service(QoS) encapsulates mechanism, which provide performance isolation and differentiated service to contending flows. It is pretty critical to offer bandwidth guarantee to real-time applications. Even so, there is still little work on the QoS schemes in HOE-NoC. Most of them are investigated in ENoCs[8,9,10]. Lee *et al.*[8] proposed Globally Synchronized Frames (GSF) mechanism to achieve good scalability with relatively low overhead. However, GSF suffers from several problems such as large buffer overhead and limited bandwidth utilization. Currently, the QoS research about optical network mainly focus on token-ring based networks which implement all optical arbitration and flow control mechanisms[11,12]. Jin *et al.* [11] adapted frame-based arbitration strategy to guarantee fairness in bandwidth allocation with low hardware overhead. Yan [12] presented FeatherWeight arbitration scheme that build a feedback control system to adaptively throttle the network nodes, which can approach a weighted max-min fairness

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among all the nodes.

Based on the above observation, we propose a QoS-enabled circuit-switched hybrid optical-electronic networks-on-chip which adapted frame-based arbitration in electrical control network to provide differentiated service for each flow.

The rest paper is organized as follows. Section II describes the architecture of the classical circuit-switched hybrid optical networks-on-chip and its flow contention model. Section III introduces the proposed frame-based arbitration and demonstration example. Section IV shows the experiment results to prove the effectiveness of our method. Section V is the conclusion of this paper.

II. The Architecture of Circuit-Switched HOE-NoC

A. *Architecture of circuit-switched HOE-NoC*

Topology is a crucial factor to influence NoC performance. At present, there are two branches in optical network research. One is token-ring-based topology used in full optical network, which can fully utilize the bandwidth advantage of optical link [7]. Another branch just follows the traditional electrical network topology such as mesh [13]. It is pretty suitable for circuit-switched NoC owing to good extensibility and simple implementation. In this paper, we instigate mesh based circuit-switched HOE-NoC, which consists of optical layer and electrical layer. The optical layer is for large data packet delivery while the electrical layer is for the small data packet and control packet. Both layers utilize mesh interconnection topology.

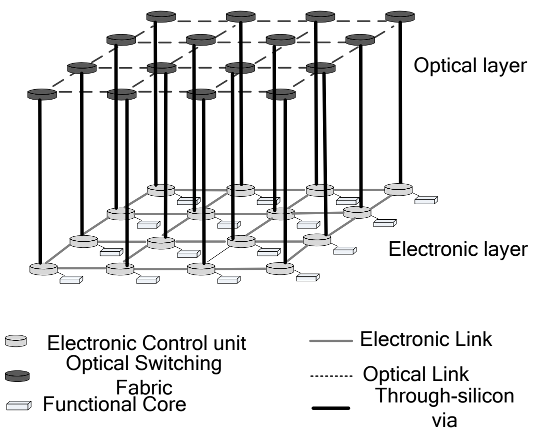

Fig. 1 .Architecture of circuit-switched HOE-NoC

A 4×4 mesh-based circuit-switched HOE-NoC is shown in Fig.1. The optical router in the network is Cygnus[14] which consists of an optical switching fabrics and an electronic control unit. The upper layer is an optical data transmission network, in which optical switching fabrics are connected by waveguides. The bottom layer electronically controls the network, in which electronic control units are connected by electrical link. The two layers are connected by TSV (through-silicon via) [15].

In electronic layer, each local electronic control unit is attached with a functional core that is processor in this paper. At the same time, the functional core is connected to the optical router switching fabrics through EO/OE interface. The electronic control unit is used to configure the optical switching fabric. The optical switching fabric is used to power on or off micro-rings.

B. *Hardware implementation in electrical router*

Since the electronic network only need support small payload packet and control packet, we optimized the electronic original router as Fig. 2 shows.

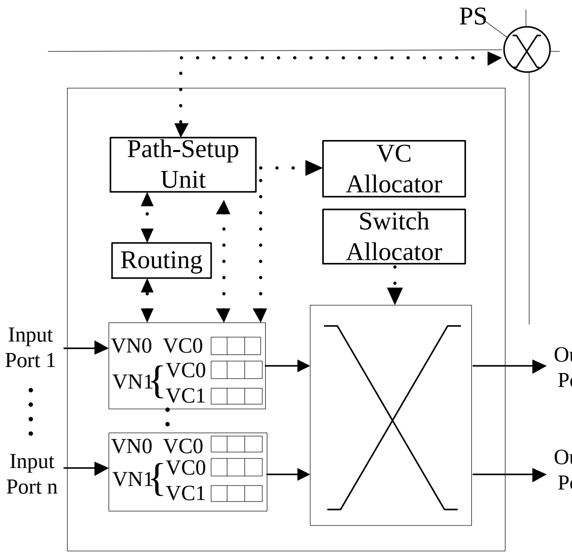

Fig. 2. Modified electronic router

The path-setup unit is used to decide whether the output port that control message needs is usable. The rest units achieve a classic four-stage pipeline structure, including routing, vc allocator, switch allocator and crossbar. Two virtual networks are used in virtual channel to transmit payload message and control message separately. The ps unit stands for optical switching fabric.

C. *The flow control of circuit-switched HOE-NoC*

Due to optical network has no ability to buffer messages, it is necessary to reserve photonic path by sending electrical control packets in electronic-controlled network. Once the path is reserved, the payload data would be transmitted in a high speed. The electronic layer can transmit small payload too. In this paper, we mainly focus on the payload data transmission in optical network.

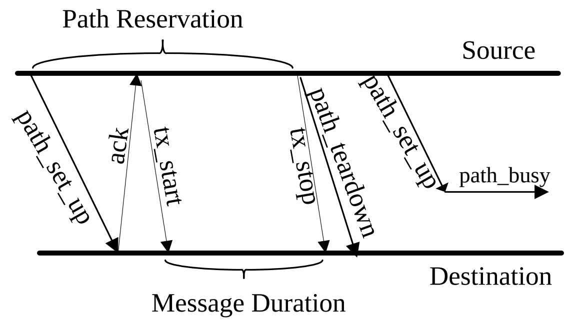

Fig. 3 Path setup and teardown process

The path setup and tear down process is shown in Fig. 3. When a source processor needs to send payload data to destination processor, it needs to send setup packets into electrical network first. Because of the deadlock-free feature of XY dimension-order routing algorithm, we adapted it in

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our work. Based on this routing algorithm, the path setup message will pass electrical routers along the path between source and destination nodes. When each router receives path setup packet, it first identify whether the corresponding output port is unoccupied. There is a port reservation table that stores the use state of all output port in every electrical router. If the required port is usable, the corresponding optical link is reserved successfully. If failed, the path-setup packet will be stalled at the current blocked router and wait for the release of the contending port. Once the setup message arrives the destination, an acknowledge packet would be sent back along the reserved optical path. Some micro-rings are added in network to realize it. When the source processor receives the acknowledge message, it sends payload data along the reserved optical path quickly without buffering. After the payload data transmission process is done, a tear-down packet would be sent along the former reserved electrical path to release reserved optical link.

Through above analyses, we can find path-setup delay is much longer than data transmission delay. When the network is lightly loaded, the path setup process meets less link contending situation. However, if the network is heavily loaded, the optical link contention may happen frequently. As Fig.3 shows, the majority of path-set-up packets are blocked in the electrical router buffer until the required optical link resource is released. At this time, the path setup process costs much time and influence the network performance and link utilization greatly.

To reduce the path setup time influence overhead, a larger payload data is preferred. The optimal size of photonic packet depends on the network size and router latency[16]. Another method we apply for improving successful path setup rate is utilize adaptive XY routing algorithm, which means when the *x* direction port is blocked the path-setup message, y direction will be tried.

All of above strategies care about the whole network performance and ignore the individual flow need. We study this problem in section 3.

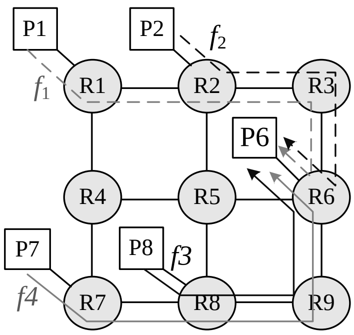
III. The Proprosed QoS- Circuit-Switched HOE-NoC

A. The flow contending model in circuit-switched HOE-NoC

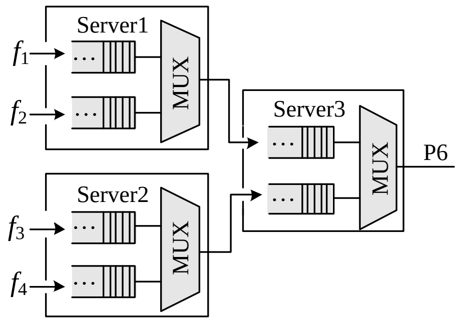
The individual flow bandwidth contending is a common problem in all Networks-on-Chip. In circuit-switched HOE-NOC, it expresses as the contention for optical link, which means that two or more flows may need the same link, causing a conflict. In fact, all individual flow contending can be abstracted as server model as shown in Fig4.

A link contention situation is shown in Fig. 4a. In the figure, P_i stands for processor, R_i stands for electronic router, and f_i represents the payload data flow. As the figure shows, flow 1 and flow 2 both need to transmit path-setup message through the east output port of router 2. Flow 4 and flow 3 need to transverse packet through the east output port of router 8. The most seriously contention exists at router6 local output port.

We can abstract the link resource contending to a server model like Fig 4b. The server stands for the electronic router output port here. And the service it can provide is the right to use the specified output port. The port allocation process is performed by a "MUX" operation. If there is no QoS support, the flow occupied the local port of router6 may not release link at a long time, which starving other flows seriously.



(a) Link resource contending



(b) Server model

Fig. 4 (a) Flow contention example (b)Abstracted server model

B. The proposed QoS mechanism for circuited-switched HOE-NoC

Based on above analyses, we proposed a link resource allocation mechanism that can provide differentiated service to individual flow according to the bandwidth need. The proposed method can be described by following steps.

We divided the link bandwidth resource as frames and allocate equal buffer size to each frame. The number of frame is N, which depends on network load condition. All frames are connected with a number. The smaller the number is, the higher priority the frame has.

Each flow is allocated a certain share according to their bandwidth need. The bandwidth is pre-allocated or decided by real application simulation. When two flows contend the same link, the flow belonging to smaller frame wins.

The highest priority frame is called head frame, which we specified as fame0 initially. When $flow_i$ need to send flit into network, it first inserted into frame1. The frame that injecting data is called current frame. If the share in current frame is used up, the $flow_i$ can overdraft the share in next frame. At the same time, the current frame pointer moves to next one. For a high loaded $flow_i$, it may exhausted N frames' share quickly, causing the current frame pointer move to head frame. At this time, we detect whether the head frame payload exist in each processor. If not, the head frame pointer will increase by one. Then the former frame resource is released and can continue to service $flow_{i.}$ Otherwise, the $flow_{i.}$ will be limited.

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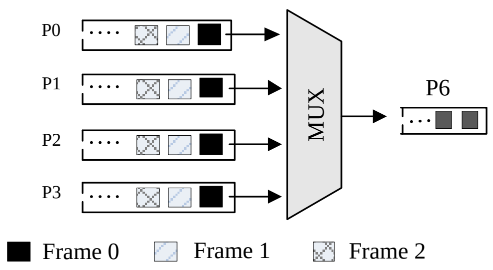
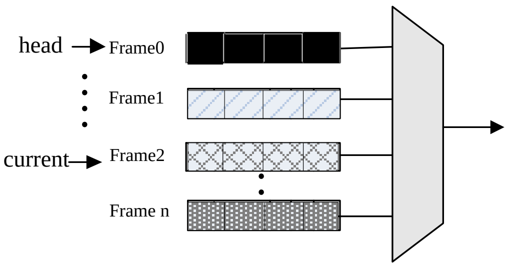


(a) Optical link allocation example



(b) Head frame movement

Fig.5 (a) Optical link allocation example (b) Head frame movement

As is shown in Fig. 5, each flow is allocated the same share in a frame. The flow flit is inserted to frame by order and the smaller frame will be serviced in priority. When flow has used up all shares in frames, the head frame pointer will move forward.

IV. EXPERIMENTS AND RESULTS

The motivation of this paper is to provide fair bandwidth allocation to individual flow. We model a 64-node optical-electronic network in 45nm as Fig. 1 shows. A cycle-accurate NoC simulator is developed for simulation[17]. Each experiment simulation time is 50000 cycles. The experiment is conducted on 64-bit Win7 operating system equipped with 3.3GHz core i5 CPU and 8G memory.

The throughput situation of our proposed network under hotspot traffic pattern is evaluated and compared with the original Optical-Electronic NoC without QoS support. Then the differentiated services that our proposed network can offer is tested. The experiment results are normalized to make it easy to compare.

A. Comparison between our proposed network and original network

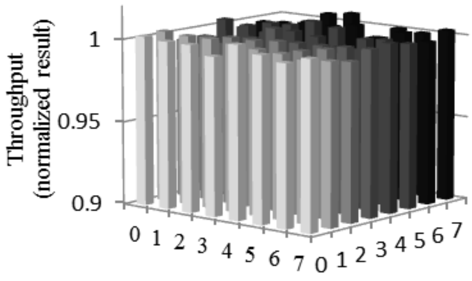


Fig.6. Fair bandwidth guarantee in our proposed network

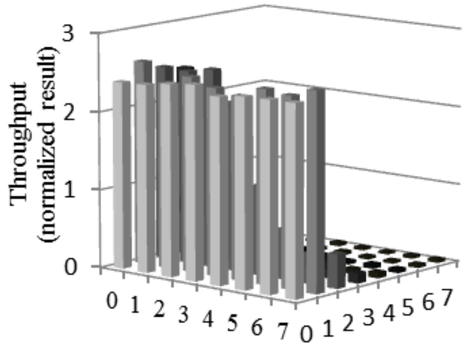


Fig.7 Bandwidth allocation in Optical-Electronic NoC without QoS support

In Fig.7, there is no QoS guarantee for individual flow. We can see that the node near the hotspot area get more throughput than farther one. Correspondingly, our proposed QoS-enabled network provides nearly equal bandwidth service to all nodes in Fig. 6.

B. The differentiated bandwidth services guarantee of our proposed network

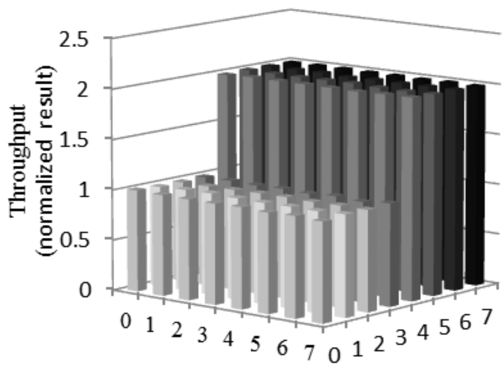


Fig.8. Differentiated bandwidth services guarantee in Traffic1

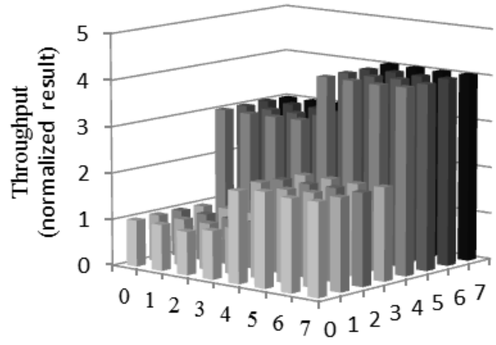


Fig.9 Differentiated bandwidth services guarantee in Traffic 2

In Fig. 8, half of the nodes in network have twice bandwidth need than the other half. In Fig. 9, the nodes are divided into four parts, in which bandwidth requirements increment step by step. It is apparently shown that our proposed network provide good differentiated bandwidth services in these two situations.

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V. CONCLUSION

In this paper, we proposed a QoS-enabled optical-electronic networks-on-chip which can provide fair bandwidth service to individual flow. The fair bandwidth guarantee and differentiated bandwidth services of proposed network have been evaluated under hotspot traffic pattern. It is found that, our proposed network can guarantee fair bandwidth service when flow contention happens.

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