Master-thesis:
A Token-based Fully Photonic Network-on-Chip with Dynamic Wavelength Allocation

by

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Abstract

Lowering power consumption with providing capability of high-performance communication is a challenging problem for the design of future Network-on-Chips(NoCs). Photonic interconnection networks have recently been proposed as an attractive solution to alleviate this issue. Recent proposals combine an electronic path setup network layer and an optical layer consisted of optical switches to realize optical communication. However, the electronic network layer is a key issue as it increases the complexity (power consumption and area) of such architectures.

In this work, we propose a new architecture that is fully optical. A key idea of our proposal is combining two types of communications: static and dynamic. A token based arbitration is used for setting up static wavelength channels for the static communication. Dynamic communication uses a manager node to optically allocate wavelengths channels. To take full advantage of both static and dynamic communications, we combine them with two selection mechanisms: basic and smart ones. The smart selection mechanism alleviates congestion in the dynamic communication and improve the performance. In addition, to reduce the congestion probability at high injection rate, we divide the available wavelengths to handle multiple communications in parallel. Although this mechanism reduces the communication bandwidth per message but obviously relieve the congestion.

Using a PhoenixSim interconnection network simulator, we evaluate our proposed architecture using different communication mechanisms: static, dynamic ,combined, and channel grouping. We show low-latency and high-throughput experimental results of the proposed NoC utilizing a smart selection of multiple communication modes.

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Chapter 1

Introduction

Interconnection network is widely used for many application domains from Network-on-Chips(NoCs), System/storage area networks(SANs), Local area networks(LANs) to wide area networks(WANs). In this thesis work, we mainly focus on on-chip interconnection networks for interconnecting microarchitecture functional units, caches, processor and IP cores with a single chip.

In recent years, with continuously growing the number of cores within the single chip, power consumption becomes a strict limitation to reach a high performance in terms of latency and bandwidth. Lowering power consumption with providing capability of high performance communication is a challenging problem for the design of future Network-on-Chips(NoC).

1.1 Problem Definition

Electrical NoC method provides significant improvements in terms of bandwidth, scalability, utilization and power consumption comparing to conventional bus-based interconnections. However, future many-core processors will require high-performance yet energy-efficient on-chip networks to provide a communication substrate for the increasing number of cores. Traditional NoC faces several issues, such as limited bandwidth, low utilization, high power consumption, and so on. To break the bottleneck of bandwidth limitation and power consumption constraints on electrical NoC, Photonic interconnection networks have recently been proposed as an attractive solution to alleviate this issue. Photonic communication technology offers an opportunity to reduce the power and increase the bandwidth performance while meeting future chip multiprocessors(CMPs) demands.

Despite these remarkable advantages, unlike electrical NoC, nanophotonic technology is not able to provide packet switching due to optical message can not be buffered as electrical data. In order to utilize nanophotonic technology, electrical data need to be converted into optical ones(E/O) in the source node while destination node receives optical data and converts them back to electrical(O/E) signals to accomplish the communication. This process leads to extra power consumption overhead of Optical/Electrical, and Electrical/Optical conversion.

An alternative hybrid solution, which consists of an electrical network layer and an optical network layer,takes advantages of both electrical and optical technologies to offer high bandwidth at acceptable power consumption cost. The performance of the electrical NoC of the hybrid architecture plays a key role as it is used for setting up the path for optical data transfer. The hybrid solution offers a feasible solution to utilize optical transmission at an acceptable path set-up latency overhead. However, frequent path set-up processing in electrical control network layer causes considerable overhead for communication performance and power consumption.

In addition, Vantrease et al. proposed the corona architecture [18] which consists of an optical crossbar with token-based arbitration using a ring topology without waveguide crossings. Comparing to the circuit-switching hybrid photonic networks [16], corona extremely reduces power consumption by eliminating electric control network layer. Unfortunately, all wavelengths in one waveguide are fairly assigned to each destination lead to limited bandwidth for optical data transfer.

1.2 Approach and Contributions

The communication sequence of the electrical NoC of an hybrid photonic NoC becomes a critical bottleneck for overall communication performance to reach low latency and high throughput at efficient power consumption. Besides latency and throughput performance, power consumption limitation and area constraints also strictly affect the overall communication performance. All the affected conditions have to be considered during the design though this thesis primarily focus on the latency and bandwidth performance.

We propose a token-based fully photonic NoC which consists of optical switches, and three rings of waveguides that connect the network nodes. These rings are used for communication on static and dynamic wavelengths allocation and arbitration, respectively. A key idea of our proposal is combining two types of communications: static and dynamic. The static communication uses a token-based arbitration to avoid communication contention at a destination node. The arbitration waveguide contains tokens for each destination node which represents the right to modulate on a specific wavelength channel. Tokens are passed around the nodes to offer global arbitration mechanism. Static communication has short overhead since an independent wavelength is assigned to each destination node, however, its bandwidth is restricted because of the limited number of wavelengths. On the other hand, dynamic communication achieves higher bandwidth data transfer than the static one by utilizing more wavelengths which are allocated on demand, although such a dynamic allocation process incurs some setup overhead. In other words, static and dynamic communications have different characteristics one another, it is important to take the advantage on how to utilize two different communication modes. This paper also considers a smart mechanism of combination for this issue. Since both static and dynamic wavelength allocation mechanisms use fully photonic communication, we can totally omit electrical layer from our NoC, hence reducing power consumption. In addition, unlike electrical communication, photonic communication has the unique feature of speed of light data transfer in silicon waveguide.

The contributions of this work are showed as follows:

- We proposed a fully photonic NoC which offers high performance at acceptable power consumption cost.
- In order to increase the utilization and reduce the congestion in proposed NoC, We proposed a smart selection and grouping mechanism to improve the performance.
- we use a modified version of Phoenixsim [4] to evaluate performance our proposed architecture using different communication mechanisms: static, dynamic ,combined, and grouping mechanisms. We show low latency and high-throughput experimental results of the proposed NoC utilizing a smart selection of multiple communication modes.

1.3 Related works

Photonic NoCs are being considered as a attractive solution to alleviate on-chip bandwidth bottlenecks and power limitations for future CMPs. Recently, many research groups developed revolutionary photonic NoC architectures with advanced arbitrations that have great progress in bandwidth performance and power consumption.

Our previous work OREX[1], which is a hybrid NoC consisting of an optical ring and an electrical central router, takes advantages of both electrical and optical technologies to offer high bandwidth with acceptable power consumption cost. However, using electrical central router can lead to a high power consumption with increasing processing unit counts in CMPs.

Pan et al. proposed in [15] used a clustered architecture with a dragonfly network topology in which nodes in the same cluster are connected by a conventional electrical interconnect while nodes from different clusters are connected by an optical crossbar. Firefly network can reduce the complexity of a wavelengths-routed architecture to save power and area by using electrical interconnects for local communication while a photonic layout for global communication. Unlike OREX and Firefly , our new proposal has the advantage to be fully optical with intrinsic low power consumption .

Ventrease et al. proposed in [18] a clustered architecture that uses an optical token-ring arbitration via a wavelength-routed ring architecture to globally reserve the right of using specified wavelength for optical data transfer through waveguides , modulators and detectors. Comparing to circuit-switching hybrid photonic networks [16], corona extremely reduces power consumption by eliminating electric control network layer. Unfortunately, bandwidth performance is limited within one single waveguide because all wavelengths are fairly assigned to each node in advance. Our proposal offer a high bandwidth data transfer using dynamic wavelength allocation.

1.4 Thesis Overview

The rest of this thesis is organized as follows:

- In Chapter 2, we introduce an overview of Network-on-Chip and photonic devices.
- In Chapter 3, we illustrate two types of the hybrid photonic NoCs, a torus hybrid photonic NoC and a ring hybrid photonic NoC.
- Chapter 4 proposes a new token-based fully photonic NoC with different communication mechanisms: static, dynamic , combined and grouping mechanisms.
- Chapter 5 presents the simulation results of token-based fully photonic NoC and shows the improvement in performance of combined communication pattern with smart selection and grouping mechanisms.

- Finally chapter 6 presents our conclusion of this thesis and outlines future research directions.

Chapter 2

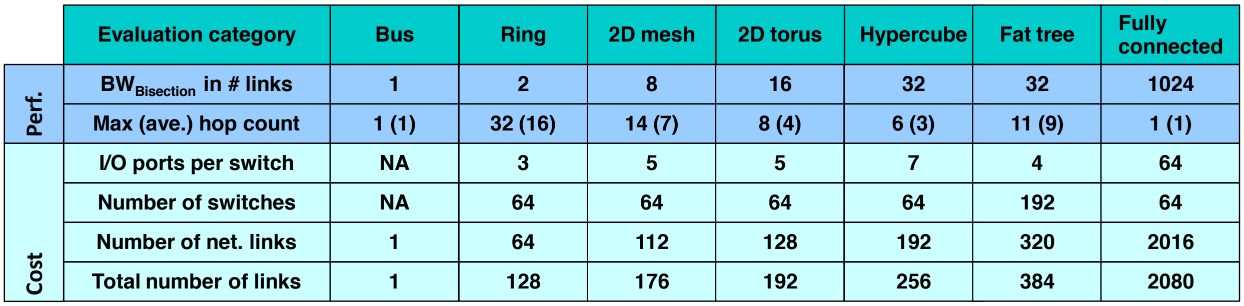
Background

2.1 Network-on-chip

Electrical Network-on-Chip is integrated a large number of functional units, caches, processor, and IP cores within a single chip. It provides improvements to scale interconnects in chip multiprocessor(CMP) and overcome the limitations of chip-crossing wire delay [10]. Network-on-Chip can mainly be described by four parameters: network topology, routing algorithm, arbitration and switching mechanisms, and Router architecture. We describe relevant characteristics of Network topology, Switching mechanism and Router architecture.

2.1.1 Network topology

Network topology is the arrangement of various components, including switches, links, and shared router nodes. For NoCs, network topology influences protocol mechanisms implemented by the routers and impacts the performance, especially when the number of nodes is very large. Many good topologies are developed to exploit the characteristics of the available packaging technology to meet the high-performance requirements of different applications at efficient cost. Figure 2.1 shows performance and cost of several



	Evaluation category	Bus	Ring	2D mesh	2D torus	Hypercube	Fat tree	Fully connected
Perf.	$BW_{Bisection}$ in # links	1	2	8	16	32	32	1024
	Max (ave.) hop count	1 (1)	32 (16)	14 (7)	8 (4)	6 (3)	11 (9)	1 (1)
Cost	I/O ports per switch	NA	3	5	5	7	4	64
	Number of switches	NA	64	64	64	64	192	64
	Number of net. links	1	64	112	128	192	320	2016
	Total number of links	1	128	176	192	256	384	2080

Figure 2.1: Performance and cost of several network topologies for 64 nodes. [10]

network topologies for 64 nodes.

In this section, we describe two types of common used network topologies in the following.

Ring Network Topology:

Ring network topology is described in figure 2.2a, all nodes in the network are fully connected with both side neighbor nodes in sequence and generate a ring architecture. Ring topology has the advantage in allowing many simultaneous transfers: the first node can send to the send while the second sends to the third, and so on. This brings efficient utilization and high throughput comparing to conventional bus and crossbar network topologies. However, as dedicated links do not exist between logically nonadjacent node pairs, packets have to hop across intermediate nodes before arriving at their destination, increasing their transport latency determined by distance [10].

We employ ring topology in our previous work[1] hybrid photonic NoC and proposed fully photonic NoC because of its simplicity of architecture. In addition, our proposal uses circuit switching mechanism and optical transfer which energy performance is independent to the distance on a chip. Therefore, the disadvantage of high transport latency caused by hop across intermediate nodes and long distance will not influent the overall communication performance on our proposal.

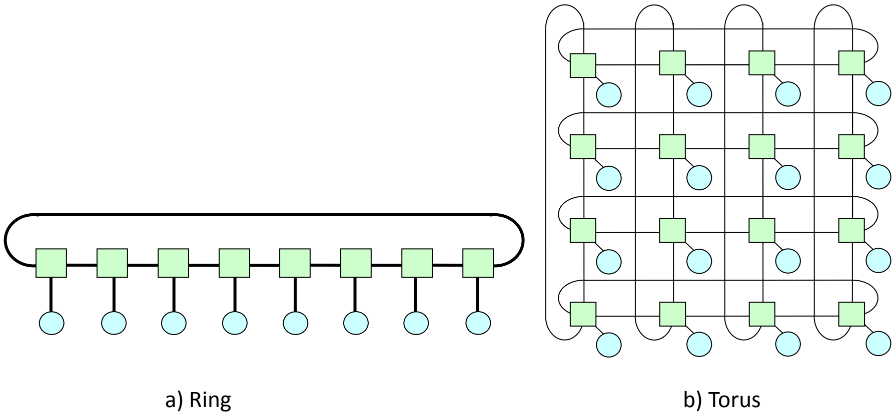


Figure 2.2: Ring(a) and Torus(b) Network Topology

Torus Network Topology:

A torus topology as shown in figure 2.2b, all the nodes in each dimension form a ring. It provides direct communication to neighboring nodes with the aim of reducing the number of hops suffered by packets in the network with respect to the ring. This is achieved by providing greater connectivity through additional dimensions, typically no more than three in commercial systems [10].

The torus topology has enormous potential to increase the throughput especially when traffic volume between nodes is large. Messages sending on a torus network have multiple possible paths to reach the destination. Unlike the ring topology, it extremely reduces the failure communication and increases throughput. As a result, the torus topology is used in the hybrid torus photonic NoC(HTPNoC) [21] to utilize photonic communication at an efficient path set-up overhead cost.

On the other hand, this topology has the disadvantage in costing requirement of path computation using routing algorithms in each node. The large cost of setting up the network also decreases the performance of the torus topology.

2.1.2 Switching mechanism

The switching technique defines how connections are established in the network. Connections at each hop along the topological path allowed by the routing algorithm and granted by the arbitration algorithm can be established in three basic ways: prior to packet arrival using circuit switching, upon receipt of the entire packet using store-and-forward packet switching, or upon receipt of only portions of the packet with unit size no smaller than that of th packet header using cut-through packet switching [10].

Packet switching

Packet switching enables network bandwidth to be shared and used more efficiently when packets are transmitted intermittently, which is the more common case. Packet switching comes in two main varieties: store-and-forward and cut-through switching. Both of them allow network link bandwidth to be multiplexed on packet-sized or smaller units of information. This better enables bandwidth sharing by packets originating from different sources. The finer granularity of sharing, however, increases the overhead needed to perform switching: routing, arbitration, and switching must be performed for every packet, and routing and flow control bits are required for every packet if flow control is used [10]. Packet switching improves channel utilization and extends network throughput.

Circuit switching

Circuit switching establishes a circuit a priori such that network bandwidth is allocated for packet transmission along an entire source-destination path. As routing, arbitration, and switching are performed only once for one or more packets, routing

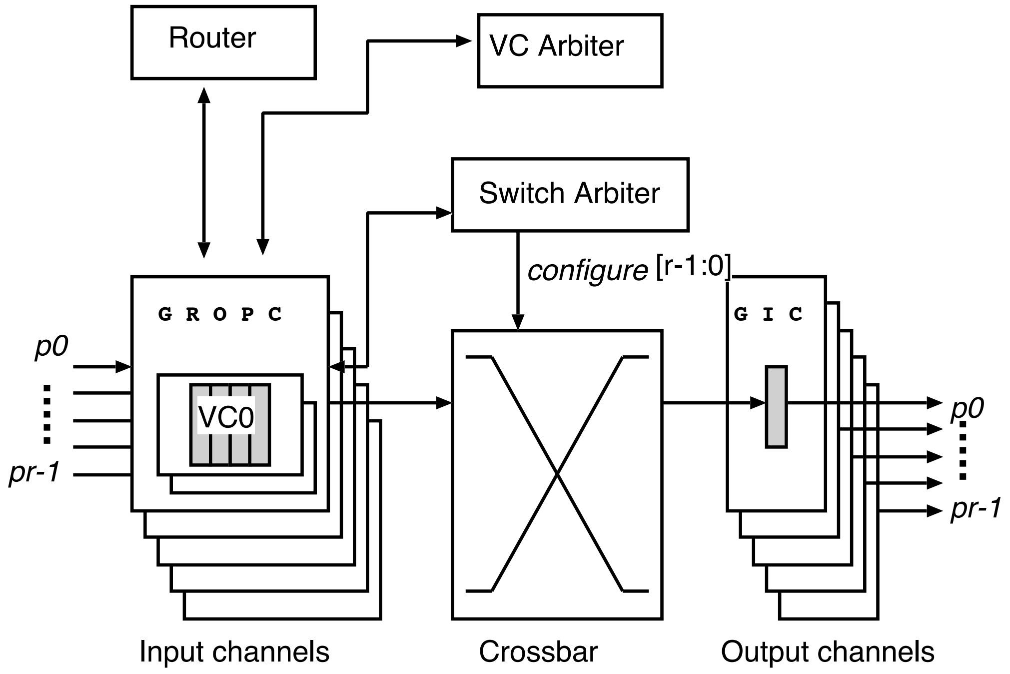


Figure 2.3: Conventional virtual-channel router

bits are not needed in the header of packets, thus reducing latency and overhead. Circuit switching has been used in our previous work, a ring hybrid photonic NoC, for reducing path set-up latency overhead.

2.1.3 Router architecture

Router is the key component that plays an important role in affecting the performance of NoC. Router consists of registers, switches, function units, and control logic. Recent years many NoC routers have been developed to meet the high performance demands. In this section, we introduce a typical virtual-channel router.

Typical electrical router:

A conventional router implement pipeline stages of routing computation(RC), virtual-channel allocation(VCA), switch allocation(SA), and switch traversal(ST) by using the router, VSA arbiter, and crossbar, respectively [6]. Figure 2.3 shows a block diagram of a typical virtual-channel router. These blocks are mainly consisted of two parts: data path and control plane. The data path compromises of a set of input buffers, a set of output buffers, and a crossbar switch to manage the storage and movements of a packet. The control plane consists of input control set, output control set, Router, VC arbiter, and switch arbiter. Input and output control sets are used for managing the input and output buffer states, respectively. The router implements routing computation while the VC arbiter allocates a virtual channel and the Switch arbiter performs switch allocation.

The input unit contains a set of flit buffers to keep incoming flits until they can be forwarded to the next router along its path. To begin forward a packet, the router has to implement routing computation in order to determine the output port(RC). According to the output port, VC arbiter manages arbitration to request an output virtual channel for the packet(VCA). The crossbar switch connects the input port to the routed output port and allocates a time slot to forward the flits(SA). When a route and a virtual channel have been determined, each flit of a packet is forwarded through allocated virtual channel to the appropriate output unit during the allocated time slot(ST). Finally, the output unit forwards the flits to the next router through its link path.

2.2 Photonic Device

Photonic technology is widely accepted as potential alternative to electrical networks because it can be much more energy efficient than electrical networks. In addition, optical fibers and waveguides with wavelength division multiplexing(WDM) to carry

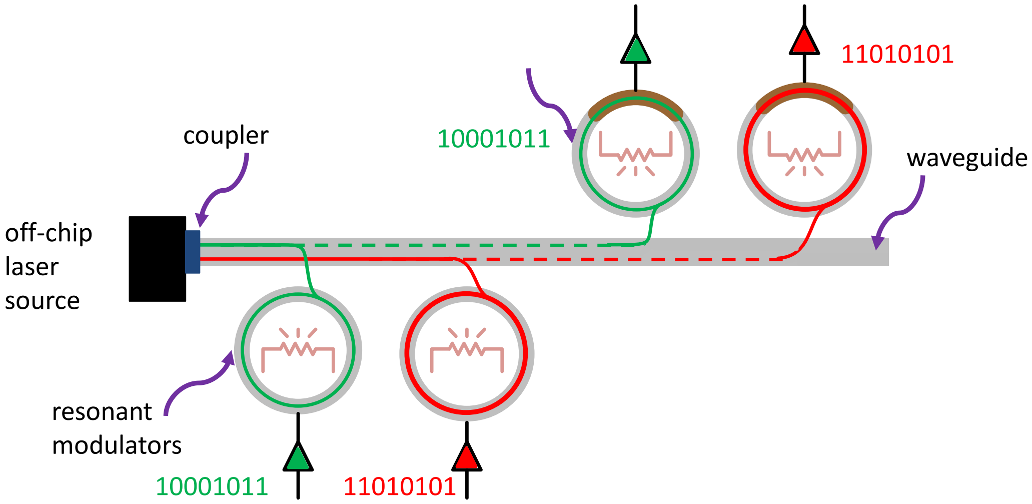


Figure 2.4: Schematic of photonic devices [15]

many information on multiple wavelength simultaneously can increase interconnect bandwidth significantly. To utilize optical interconnects into chip architecture, limited choice of materials and processes are available for fabricating optical components [8]. Because of the intrinsic features of light, chip level optical interconnects are difficult in processing and buffering optical data. To implement photonic technology, figure 2.4 describes a complete photonic network requires waveguides to carry optical data, modulators to encode electrical data into optical data by using light source, detectors located at destination to receive optical data and convert into electrical data, and laser source to provide the light.

Waveguide

The waveguide is a basic silicon photonic device which is using for carrying high-speed optical data through from one node to another [13]. Comparing to electrical links, optical waveguides have intrinsic advantage of high speed of light at lower energy cost [19] . Silicon photonic waveguides are able to transfer multiple wavelengths of optical data stream simultaneously. Furthermore, photonic waveguides can be bended, crossed, and coupled [14] from one to another in order to improve the flexibility for optical data transfer.

Recently, crystalline silicon waveguides with submicron dimension are considered as potential choice but has obvious insertion losses caused by physical crossings. Unlike crystalline silicon, deposited silicon nitride waveguide is placed as carrier medium in high speed communication links with the vision of monolithic integration of high performance. It has low crossing insertion losses and enormous potential for photonic links [3].

Modulator

The modulator is an essential component that used for high speed of conversion from electrical data to optical data. The laser source provides light source for the modulation. According to the electrical command data, the modulator is switched "ON" or "OFF" to generated a sequential optical data in the waveguide by using light source(Electrical/Optical Conversion). The speed of modulation up to 12.5Gbps has recently been proved [20]. By using wavelength division multiplexing(WDM) technology, it is preferable to have wavelength-selective modulators that can encode data on multiple wavelengths and form a cohesive parallel optical data stream within a single waveguide. WDM technology helps the modulators achieve high bandwidth modulation for photonic NoCs.

Detector

The detector is placed at the destination of optical communication link for converting incoming optical signal into electrical domain(Optical/Electrical Conversion). Selective detectors, consisted of CMOS-compatible Germanium(Ge) doped resonant rings [15],

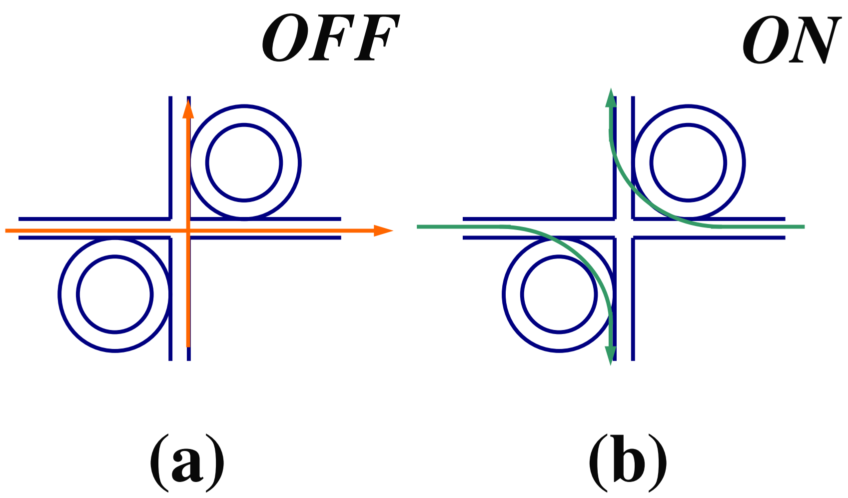


Figure 2.5: Photonic Switching Element [17]

can be used for receiving and translating different specific wavelengths. Ge-doped detector have demonstrated speed of detection up to 40Gbps.

Laser source

The off-chip laser source, provides multiple wavelengths for modulating optical data, is considered as attractive solution to support high bandwidth density at low power [7, 12].

Photonic Switch Element(PSE)

The Photonic Switching Element(PSE) is a functional component based on micro-ring resonator structures for optical data switching. PSE has two different state, “ON” and “OFF” , by shifting the resonance frequency. In the “OFF” state, as described in figure 2.5(a), incoming optical data will pass through the PSE in its original direction. In contrast, figure 2.5(b) shows that optical data coming from the west will be switched to the south while optical data coming from the east will be switched to the north.

The switching action of optical data is accomplished by changing the state of micro resonators(MR).

In Chapter 3, we will introduce two types of hybrid photonic NoCs: a torus photonic NoC and a ring photonic NoC.

Chapter 3

Hybrid Photonic Network-on-Chip

Currently, photonic technology have many advantages in providing high bandwidth and high-speed transmission at low energy cost. However, it lacks two necessary key functions, buffering and header processing [16], for packet switching. Unlike photonic technology, electrical NoCs are flexible and functional to provide buffering and header processing, but may cause high power consumption especially in high speed and long distance. Despite the limitations of photonic technology, several researches that take advantages of the unique low power and high bandwidth abilities provided by optical components have been proposed [5, 9, 2].

3.1 Hybrid Torus Photonic Network-on-Chip

3.1.1 Architecture

Figure 3.1 shows a 4X4 torus hybrid photonic NoC. It consists of two network layers: an optical high-bandwidth data transfer circuit switching network, and an electrical packet switching control network. The electrical control network consists of electrical routers(demonstrated in figure 2.3) interconnected by electrical wires in a torus topology. Path setup messages are sent by electrical network to establish the proper path

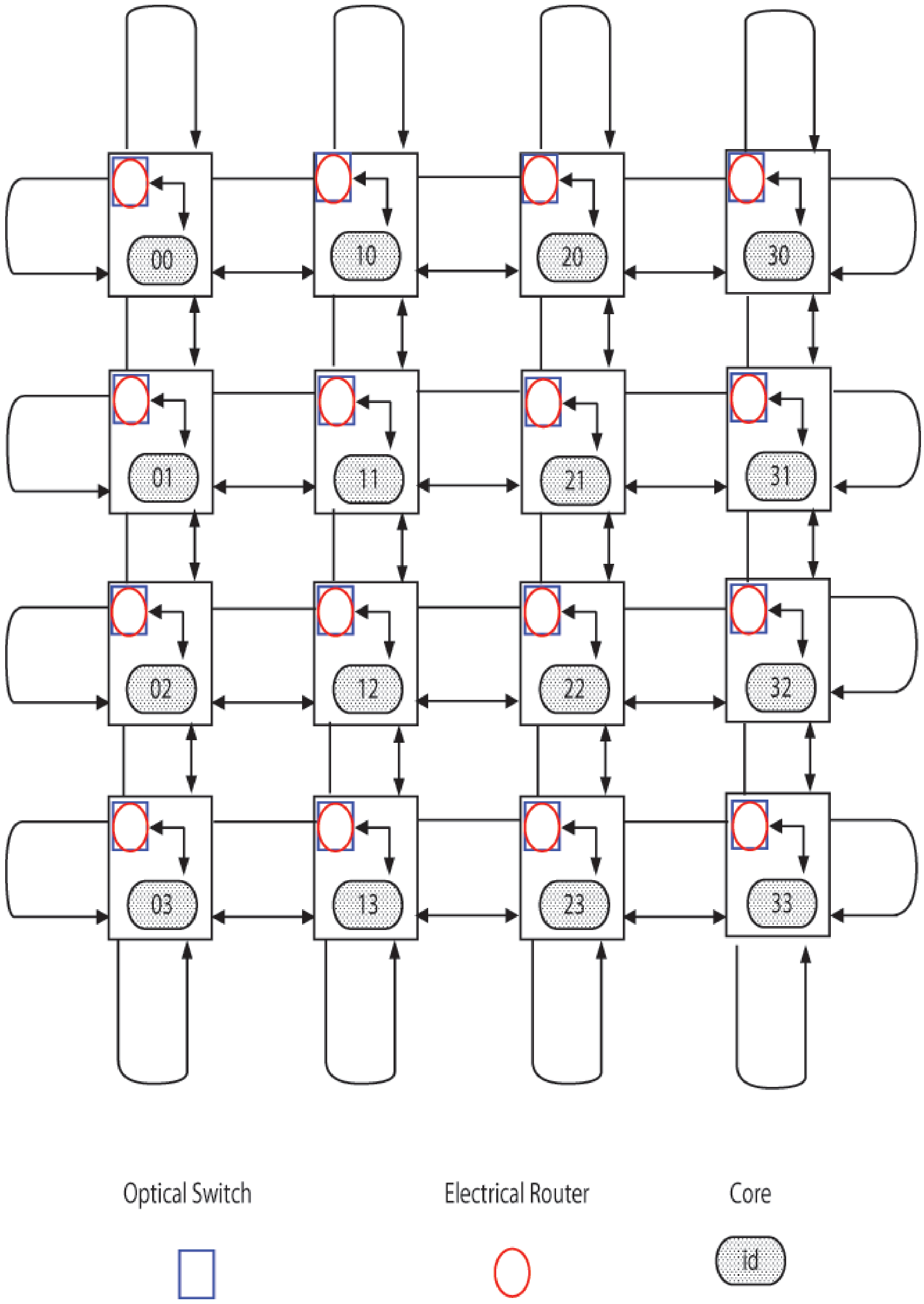


Figure 3.1: A 4X4 Torus Photonic NoC

for optical data transfer in optical network layer. The optical network consists optical switches connected by optical waveguides. Modulators and detectors are positioned at each node in order to support sending/receiving functions by implementing electrical-optical-electrical(E-O-E) conversions. To construct a 2D torus topology, figure 3.2 shows a 5X5 optical switch that consists of micro resonators(MRs), a control unit, and waveguides. In the optical switch, there is one input/output port for four directions(East, West, North and South). The MR has two states, “ON” and “OFF”. By using the control unit to switch “ON” or“OFF” the MRs, optical data can be directed from the input direction to the output direction properly. For instance, the optical data coming from Gateway port is directed to the West port by switching “ON” MR 4 as shown in figure 3.2.

3.1.2 Communication mechanism

The steps of communication in a torus HPNoC are demonstrated as follows:

Firstly, source node sends the path setup message through electrical network to set up the path for optical data transfer in optical network layer.

After the path setup is accomplished, destination node sends an acknowledgment optical signal back to the source node. Then, the source node begins modulate optical data onto waveguides through established optical path to the destination.

Finally, when optical data transfer completed, the source node sends a path release message through electrical control network to release established optical path.

3.1.3 Evaluation

Comparing to the pure electrical NoC, with the combination of optical network and electrical control network, the torus HPNoC provides a higher interconnection bandwidth and faster transmission speed by using light at acceptable power consumption cost. Unlike electrical NoC, HPNoC removes the needs for buffering optical data and

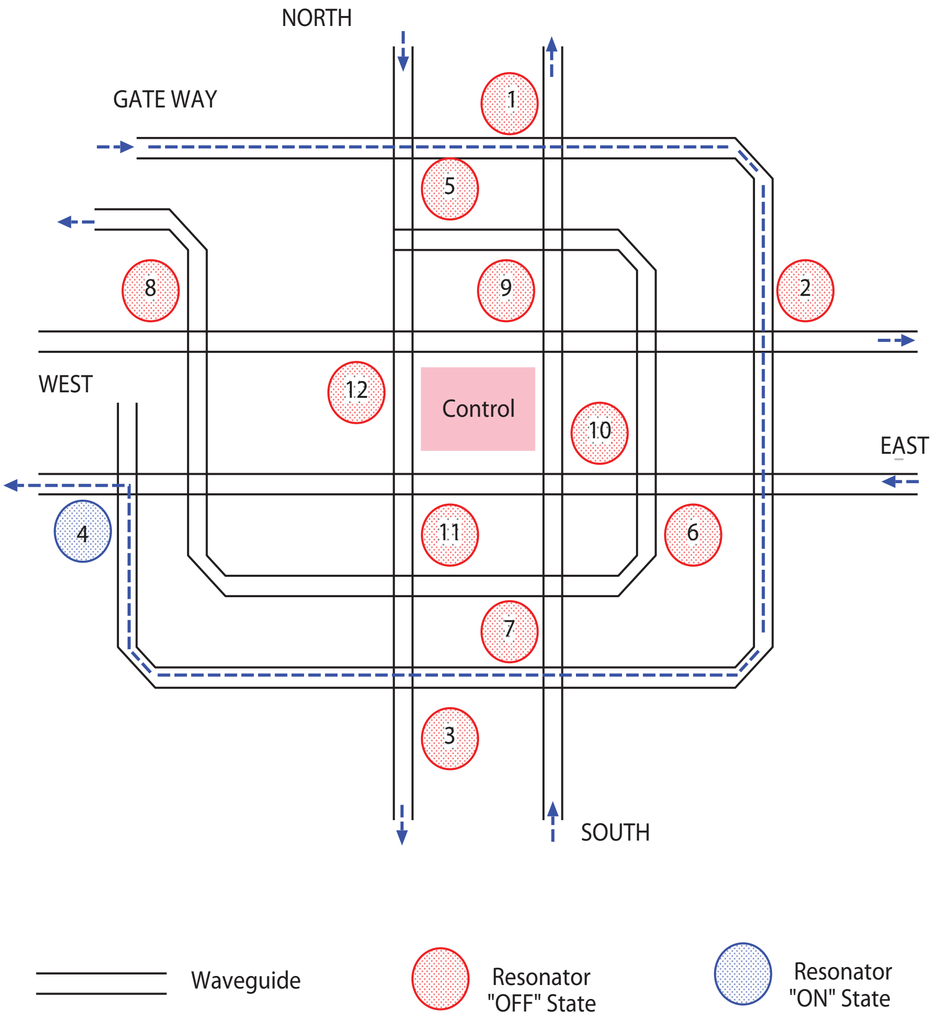


Figure 3.2: Optical switch

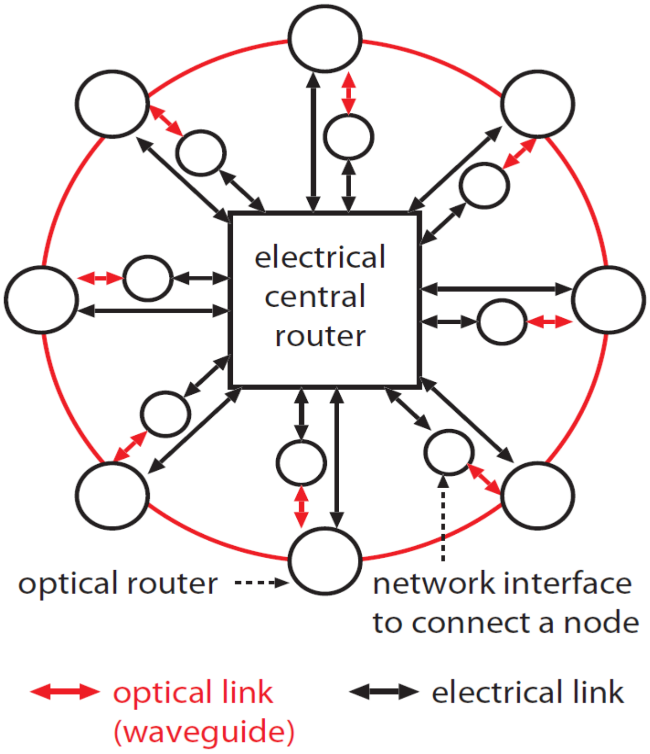


Figure 3.3: Architecture of OREX

high power consumption caused by electrical-optical-electrical(E-O-E) conversions at intermediate nodes. However, the path setup latency in electrical control network is still a key bottleneck in the overall performance of HPNoC [16]. In the next section, our previous proposal, a ring architecture HPNoC, further reduce the path setup latency by using a single crossbar router.

3.2 Hybrid Ring Photonic Network-on-Chip

3.2.1 Architecture

Figure 3.3 shows Optical Router Electrical Crossbar(OREX) NoC topology. The optical red ring consists of bidirectional waveguides interconnected by optical routers to join the nodes. Unlike a shared bus [11], many optical data transfers can take place along disjoint paths simultaneously. For instance, the first node can send to the second node while the second node sends to the third, and so on.

Figure 3.4 shows connections among a node, an electrical, and optical routers. The electrical central router consists of a crossbar switch(XBAR), an arbiter, and an optical path allocator. The optical path allocator is a unique component that is used for allocating optical paths and allocating wavelengths for source-destination communication pairs. The optical router consists of MRs, which are positioned at intersections of waveguides, and a control unit for the MRs. In order to route optical data transfer, the control unit switches “OFF” the MRs , the optical data can pass through the intersection, such as right to left, and vice versa. On the other hand, optical data turn the intersection when the control unit switches “OFF” the MRs to send/receive optical data onto/from the waveguide. To take full advantages of the wavelength division multiplexing(WDM) technology, the number of MRs equals to the number of wavelengths are required at each intersection of waveguides.

3.2.2 Communication mechanism

The steps of communication in OREX are demonstrated as follows:

1. Source node sends an electrical request packet to the central router via the network interface.

2. According to the request packet, the optical path allocator finds an available optical path for the source-destination communication pair. Then, central router sends the commands for both source and destination nodes. Controllers, on both source and destination node, switch “ON” related MRs to route optical data based on received commands.

3. An acknowledge packet is sent back to the network interface of the source node to notify the optical path establishment between source and destination. Then, optical data transmission takes place along the established optical path.

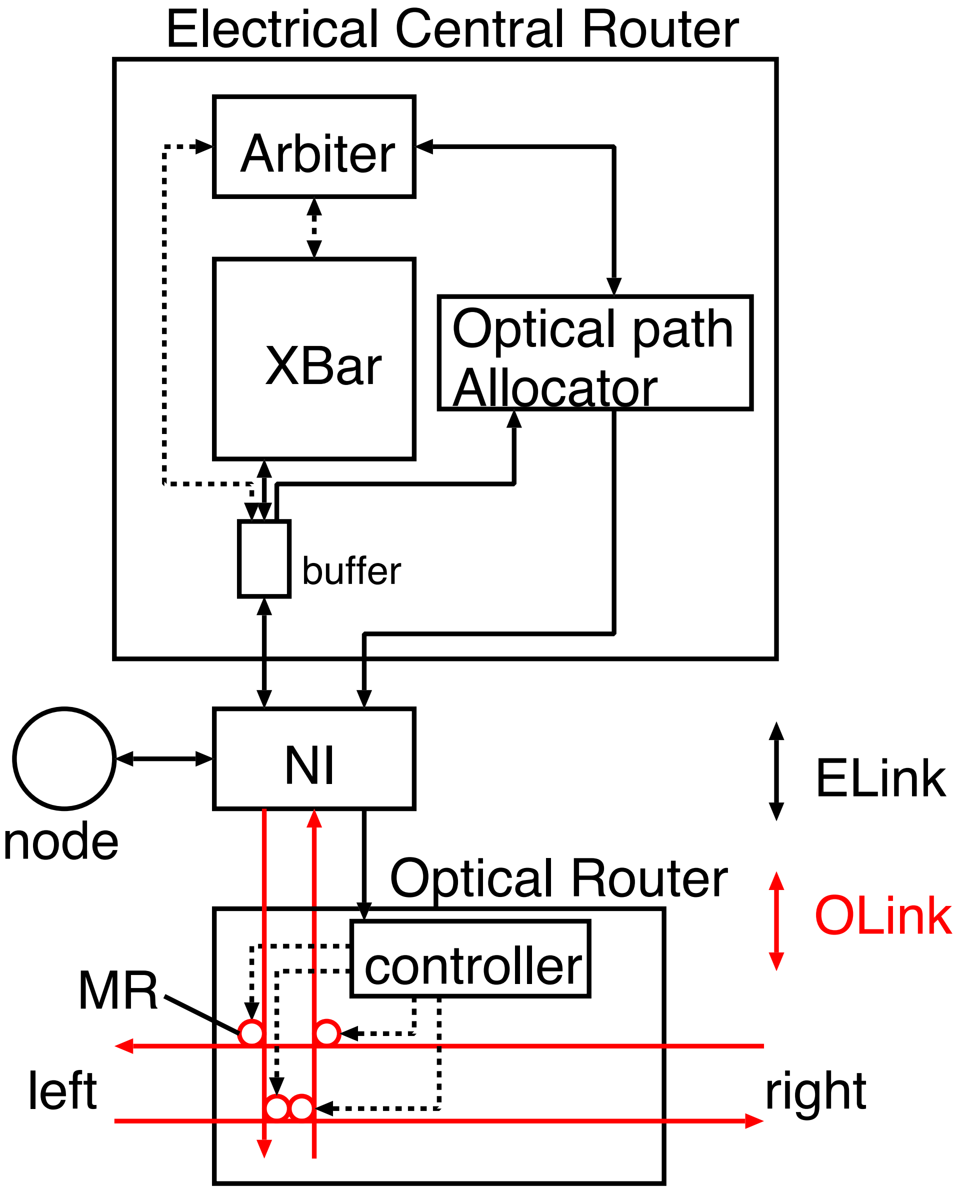


Figure 3.4: Connection between a node and routers.

4. After optical data transmission completed, a packet is sent from the source to the central router in order to release the optical path.

5. Finally, the central router sends release commands to both for source and destination nodes to release the optical path. The optical routers on both source and destination nodes switch “OFF” the related MRs.

3.2.3 Evaluation

Comparing to the torus HPNoC, OREX has advantages in reducing the scale of electrical network layer by using a single crossbar router. In addition, unlike packet switching in the electrical control network of torus HPNoC, OREX reduces path set-up latency and leads to outperform the torus HPNoC in terms of bandwidth at efficient power consumption cost. Although a size of required electrical control message is small, frequent path set-up processing in electrical control network layer however still causes considerable overhead for communication performance and power consumption. This is a motivation for us to consider a pure optical NoC. In Chapter 4, we’d like to introduce a fully photonic NoC.

Chapter 4

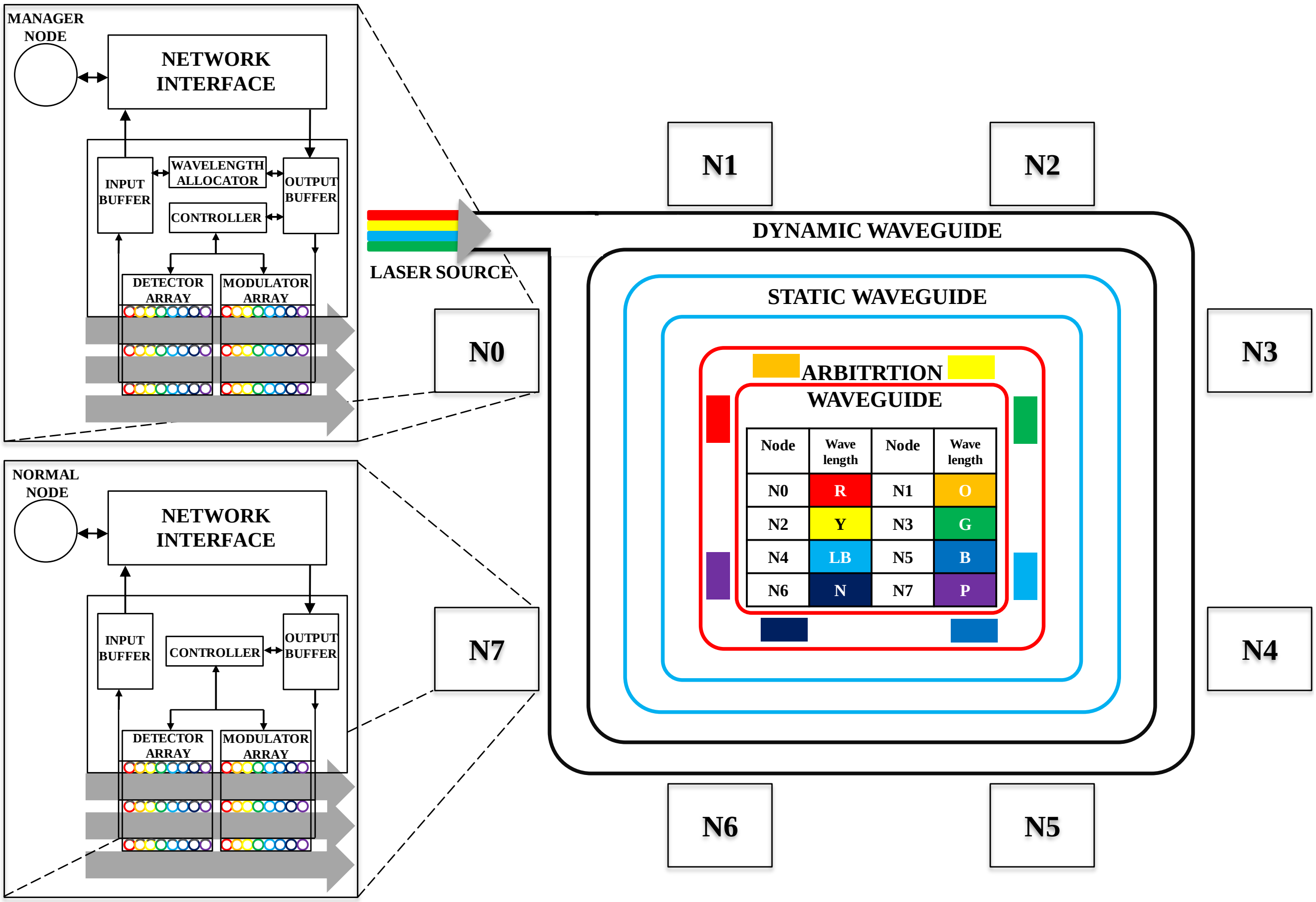
Fully Photonic Network-on-Chip

4.1 Proposed Architecture

Figure 4.1 shows our proposed token-based fully photonic NoC for a case to interconnect 8 nodes. It consists of three unidirectional waveguides to connect the nodes using a ring topology. The waveguides are used for static and dynamic communication, and arbitration, respectively. In the arbitration waveguide, in case of 8 nodes, we use 8 tokens, assigned to 8 different wavelengths. Each token represents the right to modulate on a specified wavelength for a particular node.

In the static communication waveguide, a total of 8 wavelengths are statically allocated to the 8 destination nodes. One specific optical channel organized by a single wavelength is used by each destination node to receive optical data from other nodes. At each destination node, a detector is switched "ON" to detect and receive optical data stream from the assigned optical channel.

The dynamic communication waveguide consists of multiple wavelengths which are shared by all nodes. Unlike the static waveguide, all or several wavelengths are allocated for a requested single source-destination communication pair by a manager node. The manager node is a special node, illustrated N0 in fig.1, which performs dynamic wavelength allocation.



Node	Wave length	Node	Wave length
N0	R	N1	O
N2	Y	N3	G
N4	LB	N5	B
N6	N	N7	P

Figure 4.1: Proposed Architecture

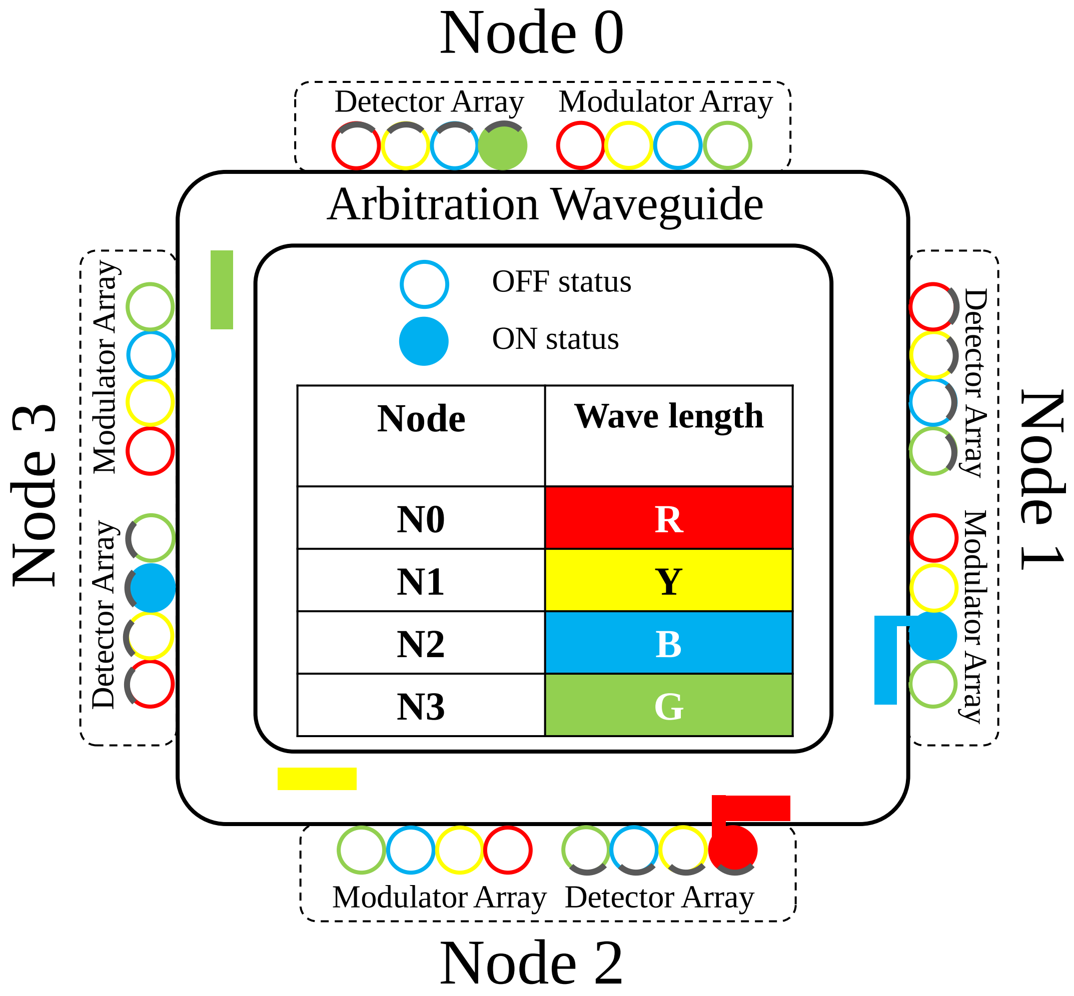
In fig 4.1, we also show the microarchitecture of the manager node N0 and a normal node N7, respectively. The normal node consists of input and output buffers, arrays of modulators and detectors, and a controller for them. The controller is a unique component that is used for switching the modulators and detectors to modulate/detect optical data stream into/from a waveguide. In additional to a normal node, the manager node contains a wavelength allocator.

Our proposal offers two types of communications: static and dynamic. Static communication is based on a token-based arbitration. The dynamic communication uses the manager node to allocate the wavelengths to a source-destination communication pair. While static communication offers a low overhead and low bandwidth communication, dynamic communication on the other hand offers high bandwidth at the cost of the arbitration overhead.

4.2 Token-based arbitration

Our proposed NoC requires a conflict resolution scheme to prevent two or more sources from simultaneously sending to the same destination. Token-based arbitration has been used in LAN systems. The function of the token is to grant the acquiring node the right to used the network. Token-based arbitration ensures a certain amount of fairness when the token circulates in a cyclic fashion between the nodes.

We utilize a distributed , all optical, token-based arbitration, referred to as corona [18], that available wavelength channels are fairly, statically allocated to each destination node to avoid the end-point contention. In our implementation, a token which consists of one-bit optical signal, represents the right to modulate on a specified wavelength channel for a particular node. Source node has to grab the token to gain the right of modulation on destination node's wavelength channel first. When a token is grabbed, the light is completely removed from the arbitration waveguide to ensure that other source nodes can not grab the token when the corresponding wavelength



Node	Wave length
N0	R
N1	Y
N2	B
N3	G

Figure 4.2: Token-based arbitration Example

channel is occupied. When the source node completes sending optical message on the specific channel, it releases the channel by switching "ON" its modulator and modulating one-bit token onto the arbitration waveguide. Each node has an array of fixed-wavelength detectors and fixed-wavelength modulators in order to grab/release any token from/onto arbitration waveguide.

Figure 4.2 demonstrates a example of token-based arbitration. The embedded table shows the wavelength channel-to-token mapping. 4 tokens, transit in clockwise, are used to arbitrate for 4 wavelength channels. Detectors are located behind the modulators to prevent from re-acquiring its self-released token. The green detector in Node 0 is switched "ON" and Node 0 is requesting for Node 3(green token), will begin modulate optical data on Node 3's wavelength channel(green) after the green token is grabbed. The blue modulator in Node 1 is switched "ON" and modulating blue token onto arbitration waveguide because Node 1 has just finished optical data transfer on Node 2's wavelength channel(blue). The red detector in Node 2 is switched "ON" and absorbing the red token, will soon begin transmit optical data on Node 0's wavelength channel(red). Node 3 is requesting the blue token which has just been released by Node 1.

4.3 Communication mechanism

4.3.1 Static communication

When a source node sends a message, electrical message data are firstly saved into the output buffer, then the controller reads out its destination address. According to the destination address, controller switches "ON" the specific detector to grab the destination node's token. After the token was grabbed from the arbitration waveguide, source node gains the right to modulate into the destination's wavelength channel for optical data transfer. Then, controller sets up the specific modulator and electrical data are modulated into optical data into destination node's channel. At the destination node, detector receives optical data and converts them into electrical data. Because a single wavelength is statically allocated to each destination node, static communication bandwidth is limited to that of a single wavelength.

Figure 4.3a shows the pipeline stages(time diagram) for the static communication. First, the controller reads destination address from a message header in the output buffer (RR). Next, a detector, associated to the wavelength for the destination node, is switched "ON" to grab a token which is circulating on the specified wavelength channel (TG). Note that TG requires multiple cycles according with the congested requests from multiple sources to send messages to the same destination. When the token is grabbed by the source node, its controller sets up related modulator(OS) to prepare for optical modulation. Electrical data are modulated into optical data(EO) and injected onto the static waveguide. Once modulation of optical data is finished, the grabbed token is released(TR) and the optical data are transferred in the statically assigned wavelength channel to the destination node (OT). At the destination node, detector receives optical data transferred on the static waveguide and converts them into electrical data(O/E).

4.3.2 Dynamic communication

In order to use the manager node to dynamically allocate wavelengths, source node sends a request message to the manager node through static communication. The manager node allocates wavelengths followed by sending simultaneously the setup messages to both source and destination nodes for the modulation and detection, respectively. Then, source node modulates optical data onto dynamic waveguide by using the allocated wavelengths. In opposite to static, dynamic communication provides a high bandwidth communication at the cost of arbitration overhead.

Figure 4.3b shows the pipeline stages for the dynamic communication.

In dynamic communication, a request message is sent to the manager node using static communication (Step 1).

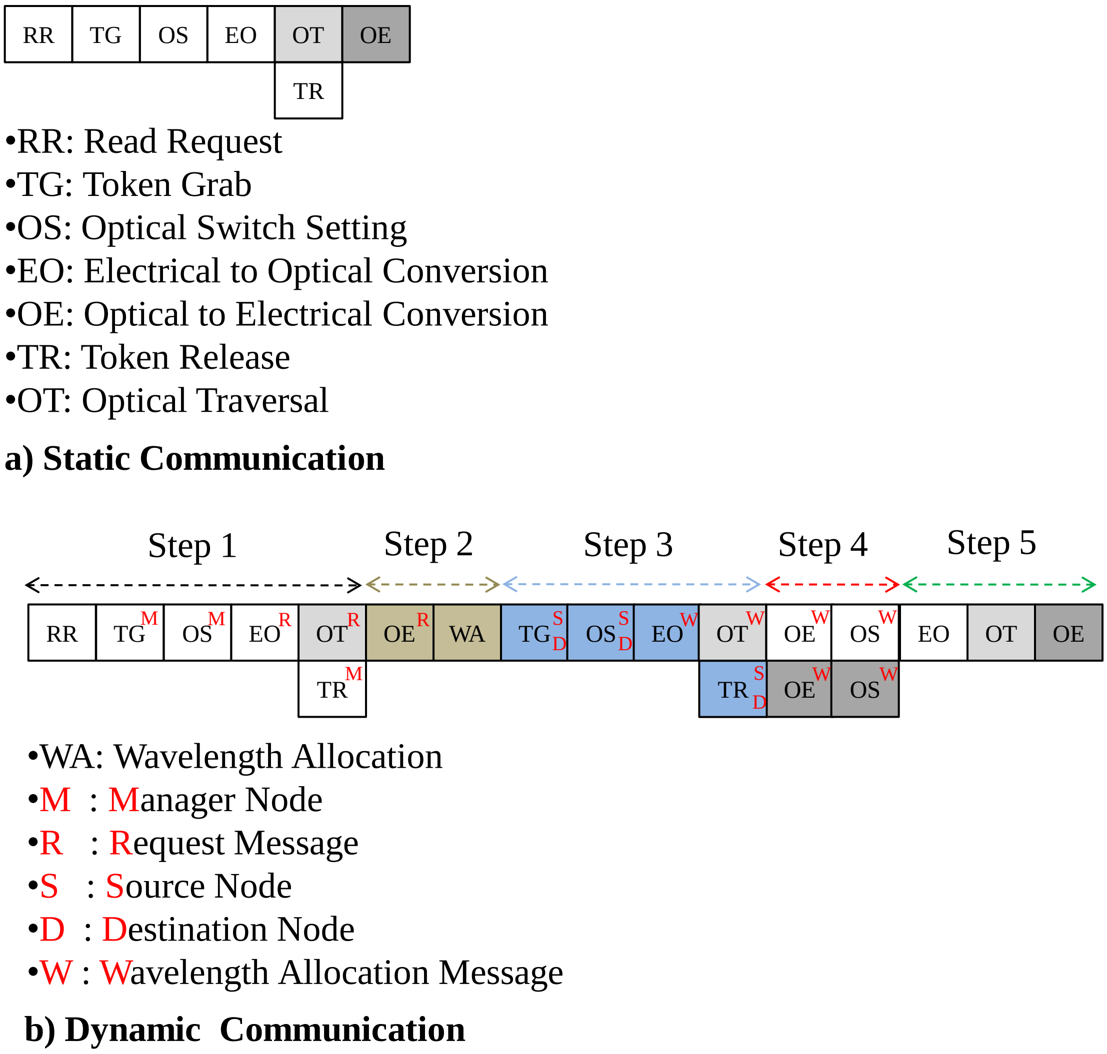


Figure 4.3: Time Diagram of Static(a) and Dynamic(b) Communications

The manager node allocates wavelengths(WA) for incoming request messages(Step 2).

In order to send the results of wavelength allocation to both source and destination nodes, the manager node grabs the tokens(TG) of both source and destination and sets up specific modulators(OS) to modulate wavelength allocation messages(EO) using static communication simultaneously(Step 3).

After both source and destination nodes receive wavelength allocation messages and convert them into electrical(OE), specific modulators are set up in the source node while specific detectors are switched "ON" in the destination node(OS)(Step 4).

Dynamic communication takes place(Step 5).

4.4 Combined communication mechanisms

Static communication has advantages in latency and bandwidth for applications whose message sizes are relatively small, while dynamic communication provides higher performance for large message sizes. To take full advantage of both static and dynamic communications, we combine them with two selection mechanisms: basic and smart ones.

4.4.1 Basic combined communication mechanism

Let's assume there are two different sizes of message: relative small and large sizes. Basically, our selection mechanism chooses the static communication when message size is small while selects the dynamic communication for messages of large size.

4.4.2 Smart selection mechanism

Because only one communication can take place in dynamic communication when all wavelengths are allocated to a single source-destination communication, many requests have to wait in the manger node for wavelengths resource under high network load. The performance of dynamic communication is suffered from the congestion. However, multiple communications can take place with their own single statically allocated wavelength in parallel by the static communication. There is a trade-off between quickly available low-bandwidth static communication and long arbitration delay for high-bandwidth dynamic one. In order to optimize the utilization of both static and dynamic communications, we introduce a smart selection mechanism that helps to choose static or dynamic communication under the congested situations. Manager node checks the number of waiting request messages to confirm dynamic communication is congested or not. The congestion status is defined based on the threshold number of waiting request messages in the manager node. The smart selection mechanism refuses overloaded requests and notifies the requestors to select static communication rather than waiting long time for the dynamic one. We can expect that this mechanism alleviates congestion in the dynamic communication and improve the performance.

4.5 Grouping mechanism

In the basic dynamic communication, we allocate all the wavelengths within a waveguide to a single source-destination pair. To reduce the congestion probability at high injection rate, we divide the available wavelengths to handle multiple communications in parallel. Although this mechanism reduces the communication bandwidth per message but obviously relieves the congestion.

Chapter 5

Performance Evaluation

In our experiments, we use a modified version of Phoenixsim, a simulation environment for the design, analysis, and optimization of high-performance interconnection networks in a manner that accurately captures the physical-layer aspects of the devices while enabling system performance evaluation [4].

5.1 Simulation Conditions

Table 5.1 summarizes the detailed simulation configurations.

Message size and traffic pattern:

In our experiments, we use two different message sizes. 20 and 400 Bytes are considered for small and large messages, respectively. In combined communication and grouping mechanisms, 20 Bytes and 400 Bytes messages are randomly generated in a uniform traffic pattern.

Table 5.1: Simulation Parameters

Parameter	**Setting**
Network Topology	Ring Architecture
Number of Nodes	64
Traffic Pattern	Uniform
Message Size	20 Bytes/400 Bytes
Number of wavelengths/ waveguide (static and dynamic)	64
Router Frequency	5GHz
Speed of Modulation/Detection	10Gbps
Utilized waveguides	Static only, dynamic only, and both

5.2 Experimental Results

5.2.1 Comparison between static and dynamic communications

Figure 5.1, 5.2, 5.3, and 5.4 show the latency and bandwidth performance of static and dynamic communications in different message sizes. The results confirms that in small message size(20 Bytes), static communication achieves higher performance in terms of latency and bandwidth than dynamic communication. However, when it comes to large message size(400 Bytes), dynamic communication outperforms static one by showing lower latency and higher bandwidth.

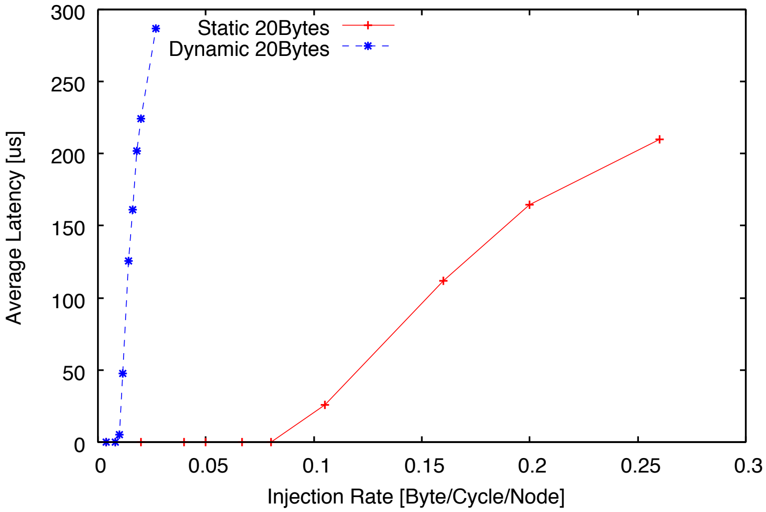


Figure 5.1: Latency Performance in 20 Bytes

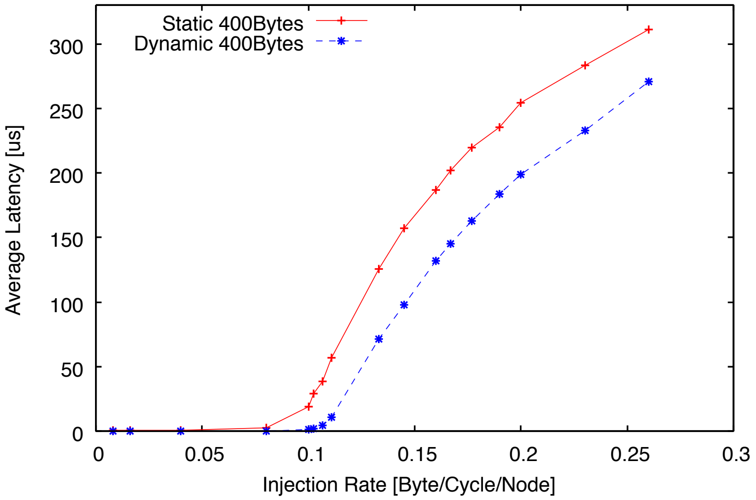


Figure 5.2: Latency Performance in 400 Bytes

5.2.2 Evaluation of basic combined communications and smart selection mechanism

Figure 5.5 and 5.6 show how the smart selection mechanism can improve the performance for a uniform traffic pattern.

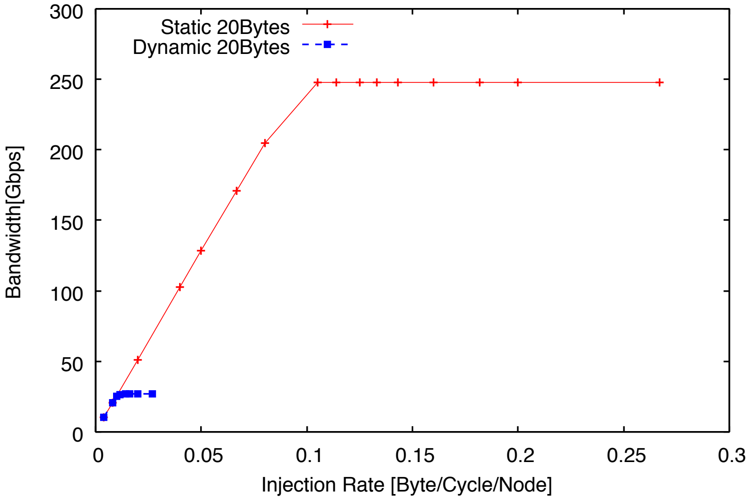


Figure 5.3: Bandwidth Performance in 20 Bytes

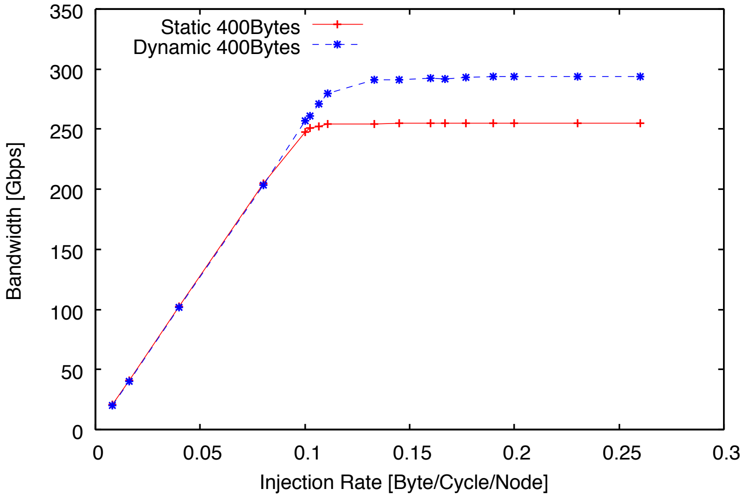


Figure 5.4: Bandwidth Performance in 400 Bytes

We find out that the threshold value is 26 in our experiment through many experimental results. Incoming request messages will be sent back and select static communication when the number of waiting requests increase to 26. It improves the utilization of static communication and reduces congestion of dynamic communication. Comparing with the basic combined communication mechanism, the smart selection

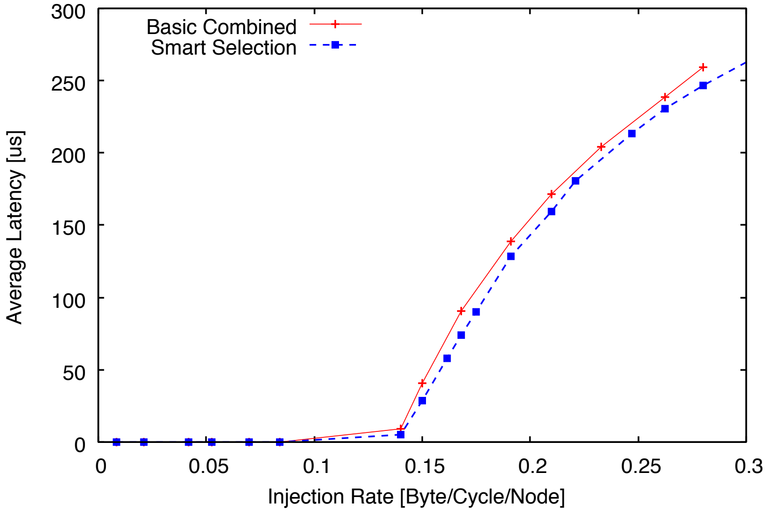


Figure 5.5: Latency with Smart Selection Mechanism

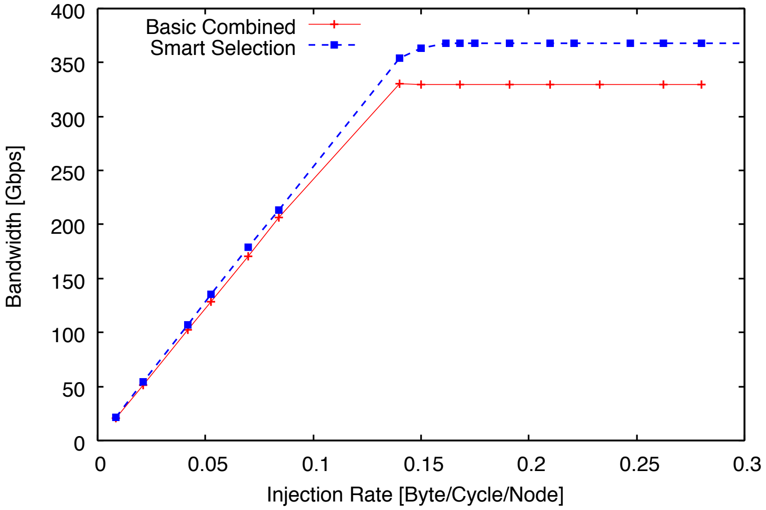


Figure 5.6: Bandwidth with Smart Selection Mechanism

mechanism increases bandwidth by an average of 11.5%.

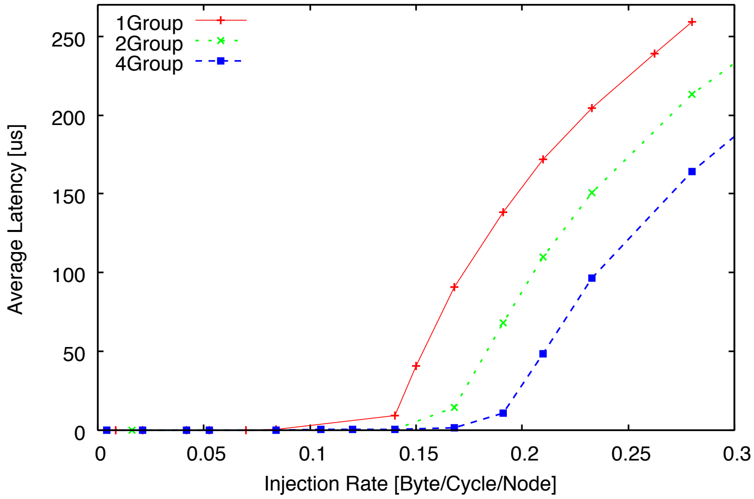


Figure 5.7: Latency with Multiple Groups of Data Stream

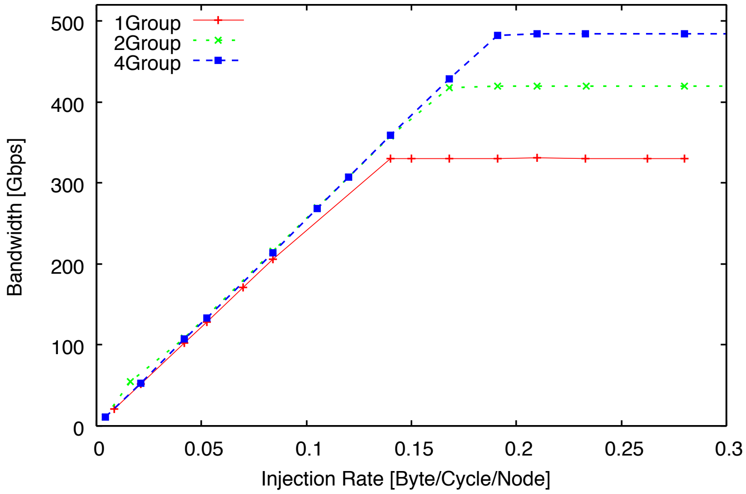


Figure 5.8: Bandwidth with Multiple Groups of Data Stream

5.2.3 Effect of grouping mechanism

In our experiments, wavelengths are divided into 2 and 4 groups to support multiple data streams in parallel for the dynamic communication. Figure 5.7 and 5.8 show the effect of the grouping mechanism. Comparing to a single case of basic combined communication, the grouping mechanism increases bandwidth by an average of 27.3% in 2 groups and 46.7% in 4 groups, respectively.

Chapter 6

Summary

Future many-core processors will require high-performance with efficient energy cost on-chip networks to provide a communication foundation for the increasing number of cores. To face these serious challenges, photonic technology presents enormous potential that overcome the limitation of electrical NoC. Recently, many state-of-art photonic NoCs improves the performance for CMPs communication by using hybrid or pure photonic architecture which fully takes advantages of optical interconnections.

6.1 Conclusion

In this paper, we proposed a token-based fully photonic NoC, which consists of three optical ring waveguides and optical routers. Our proposal was designed for a high bandwidth and low latency NoC by using token arbitration to utilize fully photonic NoC.

We evaluate the performance in terms of latency and bandwidth using two kinds of arbitration mechanisms, a smart selection and grouping mechanism, under a uniform traffic pattern. According to the experimental results, the smart selection mechanism improves 11.5% of bandwidth while grouping mechanism improves 27.3%(2 groups) and 46.7%(4 groups) of bandwidth comparing with the basic combined communication.

Therefore, the token-based fully phtonic NoC with these two mechanisms is considered a promising solution to improve the performance.

6.2 Future works

Our future work includes evaluating detailed performance, analyzing power consumption of our proposed NoC, developing a more accurate simulation environment for the future designs.

Our proposed fully photonic NoC can improve the performance with smart selection and grouping mechanisms. However, how to efficiently utilize static and dynamic communications is still a strict challenge for the future designs. In addition, we are interesting in more smart allocation for dynamic communication to reduce congestion and efficiently use wavelengths resources. Furthermore, we also identify several domains of new topologies, smart arbitration mechanisms and so on.

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