Low Latency and Energy Efficient Optical Network-on-Chip Using Wavelength Assignment

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***Abstract*— Optical network-on-chip (ONoC) is a promising technology for high-performance and energy-efficient intra-chip interconnection. Many existing proposals resort to high-density wavelength division multiplexing (WDM) to increase bandwidth and to mitigate contention. Unfortunately, high-density WDM increases the cost of optical devices and the difficulties of integration. We propose WANoC, a novel ONoC design with careful wavelength assignment aimed at more effective reuse. A novel WDM optical router is also designed with simple layout, which needs fewer waveguides and has fewer crossings. The simulation results show that the saturation load is improved more than 2.7 times, while the energy consumption is decreased by 33% compared with prior circuit-switched ONoC.**

***Index Terms*— Multiprocessor interconnection, optical router, wavelength assignment, wavelength division multiplexing (WDM) network.**

I. Introduction

RECENTLY, significant advancements in CMOS compatible silicon photonic technologies [1] have been proposed which makes optical interconnection on chip become feasible. As a novel interconnection, optical network-on-chip (ONoC) provides high transmission capacity, low power consumption and low latency, which makes ONoC a promising alternative to electrical on-chip interconnection.

Some ONoC proposals combine a high speed photonics circuit-switched network with an electronic packet-switched network [2], [3]. It has low link utilization and suffers from contention problems. Wavelength division multiplexing (WDM) can address these problems. Briere *et al.* [4] propose a contention-free ONoC, but its scalability is limited by the amount of wavelengths. Kirman and Martinez [5] propose an optically circuit-switched network, using a genetic algorithm to statically assign wavelengths to each communication pair in an N-node torus, such that at any point in time up to N distinct source-destination pairs can communicate simultaneously. The total number of the needed wavelengths is more than half of the nodes in the network. Morris and Kodi [6] propose a multi-level hybrid interconnect combining WDM, SDM and optical tokens to build a network for CMPs. The number of the used wavelengths equals the number of cores. Chan and Bergman [7] propose an efficient wavelength assignment method by dynamically checking the available wavelengths for the source and destination pair.

WANoC is proposed in this letter, which is designed with careful wavelength assignment based on the XY routing algorithm. A new non-blocking optical router is also designed for WANoC. By dynamically changing the wavelengths at the source node for different destination nodes, both the throughput and saturation load of the network are improved.

II. WANoC Architecture and Wavelength Assignment

Grid topologies, like mesh and torus, are usually employed in ONoC due to their regular shapes and good scalability. The XY routing algorithm is widely used for deadlock freedom and simple implementation. Some previous circuit-switched ONoC based on the mesh topology suffers from long latency and degraded throughput due to the high contention probability. For example, once the path from the source node to the destination node is reserved by a setup packet, this path will be exclusively occupied by this pair of nodes. As a result, other setup packets require any part of this path will be blocked, which leads to a high contention probability in circuit-switched ONoC. Even though WDM can alleviate contention probability, the router architecture is too complex to implement the function of multi-wavelength routing.

We propose a new wavelength assignment for the n × n mesh topology using the XY routing algorithm in order to address the serious contention and simplify the optical router architecture. In our wavelength assignment, each node is allocated a unique turning wavelength. To alleviate the contention in X-dimension and Y-dimension, all the nodes in the same row or column have different turning wavelengths. Packets with the same wavelength may turn at the same node in X-dimension, but no identical wavelength exists in Y-dimension. In this way, contention is limited in X-dimension, and only n wavelengths are needed for an n × n mesh network. [Fig. 1] illustrates an n × n WANoC, and the numerical value in each node represents the turning wavelength. The turning wavelength λ_i assigned to the node (x, y) can be calculated

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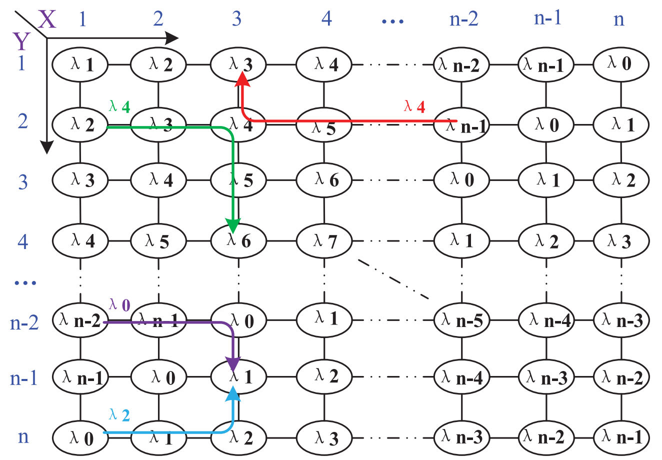

Fig. 1. $n \times n$ WANoC. The numerical value in each node presents the wavelength assignment result.

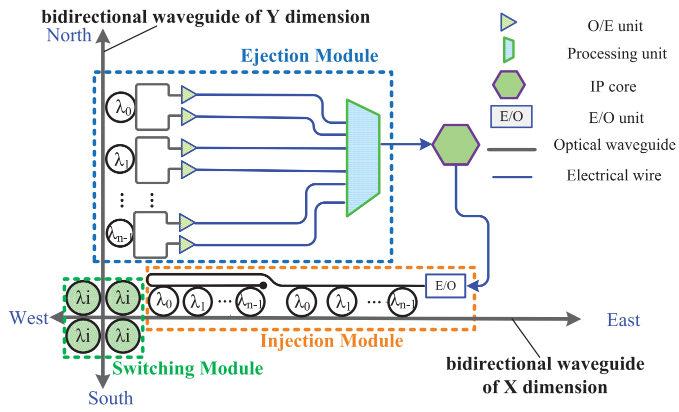

Fig. 2. 4×4 router. IP core is connected with optical router via E/O and O/E units. Processing unit deals with multiple electrical signals, arranges the right order for them, and makes them acceptable for the IP core.

by

$$i = (x + y - 1) \bmod \text{n}. \tag{1}$$

For example, when the node (n−2, 2) communicates with the node (3, 1), the packet will turn at the node (3, 2) according to the rule of XY routing algorithm. The turning wavelength of the node (3, 2) is λ_4. Consequently, this source-destination pair will communicate via the wavelength λ_4.

According to this wavelength assignment, we propose a new 4×4 non-blocking router architecture. The generic layout [Fig. 2] comprises the injection module, the switching module and the ejection module. The ejection and injection modules are comprised of cascaded microring resonators (MRs) for filtering out or coupling signals. In the switching module, the number of MRs is reduced to 4 and the turning wavelength λ_i is determined by the equation (1). The number of waveguides for packet transmission in each row and column is decreased to one. Each waveguide enables bidirectional communication, and packets with different wavelengths can be transmitted in parallel. According to the wavelength assignment, two packets will not turn at the same node simultaneously unless both of their input-ports and output-ports are different. All the packets transmitting in each vertical waveguide are of different wavelengths. Therefore, no overlap exists among the paths of packets with the same wavelength.

We modified the optical circuit switching mechanism to make the path reservation more effective. When the source node (x_S, y_S) plans to communicate with the destination node (x_D, y_D), a setup packet will be sent to the turn node (x_D, y_S) in the electrical control network. This packet just reserves the relative input and output ports of the turn node (x_D, y_S), instead of the whole path from the source node to the destination node. Once the input and output ports have been reserved successfully, the turn node will generate an ACK packet and a notification packet. The ACK packet will be sent back to the source node and the notification packet will be delivered to the destination node. The ACK packet informs the source node when to send the optical packet, while the notification packet notifies the destination node to get ready for receiving data. Data transmission then begins and optical packet follows the reserved path until it reaches the destination node.

When two or more setup packets target at the same turn node, contention will occur. Only one of the setup packets can reserve the related ports, and other setup packets will be stored in the queue of this turn node. When the required ports are released, the setup packets in the queue will be served in order. It is assumed that the uniform traffic is used and the transmitting delay is neglected. The blocking probability from the source to the destination is indicated by

$$P_{blocking} = 3/4 \left(1 - (n-1)^{n-1} / n^{n-1}\right). \tag{2}$$

As $n \to \infty$, $P_{blocking}$ approximates 0.47. However, when n exceeds 4, the blocking probability in [2] is close to 1.

III. Results and Discussion

We build a network simulator based on OPNET [8]. The performance of WANoC is simulated and compared against a mesh ONoC architecture like [2] referred as CONoC, which uses a unique wavelength. Simulations of WANoC and CONoC in both 36-core and 64-core situations are made under the uniform traffic pattern. 32 bits packets are used in electrical control network for path setup, while 1024 bits optical packets are used for data transmission. All packets are routed by using the XY routing algorithm. It is assumed that the transmission bandwidth of each wavelength is 12.5 Gbps, which can be achieved by the current nanophotonic devices [9].

The comparison of end-to-end (ETE) latency under uniform traffic pattern is shown in [Fig. 3(a)]. When the offered load is smaller than 0.15, little contention happens in both networks. However, the ETE latency of WANoC is smaller than that of CONoC. This is brought by the modified path reservation mechanism discussed in section II, which lowers the latency penalty of path reservation by half. As the offered load increases, CONoC becomes saturated soon. However, WANoC can maintain low latency until the offered load surpasses 0.6. WANoC improves the saturation load from 0.17 to 0.66 for 8×8 mesh and from 0.25 to 0.7 for 6×6 mesh respectively. With the scale increasing, the improvement gap becomes larger. The saturation throughput is improved 3.7 and 2.7 times

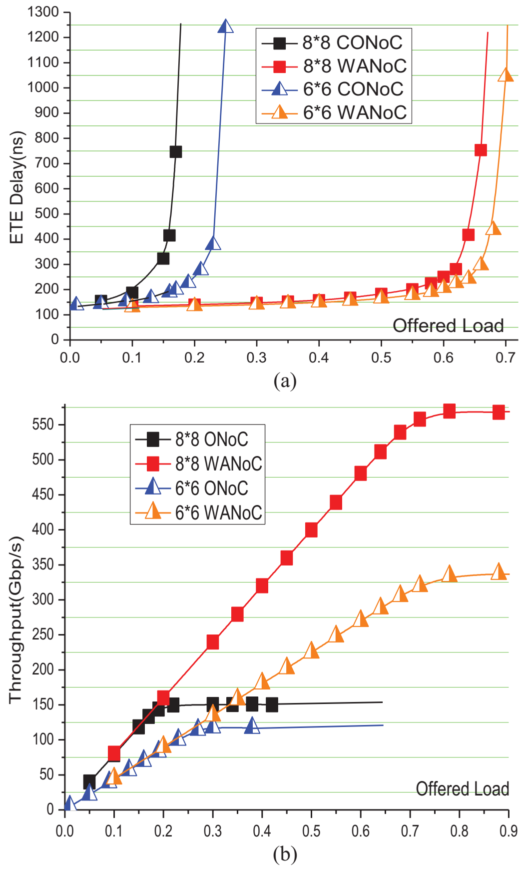

Fig. 3. Network performance of WANoC and CONoC using 1024-bit packets.

respectively as shown in [Fig. 3(b)]. The improvements are due to less contention in the network.

Energy consumption is a critical aspect of NoC design. For high-performance computing, low energy consumption can reduce the cost of packaging, cooling solution, and system integration. We calculate the total energy (E_{total}) spent on the electrical control network and optical network for transmitting each optical packet. It is determined by

$$\begin{aligned} E_{total} &= E_{control} + E_{DATA} \\ &= \left(E_{setup} + E_{ack} + E_{notf}\right) \\ &\quad + \left(E_{router} + E_{E/O} + E_{O/E}\right) \\ &= (hop_{setup} \cdot e_{setup} + hop_{ack} \cdot e_{ack} + hop_{notf} \cdot e_{notf}) \\ &\quad + \left(\sum t_{on} \cdot e_{ring} + E_{E/O} + E_{O/E}\right) \end{aligned} \tag{3}$$

where $E_{control}$ is the energy consumed by the setup, ACK and notification packets in electrical control network. We calculate $E_{control}$ by adding up energy consumed in each hop. Compared with CONoC, the total hops traversed by control packets are reduced by 25% in WANoC, which leads to an approximate 30% decrease in $E_{control}$. E_{DATA} is the energy consumed by optical network. The main part of E_{DATA} is consumed by altering the state of MRs, which depends on the number of active MRs and the duration that they are activated. In WANoC, the duration that MRs are in active state decreases because of the new path reservation method, and no more than 3 MRs along the path are needed to change their state. Both of them result in a significant reduction of E_{DATA}.

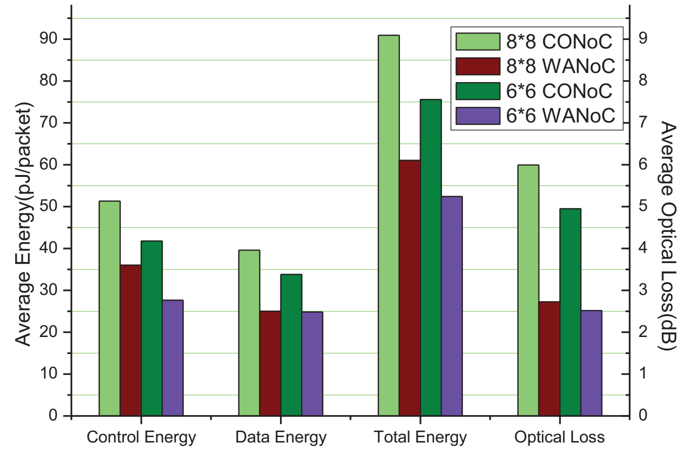

Fig. 4. Power consumption of WANoC and CONoC using 1024-bit packets under uniform traffic pattern.

As [Fig. 4] shows, WANoC decreases the E_{DATA} by 37.5% and the E_{global} by 33% for 8 × 8 mesh.

Light power from the light source must be large enough to ensure that the residual power at the destination node is above the sensitivity of the receiver circuit. The attenuation is dependent on the optical losses, such as waveguide propagation (IL_{travel}), waveguide bendings (IL_{bend}), crossings (IL_{cross}), off and on-resonance of passive or active MRs ($IL_{through}$ and IL_{drop}), modulators ($IL_{modulator}$), detectors ($IL_{detector}$), etc. The total loss is calculated as follows:

$$\begin{aligned} Loss = l_{link} \cdot IL_{travel} &+ \sum IL_{bend} + \sum IL_{cross} \\ &+ \sum IL_{through} + \sum IL_{drop} \\ &+ IL_{modulator} + IL_{detector}. \end{aligned} \tag{4}$$

In WANoC, waveguide crossings are decreased to one in each optical router, which substantially reduces the total optical loss and improves the SNR. The number of waveguide bendings and the active MRs decreases, which results in a great reduction in total IL_{bend} and IL_{drop}. However, $IL_{through}$ increases because signals need to go through more off-resonance MRs. [Fig. 4] indicates the optical loss decreases by 58% and 50% in 8 × 8 mesh and 6 × 6 mesh respectively.

In this letter, we have proposed a new wavelength assignment method for ONoC and a new architecture WANoC. By using the proposed wavelength assignment, an n × n mesh network can maintain efficient communication by reusing n wavelengths. The simulation results show that WANoC is a low-latency and high-throughput architecture. It addresses the serious contention in the circuit-switched mesh network. Moreover, it is power-efficient and reliable due to less optical loss.

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