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Mode-Division-Multiplexed Photonic Router for High Performance Network-on-Chip

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***Abstract*—The communication bandwidth and power consumption of network-on-chip (NoC) are going to meet their limits soon because of traditional metallic interconnects. Photonic NoC is emerging as a promising alternative to address these bottlenecks. Photonic routers and silicon-waveguides are used to realize switching and communication respectively. In this paper, we propose a non-blocking, low power, and high performance 5×5 photonic router design using silicon microring resonators(MRR). Mode-division-multiplexing (MDM) scheme has been incorporated along with wavelength-division-multiplexing (WDM) and time-division-multiplexing (TDM) in the router to increase the aggregate bandwidth $4\times$ times, making it a suitable candidate for high performance NoC. The technique proposed here is the first of its kind to the best of our knowledge. The MDM based design permits multi-modal (here 2 modes) communication. As compared to a high-performance 45nm electronic router, the proposed router consumes 95% less power. Further the results show 50% less power consumption and 75% less insertion loss when compared to most recently reported photonic router results.**

I. INTRODUCTION

Increasing density trend of chip-multiprocessors(CMP) requires higher bandwidth to support extensive communication among all cores. Semiconductor NoCs would not provide such a large bandwidth while maintaining an acceptable level of power consumption [1]. In order to address the growing communication requirements, alternative on-chip interconnect paradigms are required.

Recently, integrated photonic links are being adopted as reliable and attractive alternative to traditional metallic interconnects [2]. They hold promise to higher rate data transfer with minimal power dissipation [3]. Photonic links avoid capacitive, resistive and signal integrity constraints and allow efficient realization of physical connectivity. Also, *low loss in optical waveguides* [2] and *bit rate transparency* [4] are added advantages of photonic on-chip communication. All these support for a high performance, low power, and low cost photonic NoC. Optical interconnects and routers are the building blocks of photonic NoCs. A photonic router consists of high speed Microring Resonator(MRR) based switches and extremely low-latency optical waveguides to provide photonic NoC as an alternative to electrical NoCs.

Router is a critical component of NoC. Several MRR based optical routers have been proposed in the literature [5][6][18]. In [5], a low power, low cost, and non-blocking 5X5 optical router has been proposed using 16 MRRs. The design appears to be non-scalable due to significant power consumption with increase in network size. In [6], the authors have proposed a 4×4 hybrid, blocking router using 8 MRRs. This design is complex and the aggregate bandwidth is limited due to its blocking nature. The authors in [18] proposed a 4×4 λ-router using passive switching fabric with 30 MRRs incorporating Wave Division Multiplexing(WDM). Due to use of increasing number of waveguide crossings and MRRs, such a design results in higher insertion loss rendering it non-scalable. Therefore a high performance, low power, and low cost photonic router is highly desirable for scalable NoC. This paper presents a high peformance five-port photonic router by integrating Mode Division Multiplexing(MDM) scheme with WDM and TDM to design high-performance scalable NoC.

This paper has following contributions:-(1) A new 5×5 non-blocking photonic router design has been proposed by integrating *mode-wavelength-time* division multiplexing for high performance. The proposed approach is the first of its kind to the best of our knowledge. (2) A logical layout of the photonic router has been presented to achieve reduced power and area leading to scalable NoC architecture. (3) To demonstrate the proposed design, a detailed simulation platform was used to evaluate the proposed router micro-architecture. The results indicate an aggregate bandwidth of 40-Gbps which is 4 times higher than the recently reported results [3]. The proposed router consumes 95% less power than a high performance electronic router. It shows an power consumption of 2.4fW/bit per optical path and 0.38fW/bit per router which are 50% less than the recently reported results. The design has only a -2dB insertion loss for the longest optical path which is 75% less than the best available results.

The paper is organized as follows. In Section II background information on photonic network-on-chip is dscribed. Micro-architecture of the proposed photonic router is presented in Section III. Section IV presents the control mechanism adapted. Various Experiments and the results of proposed photonic router and a comparative analysis between the existing routers and the proposed photonic router are presented in Section V. We conclude the paper in Section VI with some directions for future research.

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II. PHOTONIC NETWORK-ON-CHIP

Several photonic network-on-chip architectures have been studied using topologies like mesh [3], torus [2], crossbar [8], and clos [9]. The communication techniques used in these photonic network architectures are typically (1) deterministic switching, and (2) dynamic switching. Wavelength selective passive networks utilize deterministic switching in which a fixed routing pattern is defined during the network design and the optical path between the source and destination is established by dynamically selecting a specific wavelength at the source or the destination [9]. Whereas optical networks using dynamic switching are circuit switching networks, where the routing pattern is dynamically set beforehand by an electronic controller [3][2]. It is reported in [8] that the former switching methodology exhibits low latency as the wavelength selecting time is much shorter than the network configuration time. On the contrary, circuit-switching offers higher aggregate bandwidth by adopting WDM technology. Also, circuit switching in optical domain is more compact and has better scalability [5].

Generally, CMP consists of 2D grid of homogenous IP cores [6][10]. Hence it's obvious that photonic NoC adopts regular 2D topologies like mesh and torus. For example a 16 core, 16 node $4{\times}4$ mesh NoC architecture as shown in Fig.1. A bidirectional link between two adjacent routers

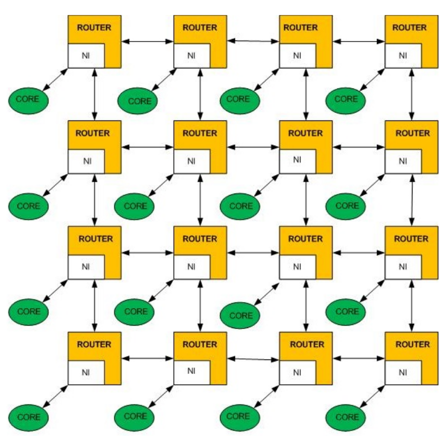


Fig. 1: Two Dimensional Photonic mesh network

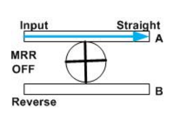
is a combination of two unidirectional waveguides because there's no practical silicon-photonic circulator [5]. The most fundamental component of an NoC is the router node. Each node is a $5{\times}5$ optical router with 5 I/O ports [Fig.1]. One of its ports is connected to local core through network interface (NI). Apart from the communication with local core, NI has an electronic controller that establishes the circuit switching through adaptive integration of MDM and WDM. This increases the aggregate bandwidth of the photonic network by manifolds. The architecture, working principles and results of router and NI are explained in detail in the following sections.

III. ROUTER ARCHITECTURE

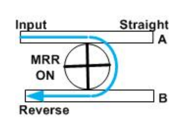
The proposed router is a fully non-blocking $5{\times}5$ photonic router for NoC design. The logical layout of MRRs of such a router is shown in Fig.3 which is adapted from [3]. Photonic router consists of a photonic switching fabric and a Network-interface (NI). A switching element in a fabric is composed of micro-ring resonators (MRR) and waveguides as shown in Fig.2. The switching fabric consists of a set of parallel and rectangular $1{\times}2$ switching elements unlike $2{\times}2$ conventional electrical switches where each $1{\times}2$ switching element serves the purpose of parallel or orthogonal routing using fewer MRRs. We introduce in brief the working principles of $1{\times}2$ switching elements before detailing router micro-architecture.

A. Basic $1{\times}2$ Switching Element using MRR

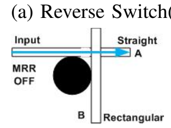
The basic switching element of a photonic router is a micro-ring resonator (MRR). A MRR is a circularly coiled waveguide which has the property of rotating the optical signal in the clock-wise direction. During 'OFF' state of MRR, optical signal with wavelength λ_{on} propagates from the input port to the straight port(refer: Fig.2a and Fig.2c). When turned 'ON' it couples the resonating optical signal (indicated by arrow) in waveguide A and transmits it by coupling it to waveguide B as shown in Fig.2b and Fig.2d. One can see that, in Fig.2d as the waveguide B is placed orthogonal to the waveguide A, the MRR helps in turning the optical signal in the rectangular direction. However it involves crossing of the two waveguides which may lead to loss due to cross-talk while passing multiple optical signals. It also results in higher insertion loss. To reverse the direction of propagation of the optical signal, one has to use combination of two rectangular switching circuits resulting in two waveguide crossing points. So, in order to decrease the number of crossing points of waveguides and usage of MRRs, a reverse parallel switching arrangement is made as shown in Fig.2b. In this arrangement when the MRR is 'ON', it helps in coupling the optical signal from waveguide A to waveguide B in reverse direction. This mechanism makes MRR an $1{\times}2$ switching element. With the help of these two types of switching arrangements, we were able to reduce the number of MRRs being used while reducing the no. of waveguide crossing points. In the proposed scheme,



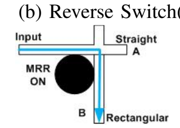
(a) Reverse Switch(OFF State)



(b) Reverse Switch(ON State)



(c) Rectangular Switch (OFF State)



(d) Rectangular Switch (ON State)

Fig. 2: MRR Switching

we have incorporated WDM. Hence optical signal of multiple wavelengths can be coupled together through MRR. This will enhance the overall bandwidth of the network communication. The fundamental difference between the two basic 1×2 switches is the position of the two waveguides. The reverse switching element does not have any waveguide crossing unlike the rectangular-switching element. The insertion loss per waveguide crossing is 0.12dB [11].

MRR needs a DC current to switch ON and it consumes power less than 20μW [11]. In the OFF state, there is negligible power consumption by the MRR [12]. The switching time of the MRR is very small and it is 10ps in our case.

B. Router layout

The 5X5 router layout which is adapted from [3], has been depicted in Fig.3. This uses suitable placement of 16 identical MRRs along with various waveguides.The router has five bi-directional ports, viz. East, West, North, South, and NI port. East, West, North, and South ports are connected with other routers to form a 2D NoC whereas the NI port is connected to the network interface. Each photonic router has a controller within NI for selecting wavelength and mode for optical signal transmission.The router can operate on multiple wavelengths simultaneously using WDM with wavelength spacing equal to the free spectrum range of the MRR. As shown in Fig.3, there are optical paths for each of the input-output combination. Complex routing in a 2D photonic layer is possible due

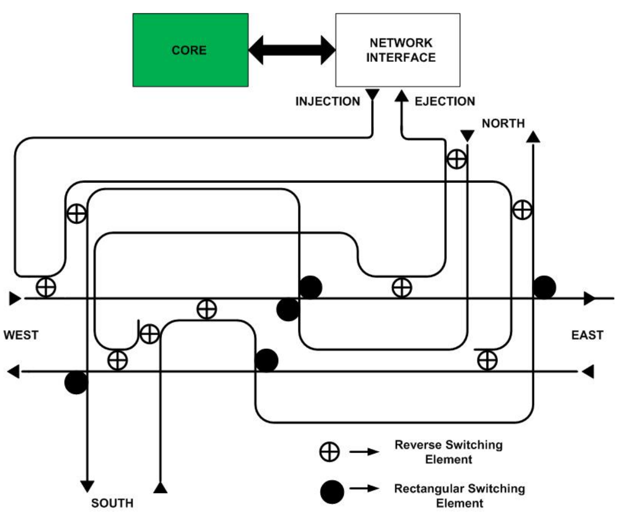


Fig. 3: Logical layout of MRRs in Photonic Router

to MRR based switches and waveguide crossings. However, waveguide crossing incurs optical insertion loss. Hence it's important to design an efficient layout of MRRs in a photonic router with least number of waveguide crossings. The proposed 5×5 non-blocking router consists of 14 waveguide crossings and 16 MRRs as in Fig.3 resulting in an optimized design. Apart from that, there are 2 more MRRs within network-interface to set-up MDM as discussed in section IV. Insertion loss and crosstalk limit the scalability of the photonic router [13][14]. Analytical results on number of MRRs and various performance parameters of photonic router are discussed in detail in the Section V.

IV. Control Mechanism

Use of WDM in photonic circuits offers limited performance gain because of its comaparatively higher power consumption [7]. MDM in conjuction with WDM and TDM can provide potential performance gains and higher aggregate bandwidth [7]. Use of MDM technology does not require increasing the number of waveguides which leads to fewer wave-guide crossings. It uses least area on chip and power. In this design the Network-interface [NI] is deployed with WDM compatible MDM technique which provides higher aggregate band-width.

The NI comprises of a WDM + MDM + TDM based electrical to optical(E/O) converter, an optical to electrical(O/E) converter and an electrical controller(Fig.4). The E/O converter includes the mode locked laser along with the MRR and waveguide arrangement facilitating (Fig.6) mode division multiplexing [7]. The electrical controller works on the basis of algorithm depicted in Algorithm 1.

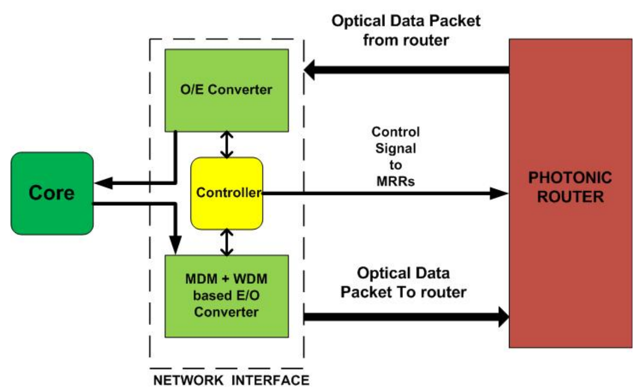


Fig. 4: MDM integrated Network-Interface

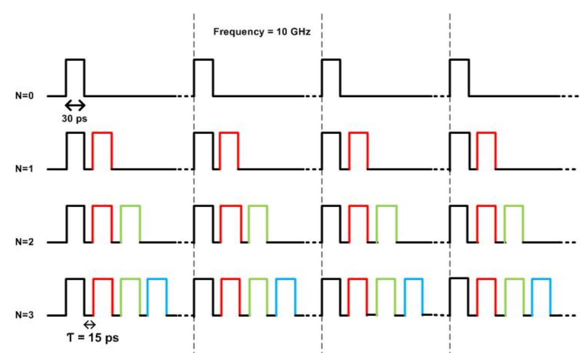


Fig. 5: Black pulse=TE_0 of λ_0, red pulse=TE_1 of λ_0, green pulse=TE_0 of λ_1, blue pulse=TE_1 of λ_1
Timing diagram of TDM integrated Mode-Division-Multiplexing

The algorithm controls the wavelength and mode selection mechanism during message passing as follows. When the

Algorithm 1 Controller Algorithm for adaptive mode division multiplexing

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procedure CORE1 WANTS TO SEND DATA TO CORE2
  N = no. of signals transmitting fully or partially along the path
  Control packet checks for the shortest availale path using electrical routing
  if (N=0) **then**
    Switch ON MRR_0 with λ_0
    Send signal from Mode-Locked Laser
  if (N=1) and (mode = TE_0) **then**
    Switch ON MRR_1 with λ_0
    Send signal from Mode-Locked Laser with a (τ+pulse-width) delay
  if (N=2) **then**
    Switch ON MRR_0 with λ_1
    Send signal from Mode-Locked Laser with a 2(τ+pulse-width) delay
  if (N=3) and (mode = TE_0) **then**
    Switch ON MRR_1 with λ_1
    Send signal from Mode-Locked Laser with a 3(τ+pulse-width) delay

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route to be followed is empty i.e it is not occupied by any other optical signal, the controller switches on MRR_0 which selects wavelength λ_0 and mode TE_0 transmitted by mode-locked laser for communication. When the route is occupied by certain mode of a specific wavelength then with the help of time-division-multiplexing a certain amount of time lag is incorporated while transmitting the next signal in a different mode so that it won't interfere in the transmission of the previous optical signal occupying the route. Fig.5 illustrates how signals of different modes are transmitted with a time lag as determined by the algorithm, hence facilitating *mode-wavelength-time* division multiplexing.

V. EXPERIMENTS AND RESULTS

IPKISS [15] platform has been used for the design and simulation of the photonic router. The tool allows the photonic component layout design, virtual fabrication of components in different technologies, physical simulation of components, and optical circuit design and simulation. We custom-designed some photonic components such as MRR, waveguide, mode-locked laser, tapered waveguide, and photodiode required for the router.

A. Microarchitecture Simulation on IPKISS

The design parameters adopted to carry out various experiments are depicted in TABLE I. The waveguide supports two optical modes TE_0 and TE_1 along with multiple wavelengths. The mode-locked laser produces hundreds of modes. But we're considering modes TE_0 and TE_1 as the proposed MDM scheme supports 2 modes (Fig.6). Using all these fundamental components, we built the router in IPKISS and performed the

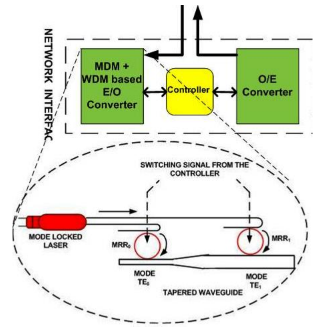


Fig. 6: Modelocked laser employing MDM

physical simulation.
A virtually fabricated layout of the router was done taking into

TABLE I: Design Parameters for Experimental Setup

Design Parameters	Value
MRR diameter	10μm
Waveguide(MRR) width	450nm
Waveguide(Signal Transmission) height	250nm
Waveguide(Signal Transmission) width	450nm
Refractive index Of waveguides	2.46
Pulse-width of Optical Signal	10ps
Frequency(mode-locked laser)	10GHz
Wavelength	1547.5nm and 1550nm

consideration the design rules. MRRs and waveguides were integrated to virtually fabricate the router. After fabrication, we carried out simulation using CAMFR [15]. It provides the refractive index profile and optical transmission profile of the fabricated design. Uniform refractive index across the router is a must for ripple free photonic transmission. After testing the uniformity of refractive index across the router, we simulated the router in CAPHE [15]. CAPHE is an optical circuit simulator for time-domain and frequency-domain analysis. It can be used to evaluate the insertion loss in an optical circuit. The insertion loss in the MRR is found to be 0.12dB. Each MRR can be tuned to multiple wavelengths. The proposed router takes into account wavelengths of 1547.5nm and 1550nm for MRR switching as these are the most suitable wavelengths(in terms of performance) for silicon photonic waveguides [16].

B. Comparitive Analysis

A comparative analysis of the proposed router with other photonic routers such as the λ-router, crossbar router, cygnus router [3], and the columbian router [17] was carried out. We analyzed important parameters of all these routers like the required number of MRRs, optical insertion losses, and power consumptions. We adopted the information on crossbar router from [3]. 2D topology based NoCs generally require 5×5 routers. But λ-router does not support odd number of input and output ports. Hence we have considered a 6×6 λ-router in which one pair of input output ports remain idle.

1) Number of MRRs: The number of MRRs utilized in a router microarchitecture determines the area overhead of the router. Reducing the number of MRRs will lower the chip size and also increase the yield. This will eventually reduce the chip cost. We compared the number of MRRs used to design each of the photonic routers. The proposed router uses 18 MRRs [16 for routing and 2 for MDM]. It is 40% lesser than the λ-router. Fig.7 represents the number of MRRs used in each of the routers. We have denoted router proposed in [5] as Ji-router for simplicity. The graph clearly shows that the proposed router outperforms all its counterpart except Ji-router in-terms of number of MRRs. Though Ji-router uses lesser number of MRRs, it is not scalable because of its higher insertion loss due to more no. of waveguide crossings.

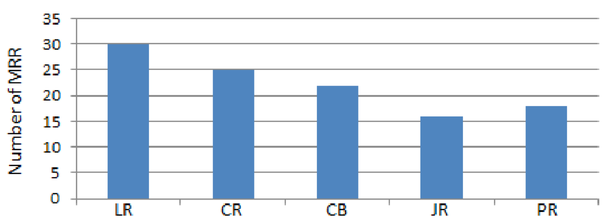


Fig. 7: Number of microring-resonator/router (LR=λ-Router CR=Columbian Router, CB=Crossbar Router, JR= Ji-router, PR=Proposed Router)

2) Power Consumption: The total power consumption in a photonic router is the sum of power consumed by the electrical controller and the power dissipated in the photonic switching fabric. The total power can be expressed as follows:

$$P_{router-total} = P_{controller} + P_{router-switching} \quad (1)$$

$$P_{controller} = P_{E/O} + P_{O/E} + P_{Laser} \quad (2)$$

$P_{E/O}$ and $P_{O/E}$ represents the power consumed by the electrical to optical and optical to electrical converter respectively. $P_{router-switching}$ represents the power dissipated in the photonic switching fabric.

TABLE II: Electrical controller power details

Design Parameters	Value
$P_{E/O}$	50 fW/bit
$P_{O/E}$	50 fW/bit
P_{Laser}	23 mW

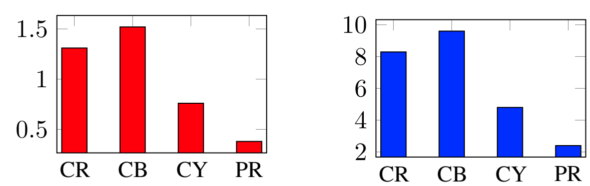
The other reported works on photonic router [3][5][17][18] lack details on electrical controller power. Hence we have compared only the power across the photonic switching fabric for a fair analysis. In the rest of the paper,P_{router} represents power consumed by the photonic switching fabric. We are not considering the λ-router in the power analysis due to lack of data provided in the literature.

We analyzed the three other routers as a part of 2D network and studied their impacts at network level. We analytically determined the power efficiency of the stated five photonic routers in a 4×4 2D mesh NoC using dimension order routing scheme. We evaluated the average power consumption per optical path in the network [P_{path}] and also the average power consumption per router [P_{router}]. We calculated P_{path} using equation(1). Here P_j represents the power consumed on j-th path when the bandwidth is 'B'. 'P' represents the total number of photonic paths in the NoC. P_{router} is calculated using equation(2) where 'R' is the average number of photonic routers in all the optical paths.

$$P_{path} = \frac{\sum_{j=1}^{P} P_j}{P \times B} \quad (3)$$

$$P_{router} = \frac{P_{path}}{R} \quad (4)$$

Network-level analysis shows that the proposed router consumes the lowest average power per optical path, 2.4fW/bit. It is 75% less than the crossbar router and 71% less than Columbian router. In the proposed router based network, average router power consumption is 0.38fW/bit, which is also 75% less than the crossbar router. These are shown in Fig.8. A deeper analysis shows that the maximum power consumption of the proposed router is also 2.4fW/bit irrespective of network size. That's because most of the packets need to turn on same number of MRRs to reach their destination. As compared to a high performance 45nm CMOS router as in [3], the proposed router consumes 95% less power.



(a) (b)

Fig. 8: (CR=Columbian Router, CB=Crossbar Router, CY=Cygnus Router, PR=Proposed Router)
(a) Average Power Consumption per router in fW/bit
(b) Average Power Consumption per optical path of 4×4 photonic mesh in fW/bit

The maximum power consumption of the proposed router based network is constant while using dimension order routing, regardless of the network size. The placement of the MRRs in the router takes care of the fact that no MRR is turned ON to

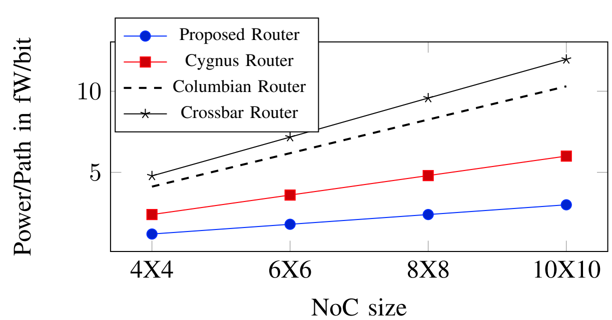


Fig. 9: Average Power/Path in fW/bit for different NoC sizes

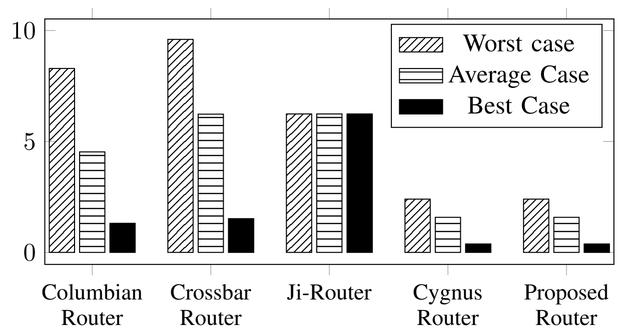


Fig. 10: Insertion loss per router in dB

transmit a message along a straight line. The router needs to switch on one MRR when a message enters the network from the NI, turns from a row to a column (and vice-versa), or exits the network to the NI. In the worst case, three MRRs need to be powered on to route a message in a network irrespective of the network size. This makes the proposed router highly scalable without worrying about the power consumption in additional routers on a longer path. Fig.9 presents the average power consumption per optical path in NoC of different sizes.

3) Optical Insertion loss: Insertion loss is the loss of signal power wherever there is a waveguide crossing or bending. Insertion loss of a router determines its feasibility and also the power required by the NI to transmit, and receive optical singals. There are two major sources of insertion loss in the proposed router, the waveguide-crossings and the MRRs. Insertion loss for one MRR is 0.5dB. A single waveguide crossing introduces an insertion loss of 0.12dB.

Insertion loss varies across input output pairs in a router. Hence we evaluated the best-case, average-case, and the worst-case insertion losses in all the routers. The result is shown in Fig. 10. It is clear from the figure that the proposed router has lowest insertion loss for all the cases. Compared to crossbar router, the proposed router has 65% lesser best-case loss, 45% lesser average-case loss, and 30% lesser worst-case loss. Similarly it outplays the other routers for all the three cases.

VI. Conclusion

In this paper we proposed a scalable, low-power WDM-compatible mode division multiplexed high performance MRR based photonic router showing significant improvement over earlier proposed photonic routers. We introduced the concept of using WDM+TDM compatible mode division multiplexing with the help of a mode-locked laser and associated circuitry. We demonstrated that the proposed router gives a $4\times$ increase in bandwidth and a 50% percent decrease in power consumption over the nearest competitive photonic router so far proposed. The router has 75% less insertion loss as compared to the most recently proposed router.The proposed router also out-performed a high performance 45 nm PTM based electronic router by 95% in terms of power.

As for the future work, an adaptive routing algorithm needs to be proposed to incorporate the proposed router in different NoC topologies and traffic patterns . Using one laser per router is expensive. Research will be carried out to reduce the number of on-chip lasers in a NoC. MRR properties vary with temperature which affects the overall performance of photonic router. Research will be carried out to design temperature aware photonic router.

VII. Acknowledgement

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