DORR: A DOR-Based Non-Blocking Optical Router for 3D Photonic Network-on-Chips

Mead FADHEL(a), Nonmember, Huaxi GU(b), Member, and Wenting WEI(c), Nonmember

SUMMARY Recently, researchers paid more attention on designing optical routers, since they are essential building blocks of all photonic interconnection architectures. Thus, improving them could lead to a spontaneous improvement in the overall performance of the network. Optical routers suffer from the dilemma of increased insertion loss and crosstalk, which upraises the power consumed as the network scales. In this paper, we propose a new $7 \times 7$ non-blocking optical router based on the Dimension Order Routing (DOR) algorithm. Moreover, we develop a method that can ensure the least number of MicroRing Resonators (MRRs) in an optical router. Therefore, by reducing these optical devices, the optical router proposed can decrease the crosstalk and insertion loss of the network. This optical router is evaluated and compared to Ye’s router and the optimized crossbar for 3D Mesh network that uses XYZ routing algorithm. Unlike many other proposed routers, this paper evaluates optical routers not only from router level prospective yet also consider the overall network level condition. The appraisals show that our optical router can reduce the worst-case network insertion loss by almost 8.7%, 46.39%, 39.3%, and 41.4% compared to Ye’s router, optimized crossbar, optimized universal OR, and Optimized VOTEX, respectively. Moreover, it decreases the Optical Signal-to-Noise Ratio (OSNR) worst-case by almost 27.92%, 88%, 77%, and 69.6% compared to Ye’s router, optimized crossbar, optimized universal OR, and Optimized VOTEX, respectively. It also reduces the power consumption by 3.22%, 23.99%, 19.12%, and 20.18% compared to Ye’s router, optimized crossbar, optimized universal OR, and Optimized VOTEX, respectively.

key words: network-on-chips, optical routers, non-blocking routers, interconnections, photonic routers, ONoCs

1. Introduction

The advantages of Integrated Circuits (ICs) technology has been manifested in the concept of Network-on-Chips (NoCs), since it can compact several billion transistors and other electronic components in a very small area. Furthermore, as this technology advances the area on the chip can be even smaller and smaller [1]. For a long time, Network-on-Chips (NoCs) played a significant role in the intra-chip multiprocessor-core interconnection. However, as the required size and performance of these interconnections continuously increase, it becomes increasingly difficult to maintain a network that can both accommodate the communication demands and stay within the power dissipation limits of the system package [2]. Therefore, it is expected that the dissipated power of the Electronic Network-on-Chips (ENoCs) will grow with time and will become the limiting factor in performance scaling.

To solve the aforementioned problems Optical Network-on-Chips (ONoCs) was proposed in 1984. ONoCs have higher bandwidth and bandwidth density, less delay, less crosstalk, lower power consumption, electromagnetic interference, and so many other advantages compared to the traditional ENoCs [3], [4]. Thus, many researches have been done on it to improve its performance such as the data exchanging device in [5]. Moreover, a survey on multicast interconnections in ONoC has been demonstrated in [6].

All types of on-chip interconnections consist of significant building blocks, such as topologies and routers. Many topologies have been proposed in the past few years, such as mesh, c-mesh, torus [7], fat tree [8] and many others [9]. Nevertheless, the master component of ONoC interconnections is Optical Routers (ORs). Routers help to send and route packets to the direction of their destinations. Many optical routers have been reported since the appearance of ONoCs, such as the routers in [10]. However, most of these ORs cannot ensure the least number of optical devices.

Therefore, we propose a new $7 \times 7$ non-blocking optical router based on the DOR algorithm. Moreover, we develop a method that can provide the least number of MRRs in an optical router and reduces optical devices accordingly. According to this method, our router enjoys the least number of optical devices possible in a $7 \times 7$ DOR-based OR, such as MRRs, waveguides, and Optical Terminators (OT). Therefore, by reducing these optical devices, our OR can decrease the crosstalk and insertion loss of the network. Furthermore, the power consumption is drastically reduced as the network scales. This reduces the cost and improves the performance of the network.

This paper is presenting some of the main related work and goals of this research in Sect. 2. Section 3 illustrates the proposed $7 \times 7$ optical router architecture and its properties. Furthermore, it introduces a least number of MRRs theorem for two types of ORs. Section 4 evaluates the proposed optical router compared to two other $7 \times 7$ optical routers for a 3D mesh. It analyzes the insertion loss crosstalk noise, and power consumption of all routers in two different levels, which are the router level and the network level. Section 5 concludes this paper.
2. Related Work

Since ONoC is providing an ultra-high bandwidth along with low power consumption, researchers have paid a significant attention on ONoC designs and architectures in the past few years. Hybrid network architectures that can join the ENoCs and ONoCs were proposed to combine the best features of each scheme while limiting their drawbacks [11]. One of the main building blocks considered to improve the performance of the ONoC is the optical router used in the network. Some ORs were designed based on Mach-Zehnder interferometer [10], some were designed based on hybrid photonic-plasmonic switch (HPPS) [13], and some were designed based on MicroRing Resonators (MRRs) [14], [15]. MRR-based routers are more flexible and widely used. Thus, several ORs were proposed in 2D mesh [16]. Cygnus [17], for example, is a low-power non-blocking 5×5 OR, which uses 16 MRRs to switch signals from and to 5 different ports. Crux [16] is a more compact 5×5 non-blocking OR. It enjoys the passive routing feature as well. However, Crux is designed based on XY routing to reduce the number of MRRs used.

When it comes to ONoCs, scalability and area are always significant matters to consider while designing the network. Accordingly, 3D technology was introduced to solve these issues. Thus, researchers tend to combine the benefits of ONoC technology with the 3D integration technology to improve the interconnection density and power efficiency, and shorten distances between nodes [18]. Min et al. [14] proposed a universal method to construct N-port non-blocking optical routers based on MRRs. Therefore, this non-blocking OR can be scaled easily. Similarly, Zhu et al. [19] proposes a 7×7 OR for 3D networks. However, for DOR networks, these ORs utilize unnecessary MRRs and experience extra waveguide crossings. Thus, they increase the area, and power consumed, as well as decrease the performance of the network. Guo et al. [20] proposes a 3D mesh-based topology with a 6×6 non-blocking OR. However, to realize the vertical switching function, they added 3×3 ORs in the middle layers, which increases the number of MRRs again and thus increase the insertion loss and crosstalk. Ye et al. [21] proposed a 7×7 OR for DOR networks. In [22], Gu et al. optimized a partial crossbar to eliminate the dispensable MRRs in mesh topology using DOR. To improve the results achieved by the last two aforemen-

tioned ORs, we are proposing a new DOR-based OR that decreases the number of MRRs and waveguide crossings experienced by the optical signal. Thus, reducing the power consumption, insertion loss, crosstalk, and area. This router is designed to fully utilize the properties of XYZ routing in 3D DOR networks, such as mesh and torus.

3. Architecture Overview

3.1 Photonic Devices

Photonic devices are an indispensable component used to construct or design an optical router, such as waveguides, MRRs, optical terminators (OTs), and basic switching elements (BSEs). BSEs are composed of two waveguides and one or two MRRs. Moreover, it can be a crossing switching element (CSE) or a parallel switching element (PSE). In PSEs, the MRR is positioned between two paralleled waveguides as shown in Fig. 1 (b). CSE has two types: 1×2 CSE, in which one MRR is positioned at the intersection of two waveguides, and 2×2 CSE, in which two MRRs are positioned at the intersection of two waveguides as shown in Fig. 1 (d) and (a), respectively. BSEs have two states depending on the MRR’s frequency. If it is the same as the signal’s, the MRR will be on and will switch the passing signal to the other directly connected waveguide. Otherwise, the signal will pass the MRR without getting switched. Figure 1 (c) and (e) exemplify the on state and Fig. 1 (b) and (d) exemplify the off state of both PSE and CSE. Finally, optical terminators are optical devices used to prevent the light reflection that is presented at opened end systems. Thus, it terminates the unused or unwanted reflections so that it will not be introduced back to the system.

3.2 3D Interconnections

In spite of the wonders that 2D integration technology has introduced to on-chip interconnections, it still suffers from some dilemmas for instance: End-to-End delay (ETE delay), power consumption, bandwidth, and limited scalability. Accordingly, 3D integrations came to overcome these limitations and become a very hot topic nowadays.

In this paper, we used Through Silicon Vias (TSVs)
to interconnect different layers as shown in Fig. 2. Furthermore, by using TSVs for vertical communications the length of wires will be reduced, thus offers higher density of packing, smaller area, and shorter transmission distance [23], [24].

3.3 DORR Architecture

The optical router proposed in this paper is a 7 × 7 Dimension Order Routing-based optical Router (7 × 7 DORR).

It is a Dimension Order Routing (DOR) router that follows the XYZ routing algorithm. This means that inputs of higher order ports can connect to more output ports than lower order ports (because lower order ports cannot inject signals to higher order ports). For instance in this router, the X dimension has the higher order (which can connect to all other ports), then the Y dimension (which can only connect to same order or lower order ports, i.e. Z dimension outputs), then finally the Z dimension (which can only connect to the output of the opposite direction and the Ejection port). The design comprises seven ports, which has 2 pairs each of an input as well as output, i.e. there are seven inputs and outputs in the router. This design simultaneously enables two-way communications among six orthogonal directions and local Intellectual Property (IP). This router is designed to suit any network that needs 7 ports and uses DOR, here we consider 3D mesh that uses XYZ routing mechanism.

Figure 3 (a) shows the layout of the 7 × 7 optical router. It has seven bidirectional ports, which are East, West, North, South, Up, Down, and Injection/Ejection port. Each port is aligned to its intended direction. Moreover, inputs and outputs of each port are aligned properly to make sure that all the waveguide crossings are considered when analyzing the router connected to 3D mesh. Optical signals are passively routed when traveling in the same direction except those from the input of the Down port to the output of the Up port.

This router has 22 MRRs, which, to the best of our knowledge, is the least number of MRRs for a DoR 7 × 7 optical router that uses single wavelength along the network. Those MRRs will allow seven concurrent transactions if there is no contention for the same output port. Since the injection and ejection ports cannot be connected directly, this router connects the injection port with the output of Up port and the ejection port with the input of the Down port. This helps to reduce the number of waveguides used. Thus, DORR reduces the waveguides used, into 7 waveguides for all the 7 ports, which is the least number of waveguides for a 7-port router. It also uses no optical terminators. Moreover, for each optical link, only one MRR is resonant at most. Finally, the internal structure of this optical router is designed to minimize waveguide crossings. All of the above helps to reduce the insertion loss, crosstalk, power dissipation, and cost of the network.

3.4 Non-Blocking Property

Some signals can block others when propagating at the same time (i.e. when two or more optical signals with the same wavelength are propagating in the same waveguide, yet they need to go to different destinations). In this case blocking occurs.

To avoid this blocking the following properties should be considered while designing an optical router:

1. Any optical signal injected into any input port should be guided to the proper output port without being misdirected or distracted by the other MRRs on the same physical link.
2. No U-turns available (i.e. no optical signal can be guided to the output of the same port of its input).
3. Between any input and any output, the physical link would never block the possible communications between any other possible links among the remaining inputs and outputs.

Any add point must be always located behind any drop point: Drop points are the points at which the MRRs download the light injected into the input port of the bus waveguide to other waveguides. On the other hand, Add points are the points at which the MRRs upload light from other waveguides to the bus waveguide. It is worth mentioning here that any MRR coupled with a waveguide crossing is a drop point to one waveguide of the crossing, while it is an add point to the other waveguide of the crossing. Hence, the connection between an add point and a drop point is actually a waveguide crossing and an MRR.

DORR satisfies all the conditions and rules mentioned above to make sure all signals can be transmitted from one
port to the other without blocking each other. However, not all the inputs of this router have to connect to all the outputs of other ports, since this router is a DOR router. It also does not implement the U-turn function and all add points are located behind drop points to avoid the blocking.

3.5 Communication Mechanism in DORR

In this subsection we further illustrate the functionality of transmitting data within our optical router. As mentioned before, DORR reduces the waveguides and terminators, thus reduces the number of MRRs. Moreover, it reduces the number of port-to-port communications that need to turn on MRRs.

Figure 4 shows an example of transmitting signals from Down port to Ejection port using 2 existing optical routers and our proposed optical router. As depicted in Fig. 4 (a), when transmitted in DORR, the signal is propagating without any necessity to turn on any MRR or to be switched by any kind of devices, instead it travels causing less insertion loss which is $-0.46$ dB (using the parameters in Table 2 in the next section). On the other hand, the signal, in both other optical routers, has to pass one ON MRR in order to be switched into its desired output port. Although the signal transmitted using Ye’s OR in Fig. 4 (b) has to pass only one ON MRR, it still has more insertion loss of $-0.5$ dB. Similarly, the signal transmitted using the optimized crossbar in Fig. 4 (c) has to pass one ON MRR, one OFF MRR and 3 waveguide crossings; however, suffers from $-0.63$ dB insertion loss. Thus, by reducing these waveguides and connecting ports directly we can guarantee that all ports can communicate with at least one other port directly without costing more energy to turn on MRRs and increase the thermal state of the network.

3.6 Formal Proof of the Least Number of MRRs

As mentioned earlier DORR implements the least number of MRRs for a DOR-based optical router that uses only one wavelength to transmit data. To prove that we present the following two theorems for a fully connected optical router and a DOR-based one.

**Theorem 1:** (for fully connected optical routers)

For every $n \times n$ non-blocking fully connected optical router, which uses a single wavelength, the least number of MRRs is given by:

$$MR_{\text{least}} = \begin{cases} n(n-2) - \left\lceil \frac{n}{2} \right\rceil & n > 3 \\ n(n-2) & n \leq 3 \end{cases}$$

(1)

Where $n$ is the number of ports in the router.

**Proof:**

Fully connected optical routers are routers in which all inputs can communicate with all other output ports. The proof of this theorem will be separated as follows:

1- Since common waveguides have two edges only, each input port can communicate with at most one output port directly without turning any MRR. Moreover, U-turns are prohibited as mentioned earlier. Thus, two output ports are excluded, and each input port needs $n - 2$ MRRs to communicate with the rest of output ports. Therefore, the total number of MRRs used by $n$ ports will be $n(n-2)$.

2- This number can, still, be reduced by reusing some MRRs for some communication paths. However, we do not want to influence the non-blocking property of the optical router. Since we mentioned earlier that in order to ensure the non-blocking property of a router all add points should be located before drop points in a waveguide, thus we only reuse and share the last add point in the first waveguide with the first drop point of the second waveguide (as will be further illustrated in the Example beneath). In other words, every two waveguides would share only one MRR to realize communications from/to the other waveguide. As a result, one MRR will be excluded from every two waveguides as illustrated in the second term of Eq. (1).

3- The MRR sharing method mentioned in 2, can only be used, when four ports are directly connected to each other. Thus, this method cannot be useful for three ports routers or less. Therefore, the second term of the equation is omitted for routers with 3 ports or less.

**Theorem 2:** (for DOR-based optical routers)

For every $n \times n$ non-blocking DOR-based optical router, which uses a single wavelength, the least number of MRRs is given by:
Proof:
As illustrated previously in this paper, DOR-based optical routers are routers in which inputs with higher order can inject signals to the same or lower order ports. Thus, we are proving this theorem as follows:

1- For DOR-based optical routers, every two ports, which occupies the two opposite directions/axes, are from the same order, except for the IP port, which is always considered with the first order category. Furthermore, like the first part of the previous proof, the first order ports have \(3(n - 2)\) MRRs, where \(3\) is the number of ports enjoying the first order priority including the IP.

2- For the remaining ports, the number of MRRs is calculated by \(\sum_{i=2}^{W} 2[n - (i \times 2)]\), where every two ports of the same order will have the same number of MRRs.

3- Unlike fully connected optical routers, the MRRs in DOR-based optical routers cannot be reduced by reusing one MRR for every two waveguides. This can be explained by the fact that ports in DOR-based routers do not transmit packets equally, instead there are restrictions, i.e. only the two ports of the same order share the same connections with each other. However, they do not need to send back to themselves. Except for the three ports of the first order, which are two ports from the opposite direction and the IP port. Since the two ports with the opposite direction cannot reuse an MRR, thus one of them can share one MRR with the IP.

4- The third term of this equation will be omitted for DOR routers with 3 ports or less, since the MRR sharing method needs four directly connected ports as mentioned in theorem 1. Moreover, the second term will be useless, since the \(i\) is only one for DOR Routers with 3 ports.

It is worth mentioning that for both theorems, the reused MRRs should connect the two waveguides in parallel not crossing mode in order to function both sides. Moreover, WDM-based routers are not included in these theorems.

The focus of this paper is the proposed DORR, thus the following example would be based on the second theorem. However, both theorems share the same concept.

Example:
To illustrate the second theorem and the reuse of MRRs, we give an example from DORR. Since DORR uses XYZ routing algorithm, X (including West and East ports) along with the IP would be the first order, Y (including North and South ports) is the second, and Z (including Up and Down ports) is the third. Thus, one of the X dimension ports and the IP can reuse one MRR to transmit data as shown in Fig. 5. The MRR in green is shared between the Injection port and the input of West port to realize the communications from Injection to East and West to Up. This MRR is the last add point for the West->East waveguide and the first drop point for the Injection->Up waveguide. Moreover, since no add point is located after a drop point, the router remains non-blocking.

According to theorem 2 and Eq. (2), the least number of MRRs in a \(7 \times 7\) DOR-based OR is 22, which is exactly the same number of MRRs used in DORR.

4. Evaluation and Analysis

To evaluate the performance of this router we compare it with the \(7 \times 7\) Ye’s OR proposed in [21] (and shown in Fig. 3 (b)), the \(7 \times 7\) optimized crossbar in [22] (and shown in Fig. 3 (c)), the \(7 \times 7\) optimized universal OR in [14] (and shown in Fig. 3 (e)), and the optimized VOTEX in [19] (and shown in Fig. 3 (d)). 3D mesh is implemented with the five routers for a fair comparison.

4.1 Layout Theoretical Analysis and Comparisons

We compared the five \(7 \times 7\) ORs in terms of 5 parameters, which are the number of MRRs, the number of waveguides, the number of waveguide crossings, the number of waveguide bends, and the number of optical terminators. These parameters can decide the performance of the network in terms of insertion loss, crosstalk, and the power consumed accordingly. Table 1 shows the basic figure of merits of this router compared with those of the other previously proposed ORs. The table shows that this router reduces the number of MRRs to 22, which is the least among its kind. It also uses 7 waveguides, which is the least number for \(7 \times 7\) ORs. The waveguide crossings are reduced to 25, which is less than the optimized crossbar, Ye’s OR, optimized universal, and optimized VOTEX by around 46.8%, 19.4%, 28.6%, and 57.7%, respectively. Waveguide bends have increased in DORR compared with the optimized crossbar, O.Uni OR and O.VOTEX; however, bend’s loss is quite low as illustrated in the next subsection. On the other hand, the waveguide bends in DORR are less than those in Ye’s OR. Finally, optical terminators do not exist in DORR and the optimized universal OR; whereas, the optimized crossbar has 14, Ye’s OR the optimized VOTEX have 2. All of this helped to reduce the loss caused by DORR compared to oth-
Table 1 The parameters comparison of DORR with other 7 × 7 different routers.

| Router          | #MRR | #Waveguides | #Crossings | #Bends | #OT |
|-----------------|------|-------------|------------|--------|-----|
| DORR            | 22   | 7           | 25         | 28     | 0   |
| Oxbar [22]      | 30   | 14          | 47         | 8      | 14  |
| Ye’s OR [21]    | 24   | 8           | 31         | 35     | 2   |
| O.Uni [14]      | 26   | 7           | 35         | 14     | 0   |
| O.VOTEX [19]    | 24   | 8           | 59         | 25     | 2   |

4.2 Insertion Loss

When an optical signal is inserted into a waveguide, it confronts several aspects, which attenuate the signal, such as free carrier absorption, light scattering at sidewall imperfections, and substrate leakage. Moreover, it encounters more loss while traversing through the waveguide crossings, bends, and optical terminators. This presents additional source of loss that must be considered when determining the scalability of the optical network. Here, we present the IL for the router level and the network level for all the five ORs. The parameters used to evaluate the IL is shown in Table 2.

Table 2 The parameters of different optical devices insertion loss and crosstalk coefficient.

| Parameters                        | Value | Unit   |
|-----------------------------------|-------|--------|
| MRR drop loss                     | -0.5  | dB [25]|
| MRR through loss                  | -0.005| dB [25]|
| Waveguide bend loss               | -0.005| dB [26]|
| Waveguide crossing loss           | -0.04 | dB [27]|
| Propagation loss                  | -0.274| dB/cm [28]|
| On-state MRR crosstalk coefficient| -25   | dB [25]|
| Off-state MRR crosstalk coefficient| -20   | dB [25]|
| Waveguide crossing crosstalk coefficient| -40   | dB [27]|

The total insertion loss from one point to another is calculated by:

$$IL_{total} = \sum(IL_{cross} + IL_{bend} + IL_{prop} + IL_{MR-off} + IL_{MR-on})$$

Where $IL_{cross}$ is the insertion loss introduced by waveguide crossings, $IL_{bend}$ is the insertion loss introduced by waveguide bends, $IL_{prop}$ is the insertion loss caused while propagating along the waveguide, $IL_{MR-off}$ is the insertion loss of passing through an OFF MRR, whereas $IL_{MR-on}$ is the insertion loss of coupling with an ON MRR.

4.2.1 Router Level

According to the parameters in Table 2, the port-to-port maximum, minimum, and average insertion losses for the five ORs are illustrated in Table 3.

Table 3 The insertion loss comparison of DORR with other routers for port-to-port communications.

| Router          | Maximum IL(dB) | Minimum IL(dB) | Average IL(dB) |
|-----------------|----------------|----------------|----------------|
| DORR            | -0.95          | -0.265         | -0.60033       |
| Oxbar [22]      | -0.09          | -0.5           | -0.76667       |
| Ye’s OR [21]    | -0.93          | -0.32          | -0.6695        |
| O.Uni [14]      | -0.87          | -0.44          | -0.67          |
| O.VOTEX [19]    | -1.19          | -0.5           | -0.782         |

4.2.2 Network Level

The amount of energy needed to be provided by the off-chip laser can be decided by the longest path loss for the whole network using all routers. The longest path loss is determined according to the concept mentioned in [29], which examines different longest paths of different directions and compares them to acquire the worst-case IL among them.

The worst-case network insertion loss in DORR is reduced by an average of 8.7%, 46.39%, 39.3%, and 41.4% compared to Ye’s OR, Oxbar, O.Uni, and O.VOTEX, respectively, for different sizes of the network as shown in Fig. 7. Thus, although DORR does not have the least maximum loss in the router level, it enjoys the least maximum loss in the network level, which significantly affects the power dissipation of the network.

4.3 Crosstalk

When optical signals propagate through crossings or MRRs, a tiny portion of it will be switched to an undesired channel. Thus, other optical signals will experience some crosstalk noise, which substantially effects the performance of optical routers.

Considering the parameters in Table 2, we analyze the crosstalk noise experienced in both the router and network levels.

4.3.1 Router Level

In the router level analysis, we examine the crosstalk noise experienced by a transmitted signal from one port to another, i.e. port-to-port communications within the router.
The crosstalk noise added to an optical signal while transmitted from the $i$th port to the $j$th port in the OR can be calculated as follows [29],

$$N_{i, j} = \sum_{m=0}^{13} P_m^0 K_{i,j,m}$$

$$= P_0^0 K_{i,j,0} + P_1^0 K_{i,j,1} + P_2^0 K_{i,j,2} + P_3^0 K_{i,j,3} + P_4^0 K_{i,j,4} + P_5^0 K_{i,j,5} + P_6^0 K_{i,j,6} + P_7^0 K_{i,j,7} + P_8^0 K_{i,j,8} + P_9^0 K_{i,j,9} + P_{10}^0 K_{i,j,10} + P_{11}^0 K_{i,j,11} + P_{12}^0 K_{i,j,12} + P_{13}^0 K_{i,j,13}$$

$i, j \in \{0, 1, 2, \ldots, 13\}$ (4)

Where $K_{i,j,m}$ is the coefficient for the crosstalk noise introduced by $P_m^0$ onto the optical signal traveling from the $i$th port to the $j$th port in the OR. Moreover, $P_m^0$ is the optical power injected into the input of the $i$th port to in the OR.

Figure 8 shows the crosstalk noise of DORR, Oxbar, and Ye’s OR in the router level. In this figure all the port-to-port communications are considered. The colors in the contour figure denote different range of noise. It is clear that the maximum noise (shown as the grey range) introduced is in Oxbar. Whereas, the other four routers experience almost the same crosstalk noise. Thus, Oxbar has the worst-case crosstalk noise in the router level, which is 3.53mW. On the other hand, DORR, Ye’s, O.Uni, and O.VOTEX routers’ worst-cases are 0.08mW, 0.06mW, 0.07mW, and 0.06mW, respectively.

4.3.2 Network Level

In the network level analysis, we used the same concept and method introduced in [29] with some changes, since we are using 3D mesh instead of 2D mesh. In other words, in this analysis we will also consider the up and down directions. We examined different longest paths and compared them to obtain the worst-case crosstalk among all. The worst-case Optical Signal-to-Noise Ratio (OSNR), which is the key parameter to estimate the performance of the optical network, of the network can be obtained as follows,

$$\text{OSNR} = \frac{P_r}{N_{\text{total}}}$$

Where $P_r$ is the received signal power, and $N_{\text{total}}$ is the total crosstalk noise corrupting the signal along the path and can be calculated as in Eq. (4). The worst-case OSNR in the five ORs for different sizes of the network, is elaborated in Fig. 9.

As the network scales, the optical signal-to-noise ratio (OSNR) of Ye’s OR, Oxbar, O.Uni, and O.VOTEX decreases faster than the OSNR of DORR. DORR router provides at least 5.49dB, 4.999dB, 2.694dB, 2.56dB, 0.997dB,
Fig. 9  Worst-case OSNR of the five optical routers for different network sizes.

Fig. 10  Laser power of the five optical routers for different network sizes.

and −0.2 dB OSNR, and increases the OSNR by an average of 27.9%, 88%, 77%, and 69.6% compared with the OSNR of Ye’s OR, OXbar, O.Uni, and O.VOTEX optical router for the sizes of 4x4x2, 4x4x4, 6x6x4, 6x6x2, 8x8x4, 8x8x2, 10x10x4, 12x12x4 and 10x10x2 of 3D mesh, respectively.

4.4 Power Consumption

The power consumption determines the maximum power dissipated in the network, which determines the amount of laser power required in the network. In ONOCs, energy can be consumed by both optical devices and electrical devices. Here, we present the one presented by optical devices, since we are evaluating an optical device. The optical energy can be presented by the laser source power, which is given by,

\[ P_{\text{laser}} = IL_{\text{max}} + 10 \log n + S \]  

(6)

Where \( IL_{\text{max}} \) is the maximum insertion loss introduced in 4.2.2, \( n \) is the number of wavelengths used in the network, and \( S \) denotes the sensitivity of photodetectors. \( S \) is −14.2 dBm (BER = 10^{-12}) [30].

As shown in Fig. 10, DORR’s laser power is reduced by an average of 3.22%, 23.99%, 19.12%, and 20.18% compared to the laser power of Ye’s OR, OXbar, O.Uni, and O.VOTEX optical routers, respectively. Thus, the laser power in DORR is reduced as the network scales compared to all other four optical routers. Furthermore, the larger the network, the sharper the laser power increases for OXbar, O.Uni, and O.VOTEX.

5. Conclusion

Optical routers are essential components in ONOCs, Therefore, we designed a new OR that reduces the number of MRRs used and waveguide crossings experienced by the optical signal. Furthermore, it uses zero optical terminators. We also introduced the least number of MRRs theorem for two types of ORs, and proved that DORR enjoys the least number of MRRs. The designing method developed by the theorem, ensures the least number of optical devices in optical routers of the two types mentioned. Accordingly, these features instantly influence the performance of the network such as the insertion loss, crosstalk, power dissipation, area and hardware cost of the system. DORR is evaluated compared to Ye’s OR, OXbar, O.Uni, and O.VOTEX using 3D mesh. The numerical analysis and evaluations show that DORR reduces the number of MRRs by 8.3%, 26.7%, 15.4%, and 8.3% whereas the waveguide crossings are reduced by 19.35%, 46.8%, 28.6%, and 57.6% compared to Ye’s OR, OXbar, O.Uni, and O.VOTEX, respectively. On the other hand, it lowers the network worst-case IL by almost 8.7%, 46.39%, 39.3%, and 41.4% compared to Ye’s OR, OXbar, O.Uni, and O.VOTEX, respectively. Furthermore, it reduces the laser power in the network by around 3.22%, 23.99%, 19.12%, and 20.18% compared to Ye’s OR, OXbar, O.Uni, and O.VOTEX, respectively.

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