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A Review of Optical Routers in Photonic Networks-on-Chip: A Literature Survey

Negin Bagheri Renani, Elham Yaghoubi
Computer Engineering Faculty, Najafabad Branch, Islamic Azad University, Najafabad, Iran.
(e.yaghoubi@pco.iaun.ac.ir)

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Abstract: *Due to the increasing growth of processing cores in complex computational systems, all the connection converted bottleneck for all systems. With the protection of progressing and constructing complex photonic connection on chip, optical data transmission is the best choice for replacing with electrical interconnection for the reason of gathering connection with a high bandwidth and insertion loss on chip was mentioned. Optical routers play an important role in the Optical Network-on-Chip (ONoC), which are responsible for selecting the path between optical signal source and the destination. In recent years, silicon optical routers based on Micro-Ring Resonators (MRRs) and Mach-Zehnder Interferometers (MZIs) have been proposed. The design of optical switches is desirable by using of Mach-Zehnder Interferometer. This is while that MRR Switches have low bandwidth, whereas Mach-Zehnder Interferometer switches have wide bandwidth inherently. Mach-Zehnder Interferometer switches are able to routing with high speed for data transmission with Nano second switching time. This is while, that MRR switches in compare to MZIs has the less power consumption and area consumption. On the other hand we can divide optical routers into parts, A. general router and B. specific- router, so that in specific routers, some of I/O paths for the reason of avoiding deadlock had be omitted. In continue, several kinds of optical router based on MZI and MRR along with researching a series of parameters was mentioned.*

Keywords: *Optical Router, Micro Ring Resonator, Mach-Zehnder Interferometer, Routing Algorithm, Optical Network on Chip, waveguide crossing*

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I. INTRODUCTION

Increasing the computer processing speed is depended on raising their working frequency. According to ITRS estimation, local clock speed of chips in 2020 will reach to tens Gigahertz. Multi-core chips are another proper approach to amplify processing power of computer systems. Nowadays, more commercial chips with increased number of processing cores, have considerably improved processing speed. Decision and communication in these processors are a challenge.

Network-on-chip is presented as a proper approach for communications in these processors. Communication structure with high bandwidth, low latency and low power consumption are required for applying processing resources in parallel. Compared to traditional electrical communications (based on metal junctions), optical communications include some advantageous as low latency, high bandwidth and low power consumption. In addition, recent development in CMOS technology are consistent with Nano silicon optical devices such as high-speed modulators, reconstruction filters, detectors and switches; so, plan of optical network-on-chip is introduced as a proper alternative for traditional network-on-chip[1].

In recent years, silicon optical routers based on MRRs and MZI have been proposed[2, 3]. MRRs have less area consumption and less power consumption but lower bandwidth compare to MZIs[4]. It is meanwhile; deadlock in network-on-chip is a challenge in routing.

Presenting optical routers opens the way for specific-purpose optical routers. In this sort of routers, regarding to special routing algorithms such as X-Y, and West-First, North-Last and Negative-First and also Odd-even during design, the possibility of blocking event in conducting current packets in network, reaches to zero[5].

Designing optical routers is a new phenomenon but due to lack of complete reference in this field, this paper aims to categorize and describe these routers since the beginning. So, after initial definitions, varieties of optical routers are presented along with their design patterns; that in turn is a new area. The objective of facilitating study and research in order to design optical routers has been improved such that has improved favor parameters of network-on-chip.

Following, Section 2 describes topologies network-on-chip; Section 3 categorizes and optical routers in network-on-chip and subsequently, conclusion is presented in Section 4.

II. TOPOLOGY IN NETWORK-ON-CHIP

Types of topology in network-on-chip

Topology or arrangement of network elements and their connection is a basic challenge in network-on-chip, such that is effective on factors like power consumption, routing delay, area consumption and total performance of network. Different forms of topology are designed for variety of applications. In one hand, it is possible to categorize topology like this[1, 2, 6]:

Shared- medium network: where transmission media between nodes (processing cores) is shared, for example, bus networks.

Direct networks: each node has a router and direct links to other nodes, mesh topology, Torus and Hyper-cube are among the most applicable networks.

Indirect networks: where each node is connected to a switch and switches are directly connected to each other, therefore, these networks are called 'multi-level networks'; for example, Clos network or butterfly network.

Hybrid networks: combination of above methods as a super graph; for example, mesh-cluster or hyper-mesh networks Following some instances of aforementioned topologies are detailed.

Mesh: in this type of topology, routers are located in crossing of two wires. This type of network is very interested due to its simplicity and ease of implementation [2]. The main issue of Mesh topology is network diagonal, yet because of its ordered structure, it is possible to easily be implemented. Also, ordered Mesh network is called Manhattan street network. Fig1 illustrates the Mesh topology.

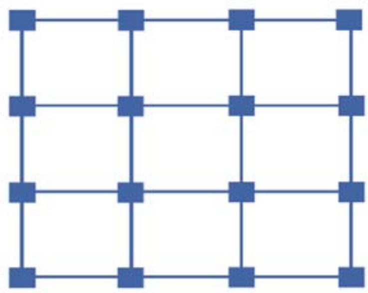


Fig1. Mesh topology [2]

Torus: this type of topology is an improved version of Mesh network. The only difference between Mesh and Torus is network edge switches that are connected to network edge switched through belts [20]. In other words, in Torus network all switches have five active ports that one of them is connected to local source and other four ports are connected to next routers whereas in Mesh topology, edge switches formed by three ports. This topology is illustrated in Fig2. Torus network is introduced regarding to reduce Mesh network delay with keeping its simplicity.

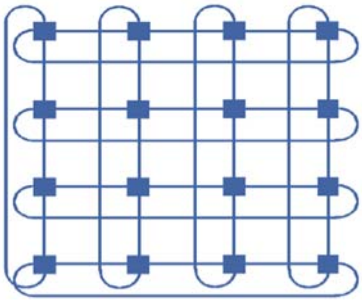


Fig2. Torus topology[2]

Polygon: circular network is the most simplest type of Polygon network where packets are moved from a router to another in rotational form. By adding chords, network would faced with more diversity. Fig3 presents a Hexagon topology.

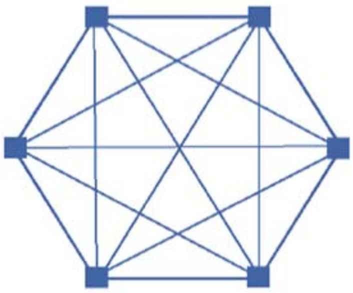


Fig3. a Hexagon topology with all possible chords[2]

When there are chords between two opposite routers, topology is called Spidergon [20]. Fig4 presents this type of topology.

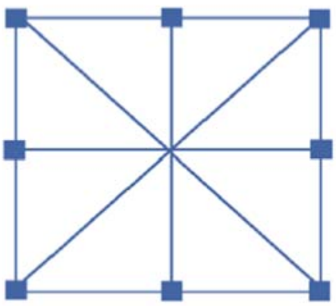


Fig4. Spidergon topology where opposite routers are communicated with each other[2]

Butterfly: a Butterfly network can be one or two-way. For instance, Fig5 shows a simple one-way Butterfly network consists of 4 input ports, 4 output ports and two router level each with two routers. The packets that are entered into the left input of network then are correctly routed to right output of network[2].

In two-way Butterfly networks, all input and outputs are located in one side of network and arrived packets into the input, first are routed to other side of network and then returned and rout into proper output.

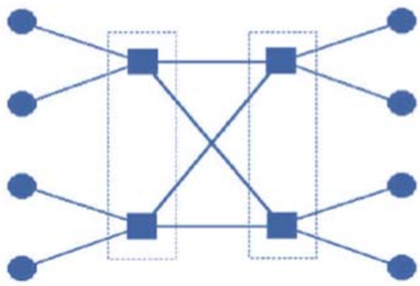


Fig5. Butterfly topology[2]

III. OPTICAL ROUTING CLASSIFICATION

Optical routers play an important role in the ONoC chip. Due to this important role, different types of routers are designed and implemented. Optical network-on-chip that is considered in recent years, opposite to traditional networks, uses different nature for information transmission. So it is led to producing consistent elements with optical nature of these networks like optical waveguides, switches and optical routers[7, 8].

To resolve the problem of deadlock in optical routers, the approach of designing specific-purpose optical routers is a hopeful plan. Specific-purpose optical routers are pre-designed based on specific routing algorithms. As we know, in optical routers, it is not possible to use buffer so using virtual channel in buffers in order to prevent blocking, has not became operational. In these routers, in order to prevent blocking, turning model or dimension-based routing algorithms, These routing algorithms are called as

West-First, Negative-First, North-Last and Odd-even are applied[9]. Accordingly, optical routers are categorized into two classes: general optical routers and specific-purpose optical routers.

1. General optical routers

Mesh is one of the topologies often mentioned in NoCs for its simplicity and regularity[2] .In these topologies, routers with 4,5,6 and 7 ports are required. Following, design of general optical routers with a number of ports based on MRRs and Mach-Zehnder interferometers are introduced.

B.E.Little et.al. (2000) introduced the first basic architecture for optical routers with MRRs. In this model, they used one 8×8 array of MRRs on a glass platform; 64 micro-ring and 64 waveguide crossings are presented in this non-blocking routing architecture[10]. Fig.1 shows the architecture of this router.

The first general four-ports router was introduced by Schaman et al. (2007) that contained 8 micro-ring resonators, 4 waveguides and 4 waveguide crossings. This structure was faced with blocking issue that imposed negative effect on routing. Architecture of this router is presented in Fig.7[11].

Accordingly, and in order to remove blocking issue, Sachman et al. (2007) introduced the first non-blocking router by increasing number of intra-router local paths. As Fig8 shows, this router with 8 micro-ring resonators, 4 waveguides and 10 waveguide crossings is the basic of many papers in order to test and producing router[12].

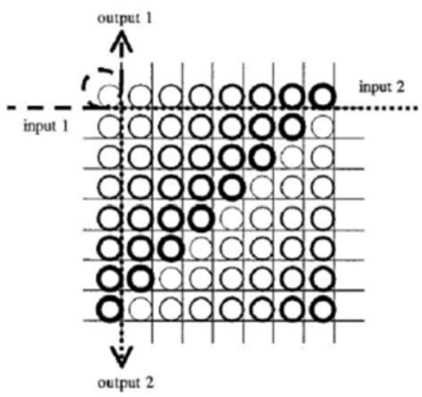
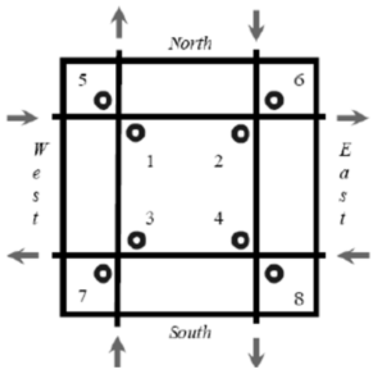


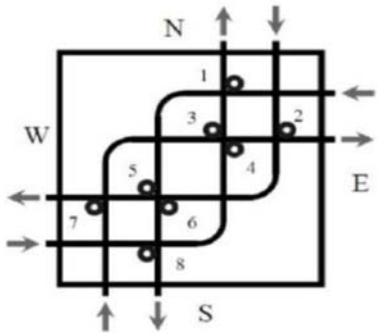
Fig6. The first basic architecture for optical routing with micro-ring resonators[10]

In 2008, S.-J.Chang et al. introduced a micro-ring resonator-based switch [4]; this architecture also made of a 8×8 matrix switch of micro-ring resonators such that 192 micro-ring resonators are located in 64 triple groups. This matrix switch is of non-blocking type and its switches are arranged in cascade form (Fig. 9)[13]. Chan et al. (2008) introduced two optical routers with 4 non-blocking ports named "direct router" and "symmetric router" (Fig. 10). Objective of this symmetric router with 8 micro-ring resonators, 4 waveguide and 8 waveguide crossings was insertion loss reduction and performance fostering[14].



		Output Port			
		N	S	E	W
Input Port	N		-	6	4
	S	-		1	7
	E	3	8		-
	W	5	2	-	

Fig7. The first 4-ports optical router[11]



		Output Port			
		N	S	E	s
Input Port	N		6	2	-
	S	3		-	7
	E	1	-		5
	W	-	8	4	

Fig8. Router with four non-blocking ports[12]

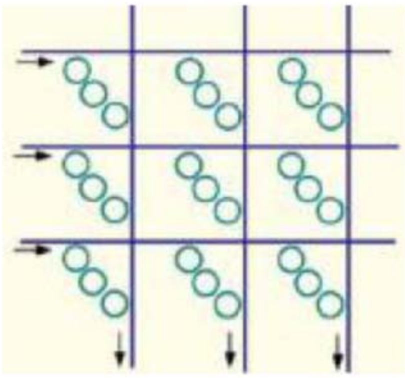
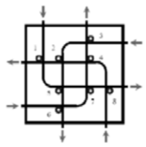


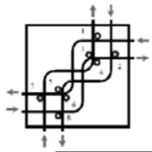
Fig9. 8×8 architecture[13]

In 2008, A.W.Poon presented a non-blocking optical router based on an improved crossbar, in optical network with mesh topology. This router has 5 ports and compose of 25 micro-ring resonators and 25 waveguide crossings. Fig. 11 shows the structure of this router[15].



		Output Port			
		N	S	E	W
Input Port	N		5	–	1
	S	4		8	–
	E	3	–		2
	W	–	6	7	

a)



		Output Port			
		N	S	E	W
Input Port	N		–	2	5
	S	–		4	7
	E	1	6		–
	W	3	8	–	

b)

Fig10. Router with 4 non-blocking ports;

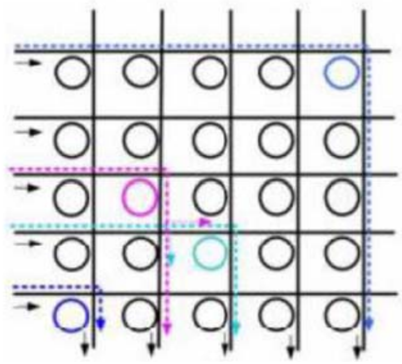
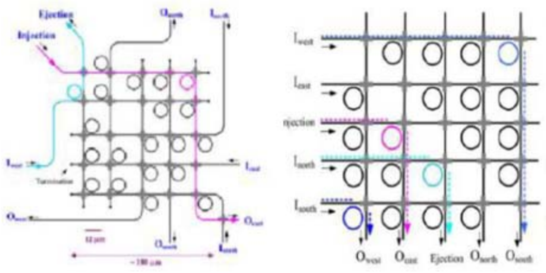


Fig11. Non-blocking optical router with 5 ports[15]

Fig. 12(b) shows the improved structure of this router where each port of router is adjusted according to its direction [14]. This router with n×n ports, includes n^2-n micro-ring resonators, 2n waveguide and n^2 waveguide crossings. The main disadvantageous of this router is the excessive number of waveguide crossings that limits its scalability[16].

J_i et al. (2011) presented the optical routing with 4-ports that includes 8 micro-ring resonators, 4 waveguides and 6 waveguide crossings. As Fig. 13 shows[17].

L-Yang et al (2011) introduced Optical non-blocking five-port router. This router was designed with aim of decreasing the number of micro-ring resonators and waveguide crossings, also improving the performance in some parameters include power consumption, cross-talking noise and optical insertion loss(Fig. 14) [18].



a) b)

Fig.12. 5×5 non-blocking optical router; a) initial design, b) improved design [16]

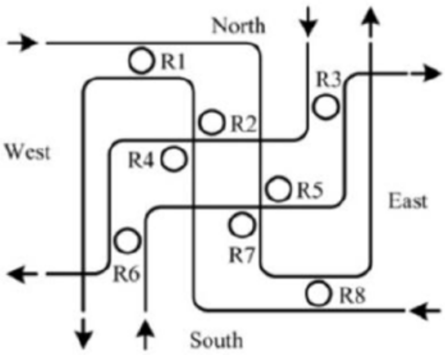


Fig13. Non-blocking Four-ports optical router[17]

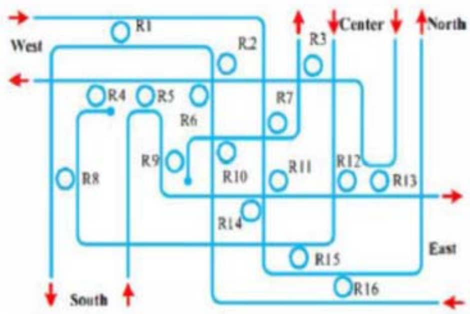


Fig14. Non-blocking Five-ports optical router[18]

R.Min (2012) presented a general method to produce a scalable non-blocking optical router. In this structure, the number of micro-ring resonators, waveguides and waveguide crossings were reduced. Fig. 15 shows the structure for Five-, six-, seven- and eight- port routers. In this structure for non-blocking optical router with n-ports, n(n-1) micro-ring resonators, n(n-2) waveguide crossings and n waveguide are required. This router has n(n-1) optical router where for each optical path, maximum a micro-ring resonator must be active (powered on)[19].

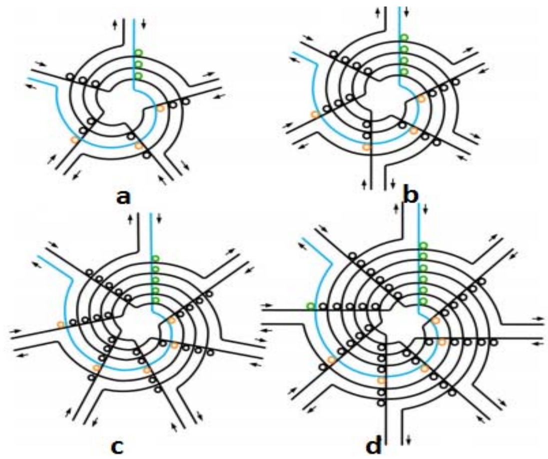


Fig15. General structure of router with n ports; a) n=5, b) n=6, c) n=7, d) n=8[19]

In other hand, considering the advantageous of Mach-Zehnder interferometers than micro-ring resonators, such as extended communication bandwidth and high thermal tolerant, researchers attracted to designing optical routers by using these elements[20].

Min Yang et al. (2011) introduced the first optical routers with Mach-Zehnder interferometers. Fig.11 shows the four-ports router. This router is of non-blocking type and includes 6 Mach-Zehnder interferometers and 6 waveguide crossings[21].

Hesamedin shabani et al.(2016) in a researching negotiation process they could present the design 4×4 non-blocking photonic router based on Micro ring resonator in order to improve in parameter power consumption, optical insertion loss and also decreasing the number of MRR and waveguide crossing[22].

This architecture contain 4 waveguide and 8 MRR and also 8 waveguide crossing.

In compare to previous optical router had an excellent improving. the Figure of this router Shows in the Fig.17.

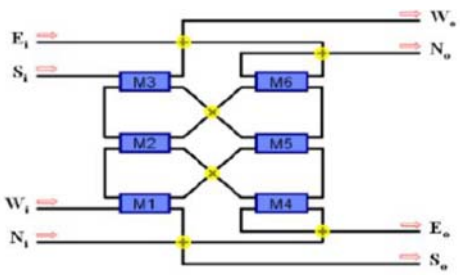


Fig16. Non-blocking 4×4 optical router based on Mach-Zehnder interferometer[21]

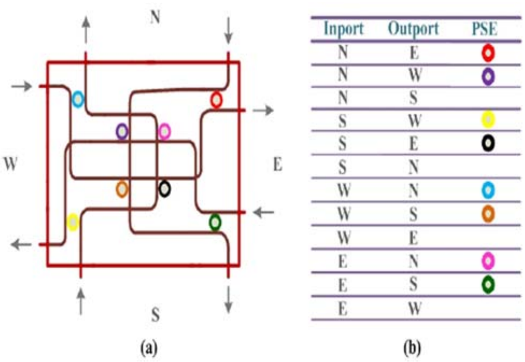
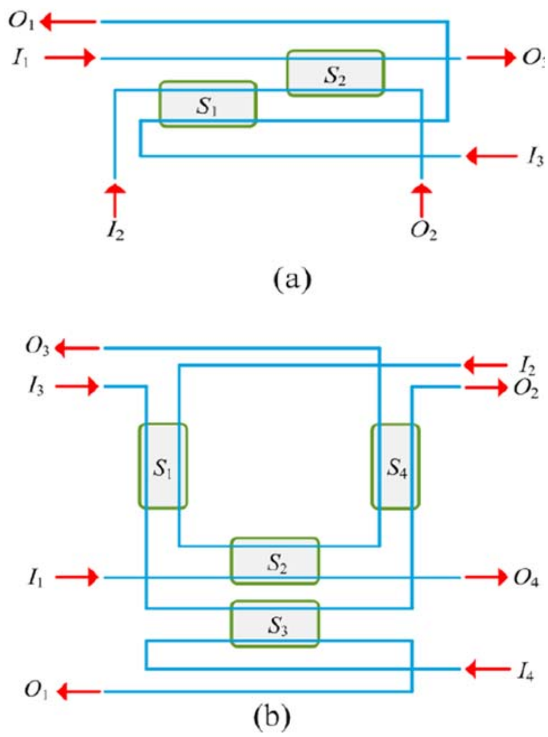


Fig17. a) 4×4 optical router based on Micro Ring Resonator b) Routing paths of the four-port optical router[22]

X.Li et al. (2013) presented a silicon optical router with 5 ports by using Mach-Zehnder switches. Fig.19 shows these routers. This router has used 10 Mach-Zehnder switching components and 5 waveguide crossings. Router port is named as Center, East, West, North and South. The structure of this router is symmetric; also, compared to last 5-ports routers with micro-ring resonators, this router has less switching components and waveguide crossings[23]. Among the most considerable disadvantageous is that this router is of non-blocking type. However it is to be claimed that this router is non-blocking[23]. but Yaghoubi and et al. (2015) by rejecting this claim introduced the 5-ports non-blocking router based on Mach-Zehnder interferometers[4]. This design is composed of 20 Mach-Zehnder interferometers and 12 waveguide crossings. This router is non-blocking and its design is illustrated in Fig. 20. Although, there are more interferometers are used in this design but assuring that this router is non-blocking is a big advantageous.

In 2014 Qiaoshan Chen et al. presented the design of a N-Port non-blocking optical router based on Mach-Zehnder Switch. Fig. 18 shows the structure of this design for 3- ,4- ,5- also 6-ports router.

The optical router constructed by the proposed method has minimum optical switches, in which the number of the optical switches is reduced about 50% compared to the reported optical routers based on MRR optical switches and more than 30% compared to the reported optical routers based on MZI optical switches[24].



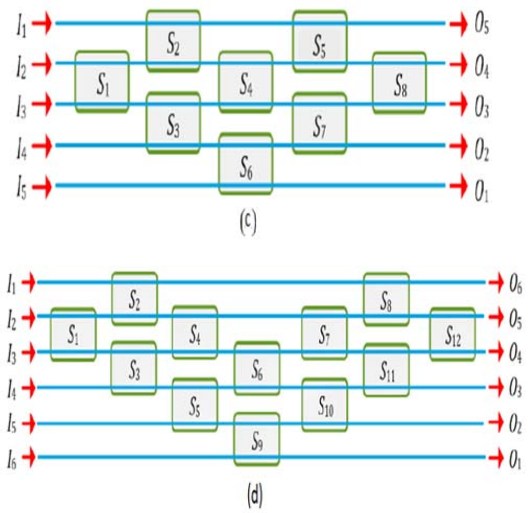


Fig18. N-Port non-blocking optical router based on MZI; a) n=3, b) n=4, c) n=5, d)n=6 [24]

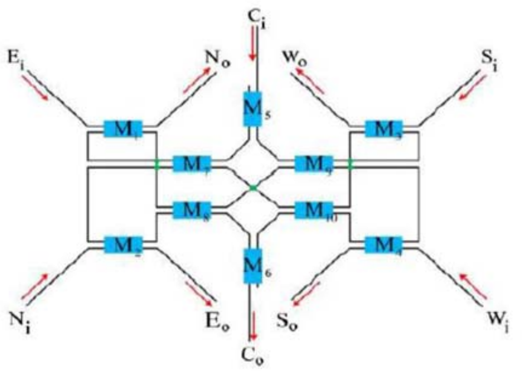


Fig19. 5×5 optical router based on Mach-Zehnder interferometer[23]

Designing the 6- and 7-ports optical routers based on Mach-Zehnder interferometers are required for 3-D mesh networks.

In 2015, Elham Yaghoubi et al. designed the first 6 and 7 ports optical routers based on Mach-Zehnder interferometers[20].

Design of these routers are presented in Fig. s21 and 22. 6-ports router has 12 Mach-Zehnder interferometers and 11 waveguide crossings. This design is superior than similar instances with micro-ring resonators due to relatively 50% reduction of switching components and waveguide crossing numbers; thereby improving area consumption, power consumption, insertion loss improvement and cross-talk noise reduction.

Fig.22 shows that this router has 22 Mach-Zehnder switching components and 24 waveguide crossing. This router compared to similar instance with micro-ring resonators has less switching components and waveguide crossings; thereby caused to improving area consumption, power consumption, Insertion loss and cross-talk noise reduction.

Minmign Geng et al. introduced the design of a scalable non-blocking optical router, based on MZI. Fig. 23 shows the structure of this design for 4- ,5- ,6-, also 7-ports routers. Although, this design uses more switching components than similar instances, but is acceptable because presenting a scalable design that does not have any similar instance before[25].

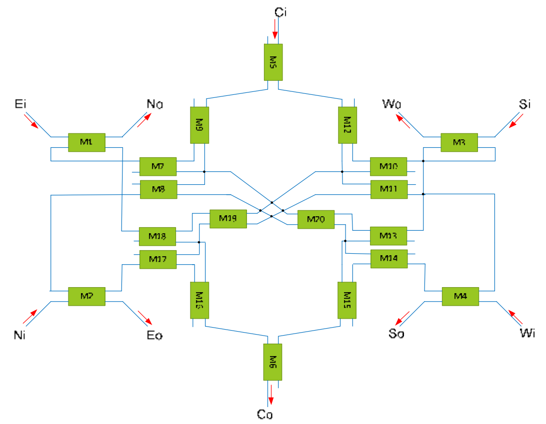


Fig20. 5×5 optical router based on Mach-Zehnder interferometer[4]

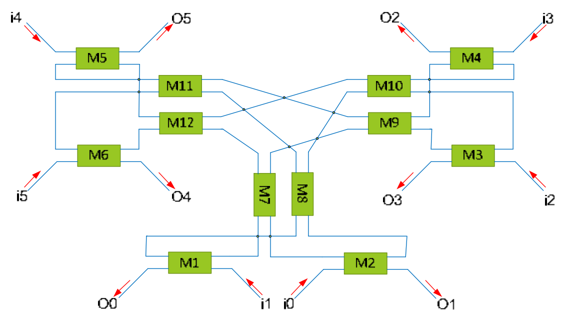


Fig21. 6×6 optical router based on Mach-Zehnder interferometer[20]

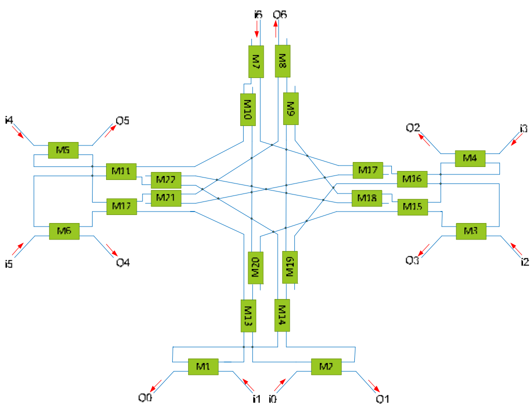


Fig22. 7×7 optical router based on Mach-Zehnder interferometer[20]

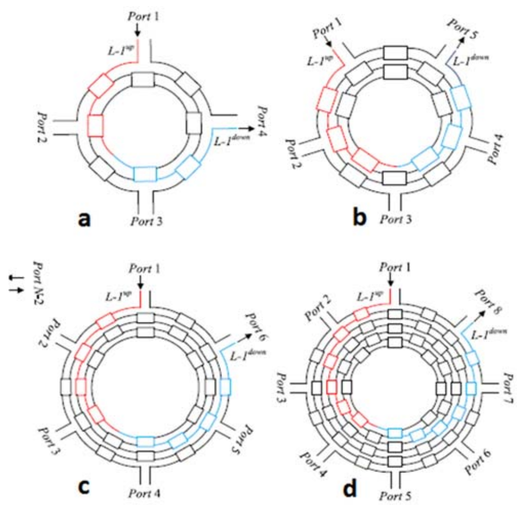


Fig23. Total structure of router with n ports; a) n=4, b) n=5, c) n=6, d) n=7[25]

2. Specific-purpose optical routers

Specific-purpose optical routers are predesigned based on a routing mechanism. The basis of this router is similar to its general instances except that in their designing process, consistency for selecting path and directing packets is anticipated according to specific routing algorithms. Among advantageous of this design is reduction of area consumption because we do not need complete communication between ports. Accordingly, different specific-purpose routers are designed by using micro-ring resonators. Following, we verify them.

In XY routing algorithm only those routes are legal which initially traverse X dimension and then go to Y dimension.Fig. 24 presents the first specific-purpose optical router that uses XY routing algorithm. This router that initially was introduced by G.Hauxi et al. (2008), was named OXY and includes 12 micro-ring resonators, 6 waveguides and 1 waveguide crossing. Design of this router is such that makes it non-blocking[26].

In 2010, Hendry et al. presented the second router. This router is non-blocking and includes 12 micro-ring resonators, 6 waveguides and 19 waveguide crossings. Fig. 25 presents the total design of this router[27].

Hesamedin Shabani et al. (2011) after a series of research customized Shacham general router under XY algorithm[12]. Fig.26 shows that they reduce physical parameters optical router through reduction the number of waveguide crossings and micro-ring resonators.

Hesamedin Shabani (2012) et al. introduced the design of special-purpose 4-and 5-ports optical routers with aim of reducing number of waveguide crossings and thereby, reduction of total losses. These routers are also designed based on XY routing algorithm and are non-blocking. Figs.26 and 27 presents the design of these routers. 4-ports proposed router uses 5 micro-ring resonators, 4 waveguides and 9 waveguide crossings.

5-ports router also includes 12 micro-ring resonators, 6 waveguides and 9 waveguide crossings[3].

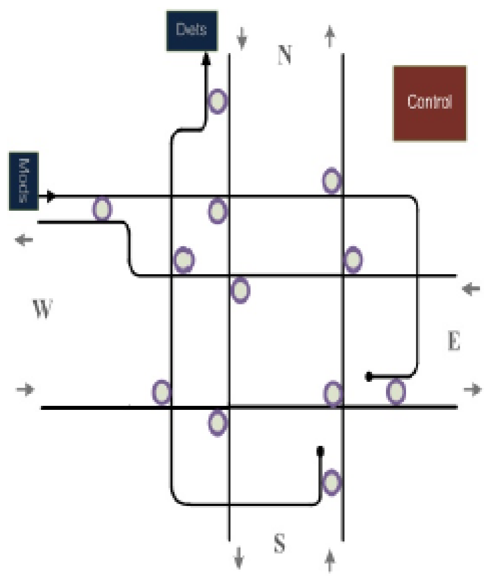


Fig24. 5-ports optical router OXY[26]

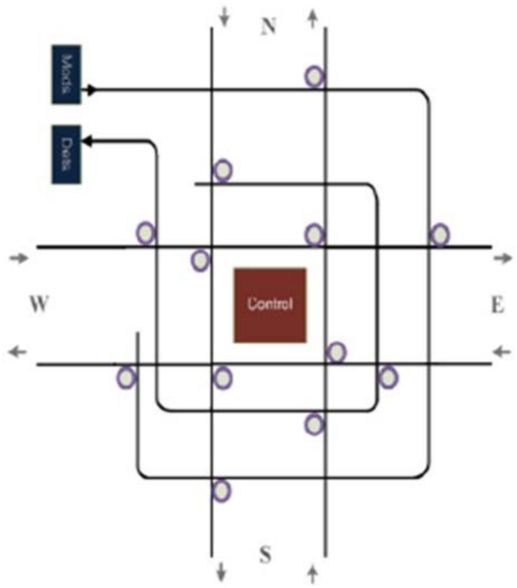
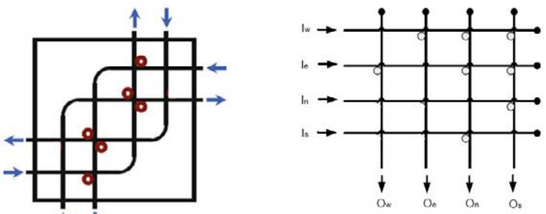


Fig25. 5-ports optical router [27]



A) B)

Fig26. Customization of two 4×4 optical routers under XY algorithm [12]

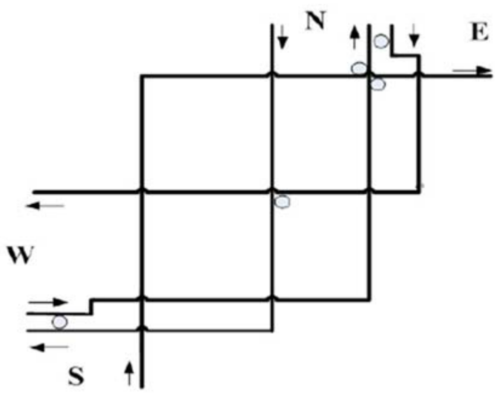
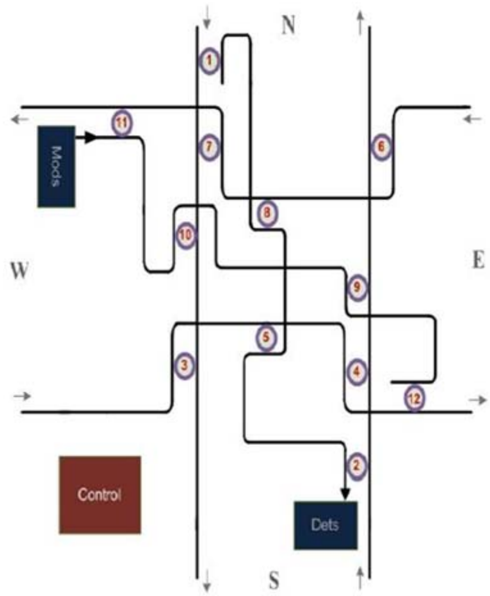


Fig27. Specific-purpose optical router under XY algorithm with 4-Port[3]



Inport	Outport	PSE
N	S	–
N	Dets	1
S	N	–
S	Dets	2
W	S	3
W	N	4
W	E	–
W	Dets	5
E	N	6
E	S	7
E	W	–
E	Dets	8
Mods	N	9
Mods	S	10
Mods	W	11
Mods	E	12

Fig28. 4×4 Specific-purpose optical router under XY algorithm with 5-Port[3]

This section studied on a variety of specific-purpose optical routers. As it was seen, current specific-purpose optical routers were based on micro-ring resonators. Designing of Specific-purpose optical routers based on Mach-Zehnder interferometer, in order to utilizing its benefits, can be the basis of future researches.

In table 1 there is a comparison on Specific-purpose optical routers and General optical routers from the point of the number of switching elements, the number of waveguide crossing, blocking or non-blocking and the amounts of port was done.

IV. CONCLUSION

Designing optical router could led to constructing router which from the point of parameter such as power consumption, insertion loss, area consumption and noise and also blocking has the potential of improving better.

In this paper, we considered negotiation and gathering optical router in two basic part of general-routers and specific-routers based on Mach-Zehnder interferometers and micro ring resonator. In introducing routers, the main designing factors for instance the number of switching elements and the amount of waveguide crossing, waveguide and also blocked or not blocked was presented.

The best router, is a kind of router that with the least switching elements and waveguide crossing, it could presented non-blocking router with the minimum power consumption and the least delay and the maximum bandwidth.

In sequence of this research could evaluate the other effective factors in designing such as delay and cross-talk noise, for optical routers.

TABLE1: A comparative table Specific-purpose optical routers and General optical routers

Number of Port	Blocking	Number Of Waveguide Crossing	Number of Switching Elements	Authors / Year	Rows
8*8	Blocking	64 Waveguide Crossing	64 MRR	Little B. E. et al / 2000[11]	1
8*8	Blocking	4Waveguide Crossing	4waveguide , 8MRR	Shacham et al / 2007[11]	2
4*4	Non-Blocking	10 Waveguide Crossing	4waveguide , 8MRR	Shacham et al / 2007[12]	3
8*8	Non-Blocking	-	192 MRR	Chan et al / 2008[13]	4
4*4	direct router = Non-Blocking symmetric router = Non-Blocking	direct router = 8 Waveguide Crossing symmetric router = 8 Waveguide Crossing	direct router = 4 waveguide, 8 MRR symmetric router = 4 waveguide, 8MRR	Chan et al / 2008[14]	5
5*5	Non-Blocking	25 Waveguide Crossing	10 waveguide , 25 MRR	A.W.Poon et al / 2008[15]	6
N*N	Non-Blocking	N^2 Waveguide Crossing	2N waveguide , N2-N MRR	A.W.Poon et al / 2008[16]	7
4*4	Non-Blocking	6 Waveguide Crossing	4 Waveguide , 8 MRR	R.Ji et al / 2011[17]	8
5*5	Non-Blocking	12 Waveguide Crossing	10 Waveguide , 16 MRR	L.Yang et al / 2011[18]	9
N*N	Non-Blocking	N(N-2) Waveguide Crossing	N Waveguide , N(N-2) MRR	R.Min et al / 2012[19]	10
4*4	Non-Blocking	6 Waveguide Crossing	6 Waveguide , 6 MRR	Min Yang et al / 2011[21]	11
4*4	Non-Blocking	8 Waveguide Crossing	4 Waveguide , 8 MRR	H.Shabani et al / 2016[22]	12
N*N	Non-Blocking	3*3 = 2 4*4 = 4 5*5=0 6*6 = 0 Waveguide Crossing	3*3 = 2 MZI 4*4= 4MZI 5*5= 8MZI 6*6 = 12MZI	Q.Chen et al / 2014[24]	13
5*5	Blocking	5 Waveguide Crossing	10 MZI	X.Li et al /2013[23]	**14**
5*5	Non-Blocking	12 Waveguide Crossing	20 MZI	E.Yaghoubi et al /2015[4]	**15**
6*6	Non-Blocking	11 Waveguide Crossing	12 MZI	E.Yaghoubi et al /2015[20]	**16**
7*7	Non-Blocking	24 Waveguide Crossing	22 MZI	E.Yaghoubi et al /2015[20]	**17**
n*n	Non-Blocking	5*5 = 0 Waveguide Crossing 6*6 = 0 Waveguide Crossing 7*7 = 0 Waveguide Crossing	5*5=15 MZI 6*6=24 MZI 7*7=48 MZI	Minming Geng et al / 2016[25]	**18**
5*5	Non-Blocking	19 Waveguide Crossing	6 waveguide , 12 MRR	G.Huaxi et al / 2008[26]	**19**
5*5	Non-Blocking	11 Waveguide Crossing	6 waveguide , 12 MRR	G.Hendry et al / 2010[27]	**20**
4*4	Non-Blocking	9 Waveguide Crossing	4 waveguide , 5 MRR	H.Shabani et al / 2015[3]	**21**
5*5	Non-Blocking	9 Waveguide Crossing	6 waveguide , 12 MRR	H.Shabani et al / 2015[3]	**22**

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