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Synthesis of Large-Scale Wavelength-Routed Optical Networks-on-Chip Using Active Routers

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Abstract

With the development of silicon photonics, wavelength-routed optical networks-on-chips (WRONoCs) provide a promising solution for next-generation multi-processor design, thanks to their advantages in power-efficient on-chip communication and higher potential bandwidth. Optical routers can be classified into two classes: active and passive routers according to their tuning mechanisms and whether transmission paths are allocated dynamically. However, these two router architectures are not completely contradictory. We propose the first optimisation framework that systematically optimises a passive optical network in application-specific design by including the advantages of existing active optical routers. Experimental results show that by considering the interplay among design procedures, our tool can significantly reduce the time to design an WRONoC, making it possible to design a large-scale WRONoC within an acceptable time.

Contents

1. Introduction

Multi-core integrated circuits are currently widely used due to their high computational performance [1, 2]. As the number of parallel computing cores increases, the communication cost among these cores becomes a bottleneck that limits the chip performance. Although electrical Networks-on-chips (NoCs) have been proposed to replace the traditional bus-based on-chip traffic [3], their increasing bandwidth and latency cannot keep up with technology scaling due to conventional metallic interconnections [4].

With advanced fabrication technologies for CMOS-compatible optical components [5], Optical NoCs (ONoCs) have become an appealing next-generation design option which exhibits better power efficiency for signal transmission [1, 6].

An ONoC includes an electronic layer, a photonic layer, and optical/electronic interfaces that transform electrical signals into light signals [7]. Traditional metal interconnects are replaced by optical waveguides in the photonic layer, and the transformed signals are transmitted via these waveguides. Optical routers consist of Micro-Ring Resonators (MRR) and waveguide sections, and they are used as switch nodes in optical networks [8, 9]. They can be classified into two classes: active and passive routers.

Active optical routers are optical components in active networks. Signals are dynamically guided within a router by switchable MRRs and waveguides to target ports so that they can be transmitted to cores and other routers. Active optical routers used in large-scale active networks perform better than other optimized traditional optical routers [10, 11, 12].

A passive network is also called Wavelength-Routed ONoC (WRONoC). In passive networks, transmission paths for each data stream are set up at design time. Hence, network delay caused by path allocation and energy consumption resulting from extra control circuits is eliminated [13].

Compared with passive networks, active networks with lower design complexity and higher scalability are more suitable for large-scale ONoCs [10]. On the other hand, without extra control circuits, passive routers consume less power and have less insertion loss in smaller size [14]. Actually, these two router topologies are not completely contradictory. With specific constraints, the design of active routers can be used to design passive routers. Here we construct the first optimization framework that constructs large-scale WRONoCs by including the advantages of existing active optical routers.

So far various methods have been developed to optimize the design of WRONoCs.

However, they suffer from limited scalability and long optimization time [13, 15, 16]. Our tool solves the scalability problems inherent in passive ONoCs and significantly decreases the time required for optimization.

By combining switchable MRRs in specific structures of active routers, complex signal transmissions can be organized. Thus, the electrical and optical components can be connected under a chosen topology and form a complete network. In our work, after all transmission paths have been allocated with certain constraints and a complete network has been built, all switched-off MRRs can be removed from the network to reduce the power consumption. Remaining switched-on MRRs will always be on in the network so that a WRONoC is built. With this procedure, our tool can significantly reduce the time to design an WRONoC, making it possible to design a large-scale WRONoC within an acceptable time.

For application-specific designs, since core-to-core transmission loads are imbalanced, it is necessary to optimize the structure according to transmission needs, and to route signals utilizing the most power-effcient transmission paths. Therefore, in this work, we propose a tool which provides an optimization for large-scale application-specific WRONoC designs to reduce insertion loss and the number of wavelengths [17, 18]. Our experimental results show that this tool significantly reduces the program runtime compared to other tools and keeps the number of wavelengths equivalent and small [13, 15, 16].

The rest of this paper is organized as follows. Section 2 introduces the physical layout template idea and Section 3 introduces the optimization problem. Section 4 formulates the mathematical model used for network optimization. Section 5 shows the experimental results and Section 6 concludes this paper.

2. PHYSICAL LAYOUT TEMPLATE

An initial network topology is needed for our method. Specifically, we construct a *physical layout template* which consists of a collection of ONoC router placeholders, cores and waveguide sections. The physical layout template also defines how waveguide sections connect cores and routers by choosing a specific topology. In this work, our tool can accept a physical layout template with a mesh-based topology or a torus-based topology.

2.1. Template elements

In our model layout templates, there are three layout elements:

Cores are processing units, each of which reads and executes program instructions.

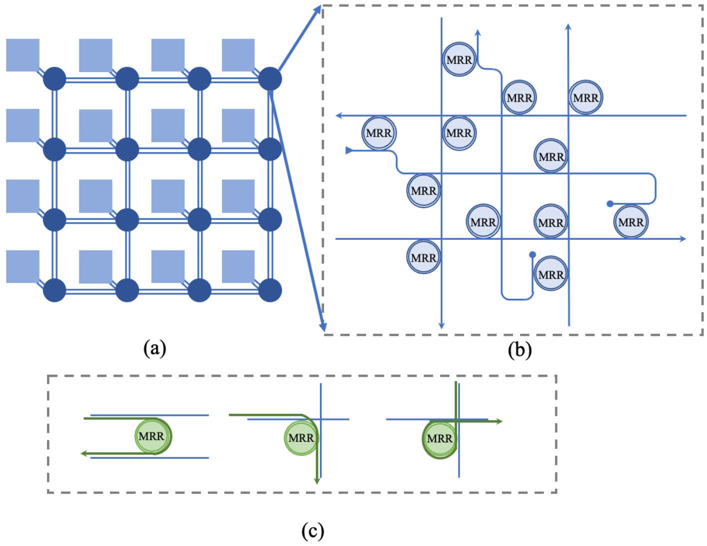


Figure 2.1.: Light signal routing in a mesh-based topology. (a) A mesh-based topology. (b) A 5×5 Crux-model optical router used to route light signal. (c) Light signal routing possibilities using an MRR.

Active routers are constructed to organize complex signal transmissions. As shown in Fig. 2.1, when a light signal is routed through a mesh-based topology (Fig. 2.2a), the light signal can be routed through a turned-on MRR in an active router. In our work, for each router placeholder, we can assign a router type from our router library to it. Here we show a Crux router as an example (Fig. 2.2a). When an MRR is on, the signal can be directed to the other waveguide (Fig. 2.2c).

Waveguide sections connect two routers or a router and a core. Signals are transmitted along the waveguide sections.

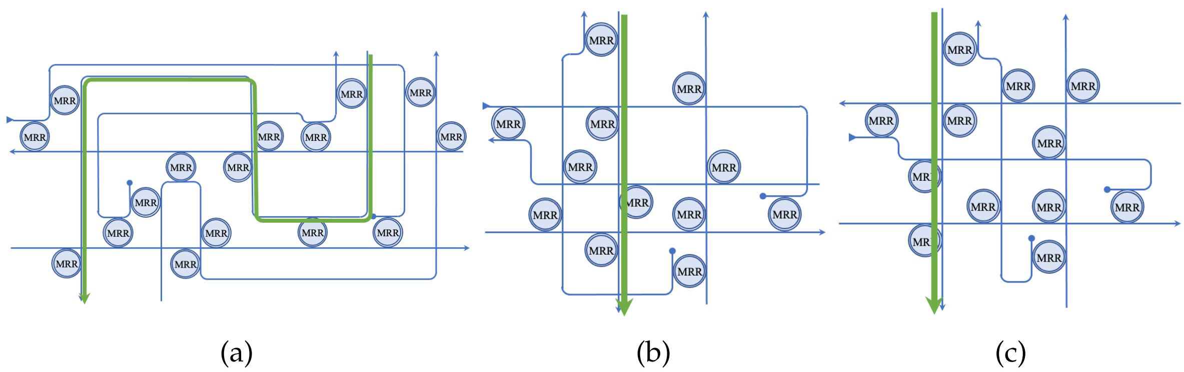


Figure 2.2.: (a) A 5×5 Cygnus-model optical router [10]. (b) A 5×5 OXY-model optical router [11]. (c) A 5×5 Crux-model optical router [12].

2.2. Insertion Loss

Message insertion loss is the sum of five types of losses: 1) crossing loss, 2) drop loss, 3) propagation loss, 4) modulator loss and 5) demodulator loss. We ignore the last two during optimization because all messages suffer from the same modulator and demodulator loss [13].

To allocate the most power-effcient transmission paths, we need the insertion loss value from port to port inside each router type. The insertion loss inside a router from port to port will be calculated according to the number of passed waveguide crossings (crossing loss), and the number of passed MRRs (drop loss). In the Table A.1, we show the insertion loss parameters we are using to calculate the insertion loss inside a router [19]. For example, in Fig. 2.2 we denote a signal transmission path inside the routers by green lines. The signal from the north port to the south port, needs to pass six switched-off MRRs and six waveguide crossings in a Cygnus router or four switched-off MRRs and four waveguide crossings in an OXY router or four switched-off MRRs and three waveguide crossings in a Crux router, leading to $6 \times 0.005 + 6 \times 0.04 = 0.27$ dB and $4 \times 0.005 + 4 \times 0.04 = 0.18$ dB and $4 \times 0.005 + 3 \times 0.04 = 0.14$ dB power loss respectively. We construct an insertion loss table for each type of router and show the result in Tables A.2, A.3 and A.4.

3. Optimization problem

The optimization problem considered in this work for WRONoCs is as follows [20]:

3.1. Input

An initial network topology, a message description list, technology parameters and a router library:

- Initial network topology describes the initial structure of a to-be-optimized ONoC design. It specifies the number and physical positions of the cores and routers.
- Message description list describes the application-specific signal transmission tasks by specifying the source component and target component.
- Technology parameters include insertion loss parameters and calculated insertion loss of each router types. Table A.1 shows the parameters we used. Tables A.2, A.3 and A.4 show the insertion loss of each router type.
- Router library is a library of real router designs such as those shown in Fig. 2.2.

3.2. Output

- Wavelength (symbolic) of each message
- Routing of each message
- Router design used for each router in the topology

3.3. Minimization objectives

- Message insertion loss
- Number of wavelengths

4. Mathematical Model

We propose a Mixed Integer Programming approach to solve this optimization problem. With this approach, we can get a global optimal solution, or at least an upper/lower bound to the optimal value of our optimization problem. Besides, an MIP model can optimize several objectives. Therefore, it is flexible to design our model with different optimization objectives.

We list the model constants and indices in Table A.5. Table A.6 then lists all model variables. Required constraints and the optimization function are explained below.

4.1. Constraints

4.1.1. Wavelength assignment

Each message can use a wavelength and be transmitted by light signal to go through waveguide sections. The following wavelength constraints must be fulfilled.

Firstly, only exactly one wavelength can be assigned to each message:

$$\sum_{\lambda}^{N_\lambda} mwl_{m,\lambda} = 1 \qquad \forall m = 1...N_m$$

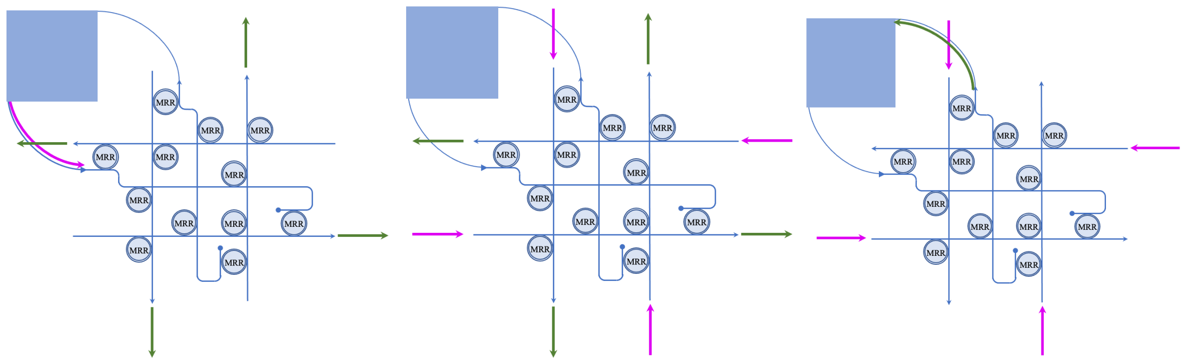
Secondly, when a wavelength is assigned to a message, the value of wlu_λ will be set by the constraint:

$$mwl_{m,\lambda} \leq wlu_\lambda \qquad \forall \lambda = 1...N_\lambda, \forall m = 1...N_m$$

Variables $mwe_{m1,m2}$ denote message $m1$ and $m2$ use the same wavelength, and the value of $mwe_{m1,m2}$ can be set according to the following constraint:

$$\begin{aligned} mwl_{m1,\lambda} + mwl_{m2,\lambda} \leq mwe_{m1,m2} + 1 \\ \forall \lambda = 1...N_\lambda \\ \forall m1, m2 = 1...N_m : m1 \neq m2 \end{aligned}$$

Lastly, each waveguide section has at most one message going through it for each



(a) (b) (c)

Figure 4.1.: (a) Light signal (purple dotted line) is injected into a router (b) Alternative waveguide sections for light signal (c) Light signal (green dotted line) is ejected to a core

wavelength.

$$mwg_{m1,wg} + mwg_{m2,wg} + mwe_{m1,m2} \leq 2$$
$$\forall m1, m2 = 1...N_m : m1 \neq m2$$
$$\forall wg = 1...N_{wg}$$

4.1.2. Message routing

To find a path for each message, we apply the following sets of constraints:

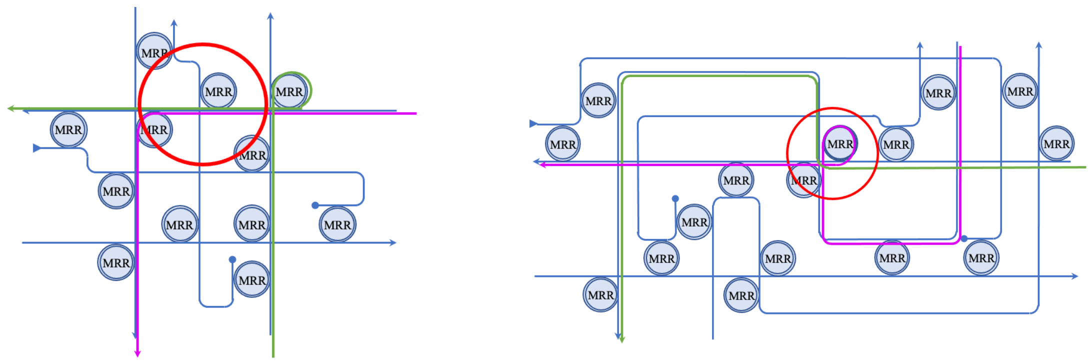
Each message must be on two waveguide sections. One waveguide is connected to the core where the message is sent from and the other is linked to the core where the message is received by.

$$mwg_{m,W^{R^S_m}_{C^S_m}} = 1 \quad mwg_{m,W^{C^R_m}_{R^R_m}} = 1 \quad \forall m = 1...N_m$$

Except for the cores which are sending or receiving a message, this message should not be present on the waveguide sections of other cores.

$$mwg_{m,W^c_r} = 0 \quad mwg_{m,W^r_c} = 0$$
$$\forall m = 1...N_m$$
$$\forall c = 1...N_c \setminus \{C^S_m, C^R_m\}$$
$$\forall r = 1...N_r \setminus \{R^S_m, R^R_m\}$$

When a message is sent from a core c and injected into a router r linked to the core, one waveguide section from D^S_r should be chosen. Fig. 4.1a shows an example,



(a) (b)

Figure 4.2.: (a) Transmission conflict case 1. (b) Transmission conflict case 2.

light signal (purple dotted line) is injected into a router and there are four candidate waveguide sections (green dotted line) can be chosen to send signal out of the router.

$$\sum_{d}^{D^S_{R^S_m}} mwg_{m,W^d_{R^S_m}} = 1 \qquad \forall m = 1...N_m$$

Also when a message is received by a core c and sent from router r, one waveguide section from D^R_r should be chosen to send the signal out of the router. We also show an example in Fig. 4.1c, there are four alternative waveguide sections (purple dotted line) can be chosen to send signal into the router.

$$\sum_{d}^{D^R_{R^R_m}} mwg_{m,W^{R^R_m}_d} = 1 \qquad \forall m = 1...N_m$$

If a router r is not connected to the core which sends message m out nor the core which received message m, when an alternative waveguide section in D^S_r is activated then one waveguide section in D^R_r must be chosen and vice versa. In the Fig. 4.1b, we show an example, D^S_r and D^R_r respectively has 4 alternatives waveguide sections.

$$\sum_{d_1}^{D^R_r} mwg_{m,W^r_{d_1}} \geq mwg_{m,W^{d_2}_r}$$
$$\forall m = 1...N_m, \forall d_2 \in D^S_r, \forall r = 1...N_r \setminus \{R^S_m, R^R_m\}$$
$$\sum_{d_1}^{D^S_r} mwg_{m,W^r_{d_1}} \geq mwg_{m,W^{d_2}_r}$$
$$\forall m = 1...N_m, \forall d_2 \in D^R_r, \forall r = 1...N_r \setminus \{R^S_m, R^R_m\}$$

4.1.3. Overlap avoidance

Our model guarantees that all messages are able to be transmitted simultaneously, which greatly increases the speed of parallel computing. Because of this, different messages sharing the same wavelength cannot physically overlap at any point on a waveguide. We show two examples in Fig. 4.2a. They both have two messages go through a router at the same time. Fig. 4a shows two messages: one from south port to west port, and the other from east port to south port. And in Fig. 4b, there are two messages: one from north port to west port, and the other from east port to south port. The red circle points out the overlapped part. And we apply the following constraints to prevent these overlaps.

$$dc_{m1,W^r_{d1},W^{d2}_r,t} + dc_{m2,W^r_{d3},W^{d4}_r,t} + mwe_{m1,m2} <= 2$$
$$\forall r = 1...N_r, \forall t = 1...N_t,$$
$$\forall m1, m2 = 1...N_m : m1 \neq m2,$$
$$\forall (W^r_{d1}, W^{d2}_r : W^r_{d3}, W^{d4}_r) \in P_t$$

4.1.4. Router assignment

For each individual router that should be utilized according to the routing solutions, one of following router types should be assigned to it: 5×5 Cygnus, 5×5 OXY and 5×5 Crux .

$$\sum_t^{N_{rt}} rt_{r,t} = 1 \quad \forall r = 1...N_r$$

4.1.5. Loss calculation

According to the loss tables of each type of router we introduced before, we can calculate the total loss of the messages transmission in the template, we need a variable which denotes where the message is transmitted in the template. Then the value of $dc_{m,wg1,wg2,t}$ is set accordingly:

$$mwg_{m,W^r_{d1}} \wedge mwg_{m,W^{d2}_r} \wedge r_t \implies dc_{m,W^r_{d1},W^{d2}_r,t}$$
$$\forall m = 1...N_m, \forall d_1 \in D^R_r, d_2 \in D^S_r : d_1 \neq d_2,$$
$$\forall r = 1...N_r, \forall t = 1...N_t$$

Propagation loss: The length of each waveguide section between two adjacent routers is constant. The length of waveguide sections inside a router is negligible, since it is too small. And propagation loss of a message is proportional to the length

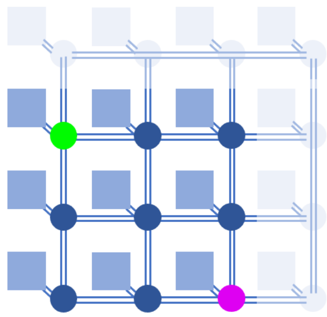


Figure 4.3.: Removing detour waveguide sections

of the waveguides the message goes through [13]. Therefore, the propagation loss of a message over the whole template can be calculated by:

$$pl_m = \sum_{wg}^{N_{wg}} mwg_{m,wg} * L_{wg}^{P} \qquad \forall m = 1...N_m$$

Message loss: The total loss of a message over the whole template can be calculated by:

$$mil_m = \sum_{d_1}^{D_r^R} \sum_{d_2}^{D_r^S} \sum_{r}^{N_r} \sum_{t}^{N_t} dc_{m,W_{d1}^r,W_r^{d2},t} \times \Psi_{W_{d1}^r,W_r^{d2},t} + pl_m$$

$$d_1 \neq d_2, \forall m = 1...N_m$$

To determine the maximum loss over all messages, we set the following set of constraints:

$$maxil \geq mil_m \qquad \forall m = 1...N_m$$

4.1.6. Heuristics and model reduction

Using the MIP approach to find optimal solutions makes the solving process inherently slow because the problem space is huge. Thus, a heuristic was developed to speed up this process.

To apply constraints for message routing increases complexity in our design problem. Thus, it is important to cut down the problem space of message routing. We force all messages to choose their path without taking any detours which lead to higher propagation loss and drop loss. Fig. 4.3 shows an example, when we want to find the path for a message start from the green router and end at the purple router in a mesh, detour waveguide sections(the part colored in gray) won't be considered.

For each message, We remove detour waveguide sections simply with following constraint:

$$mwg_{m,wg} = 0 \qquad \forall m = 1...N_m, \forall wg = 1...D_m$$

4.2. Objective function

The optimization objectives of the model are described at the end of Section II. We take two optimization objectives into consideration: the number of wavelengths and message insertion loss. Because both the feasibility and the power consumption of an optical router are determined by the insertion loss and the number of wavelengths required to satisfy the network traffic [17, 18].

To maximize the energy efficiency of ONoCs, we need to minimize the insertion loss and the number of wavelengths.

The number of wavelengths can be calculated as follows:

$$nwl = \sum_{\lambda}^{N_\lambda} wlu_\lambda$$

We have introduced the worst insertion loss over all messages before. Thus, our objective function is:

$$\alpha * nwl + \beta * maxil$$

where α and β are optimization weights chosen by the designer.

5. Experimental Results

The MIP model and accompanying heuristics have been implemented in Python and make use of Gurobi [21], an MIP solver, on a six-core Intel Core 3.0 GHz CPU with 8GB memory.

We tested our tool on 7 test cases that are different in communication density and the size of case. The case 1,2,3,7 refer to [22, 23, 24, 25] and other cases were created randomly with high density.

We compare our work against the state-of-the-art comprehensive WRONoC synthesis tool, PSION + [26]. We used the same parameters and solved the same test cases with the same communication matrix, the number of cores and node placement. We compared the number of wavelengths, maximum insertion loss and execution time. Detailed test case information and comparison results are shown in Table A.7.

We can see in all cases that our tool is much faster than PSION+. Although PSION+ produces designs with lower maximum insertion loss, our tool can generate results for large test cases with fewer or equal number of wavelengths, for which PSION+ is not able to solve in acceptable time. For case 5 and 6, the optimized results has not been solved and were unknown.

We illustrate the experimental results of test case 3 in Fig. A.1 to give an overview of the result of our tool. For the highlighted node, a Crux router is chosen during optimization. Five wavelengths are used, 11 messages going through the Crux router and all unused MRRs have been removed. Since we minimize the number of wavelengths, some messages which do not use have overlapping waveguide usage share the same wavelength. For example, the pink wavelength has been used three times to transmit three messages which go through the Crux router.

6. Conclusion

Network topology, router design, application mapping and message routing are four major ONoC design factors that interact closely with one another, but used to be optimized separately. In this work we present an automation tool that systematically optimizes the interplay among the four ONoC design factors. We used an MIP model to solve physical layout templates for their optimal solution, we also defined multiple heuristics to accelerate the solving process. We used two general layout templates, the mesh-based template and the torus-based template, and described their features. Finally, we analyzed the performance of our tool and compared its performance with other state-of-the-art design tools.

In the future, the presented MIP model may be expanded to include other router types. As feasible ONoC sizes increase, our tool will also be improved to handle them within acceptable optimization timeframes. Besides, in this work we only randomly map the computing tasks to cores and our tool should also be improved to map specific applications to cores in order to minimize insertion loss.

A. Appendix

Table A.1.: Insertion Loss Parameters

Parameter	Value
Crossing loss	0.04 dB
Drop loss per MRR in OFF state	0.005 dB
Drop loss per MRR in ON state	0.5 dB
Propagation per unit length	0.274 dB/cm

Table A.2.: Cygnus

in \ out	Ej	N	W	S	E
In	–	0.59	0.5	0.59	0.68
N	0.58	–	0.77	0.27	0.63
W	0.68	0.68	–	0.50	0.19
S	0.68	0.19	0.95	–	0.60
E	0.67	0.51	0.27	0.76	–

Table A.3.: OXY

in \ out	Ej	N	W	S	E
In	–	0.59	0.50	0.68	0.68
N	0.50	–	0.68	0.18	0.73
W	0.59	0.68	–	0.59	0.14
S	0.68	0.14	0.73	–	0.59
E	0.68	0.59	0.18	0.67	–

Table A.4.: Crux

in \ out	Ej	N	W	S	E
In	–	0.64	0.50	0.55	0.64
N	0.50	–	0.59	0.14	0.77
W	0.64	0.68	–	0.50	0.14
S	0.64	0.14	0.77	–	0.59
E	0.55	0.50	0.14	0.68	–

Table A.5.: Model constants & indices

Constants	
N_c, N_{wg}, N_r, N_m, N_λ, N_{rt}	Total number of cores, waveguide sections, routers, messages, wavelengths and router types
L^C, L^D	Values for crossing loss and drop loss
L^P_{wg}	Propagation loss of waveguide section wg

Indices	
$W^{c_2}_{c_1}$	Waveguide section which can transmit light signal from c_1 to c_2
C^S_m, C^R_m	Core sends out message m and receives message m
R^S_m, R^R_m	Router which connected to core which sends message m and receives message m
D^S_r, D^R_r	Candidate waveguide section set includes waveguide sections which can transmit signal out of or into router r
P_t	A set includes all pairs of waveguides that cannot simultaneously use the same wavelength in type t router.
D_m	A set includes all waveguide sections which cause detour when message m is transmitted.
$\Psi_{W^{c_2}_{c_1}, W^{c_3}_{c_2}, t}$	Insertion loss happens when light signal goes through waveguide $W^{c_2}_{c_1}$ and $W^{c_3}_{c_2}$ in type t router

Table A.6.: Model variables

Binary	
$mwl_{m,\lambda}$	Message m uses wavelength λ
$mwe_{m1,m2}$	Messages $m1$ and $m2$ use the same wavelength
$mwg_{m,wg}$	Message m goes through waveguide section wg
wlu_{λ}	Wavelength λ has been assigned to at least one message
$rt_{r,t}$	Type t is assigned to router r
$dc_{m,wg1,wg2,t}$	Message m goes through waveguide sections $wg1$ and $wg2$, and router with type t is connected to them
Integer	
nwl	Number of used wavelengths
Continuous	
mil_m	Insertion loss for message m
pl_m	Propagation loss for message m
$maxil$	Maximum insertion loss over all messages

Index $c_1, c_2 \in \{ C_m^S, C_m^R, R_m^S, R_m^R\}$

Table A.7.: Comparison among passive router design approaches

Nr.	#Cores	#M	Method	Loss	#W	Time
1	8	44	PSION+	1.90	7	643s
			M^m	2.69	7	19s
2	16	22	PSION+	1.77	7	69s
			M^m	2.52	7	11s
3	8	24	PSION+	1.68	6	331s
			M^m	2.54	6	3s
4	9	72	PSION+	1.90	11	83941.3s
			M^m	3.19	8	414.2s
5	12	84	PSION+	N/A	N/A	>10h
			M^m	3.07	9	779.07s
6	16	112	PSION+	N/A	N/A	2.33d
			M^m	5.18	4	8484.35s
7	40	38	PSION+	2.20	2	51139.5s
			M^m	2.53	2	237.38s

M^m: Our model on a mesh-based topology
#Cores, #M, #W: Number of cores, messages, wavelengths
Loss: Maximum loss

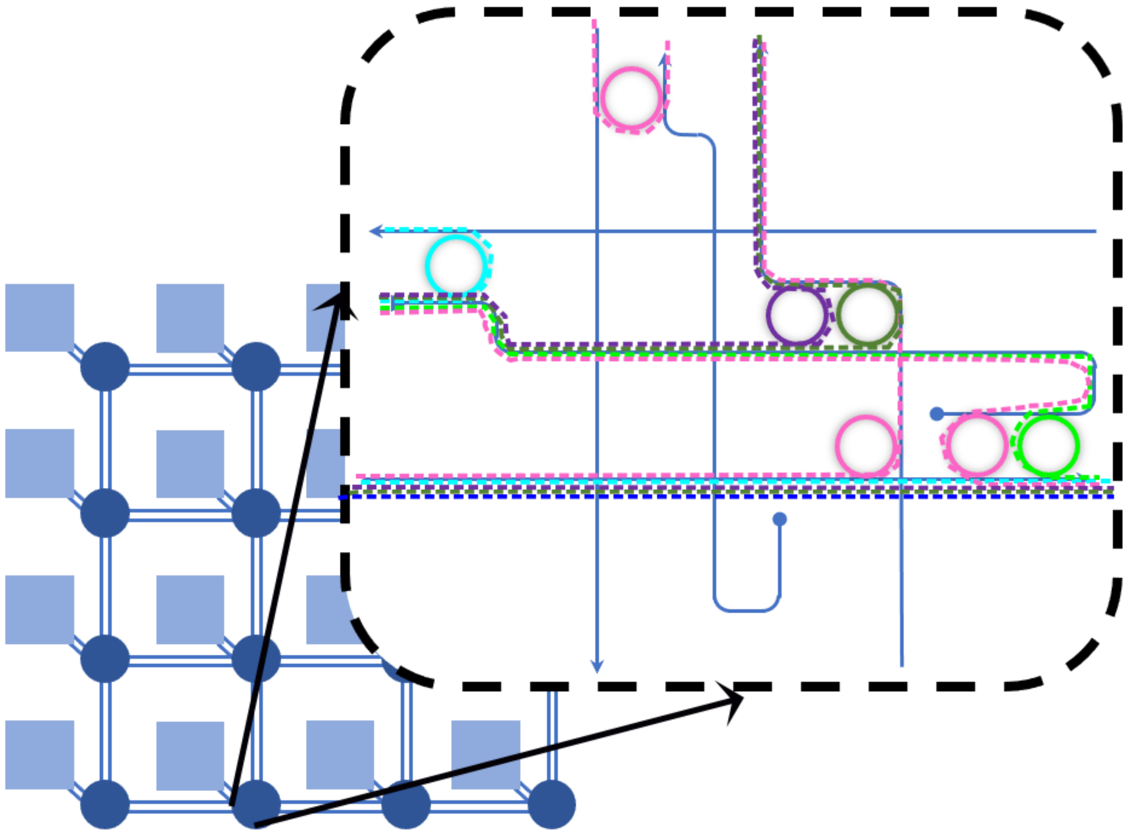


Figure A.1.: Illustration of test case 3.

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