MRR Usage Optimization for WRONoC Topology Generation and Communication Parallelism Depending on Bandwidth Requirements

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Abstract—Most studies of current Wavelength-routed optical networks-on-chip (WRONoC) topology generation methods are based on a single resonant wavelength of each silicon microring resonator (MRR). In this paper, we propose an MRR usage optimization method considering multiple resonant wavelengths for individual MRRs. Experimental results show that our approach can reduce MRR usage by 20% compared to the state of the art. Moreover, while communication parallelism methods for WRONoCs have mainly focused on maximizing the total bit parallelism regardless of message requirements, this paper illustrates wavelength assignments depending on the number of bit parallelism that each communicating pair requires.

I. Introduction

The ever-increasing number of cores on a chip brings the fatal problems of increasing power consumption in a total system and severe intercommunication between nodes on networks-on-chips (NoCs). Optical networks-on-chip (ONoC) is a promising platform beyond conventional electronic NoCs; ONoCs can provide much more efficient interconnection for its characteristics of both high bandwidth and ultra-low signal delay [1], [2]. Moreover, ONoCs yield power-efficient NoC design, which derives from its power consumption relatively independent of path distance [3], [4].

ONoCs replace electronic signals on conventional NoCs with optical signals for each optical communications in the networks. Optical signals on different wavelengths identify different communication pairs between senders and receivers. Wavelength-division-multiplexing (WDM) allows multiple optical signals on different wavelengths to travel on a single waveguide [2], providing its advantage of high throughputs and parallelism of communications on a chip. On the other hand, any wavelength assignments must not accommodate any optical signals on the same wavelength to avoid signal conflicts for routing faults. Wavelength-routed optical networks-on-chips (WRONoCs) statically assign optical wavelengths to each of the communication pairs and determine those communication paths on a chip at the design phase. This reservation-based interconnection can avoid dynamic reconfigurations without additional signal delay for path setup in progress at the later phases.

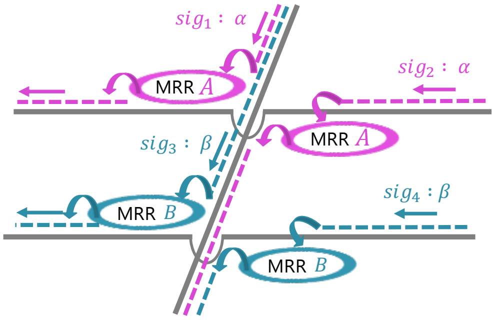


Fig. 1. The pink and blue optical signals can be "*on-resonance*" with the MRR A or MRR B, respectively.

Silicon microring resonators (MRRs) [5] enable optical signals to move to another waveguide, depending on the optical resonance principle. An MRR is composed of a looped waveguide, and it has its unique coupling mechanism between the ring and an adjacent bus waveguide. A microring has the specific radius of the ring as its parameter to identify types of MRRs. Individual values of the radius on MRRs provide the different optical path length on the ring resonator. An optical resonance occurs when the optical length of an MRR is equal to an integer multiple of the wavelength on the optical signals; this situation is called "*on-resonance*." Fig. 1 illustrates an example of switching signals by the resonance between MRRs and optical signals. The two pink signals, sig_1 and sig_2, have the wavelength α, and those optical signals are going to resonate with the MRR A. In contrast, the blue signals, sig_3 and sig_4, do not resonate with the MRR A, and those signals are going to pass through the MRR A without coupling.

Fig. 2 (a) shows a periodic transmission spectrum of three distinct MRRs. The colored arrow lines represent the distance between the nearest peaks, called the free-spectrum-range (FSR). An MRR has multiple resonant wavelengths depending on different FSRs based on the microring radius. Each peak of a transmission spectrum represents the distinct resonant mode, which provides a wavelength to resonate with a corresponding MRR. In Fig. 2 (a), the signal on λ_1 resonates with MRR R_1, and

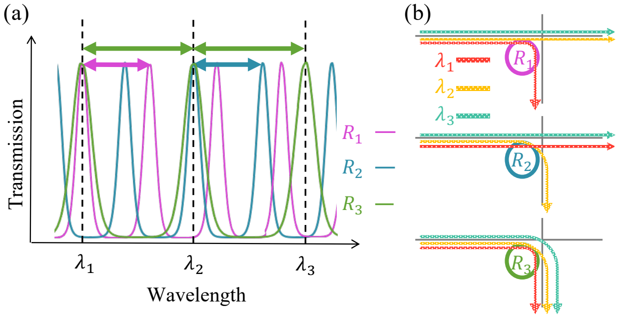


Fig. 2. (a) The periodic transmission spectrum of three distinct MRRs. (b) R_1 and R_2 resonate with the red and yellow signals, respectively. R_3 can be "*on-resonance*" with the red and yellow, and green signals.

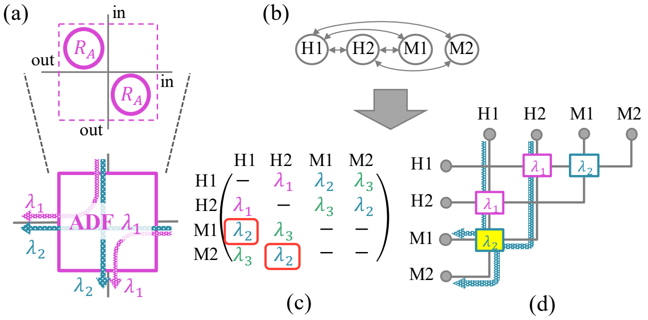


Fig. 3. (a) 2-input × 2-output ADF structure. (b) A graph to show the required communications. (c) Wavelength assignments. (d) A topology generation by CustomTopo.

the signal on λ_2 resonates with MRR R_2. Moreover, the two wavelengths can resonate with R_3 when it includes λ_1 and λ_2 in its set of resonant wavelengths with different resonant modes. Fig. 2 (b) gives an example that R_3 can change the directions of the three types of optical signals on λ_1 and λ_2, and λ_3. Note that the signal on λ_1 does not resonate with R_2 because R_2 does not have λ_1 in its resonant wavelengths with any resonant mode. Similarly, the situation in Fig. 2 (a) does not allow λ_2 to resonate with R_1.

An individual MRR has multiple resonant modes. For example, MRR R_3 in Fig. 2 can resonate with the optical signals on λ_1 and λ_2, and λ_3 with different resonant modes, respectively. Several studies for WRONoCs have applied the multi-mode resonance for each MRR to increase the bit-level parallelism after the stage of topology generations [6], [7]. However, WRONoC topology generation approaches have not taken it into account to utilize the multi-mode resonance of a single MRR. It seems challenging to design WRONoC topologies considering the same wavelength to resonate with different MRRs satisfying routing fault-free designs. In addition, any communication parallelism approach does not intend to allocate wavelengths according to the bandwidth requirement for each communicating pair.

This paper proposes an efficient usage of the multi-mode resonance for WRONoC topology generation for the first time to the best of the authors' knowledge. Then, we explain our method that indeed follows the state of the art WRONoC topology generation method, CustomTopo [8]; our method converts the topology generation problem into an integer-linear-programming (ILP) problem similar to CustomTopo. In this paper, we show a non-trivial way to represent constraints for our ILP formulation to allow multiple wavelengths resonate with the same MRR. Apart from our proposed optimization for the topology generation, we introduce communication parallelism problem to try to assign physical parameters according to bit parallelism requirements for a distinct communication.

The rest of this paper is organized as follows. Section II introduces the related approach and the necessary knowledge for our proposed method. In Section III, we first show an example how we can utilize multi-mode resonances, and then we explain how to formulate the proposed method into an ILP model. Section IV shows the experimental results on eight test cases for our proposed topology generation. Section V concludes our method and describe some possible future challenges.

II. Related works

WRONoC topologies with a large amount of optical resource usage lead to higher MRR tuning power [4] and laser power [7]. Thus, the reduction of those resource usage is a significant challenge for WRONoC designs and applications, especially for scalable NoCs with power-efficiency.

General WRONoC topologies focus on full connectivity topologies that all sender nodes send messages to all receiver nodes [9], [10], [11]. CustomTopo [8] does not require the communication graphs to be complete or symmetric because fully connected WRONoC topologies increase the number of MRRs quadratically with the number of sender/receiver nodes. CustomTopo utilizes the first mathematical formulation of the topology synthesis automation and provides optimized WRONoC topologies to minimize both usage of MRR and wavelengths for topology customizations [12].

CustomTopo applies add-drop filters (ADFs) for the optical switching element, which is composed of two MRRs at a crossing point between different waveguides as shown in Fig. 3 (a); an ADF has two input ports at the northern or the eastern port and two output ports at the southern and the western port.

CustomTopo generates a customized topology in according to communication requirements; for example, a directed graph in Fig. 3 (b) illustrates the definition of required communications. CustomTopo can provide the automated simulation to decide the best wavelength assignment to each communicating pair (Fig. 3 (c)), and to determine to place ADFs on necessary waveguide intersections (Fig. 3 (d)).

III. Proposed method

In this section, we explain how our WRONoC topology generation can reduce the ADF number by considering multi-mode resonance for signal routing. In the following section, we illustrate the proposed method to formulate the reduction of ADFs as an ILP problem.

A. *The proposed topology construction considering multi-mode resonaces*

While CustomTopo provides the most effective way to generate WRONoC topology with its design automation, the topology synthesis does not consider multiple resonant

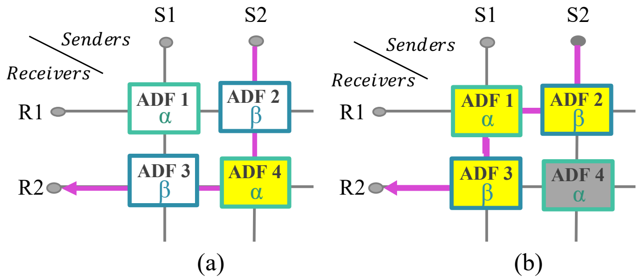


Fig. 4. (a) A signal from *S2* to *R2* can resonate with *ADF 4* in CustomTopo. (b) The proposed topology generation considers the signal on α resonate with both ADFs on α and β.

wavelengths on a single ADF for its routing of optical signals. On the contrary, our method considers multi-mode resonance for each MRR; an ADF can resonate with multiple wavelengths. Fig. 4 gives an example to show the difference between the routing in CustomTopo and that of the proposed method considering multi-mode resonance. In the given topology in Fig. 4, four messages from sender nodes to receiver nodes are required to be transmitted, i.e., *(S1,R1), (S1,R2), (S2,R1), (S2,R2)*. Fig. 4 (a) shows that CustomTopo decides to put an ADF on each intersection between different waveguides to realize the routing of individual signals. For example, the wavelength α ($\neq \beta$) is assigned to the signal from *S2* to *R2*; the signal resonates with the MRR in *ADF 4* in Fig. 4 (a), and thus changes its direction at *ADF 4*. Note that the transmission spectrum of MRR α is chosen such that it does not overlap on any one of resonant wavelength for MRR β in Fig. 4 (a).

On the other hand, our method tries to utilize multiple resonant modes for an ADF, and then our method can find a topology as shown in Fig. 4 (b) where both *ADF 2* and *ADF 3* can resonate with the two resonant wavelengths α and β according to its different resonant modes. In this example, the signal on wavelength α can resonate with two different ADFs on α and β. While the signal from *S2* to *R2* resonates with only *ADF 4* in the topology synthesized by CustomTopo (as shown in Fig. 4 (a)), our method allows the same signal (from *S2* to *R2*) to resonate with *ADF 1*, *ADF 2* and *ADF 3* in Fig. 4 (b). By doing this, we can omit *ADF 4* which is filled with gray in Fig. 4 (b) because no message transmissions need *ADF 4* for routing.

The above example illustrates our main idea to reduce ADFs by using multiple resonant wavelengths for one ADF. However, it is not straightforward about how to reduce ADFs by using the above idea; we explain how to formulate this reduction technique as an ILP problem in the next section.

B. Our Proposed ILP Formulation

Our problem is formally stated as follows:
Input. The number of nodes and the communication requirements between nodes are given as the input. We denote the number of communication nodes as an integer number n. In an ILP problem, we define $n \times n$ binary variables $msg_{i,j}$ according to a required communications; $msg_{i,j}$ is defined as follows:

$$msg_{i,j} = \begin{cases} 1 & sender_i\ communicates\ with\ receiver_j. \\ 0 & otherwise. \end{cases} \quad (1)$$

TABLE I
CONSTANTS AND VARIABLES USED IN OUR ILP FORMULATION

Constants	
n	The number of nodes.
p	The minimum number of the necessary signal types.
wv_mode_1	The set of allocatable integers : $\{1, 2, \cdots, p\}$
wv_mode_2	The set of allocatable integers : $\{p+1, p+2, \cdots, 2p\}$
wv_mode_3	The set of allocatable integers : $\{1-p, 2-p, \cdots, 0\}$
$weight_{wv}$	The weight coefficient on the cost of wavelengths.
$weight_{adf}$	The weight coefficient on the cost of ADFs.

Binary variables	
$msg_{i,j}$	$sender_i$ communicates with $receiver_j$.
$adf_{i,j}$	An ADF is placed at $int_{i,j}$.
$rmv_{k,i,j}$	The $k-th$ condition to remove $adf_{i,j}$ is satisfied.
wv_λ	Wavelength λ is assigned to any ADFs.

Integer variables	
$wv\_assign_{i,j}$	An assigned wavelength to a signal for $msg_{i,j}$.
wv_cost	The number of wavelengths assigned to ADFs.
adf_cost	The number of ADFs.

If $msg_{i,j} = 1$ is given, the *i-th* sender node needs to transmit a message to the *j-th* receiver node. On the contrary, there is no message from the *i-th* sender to the *j-th* receiver when $msg_{i,j}$ is 0.
Our task. Our proposed method generates a WRONoC topology as output for all messages to communicate. We need to decide wavelength assignments for each message and ADF positions to realize all the required communications on a WRONoC topology. Our objective is to reduce the numbers of necessary wavelengths and ADFs.

We formulate our problem as an ILP problem. Table I contains constants and variables in our ILP problem. In the following, we explain how we formulate the constraints as an ILP problem.

B.1. Signal conflict-free communications

Every node, including both sender and receiver nodes, connects with a waveguide. Since all the signals from a single sender node enter into one of those corresponding waveguides, all messages from a single node are overlapped on the waveguide with the inevitable wavelength multiplexing. Moreover, each receiver node can receive messages addressed to them from the individual connected waveguides. Thus, a receiver node needs to identify each sender from the collective signals. WDM does not allow multiple signals on the same frequency to travel on a single waveguide, which leads to the following constraint that requires any wavelength of all the multiplexed messages to be different from each other.

$$\forall 0 \leq i, j, s, t < n, s \neq t :$$
$$(msg_{i,s} = msg_{i,t} = 1) \Rightarrow wv\_assign_{i,s} \neq wv\_assign_{i,t} \quad (2)$$
$$(msg_{s,j} = msg_{t,j} = 1) \Rightarrow wv\_assign_{s,j} \neq wv\_assign_{t,j} \quad (3)$$

where $wv\_assign_{i,j}$ is an integer variable to represent the wavelength value assigned to the message from the *i-th* sender to the *j-th* receiver.

B.2. Wavelength formulation

A message can share the same wavelengths for data transmissions between different messages as long as both (2) and (3) constraints are satisfied. On the contrary, this means that for any pair of two messages going through the same waveguide should use different wavelengths. Thus, if we define an integer variable, p, to denote the necessary number of wavelengths to be multiplexed on a single waveguide, p should be equal to the maximum number of entries for each column or row in $msg_{i,j}$. For example, as for the wavelength assignments in Fig. 3 (c), three signals whose sender-receiver pairs are different should go through the same waveguide; we need at least three wavelengths to assign such three signals, and so p becomes 3 for this example.

As mentioned in Section *III-A*, our method considers allocating multiple resonant wavelengths for each MRR; an example in Fig. 4 (b) shows that ADFs on β resonate with wavelength α and β. We formulate multiple resonant modes for an individual MRR as different sets of allocatable integers as follows:

$$wv\_mode_1 = \{1, 2, \cdots, p\} \tag{4}$$

$$wv\_mode_2 = \{p+1, p+2, \cdots, 2p\} \tag{5}$$

$$wv\_mode_3 = \{1-p, 2-p, \cdots, 0\} \tag{6}$$

In our ILP formulation, we need to check whether any pair of two wavelengths can resonate with the same ADF or not. By the above integer assignment to wavelengths, we can derive this condition very easily as follows.

$$|wv\_assign_{i,j} - wv\_assign_{s,t}| = p \tag{7}$$

In our framework, we consider that any two signals on wavelengths from wv_mode_2 or wv_mode_3 do not have any resonant relations between each other. For an example as shown in Fig. 2, R_3 provides λ_3 as the basic wavelength, and it allows λ_1 and λ_2 to resonate with itself on its different modes. However, λ_1 does not resonate with R_2, and λ_2 does not resonate with R_1. Thus, wv_mode_2 has integer values from $p+1$ to $2 \times p$, and wv_mode_3 takes integer values in the range of $1-p$ to 0 so that any two integers from wv_mode_2 and wv_mode_3 do not satisfy Equation (7).

B.3. ADF reduction modeling

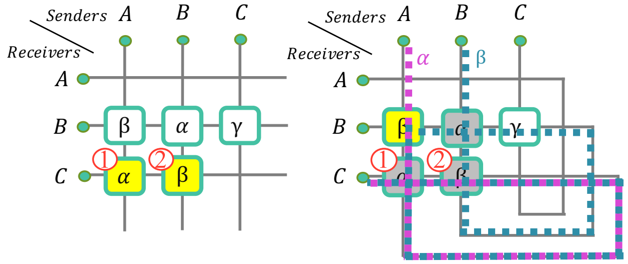
We introduce a binary variable $adf_{i,j}$ to model the need to put an ADF at the intersection between the *i-th* sender waveguide and the *j-th* receiver waveguide. If $adf_{i,j}$ is set to 1, an ADF is placed at the intersection between two waveguides, which corresponds to sender/receiver nodes. $adf_{i,j} = 0$ means the ADF placement at the corresponding point is not required.

The simplest solution of topology generation is to construct an ADF for each sender-to-receiver transmission requirement. This solution can be achieved by setting $adf_{i,j} = 1$ when the *i-th* sender communicates with the *j-th* receiver. Therefore, the following constraint is necessary:

$$\forall 0 \le i,j < n: \quad adf_{i,j} \le msg_{i,j} \tag{8}$$

We propose three types of ADF removal conditions including the proposed reduction approach introduced in Section *III-A*. The constraint (8) implies that the ADF usage can be reduced when one of the following ADF reduction constraints work for setting $adf_{i,j}$ to 0. We use a binary variable $rmv_{k,i,j}$ such that $rmv_{k,i,j} = 1$ implies that the *k-th* condition to remove the ADF at $int_{i,j}$ is satisfied. That is, if the one of $rmv_{k,i,j} (k = 1, 2, 3)$ is 1, we can set $adf_{i,j} = 0$. Thus we have the following constraint:

$$\forall 0 \le i,j < n, msg_{i,j} = 1: \sum_{k=1}^{3} rmv_{k,i,j} \ge 1 \Rightarrow adf_{i,j} = 0 \tag{9}$$



(a) (b)

Fig. 5. (a) A topology without any waveguide loop. (b) An example to reduce ADFs with waveguide loops.

B.4. The 1st and 2nd condition to remove ADFs

CustomTopo utilizes waveguide loops to reduce the number of ADFs.

A temporary topology in Fig. 5 (a) does not consider any waveguide loop. On the other hand, Fig. 5 (b) illustrates an example where waveguide loops are used. We omit the ADF which is filled with gray by attaching a waveguide loop as shown in Fig. 5 (b). In this case, without the ADF, a signal from $sender_A$ can go to $receiver_C$; the corresponding intersection is called waveguide-looped. Since we can take one waveguide-looped intersection per column and row, we formulate this *1st* ADF removal condition as follows:

$$\forall 0 \le i < n: \quad \sum_{j=0}^{n-1} rmv_{1,i,j} = 1 \tag{10}$$

$$\forall 0 \le j < n: \quad \sum_{i=0}^{n-1} rmv_{1,i,j} = 1 \tag{11}$$

In addition, CustomTopo utilizes its unique ADF reduction approach called "*ADF-sharing structure*." The ADF indicated by encircled 2 in red in Fig. 5 (b) can be reduced by this approach. The constraints of "*ADF-sharing structure*" in [8] can be written into our ILP formulation as follows:

$$\forall 0 \le i_1, i_2, j_1, j_2 < n:$$

$$wv\_assign_{i_2,j_2} = wv\_assign_{i_1,j_1} \tag{12}$$

$$adf_{i_1,j_1} = rmv_{1,i_1,j_2} = rmv_{1,i_2,j_1} = 1 \tag{13}$$

rmv_{2,i_2,j_2} can be set to 1 when the above constraints (12) and (13) are satisfied to omit the ADF at int_{i_2,j_2}.

B.5. The 3rd condition to remove ADFs

Now we are ready to explain our main technique in this paper; the *3rd* condition to remove ADFs is explained in the following. If the following constraints are satisfied, we can remove an ADF by considering multi-mode resonances as mentioned in Section *III-A*.

$$\forall 0 \leq i_1, i_2, j_1, j_2 < n :$$

$$msg_{i_1,j_1} = msg_{i_1,j_2} = msg_{i_2,j_1} = msg_{i_2,j_2} = 1 \quad (14)$$

$$wv\_assign_{i_1,j_1} - wv\_assign_{i_2,j_2} = 0 \quad (15)$$

$$wv\_assign_{i_1,j_2} - wv\_assign_{i_2,j_1} = 0 \quad (16)$$

$$|wv\_assign_{i_2,j_2} - wv\_assign_{i_2,j_1}| = p \quad (17)$$

$$adf_{i_1,j_1} = adf_{i_1,j_2} = adf_{i_2,j_1} = 1 \quad (18)$$

The binary value of rmv_{3,i_2,j_2} is set to 1 only when the above constraints (14)-(18) are satisfied to omit the ADF at int_{i_2,j_2}.

B.6. Objective function

There are two optimization targets, the number of wavelengths for ADFs and that of ADFs in a topology. We introduce two integer variables , wv_cost and adf_cost, to count the both costs, respectively. Besides, an additional binary variable wv_λ is used to represent the wavelength λ to be assigned to any ADFs. Therefore, the two target costs are formulated as follows:

$$wv\_cost = \sum_{1-p}^{2\cdot p} wv_\lambda \quad (19)$$

$$adf\_cost = \sum_{i=0}^{n-1}\sum_{j=0}^{n-1} adf_{i,j} \quad (20)$$

In an ILP problem, objective function is expressed as a linear function with weight coefficients. The objective function in our method can be formulated as follows:

$$Min : weight_{wv} \cdot wv\_cost + weight_{adf} \cdot adf\_cost \quad (21)$$

where $weight_{wv}$ and $weight_{adf}$ are weight coefficients for both costs of wavelengths and ADFs.

C. The proposed bit parallelism method along communication requirements

While most communication parallelism approaches for WRONoCs aim to maximize the total parallelism per unit time, our parallelism simulation can deal with the number of transmissions that each sender-receiver pair requires to communicate. In a problem of communication parallelism in WRONoCs, three types of input are necessary as follows:

- An MRR radii domain depending on the design environment.
- A frequency bandwidth to define values of allocatable wavelengths
- WRONoC topology to provide reserved signal paths between communicating pairs after a topology generation.

In our simulation, we handle bandwidth requirements for each communicating pair. If we try to ideally assign the same number of wavelengths as many as the required bit parallelism per unit time for each sender-receiver pair, there are possibly two scenarios to provide the best solution to realize the required bit parallelism. The first scenario has many MRR radii options and allocatable wavelengths to assign values to all the required communications. On the contrary, the second scenario makes us decide how much we give up allocating wavelengths when available physical parameters are not enough to satisfy every requirement. We formulate this problem as another constraint optimization problem to maximize communication parallelism as long as solutions satisfy that assigned communications must not exceed the number of requirements and available resonant wavelengths for an MRR.

Since the best solution depends on the designer's situations, our method provides multiple targets; for example, one approach tries to increase the total throughputs per unit time, and another way maximizes the minimal number of bit parallelism for each pair. We formulate these variable designs as the objective function that includes the following values:

- The total number of communications per unit time.
- The total difference between assignments and requirements for each pair.
- The difference between the average assignments and requirements for every pair.
- The total difference between assignments for a pair and the average assignments for all pairs.

In our wavelength assignment problem, the optimization objective can be formulated as:

$$Maximize : \alpha \cdot \sum_{i=0}^{n-1}\sum_{j=0}^{n-1} com_{i,j} + \beta \cdot \sum_{i=0}^{n-1}\sum_{j=0}^{n-1} (com_{i,j} - req_{i,j}) + \gamma \cdot (\overline{com} - \overline{req}) + \delta \cdot \sum_{i=0}^{n-1}\sum_{j=0}^{n-1} (com_{i,j} - \overline{com}) \quad (22)$$

where $com_{i,j}$ has an integer to express the number of assigned wavelengths to communicate between $sender_i$ and $receiver_j$. $req_{i,j}$ implies the number of requirements to communicate for the same pair per unit time. $\overline{com}$ and $\overline{req}$ illustrate the average assignments and requirements for every pair, respectively. $\alpha, \beta, \gamma, \delta$ are weight parameters that allow designers to adjust targets.

IV. Experimental Results

We implemented the proposed method in C++ and solved the generated ILP problem with IBM ILOG CPLEX [14]. Since the hardware cost and the static power consumption increase as the number of MRRs increases, we tried to minimize both the number of MRRs and the number of distinct wavelengths in our experiments.

We simulated the topology generation with our proposed method and CustomTopo on a machine with an AMD Ryzen 7 3800X BOX. Table II provides the comparison of the WRONoC design costs between the results of CustomTopo and the proposed method for eight different communication graphs. Cases *1*, *7*, and *8* have a similar feature: only two nodes receive messages from other nodes. For Case *2* and Case *3*, #n and #m are the same, but the communication graphs are slightly different. In the communication graph in Case *2*, there are two nodes which send/receive messages to/from the other six nodes. Case *3* has four nodes which transmit four messages, and the other four nodes which have two message requirements. Case *4* is 4-hub-4-memory case. Hubs talk to all the others and memories talk only to hubs. Case *5* includes a high network density with a fully symmetric communication requirement. By contrast, Case *6* has

TABLE II

Comparison of the WRONoC costs of topology generations with the state-of-the-art approach.

Case	#n	#m	Method	#wv	#MRR	MRR ratio	IL ratio	Time
1	8	12	CustomTopo	5	18	1.00	1.00	<1
			Proposed	5	14	0.78	1.26	<1
2	8	24	CustomTopo	6	24	1.00	1.00	<1
			Proposed	6	18	0.75	1.17	<1
3	8	24	CustomTopo	5	28	1.00	1.00	<1
			Proposed	5	24	0.86	1.11	<1
4	8	44	CustomTopo	6	48	1.00	1.00	<1
			Proposed	6	40	0.83	1.20	63
5	8	48	CustomTopo	5	40	1.00	1.00	<1
			Proposed	5	32	0.80	1.12	15
6	16	22	CustomTopo	6	20	1.00	1.00	<1
			Proposed	6	18	0.90	1.18	<1
7	16	28	CustomTopo	13	50	1.00	1.00	<1
			Proposed	13	38	0.76	1.15	10
8	24	44	CustomTopo	21	82	1.00	1.00	<1
			Proposed	21	62	0.76	1.10	177

#n is the number of communication nodes, #m is the number of required messages, #wv represents the necessary number of wavelengths, #MRR shows the number of MRRs in a generated topology, 'MRR ratio' illustrates the ratio of #MRR of the proposed method to that of CustomTopo, 'IL ratio' means the ratio of the avarage insertion loss of the proposed method to that of CustomTopo, and 'Time' shows the computation time in minutes to find the optimized solution.

sparse network connectivity. We obtained the improvement of the MRR usage for all eight test cases. We consider that one of the reasons why our method can remove more MRRs than CustomTopo is "the *3rd* condition to remove ADF" mentioned in Section *III-B-6*.

In order to minimize total power consumption in WRONoC designs, a logical topology generation needs to cut down possible insertion loss for each signal routing. Thus, we calculated the average value of insertion loss for each optical signal from the generated topologies. The column of *'IL ratio'* in Table II shows the ratio of the average insertion loss of the proposed method to CustomTopo. The insertion loss parameters from [13] show that the most influential loss is the drop loss, which is caused by occurrences of resonances between optical signals and MRRs. For the signal routing to utilize the *3rd* condition to remove ADFs, the transmission path requires more drops than any other signal routing in CustomTopo. Therefore, our proposed method may increase the insertion loss in WRONoC designs. However, since the logic topology synthesis does not calculate the accurate insertion loss without the physical placement of communication nodes, the highest insertion loss could be optimized on the later physical design.

V. Conclusion

In this paper, we have proposed a topology generation method considering multi-mode resonances between different wavelengths. Our method can utilize the ADF removal condition by considering the wavelengths that can resonate with multiple ADFs for our WRONoC topology generation. Our method is formulated as an ILP problem to minimize the both costs of the number of assigned wavelengths to ADFs and that of necessary ADFs. The ADF removal condition considering multi-mode resonances on MRRs leads to reduce more ADFs compared with the state-of-the-art topology generation method, CustomTopo, with a little deterioration of insertion loss. In addition to a topology generation approach, we propose the communication parallelism approach to deal with the number of communication requirements for each node pair. Since our proposed parallelism method would take more time to execute and show the best solution as the data set becomes complexed and available resources increase, our future work would consider heuristic approach to solve the same problem in a practical time.

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