A Provably Good Wavelength-Division-Multiplexing-Aware Clustering Algorithm for On-Chip Optical Routing

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***Abstract*—As the VLSI technology continues to scale down, combined with increasing demands for large bandwidth and low-power consumption, the optical interconnections with Wavelength Division Multiplexing (WDM) become an attractive alternative for on-chip signal transmission. Previous WDM-aware optical routing works consist of two main drawbacks: they are based mainly on heuristics or restricted integer linear programming to handle optical routing, and the addressed types of transmission loss and WDM overheads are incomplete. As a result, no performance guarantees can be achieved on their WDM clustering results, and/or their computations are too time-consuming. To remedy these disadvantages, we present a polynomial-time provably good WDM-aware clustering algorithm and a new WDM-aware optical routing flow to minimize the transmission loss and the WDM overheads with a significant speedup. The proposed WDM-aware clustering algorithm guarantees to find an optimal solution for 1-, 2-, and 3-path clustering, and has the constant performance bound 3 for most cases of 4-path clustering. Experimental results based on the ISPD 2007 and 2019 contest benchmarks and a real optical design show that our optical router significantly outperforms published works in wirelength, transmission loss, wavelength power, and runtimes.**

I. Introduction

With the VLSI process technology scaling into the deep nanometer era and the increasing demands for large bandwidth and low-power transmission, the performance of interconnections becomes a key bottleneck in modern circuit designs. As a result, electrical wires might not meet the design requirements, and thus various techniques have been proposed to resolve the problems [2], [3], [6], [14], [18], [19], [20]. Among these techniques, optical communication based on nanophotonic devices and interconnections attracts much attention, due to its large bandwidth, low interconnection delay, and low-power consumption. For example, one of the main goals in the US DARPA-launched Electronic Resurgence Initiative (ERI) project is to bring photonic signaling to digital microelectronics [7]. Semiconductor giants like Intel and TSMC are also actively exploring the technologies for integrating optical interconnections [13], [17].

However, the layout synthesis for optical interconnections, called *the optical routing problem*, is quite different from the traditional electrical one. During optical routing, not only wirelength but also transmission loss needs to be minimized. Therefore, new optimization strategies are required for the optical routing problem.

Among many recent advanced techniques for the optical routing problem, Wavelength Division Multiplexing (WDM) shows a great potential of providing higher bandwidth with reasonable overheads [12]. Figure 1 shows the structure and the representation of a WDM waveguide. By using multiplexers and demultiplexers, signal nets with different wavelengths can be clustered into a single WDM waveguide for signal transmission, saving more routing resources and reducing potential crosses.

However, the use of WDM waveguides in optical transmission needs to be considered carefully. Take Figure 2 as an example. If we perform optical routing without using WDM, we must trade off between signal crossing and wire detouring, as shown in Figure 2(a). If the WDM signal nets are clustered poorly, however, the total wirelength might be even worse, as shown in Figure 2(b). Furthermore, using WDM waveguide for signal transmission also requires additional power overheads, including drop loss and laser wavelength power, which will be detailed in Section II-A. In this work, we instead propose a provably good WDM clustering algorithm that can generate a desired

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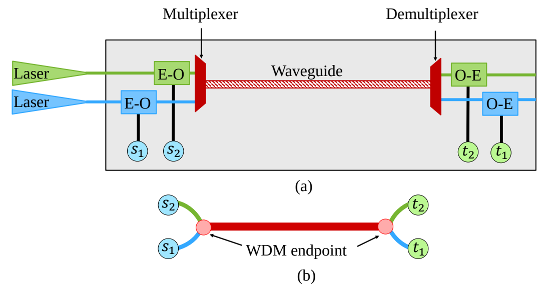

Fig. 1. (a) The structure of the Wavelength Division Multiplexing (WDM) technique and (b) the representation of the WDM waveguide in this work. The WDM endpoints represent the start/end points of the WDM waveguides.

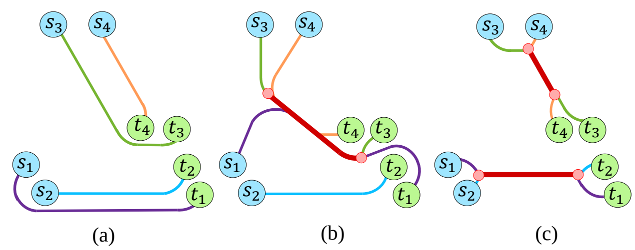

Fig. 2. (a) If we perform optical routing without using any WDM waveguide, detouring or crossing could occur. (b) If we use WDM waveguides unwisely, the wirelength, transmission loss, and wavelength power could be even worse. (c) Our WDM-aware clustering algorithm can achieve a desired clustering result.

clustering solution considering wirelength, transmission loss, and wavelength power, as shown in Figure 2(c).

A. Previous Works

Optical routing problems addressing different types of transmission loss have been studied recently. For optical routing without WDM waveguide clustering, Ding *et al.* proposed an ILP-based pattern routing framework for low-power optical Network-on-Chip (NoC) design [8], Boos *et al.* proposed a placement-and-routing engine for fast performance degradation evaluation [2], Chuang *et al.* proposed a graph-based concurrent placement and routing scheme for planar circuits to minimize the number of signal crosses [4], and Li *et al.* proposed an ILP-based topology generation method for wavelength-routed optical NoCs [11]. For the WDM-aware optical routing problem, Ding *et al.* proposed an ILP-based thermally reliable global router for optical interconnection synthesis [9], and Liu *et al.* proposed an ILP-based optical-electrical routing scheme for power optimization [12]. The works [9] and [12] both used heuristics to place WDM waveguides. Table I compares these works.

The aforementioned previous works have three main drawbacks:

- No performance guarantees are obtained for their WDM-aware clustering results.
- Their optimization techniques are time-consuming.
- Their considerations of transmission loss and WDM overheads are incomplete.

To remedy these drawbacks, this paper presents the first provably good WDM-aware clustering algorithm and a comprehensive WDM-aware optical routing flow to minimize wirelength, transmission loss, and wavelength power effectively and efficiently.

TABLE I

COMPARISONS OF THE COMPLETENESS OF ROUTING FLOWS AND PERFORMANCE GUARANTEES BY DIFFERENT METHODOLOGIES. THE WORK [4] GUARANTEES TO MINIMIZE THE NUMBER OF CROSSES, WHILE THE WORK [11] OPTIMIZES THE CROSSING AND PATH LOSS OF AN ADJUSTABLE OBJECTIVE FUNCTION. HOWEVER, BOTH WORKS DO NOT HANDLE THE OPTICAL ROUTING USING WDM WAVEGUIDES.

Work	Methodology	WDM Consideration	Detail Routing	Addressed Transmission Loss					Performance Bound
				Crossing	Bending	Splitting	Path	drop	
Ding09 [8]	ILP with Variable Reduction	No	Yes	Yes	Yes	No	Yes	No	No
Boos13 [2]	Maze Routing	No	Yes	Yes	No	No	Yes	No	No
Chuang18 [4]	Planar Graph Algorithm	No	No	Yes	No	No	No	No	Yes
Li18 [11]	ILP with Adjustable Parameters	No	No	Yes	No	No	Yes	No	Yes
Ding12 [9]	ILP	Yes	No	Yes	No	No	Yes	Yes	No
Liu18 [12]	ILP and Network Flow	Yes	No	Yes	Yes	Yes	Yes	Yes	No
This work	Approximation Algorithm	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

B. Our Contributions

We summarize the main contributions of this paper as follows:

- We propose a provably good approximation algorithm for WDM-aware path clustering to minimize the wirelength, transmission loss, and wavelength power. The WDM-aware clustering algorithm is exact for 1-, 2-, and 3-path clustering and has the constant performance bound 3 for most cases of 4-path clustering. To our best knowledge, this is the *first* polynomial-time algorithm that can guarantee a performance bound for WDM-aware clustering.
- We formulate the WDM-aware optical routing problem and divide it into two subproblems, called the *WDM-aware path clustering subproblem* and the *pin-to-waveguide routing subproblem*. Then we present a complete WDM-aware optical routing flow which combines a WDM-aware path clustering scheme and a pin-to-waveguide routing one to minimize wirelength, transmission loss, and wavelength power.
- An accurate wirelength, transmission loss, and wavelength power estimation method is proposed. The prediction and evaluation of optical routing results are substantially improved.
- Experimental results based on the ISPD 2007 and 2019 contest benchmarks and a real design show that our optical router significantly outperforms published works in wirelength, transmission loss, wavelength power, and runtimes.

The remainder of this paper is organized as follows. Section II introduces the types of transmission loss and the WDM overheads, and then formulates the WDM-aware optical routing problem and its subproblems. Section III presents our WDM-aware optical routing flow. Section IV reports and analyzes the experimental results. Finally, Section V concludes this paper.

II. PRELIMINARIES

In this section, we first introduce the types of transmission loss and WDM-induced overheads in optical routing addressed in this work, and then give our formulation of the WDM-aware optical routing problem.

A. Transmission Loss and WDM Overheads

Here we introduce five major types of transmission loss in optical routing: *crossing loss*, *bending loss*, *splitting loss*, *path loss*, and *drop loss* as shown in Figure 3.

- *Crossing Loss* (L_{cross}): The crossing loss is induced by two wires intersecting with each other. Based on the crossing angle between two wires, its values range from 0.1dB to 0.2dB per crossing [1], [16].
- *Bending Loss* (L_{bend}): The bending loss occurs when a signal is transmitted through a bending wire. Its values range from 0.01dB to 0.1dB per bend, which is inversely proportional to the radius of curvature [8], [5]. To reduce excessive optical signal losses, the bending radii of wires need to satisfy the minimum/maximum bending radius constraints, which is specified by the designers.
- *Splitting Loss* (L_{split}): The splitting loss happens when a signal splits into multiple sinks. Its values range from 0.01dB to 2dB per split, determined by the efficiency factor of a signal splitter [21].
- *Path Loss* (L_{path}): The path loss is induced when a signal is transmitted through a long wire. It is often neglected in previous works. Its values range from 0.01dB to 2dB per centimeter, which is proportional to the wirelength.
- *Drop Loss* (L_{drop}): The drop loss is induced when a signal is switched from one waveguide to another. Its values range from 0.01dB to 0.5dB per switch [2], [4], [20]. It is a WDM-induced overhead.

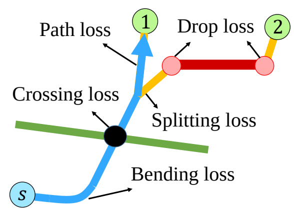

Fig. 3. Five major types of transmission loss in optical routing.

In this work, the total transmission loss L is calculated as follows:

$$L = L_{cross} + L_{bend} + L_{split} + L_{path} + L_{drop}. \tag{1}$$

Besides drop loss, using WDM waveguides could also incur another power overhead: *wavelength power*.

- *Wavelength Power* (H_{laser}): When multiple signals are clustered into a WDM waveguide, different wavelengths are needed for signal transmission. This requires more laser sources, which implies more power consumption.

B. Problem Formulation

The WDM-aware optical routing problem addressed in this paper can be formulated as follows:

*Problem 2.1 (**WDM-aware Optical Routing**):* Given a signal netlist, pin locations, and a maximum capacity for a WDM waveguide C_{max}, generate a routing result that minimizes total wirelength, transmission loss, and wavelength power, while the number of nets in each WDM waveguide does not exceed C_{max}.

In this WDM-aware optical routing problem, however, it is too complicated to determine both the clusters of signal nets and the route at the same time, so we divide this problem into two subproblems:

*Problem 2.2 (**WDM-aware Path Clustering**):* Given a signal netlist, pin locations, and a maximum capacity for a WDM waveguide C_{max}, determine the clusters of signal nets and corresponding positions of WDM waveguides to minimize the estimated wirelength, transmission loss, and wavelength power, while the number of nets in each WDM waveguide does not exceed C_{max}.

*Problem 2.3 (**Pin-to-Waveguide Routing**):* Given a signal netlist, pin locations, net clusters, and WDM waveguides positions for each net, generate a routing result which minimizes total wirelength and transmission loss.

III. WDM-AWARE OPTICAL ROUTING FLOW

In this section, we first give an overview of our WDM-aware optical routing flow, and then introduce how we handle the aforementioned two routing subproblems. Figure 4 shows the WDM-aware optical routing flow which consists of the following four stages: (1) *Path Separation*, (2) *Path Clustering*, (3) *Endpoint Placement*, and (4) *Pin-to-Waveguide Routing*. Path Separation identifies the signal net candidates for using WDM waveguides, Path Clustering finds the clusters of the signal nets based on a provably good approximation algorithm, Endpoint Placement finds the legal locations for WDM endpoints, and Pin-to-Waveguide Routing connects all pins to the corresponding WDM waveguides.

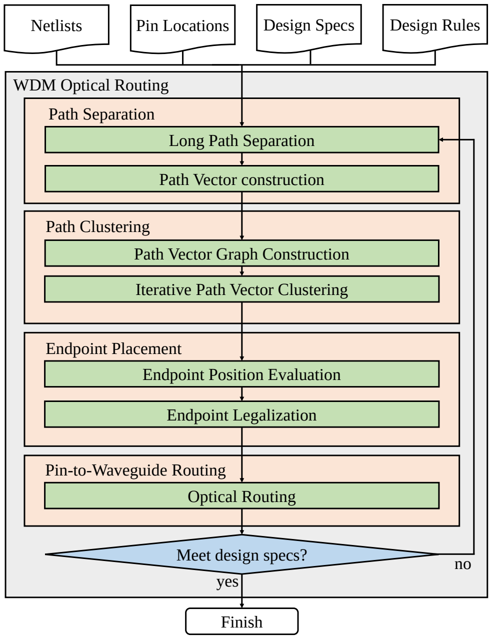

Fig. 4. The WDM-aware optical routing flow.

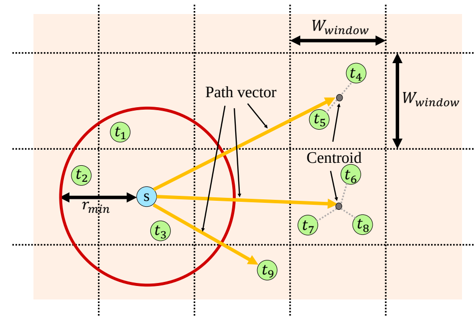

Fig. 5. The signal paths are separated into two sets: S for WDM-aware path clustering and S' for direct routing. Then the path vectors are generated for all windows that contain the straight paths in S.

A. Path Separation

Since there is a maximum capacity C_{max} for each WDM waveguide, the WDM waveguide bandwidth is limited, and thus should be reserved for suitable signal nets to avoid redundant WDM waveguide generation, which could incur excessive routing resource and power overheads. Therefore, we perform Path Separation to identify the signal path candidates for clustering. Here a signal path represents a source-to-target path that transmits a signal.

1) Long Path Separation: Given the locations of the source pin and the target pins in a net, we first calculate all source-to-target Euclidean distances, and then select the target pins with the distances longer than a user-defined threshold distance r_{min} to form the set S, and the target pins with distances shorter than r_{min} to form the set S'.

The signal paths from the source to pins in S might incur crosses and/or detours caused by other signal paths, and are thus suitable to use the WDM waveguides. In contrast, the signal paths from the source to pins in S' are regarded as simple routes, which can be routed directly with short wirelength and without crossing, and are thus prohibited from using the WDM waveguides.

2) Path Vector Construction: After identifying the long signal paths, we generate path vectors accordingly. A path vector is composed of a starting point and an end point, which represents the direction, distance, and spatial location of a signal path. The path vectors are candidates for clustering in the next stage. In order to reduce the number of candidates generated after Path Separation, we split the routing area into grid-like windows by a user-defined parameter W_{window}. In each window, the target pins that belong to the same net, and the source pin of that net, are grouped to form a path vector. The starting point of a path vector is the location of the source pin, while the end point of a path vector is the centroid of all target pins, as shown in Figure 5.

B. Path Clustering

Different combinations of signal path grouping significantly affect the final routed wirelength, transmission loss, and wavelength power, as shown previously in Figure 2. Therefore, determining the groups of signal paths—called path clusters—to share the same WDM waveguides plays a crucial part before the routing stage.

To best use the WDM waveguides, we need to estimate the total wirelength, transmission loss, and wavelength power induced by the path clusters. Hence we propose a scoring strategy to evaluate the path clusters as follows:

$$
\begin{aligned}
Score(c_i) &= c_i^{sim} - c_i^{pen} \\
&= \frac{2\sum_{\substack{p_a,p_b\in c_i \\ p_a\neq p_b}} p_a\cdot p_b}{|\sum_{p_a\in c_i} p_a|} - \sum_{\substack{p_a,p_b\in c_i \\ p_a\neq p_b}} d_{ab} \\
&\quad - |c_i|(H_{laser}+2L_{drop}),
\end{aligned} \tag{2}
$$

where c_i denotes the path cluster i, $p_a = (s_a, t_a)$ denotes the path vector a starting from s_a and ending at t_a, d_{ab} represents the distance between the path vectors a and b, and $|c_i|$ represents the number of nets in c_i.

Here we give the definition of new operators and notations on path vectors first.

- Inner product: The inner product between p_a and p_b represents the inner product formed by two mathematical vectors which start from s_a, s_b and end at t_a, t_b, respectively.
- Summation: The summation of path vectors represents the vector sum of all path vectors.
- Absolute value (Length): The absolute value of p_a represents the distance between s_a and t_a.
- Distance: The distance between p_a and p_b is the minimum distance between two line segments formed by p_a and p_b.

The score in Equation (2) consists of two terms: c^{sim} and c^{pen}. The first term represents the similarity of the path vectors. Since clustering the path vectors with the same direction and longer lengths will significantly reduce the total wirelength and transmission loss, we regard the clustering of these path vectors as a gain. In the second term, since clustering the path vectors with long distances will increase the total wirelength and transmission loss, we regard the clustering of these path vectors as a penalty. And the overheads of using the WDM waveguides are also considered as a penalty to avoid redundant WDM waveguide generation.

Our objective in this stage is to find the path clusters that minimize the total wirelength, transmission loss and wavelength power after routing, which is equivalent to maximizing the sum of the scores of all path clusters.

Here we explain our proposed provably good WDM-aware path clustering algorithm, as summarized in Algorithm 1. Given the path vector set P, Lines 1–5 generate the nodes and edges from the path vectors and construct the path vector graph, which will be detailed in Section III-B1. Then Line 12 checks if the two nodes connected by the edge with the largest gain, e_{max}, can be clustered. If so, Lines 13–14 then merge the two nodes and update the gain. After that, Line 15 finds the next edge with the largest gain. Lines 9-15 continue until no edges remain or the largest gain is negative. The iterative step will be detailed in Section III-B2. Then we complete the algorithm by returning V, where each node n in V represents a path cluster of all signal paths in it.

1) Path Vector Graph Construction: A *Path Vector Graph* is a graph defined as $G = (V, E)$. Here V is the set of nodes, where each node includes path vectors that form a path cluster. And E includes weighted edges that indicate the gains of our objective function after merging the path clusters connected by the edges. The edge exists when there is at least a pair of signal paths from both clusters with a non-zero overlap segment. Here the overlap segment represents the overlap of two line segments, which are the projections of two path vectors onto their angle bisector. This is to ensure that

Algorithm 1 Path Clustering

Require: P
Ensure: The optimal clustering for all paths
for all path vector p_i in P **do**
  generate a node n_i in V
for all $(n_i, n_j), i \neq j$ **do**
  generate an edge e_{ij} in E
$G = (V, E)$ is the path vector graph
if $E = \emptyset$ **then**
  return V
e_{max} is the first edge with maximum gain g_{max} in E
while $E \neq \emptyset$ **do**
  if $g_{max} < 0$ **then**
    break
  if *isClusterable*(e_{max}) **then**
    merge(G, e_{max})
    updateGain(G, e_{max})
  $e_{max} =$ *findMax*(G)
return V

these path clusters can share an effective WDM waveguide. The weight of an edge $e = (n_1, n_2)$, where n_i is the path cluster node i in V, is defined as follows:

$$\begin{aligned} g_{ij} &= Score(n_i, n_j) - Score(n_i) - Score(n_j) \\ &= \frac{c_i^{sim} \cdot |\sum_{a \in n_i} p_a|}{|\sum_{a \in n_i} p_a + \sum_{b \in n_j} p_b|} + \frac{c_j^{sim} \cdot |\sum_{b \in n_j} p_b|}{|\sum_{a \in n_i} p_a + \sum_{b \in n_j} p_b|} \\ &+ \frac{|\sum_{a \in n_i} p_a| \cdot |\sum_{b \in n_j} p_b|}{|\sum_{a \in n_i} p_a + \sum_{b \in n_j} p_b|} - c_i^{pen} - c_j^{pen}, \end{aligned} \quad (3)$$

where g_{ij} is the gain of the objective function, $Score(n_i)$ represents the score of the path cluster in n_i, and $Score(n_i, n_j)$ represents the score of the path cluster of n_i and n_j. For easier presentation, we use the overloaded notation $Score$ for the score with 1- or 2-node clustering here.

In the initial path vector graph construction, each single path vector forms a unique node. In each node n_i, we record c_i^{sim}, c_i^{pen}, and $\sum_{a \in n_i} p_a$. Then we set c_i^{sim} to zero, and calculate c_i^{pen}. After that, the gain of each pair of nodes is computed to form the edges. Finally, we sort the edges in the non-increasing order to record the edge with the largest gain.

2) Iterative Path Vector Clustering: After Path Vector Graph Construction, we propose a provably good path clustering algorithm to find optimal path clusters that maximize the total score.

In each iteration, we choose the edge with the largest gain that satisfies the maximum capacity C_{max} of a WDM waveguide for the number of nets in the adjacent nodes of this edge, or the algorithm terminates if merging any two path clusters will violate the WDM waveguide capacity constraint. After finding the edge, we merge the nodes connected by the edge, as shown in Figure 6(b). The merging of nodes represents the clustering of all path vectors in these nodes.

After the nodes are merged, the edge connecting these nodes is removed, and then the edges connecting the newly merged node are created. The gains of edges adjacent to the merged node are calculated by Equation (3). The graph after merging is still a path vector graph, and the nodes in each cluster form a clique in the original path vector graph, as shown in Figure 6(c). We continue this iteration until no edges can be merged or the largest gain is negative, which means that the total wirelength and transmission loss can no longer be improved after clustering.

We show that our algorithm can achieve an optimal path clustering for 1-, 2-, and 3-path clustering, and has the constant performance bound 3 for most cases of 4-path clustering as follows:

Theorem 1: The path vector clustering algorithm guarantees to find an optimal solution when $|V| \leq 3$, where $|V|$ is the size of the node set in the path vector graph.

Proof 1: For $|V| = 1$, there are no edges, so no path clustering is needed in the optimal solution. For $|V| = 2$, there is only one edge. If the gain of this edge is positive, this edge will be clustered in the optimal solution. Otherwise, no further path clusterings are needed in the optimal solution. Since our algorithm clusters the edge e_{max} if $g_{max} > 0$ and terminates if $g_{max} < 0$, the result must be the same as the optimal solution. For $|V| = 3$, there are three cases of optimal solutions: (a) no nodes are clustered, (b) two nodes are clustered, or (c) all nodes are clustered. Case (a) implies that

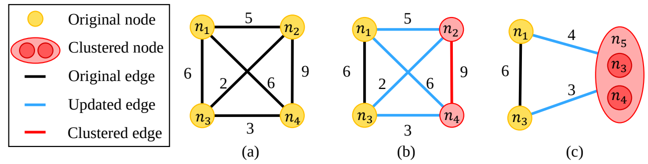

Fig. 6. During path clustering, (a) given a path vector graph, (b) we cluster the edge with the largest gain in the path vector graph, and (c) update the gain of its adjacent edges to get the updated path vector graph for the next iteration.

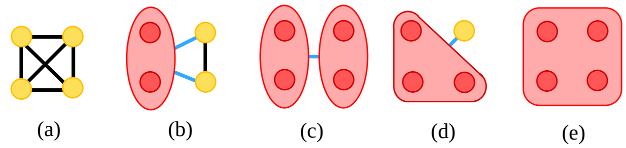

Fig. 7. Five cases of optimal solutions in 4-path clustering.

$g_{max} < 0$. Since our algorithm terminates if $g_{max} < 0$, the result remains the same as this solution. Case (b) implies that g_{max} is positive, and is the score of this solution. Since our algorithm always clusters e_{max} if $g_{max} > 0$, the result will be the same as this solution. In Case (c), according to Equation (2), the optimal score is positive, implying that there exist two path vectors p_a and p_b such that $p_a \cdot p_b > 0$, and thus at least one edge gain is positive. Furthermore, since three nodes are clustered in this optimal solution, the gain of the remaining edge after the first path clustering is still positive. Since our algorithm always clusters e_{max} if $g_{max} > 0$, the result remains the same as this solution. So our algorithm guarantees to find an optimal solution when $|V| \leq 3$.

Theorem 2: The path vector clustering algorithm has the performance bound 3 when $|V| = 4$ and $cos\theta > \frac{-|p_k|}{2|p_i + p_j|}$, where p_i, p_j, p_k are the path vectors in nodes n_i, n_j, n_k in V, respectively, and θ is the angle between $p_i + p_j$ and p_k.

Proof 2: For $|V| = 4$, since the nodes in each cluster form a clique in the original path vector graph, there are five cases of optimal solutions in 4-path clustering: (a) no nodes are clustered, (b) two nodes are clustered, (c) two node pairs with no common edges are clustered, (d) three nodes are clustered, and (e) all nodes are clustered, as shown in Figure 7. In Cases (a), (b), and (e), our algorithm can generate an optimal solution, and the proofs are similar to the case when $|V| = 3$ (see Proof 1). In Case (c), let e_1 and e_2 be the two edges in an optimal solution. Since $0 \leq g_1, g_2 \leq g_{max}$, which implies that $g_1 + g_2 \leq 2 \cdot g_{max}$, we have the constant performance bound 2. In Case (d), if the angle condition holds, then

$$|p_i + p_j + p_k| > |p_i + p_j|, \quad (4)$$

implying that

$$\begin{aligned} g_{ijk} &= \frac{2 \sum_{\substack{a,b \in \{i,j,k\} \\ a \neq b}} p_a \cdot p_b}{|p_i + p_j + p_k|} - \sum_{\substack{a,b \in \{i,j,k\} \\ a \neq b}} d_{ab} + h_{ab} \\ &< \sum_{\substack{a,b \in \{i,j,k\} \\ a \neq b}} \frac{2(p_a \cdot p_b)}{|p_a + p_b|} - (d_{ab} + h_{ab}) \\ &= g_{ij} + g_{ik} + g_{jk} \\ &\leq 3 \cdot g_{max}, \end{aligned} \quad (5)$$

which holds for any i, j, and k. Therefore, we have the constant performance bound 3. Overall, our algorithm has the constant performance bound 3 for most cases of $|V| = 4$.

C. Endpoint Placement

After Path Clustering, the clusters of signal paths for the WDM waveguides are determined. The drop loss and wavelength power are thus determined. In this stage, based on the path clustering result, we place the endpoints of the WDM waveguides to minimize the estimated routing cost.

1) End Point Evaluation: To place the endpoints of the WDM waveguides to minimize the total wirelength and transmission loss, we use a hybrid cost function to guide the gradient-search method to find optimal endpoint positions as follows:

$$cost = \alpha * W + \beta * \sum l + \gamma * l_{max}, \quad (6)$$

where W is the estimated wirelength, l is the estimated signal path length, l_{max} is the longest estimated signal path length, and α, β, γ are user-defined coefficients.

Through the gradient-search method, we can find optimal endpoint positions to minimize the cost function.

2) End Point Legalization: Since the positions of the endpoints from the previous stage may be illegal when overlapping with obstacles, pins, or routed wires, in this stage we determine the actual positions of the endpoints of the WDM waveguides based on the best positions. We move the endpoints to the nearest legal positions to minimize the displacement, so that the degradation of the result after legalization is minimized.

D. Pin-to-Waveguide Routing

In this stage, we perform A* search routing to minimize the total wirelength and transmission loss. We first set the sizes of routing grids to meet the minimum/maximum bending radius constraints. Then, we route each WDM waveguide from one endpoint to the other. Finally, we route the signal paths from the source pins to the directly routed pins, from the source pins to the WDM waveguides, and from the WDM waveguides to the target pins.

For the minimum/maximum bending radius constraints, we follow the method in the work [15] to adjust the routing grid size such that both minimum and maximum radii constraints are satisfied. We further require the path searching directions larger than 60° to avoid any sharp bending.

To guide the routing algorithm to find a better route, we use the following equation to predict the routing cost:

$$\alpha * W + \beta * L, \quad (7)$$

where W is the estimated wirelength, L is the total transmission loss described in Section II-A, and α, β are coefficients in Equation (6). For transmission loss estimation, bending loss, splitting loss, and path loss are straightforward to be estimated by examining the current routed path. For crossing loss estimation during A* search routing, if the current routing path propagates across a routed signal, a unit of crossing loss will be added to its estimated transmission loss.

IV. Experimental Results

We implemented our WDM-aware path clustering algorithm and the WDM-aware optical routing flow in the C++ programming language. All experiments were performed on an Intel Xeon 2.1GHz Linux workstation with 16GB memory. For fair comparison, we performed the experiments based on the seven ISPD 2007 contest benchmarks, the ten ISPD 2019 contest benchmarks, and a real optical design from the authors of the work [2]. For the ISPD benchmarks, the preprocessed setting is the same as those in the previous work [9]. In these benchmarks, we set the WDM waveguide capacity to 32, and the transmission loss for crossing, bending, splitting, path loss, drop loss, and wavelength power to 0.15dB per cross, 0.01dB per bend, 0.01dB per split, 0.01dB per centimeter, 0.5dB per drop, and 1dB, respectively.

To show the completeness, effectiveness, and efficiency of our optical routing flow and the path clustering algorithm, we performed two experiments. First, we evaluated the results of the path clustering algorithm and the optical routing flow of our work, implemented the engines of the state-of-the-art works GLOW [9] and OPERON [12], and compared with them. Then, we compared our algorithm without using any WDM waveguides to examine the quality of our path clustering algorithm. The wirelength computation consists of the length of both WDM waveguides and normal optical waveguides, and the transmission loss is calculated by Equation (1).

Table II summarizes the experimental results of the ISPD 2019 contest benchmarks and the real design. Due to the space limitation, we will only summarize the results of the ISPD 2007 ones, without showing the details. In the first experiment, we implemented GLOW with the Gurobi ILP solver [10]. The path clustering method OPERON handled the electrical-optical co-design first and then clustered optical nets. For fair comparison, we made all the nets in the benchmarks optical ones. Their detailed routing was performed by the routing scheme presented in Section III-D. As shown in Table II, for the ISPD 2019 contest benchmarks and the real design, our proposed path clustering algorithm achieved a 60% wirelength reduction, a 45% transmission loss reduction, an 86% number of wavelengths reduction, and a 1.9X speedup compared with GLOW, and a 64% wirelength reduction, a 46% transmission loss reduction, an 84% number of wavelengths reduction, and a 5.7X speedup compared with OPERON. For the ISPD 2007 contest benchmarks, our algorithm achieved a 66% wirelength reduction, a 51% transmission loss reduction, an 87% number of wavelengths reduction, and a 1.8X speedup compared to GLOW, and a 74% wirelength reduction, a 53% transmission loss reduction, an 86% number of wavelengths reduction, and a 6.1X speedup compared to OPERON.

In the second experiment, for the ISPD 2019 contest benchmarks and the real design, our path clustering algorithm reduced 16% wirelength and 5% transmission loss in these benchmarks with a 1.9X speedup, compared with the routing without using any WDM waveguide. For the ISPD 2007 ones, our algorithm reduced 14% wirelength and 4% transmission loss in these benchmarks with a 2X speedup, over the routing without using any WDM waveguide. Figure 8 shows the resulting layout of ispd_19_7.

The reasons why our proposed algorithm can achieve significant reductions in wirelength, transmission loss, and number of wavelengths with a signification speedup are analyzed as follows:

- Our algorithm does not assign redundant WDM waveguides, which could substantially reduce the number of crosses and thus the transmission loss. In contrast, the WDM waveguides in GLOW and OPERON could redundantly be placed across the routing regions. As a result, the utilization rate of WDM waveguides is small, and thus excessive crosses between WDM waveguides might occur, which would incur large wirelength and transmission loss.
- We prevent signal paths of different directions from sharing a WDM waveguide, which could avoid wire detouring. In contrast, the flows in GLOW and OPERON do not consider this issue.
- We consider the total wirelength, the total path length, the maximum path length, and transmission loss minimization during WDM endpoint placement for routing cost minimization. In contrast, the flows in GLOW and OPERON also do not consider this issue.
- During path clustering, we consider the WDM overheads, including drop loss and wavelength power. Such consideration helps us prevent excessive laser power consumption for WDM usage. In contrast, the flows in GLOW and OPERON try to maximize the utilization rate of each WDM waveguides, and thus increase the number of wavelengths.
- Our algorithm can generate a provably good path clustering result with a constant performance bound for most cases. To show the effectiveness, we calculate the percentages of 1-, 2-, 3-, and 4-path clusterings in all paths, which can be clustered optimally or with a constant performance bound by our WDM-aware path clustering algorithm. As shown in Table III, the 1-, 2-, 3-, and 4-path clusterings are the majority (84.51%) in the optical interconnections. Therefore, our performance bound can be applied to most cases.
- We divide the WDM-aware optical routing problem into two subproblems, and handle them in two separate stages, which decreases the problem size and the distances between the routing sources and the targets. Furthermore, we adopt an approximation algorithm, instead of a time-consuming ILP solver, to solve the WDM path clustering problem. As aforementioned, we consider several WDM-aware features to improve the WDM clustering quality. So we could significantly reduce the runtime and transmission loss even with the separate stages. In contrast, both GLOW and OPERON handle the WDM-aware optical routing problem as a whole by ILP formulations, and their considered WDM-aware features are incomplete, which substantially increases the runtimes and reduces the solution quality.

Our proposed scheme can also work well for short-distance communication and crowded networks theoretically and empirically. Theoretically, our proposed scheme includes a scoring function which normalizes the distance impact, as shown in Equation (2). Therefore, the distance of communication would not affect the quality. Moreover, since the WDM technique is supposed to handle crowded networks by reducing routed area and wirelength, our proposed scheme works relatively even better for crowded networks. Empirically, our benchmarks contain both short- and long-distance communications, and each benchmark contains crowded networks. The experimental results show that our proposed scheme can handle these benchmarks with various configurations well.

TABLE II

COMPARISONS OF THE TOTAL WIRELENGTH (WL), TRANSMISSION LOSS (TL) (%), NUMBER OF WAVELENGTHS (NW) AND CPU TIMES (SEC) FOR GLOW [9], OPERON [12], AND OUR WORK.

Benchmark	GLOW				OPERON				Ours w/ WDM				Ours w/o WDM		
	WL	TL	NW	Time	WL	TL	NW	Time	WL	TL	NW	Time	WL	TL	Time
ispd_19_1	14070	53.78	18	1.41	22587	48.44	32	7.44	4098	14.55	3	0.54	4181	14.75	0.55
ispd_19_2	23405	69.97	13	8.05	29622	47.49	32	5.18	9988	22.92	5	0.81	11028	23.66	0.83
ispd_19_3	20506	72.66	32	4.6	22375	49.40	32	5.02	7509	21.13	2	0.84	7596	21.16	0.75
ispd_19_4	23612	75.71	32	3.42	25308	55.56	32	6.83	8609	24.86	2	0.81	9012	25.37	0.78
ispd_19_5	29211	61.05	21	13.02	32943	50.29	32	13.68	17027	30.34	4	1.4	17745	30.82	1.86
ispd_19_6	40777	70.44	32	32	36685	41.66	32	17.89	16785	22.68	5	1.58	20009	22.72	1.67
ispd_19_7	39823	62.82	32	27.98	38361	39.78	32	39.73	16979	22.61	5	1.75	19294	23.00	2.93
ispd_19_8	45850	72.33	32	31.93	43938	34.42	32	13.17	15043	15.78	4	0.94	16933	16.13	1.34
ispd_19_9	40447	38.81	32	104.21	48746	31.24	32	8.72	19625	16.64	4	1.41	22186	16.64	1.7
ispd_19_10	112229	81.55	32	295.8	63762	28.89	32	30.15	29318	17.64	6	4.64	34933	18.08	3.64
8*8	11951	27.36	8	23.68	8868	26.7	8	26.52	9575	25.61	5	9.21	11091	28.62	6.96
Comparison	2.60	2.92	6.31	22.82	2.41	1.93	7.29	7.28	1	1	1	1	1.13	1.03	0.96

TABLE III

BENCHMARK STATISTICS INCLUDING THE NUMBER OF NETS, THE NUMBER OF PINS, AND THE PERCENTAGES (%) OF 1-, 2-, 3-, AND 4-PATH CLUSTERINGS OF THE TEN CIRCUITS FROM THE 2019 ISPD CONTEST AND ONE REAL OPTICAL DESIGN.

Circuits	#Nets.	#Pins	% 1-, 2-, 3-, and 4-path clusterings
ispd_19_1	69	202	78.02
ispd_19_2	102	322	89.55
ispd_19_3	100	259	66.44
ispd_19_4	78	230	89.66
ispd_19_5	136	381	89.82
ispd_19_6	176	565	91.24
ispd_19_7	179	590	89.49
ispd_19_8	230	735	96.10
ispd_19_9	344	1056	91.41
ispd_19_10	483	1519	90.70
8x8	8	64	57.14
Average	–	–	84.51

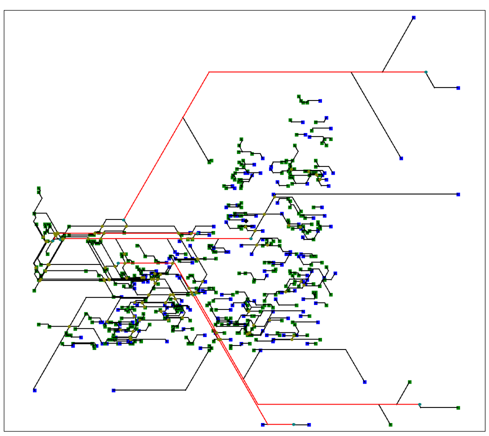

Fig. 8. The resulting layout of ispd_19_7. The black segments are normal optical waveguides, while the red ones are WDM waveguides. The blue and green pins are source pins and target pins, respectively.

V. CONCLUSIONS

We have proposed a provably good WDM-aware path clustering algorithm and a novel WDM-aware optical routing flow. With the performance-bounded path clustering algorithm, we can find a good path clustering result in polynomial runtime. And our flow can determine the optimal locations for WDM waveguides that minimize the total wirelength, transmission loss, and wavelength power. Experimental results have shown that our algorithm is superior to existing optical routing works in both solution quality and runtime.

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