CPONoC: Critical Path-aware Physical Implementation for Optical Networks-on-Chip

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Outline

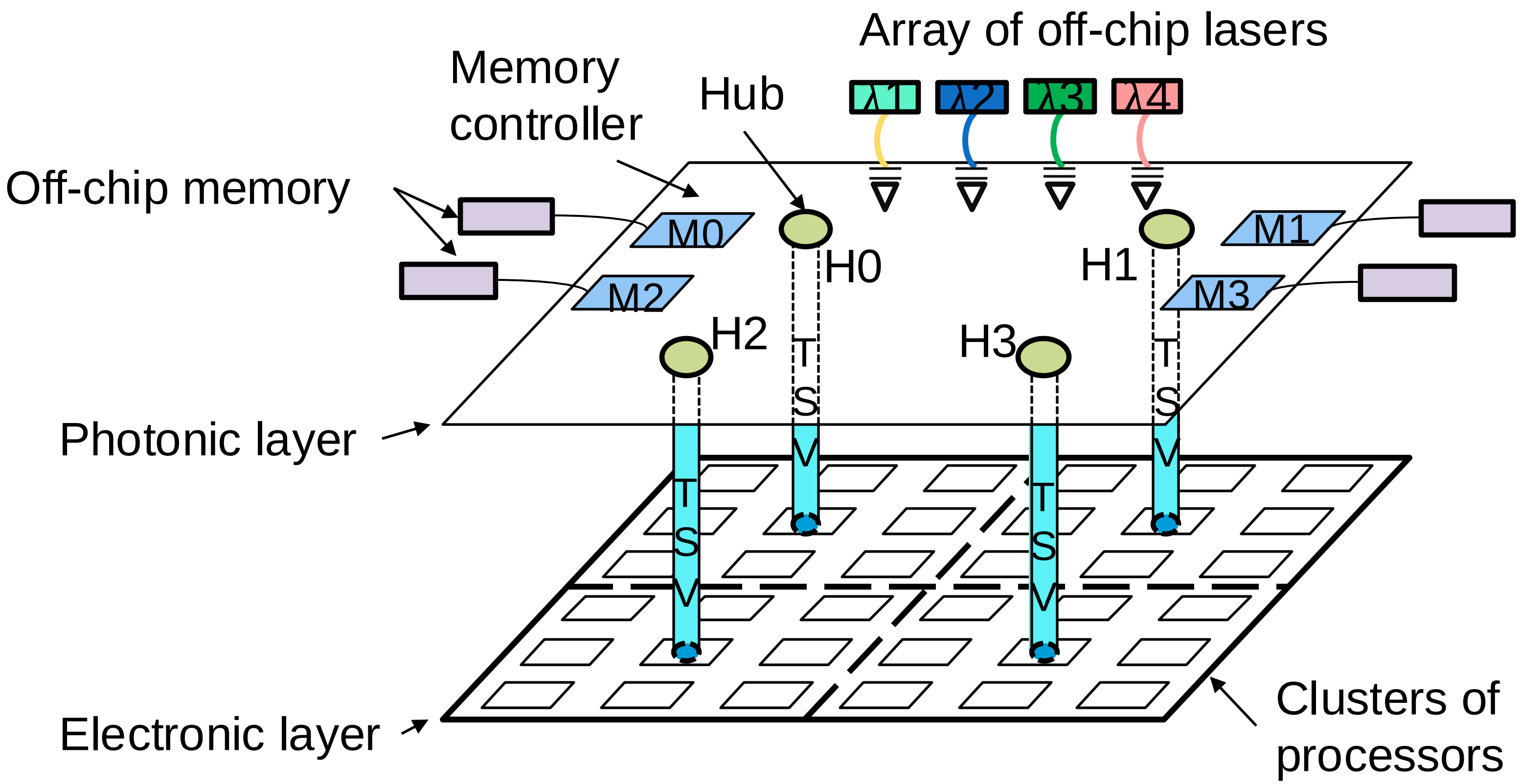
1. Introduction
2. Methodology
3. Experimental Results
4. Conclusions

1. INTRODUCTION

2. METHODOLOGY 3. EXPERIMENTAL RESULTS
4. CONCLUSIONS

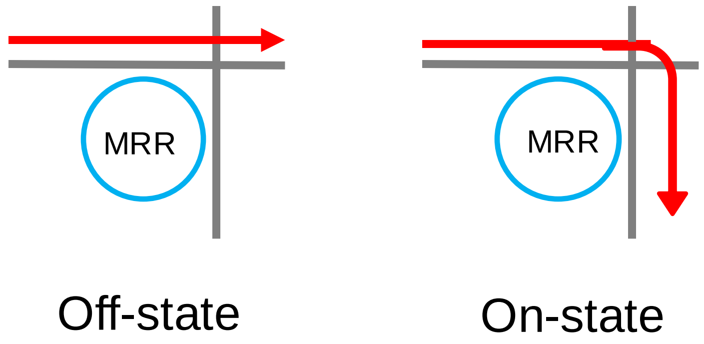
Optical Networks-on-Chips (ONoCs)

- A 3-D stacked multicore processor

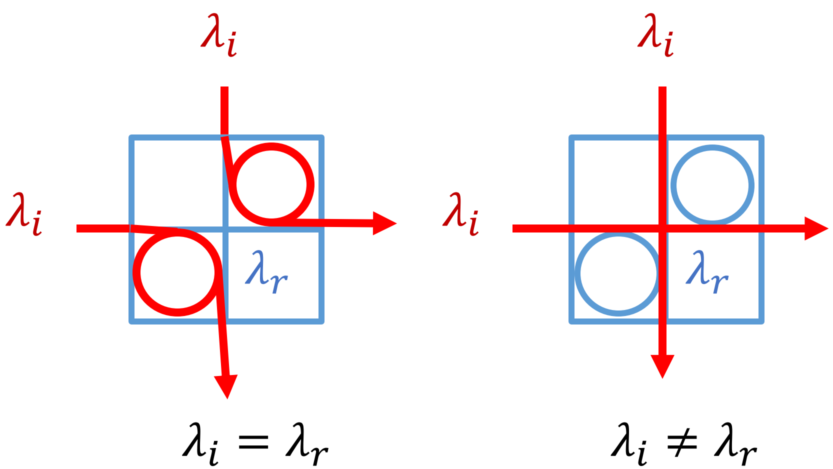


Micro-Ring Resonator (MRR)

- The working principle of MRR

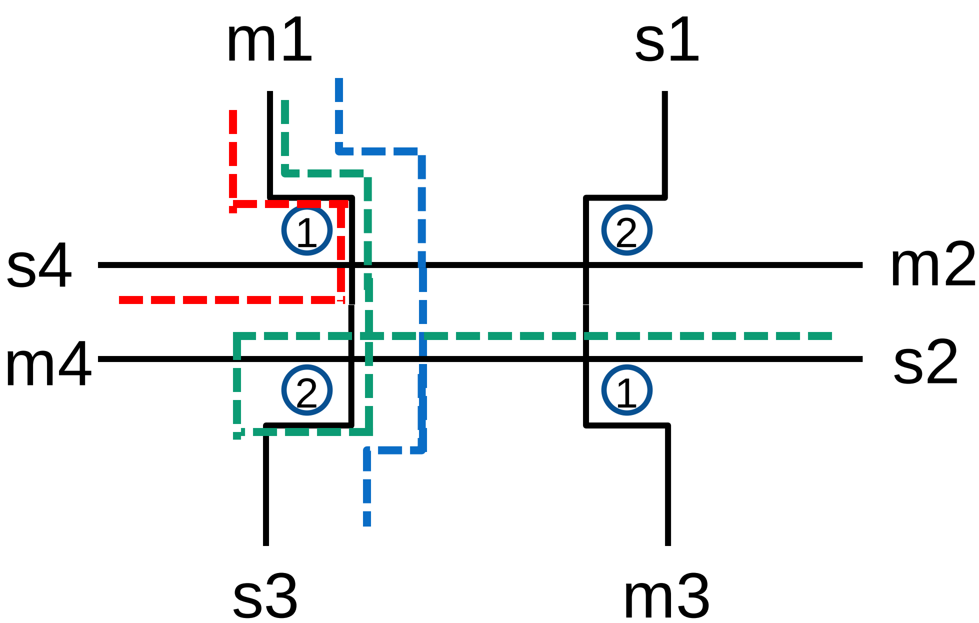


- Photonic switching element (PSE)



Wavelength Routed ONoC (WRONoC)

- Two Types of Classifications for the WRONoC
  - Topological design
  - Physical implementation



$$
\begin{array}{c c}
 & \begin{array}{cccc} m1 & m2 & m3 & m4 \end{array} \\
\begin{array}{c} s1 \\ s2 \\ s3 \\ s4 \end{array} &
\begin{bmatrix}
\times & \lambda_2 & \lambda_3 & \lambda_1 \\
\lambda_2 & \times & \lambda_1 & \lambda_3 \\
\lambda_3 & \lambda_1 & \times & \lambda_2 \\
\lambda_1 & \lambda_3 & \lambda_2 & \times
\end{bmatrix}
\end{array}
$$

Insertion Loss

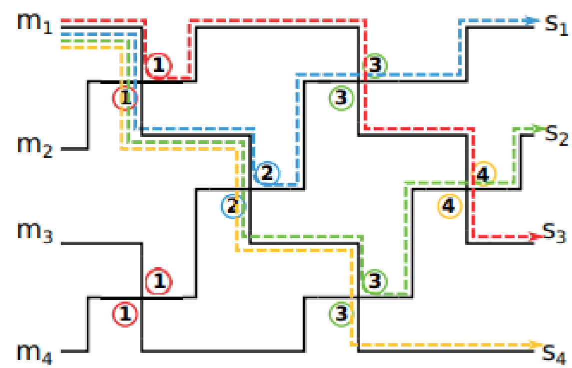
- Insertion loss in an optical router is caused by
  - Propagation loss
  - Crossing loss
  - Bending loss
  - Drop loss

$$il = 1.5\frac{db}{cm} \cdot L + 0.15db \cdot C + 0.5db \cdot D + 0.005db \cdot B$$

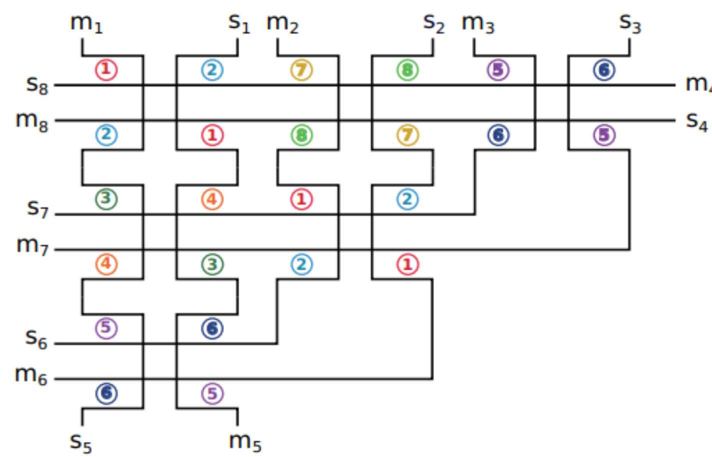
  - Where L, C, D, B separately represent the waveguide length, the number of waveguide crossings, the number of MRR drops, and the number of waveguide bends in p

Related Work

- Topological design
  - λ-Router [Briere et al., DATE'07]
  - GWOR [Tan et al., SOPO'11]
  - Light [Zheng et al., ASP-DAC'21]
- Physical Implementation
  - PROTON+ [Beuningen et al., ACM'15]
  - PlanarONoC [Chuang et al., DAC'18]
  - ToPro [Zheng et al., CAD'21]



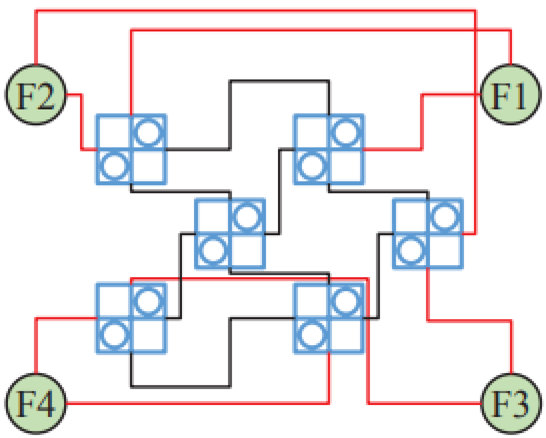
λ-router

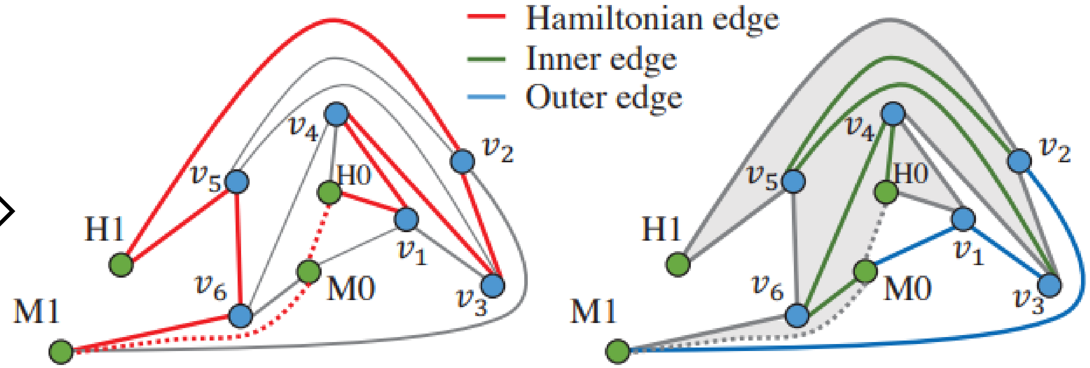


Light

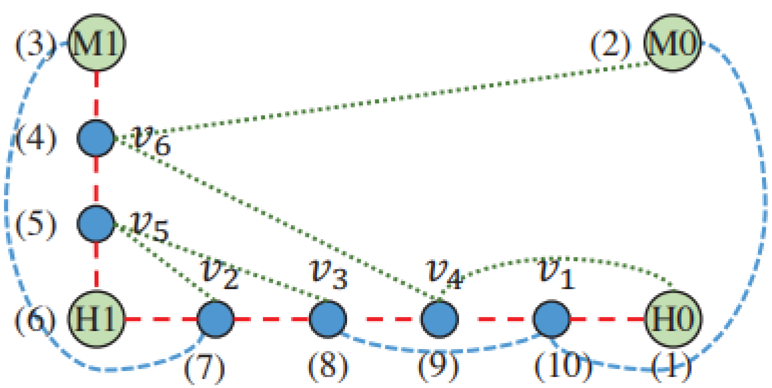
PlanarONoC [Chuang et al., DAC'18]

- Based on Hamiltonian cycle finding





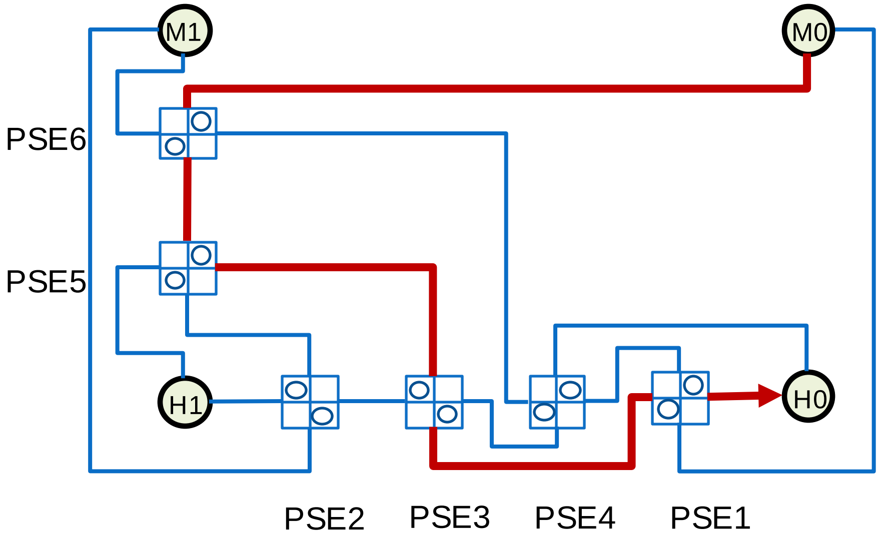
(a) (b)

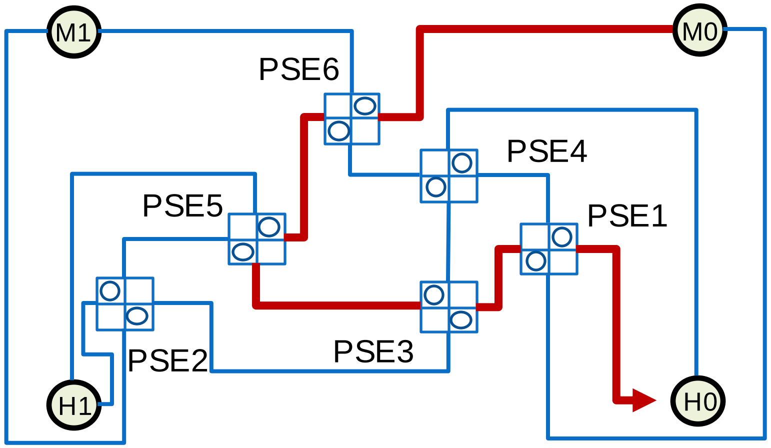


(a)

Cons of PlanarONoC

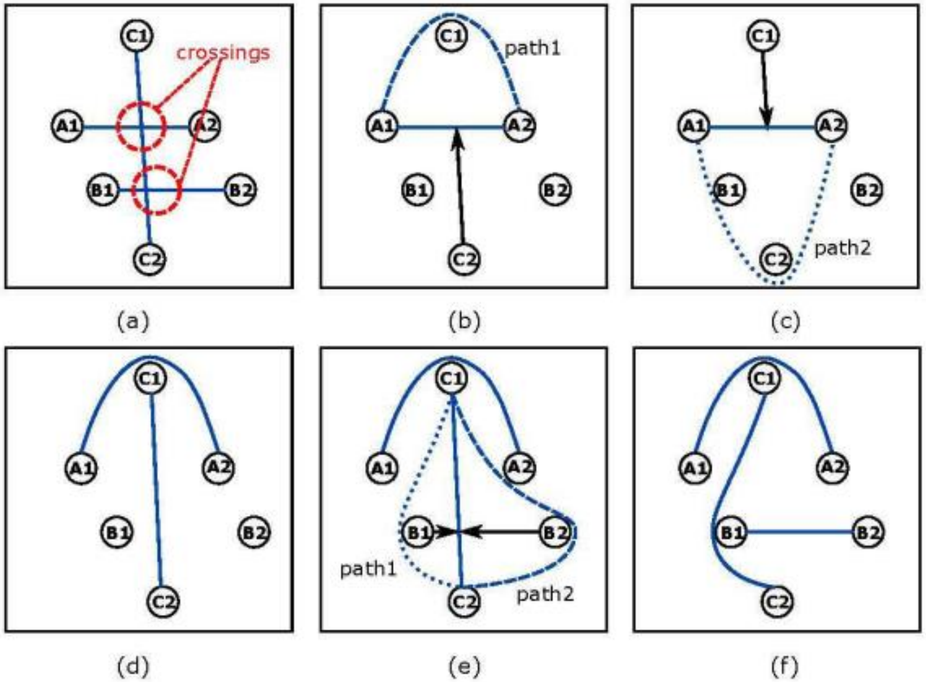
- Critical path causing the maximum insertion loss is not addressed

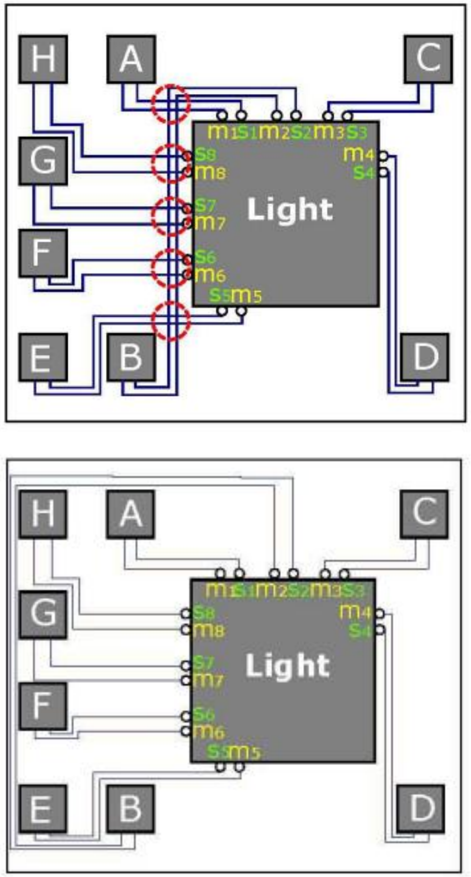




ToPro [Zheng et al., CAD'21]

- Based on a dynamic pushing mechanism
  - Without making a trade-off between detours and crossings





Contributions

- We proposes the APR tool for minimizing worst-case insertion loss using a force-directed algorithm.
- The approach is highly versatile, suitable for existing and future topologies.
- Experiments show the method reduces maximum insertion loss by an average of 9.6% compared to the state of the art.

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1. INTRODUCTION

2. METHODOLOGY

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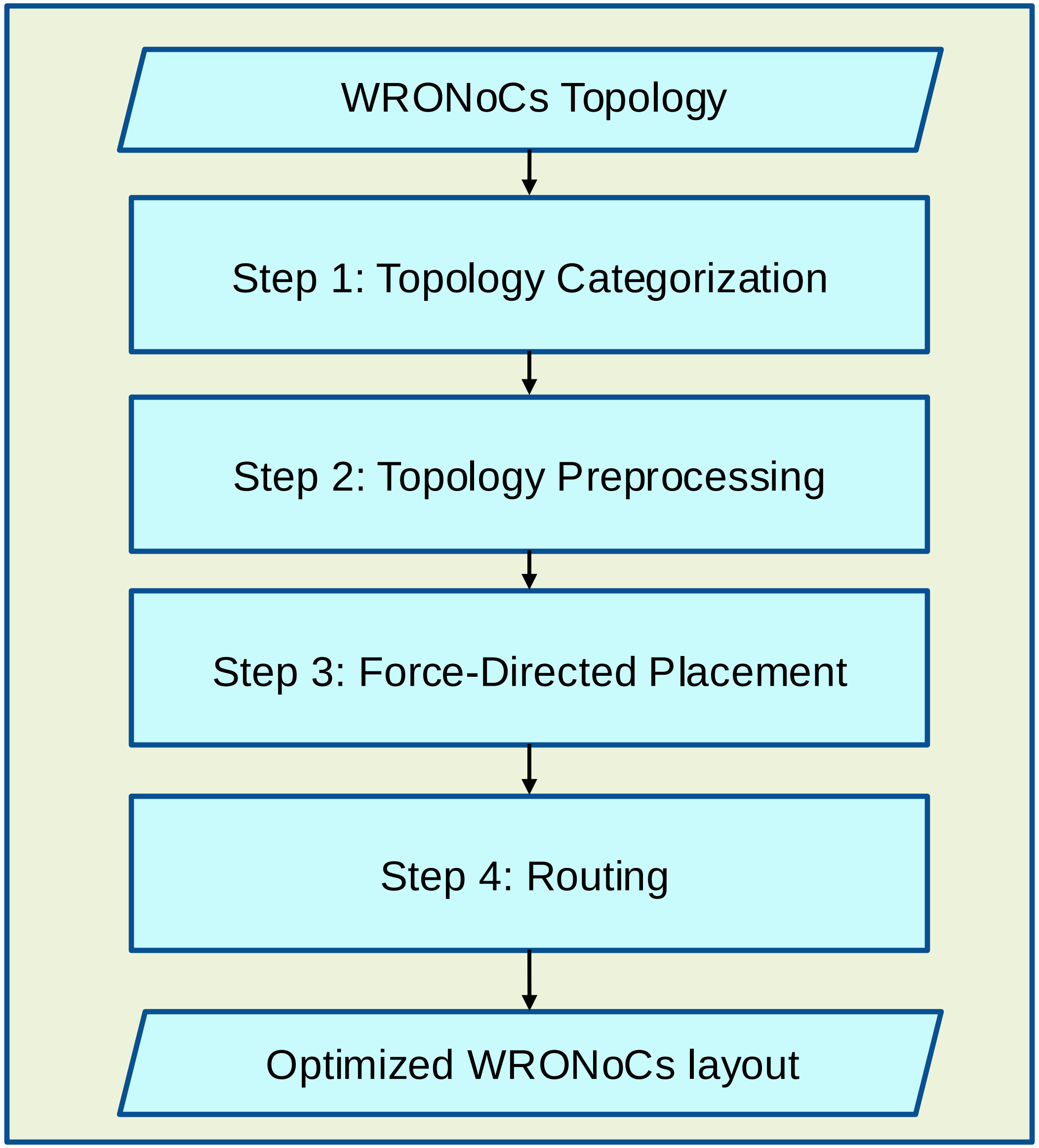
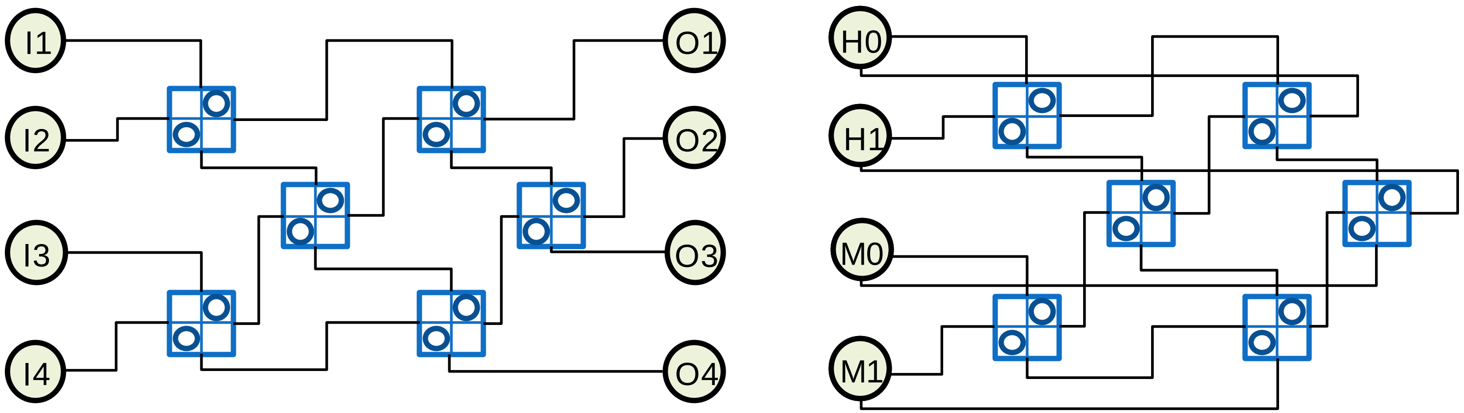
Design Flow


WRONoCs Topology
Step 1: Topology Categorization
Step 2: Topology Preprocessing
Step 3: Force-Directed Placement
Step 4: Routing
Optimized WRONoCs layout

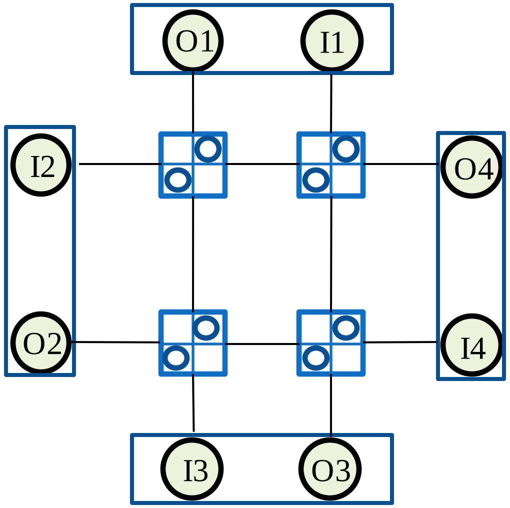
Step 1: Topology Categorization

- Merging inputs and outputs of a non-physical-aware topology results in additional crossings



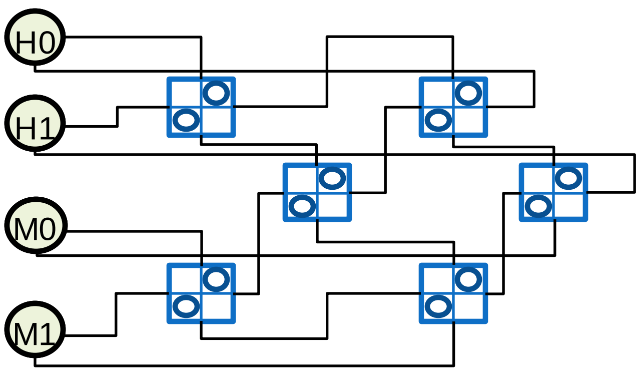
Step 1: Topology Categorization (cont'd)

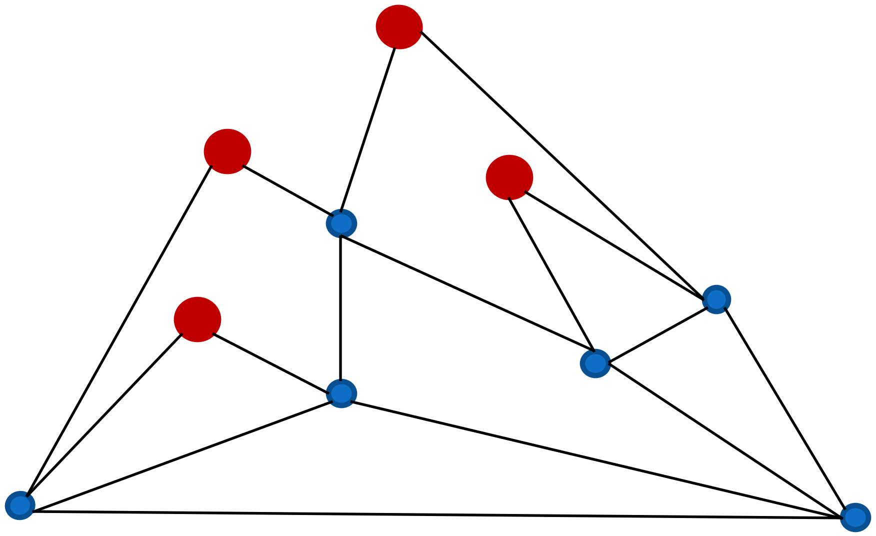
- Merging inputs and outputs of a physical-aware topology does not result in additional crossing



Step 2 : Topology Preprocessing

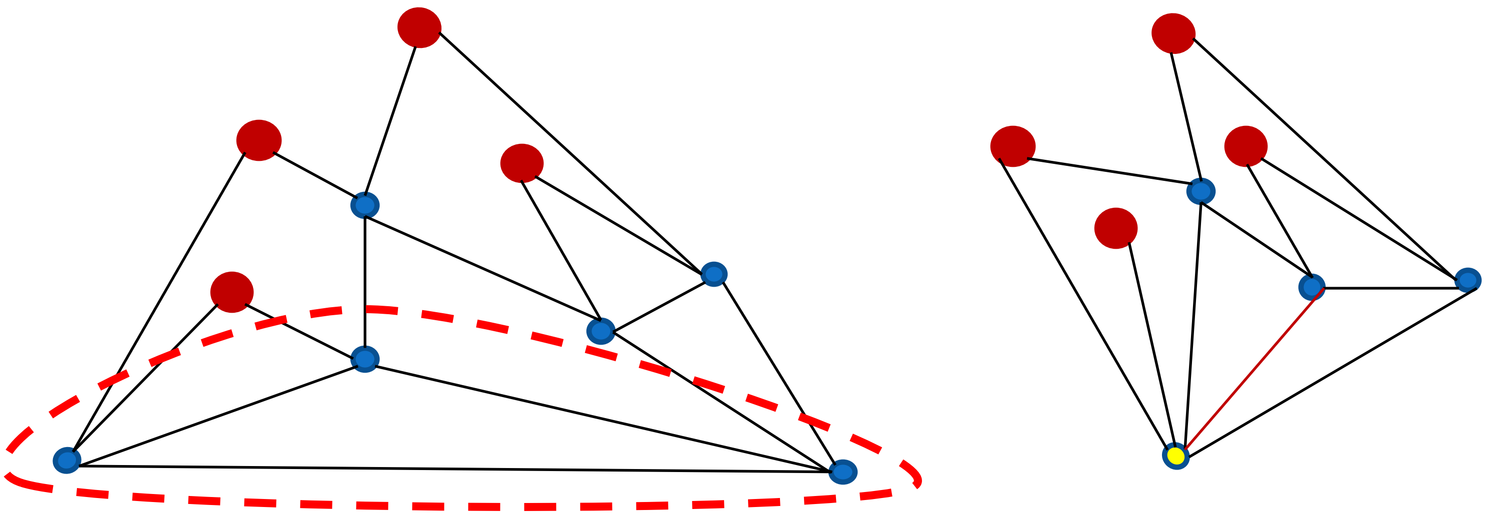
- Apply straight-line embedding without crossings for non-physical-aware topologeis
  - $\boldsymbol{N} = \boldsymbol{N}_{\boldsymbol{fixed}} \cup \boldsymbol{N}_{\boldsymbol{moveable}}$
    - $\boldsymbol{N}_{\boldsymbol{fixed}}$: fixed ports
    - $\boldsymbol{N}_{\boldsymbol{moveable}}$: PSEs
  - $e \in E$: an edge in the edge set **E** in the straight-line embedding





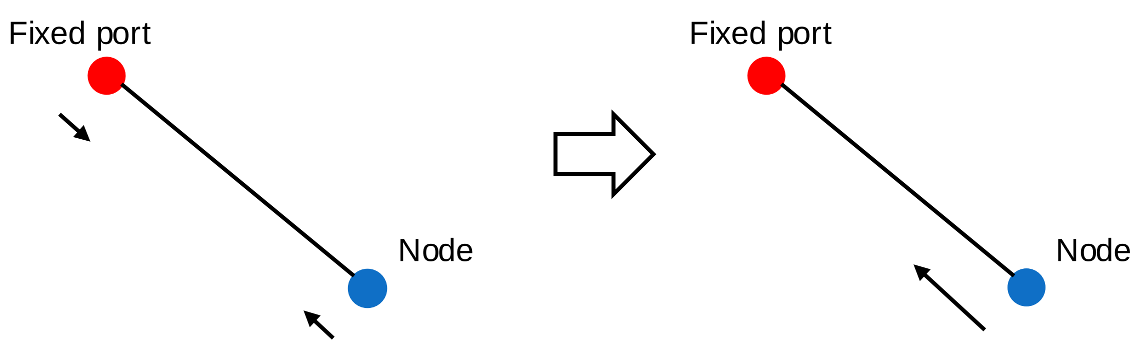
Step 2 : Topology Preprocessing (cont'd)

- Clustering nodes forming a 3-clique without any crossing
  - Reduce problem size
  - Ensure no additional crossings within clustered nodes



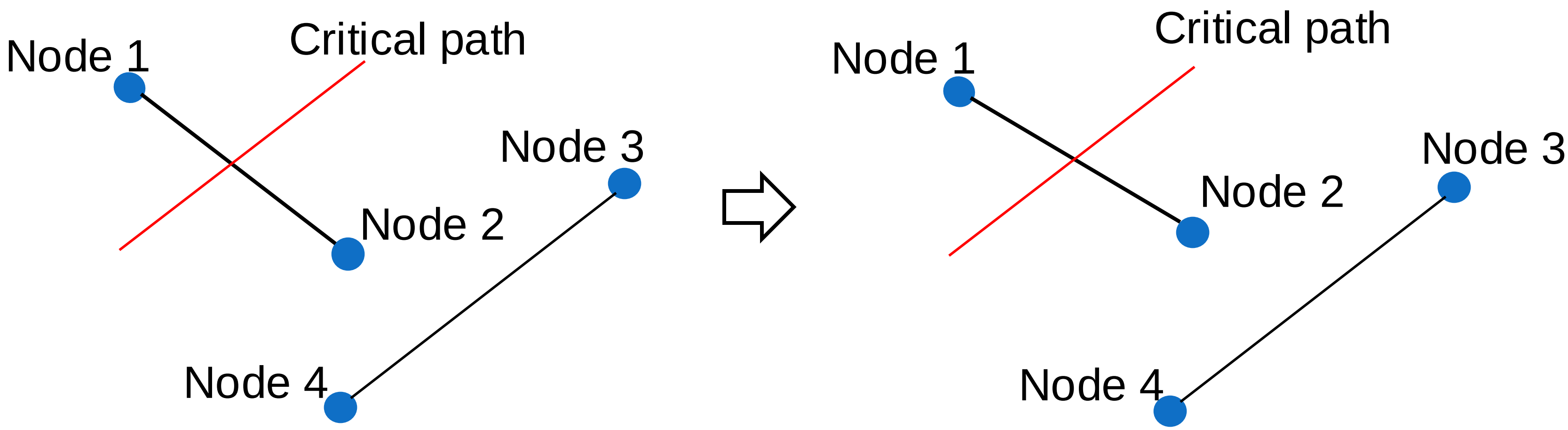
Step 3: Force-Directed Placement

- Define the attractive and repulsive force
  - $k = \sqrt{\frac{zone\ area}{|N|}}$
  - $F_a = w_i \times \left(\frac{d^2}{k}\right)$
  - $F_r = w_i \times \left(\frac{k^2}{d}\right)$
- Adapt the FR force-directed algorithm [FRUCHTERMAN et al., SPE91]



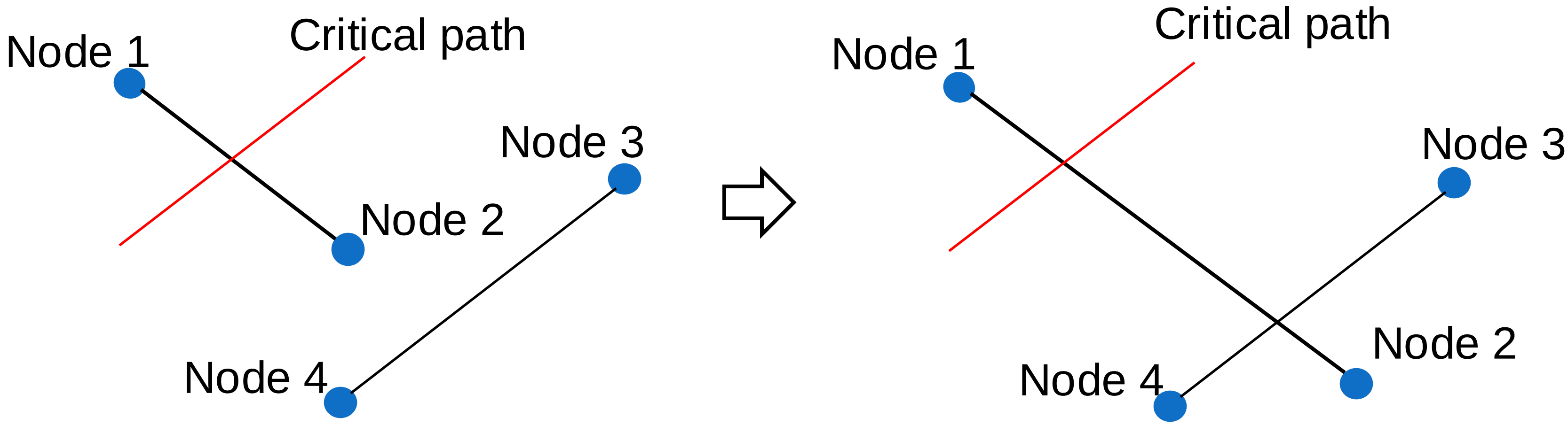
Critical Path-Aware Move

- According to ΔIL and Δ#crossings
  - Move without affecting the critical path



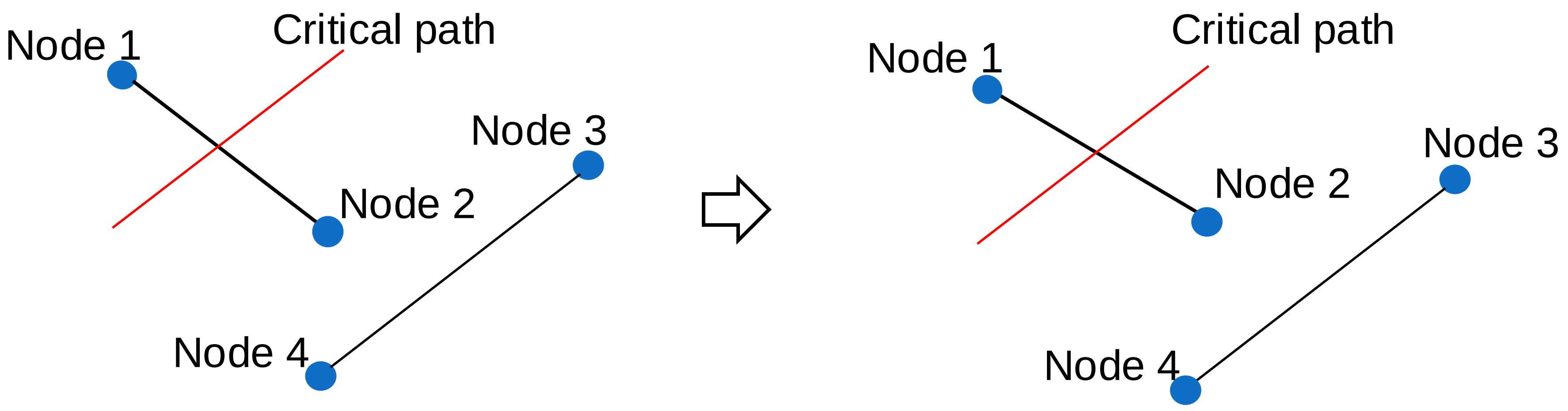
Critical Path-Aware Move

- According to ΔIL and Δ#crossings
  - Move without affecting the critical path



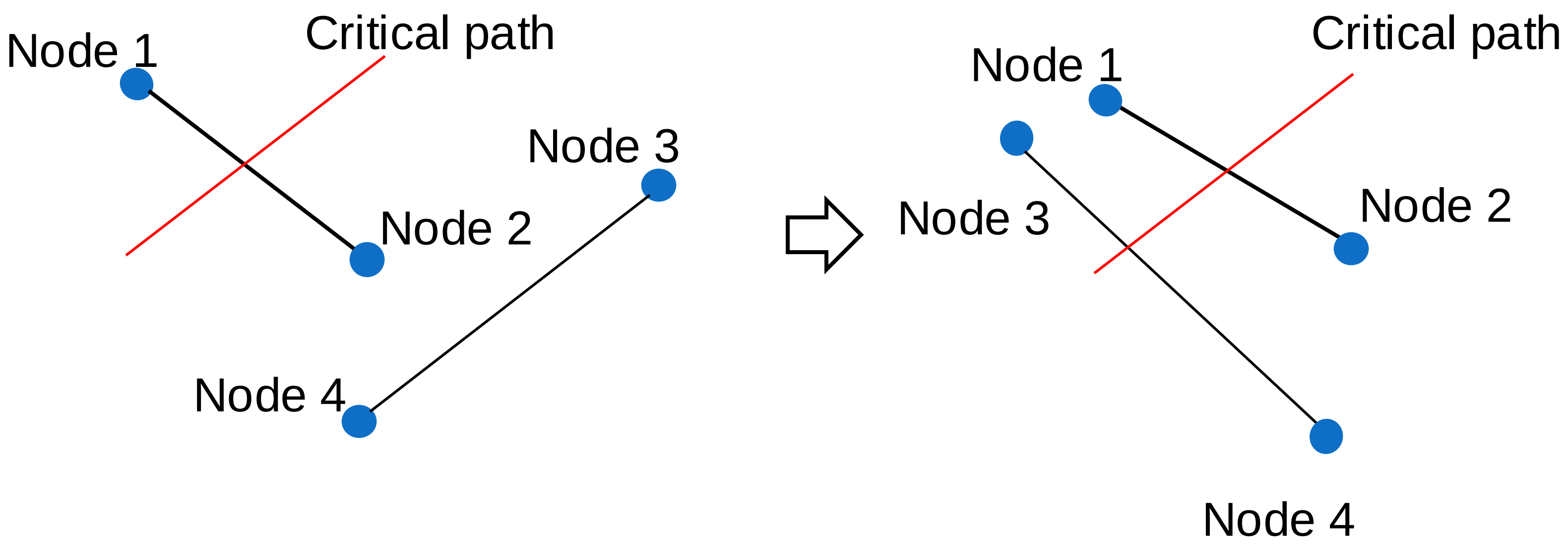
Critical Path-Aware Move

- According to ΔIL and Δ#crossings
  - Move affecting the critical path



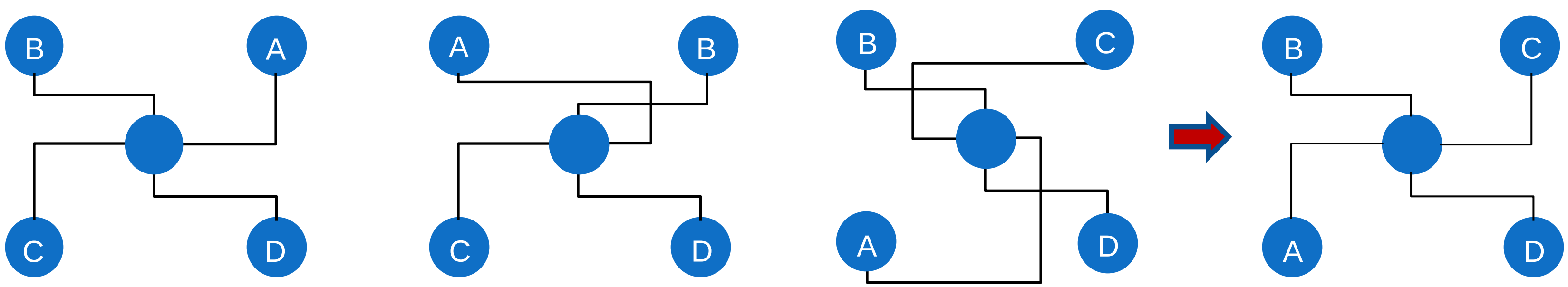
Critical Path-Aware Move

- According to ΔIL and Δ#crossings
  - Move affecting the critical path



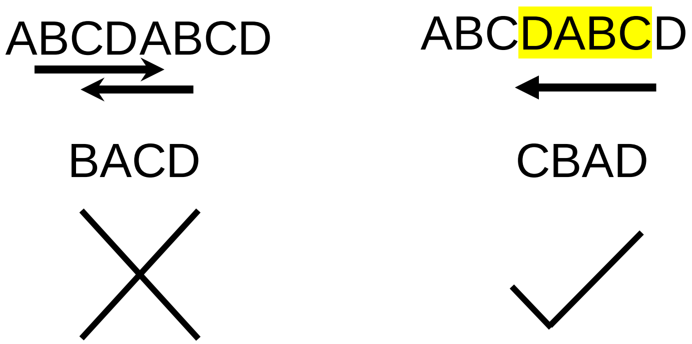
Connection Order

- Graph lacks directional information
  - (a) ABCD
  - (b) BACD
  - (c) CBAD



Connection Order (cont'd)

- Find the longest common substring to check the feasibility of a connection order
  - Original order of a PSE: ABCD
  - Duplicated string: ABCDABCD



Congestion Awareness

- Eliminate the crossings inherent in the topology
  - Move the node to the position with the minimal insertion loss
  - $score = \alpha * d + \beta * i, where\ \alpha\ and\ \beta\ user\ define$
  - $d\ represents\ demand, i\ represents\ insertion\ loss$

2	3	4
2	5	1
1	2	3

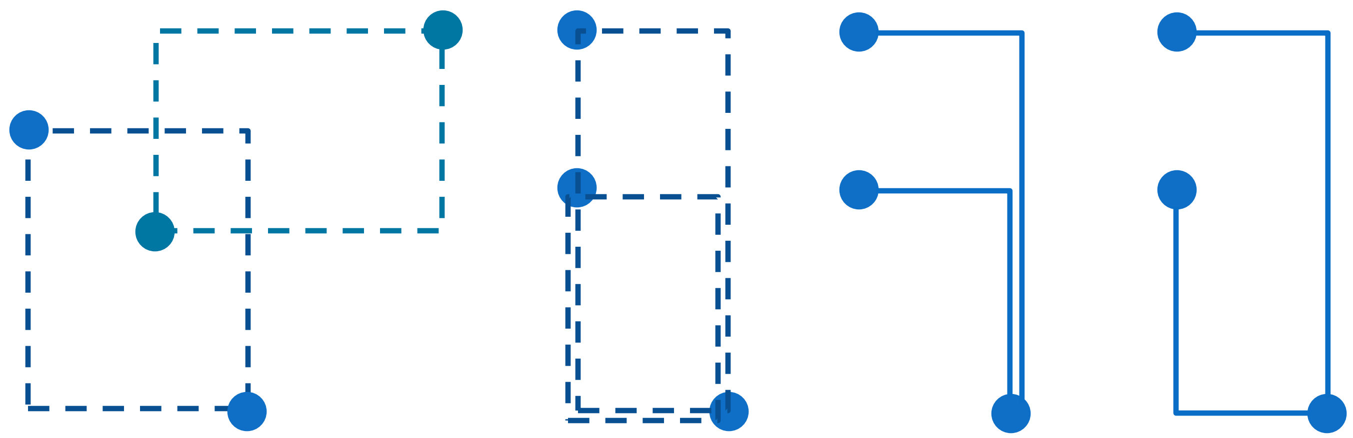
Congestion map

+0.1	+0.2	+0.5
+0.1	+0	+0.15
+0.3	+0.05	+0.2

Δil map

Step 4 : Routing

- L-shaped routing
  - Apply simple L-shaped routing for waveguides.
    1. Clustered node
    2. Critical Path
    3. Remaining node



(a) (b) (c) (d)

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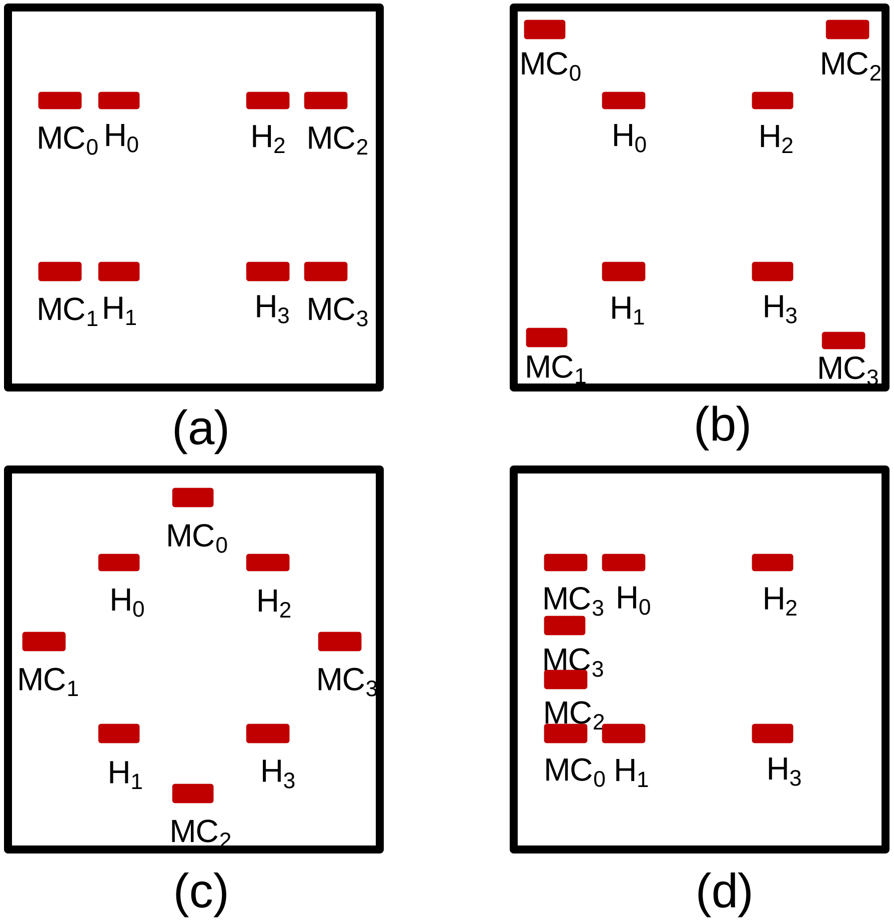
Experimental Settings

- Implementation language: C++
- CPU: 2.0 GHz Intel Xeon E5-2643
- Operating system: Linux workstation with 72 GB RAM
- Compared state-of-the-art works
  - PROTON+ [Beuningen et al., ACM'15]
  - PlanarONoC [Chuang et al., DAC'18]
  - ToPro [Zheng et al., ICCAD'21]

Different Hardware Configurations

- Four different hardware locations



Results for 8-node network on different node positions

- il_{max} - maximum insertion loss
- C - the number of crossings
- L - the total waveguide length
- t - the runtime in seconds

		Pos(a)				Pos(b)			
Topology	Work	il_{max}	C	L	t	il_{max}	C	L	t
λ-router	PROTON+	7.9	27.0	20817.0	146.9	7.8	29.0	18513.0	136.5
	PlanarONoC	5.23	7.0	24140.0	0.3	n/a	n/a	n/a	n/a
	ToPro	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	Our	**4.8**	17.0	11755.0	7.2	**5.2**	15.0	16600.0	7.8
GWOR	PROTON+	8.4	38.0	13000.0	77.1	8.5	37.0	14661.0	7.7
	PlanarONoC	6.38	10.0	28620.0	0.1	n/a	n/a	n/a	n/a
	ToPro	3.8	8.0	14200.0	0.19	5.0	8.0	22200.0	0.15
	Our	**3.6**	11.0	9851.0	10.2	**4.2**	10.0	14528.0	11.9
Light	PROTON+	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	PlanarONoC	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	ToPro	5.5	12.0	21000.0	0.19	6.4	6.0	33300.0	0.2
	Our	**4.4**	15.0	11131.0	8.9	**4.7**	11.0	17249.0	8.5

Results for 8-node network on different node positions

- il_{max} - maximum insertion loss
- C - the number of crossings
- L - the total waveguide length
- t - the runtime in seconds

		Pos(c)				Pos(d)			
Topology	Work	il_{max}	C	L	t	il_{max}	C	L	t
λ-router	PROTON+	7.5	31.0	17748.0	135.4	6.6	27.0	12726.0	134.0
	PlanarONoC	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	ToPro	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	Our	**5.3**	18.0	13801.0	8.2	**4.7**	16.0	11958.0	6.2
GWOR	PROTON+	8.0	36.0	12528.0	90.7	8.1	35.0	13806.0	79.0
	PlanarONoC	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	ToPro	4.5	8.0	18400.0	0.14	**4.0**	10.0	13500.0	0.17
	Our	**4.0**	13.0	10323.0	11.4	**4.0**	12.0	11247.0	9.7
Light	PROTON+	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	PlanarONoC	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	ToPro	5.2	12.0	19000.0	0.15	4.3	12.0	13500.0	0.07
	Our	**4.2**	14.0	10639.0	8.3	**3.8**	12.0	10142.0	8.2

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Results for 8-node network on different node positions

- We propose the first automatic placement and routing approach considering insertion loss minimization for critical paths based on a force-directed algorithm.

- The approach has outstanding generality, making it applicable to various topologies.

- Experimental results show that the proposed method can averagely reduce the maximum insertion loss by 9.6% compared to the state-of-the-art studies.

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THANKS FOR LISTENING