Constraints-aware Adaptive Routing with Hybrid Waveguides for Photonic Integrated Circuits

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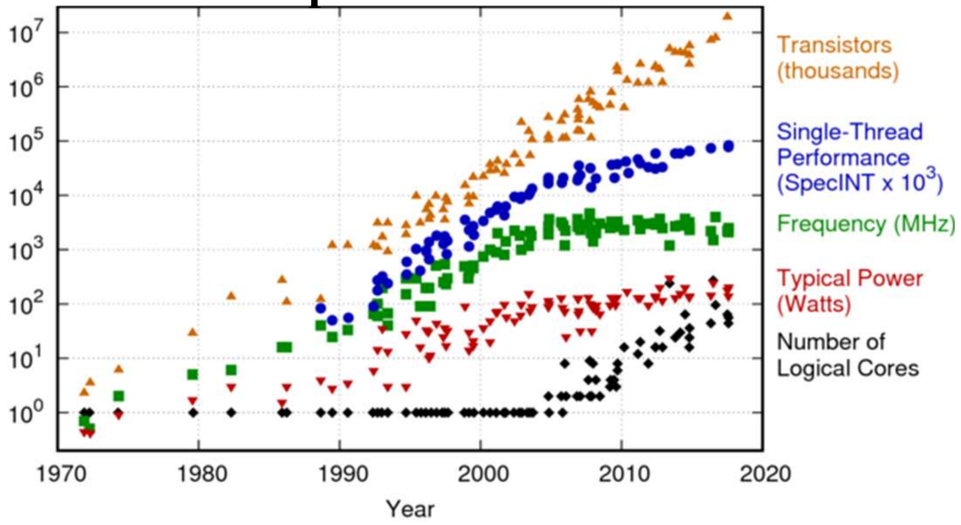
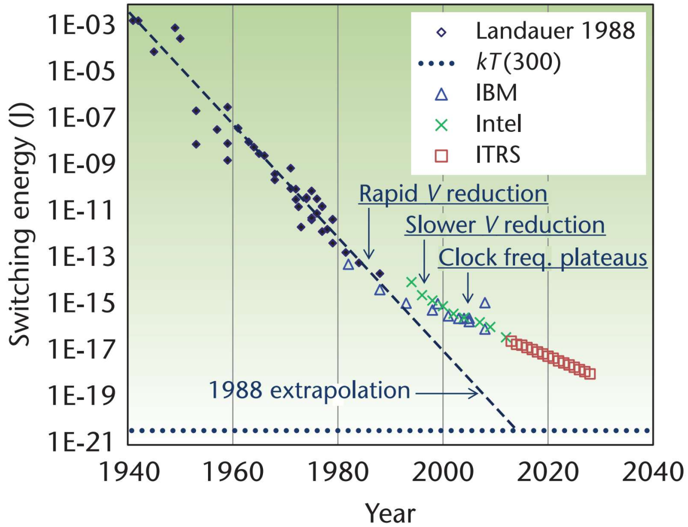
Electronics Bottleneck

- **Moore's Law is slowing down**
- The electronics efficiency bottlenecks (frequency, power, cooling)
  - Microprocessor Frequency is limited to <6 GHz
  - Performance scaling now relies on adding more transistors/cores
  - Transistor energy efficiency has stalled

Microprocessor Trend[1]



Switching Energy Trend[2]

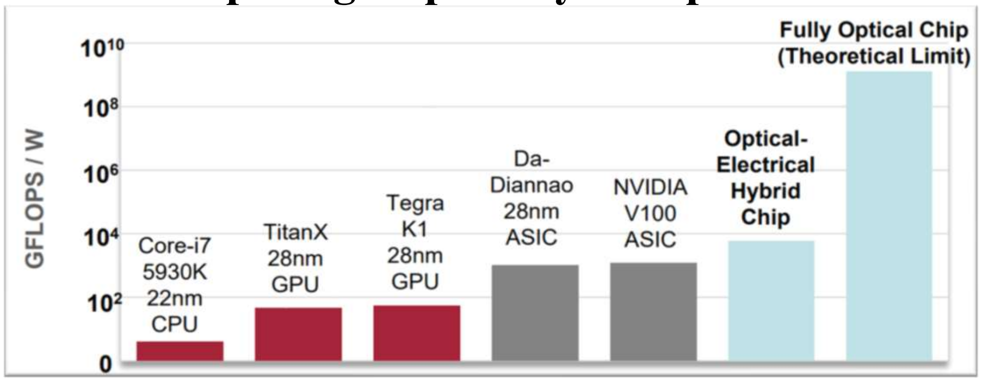


[1]https://www.karlrupp.net/2018/02/42-years-of-microprocessor-trend-data/
[2]Thomas N. Theis, H.-S. Philip Wong, Computing in Science and Engineering, IEEE CS and AIP, 2017.

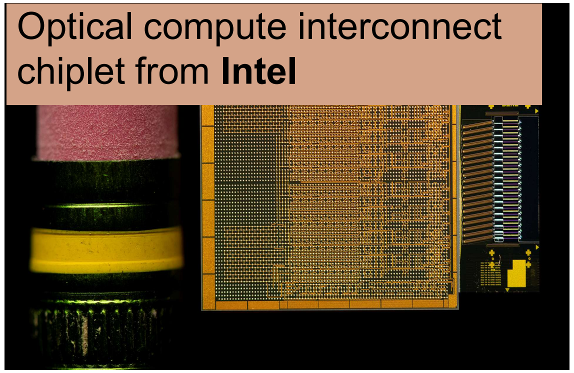
Photonic Integrated Circuit

- **Photonic Integrated Circuits have emerged as a promising solution**
- Advantages
  - Low transmission loss
  - No electrical shorts and ground loops
  - Low cost and abundant material sources
  - No heat dispassion when propagating or interfering
  - Large photonic bandwidth and multiplexing

Computing Capability Comparison[1]



Optical IO Chiplet[2]

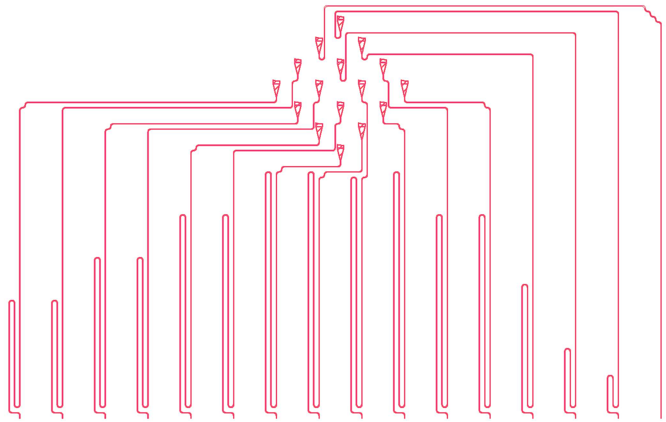


[1]Xu Z et al. Large-scale photonic chiplet Taichi empowers 160-TOPS/W artificial general intelligence[J]. Science, 2024.
[2]https://newsroom.intel.com/artificial-intelligence/intel-unveils-first-integrated-optical-io-chiplet

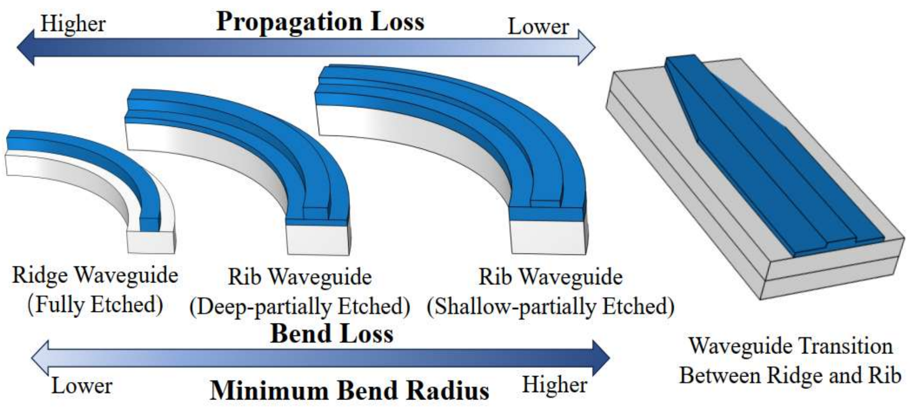
Routers for Photonics

- **Existing routers for photonics are limited**
- Lack of routers that consider matching constraints
  - Matching constraints are crucial for signal integrity
- Lack of routers that consider hybrid waveguides
  - Utilizing hybrid waveguides can further reduce insertion loss

Design with Matching Constraints



Hybrid Waveguides



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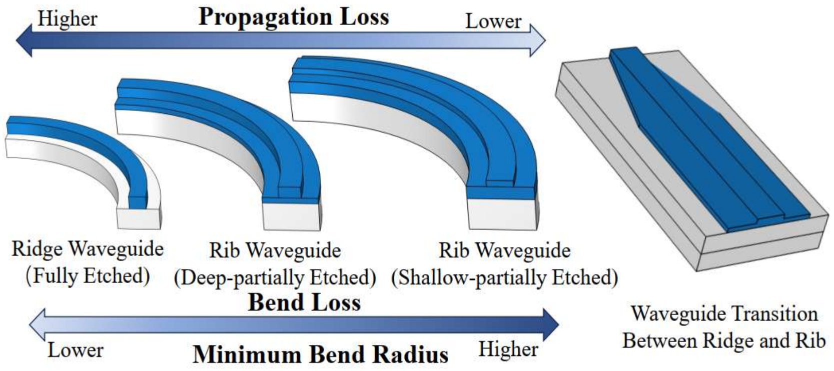
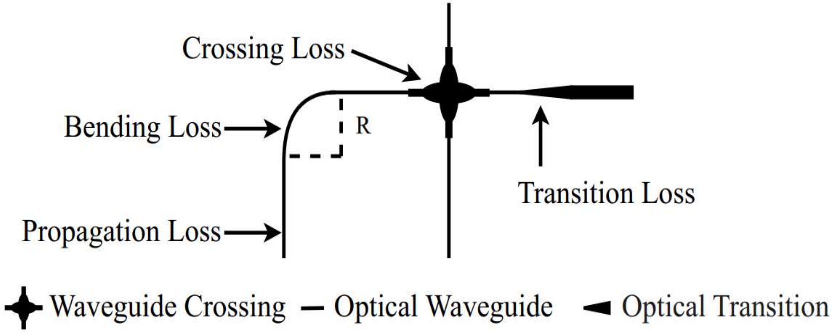
Problem Definition

- Problem
  - Constraints-aware adaptive waveguide routing problem
- Given
  - A netlist
  - Placement information
  - Matching groups
  - Waveguides and transitions
- Output
  - A valid layout
- Objective
  - Minimize the insertion loss
  - Satisfy the matching constraints

Waveguide and Transition

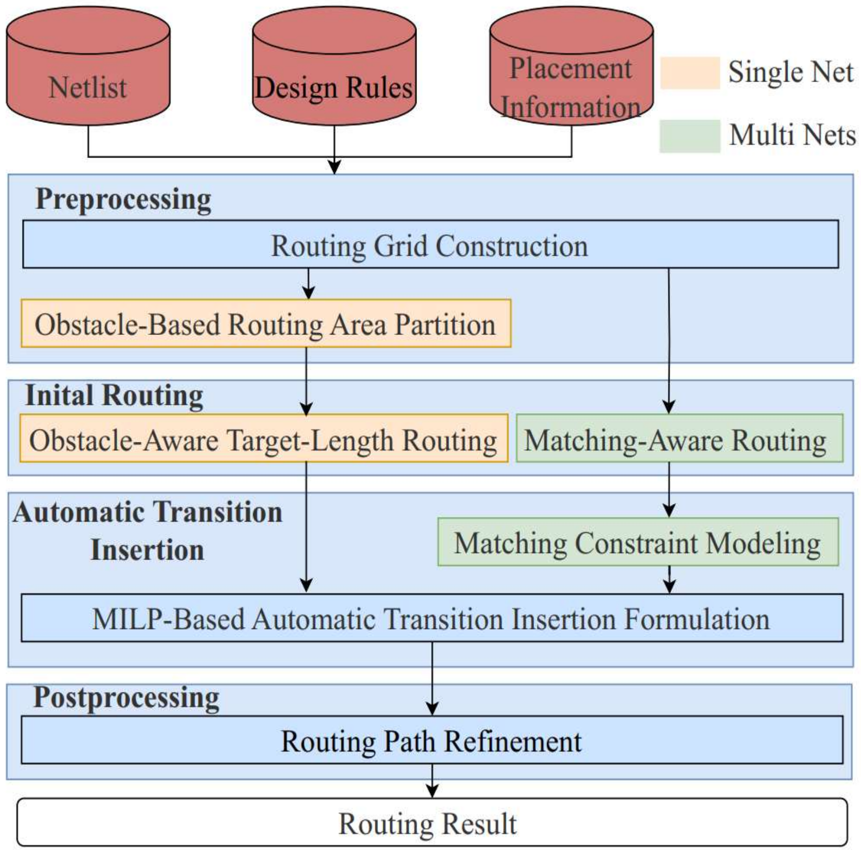


Optical Insertion Loss

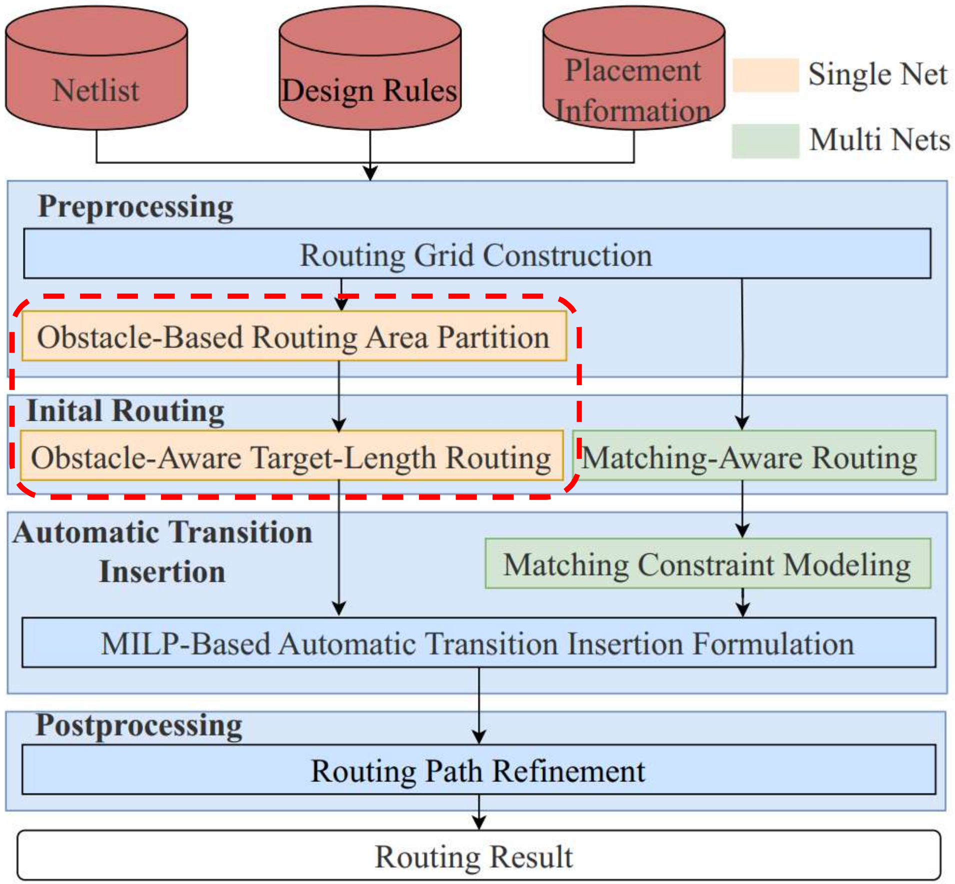


Framework Overview

- Preprocessing
  - **Conduct grids for routing**
  - **Partition regions** for single-net routing
- Initial routing
  - **Single-net routing**: obstacle-aware target-length routing
  - **Multi-net routing**: matching-aware A*-routing
- Automatic Transition Insertion
  - **Optimize the insertion loss** using MILP with **loss matching constraint**
- Postprocessing
  - **Convert coordinates to physical ones**



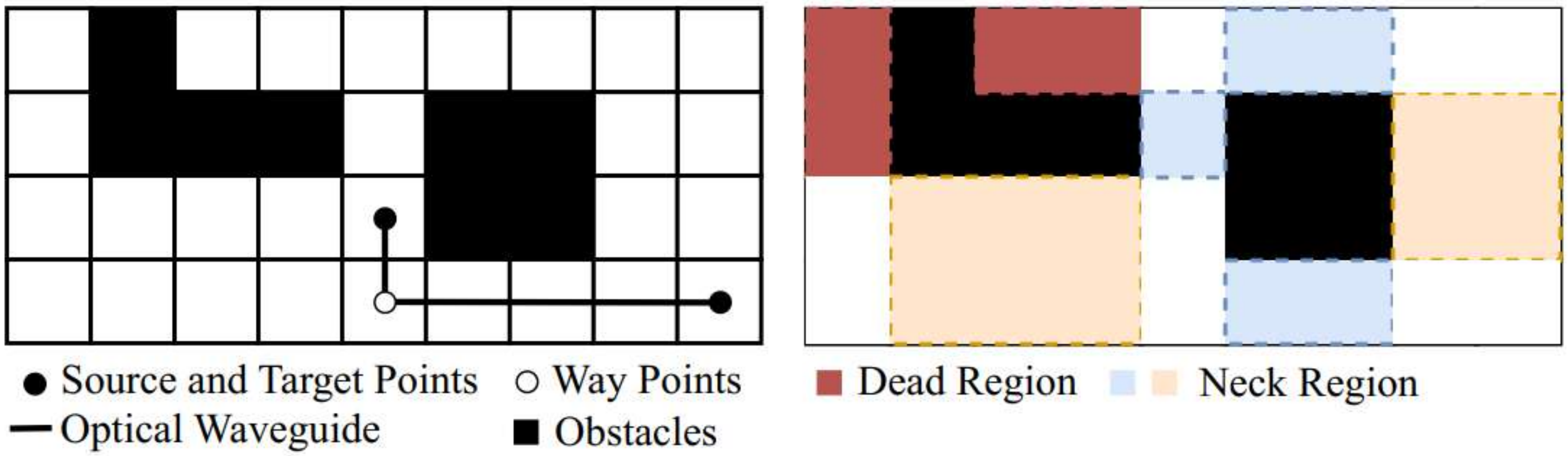
Initial Routing – Single-Net Routing



Obstacle-Aware Target-Length Routing

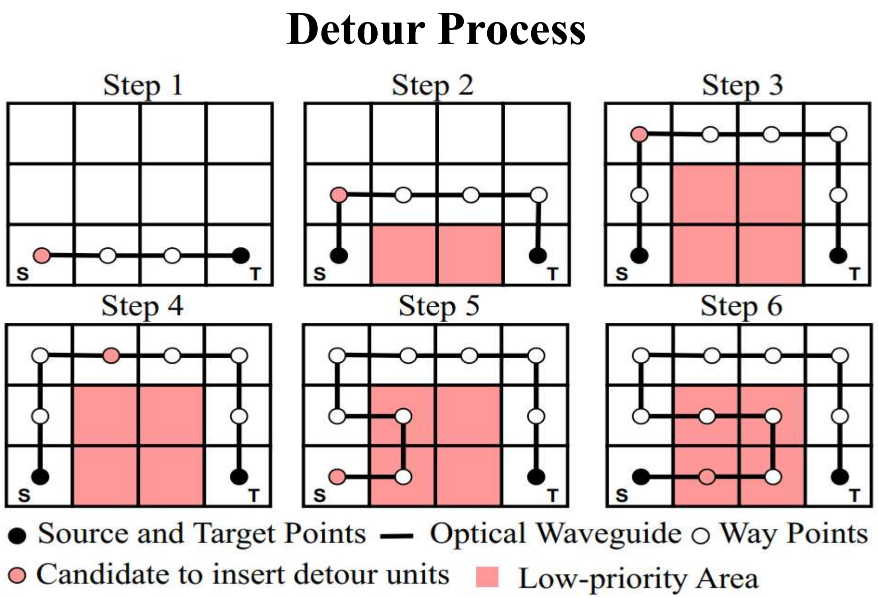
- Determine the priority of regions according to obstacles
  - **Dead region**: areas fully enclosed by obstacles
  - **Neck region**: areas with limited routing capacity

Region Partition



Obstacle-Aware Target-Length Routing

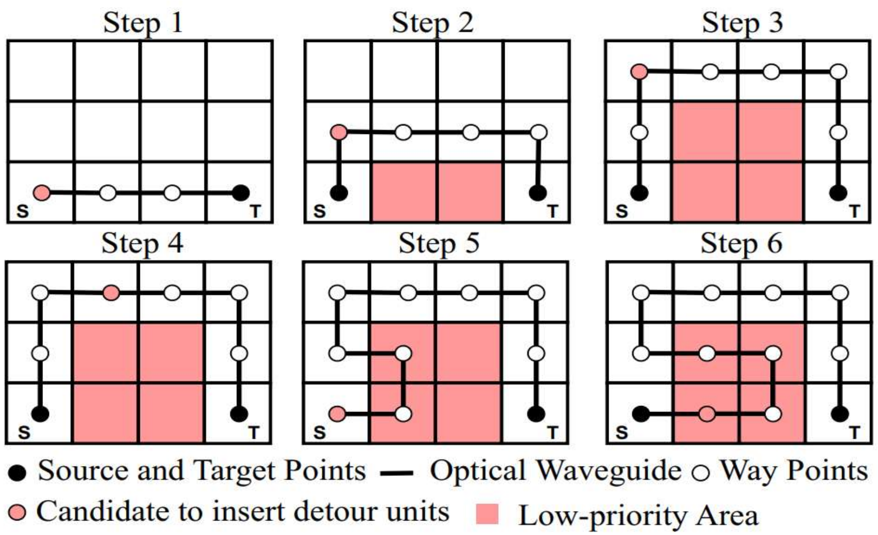
- Detour process
  - **Insert rectangular detour units** to increase the path length and mark visited regions
  - **Determine detour units** based on the grid size and minimum bend radius



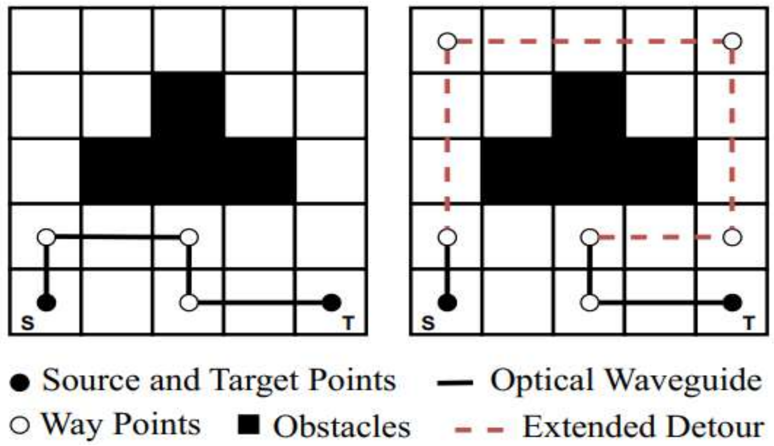
Obstacle-Aware Target-Length Routing

- Detour process
  - **Insert rectangular detour units** to increase the path length and mark visited regions
  - **Determine detour units** based on the grid size and minimum bend radius
- Extended detour mode
  - **Bypass obstacles through the outer boundary** when encountering a neck region

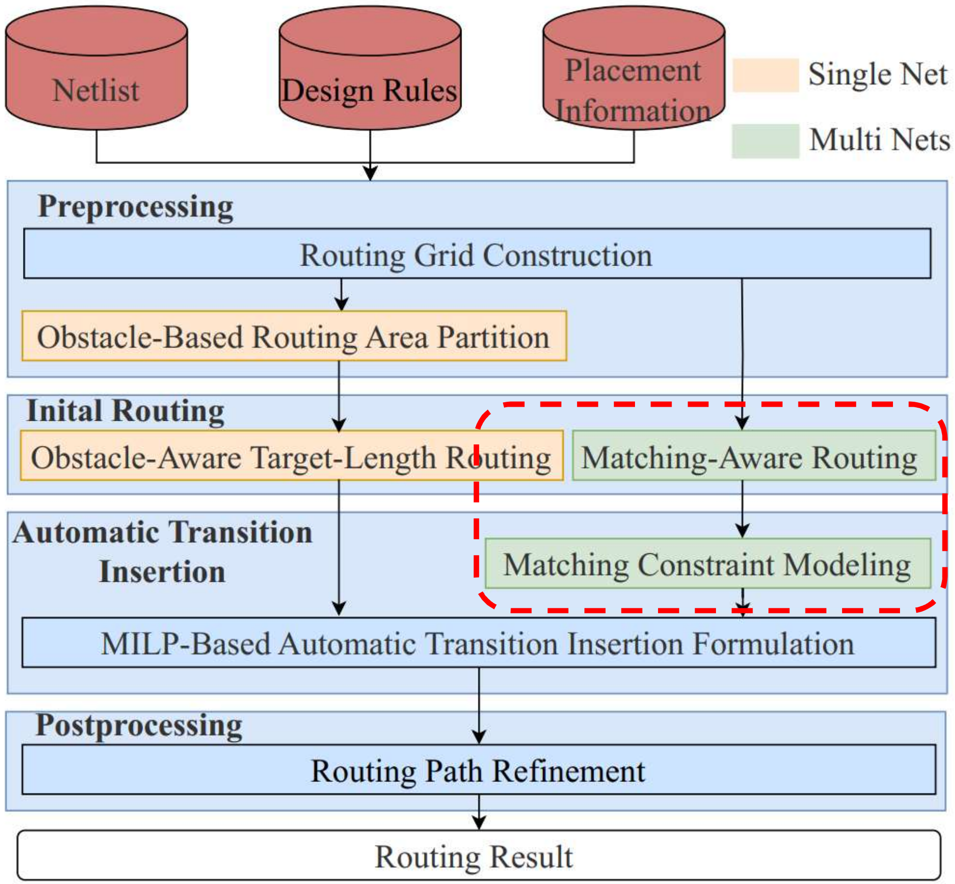
Detour Process



Extended Detour Mode



Initial Routing – Multi-Net Routing



Matching-Aware A*-Routing

- Cost function $f(x) = c(x) + g(x') + h(x)$
  - $c(x) = (1 + p_t(x) + p_s(l(x))) \times (g(x) - g(x'))$
  - $c(x)$: the weighted cost of the current node
  - $g(x')$: the cost of previous node
  - $h(x)$: the Manhattan distance to the target grid

Length Penalty

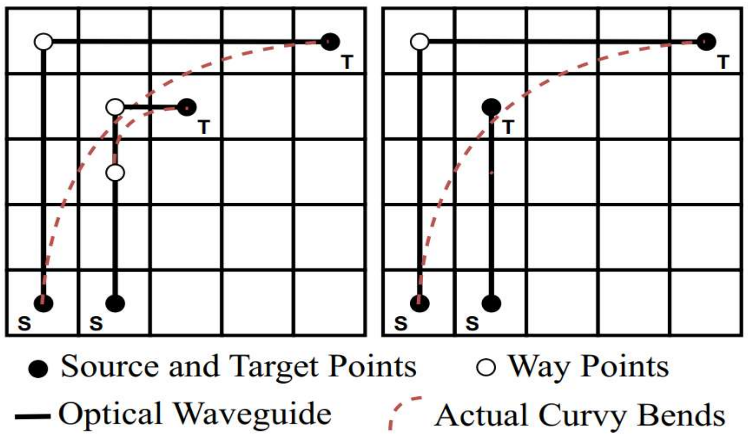
$$p_s(l) = \begin{cases} P_1, & 0 < l \leq R_1, \\ P_2, & R_1 < l \leq R_2, \\ \vdots & \\ 0, & l > R_{k-1}. \end{cases}$$

Terminal Penalty

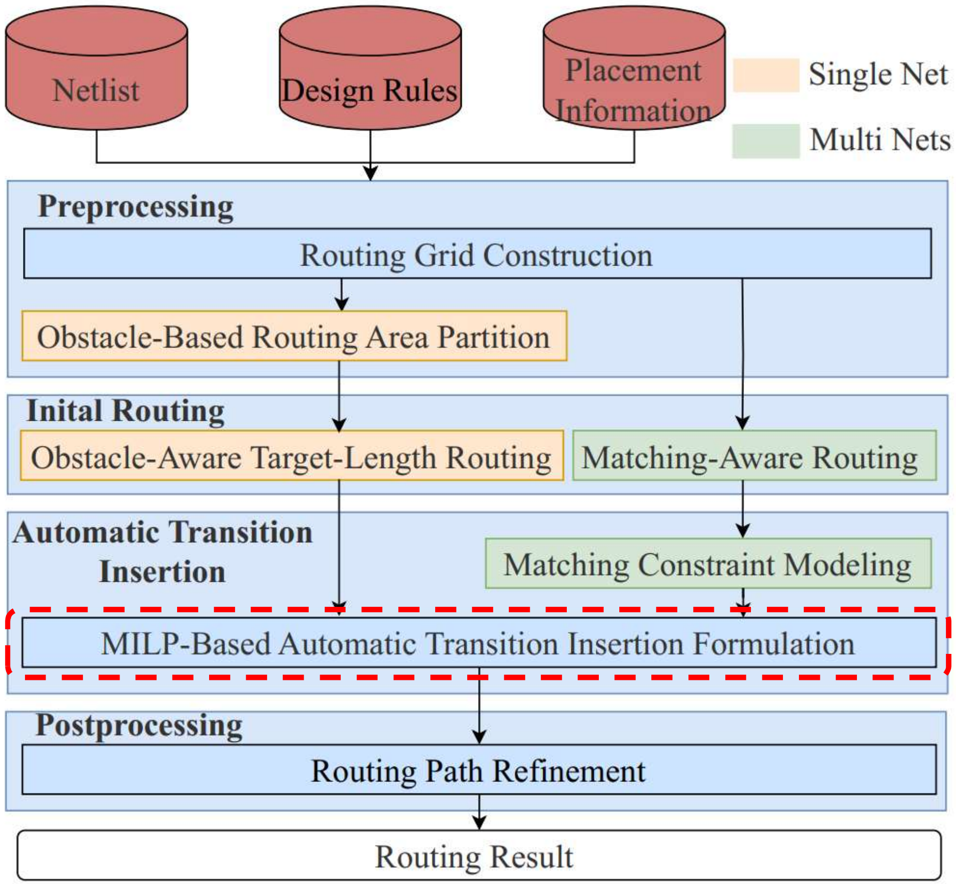
$$p_t(x) = \begin{cases} P_{\text{term}}, & \text{if } x \in N_t, \\ 0, & \text{otherwise.} \end{cases}$$

- Features
  - Encourage A* to **generate long segments for transition insertion**
  - Penalize paths that are close to terminals to **avoid overlap with bends**
  - Insert detour patterns for **length matching**

Bend Overlap



Automatic Transition Insertion

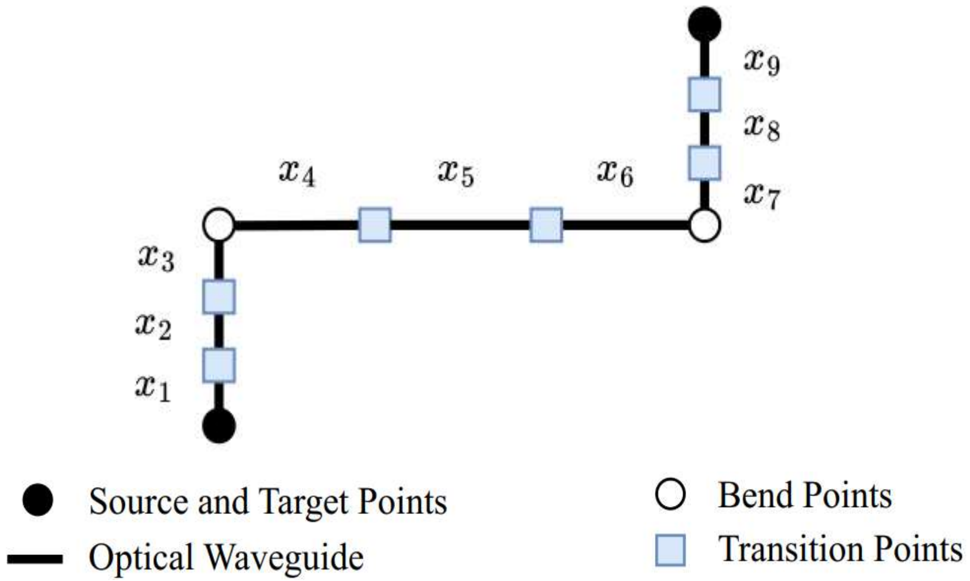


MILP-Based Transition Insertion

- Objective
  - Minimize total insertion loss, $\sum_{p=1}^{|N|} O_p^{total}$
  - $O_p^{total} = O_p^{bend} + O_p^{prop} + O_p^{tran}$
  - Crossed paths are divided into separate paths
- Constraints
  - Waveguide type constraint
  - Radius violation constraint
  - Transition overlap constraint
  - Matching constraint

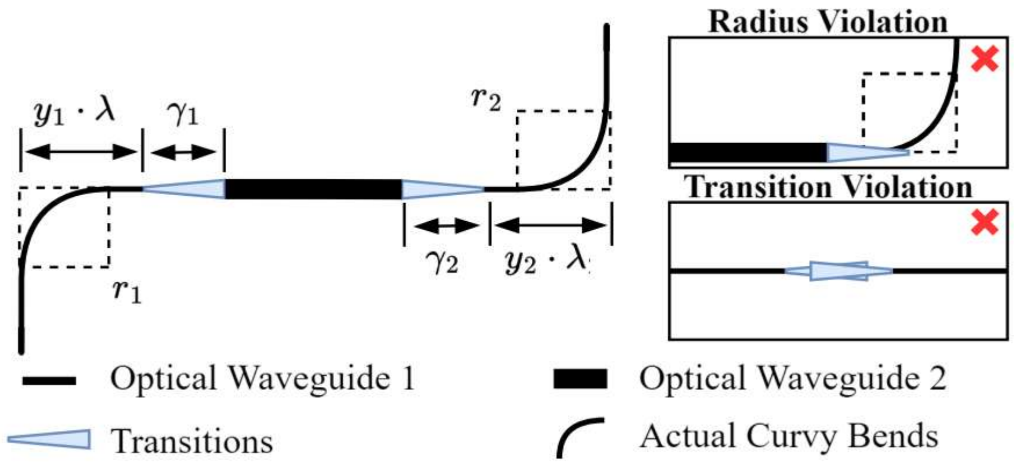
MILP-Based Transition Insertion

- **Waveguide type constraint**: $x_3 = x_4$ and $x_6 = x_7$
  - Segments are divided into 3 subsegments
  - x is a binary variable set for the waveguide type of the subsegment



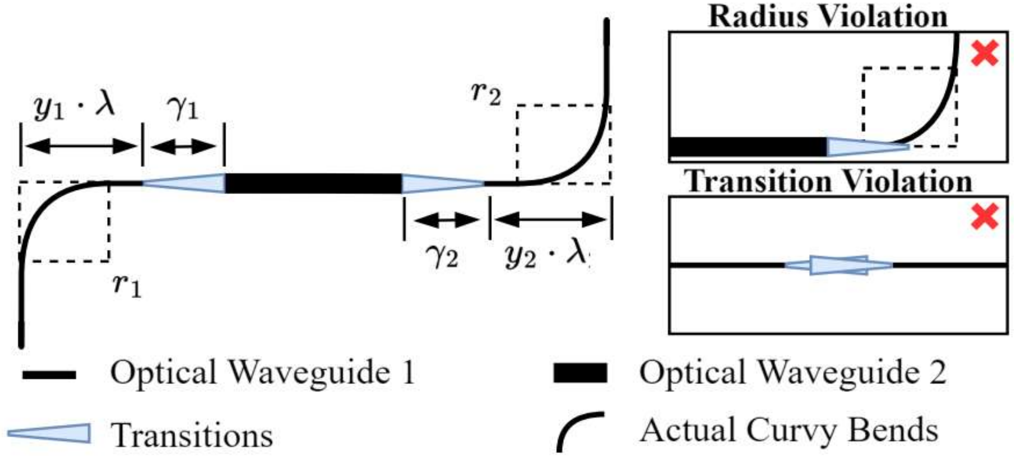
MILP-Based Transition Insertion

- **Radius violation constraint**: $y_1 \cdot \lambda \geq r_1,\ y_1 \cdot \lambda + \gamma_1 \leq \lambda - r_2$
- **Transition overlap constraint**: $1 - y_1 - y_2 \geq \frac{\gamma_1 + \gamma_2}{\lambda}$
  - The transition location is normalized by the length of segment λ
  - y is a 0-1 continuous variable to determine the transition location
  - r is the bend radius, γ is the length of transition,



MILP-Based Transition Insertion

- **Radius violation constraint**: $y_1 \cdot \lambda \geq r_1, \; y_1 \cdot \lambda + \gamma_1 \leq \lambda - r_2$
- **Transition overlap constraint**: $1 - y_1 - y_2 \geq \frac{\gamma_1 + \gamma_2}{\lambda}$
  - The transition location is normalized by the length of segment λ
  - y is a 0-1 continuous variable to determine the transition location
  - r is the bend radius, γ is the length of transition,
- **Matching constraint**: $\left| O_p^{total} - O_q^{total} \right| \leq \epsilon, \quad n_p, n_q \in G$



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Benchmark

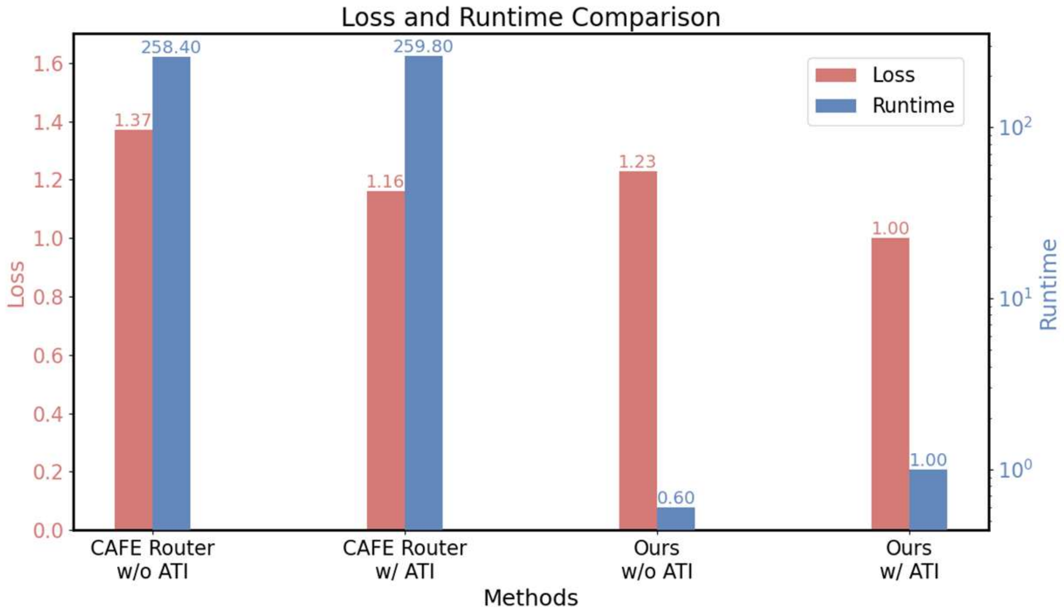
- **Testcases**
  - 10 photonic cases
- **Environmental settings**
  - C++ for initial routing and Python for remaining components
  - 2.00GHz Intel Xeon Gold 6338 CPU with 256GB memory
  - Gurobi ILP solver
- **Insertion loss value and transition specification**

Waveguide Type	Bending Loss (dB/bend)	Crossing Loss (dB/crossing)	Propagation Loss (dB/cm)
Full-etched	0.01	0.20	1.67
Deep-etched	0.02	-	1.02
Shallow-etched	0.04	-	0.57

Transition Type	Transition Loss (dB/transition)	Specification (μm)
Full-deep	0.01	20×11
Full-shallow	0.04	20×11
Deep-shallow	0.05	40×11

Experimental Results – Single-Net Routing

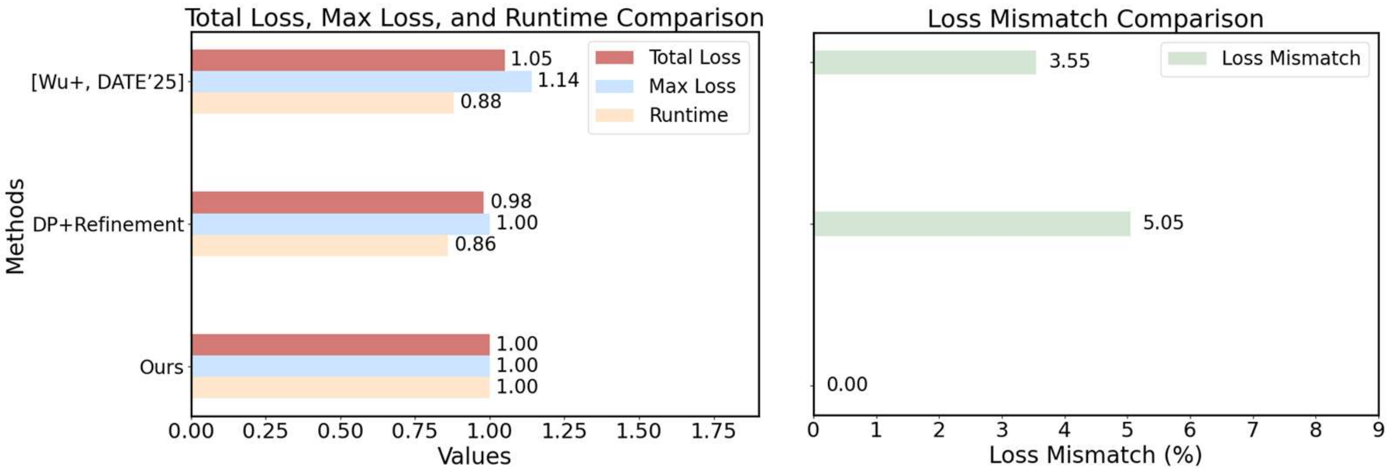
- **Compared to CAFE Router**[1]
  - **10.2%** loss improvement without transition insertion
  - **15.3%** (CAFE) and **18.7%** (Ours) loss improvement with transition insertion
  - Runtime: CAFE **506 s**, Ours **2 s (with ATI contributing 1 s)**



[1]Kohira Y, et al. A fast longer path algorithm for routing grid with obstacles using biconnectivity based length upper bound[J]. IEICE, 2009.

Experimental Results – Multi-Net Routing

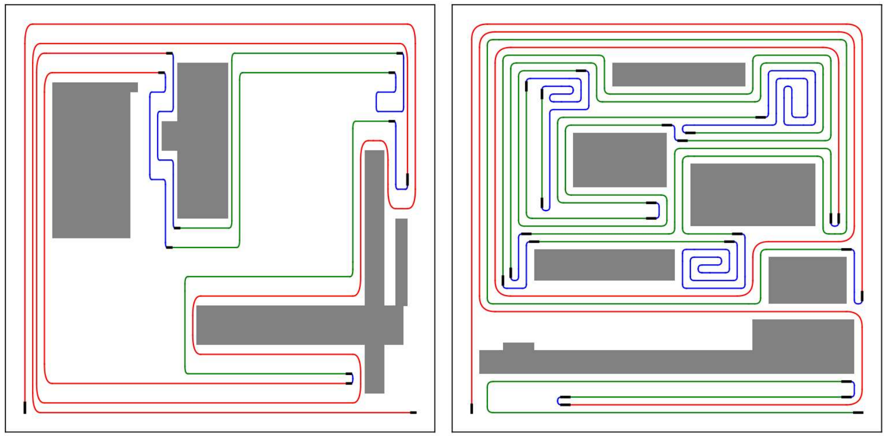
- **Compared to [Wu+, DATE'25][1]**
  - Total loss and maximum loss improved by **4.8%** and **12.3%**, respectively
  - **3.55%** ([Wu+, DATE'25]) and **0%** (Ours) loss mismatch
- **Compared to DP+Refinement**
  - The total loss and maximum loss values are **nearly identical**
  - **5.05%** (DP+Refinement) and **0%** (Ours) loss mismatch



[1]Wu Y, Guan W, Tong Y, et al. Automatic Routing for Photonic Integrated Circuits Under Delay Matching Constraints[C]. DATE, 2025.

Layout for Cases

PIC1 PIC4

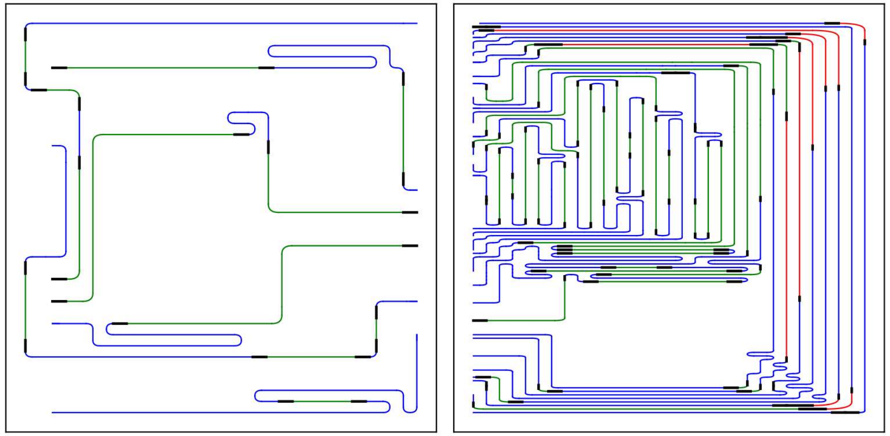


(a) (b)

Rib Waveguide (Deep) Rib Waveguide (Shallow)

Ridge Waveguide Transitions Obstacles

PIC5 PIC9



(a) (b)

Rib Waveguide (Deep) Rib Waveguide (Shallow)

Ridge Waveguide Transitions

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Conclusion

- We proposed the **first** optical routing framework considering hybrid waveguides
- Our initial routing algorithms
  - **Minimize bends and short segments** while considering the target path length
  - Consider the terminal location to **avoid physical violations**
- Our automatic transition insertion method
  - **Optimally assign waveguide types** to reduce total loss
  - Ensure compliance with **matching constraint**
- Experimental results have shown that our method substantially outperforms the existing routers

Thank you & Questions

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