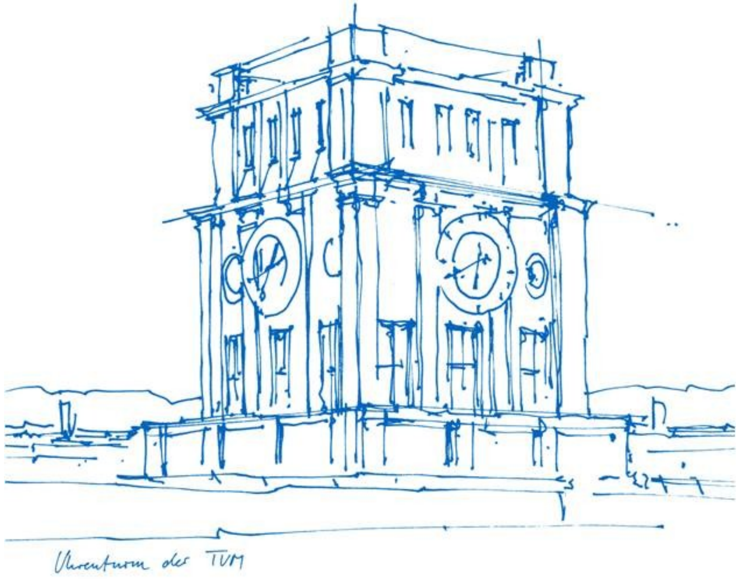
Design Automation for Wavelength-Routed Optical Networks-on-Chip:

Current Solutions and Reliability Challenges

Technical University of Munich (TUM)

Chair of Electronic Design Automation

Presenter: Dr.-Ing. Tsun-Ming Tseng



Outline

- Introduction of WRONoC
- Representative WRONoC Design Synthesis Methodologies
- Reliability Challenges

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- **Introduction of WRONoC**
- Representative WRONoC Design Synthesis Methodologies
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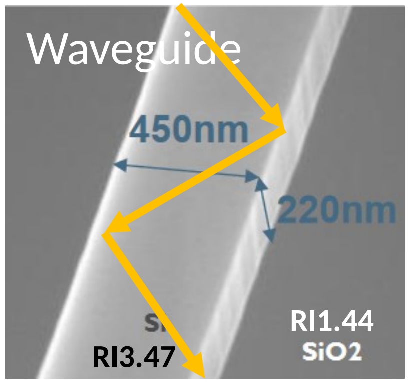
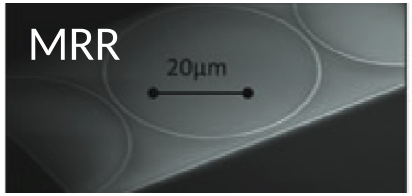
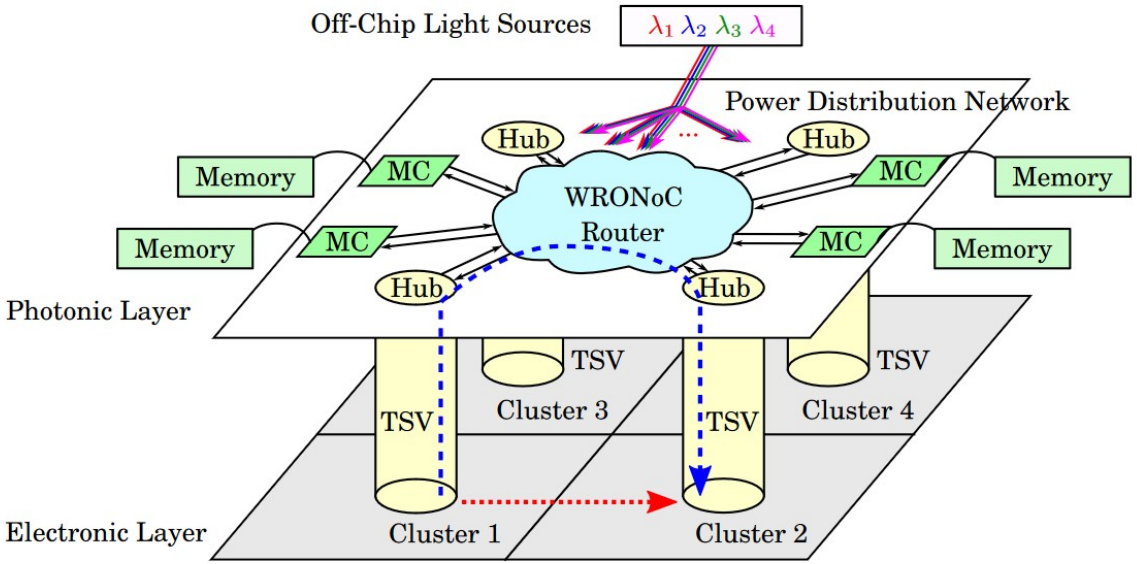
Introduction of WRONoC

- Key components: **waveguides** and **microring resonators (MRR)**
- New option for signal transmission
- High bandwidth enabled by **wavelength-division multiplexing (WDM)**



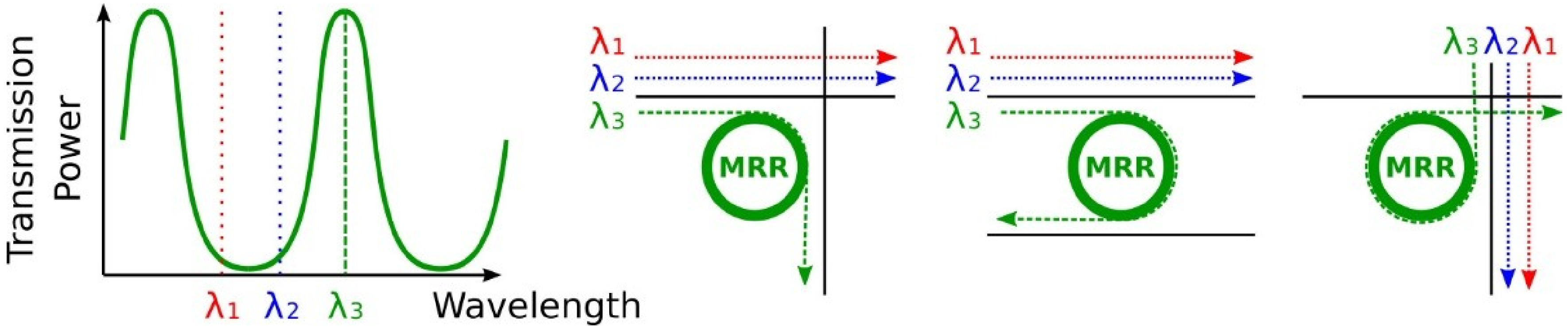




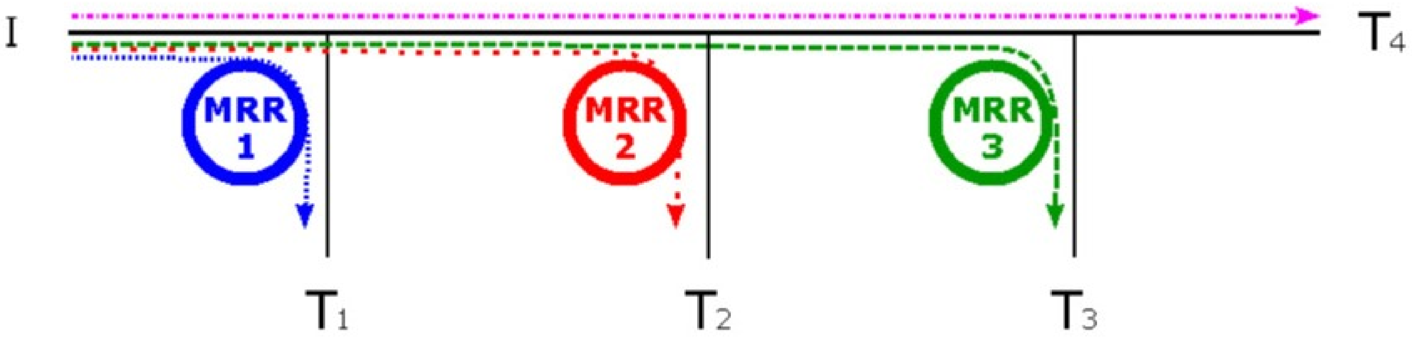
Sources:
1) *Silicon Photonics Platform for 50G Optical Interconnects, Photonics Summit and Workshop 2017*, Michal Rakowski.
2) *Silicon Microring Resonators, Laser & Photonics Reviews 2012*, Wim Bogaerts et al.

Wavelength-Division Multiplexing (WDM)

- MRR coupling: demultiplex and direct on-resonance signals

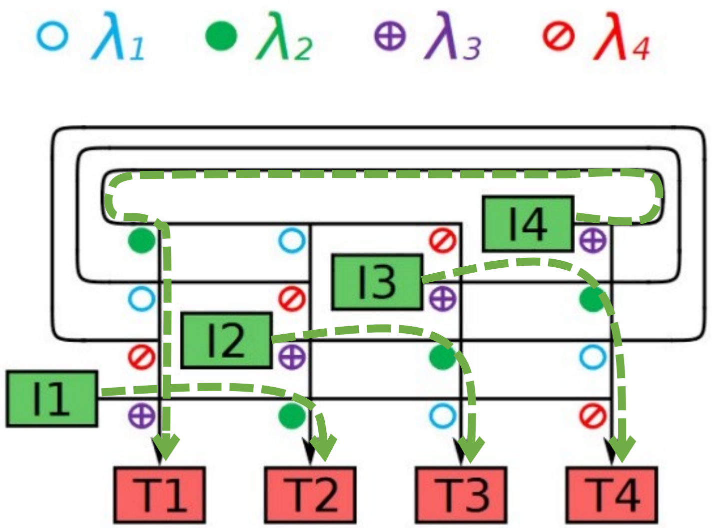


- Signals are routed based on the wavelengths
  wavelength-routed



WRONoC Features

- Full bandwidth: all nodes can talk simultaneously
- Signal paths determined **in design phase**
- Advantages (vs ENoC and active ONoCs)
  - No control resource
  - No scheduling effort
  - No congestion control
  - No real-time path construction no uncertain delay
- Disadvantages (vs active ONoCs)
  - Many MRRs (MRR serve for dedicated paths)
  - High design difficulty (paths on the same wavelength should not overlap)



WRONoC Design Features

Topological features:

- Waveguide connection structure
- MRR topological locations
- MRR resonance
- Signal wavelength assignment
- Signal path routing

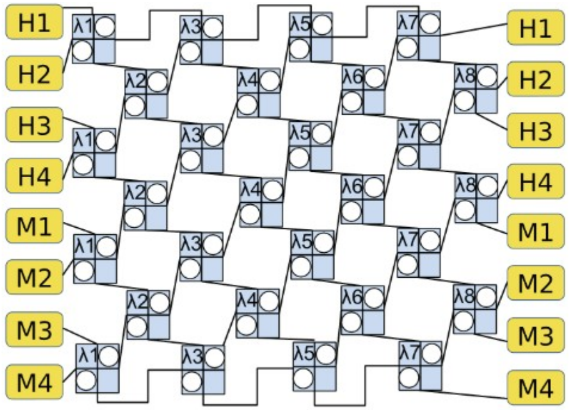
Physical design features:

- Waveguide routing
- MRR placement

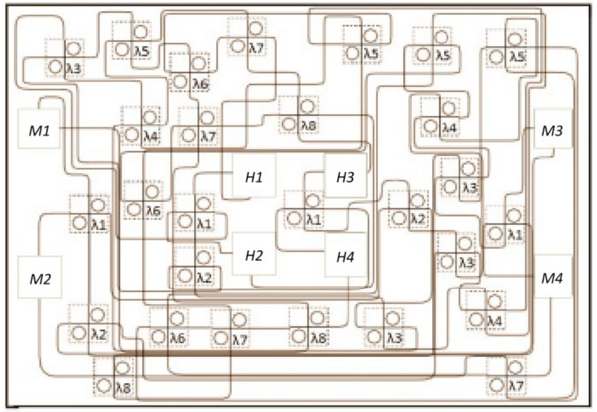
All must be done in the design phase

Challenge of efficiency!

Manual topology



Manual layout



Sources:

1) *Engineering a Bandwidth-Scalable Optical Layer for a 3D Multi-core Processor with Awareness of Layout Constraints*, NOCS'12, Luca Ramini et al.

Outline

- Introduction of WRONoC
- **Representative WRONoC Design Synthesis Methodologies**
- Reliability Challenges

WRONoC Design Synthesis Methodologies

- Application-specific topology synthesis, followed by layout synthesis
  - *CustomTopo (ICCAD'18)*, *FAST (DATE'21, TCAD'22)*
- Layout-aware topology projection, followed by external waveguide routing
  - *Light (ASP-DAC'21)*, *ToPro (ICCAD'21)*
- Topology & layout co-synthesis
  - *PSION (ISPD'19, TCAD'20, ICCAD'20)*

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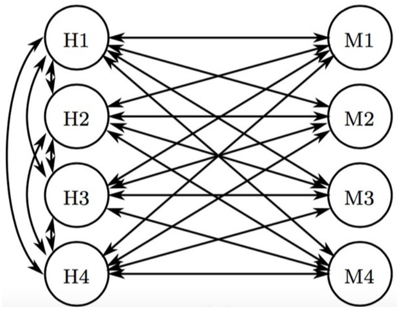
Topology Synthesis by CustomTopo

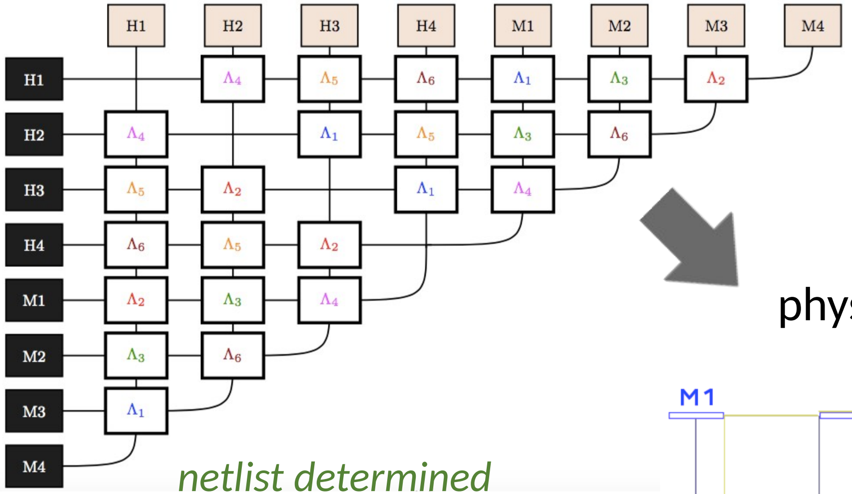
Input: communication graph



communication matrix

	H1	H2	H3	H4	M1	M2	M3	M4
H1		4	5	6	1	3	2	0
H2	4		1	5	3	6	0	2
H3	5	2		1	4	0	6	3
H4	6	5	2		0	4	3	1
M1	2	3	4	0				
M2	3	6	0	4				
M3	1	0	6	3				
M4	0	1	3	2				

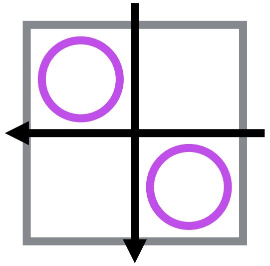
topology



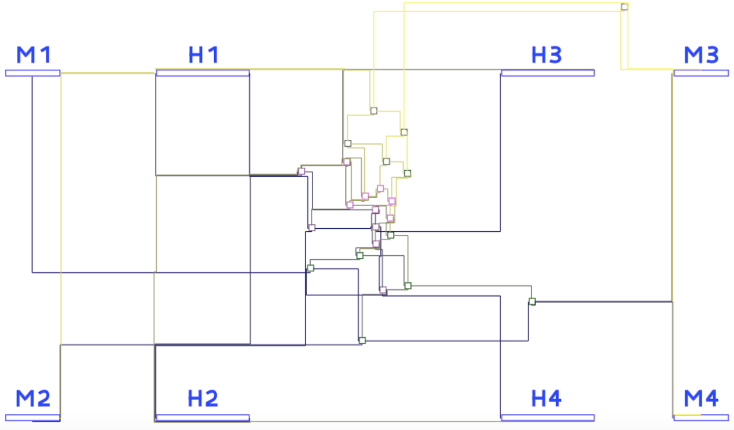
netlist determined

wavelength for each message determined
wavelength for each ADF determined
#ADF-sharing structures maximized

Add-drop filter (ADF) with 2 MRRs



physical design (by PROTON)



Sources:

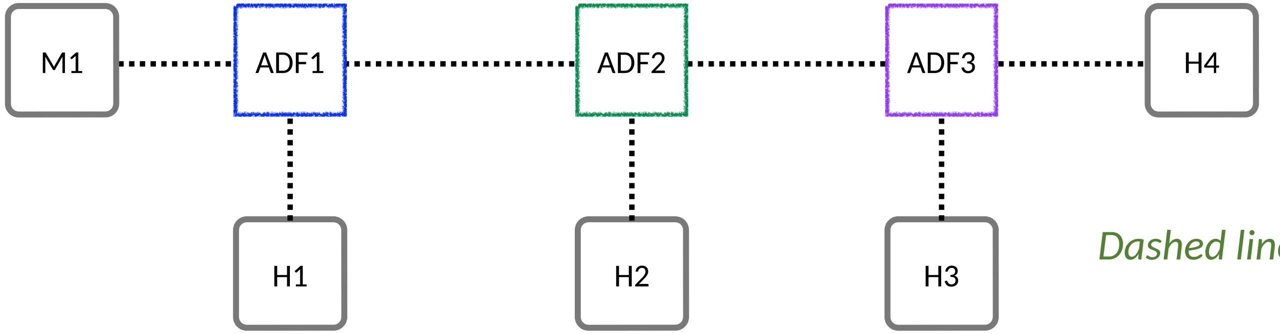
1) *CustomTopo: A Topology Generation Method for Application-Specific Wavelength-Routed Optical NoCs*, *ICCAD'18*, Mengchu Li et al.
2) *PROTON+: A Placement and Routing Tool for 3D Optical Networks-on-Chip with a Single Optical Layer*, *JETC'15, Anja von Beuningen et al.*

Information in the Communication Matrix

Initiators

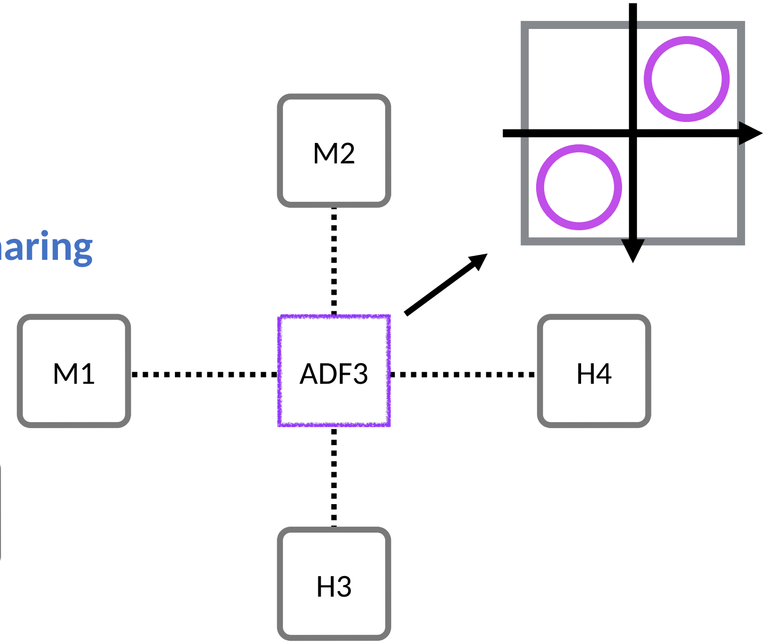
Targets

	H1	H2	H3	H4	M1	M2	M3	M4
H1		4	5	6	1	3	2	0
H2	4		1	5	3	6	0	2
H3	5	2		1	4	0	6	3
H4	6	5	2		0	4	3	1
M1	2	3	4	0				
M2	3	6	0	4				
M3	1	0	6	3				
M4	0	1	3	2				



Add-drop filter (ADF) with 2 MRRs

ADF sharing



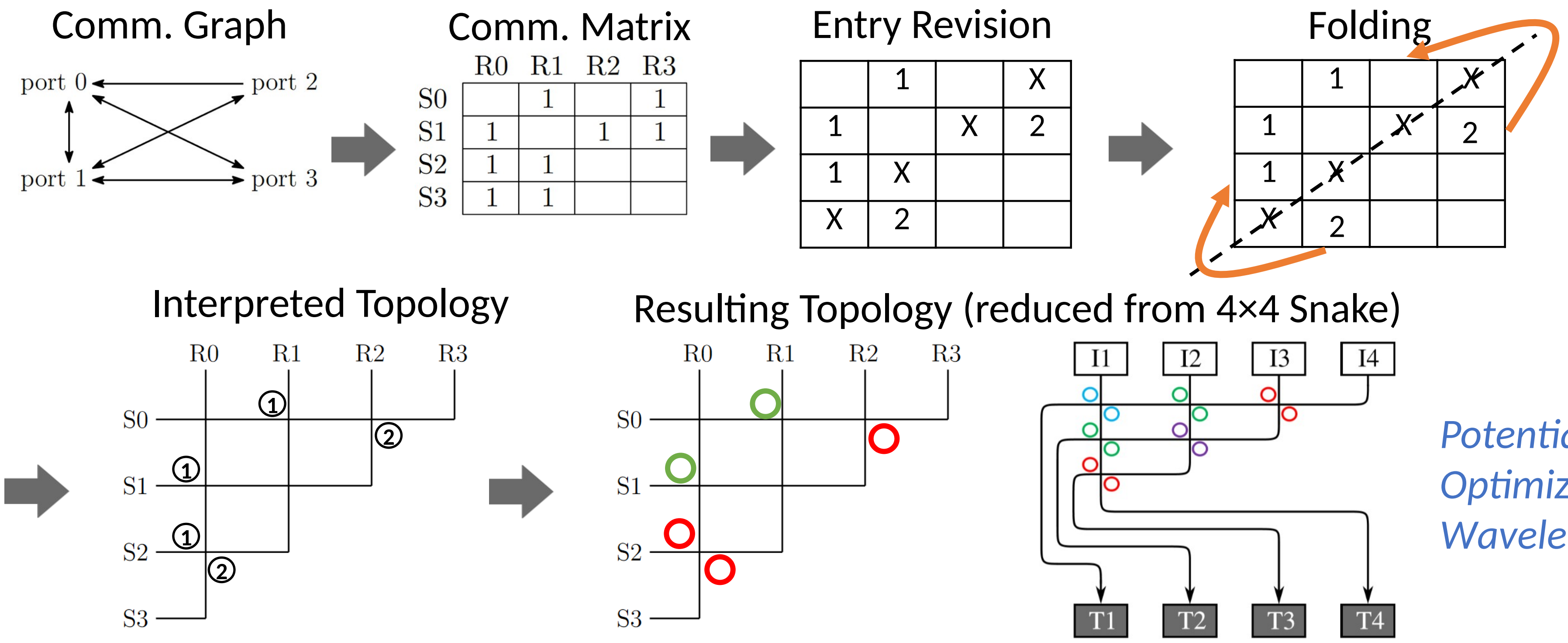
Dashed lines: components may not be directly connected

Sources:

1) *CustomTopo: A Topology Generation Method for Application-Specific Wavelength-Routed Optical NoCs*, *ICCAD'18*, Mengchu Li et al.

Topology Synthesis by FAST

- Reduced from Snake topology



Potential of Further Optimization by Wavelength Re-assignment

Sources:
1) *Contrasting Wavelength-Routed Optical NoC Topologies for Power-Efficient 3D-stacked Multicore Processors using Physical-Layer Analysis*, *DATE'13*, Luca Ramini et al.
2) *FAST: A Fast Automatic Sweeping Topology Customization Method for Application-Specific Wavelength-Routed Optical NoCs*, *DATE'21*, Moyuan Xiao et al.
3) *Crosstalk-Aware Automatic Topology Customization and Optimization for Wavelength-Routed Optical NoCs*, *IEEE TCAD'22*, Moyuan Xiao et al.

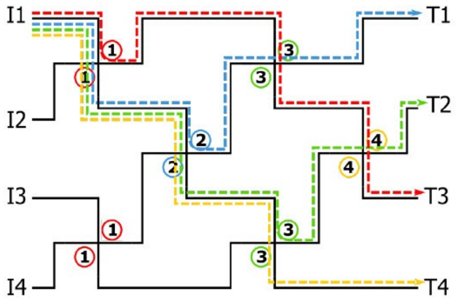
WRONoC Design Synthesis Methodologies

- Application-specific topology synthesis, followed by layout synthesis
  - *CustomTopo (ICCAD'18), FAST (DATE'21, TCAD'22)*
- **Layout-aware topology projection, followed by external waveguide routing**
  - ***Light (ASP-DAC'21), ToPro (ICCAD'21)***
- Topology & layout co-synthesis
  - *PSION (ISPD'19, TCAD'20, ICCAD'20)*

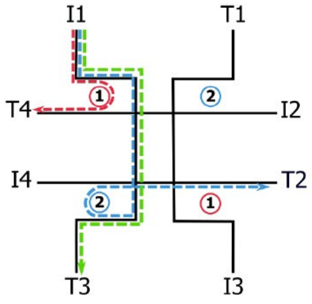
Light: WRONoC Router

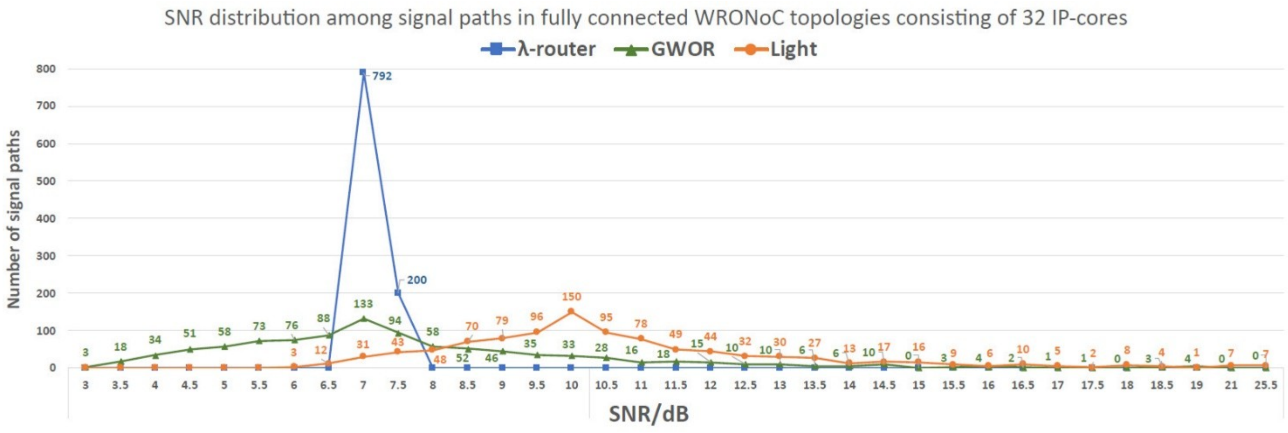
- Physical-design-aware
- A wide range of signal-to-noise ratio (SNR) distribution — good potential for signal path binding

4×4 λ-router

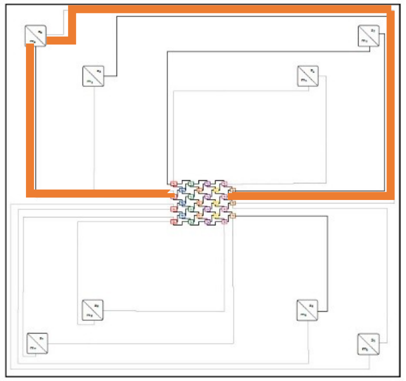


4×3 Light

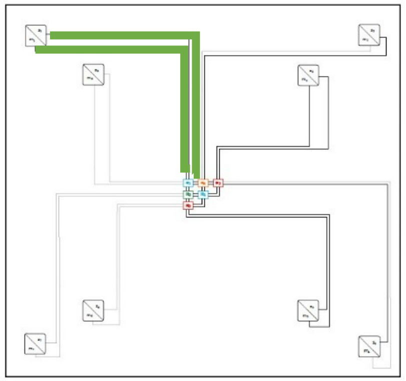




8×8 λ-router



8×7 Light



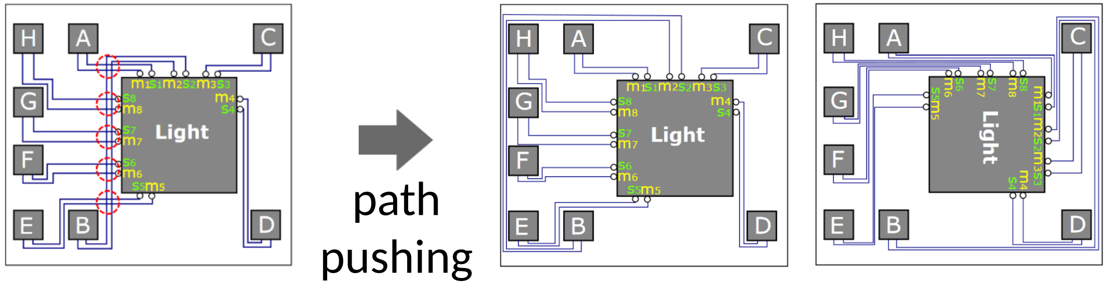
Sources:

1) *Light: A Scalable and Efficient Wavelength-Routed Optical Networks-On-Chip Topology, ASP-DAC'21*, Zhidan Zheng et al.

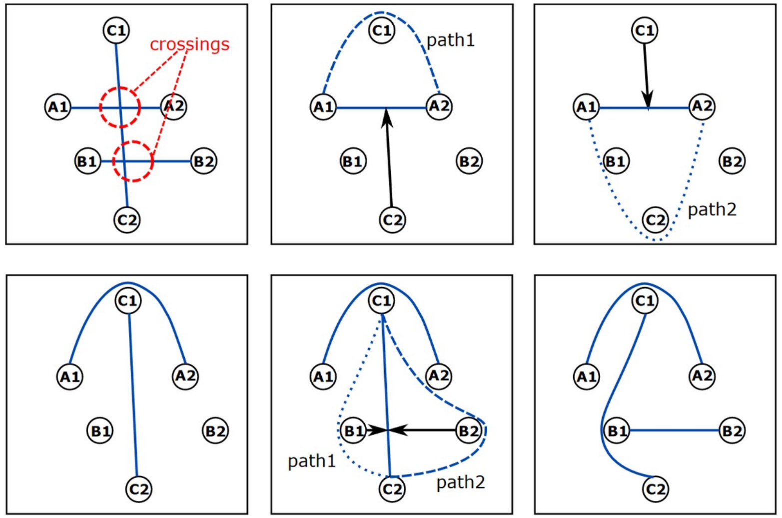
ToPro: Waveguide Router

- Steps:
  1. Project a physical-design-aware topology, e.g. Light, onto the center of the routing plane
  2. Route shortest paths
  3. Crossing resolution by path pushing
- Zero-crossing waveguide routing from router to nodes
- Minimize insertion loss & Maximize SNR

Other solutions after rotation/flip



Crossing resolution by path pushing



Sources:
1) *ToPro: A Topology Projector and Waveguide Router for Wavelength-Routed Optical Networks-on-Chip*, *ICCAD'21*, Zhidan Zheng et al.
2) *Topological routing to maximize routability for package substrate*, *DAC'08*, Shenghua Liu et al.

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- Layout-aware topology projection, followed by external waveguide routing
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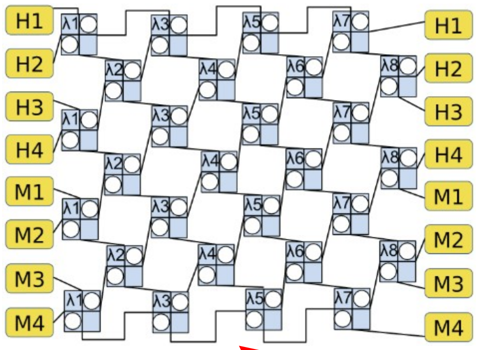
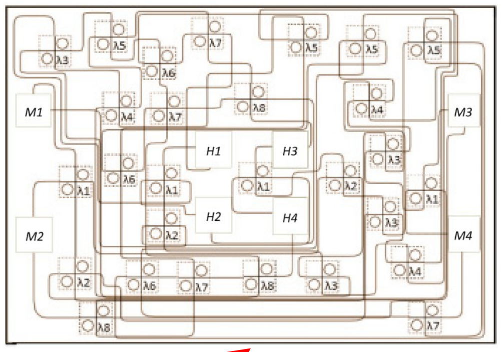
Manual topology



Manual layout



Significant mismatch!

DFG project (2020): bridge the gap between topology and layout

PSION: Template-Based Synthesis

Topological features:

- Waveguide connection structure
- MRR topological locations
- MRR resonant wavelengths
- Signal wavelength assignment
- Signal path routing

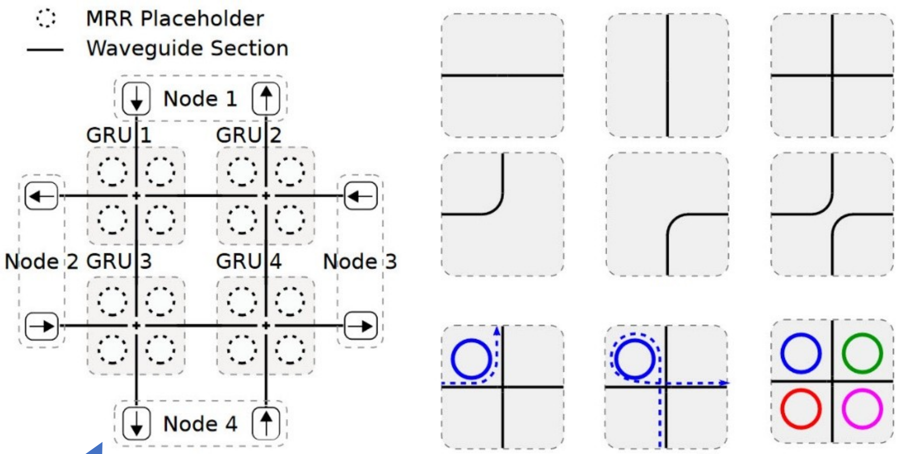
to be determined

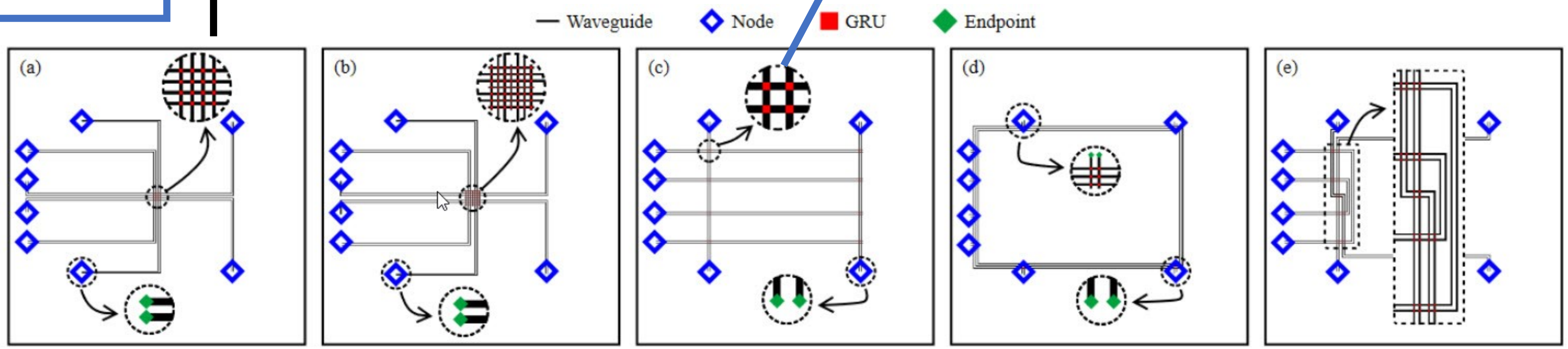
Physical design features:

- Waveguide routing
- MRR placement

fixed

placeholders

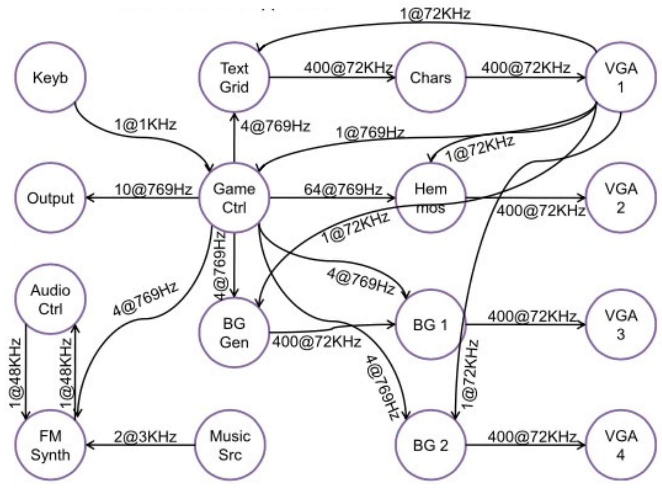




Sources:
1) *PSION: Combining logical topology and physical layout optimization for Wavelength-Routed ONoCs*, *ISPD'19*, Alexandre Truppel et al.
2) *PSION+: Combining logical topology and physical layout optimization for Wavelength-Routed ONoCs*, *IEEE TCAD 2020*, Alexandre Truppel et al.
3) *PSION 2: Optimizing Physical Layout of Wavelength-Routed ONoCs for Laser Power Reduction*, Alexandre Truppel et al.

WRONoC Synthesis by PSION

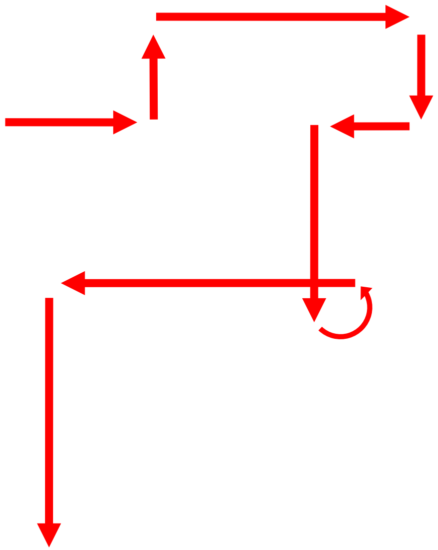
a “Screen Savor” multimedia application



16 nodes, 22 messages

- **240 MRRs** required for 1616 Lambda-router
- Here only **27 MRRs** are used

WRONoC router synthesized by PSION



Sources:

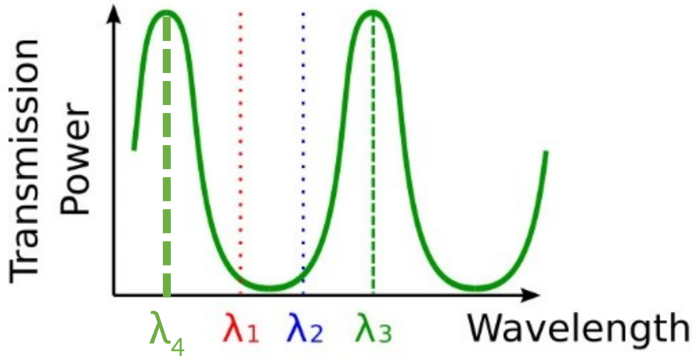
1) *PSION: Combining logical topology and physical layout optimization for Wavelength-Routed ONoCs, ISPD’19*, Alexandre Truppel et al.
2) *A scalable, non-interfering, synthesizable Network-on-chip monitor — extended version, Microprocessors and Microsystems 2013, Antti Alhonen et al.*

Outline

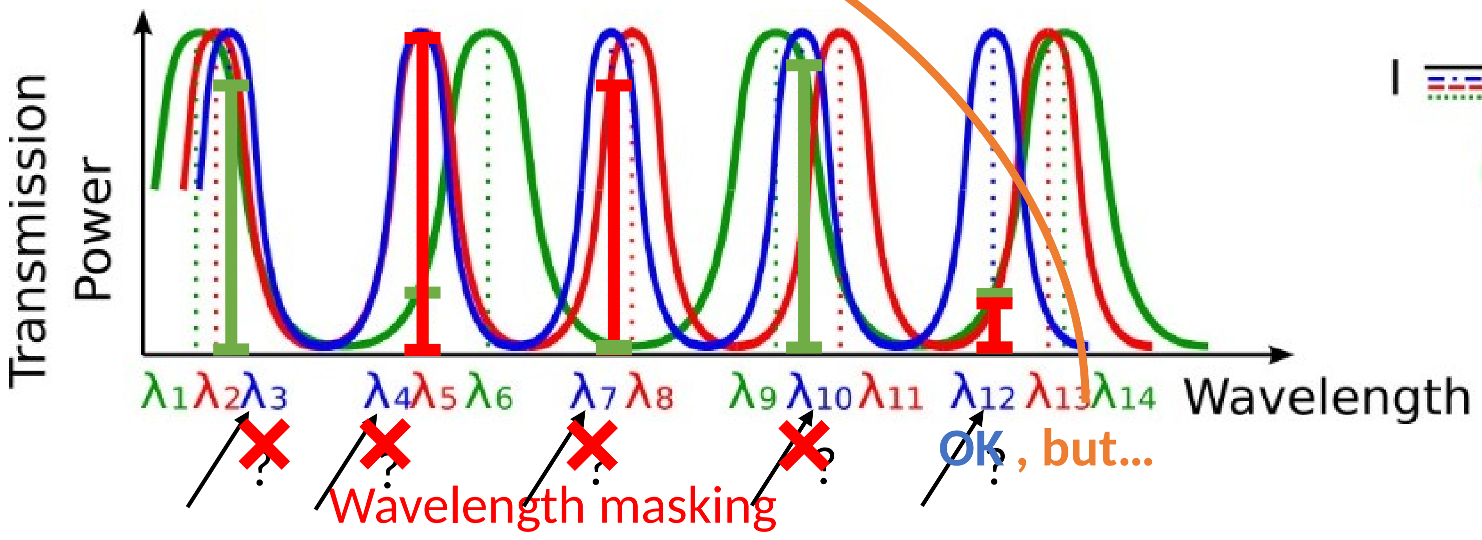
- Introduction of WRONoC
- Representative WRONoC Design Synthesis Methodologies
- **Reliability Challenges**

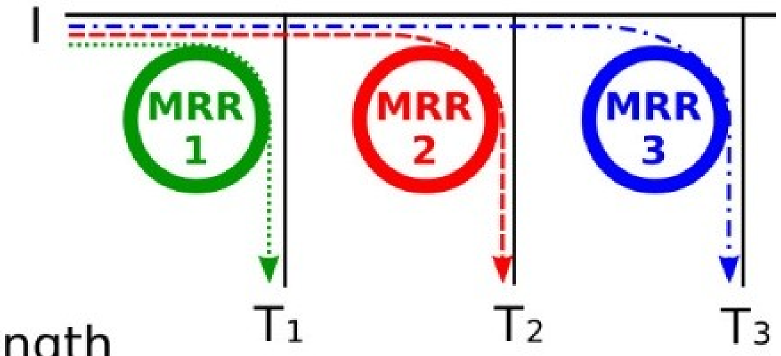
MRR Transmission Characteristics

- MRR periodic transmission spectrum, which brings
  - Optimization room for bit-level parallelism DFG project (2023)
  - **Crosstalk!**

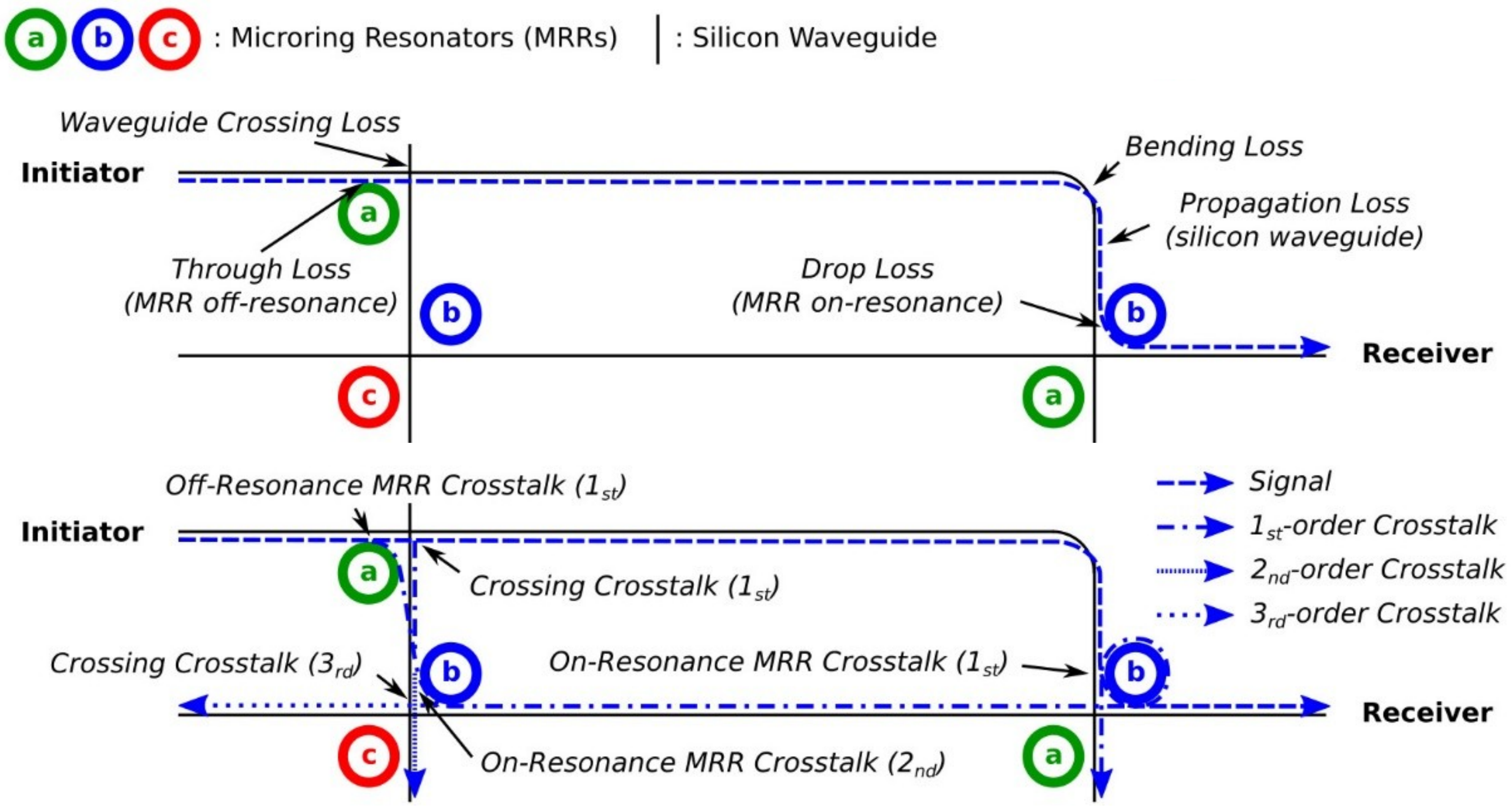


Transmission spectra of three MRRs.





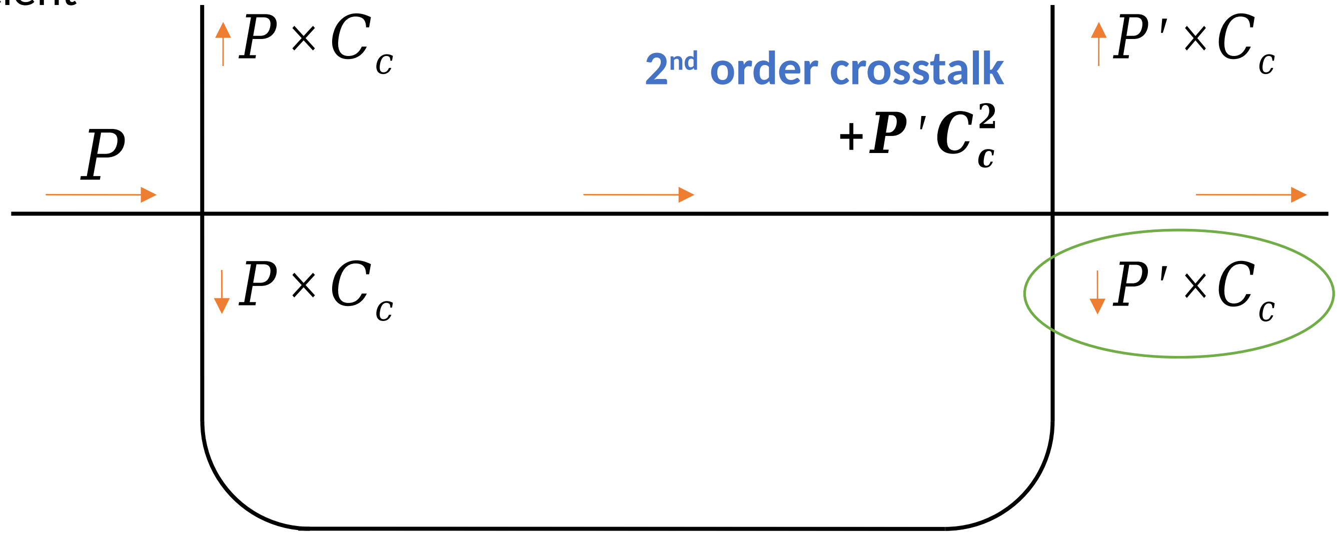
Insertion Loss and Crosstalk



Infinite-order Crosstalk Calculation

- : crossing loss
- : crossing crosstalk coefficient

… and eventually this can be endless (infinite-order)

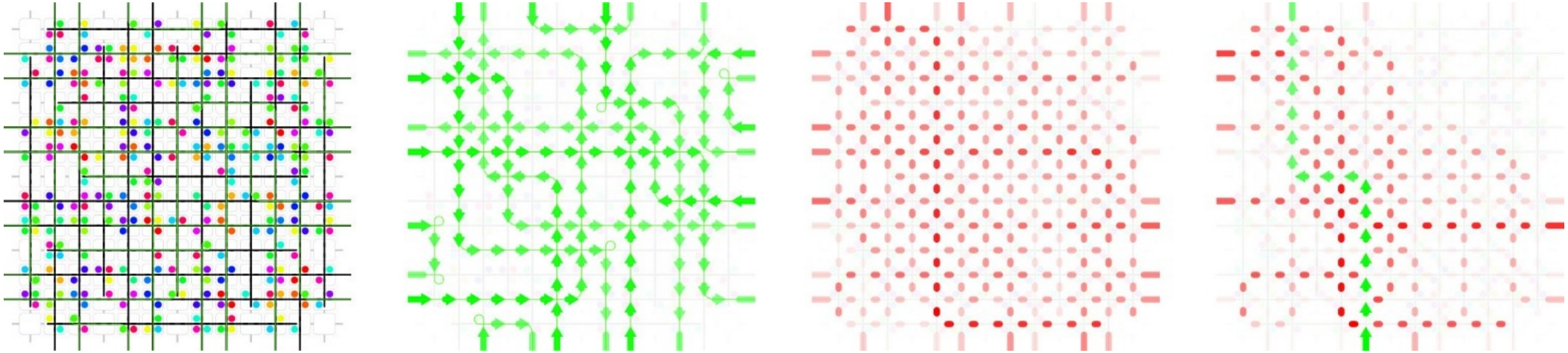


We apply the closed-form formula for computing an infinite geometric series, i.e., with its matrix analogue

Sources:

1) *Accurate Infinite-order Crosstalk Calculation for Optical Networks-on-Chip*, *IEEE/OSA Journal of Lightwave Technology (JLT) 2023*, Alexandre Truppel, Tsun-Ming Tseng, and Ulf Schlichtmann

Crosstalk Distribution Visualization



A design with components/ports, i.e., million different power values, can be evaluated in on a single thread.

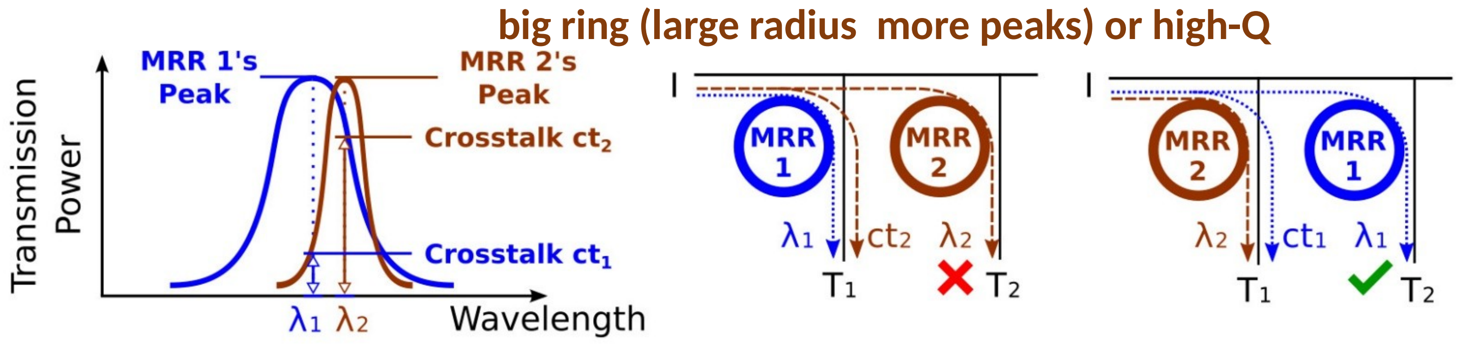
Sources:

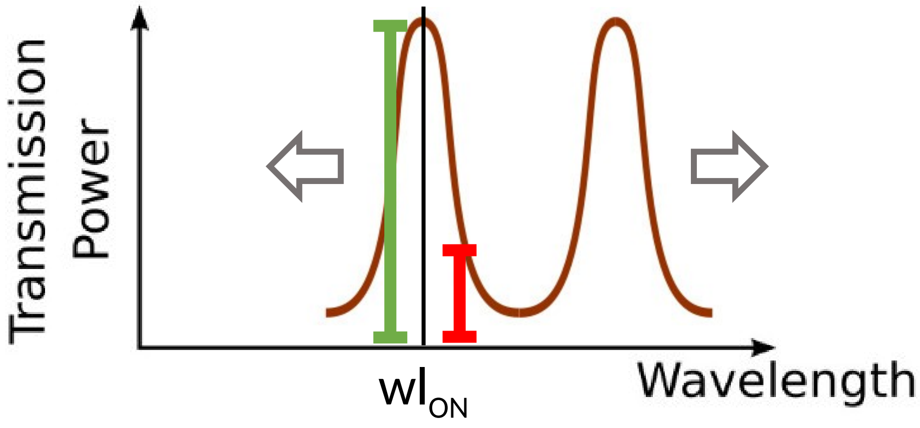
1) *Accurate Infinite-order Crosstalk Calculation for Optical Networks-on-Chip*, *IEEE/OSA Journal of Lightwave Technology (JLT) 2023*, Alexandre Truppel, Tsun-Ming Tseng, and Ulf Schlichtmann

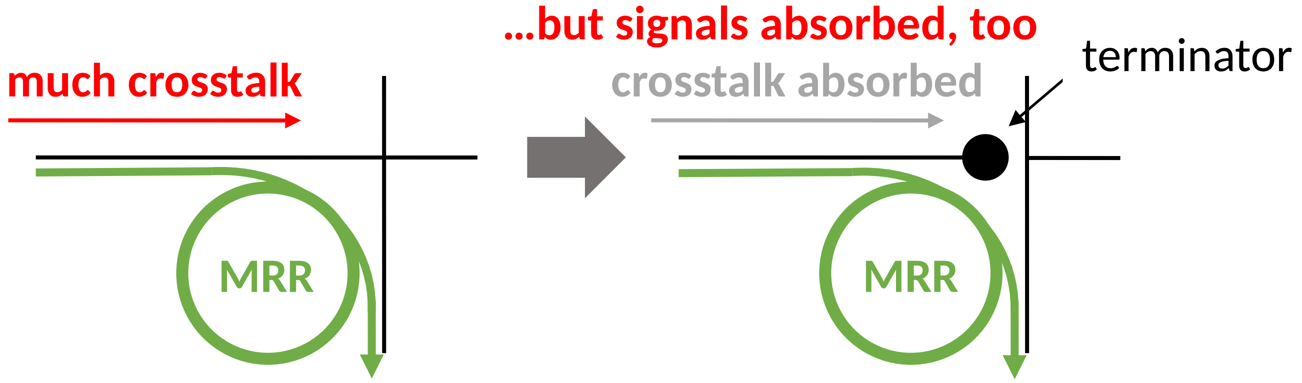
Crosstalk Issue

- MRRs are sensitive to **process variation** and **temperatures** further spectrum shift

- Possible topics:
  - Robust network topology
  - Spare components
  - Crosstalk elimination by terminator







Thank you for your attention!

Any Question?

Many thanks to the researchers working with me:

- *Prof. Dr.-Ing. Ulf Schlichtmann*
- *Dr.-Ing. Mengchu Li*
- *Dr.-Ing. Alexandre Truppel*
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- *M.Sc. Liaoyuan Cheng*
- *M.Sc. Moyuan Xiao*

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- *Dr. Mahdi Tala*
- *Prof. Mahdi Nikdast*
- *Prof. Shigeru Yamashita*
- *Prof. Shao-Yun Fang*