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Amon: Advanced Mesh-Like Optical NoC

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Bottleneck: On-chip Interconnects in Many-core Systems

Metal Wires

- Increasing Signal Delay with technology scaling while gate delays decrease
- Increasing Power Consumption in global core-to-core interconnects due to repeaters, regenerators, or buffers

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-> Performance and Power demands cannot be met by metal wires in future many-core chips[1]

[1] O'Connor, Ian, and Gabriela Nicolescu. Integrated Optical Interconnect Architectures for Embedded Systems. Springer Science & Business Media, 2012.

Motivation for Optical Networks-on-chip

1. Optical data transmission by using light -> low latency (signal propagation 15ps/mm) (global metal wire: ~262ps/mm)
2. Data can be transmitted simultaneously on the same waveguide at different wavelengths -> high bandwidth without adding wires
3. (Almost) Distance independent energy consumption

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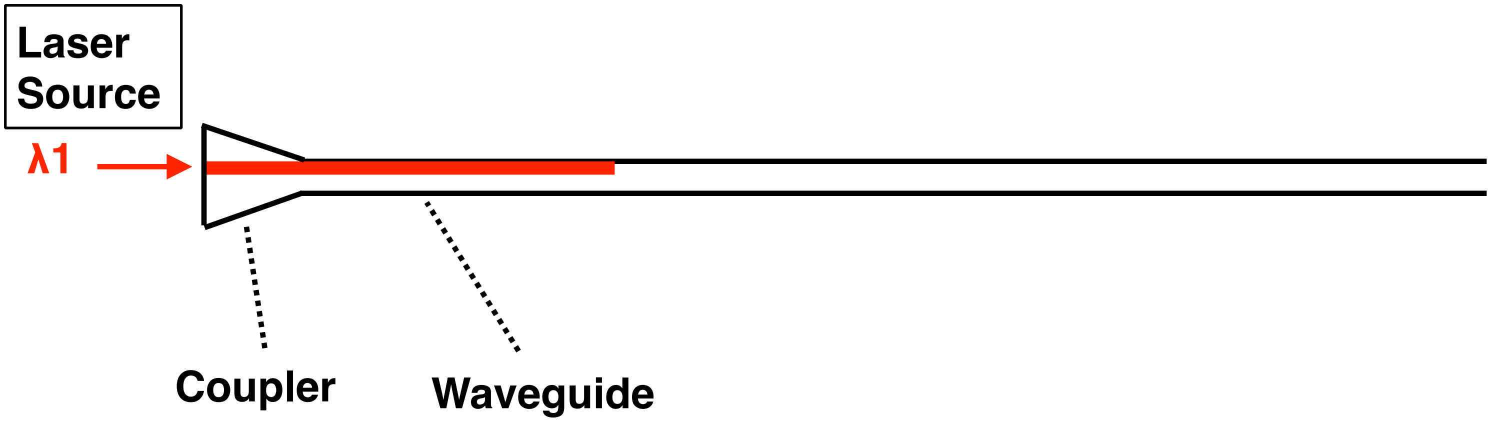
Huge Potential, **BUT:** Nanophotonic components may have **high power demands**

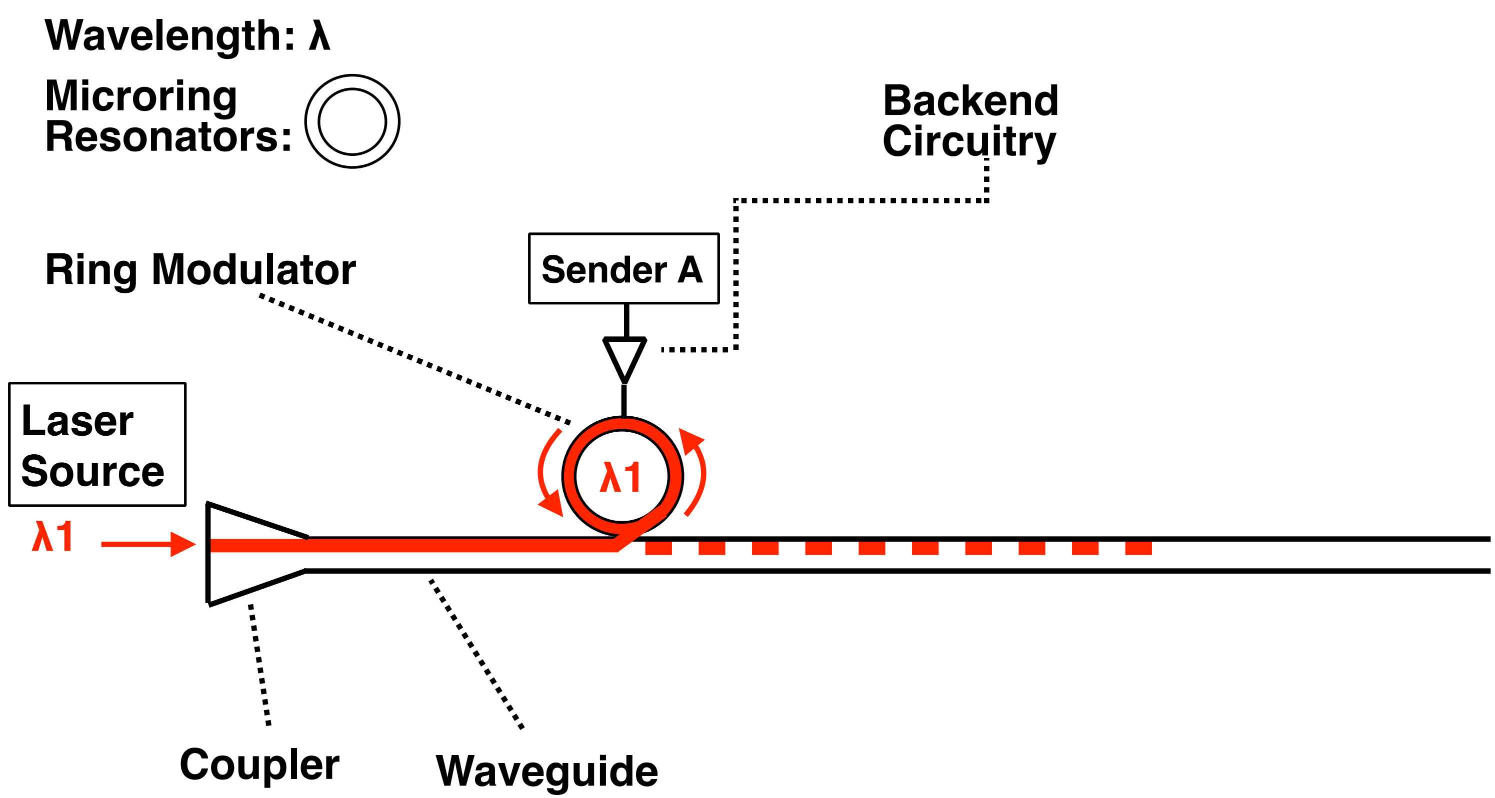
-> Novel network architectures required to enable efficient, low-power operation

Optical on-chip Data Transmission

Wavelength: λ



Optical on-chip Data Transmission



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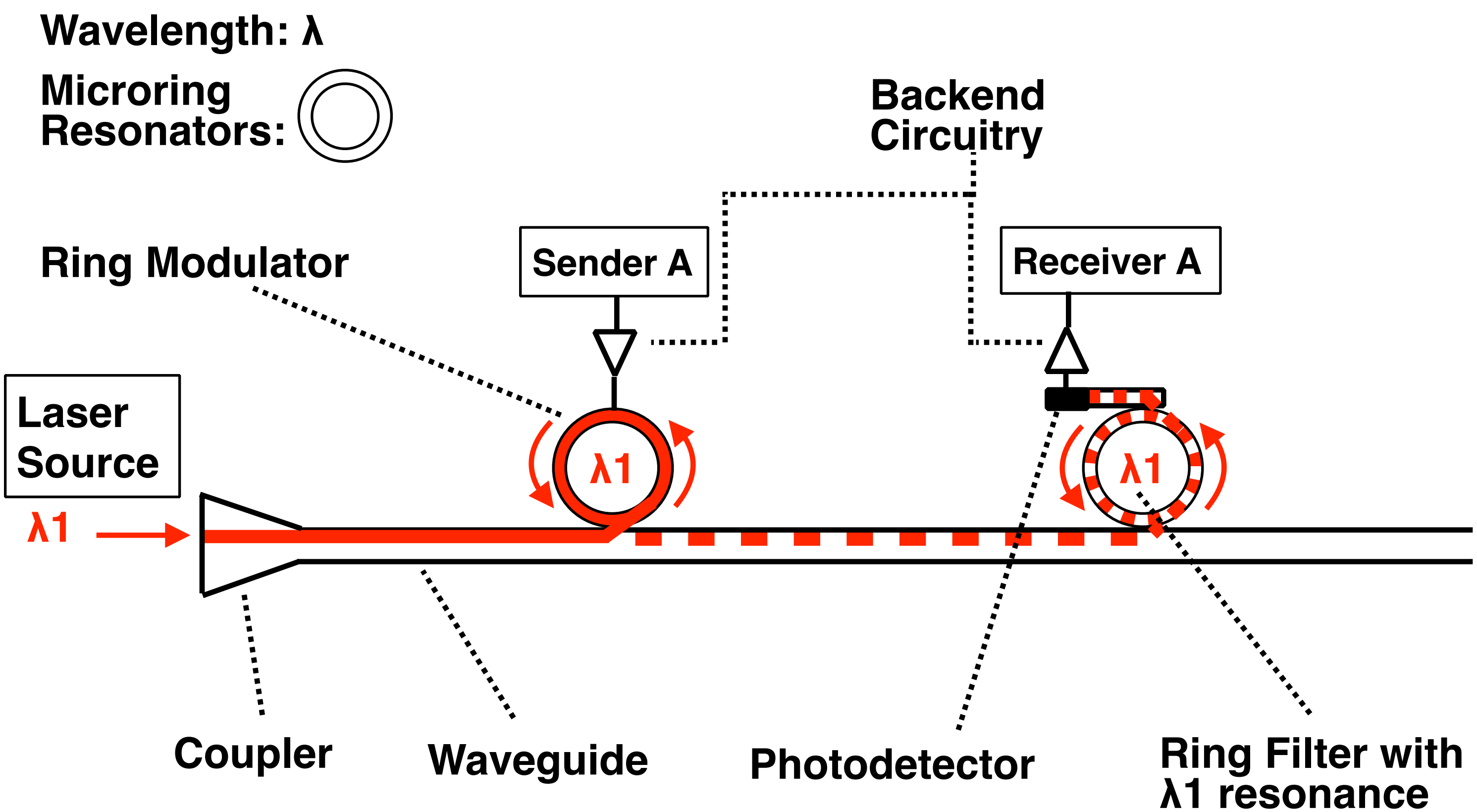

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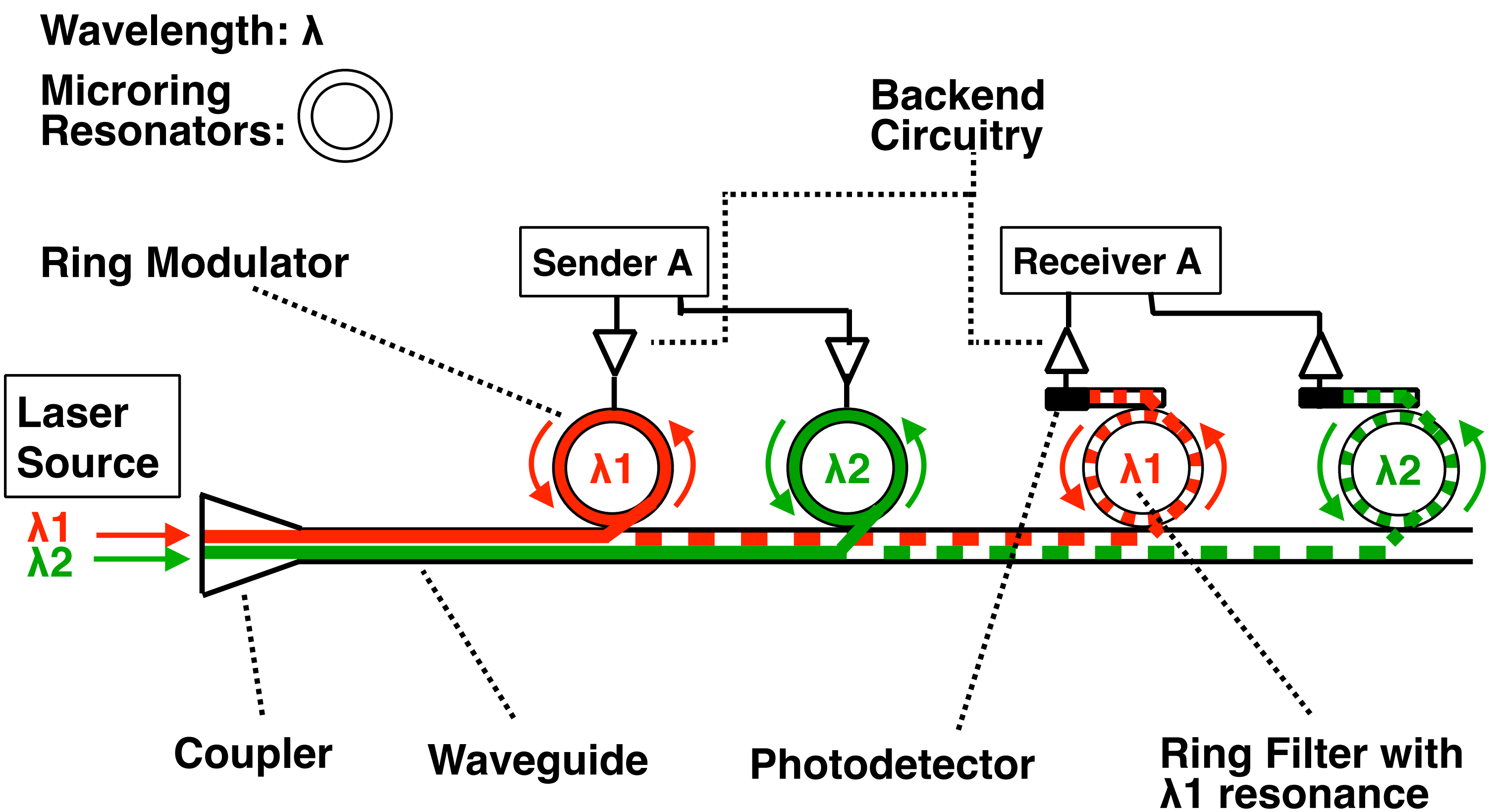

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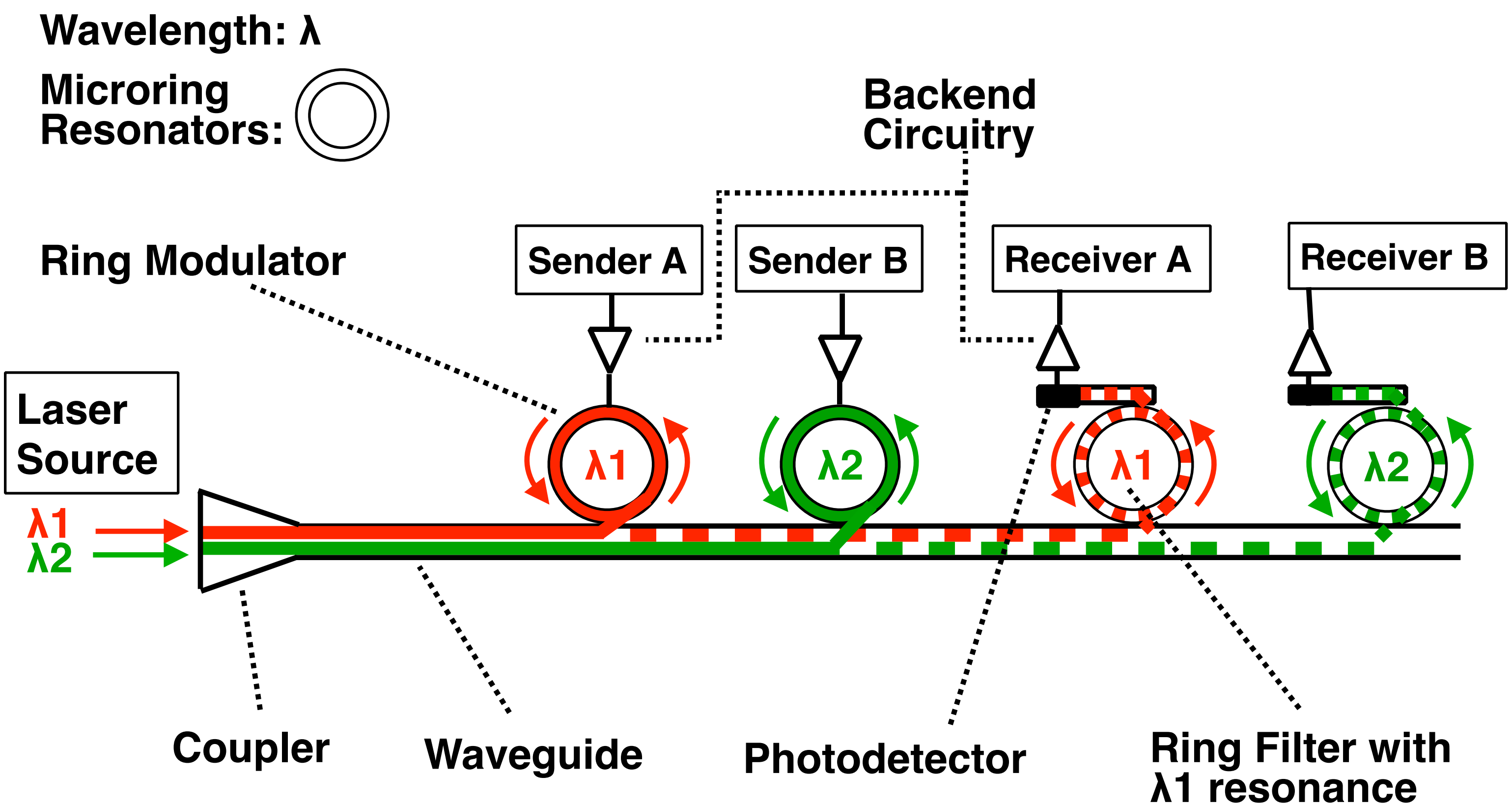

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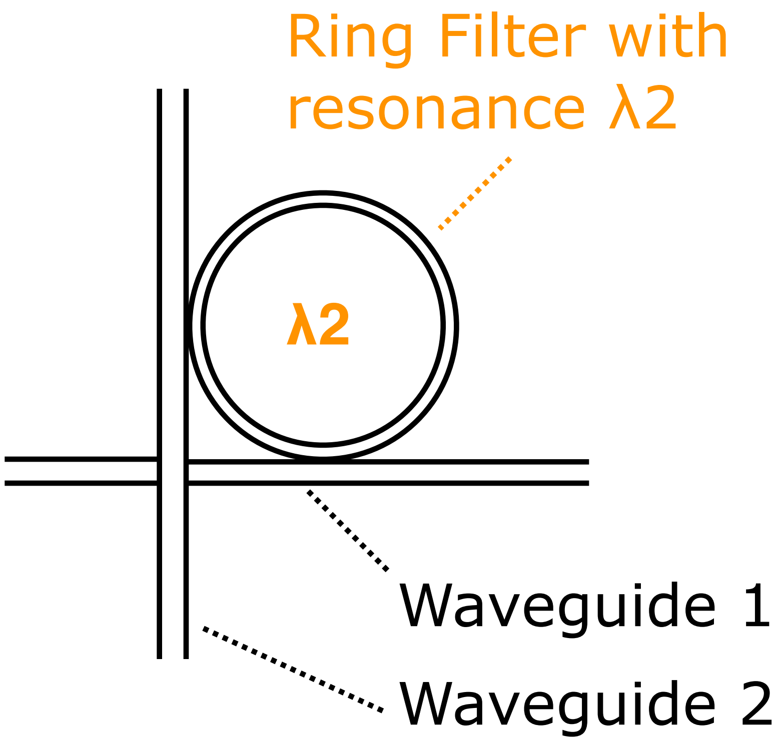

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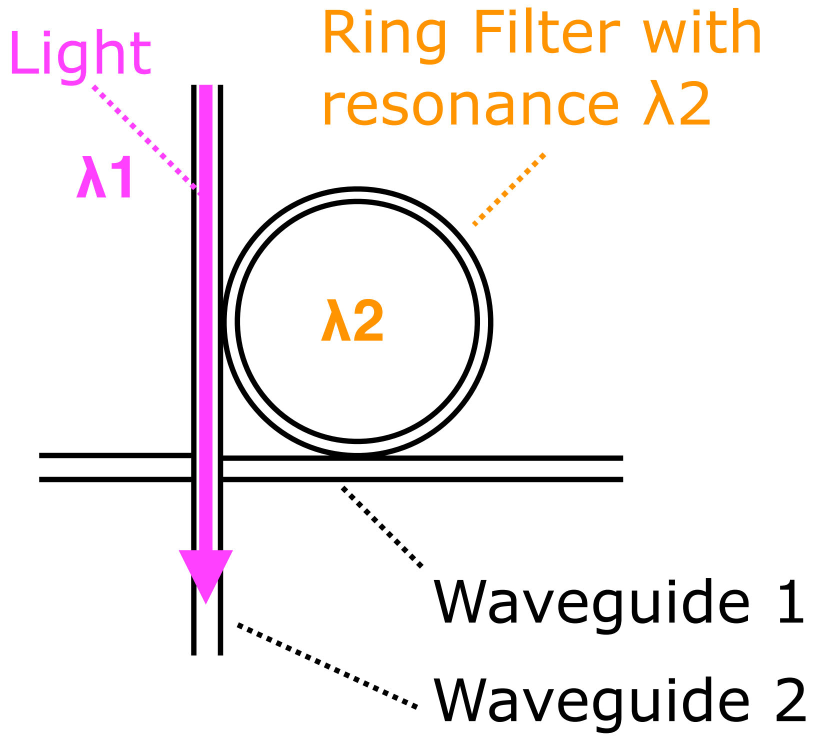

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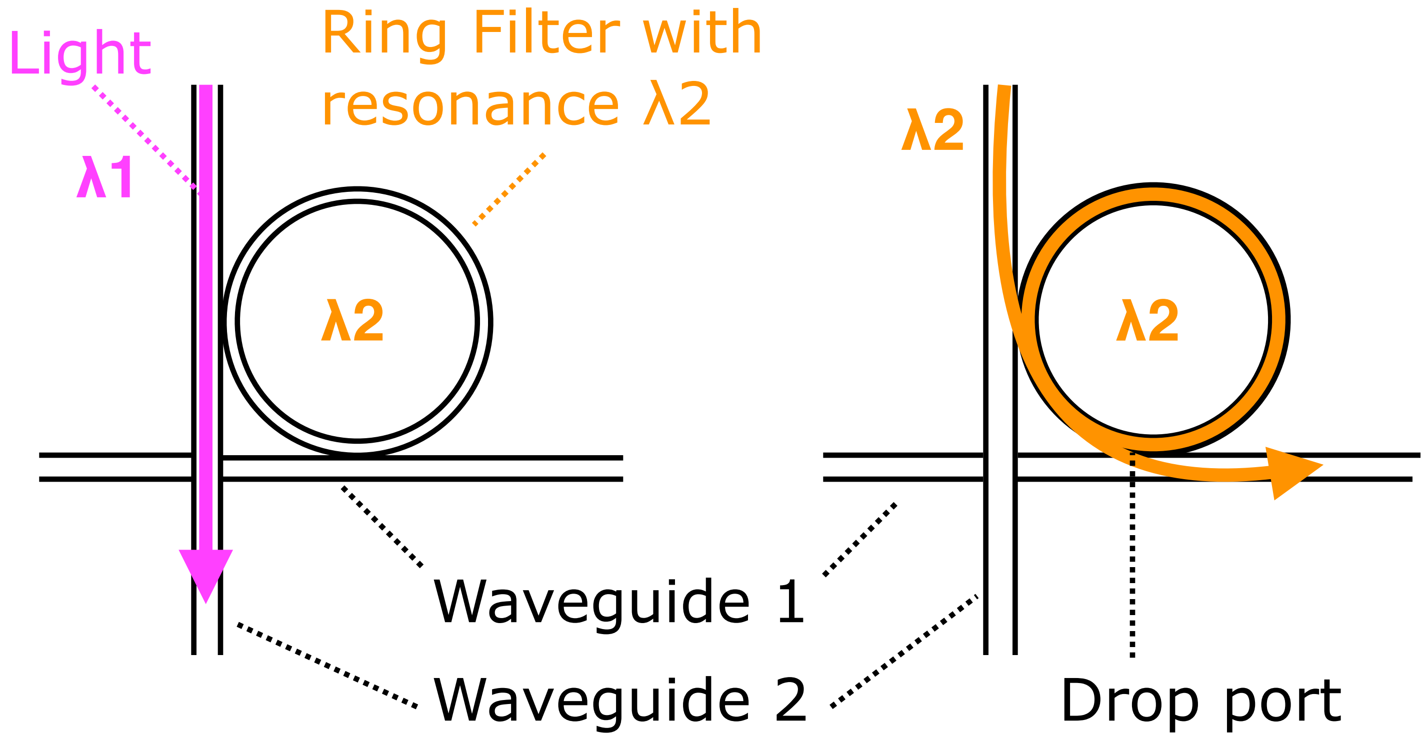
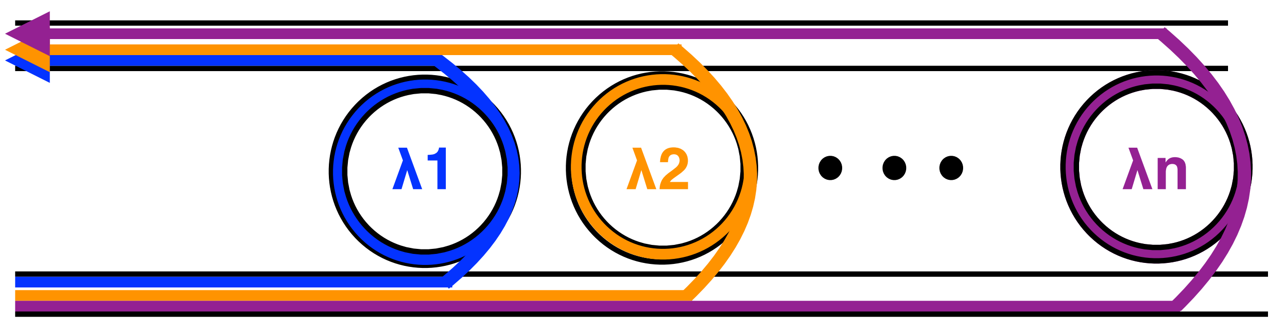
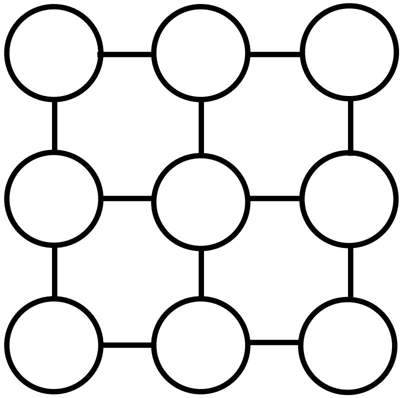


Ring Filters for Switching (2)

Number of λ = Number Ring Filters



Optical Switch for 2D Mesh



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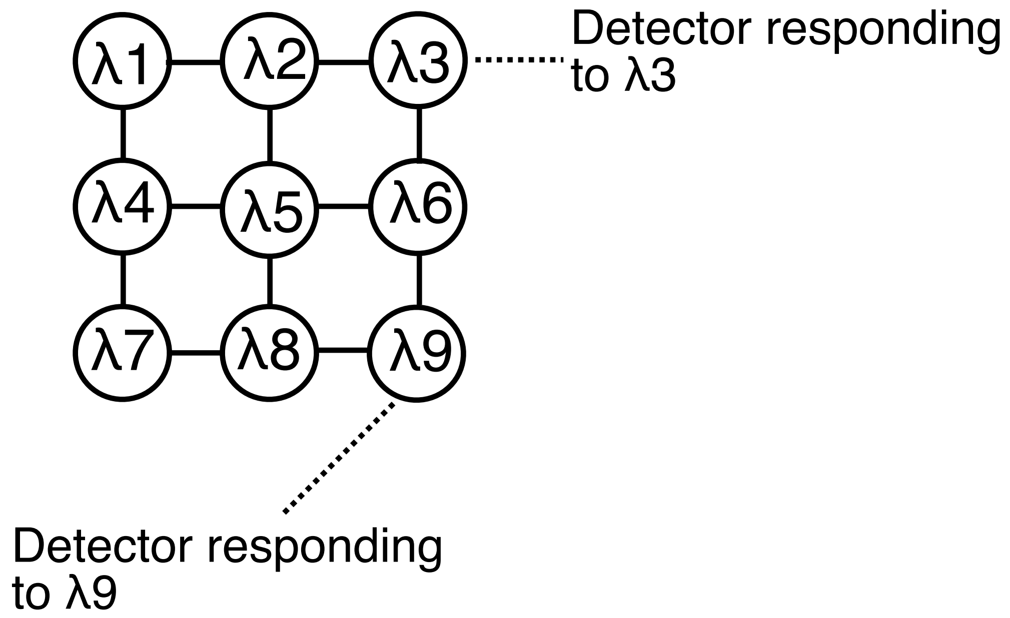

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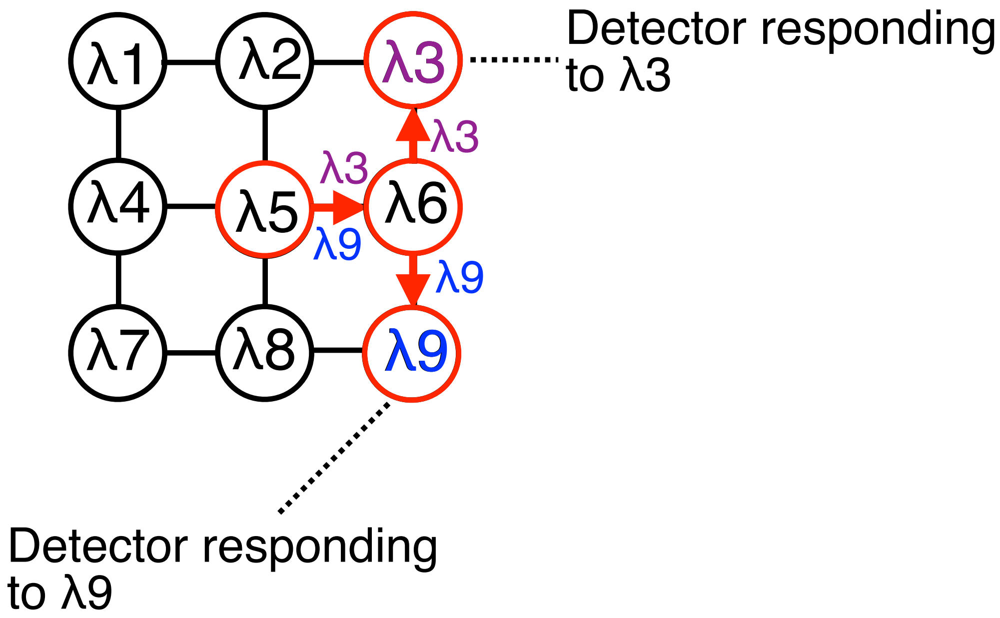

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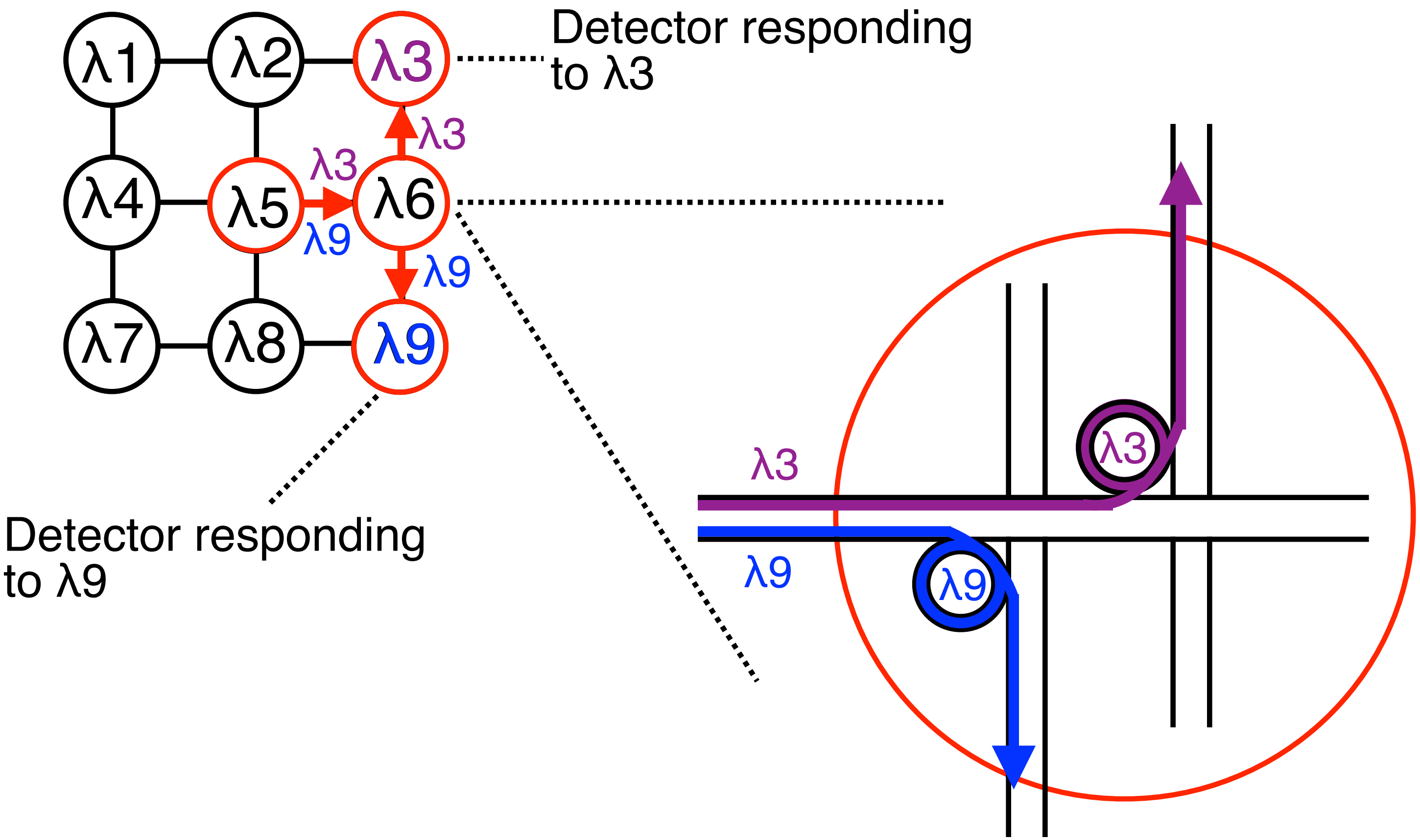


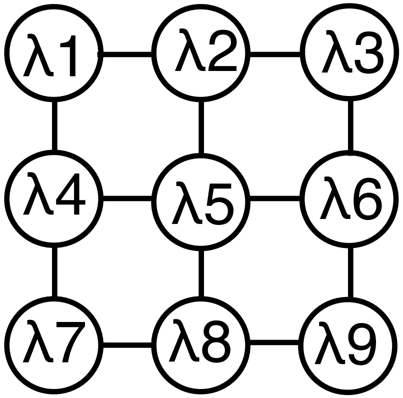
ONoC Design Properties

- Network design using microring resonators is based on **deterministic** routing
- **Hardwired**, pre-defined paths between each source-destination pair

Switching equals routing algorithm

-> ONoC design comprises Topology, Routing algorithm and Switch architecture

Contention in Optical NoCs



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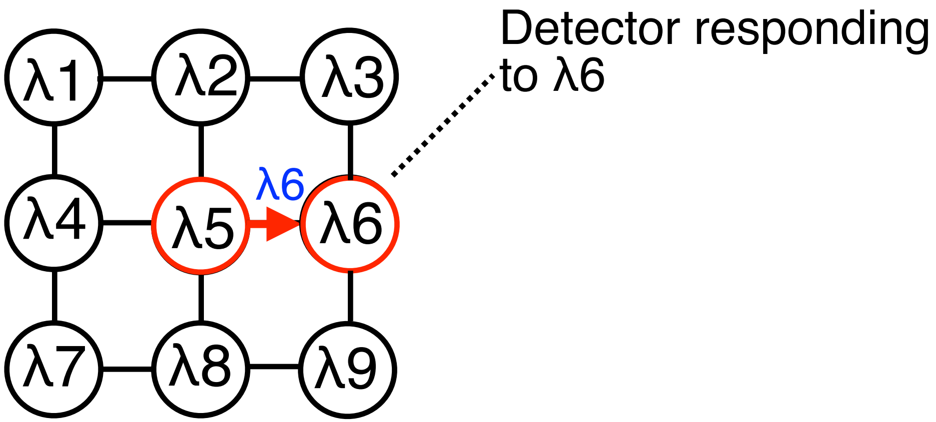

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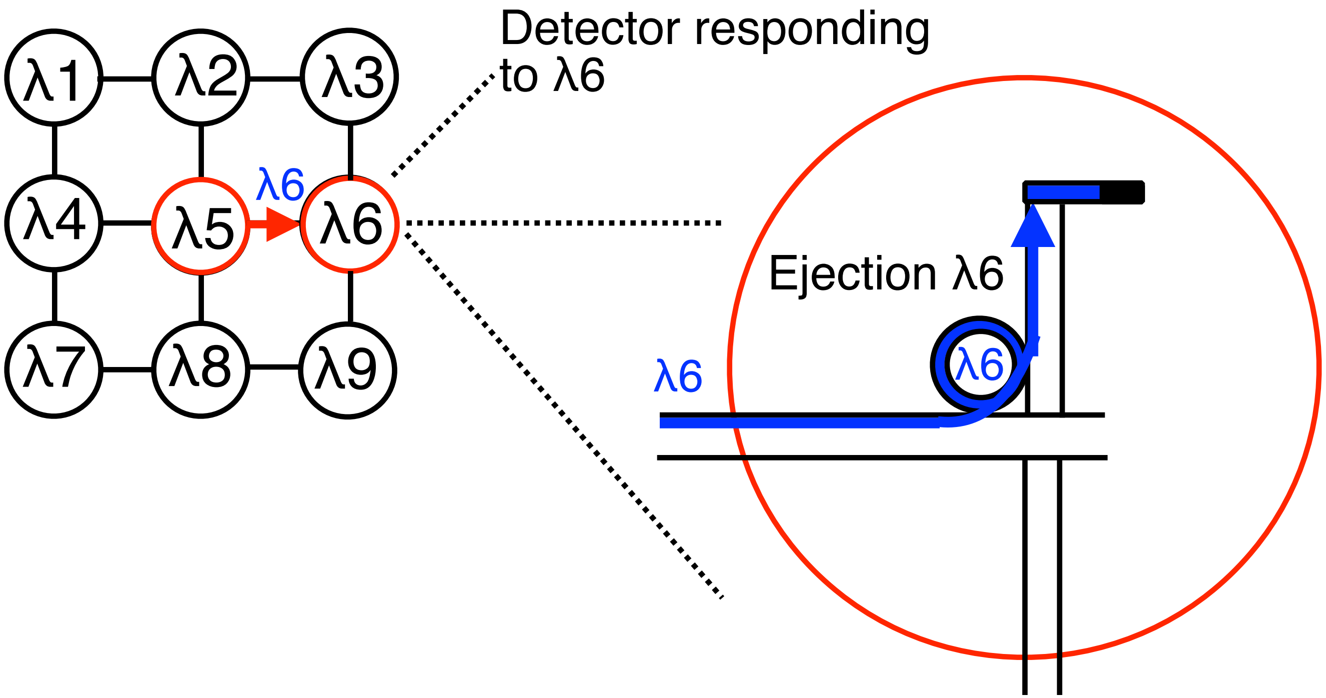

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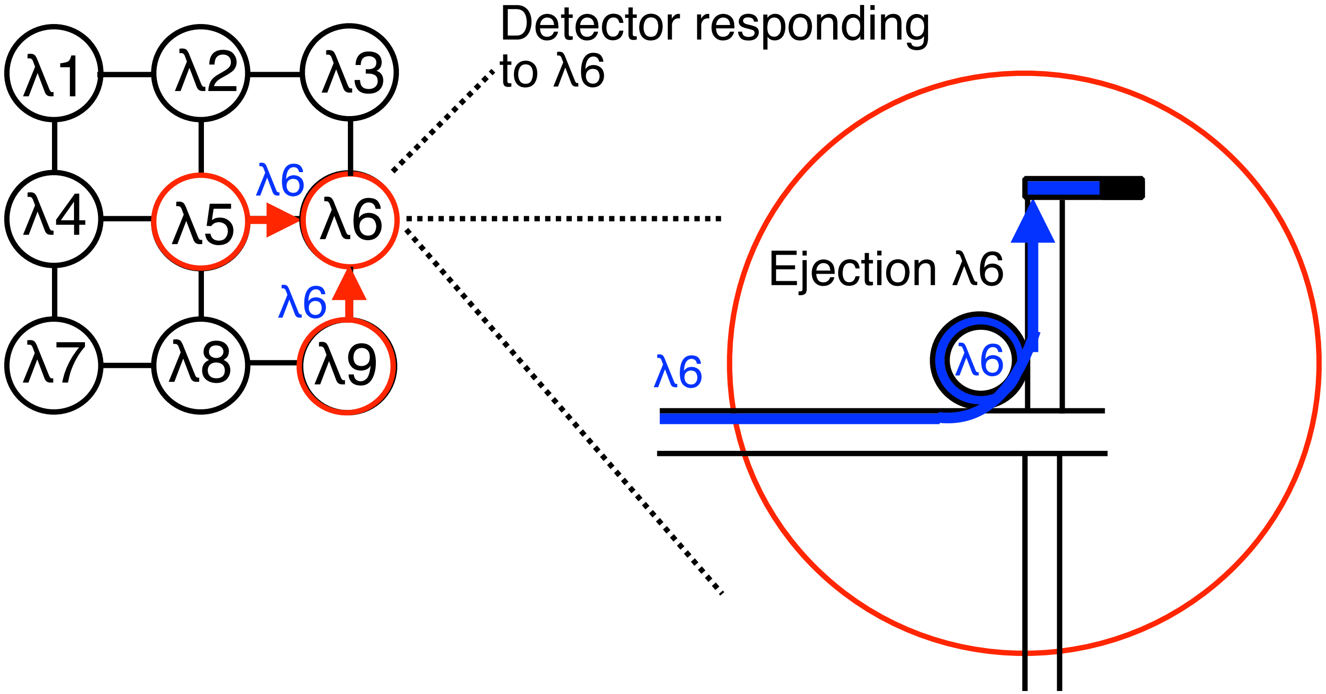

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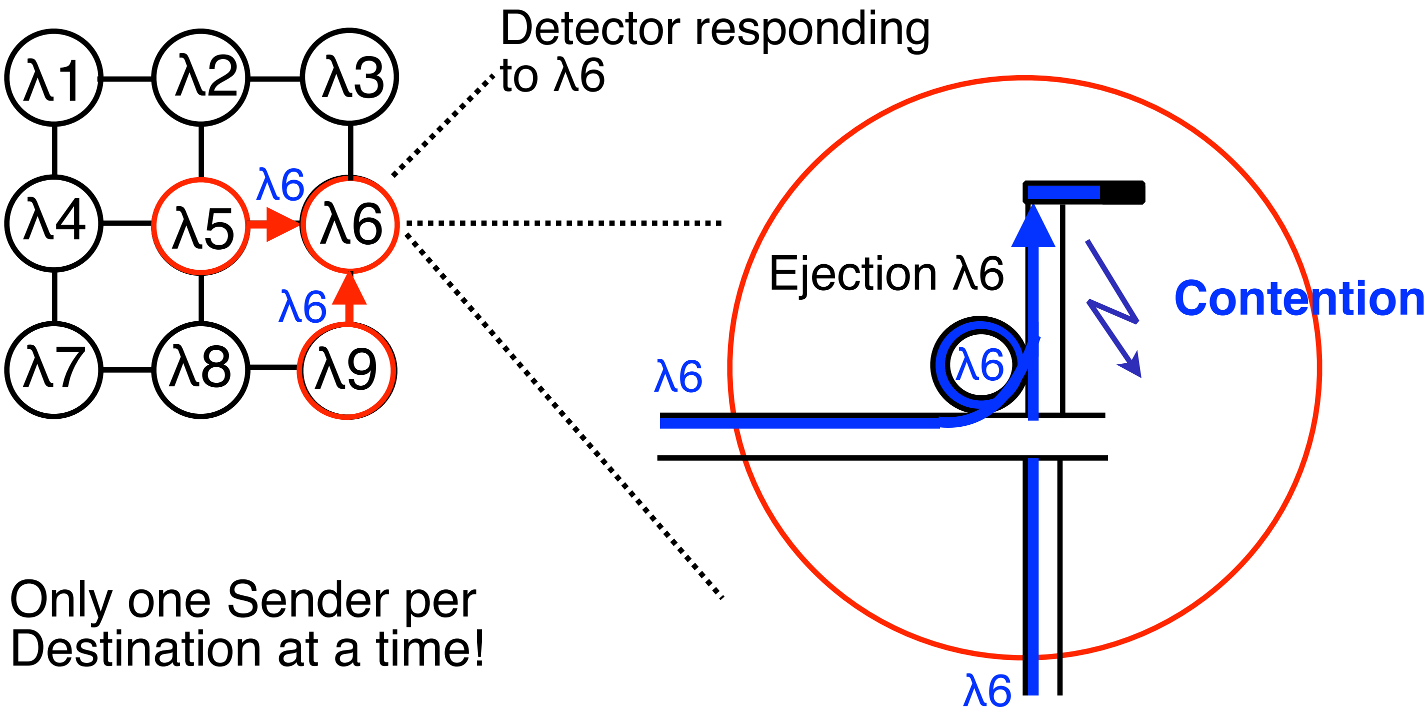
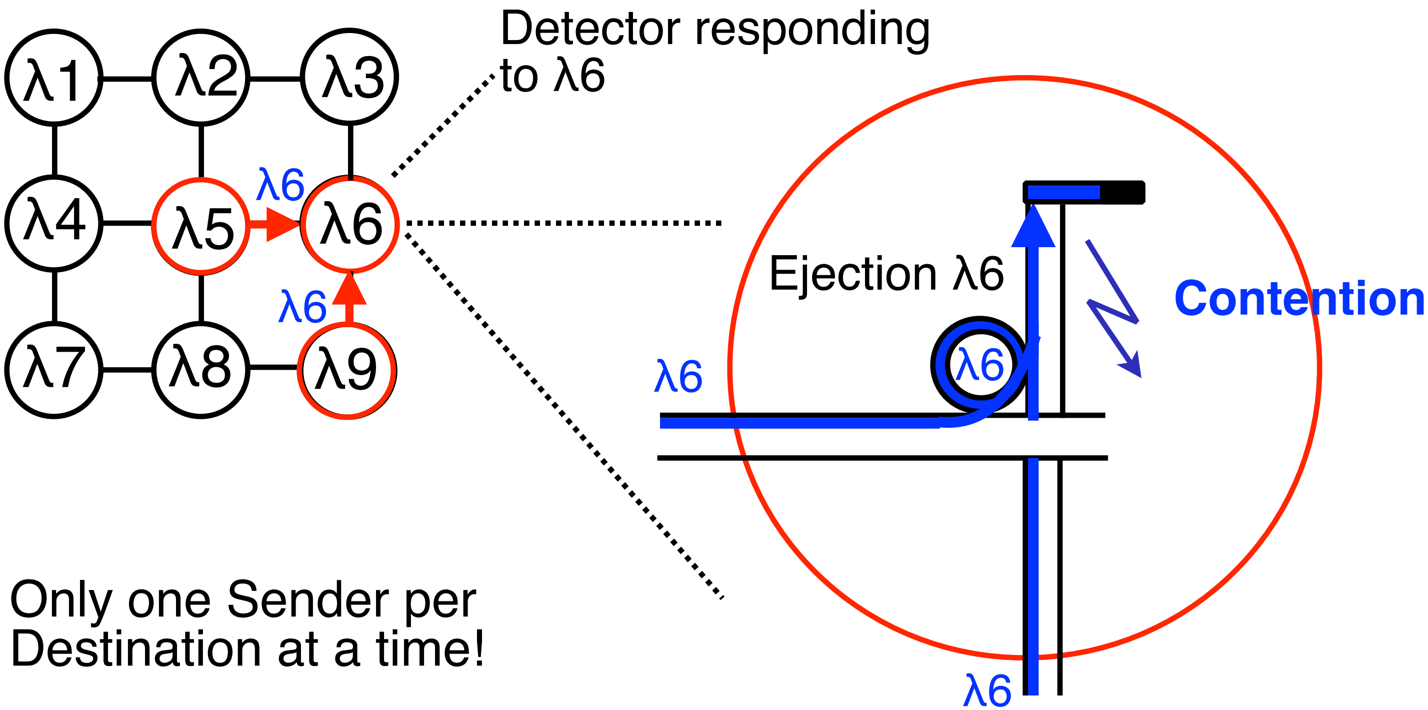


Only one Sender per Destination at a time!

Contention in Optical NoCs



Only one Sender per Destination at a time!

Underlying **Control Network** required for destination reservation -> Req / Ack message exchange

Objectives of low-power ONoC Design

Low Laser Power

- Min. path loss -> short paths ->Low diameter
- Small #λ for addressing ->fewer laser sources

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Low Ring Heater Power

- Small #Microrings (20μW/Ring)
- Small #λ -> Fewer Ring Filters for Switching

State-of-the-art solutions are
1. Optical Spidergon[1]
2. QuT[2]

- Aim low-power
- Microring resonators
- Ring-based topology

[1] S. Koohi and S. Hessabi, "Scalable architecture for a contention-free optical network on-chip," Journal of Parallel and Distributed Computing, vol. 72, no. 11, pp. 1493–1506, 2012.
[2] P. K. Hamedani, N. E. Jerger, and S. Hessabi, "Qut: A low-power optical network-on-chip," in NOCS, 2014. IEEE, 2014, pp. 80–87.

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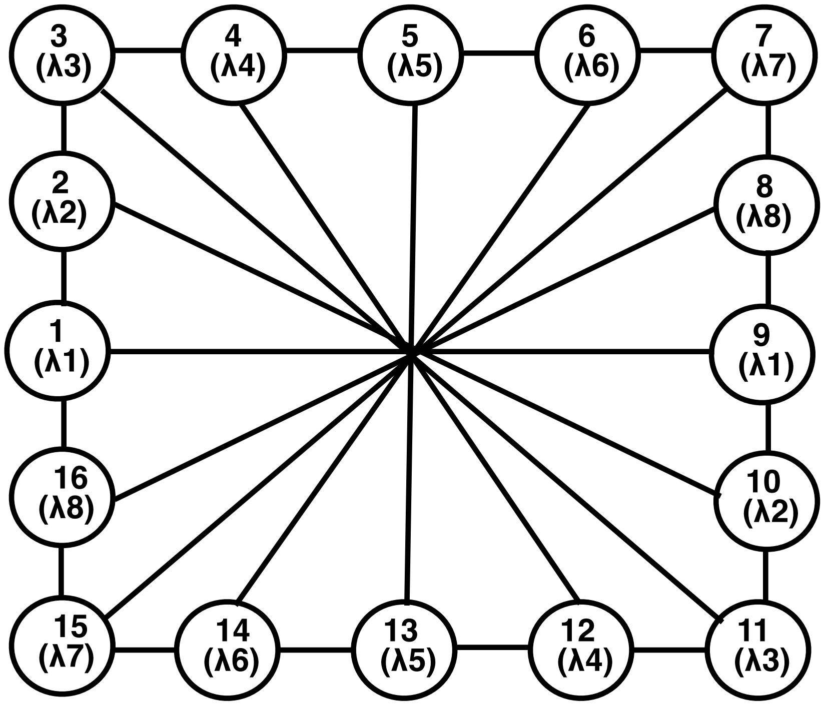
Optical Spidergon



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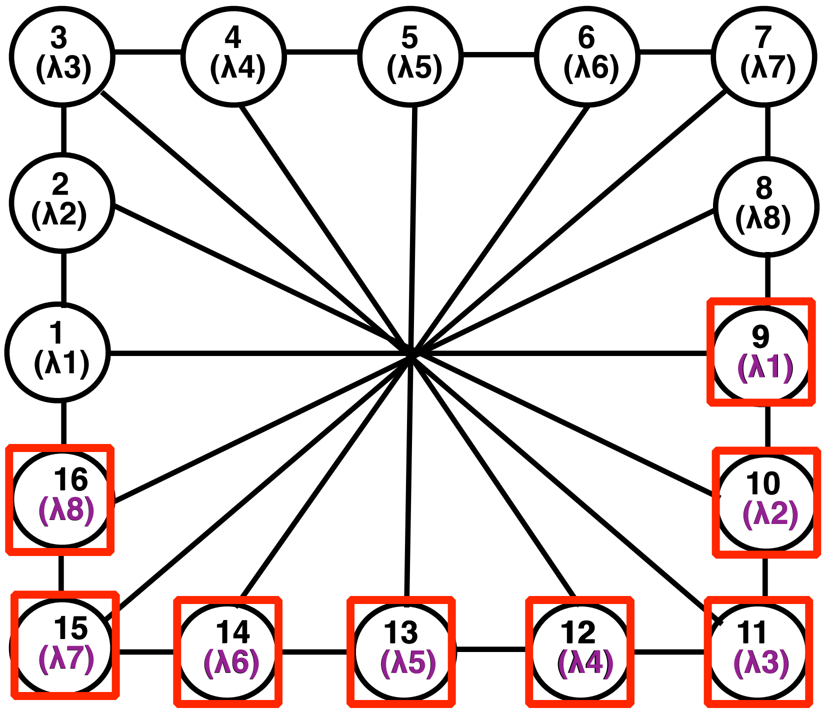

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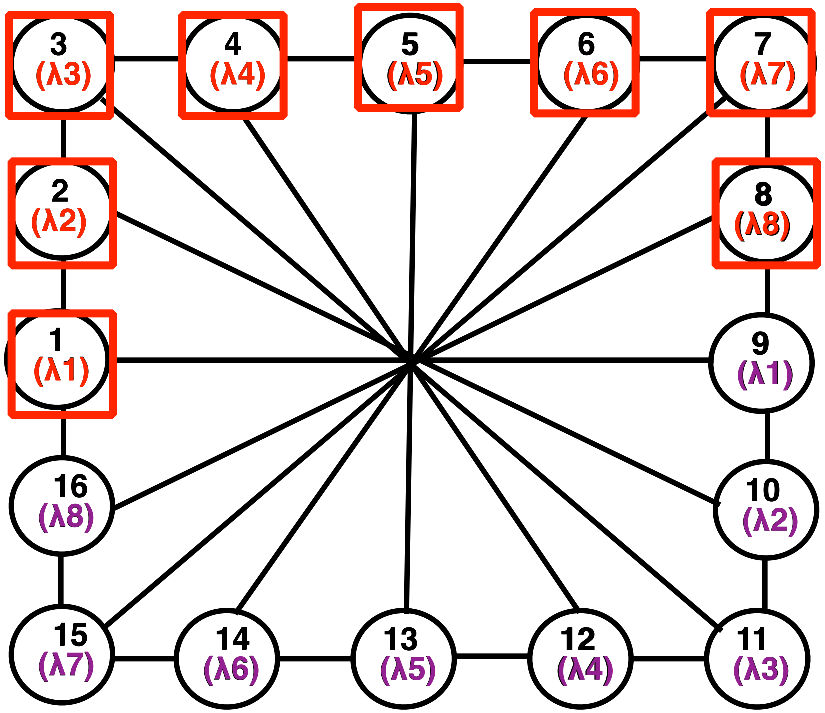

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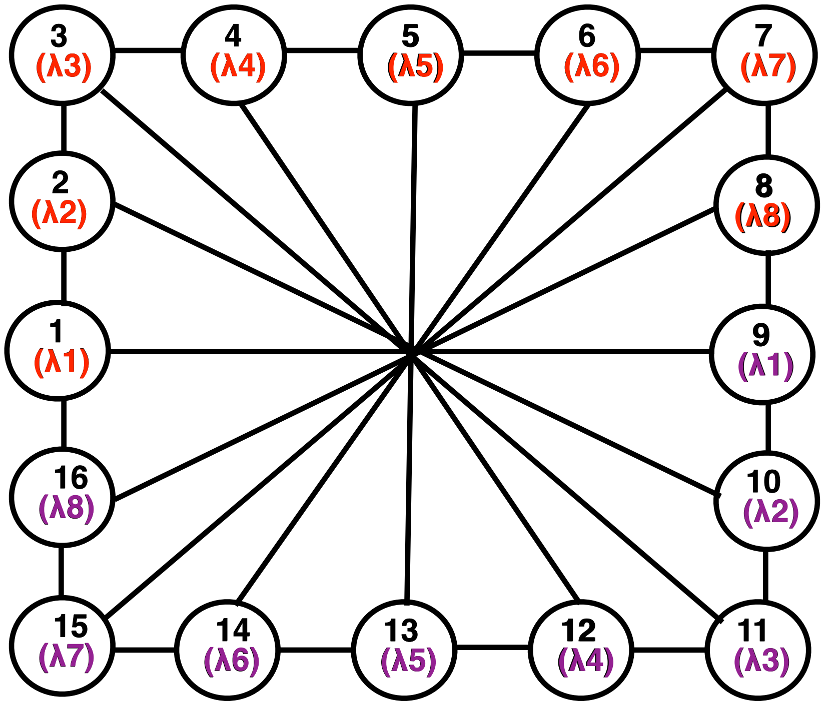

N/2 λs in Network for addressing
-> Reduces Laser Power

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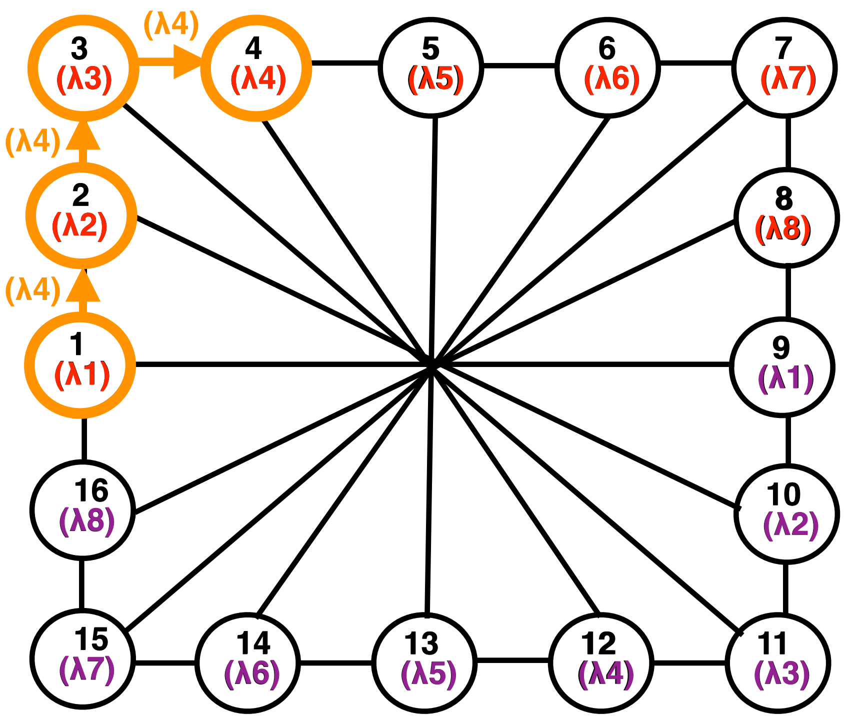

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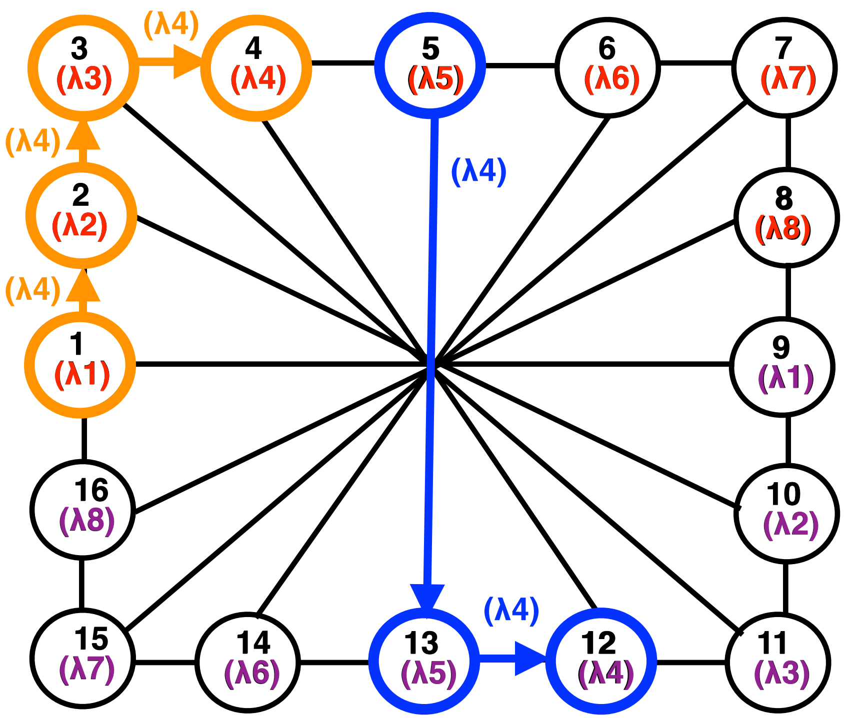

N/2 λs in Network for addressing
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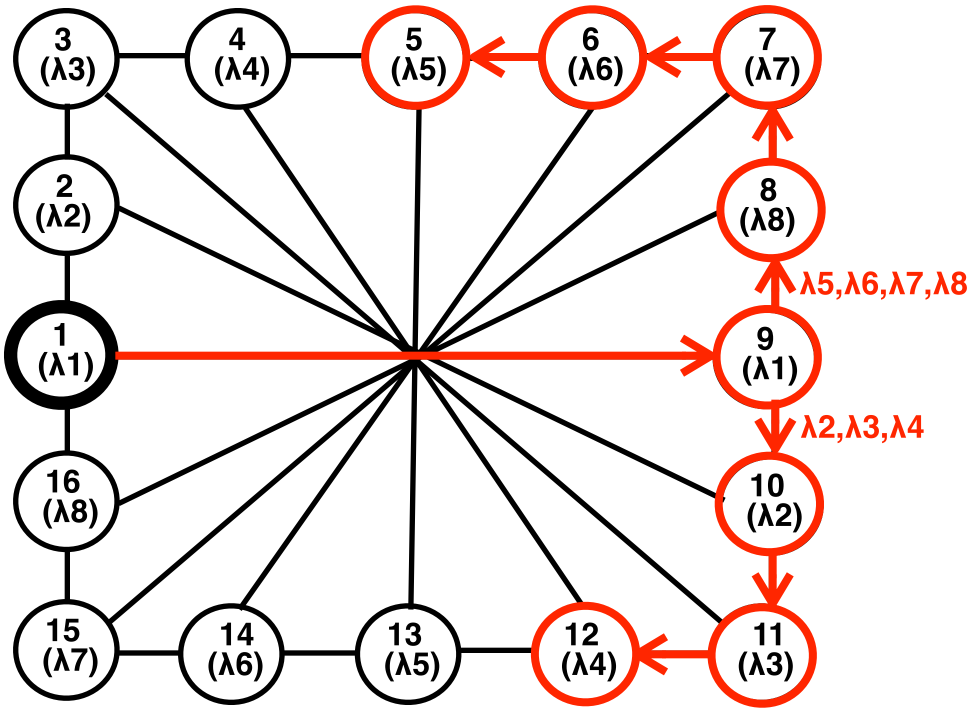
Different paths to prevent overwriting data !

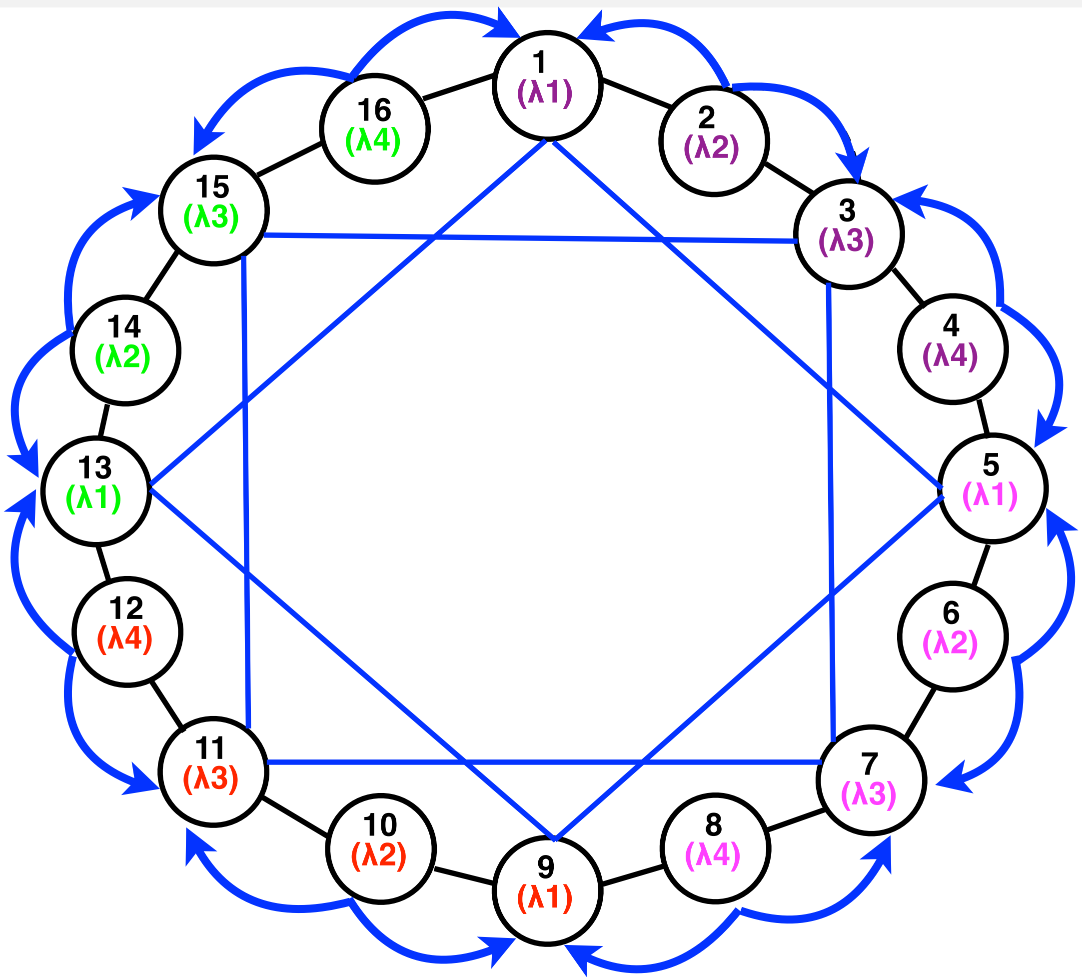
Optical Spidergon



1 Switch Design

(N/2 -1) Ring Filters for Switching at each node

QuT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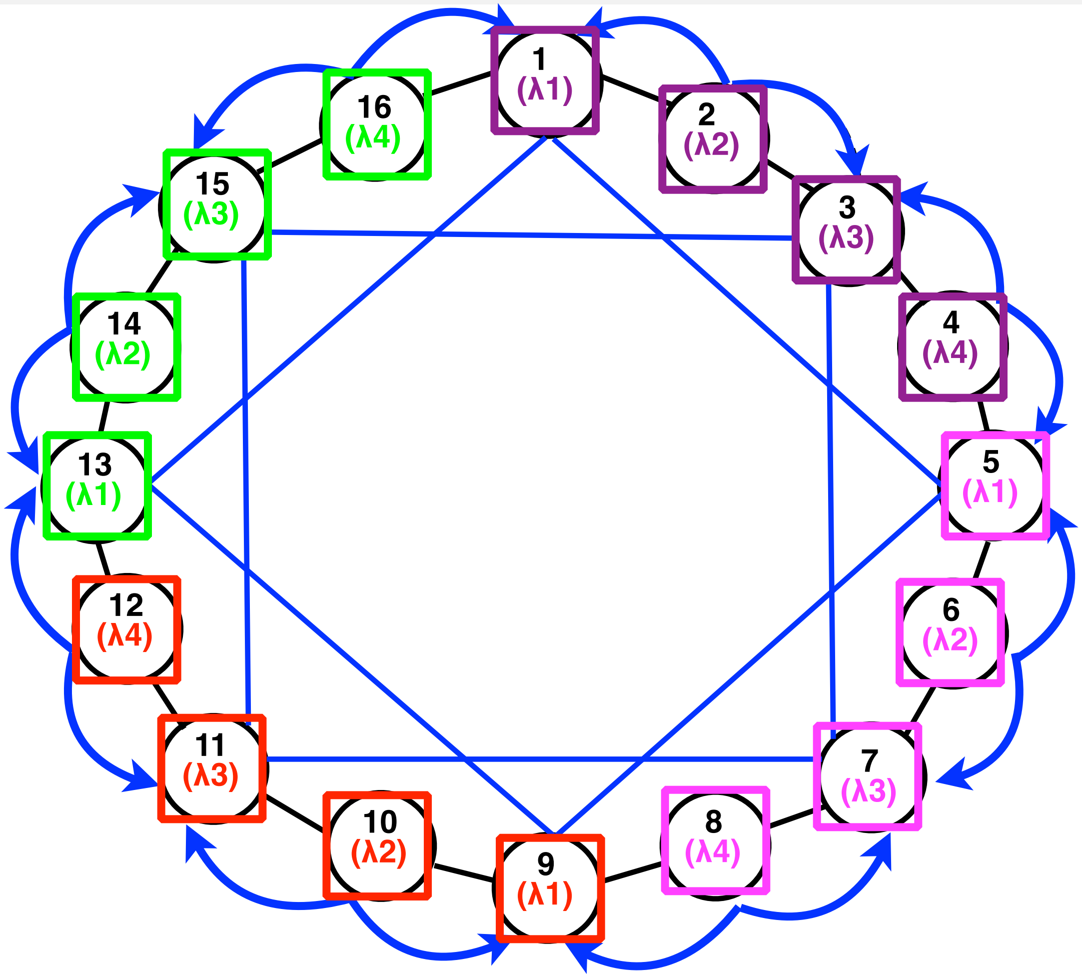

N/4 λs in Network for addressing

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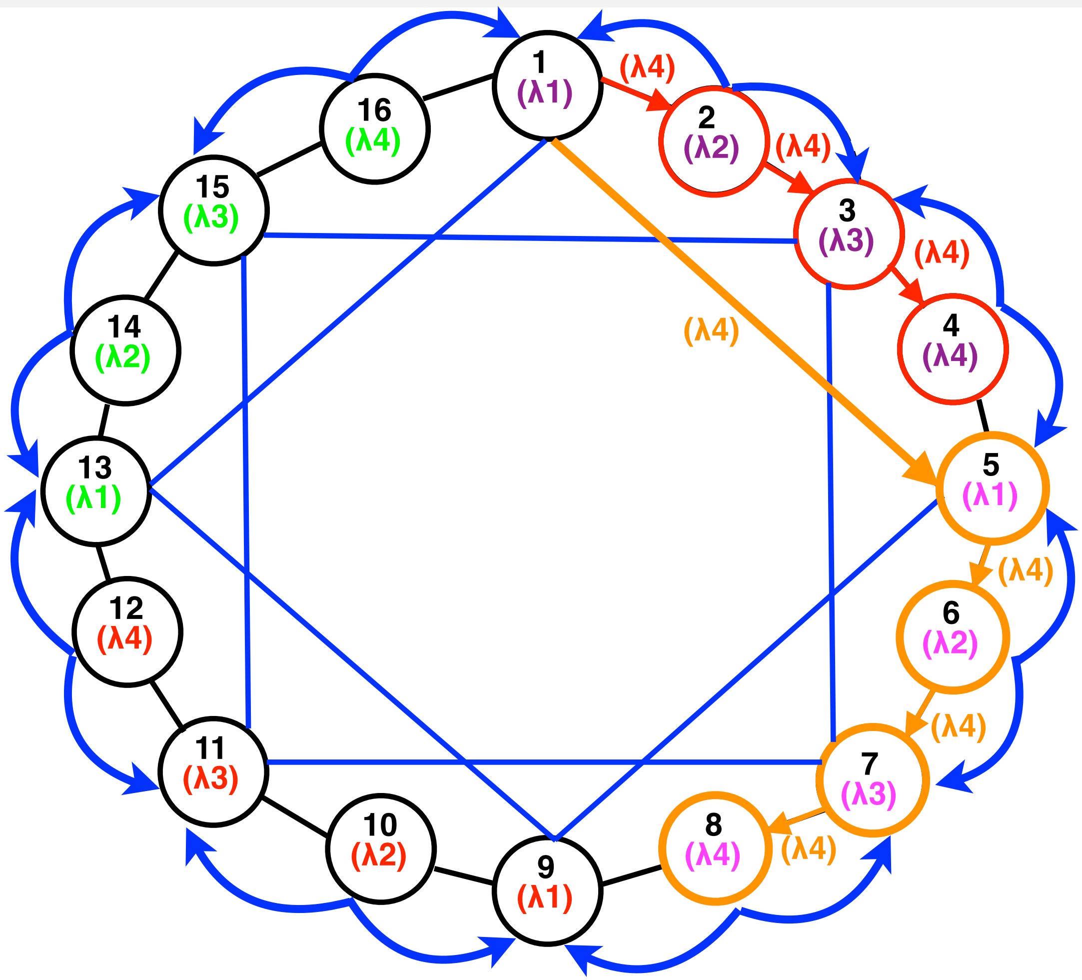


N/4 λs in Network for addressing

2 Switch Designs (Odd/ Even)

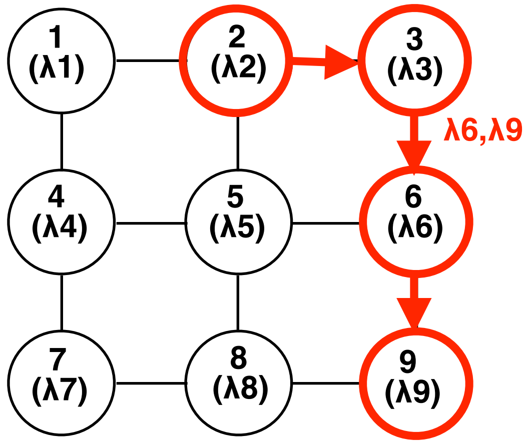
- Even Switches cheap
- Odd Switches still as expensive as in Spidergon (Ring-based Topology have similar switching demands)

Spidergon/QuT

+ N/2 and N/4 number of wavelengths in network, providing different paths to avoid contention

- Long paths in ring topologies
- Large number of ring filters for switching required

Proposal: Mesh-based Topology



Advantages over ring-topologies in oNoCs:

- **Shorter paths**/diameter than ring-based networks
- In XY Routing: At most **√N-1 Ring** Filters in each switch (every other node in column)

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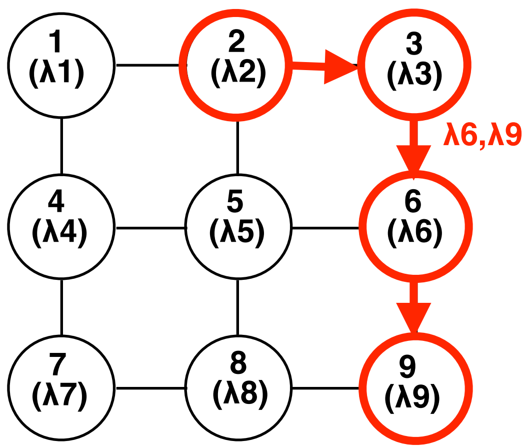

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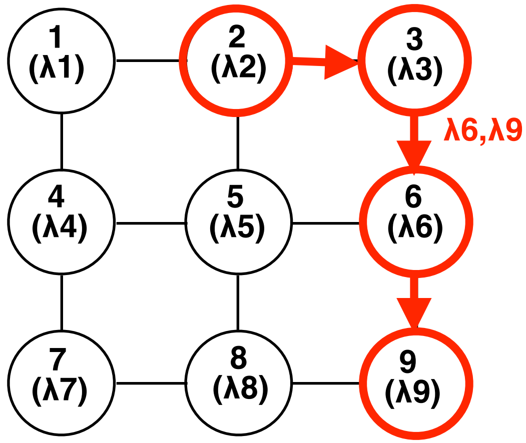

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Solution: Split Mesh in 4 parts

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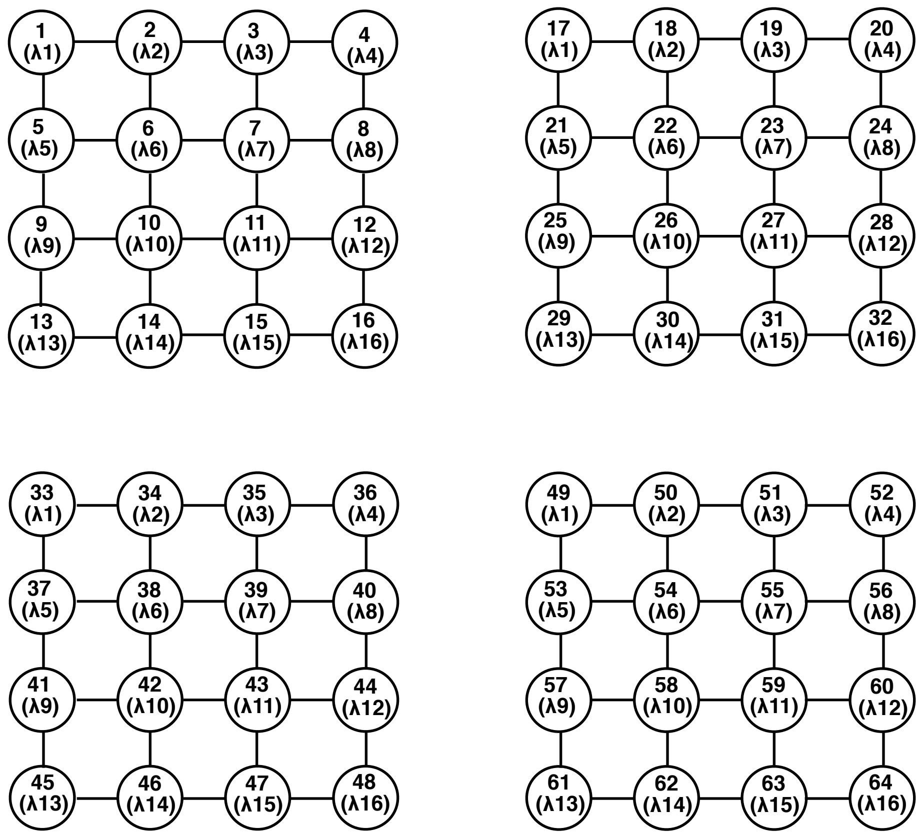
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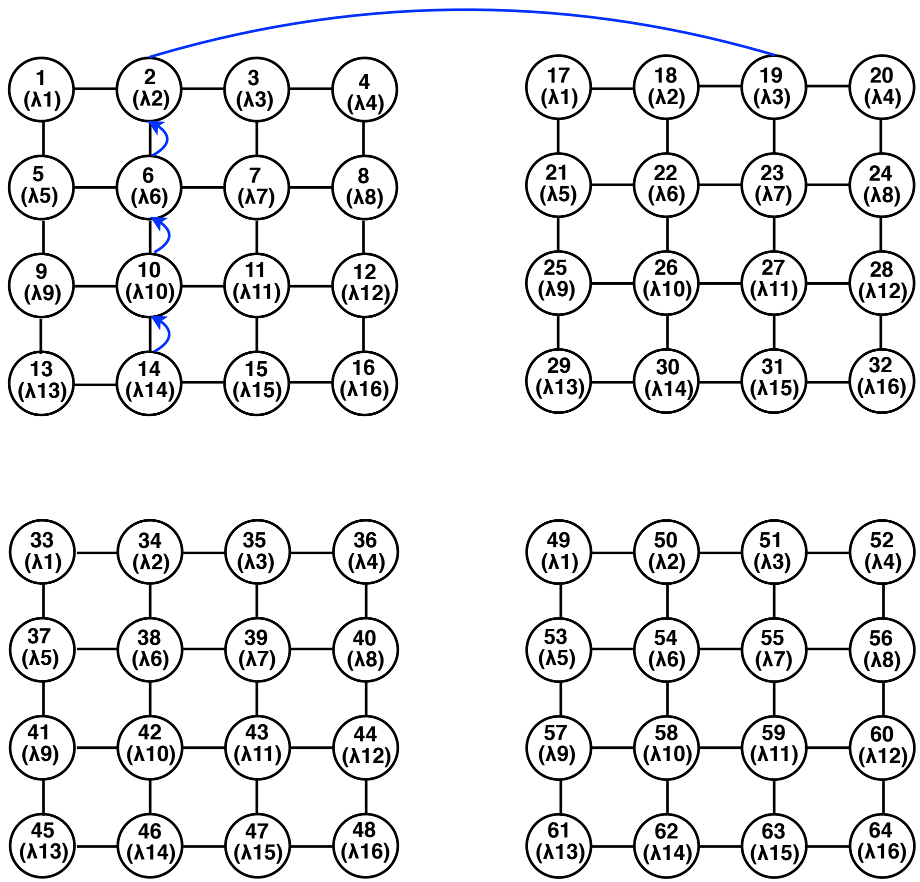
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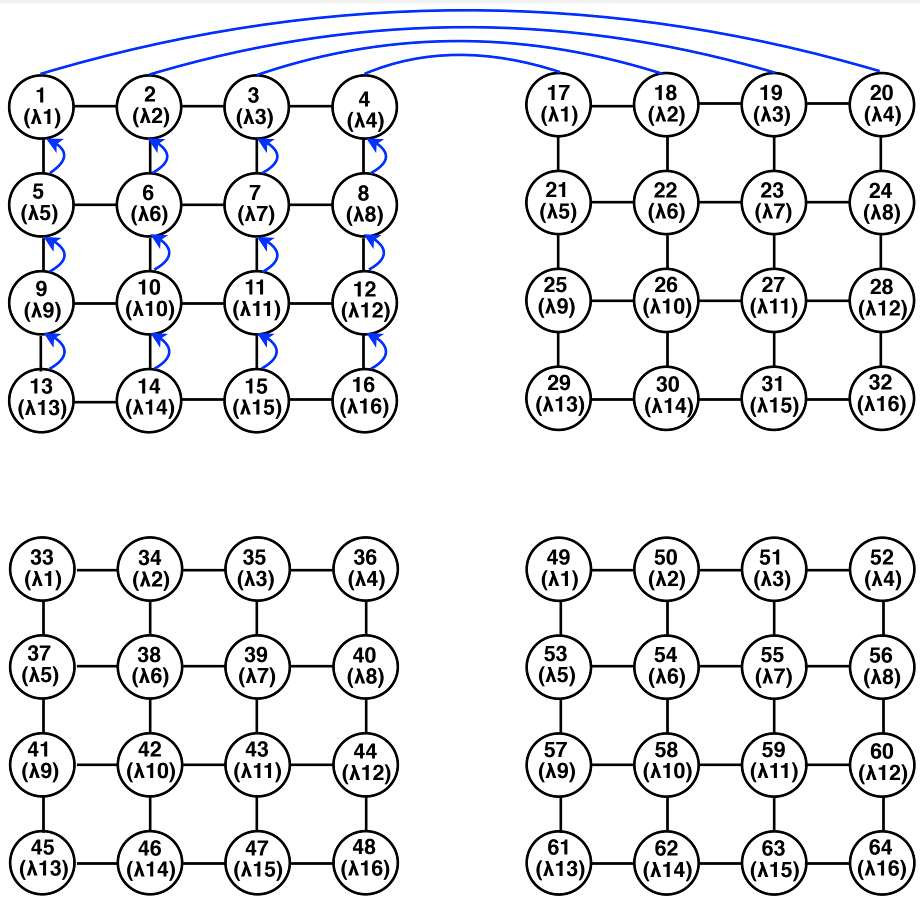
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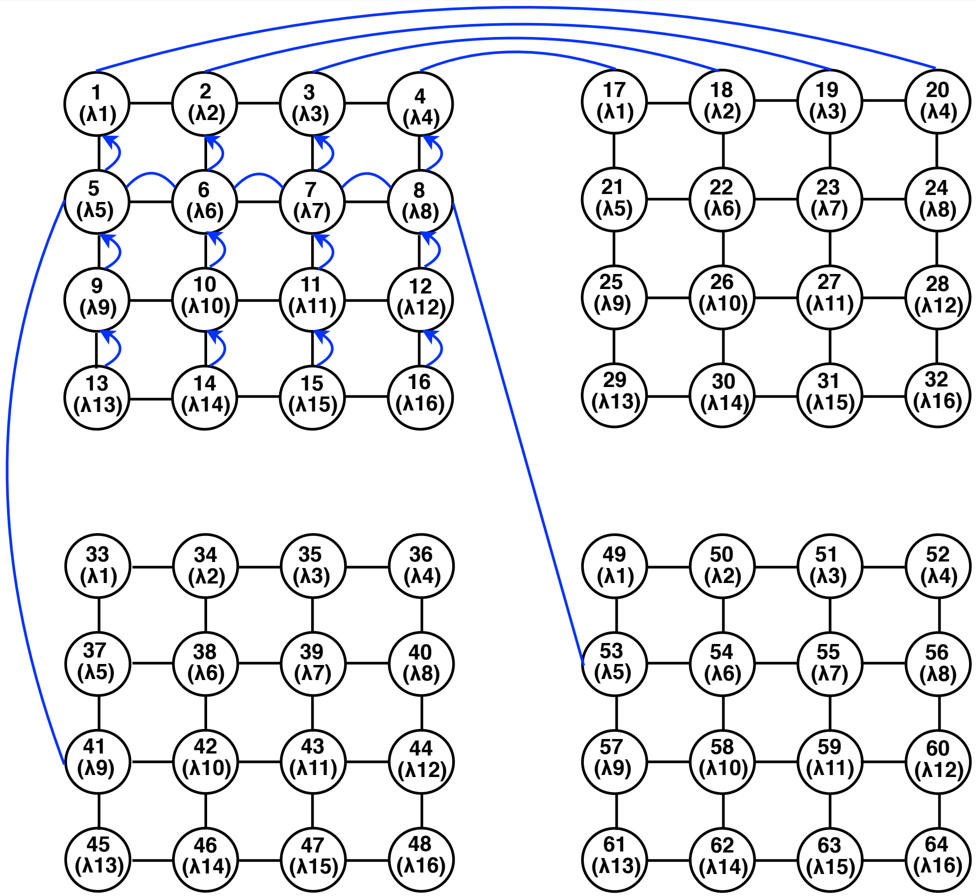
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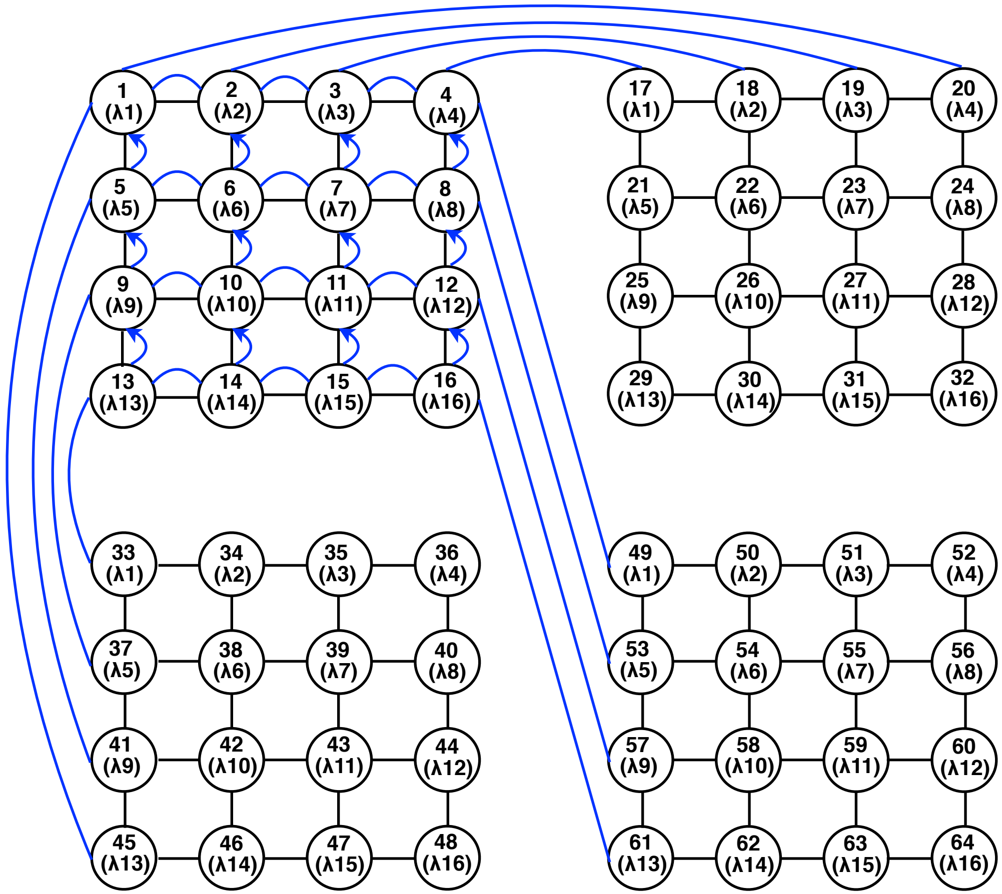
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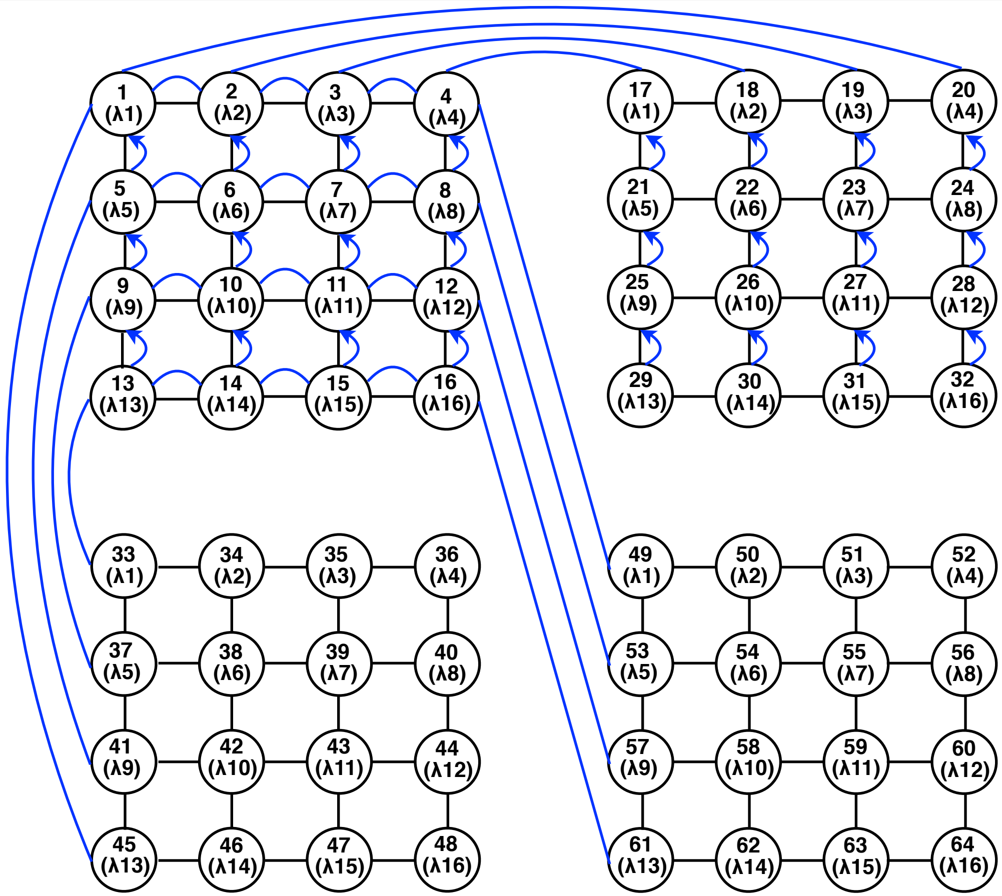

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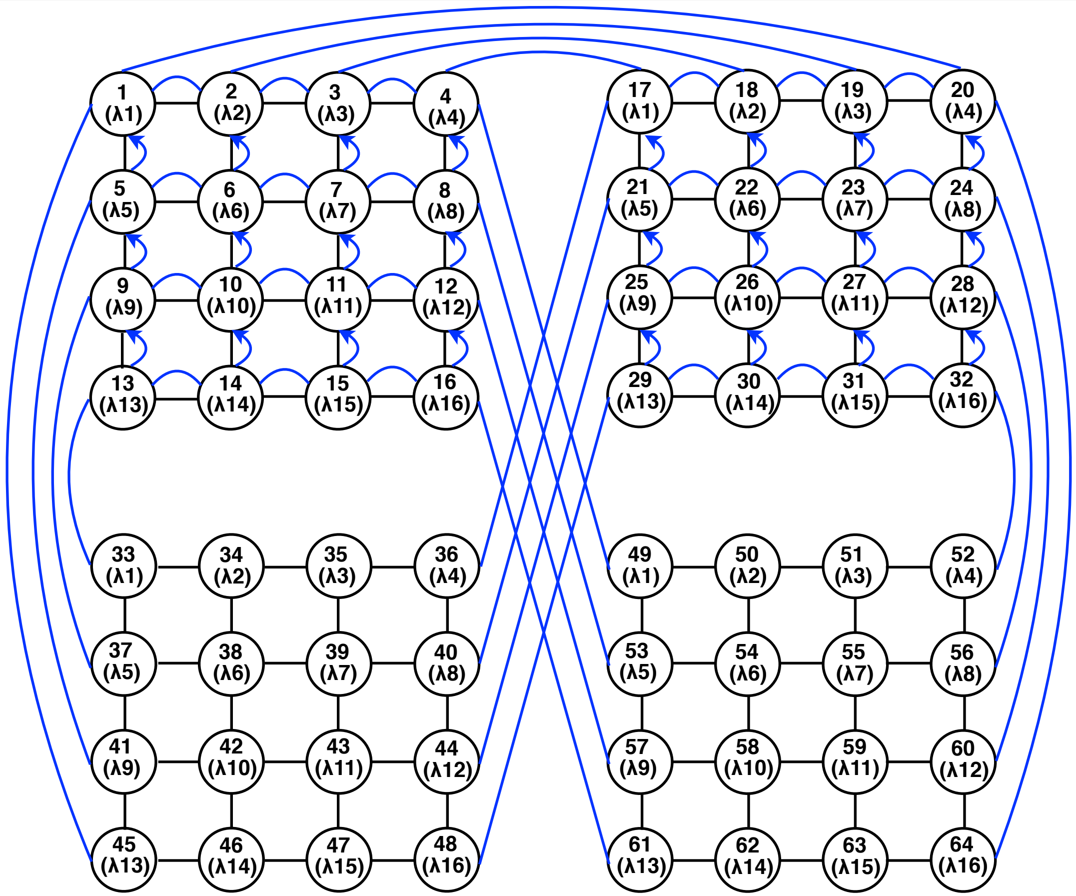

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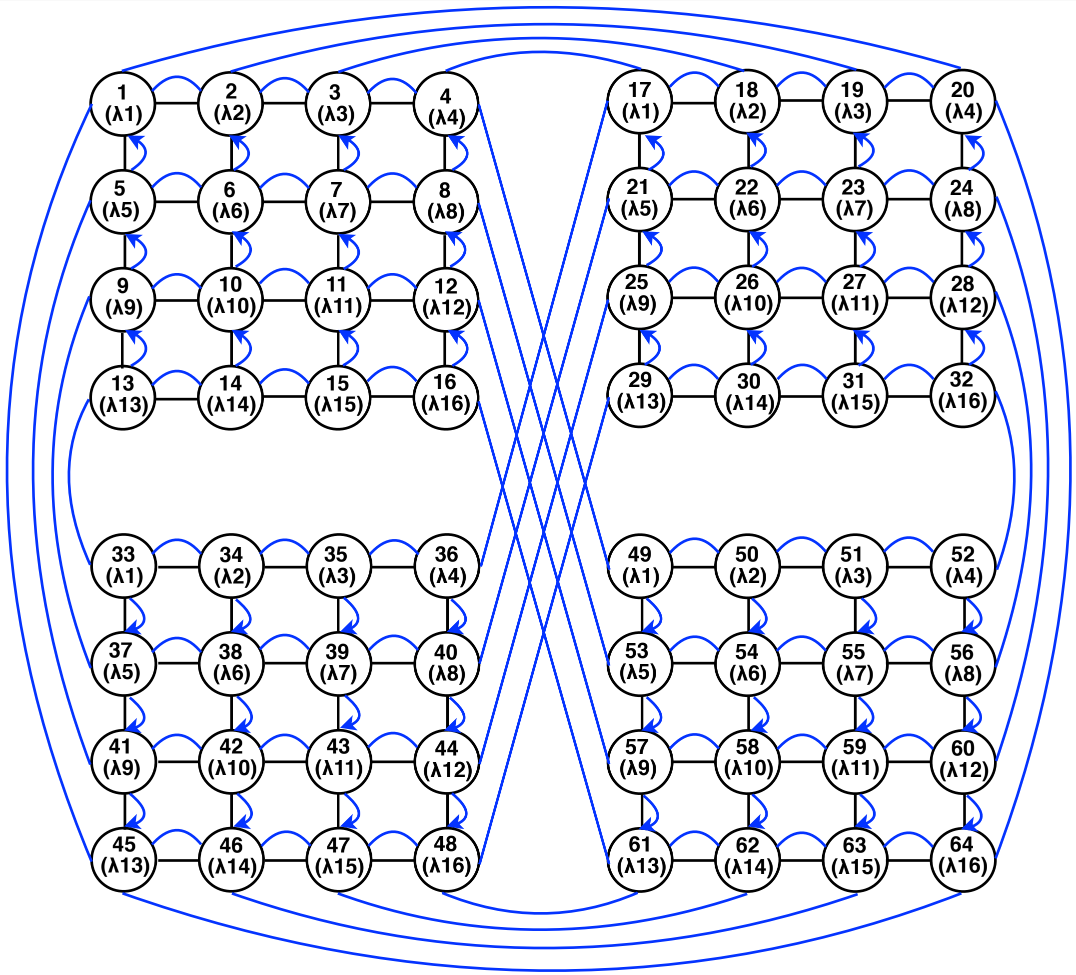
Amon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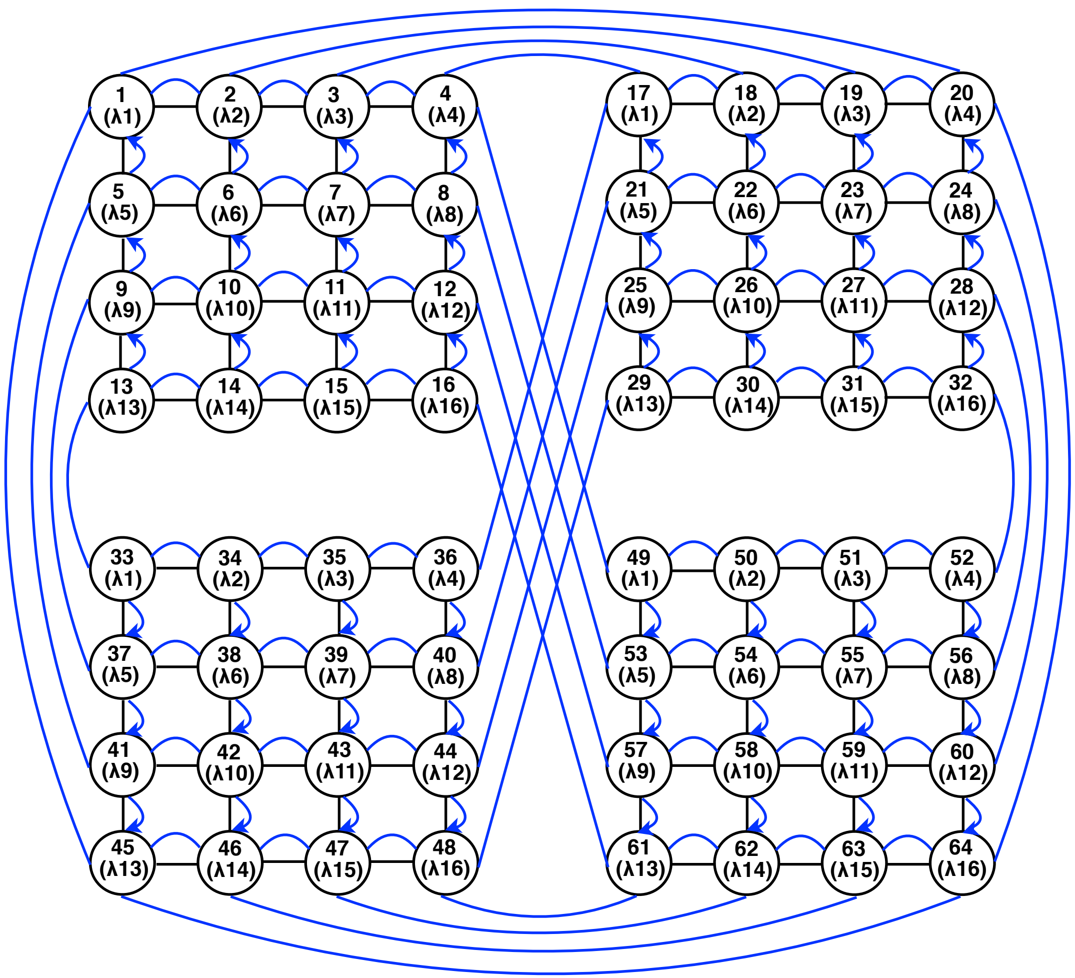
Amon: Routing



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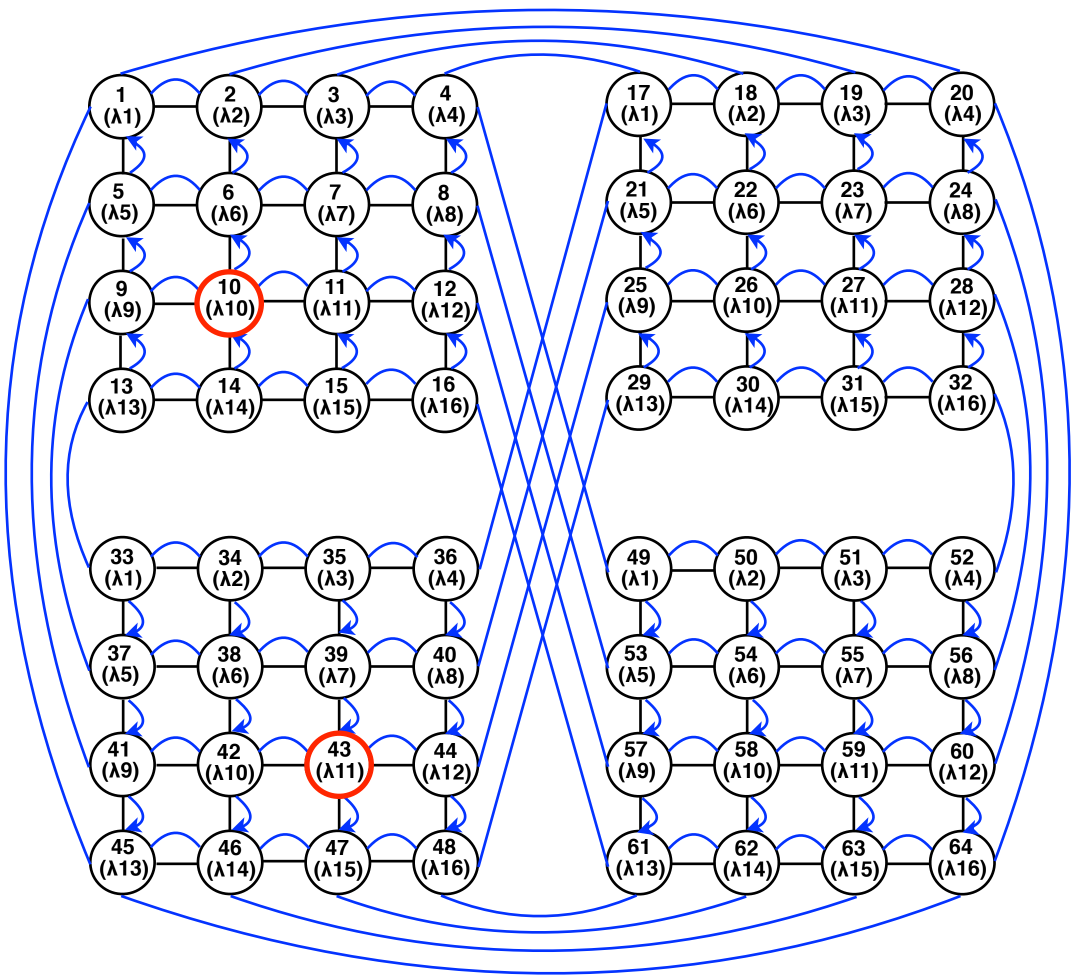

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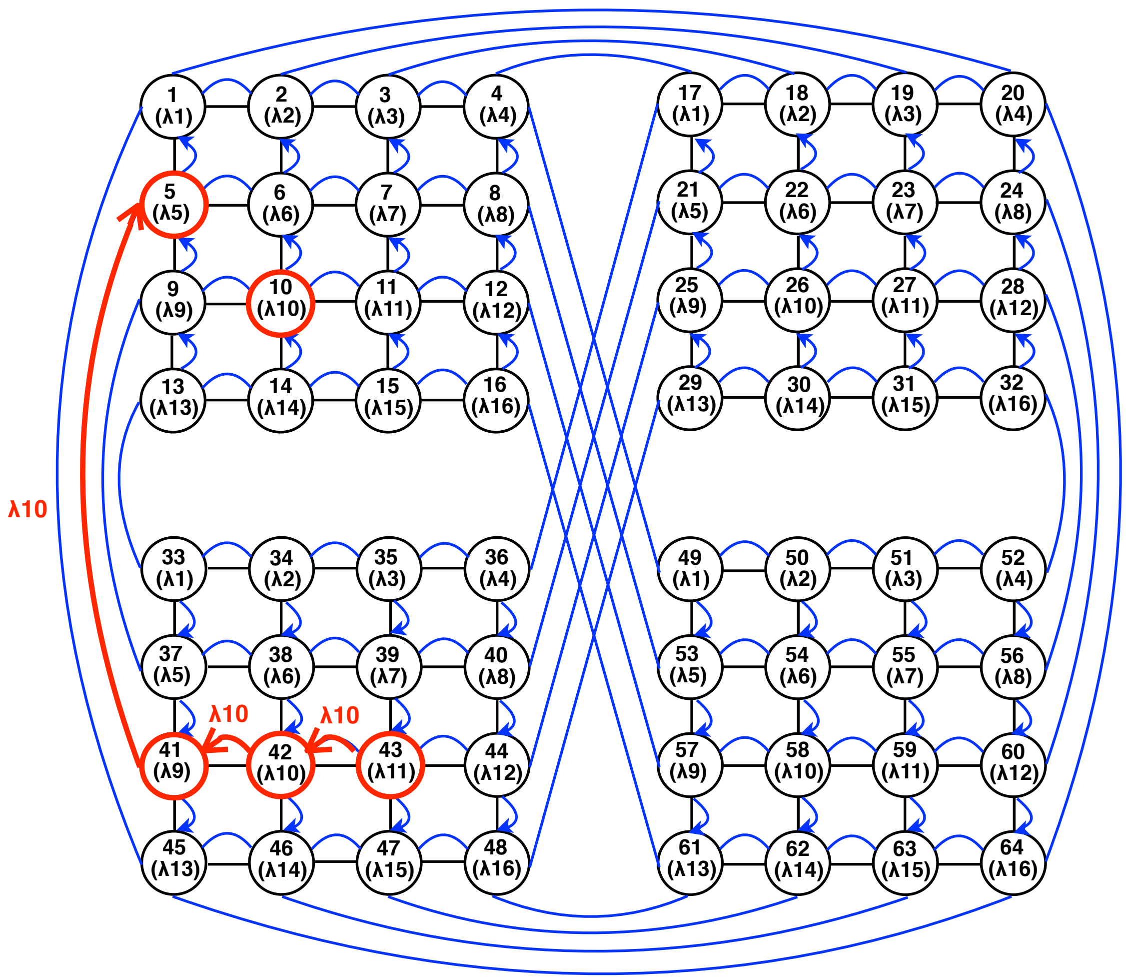

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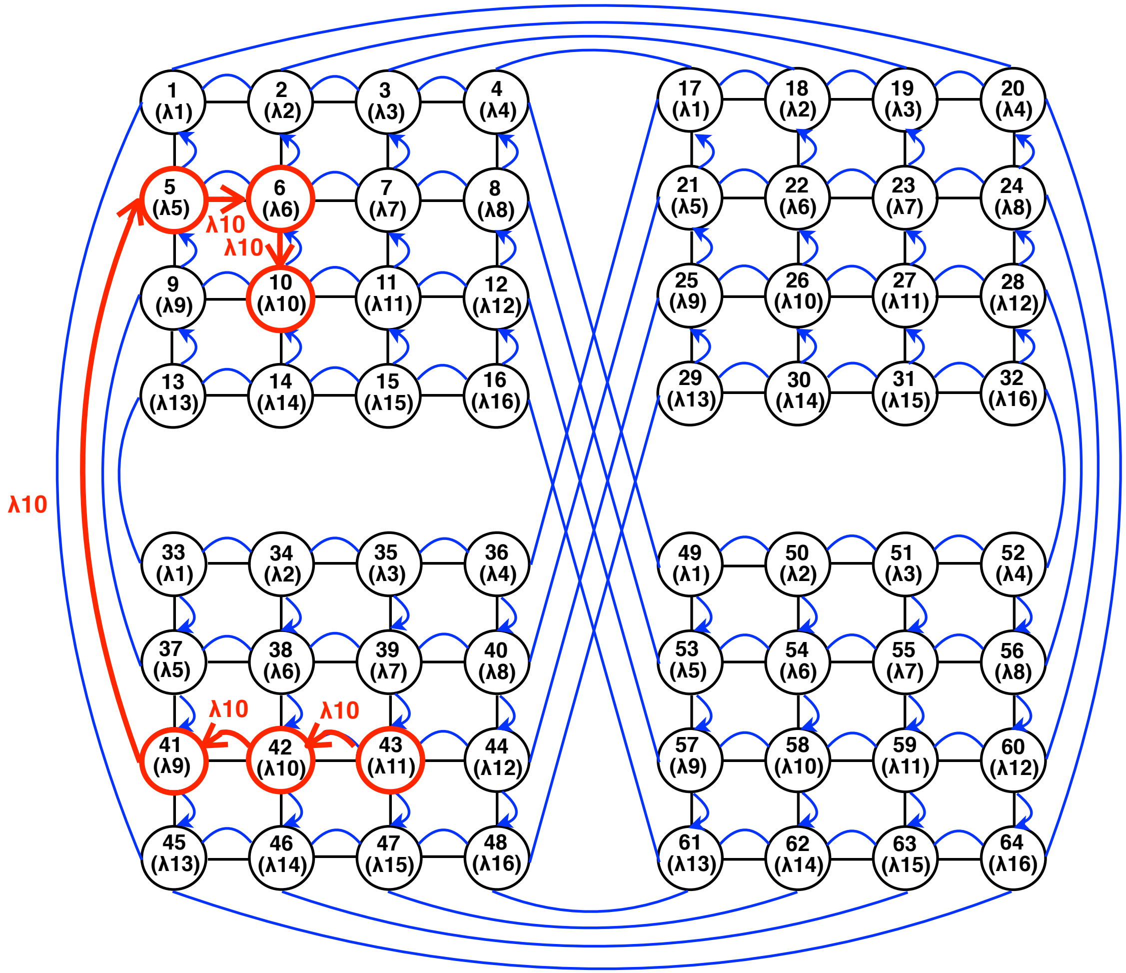

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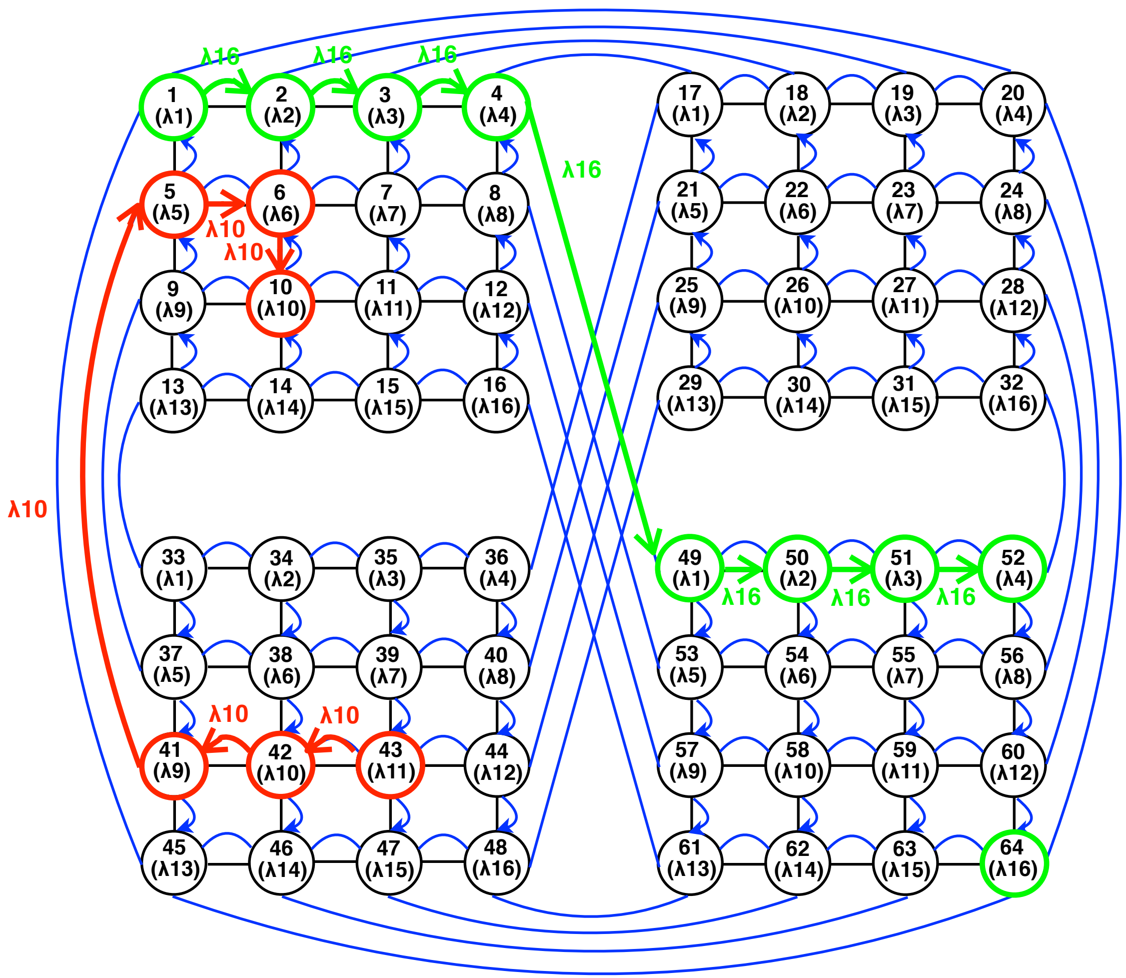
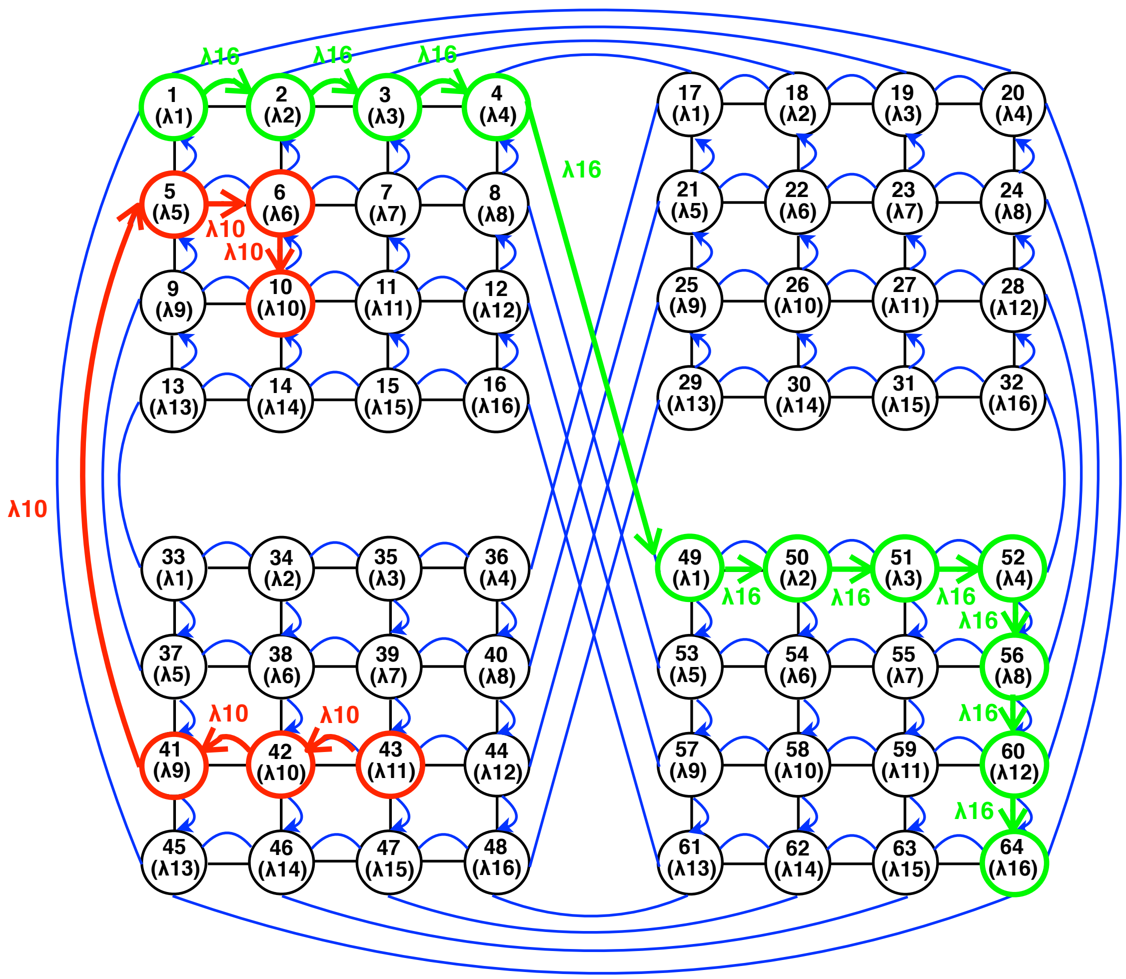
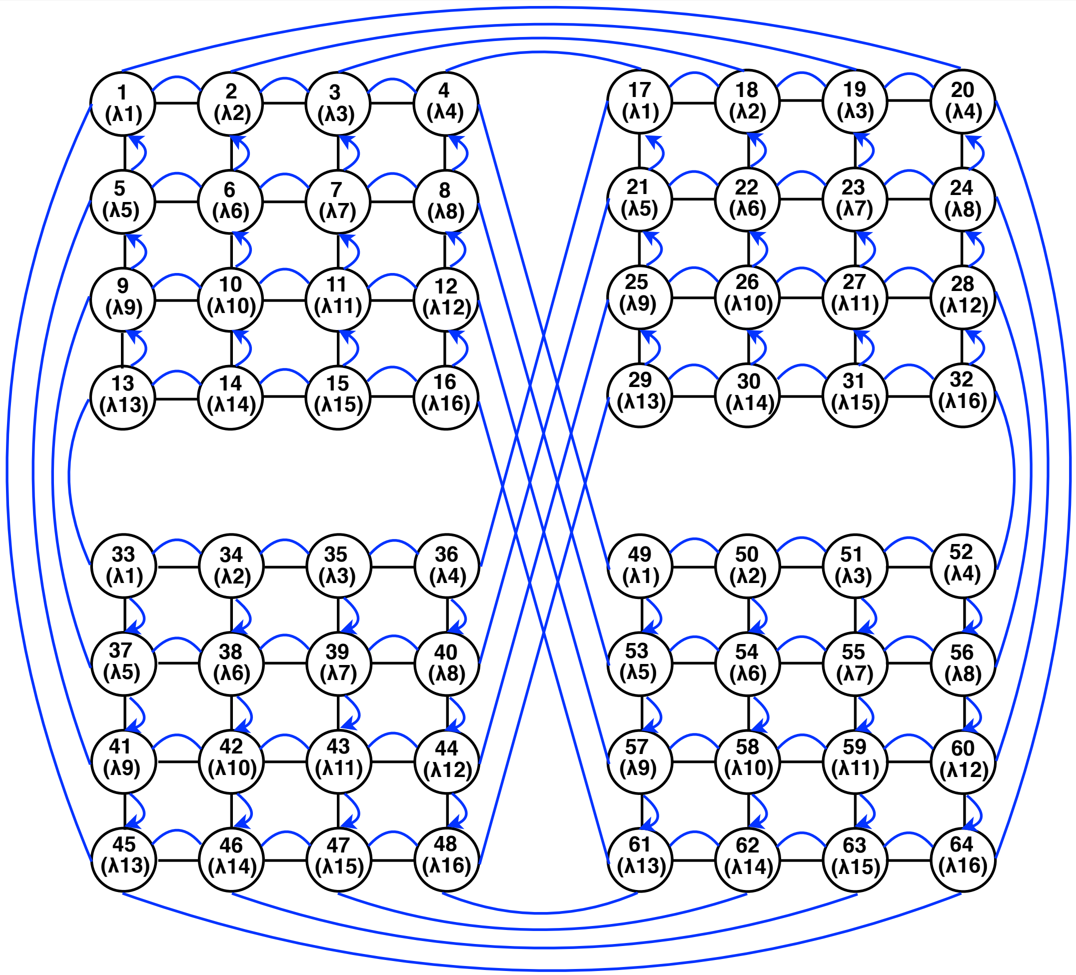


Amon: Routing



Contention-free Routing



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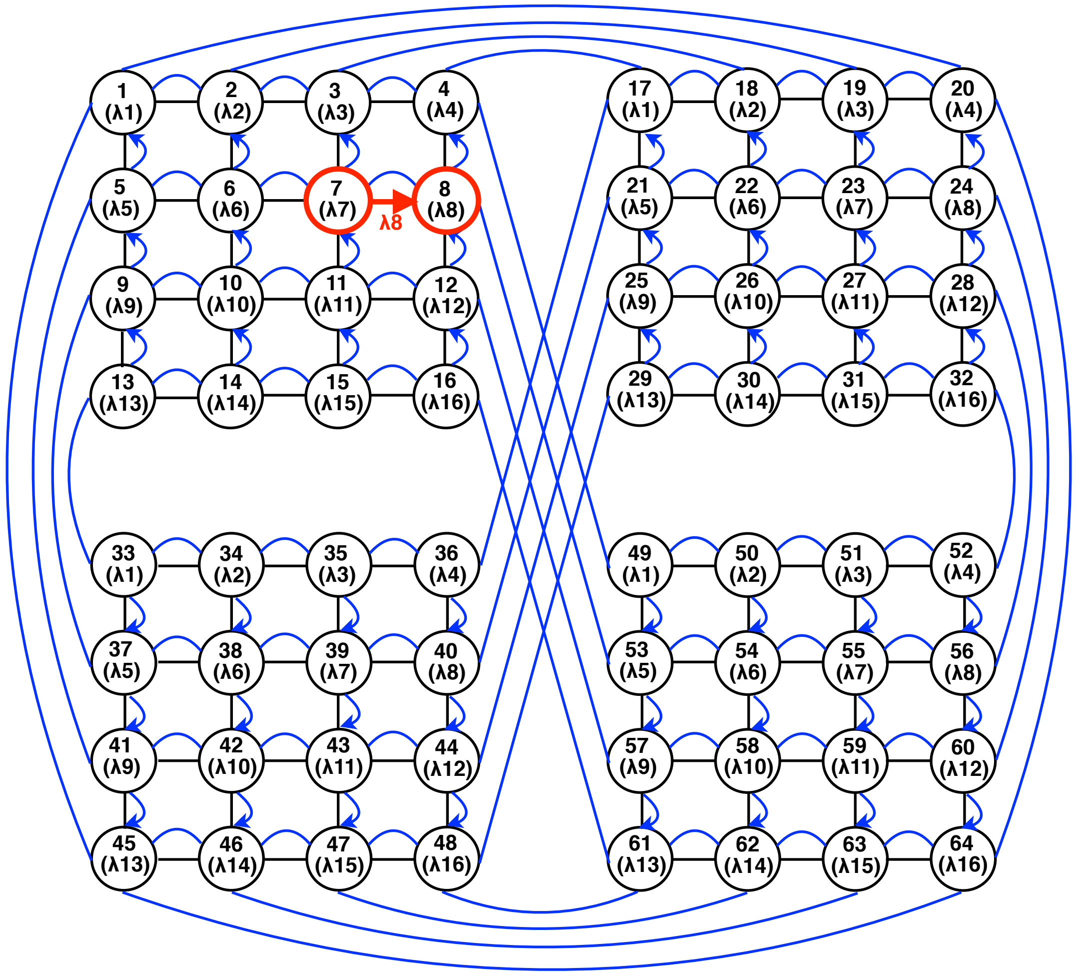

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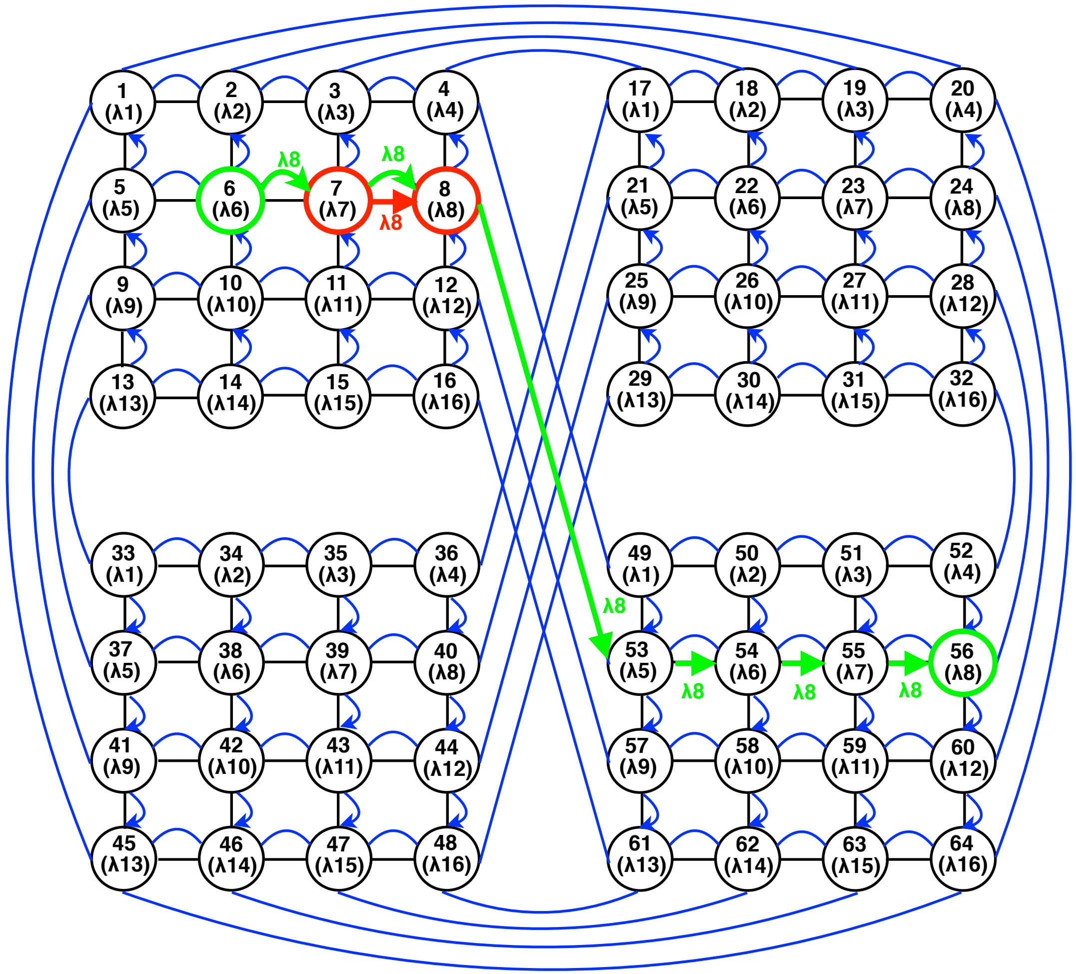

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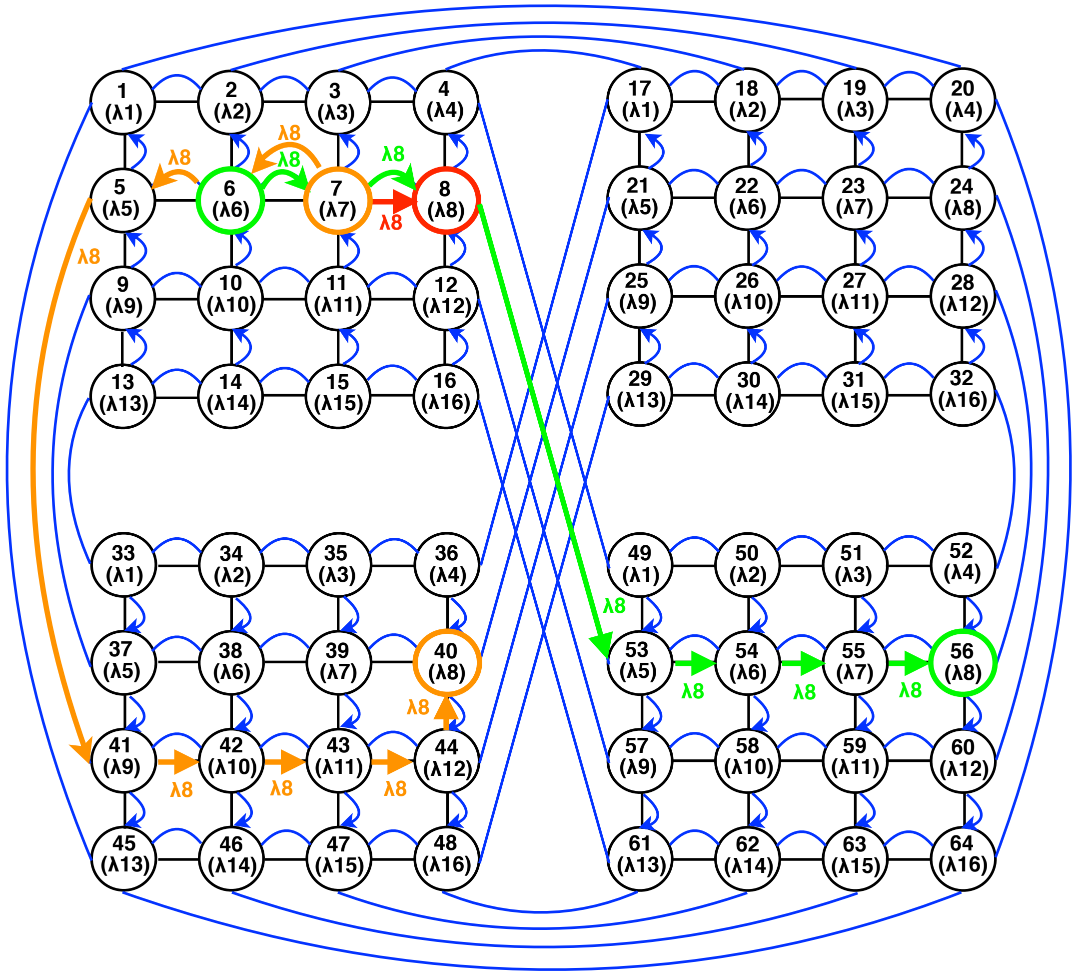

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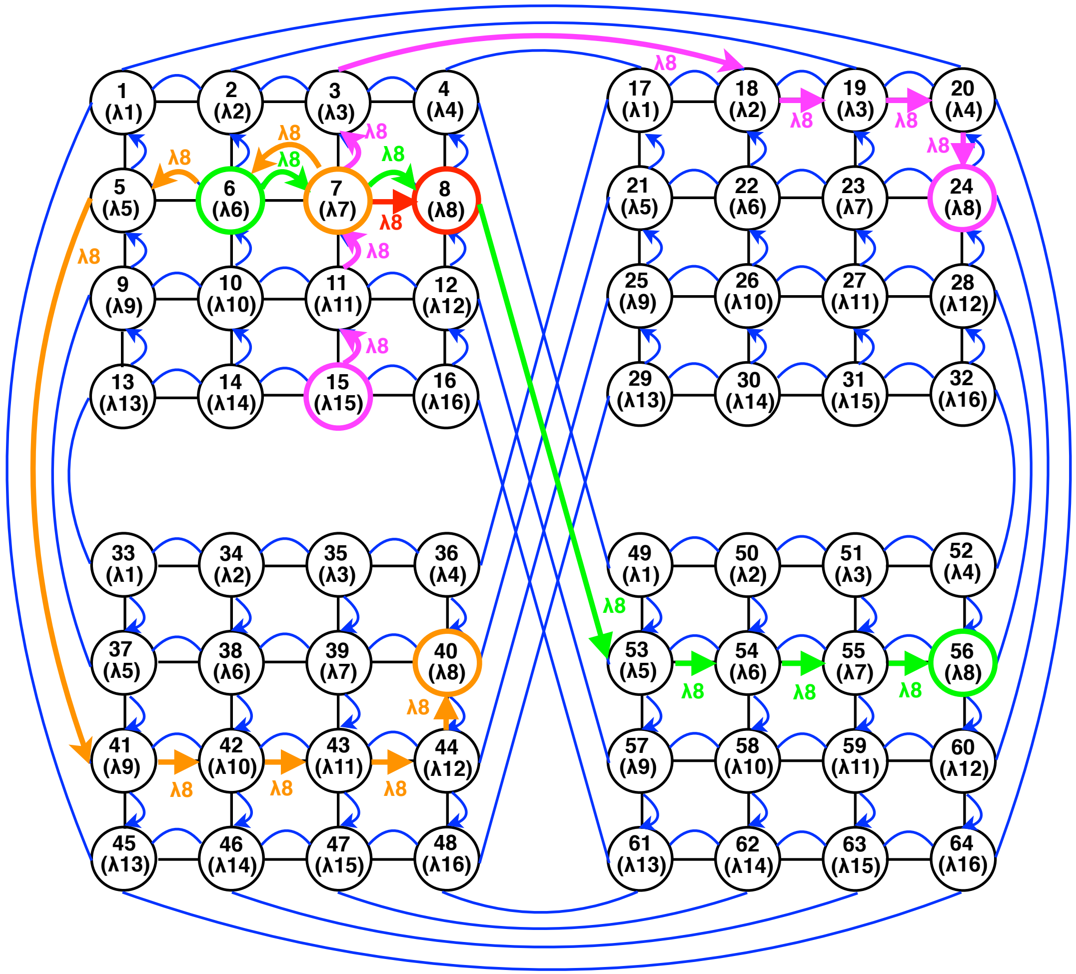
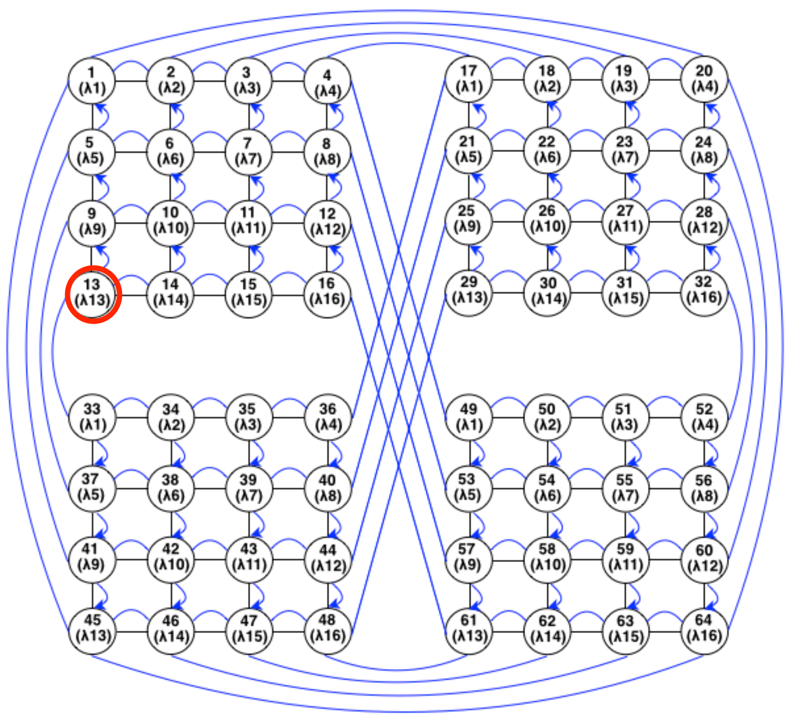
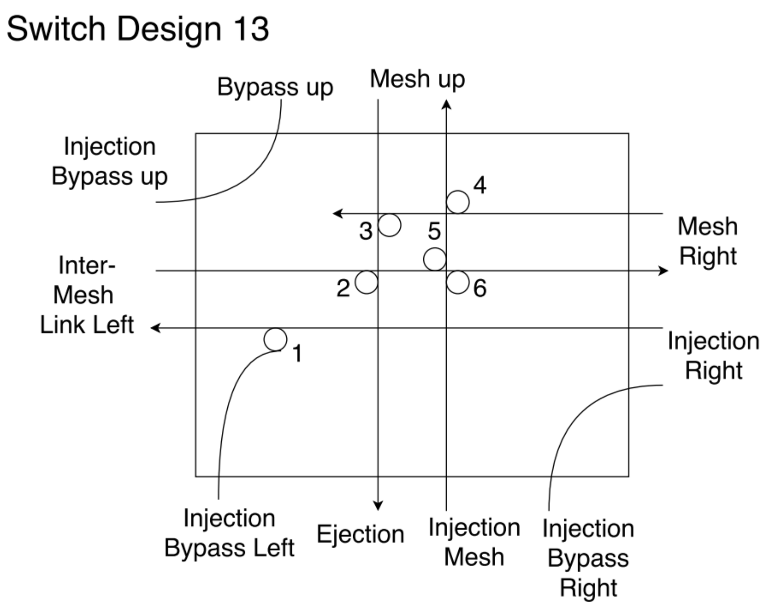


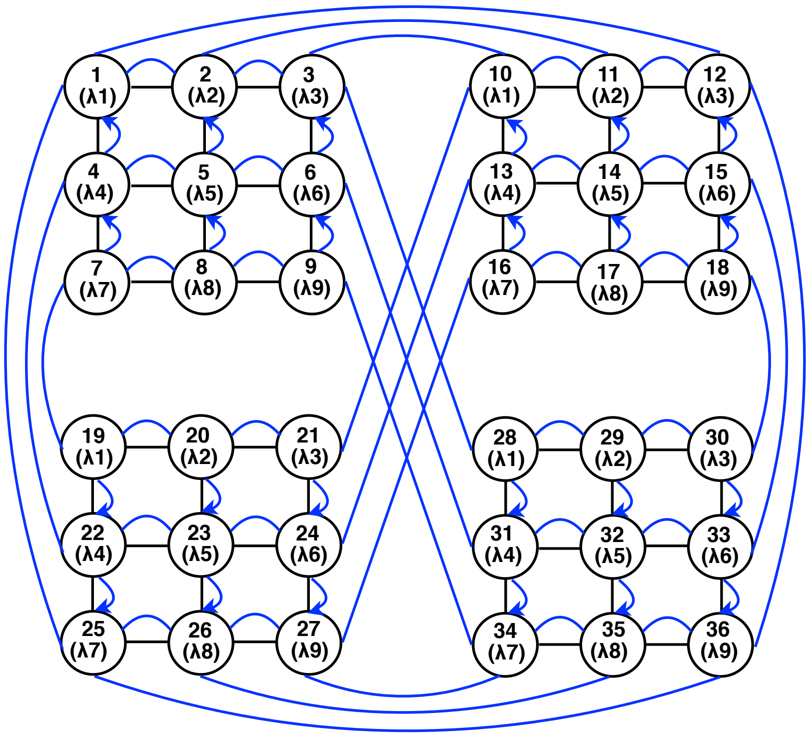
Switch Architecture





Other Switches are designed accordingly

36 Node Amon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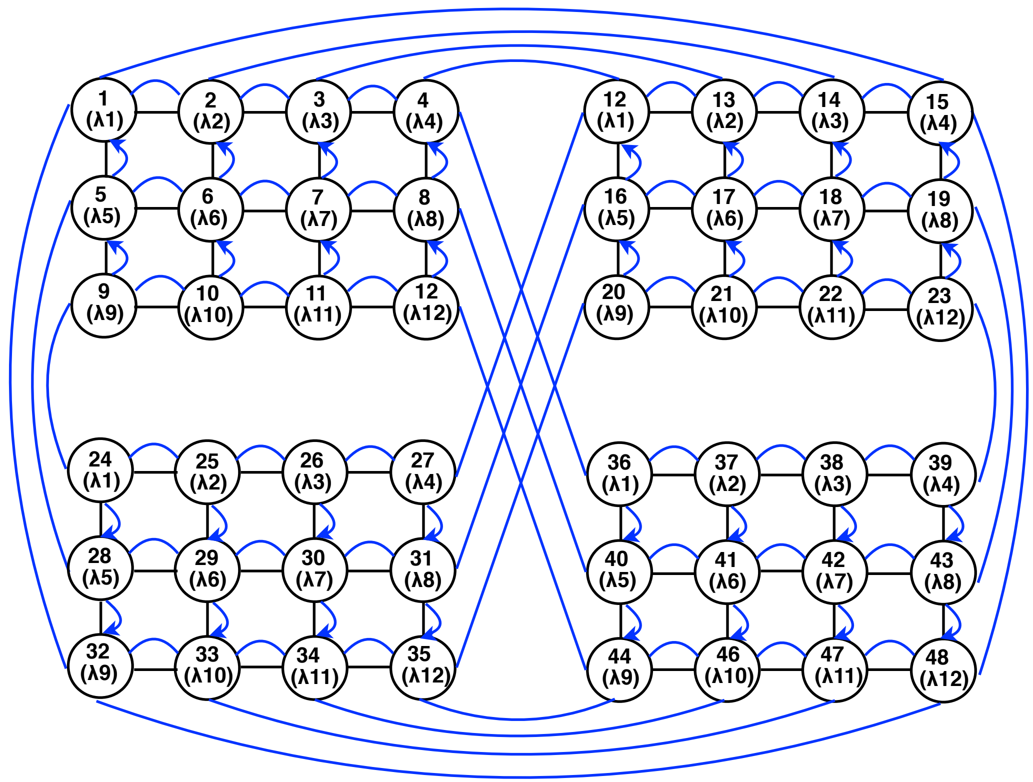
48 Node Amon



Scaling Symmetrical to X/Y Axis

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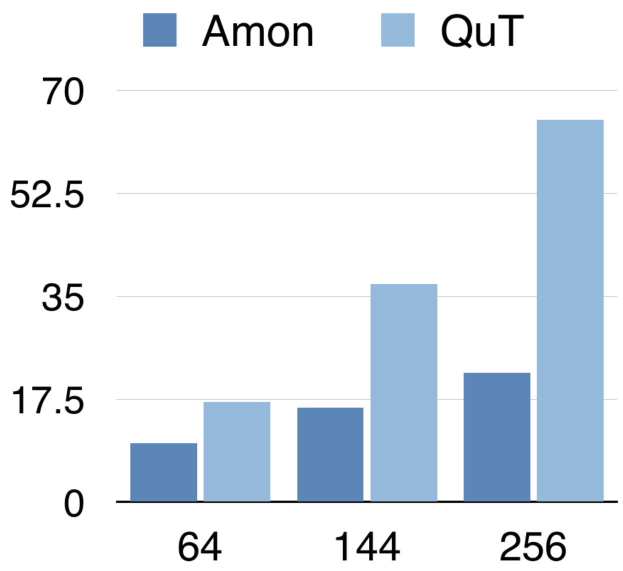
Diameter

	Diameter
Spidergon	$N/4$
QuT	$N/4 + 1$
Amon	$(3\sqrt{N}/2) - 2$



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Diameter

	Diameter
Spidergon	$N/4$
QuT	$N/4+1$
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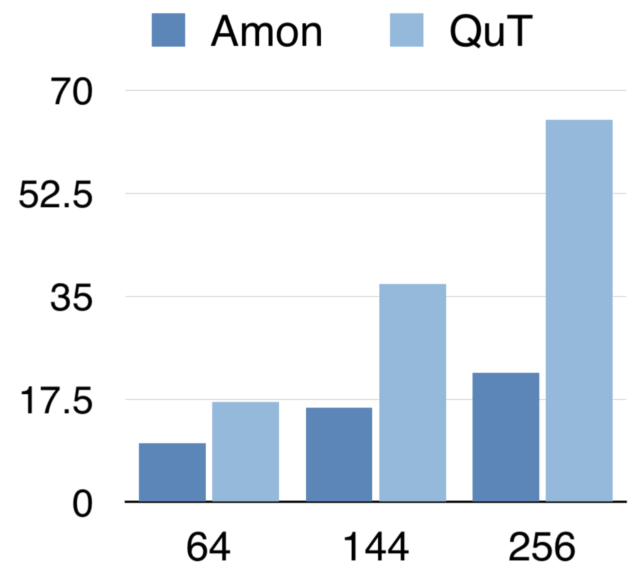

Much smaller diameter with better scalability

-> shorter paths

-> less laser power

Design Configuration

- Aim: Low-power design, parameters are accordingly:
- **22nm** low-voltage technology library
- Core data rate: **4Ghz**
- Modulator/Detector: **8Gb/s**
- Flit Size: **16bit**
- Standard Laser type: Laser is always on
- Tile-width: **1mm**
- Injection rate 0.5
- Data is modulated on **8 wavelengths** per sender
- Control network: Multi-Write-Single-Read Bus
- Implementation with **DSENT**[1] network modeling tool
- 64-, 144- and 256-Node networks to assess scalability

[1] C. Sun et al., "Dsent - a tool connecting emerging photonics with electronics for opto-electronic networks-on-chip modeling," in NOCS, 2012. IEEE, 2012, pp. 201–210.

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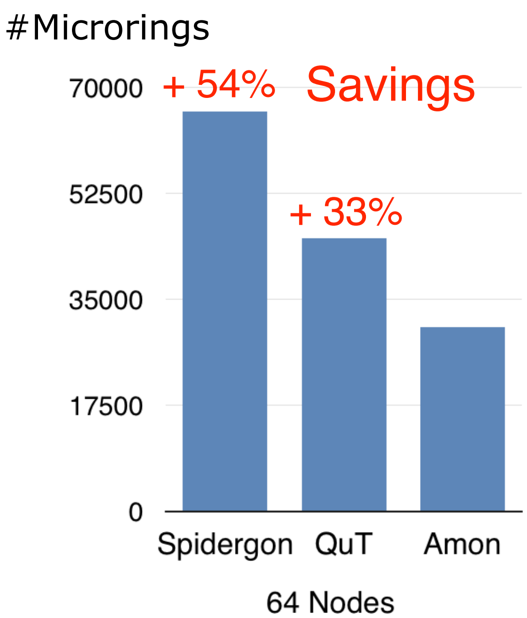
Number of Microrings

Microrings: Modulators, Detectors, Filters



Number of Microrings

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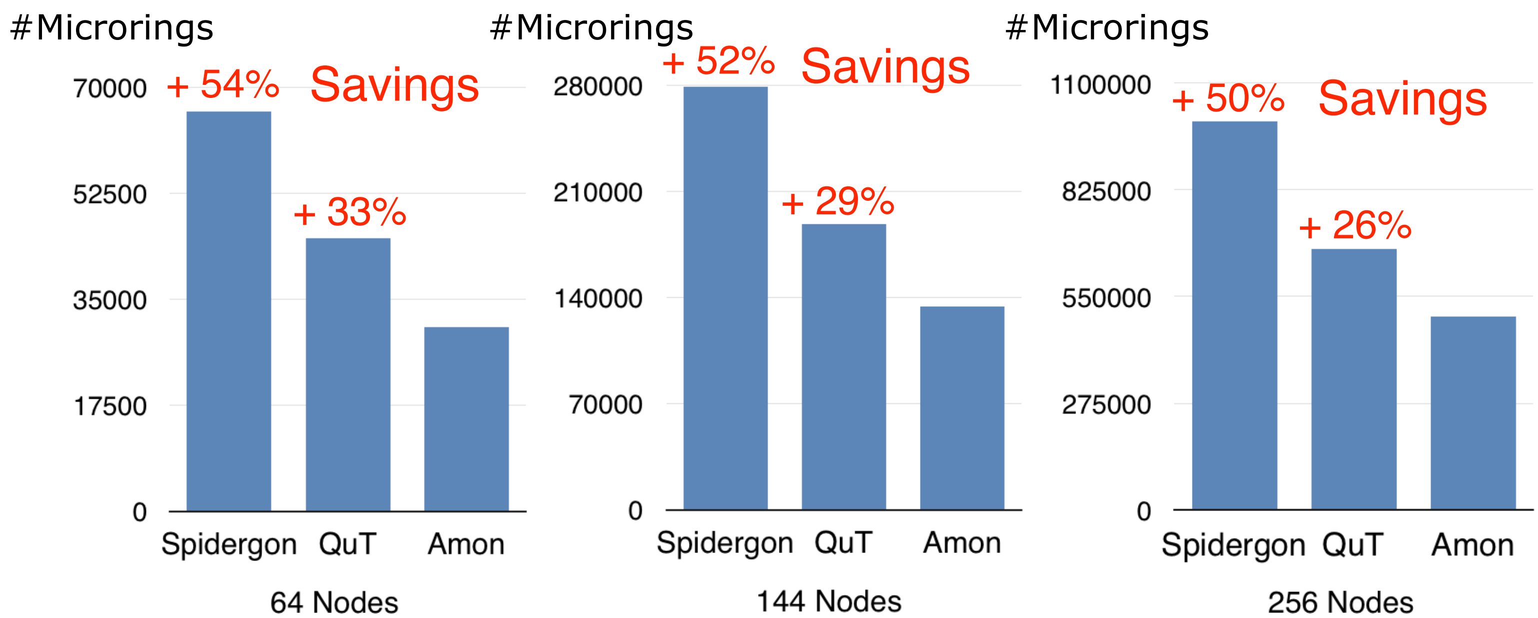

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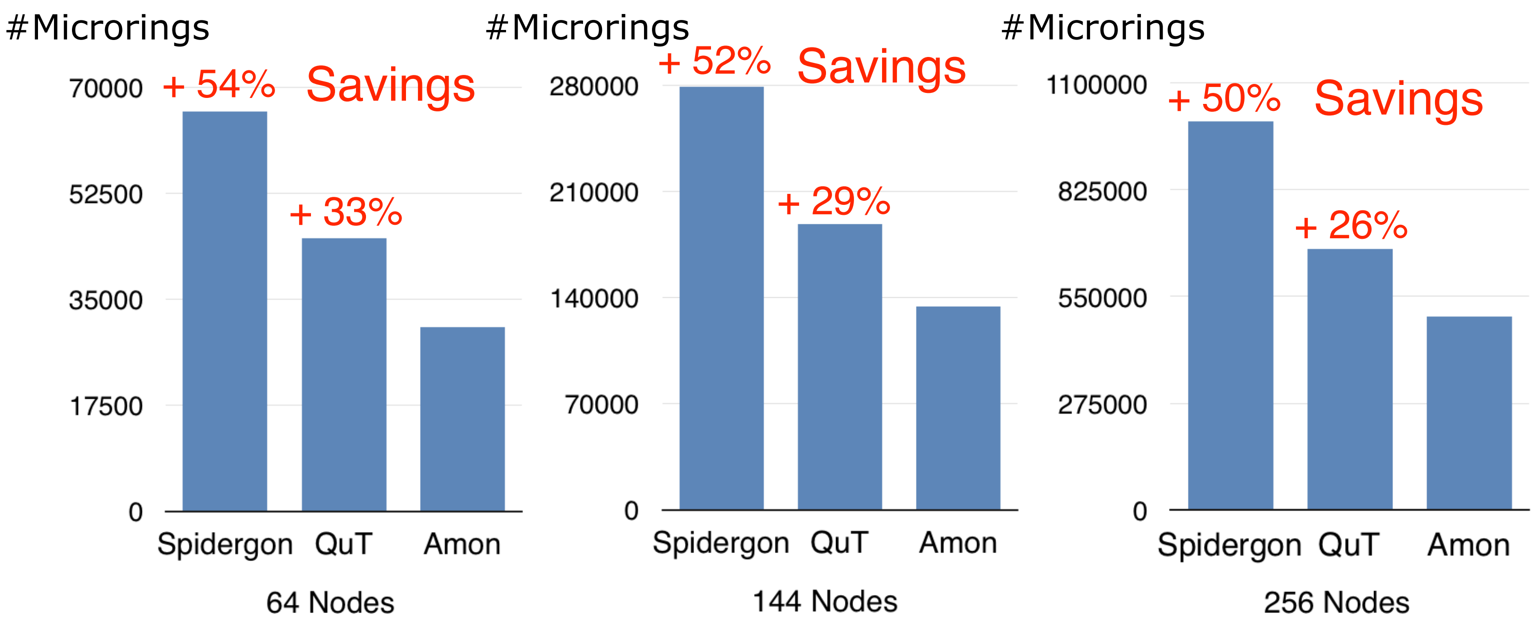
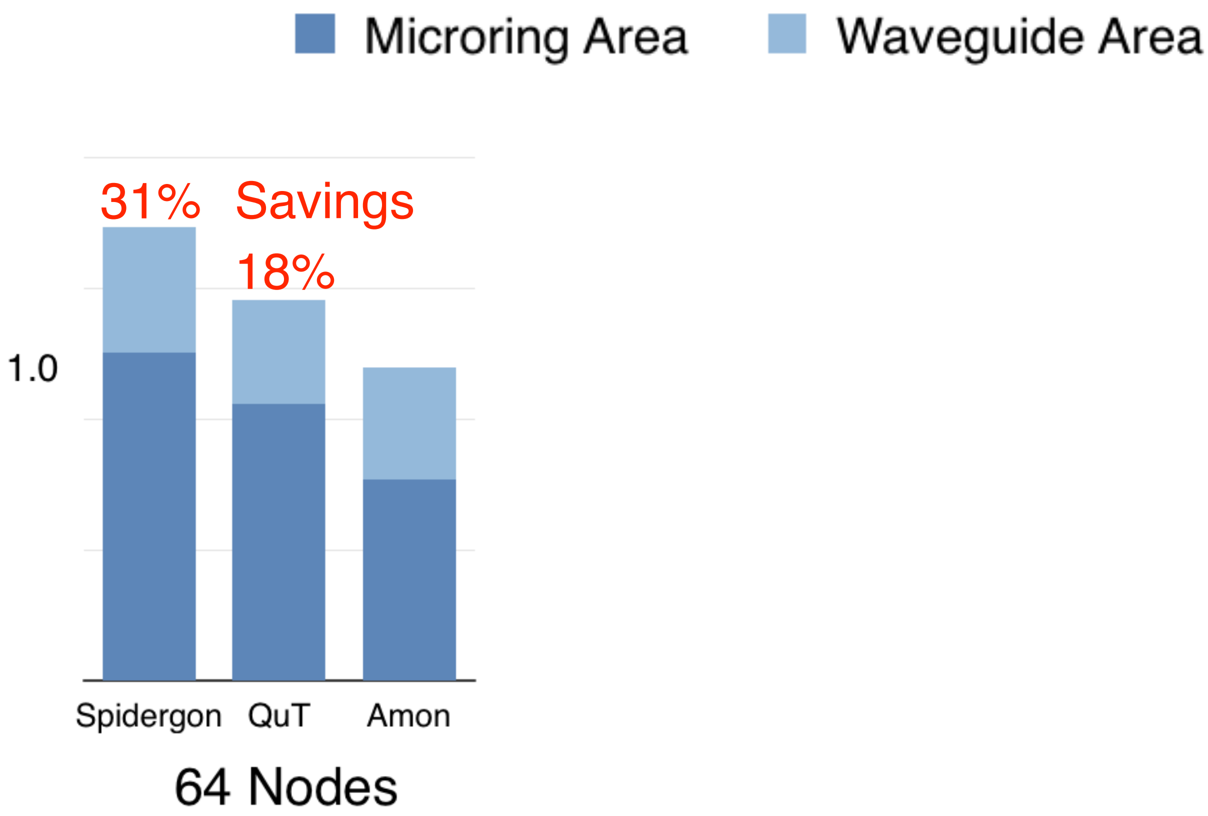


Up to 54% savings in microrings !

Area Results



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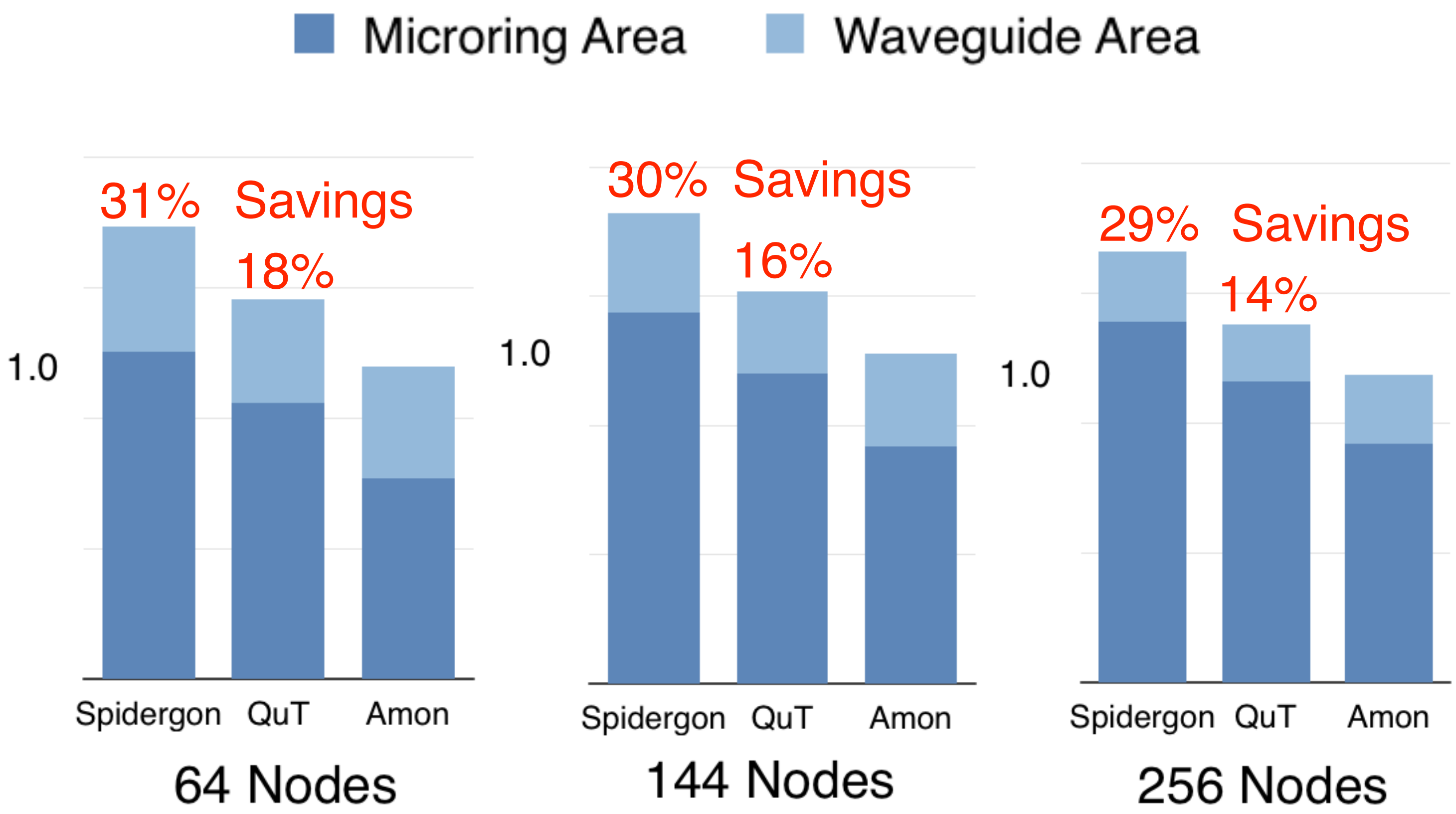

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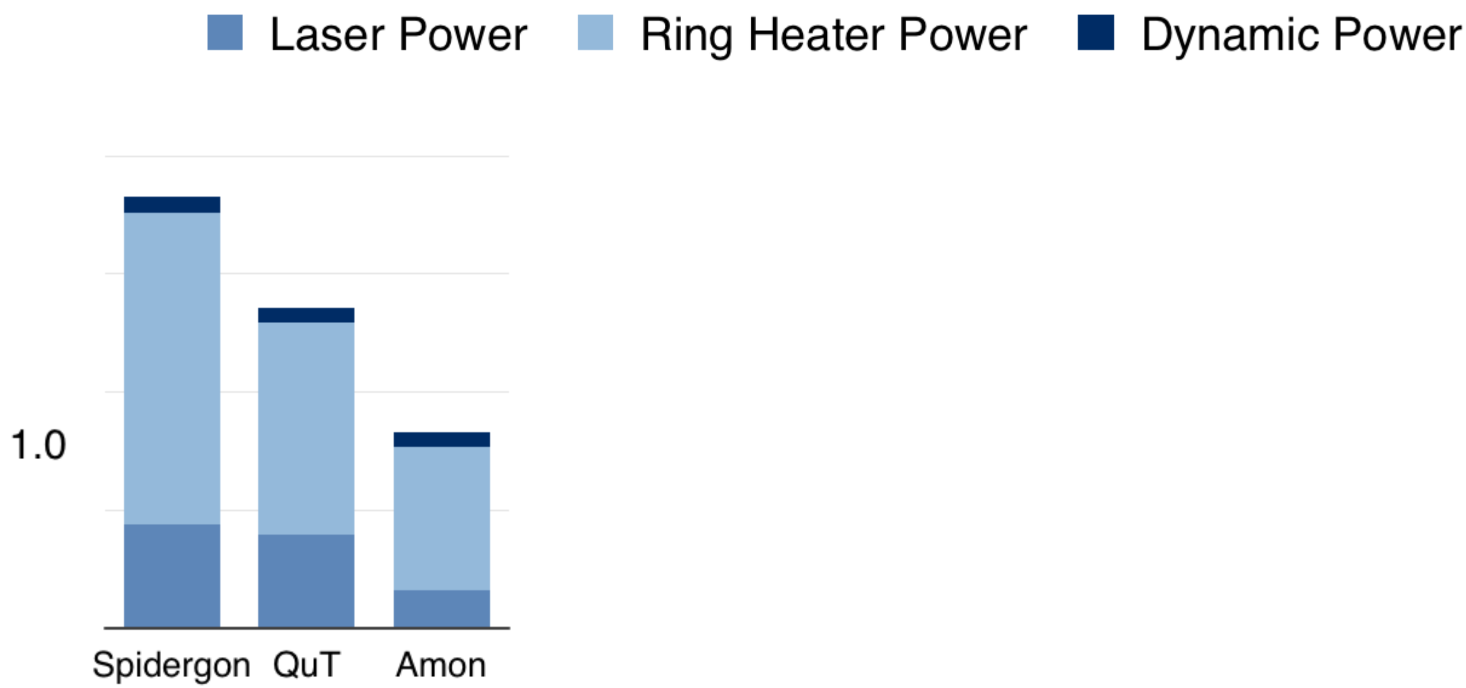
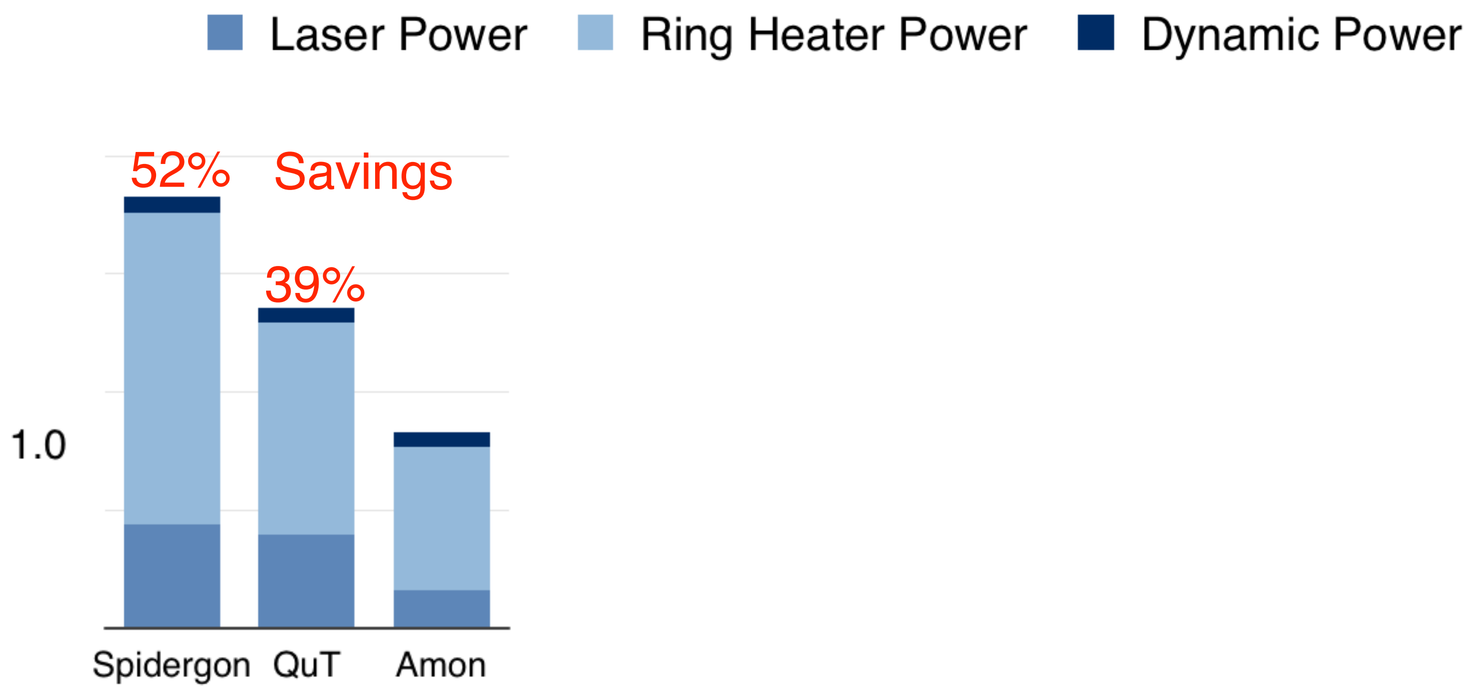
Power Consumption



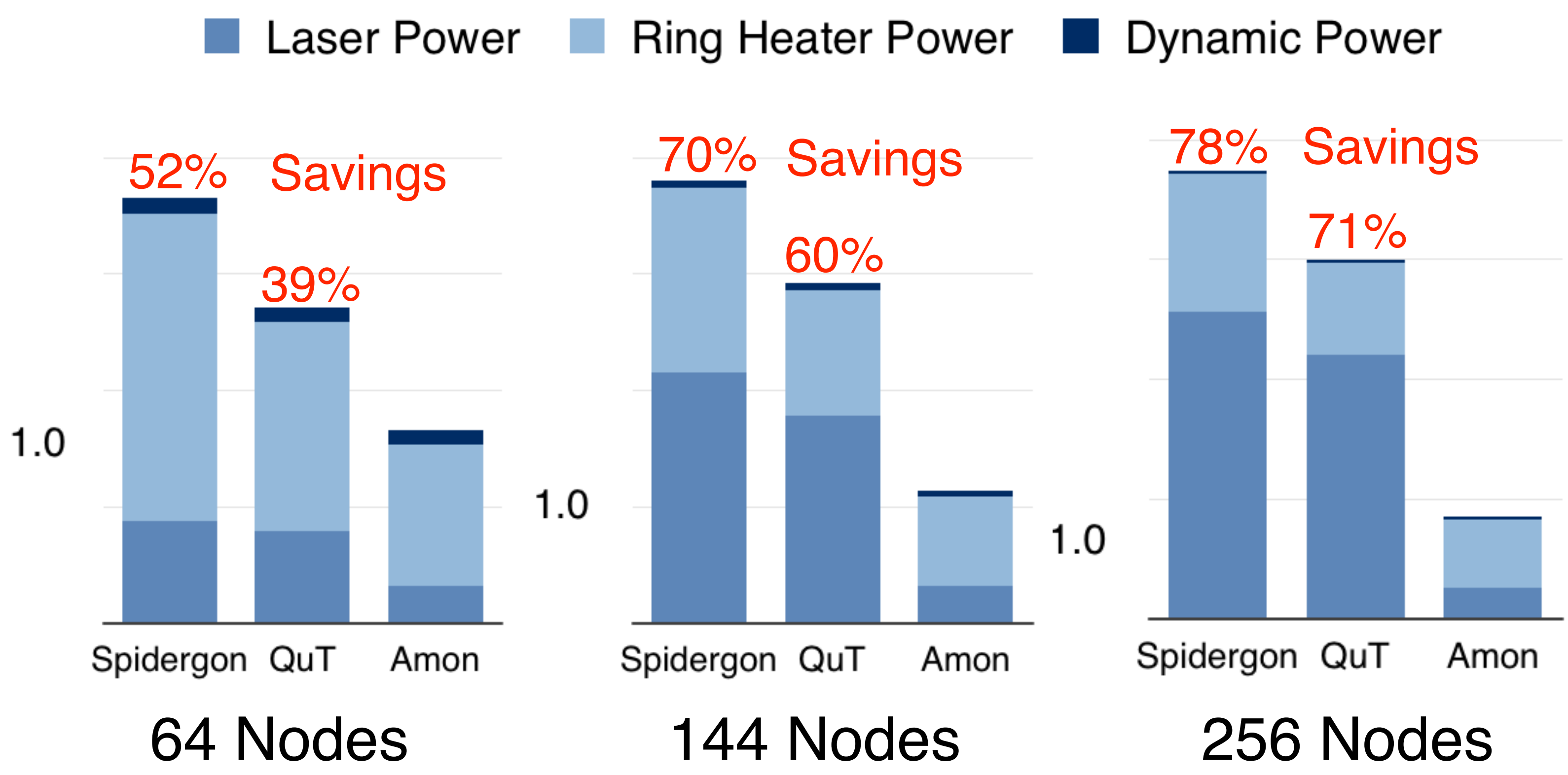
64 Nodes

Power Consumption



64 Nodes

Power Consumption



Summary

Amon is a novel mesh-based optical NoC comprising topology, switch architecture and routing algorithm

Summary

Amon is a novel mesh-based optical NoC comprising topology, switch architecture and routing algorithm

Compared to ring-based Spidergon and QuT, Amon saves:

- Laser Power:
    - Short paths -> lower path losses
    - N/4 Wavelengths in Network
- Ring Heater Power:
    - Fewer Ring filters for switching -> less ring tuning required
- Total Power Savings up to 78% / 71%
- Area due to fewer microrings (up to 31% / 18%)
- Mesh Structure suitable for tile-based VLSI implementation

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Thank you!
Questions?

Zero Load Latency

Control Network:

- Packet Size 2bit for packet type (req/ack/nack)
- 4Ghz Core clk and 8Gb/s Modulator: 2 bits per clock clk
- Total latency: Modulation (1 cycle) + On-the-fly (1 cycle) + Detection (1 cycle) = 3 cycles
- **Destination checking: 6 cycles (req + ack)**

Zero Load Latency

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Data Network:

- Assuming 128bit data packet
- Data transmission with 8 modulators: 128 / 8 / 2 = 8 cycles for modulation, 1 on-the-fly, 8 for detection -> **17 cycles**
- **Total: 23 Cycles**

Zero Load Latency

Control Network:

- Packet Size 2bit for packet type (req/ack/nack)
- 4Ghz Core clk and 8Gb/s Modulator: 2 bits per clock clk
- Total latency: Modulation (1 cycle) + On-the-fly (1 cycle) + Detection (1 cycle) = 3 cycles
- **Destination checking: 6 cycles (req + ack)**

Data Network:

- Assuming 128bit data packet
- Data transmission with 8 modulators: 128 / 8 / 2 = 8 cycles for modulation, 1 on-the-fly, 8 for detection -> **17 cycles**
- **Total: 23 Cycles**

- with 200ps clock cycle and 15ps/mm propagation delay, every **destination within 18 hops is reached in one clock cycle** -> Larger network size has insignificant impact on latency
- Adding modulators or using faster ones (up to 40Gb have been fabricated) further decreases latency

Insertion Loss Parameters

Parameter	Value
Laser efficiency	5 dB
Coupler loss	1 dB
Waveguide propagation loss	100 dB/m
Ring: Through loss	0.01 dB
Ring: Drop loss	1 dB
Modulator Insertion Loss	1 dB
Modulator Extinction	1 dB
Photodetector loss	1 dB

Control Network MWSR

Power:
21%, 19%, and 17% of Amon (64, 144, 256 Nodes)
Only 1 Modulator compared to 8 leads to small ring heater power and area

Waveguide Area becomes significant as one waveguide reaching to every other node in the oNoC is added for each node

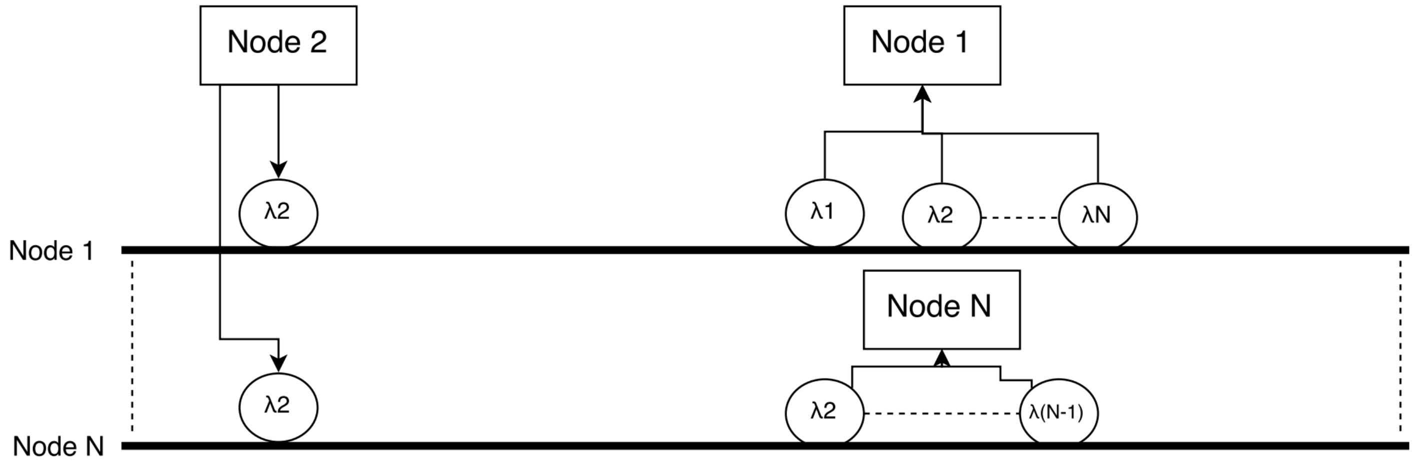
Control Network

Control Network

- **Req - Ack/NegAck** messages for destination reservation

Control Network

- **Req - Ack/NegAck** messages for destination reservation
- Commonly implemented as a **Multiple-Write-Single-Read bus**



Technology Parameters Area

Waveguide->Pitch	= 4e-6	# m
Ring->Area	= 100e-12	# m2
Photodetector->Area	= 10e-12	# m2

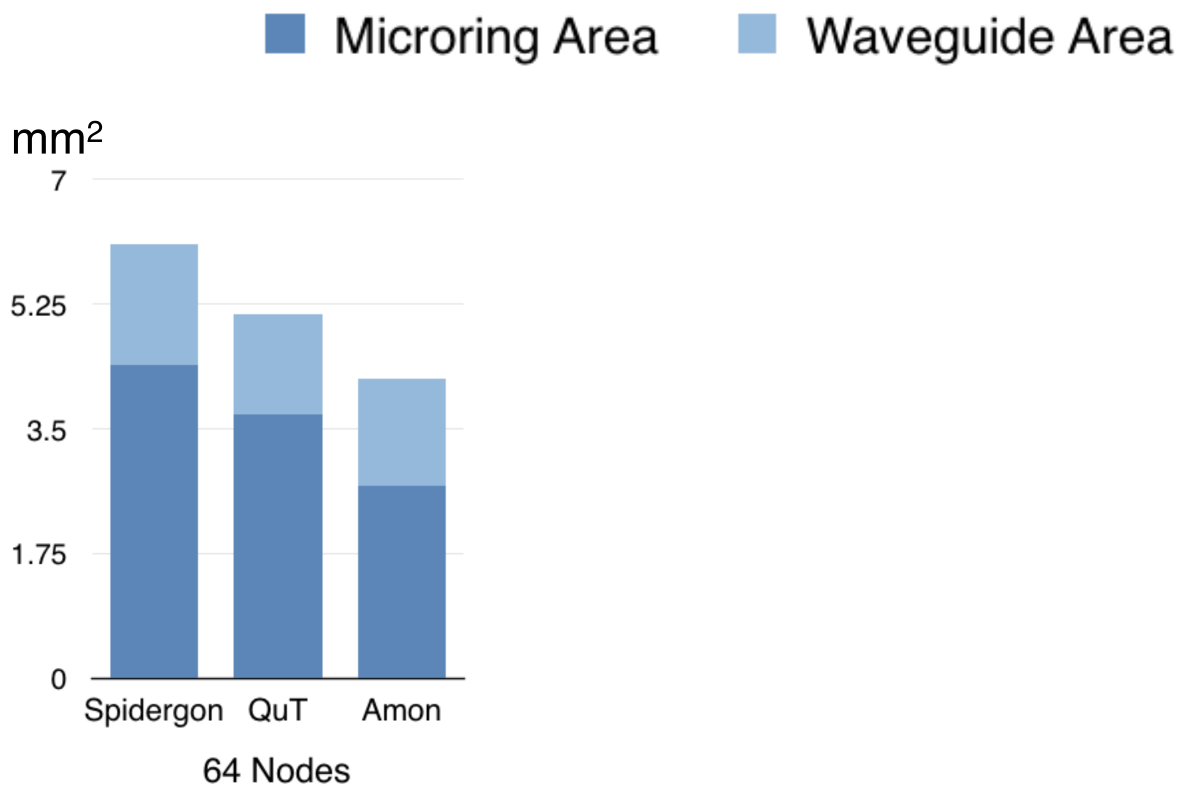
Power Consumption

Amon total power :

64 Nodes: 0.83W
144 Nodes: 4W
256 Nodes: 15W

Area Results

Area Results



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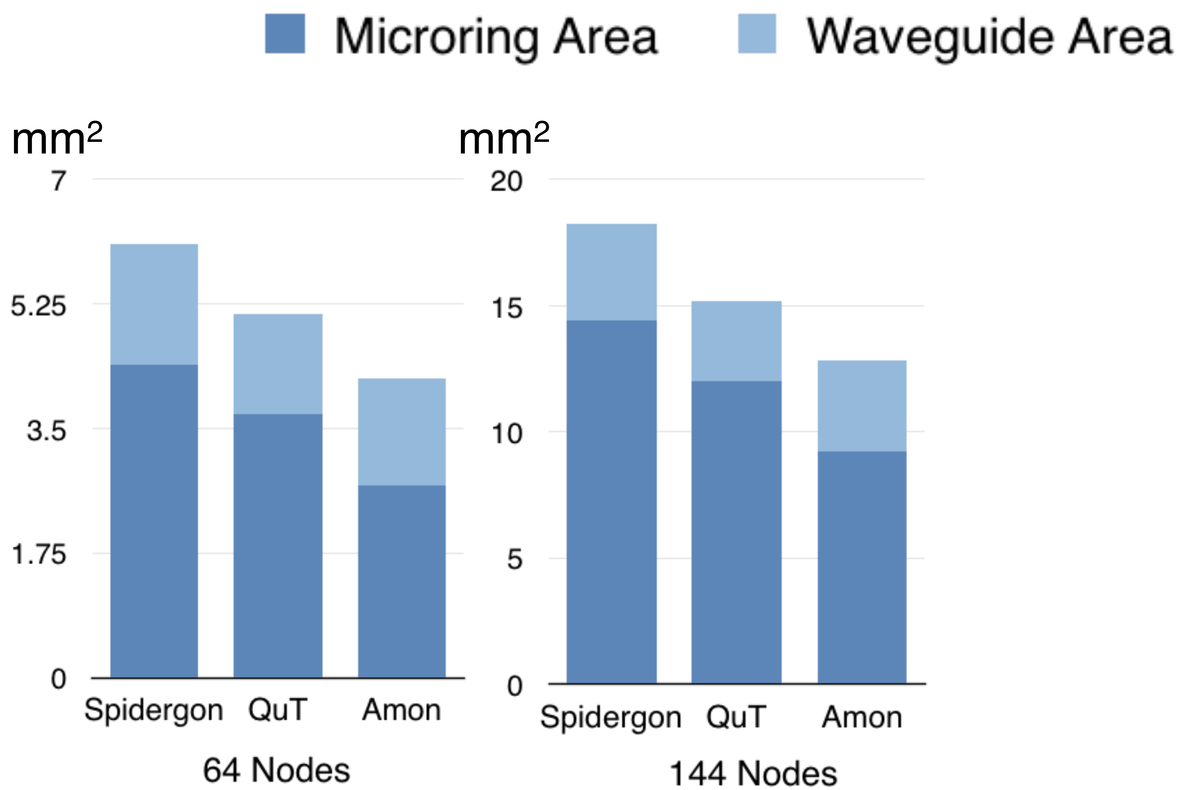
Area Results



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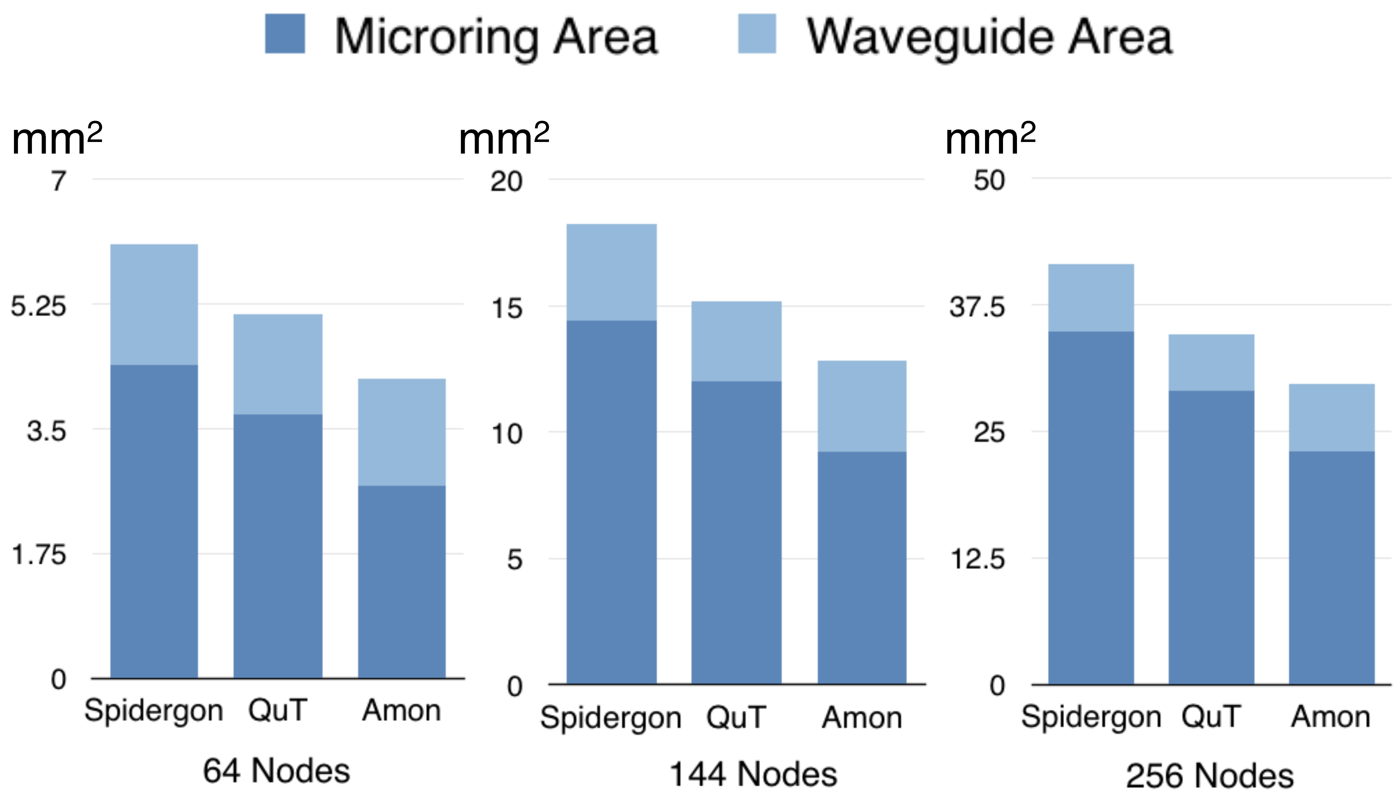

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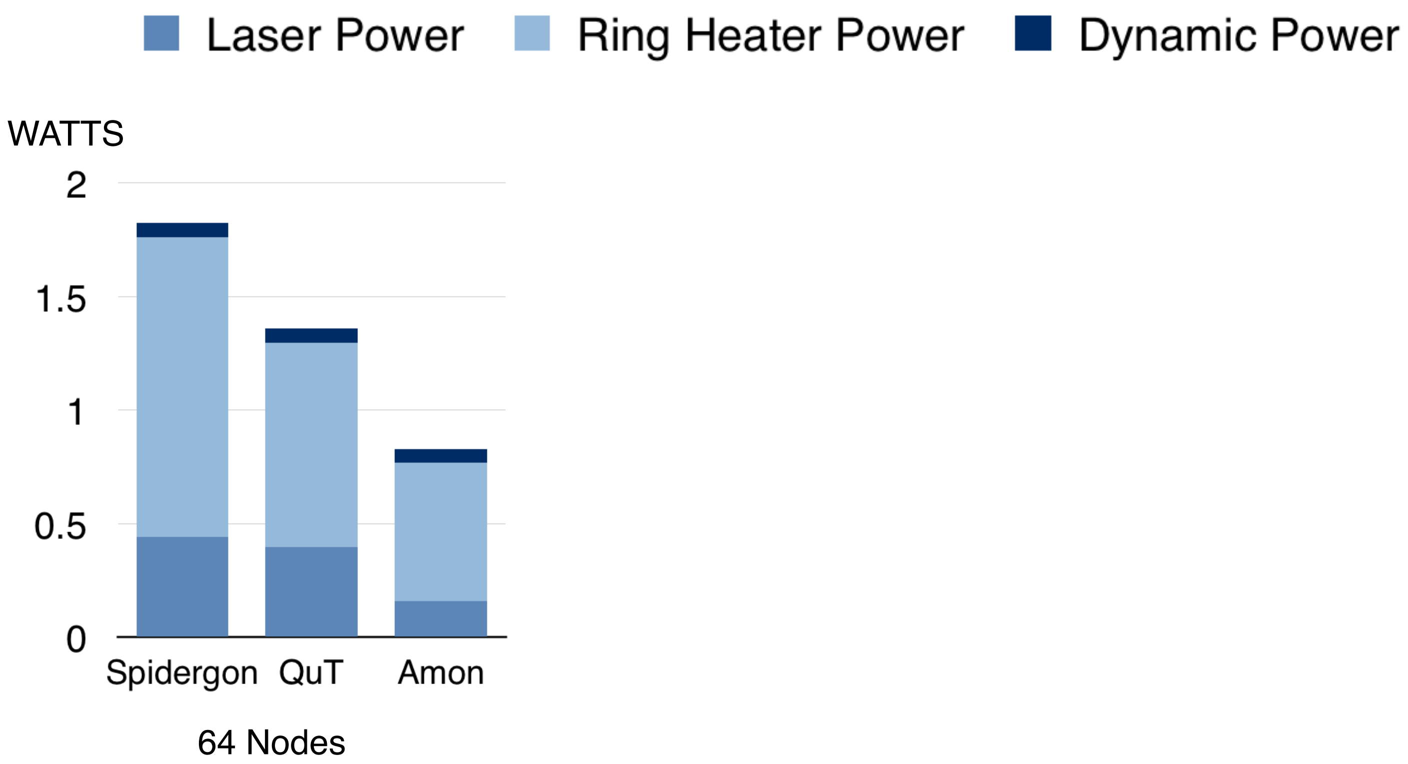

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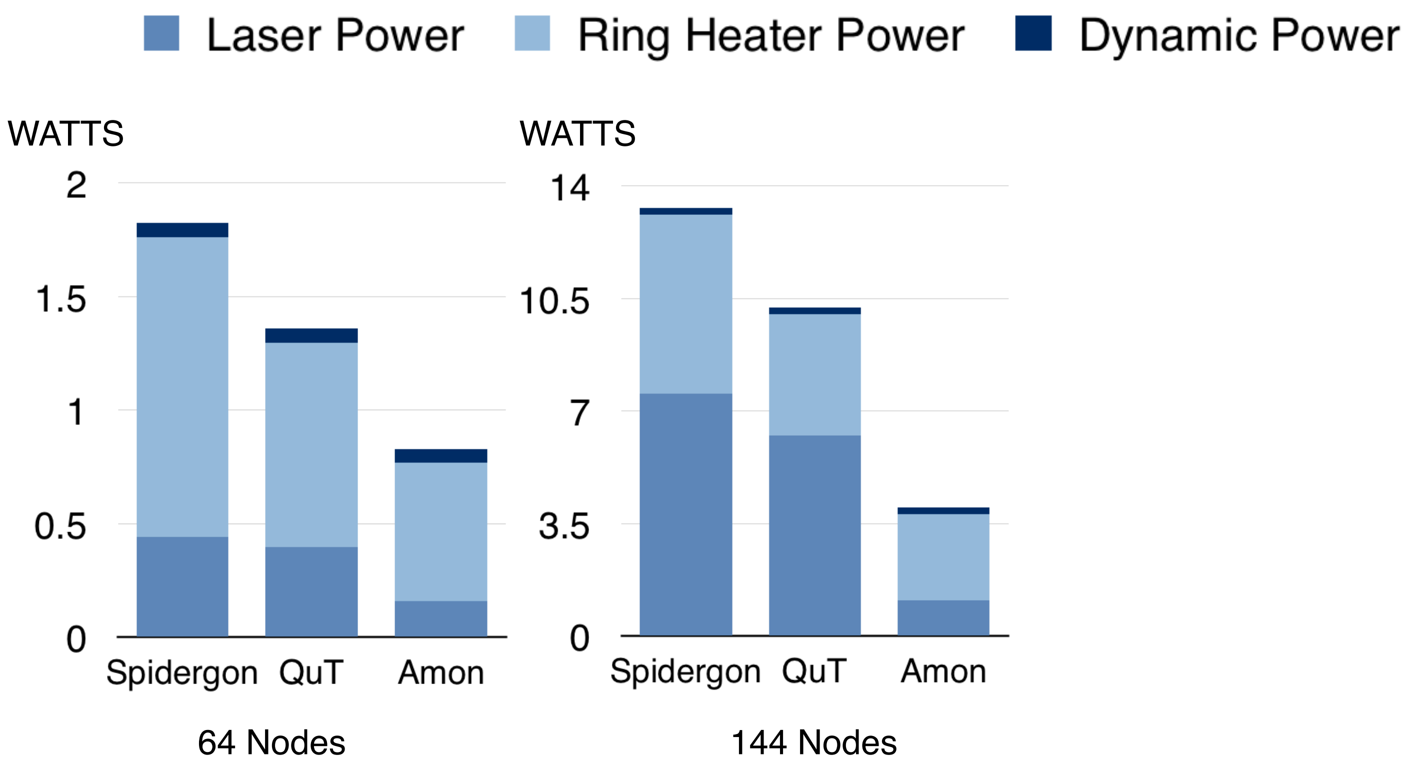

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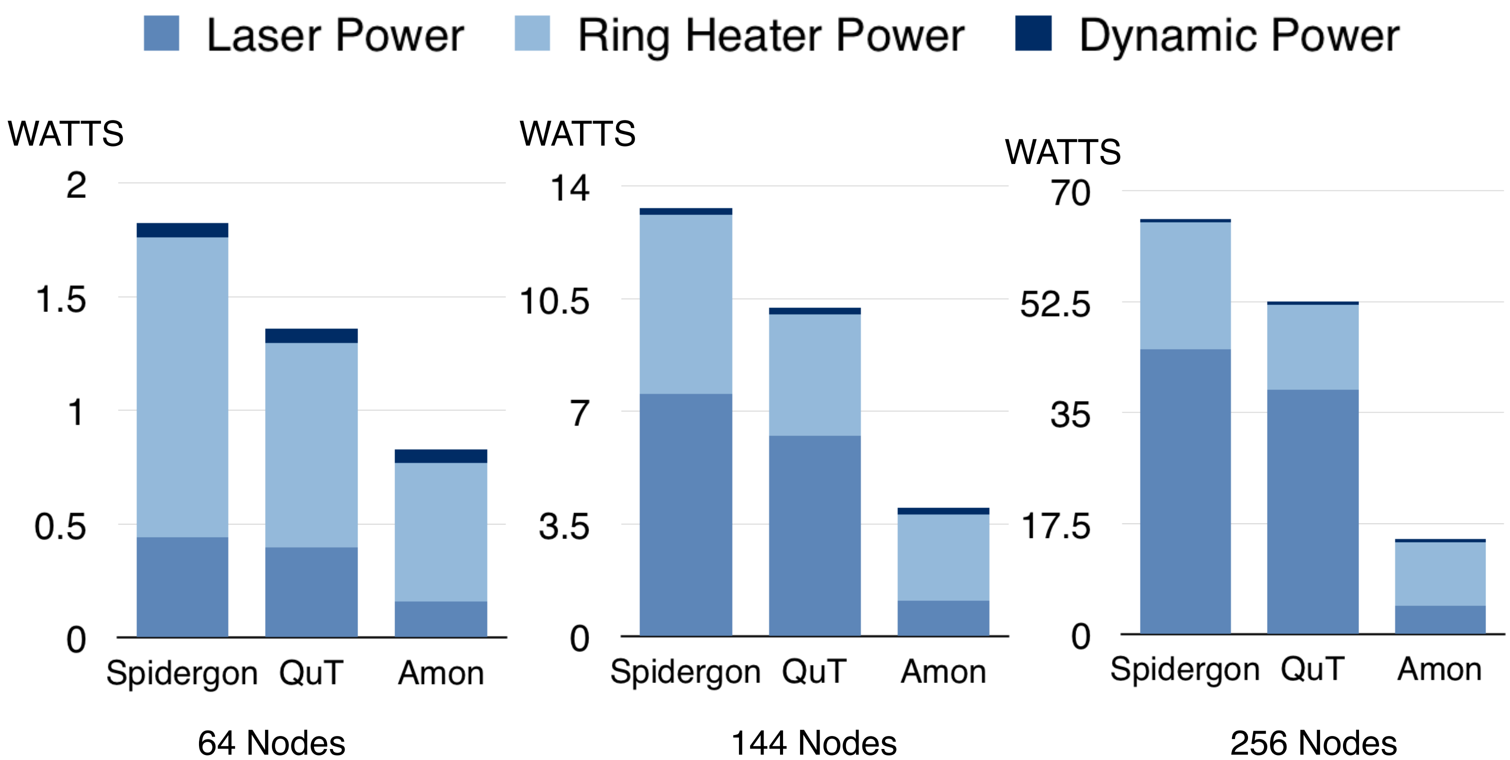
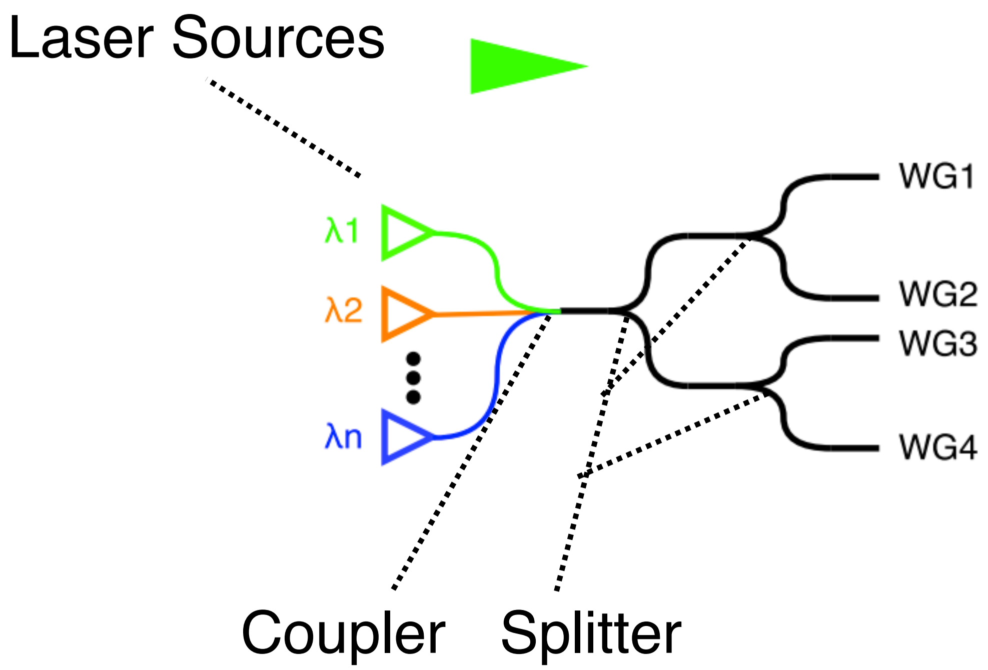
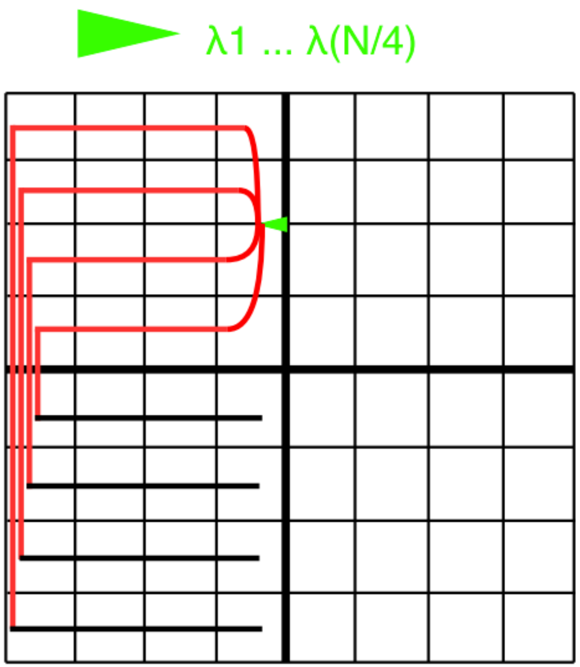


VLSI Layout: Shared Laser Sources



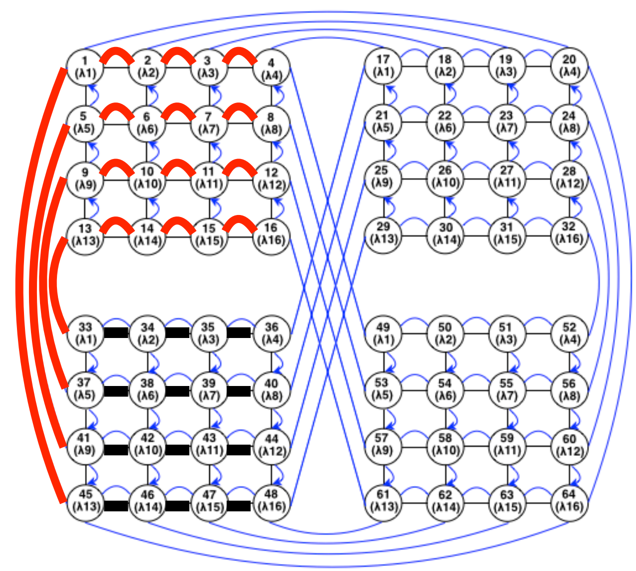
VLSI Layout: Shared Laser Sources

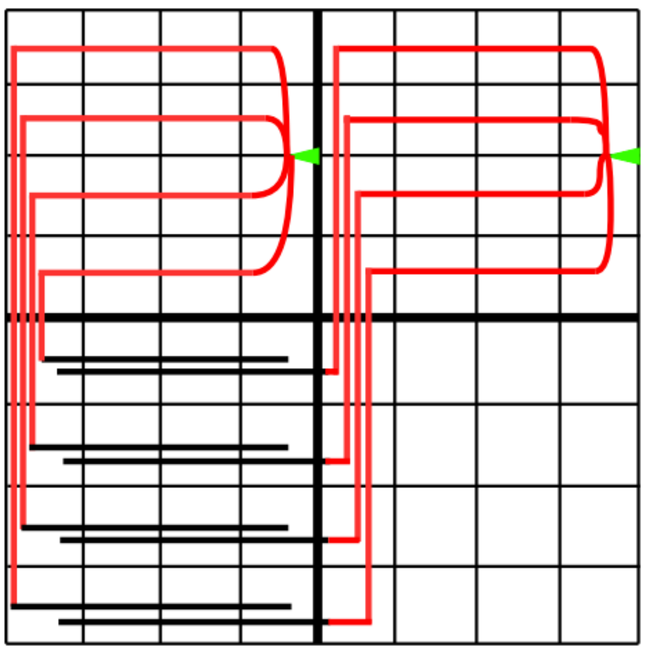


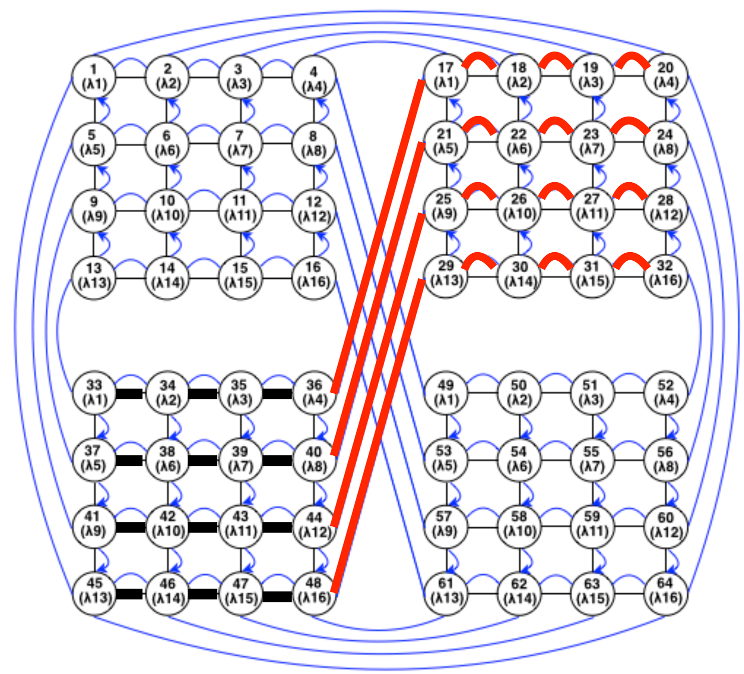
Bypass/Intermesh Link

Mesh link

Laser Sources + Couplers + Splitters



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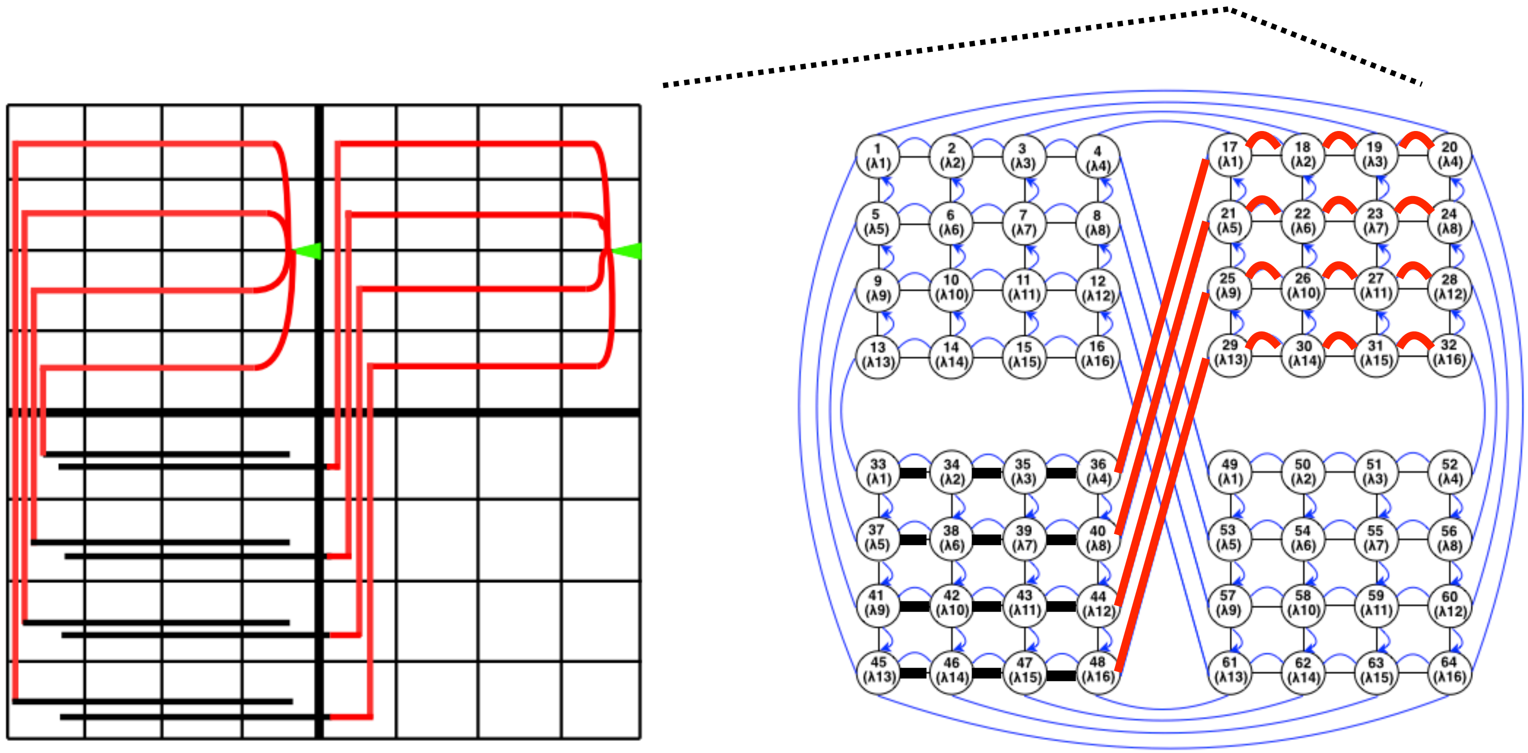
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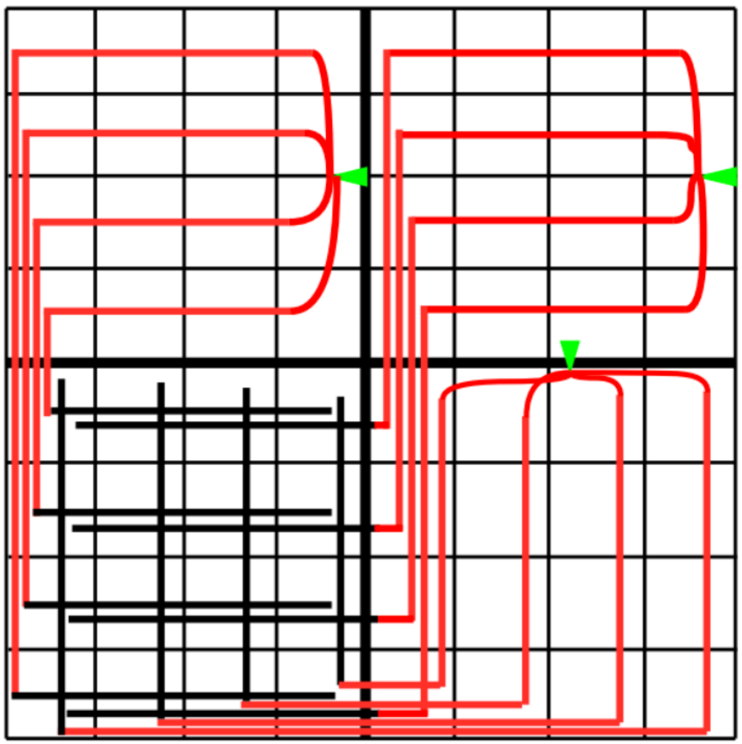

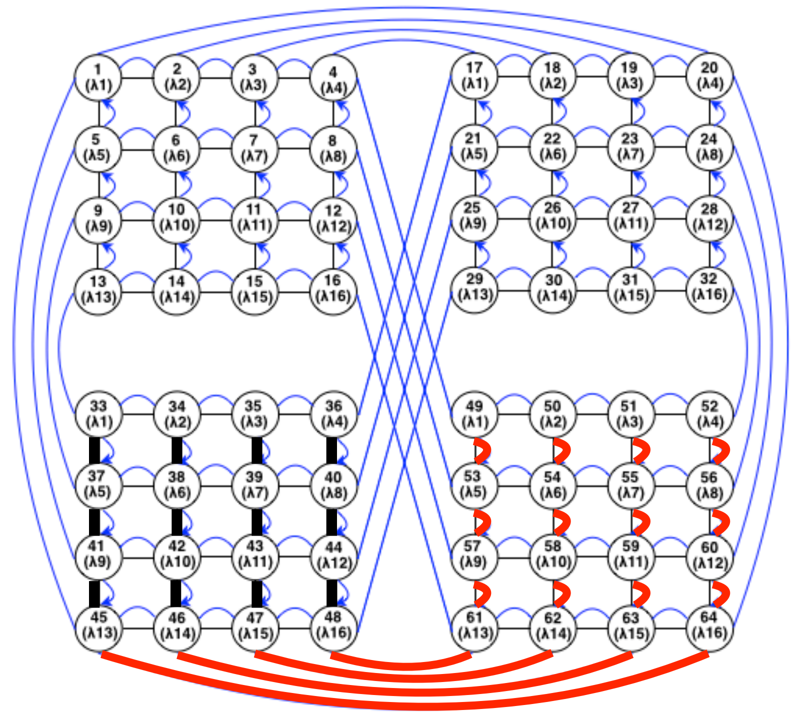
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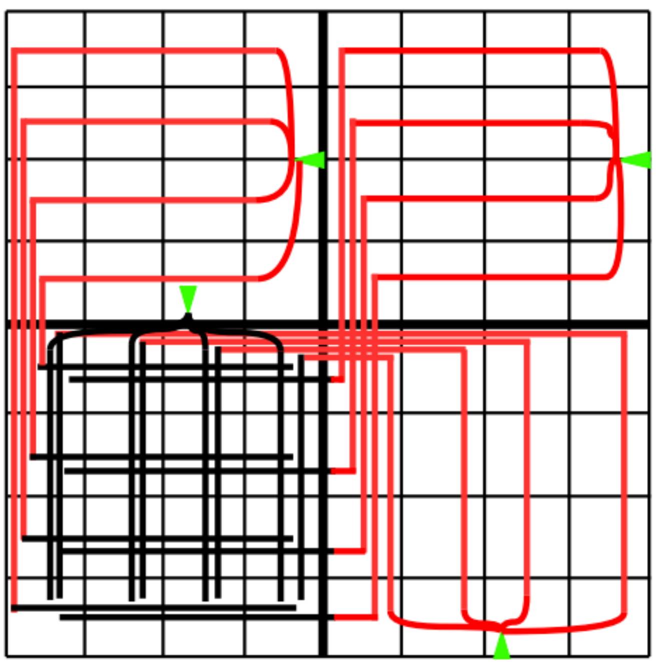
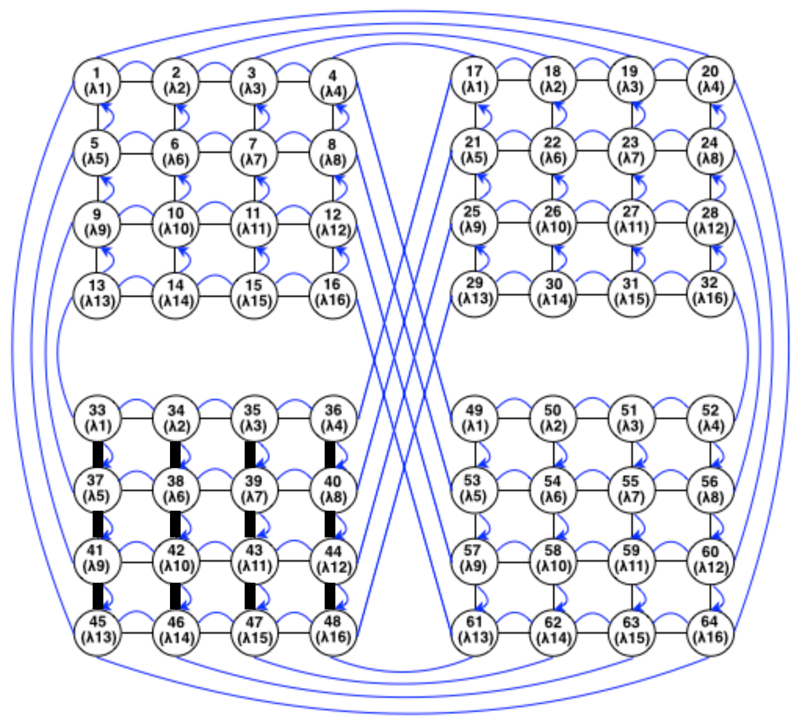
63 (λ15)
64 (λ16)




1 (λ1)
2 (λ2)
3 (λ3)
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MANCHESTER 1824

The University of Manchester

Amon: Evaluation & Comparison

Microring area (m^2)

#Nodes	Spidergon	QuT	Amon	CN
64	4.4e-06	3.7e-06	2.7e-06	7.0e-07
144	1.44e-05	1.2e-05	9.2e-06	2.3e-06
256	3.48e-05	2.9e-05	2.3e-05	5.0e-06

Waveguide area (m^2)

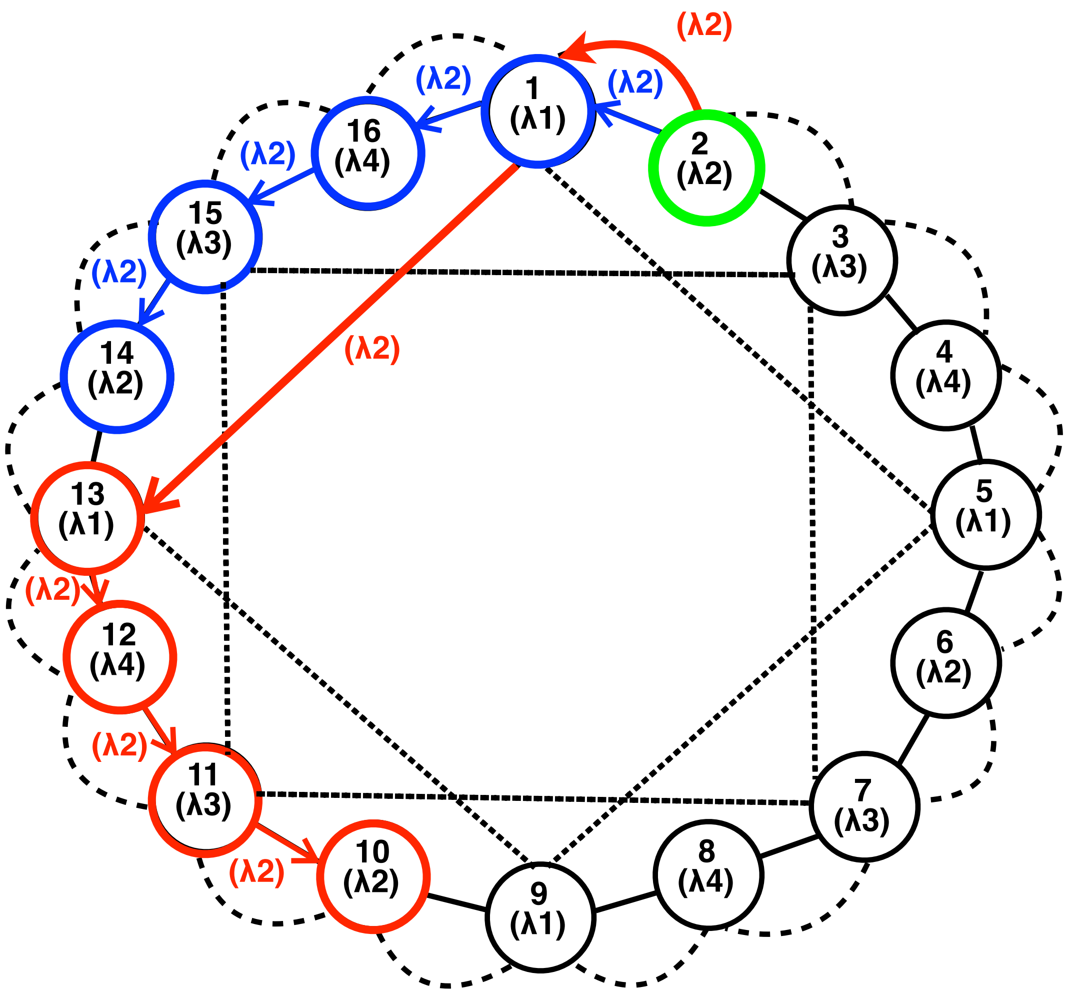
#Nodes	Spidergon	QuT	Amon	CN
64	1.68e-06	1.4e-06	1.5e-06	3.1e-06
144	3.84e-06	3.2e-06	3.6e-06	9.1e-06
256	6.7e-06	5.5e-06	6.6e-06	4.3e-05

Total area normalized to Amon

#Nodes	Amon	QuT	Spidergon	CN
64	1	1.21	1.44	0.88
144	1	1.19	1.42	0.94
256	1	1.16	1.40	1.61

For comparison:
eNoC 64-node Mesh: Area: 1.77e-06 (~ 40% of Amon)

QuT



4 injection channels for destinations in
< N/4 (left/right)
> N/4 (left/right)
hop distance

N/4 wavelengths in network
-> less switching rings
-> Same #modulators at each node

But:
Ring topology causes long paths leading to high IL