A Backup Resource Customization and Allocation Method for Wavelength-Routed Optical Networks-on-Chip Topologies

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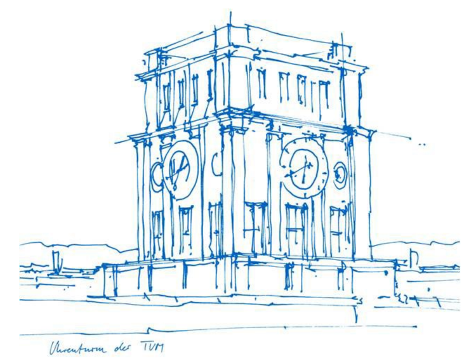


Outline

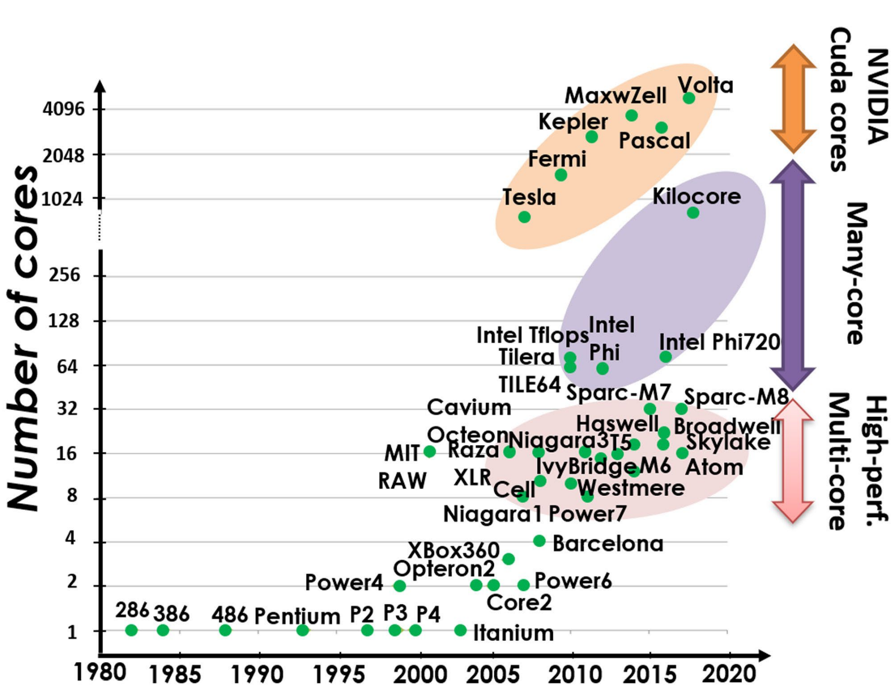
- Motivation
- Related Works
- Our Method
- Experimental Results
- Conclusion

Outline

- **Motivation**
  - ***Introduction to wavelength-routed optical networks-on-chip (WRONoCs)***
  - ***Reliability concerns in WRONoCs***
- Related Works
- Our Method
- Experimental Results
- Conclusion

Motivation

Evolution from single- to many-core computing system



- Challenges of on-chip communi-cation
  - High communication throughput
  - Low communication latency
  - High power efficiency

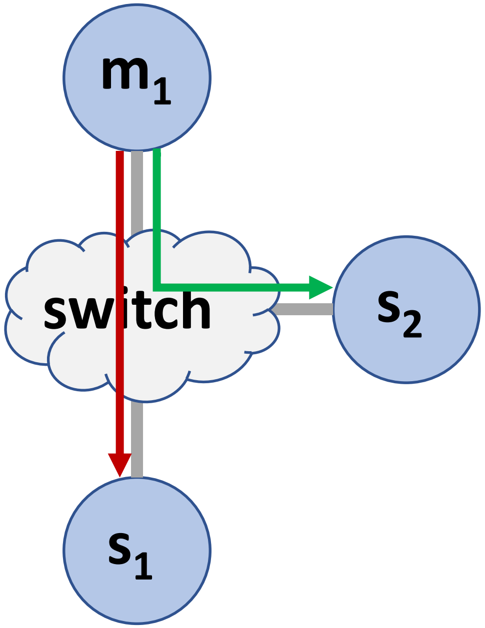
- Demand for developing **advanced interconnect technologies**

Figure source: T. Alexoudi et al., “Optics in Computing: from Photonic Network-on-Chip to Chip-to-Chip Interconnects and Disintegrated Architectures,” In IEEE JLT 2018.

Introduction to WRONoCs

WRONoC emerges as a promising option for advanced interconnect technologies for **critical advantages**:

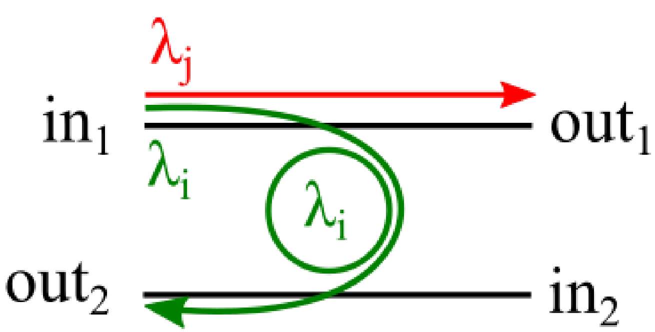
- High bandwidth communication
  - Multiple optical signals can simultaneously travel along a single waveguide without affecting each other.
- Ultra-low propagation latency
  - The propagation speed of optical signals in a waveguide is fast, such as $\mathbf{10.45 ps/mm}$[1].
- Power-efficient devices
  - The switches, i.e, microring resonator (MRRs), have low power consumption, around $\mathbf{0.06 \mu w/ring}$[2].
- **No extra arbitration overhead**



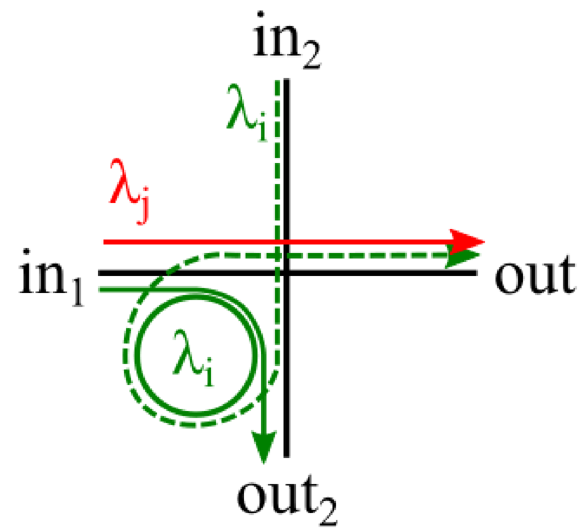
[1] S. Van Winkle et al., "Extending the Power-Efficiency and Performance of Photonic Interconnects for Heterogeneous Multicores with Machine Learning," 2018 IEEE HPCA.
[2] M. Ortín-Obón et al., "Contrasting Laser Power Requirements of Wavelength-Routed Optical NoC Topologies Subject to the Floorplanning, Placement, and Routing Constraints of a 3-D-Stacked System," in 2017 IEEE TVLSI.

Key Components of WRONoCs

Optical switches can change the propagation directions of **on-resonance** optical signals[1].



Parallel Switching Elements (PSEs)



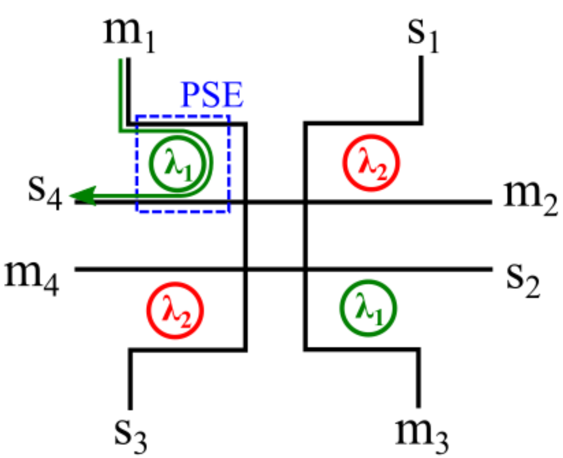
Crossing Switching Elements (CSEs)

- PSEs support 180-degree turns for on-resonance signals
- CSEs support both 90-degree turns and 270-degree turns for on-resonance signals
- Both CSEs and PSEs do not change the directions of the off-resonance signals

[1] T. Tseng, et al. ”Wavelength-routed optical NoCs: Design and EDA - state of the art and future directions: Invited paper”, in ICCAD, 2019.

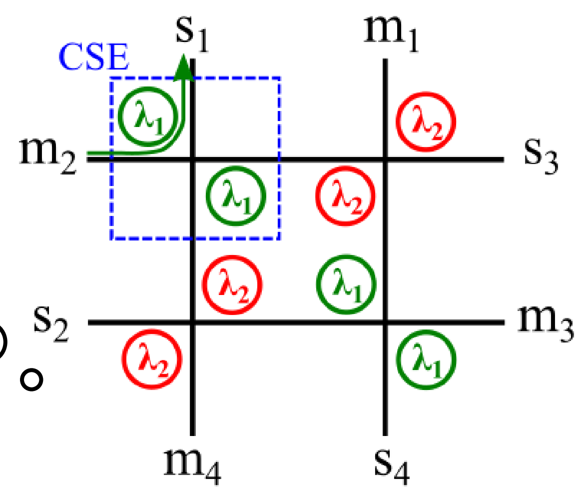
Typical WRONoC Topologies

A topology specifies the logic connections among N masters and N slaves.



A 4-master x 4-slave Light topology formed by PSEs[1]

Each master-slave pair has **one signal path**.



A 4-master x 4-slave GWOR topology formed by CSEs.[2]

[1] Z. Zheng, et al. "Light: A Scalable and Efficient Wavelength-Routed Optical Networks-On-Chip Topology", in ASPDAC, 2021.
[2] X. Tan, et al. "On a Scalable, Non-Blocking Optical Router for Photonic Networks-on-Chip Designs", in SOPO, 2011

Reliability Concerns of WRONoCs

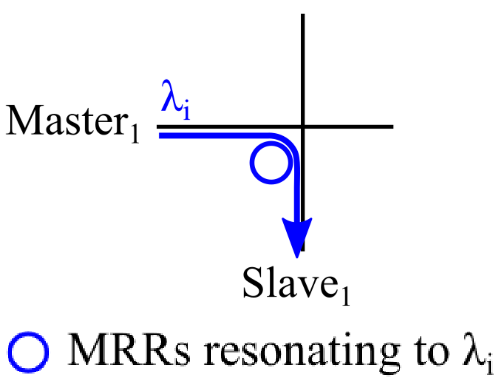
MRRs are sensitive to **thermal and process variation**

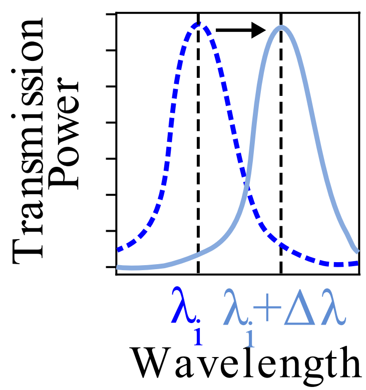
→ a shift in transmission spectrum → signal deviation

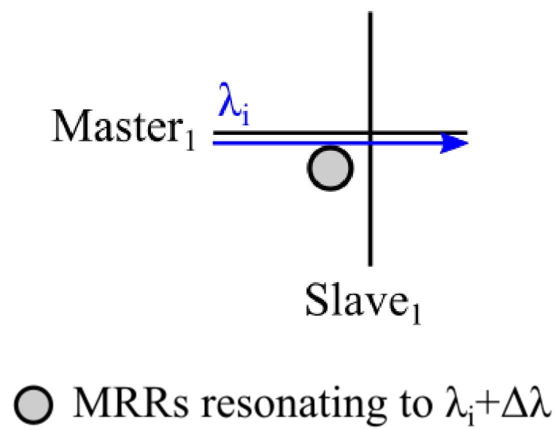
→ **communication failure**

↑

if one signal path/master-slave pair







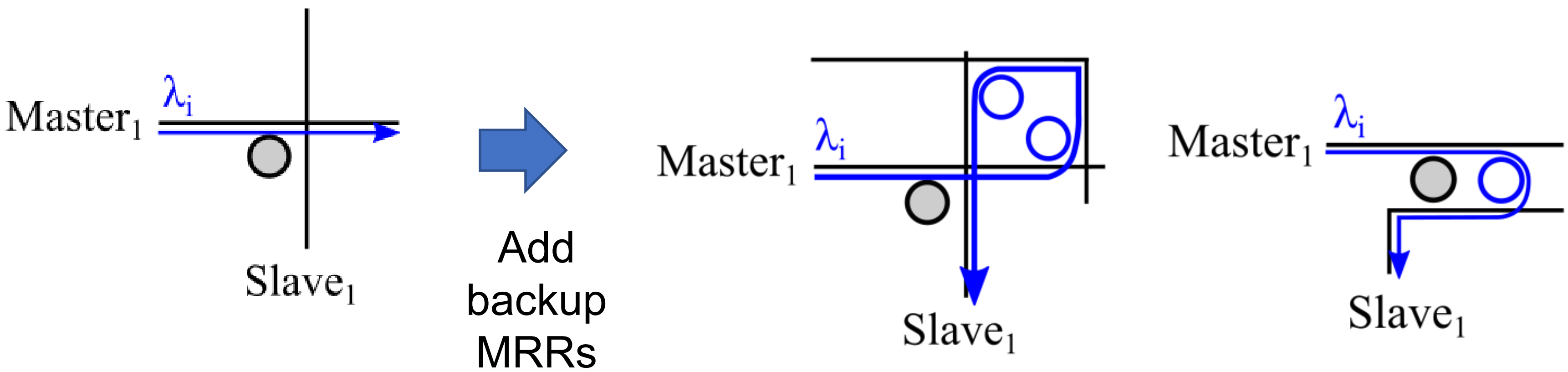
Require to **enhance the reliability** of WRONoCs

Outline

- Motivation
- **Related Works**
  - ***The common idea of fault-tolerant designs***
  - ***Current fault-tolerant designs***
- Our Method
- Experimental Results
- Conclusion

The Common Idea of Fault-tolerant Designs

Backup paths are constructed to ensure the connectivity between masters and slaves when MRRs are malfunctioning.



○ MRRs resonating to λ_i

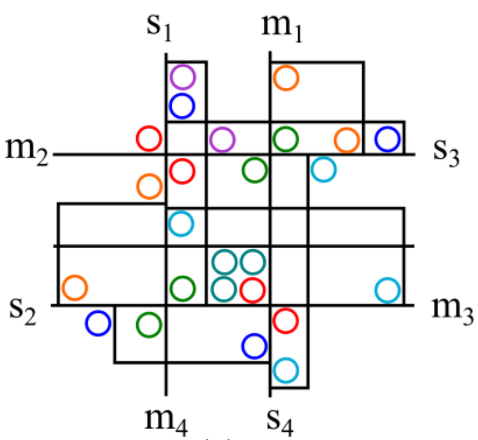
● MRRs resonating to $\lambda_i+\Delta\lambda$

A backup signal path **using CSEs**.

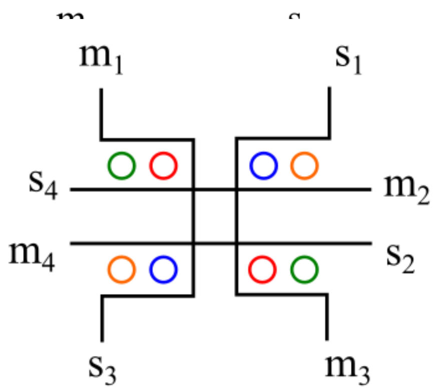
A backup signal path **using PSEs**.

No waveguide crossings!

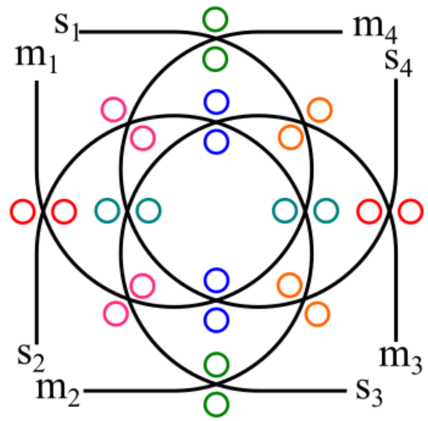
Current Fault-tolerant Designs



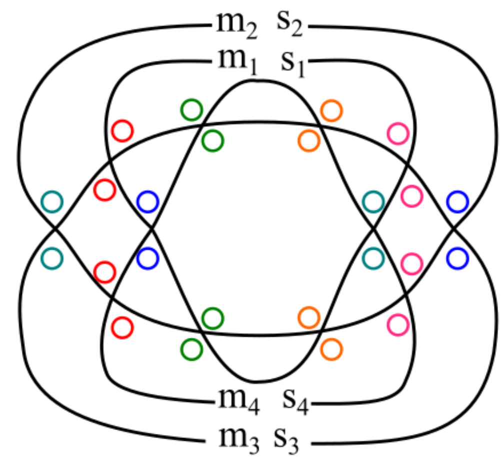
GWOR topology
RobustONoC[1]



Light topology
LightR[2]



Actin-STAR[3]



Zygo-STAR[3]

In current fault-tolerant topologies, every master-slave communication has **one backup signal path**.

[1] Y. Chuang, et al. ” RobustONoC: Fault-Tolerant Optical Networks-on-Chip with Path Backup and Signal Reflection”, in ISQED, 2021.
[2] Z. Zheng, et al. “LightR: A Fault-Tolerant Wavelength-Routed Optical Networks-on-Chip Topology“, in App. Sci., 2023
[3] Y. Chen, et al. “A General Wavelength-Routed Optical Networks-on-Chip Model with Applications to Provably Good Customized and Fault-Tolerant Topology Designs“, in ICCAD, 2023.

Current Fault-tolerant Designs

The limitations of current fault-tolerant designs:

- **Lack of accurate fault modeling**
  - Current fault models assume only one fault will appear, regardless of the network scale.
  - It is commonly assumed that the MRRs for backup paths cannot cause faults.

➡ Potential faults are ignored.

- **Inefficient usage of backup resources**
  - Insufficient backup paths for the communication that can easily fail.
  - More than sufficient backup paths for the communication that can hardly fail.

➡ Redundant backup resources cause power waste.

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- Motivation
- Related Works
- **Our Method**
  - ***The General Flow***
  - ***A Fault Model***
  - ***A Backup Resource Customization and Allocation Method***
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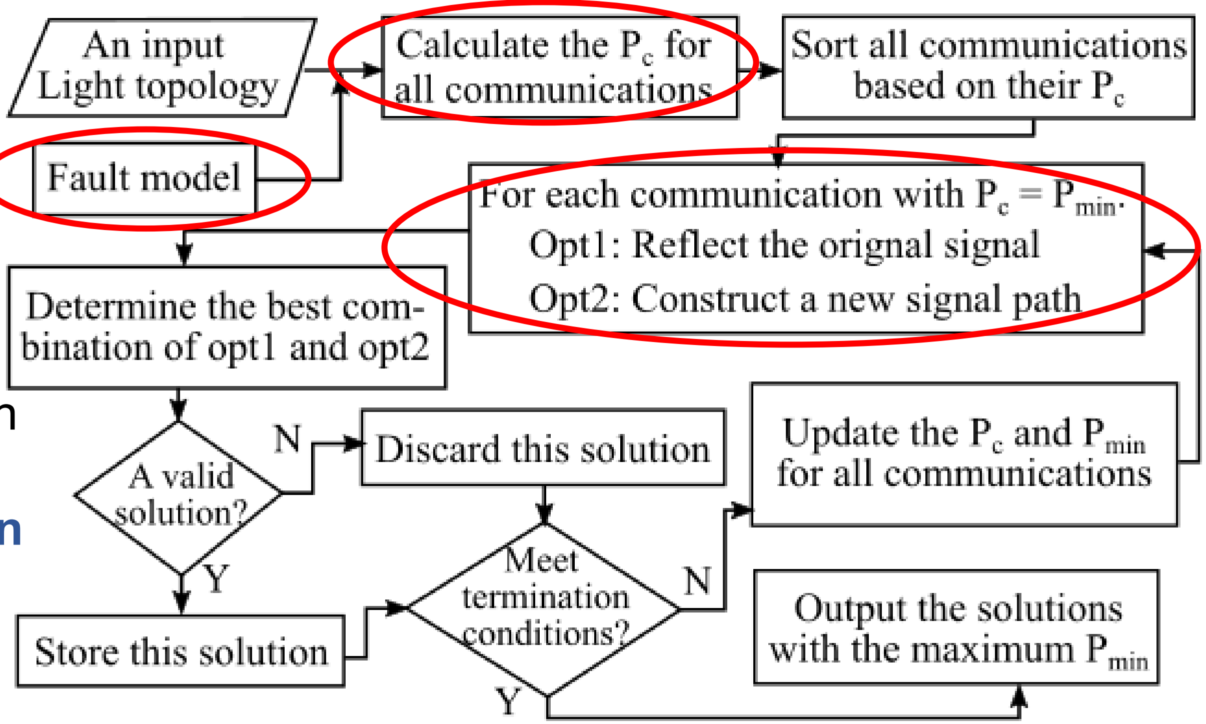
The Overview of Our Method

Determine the probability of **a failed master-slave communication**

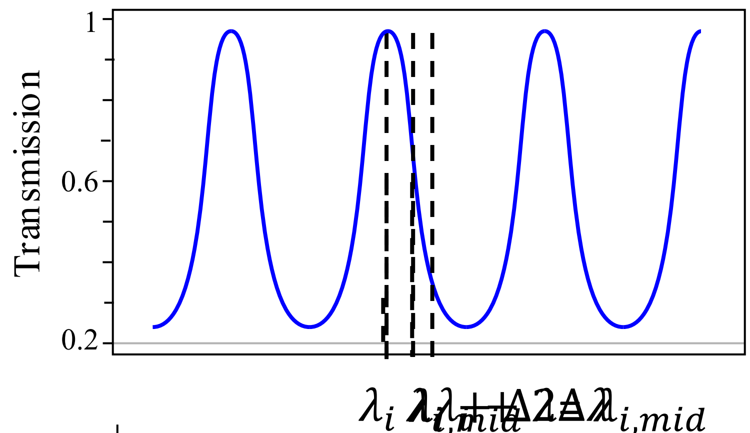


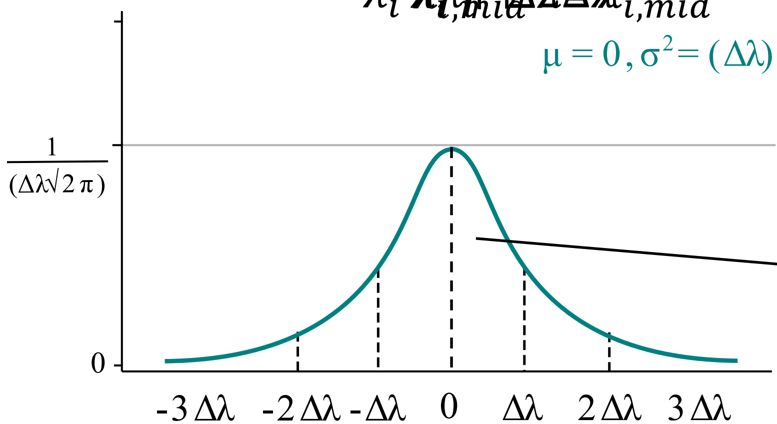
Model the **shifting** of an MRR's **transmission spectrum**

Construct a **backup paths** for the master-slave communicati on that **is most likely** to fail.

Our Fault Model

The possibility of an MRR transmission spectrum's shift is modeled as a **Gaussian Distribution**:



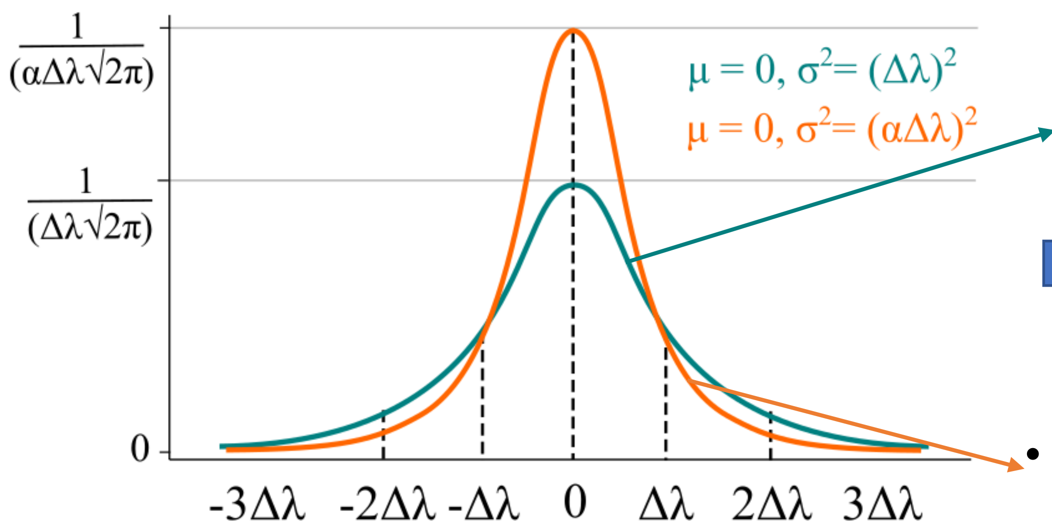


Gaussian Distribution $S \sim N(0, (\Delta\lambda)^2)$

- The possibility of an MRR's transmission spectrum shifting from its planned position.
- We set $\sigma = \Delta\lambda$, the minimum positive difference between λ_i and $\lambda_{i,mid}$ (The wavelengths at the midpoints of the spectrum).
- The probability of the shift being within $[\lambda_i , \lambda_{i,mid}]$ is around 68.2%.

Our Fault Model

The model of an MRR's spectrum shifting:



- The probability distribution of the event: an MRR's spectrum shifts from a target **on-resonance** wavelength.

➡ The on-resonance fault

- The probability distribution of the event: an MRR's spectrum **shifts from a target off-resonance** wavelength.

➡ The off-resonance fault

Our Fault Model

The probability of a signal transmitted to its planned destination:

$$P_s = \underbrace{(1 - P_{on})^{N_{on}^{S}}} \times \underbrace{(1 - P_{off})^{N_{off}^{S}}}$$

The probability of **no MRRs** along this signal path **causing on-resonance faults**

The probability of **no MRRs** along this signal path **causing off-resonance faults**

The probability of a master communicates to a slave correctly:

$$P_c = 1 - \underbrace{\prod_{s \in S_c} (1 - P_s)}$$

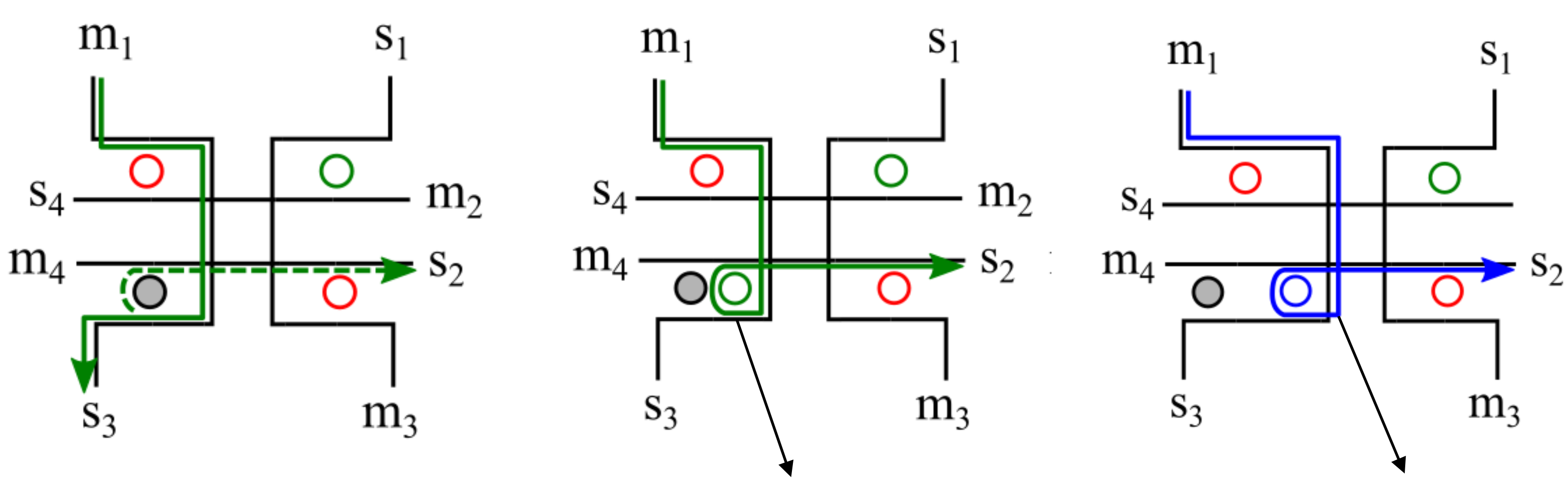
The probability of **at least one signal path for this communication does not have any faults**

The **minimum P_c (P_{min})** among all master-slave communications reflects the reliability of a network.

Backup Resource Customization and Allocation

Two options for constructing backup paths:

- An extra MRR to direct the deviating signal back to its original path
- A new path for the communication



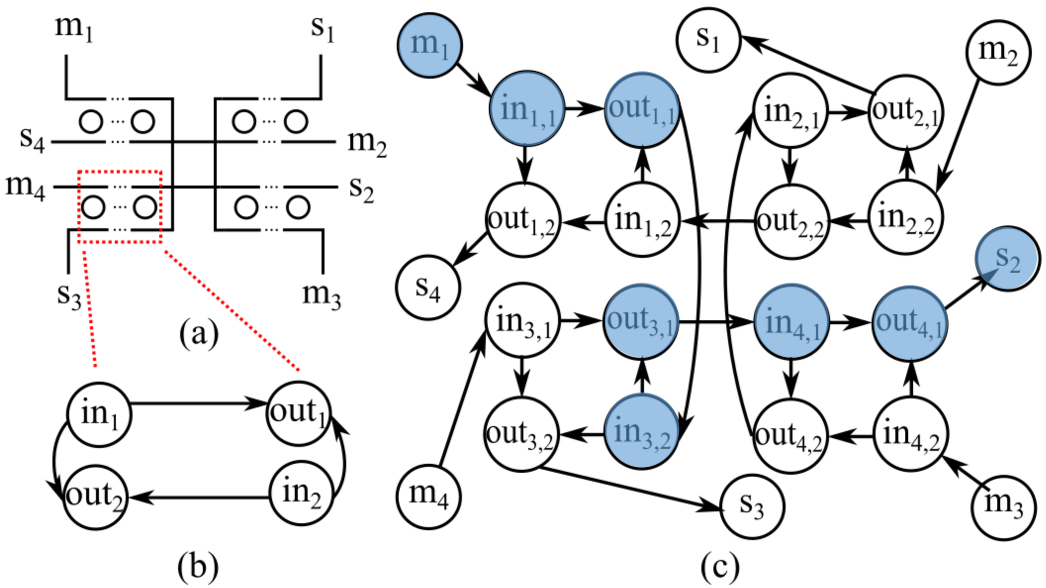
The signal path from m1 to s2 encounters an on-resonance fault.

An MRR to direct the signal back to s2.

An example of a new signal path for m1->s2

Backup Resource Customization and Allocation

The construction of new signal paths:



(a) (b) (c)

- Graph modeling
  - A set of PSEs -> a small graph with 4 nodes and 4 edges.
  - The connections are same as the connections in a Light topology.
- Path Construction
  - **Breadth-first search algorithm** to search for the **lowest-loss path**.
  - **Recursive largest first algorithm** to configure the wavelengths with **the minimum wavelength usage**.

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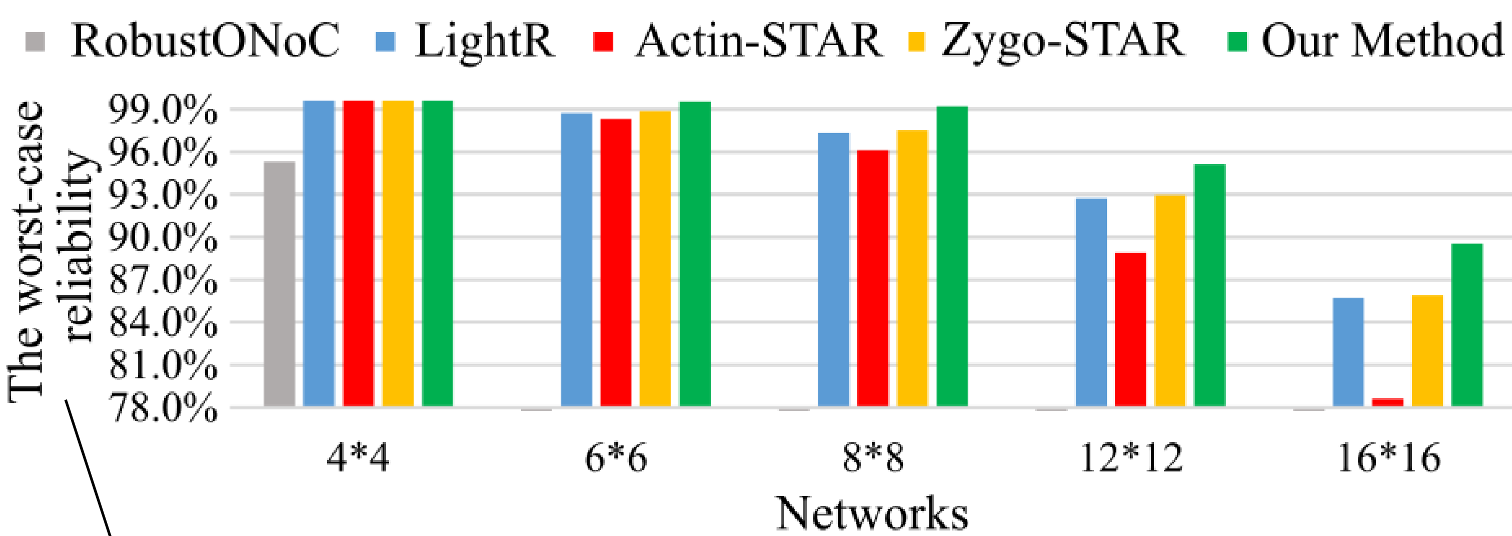
Experimental Results

Comparison to the state-of-the-art fault-tolerant designs in terms of reliability:



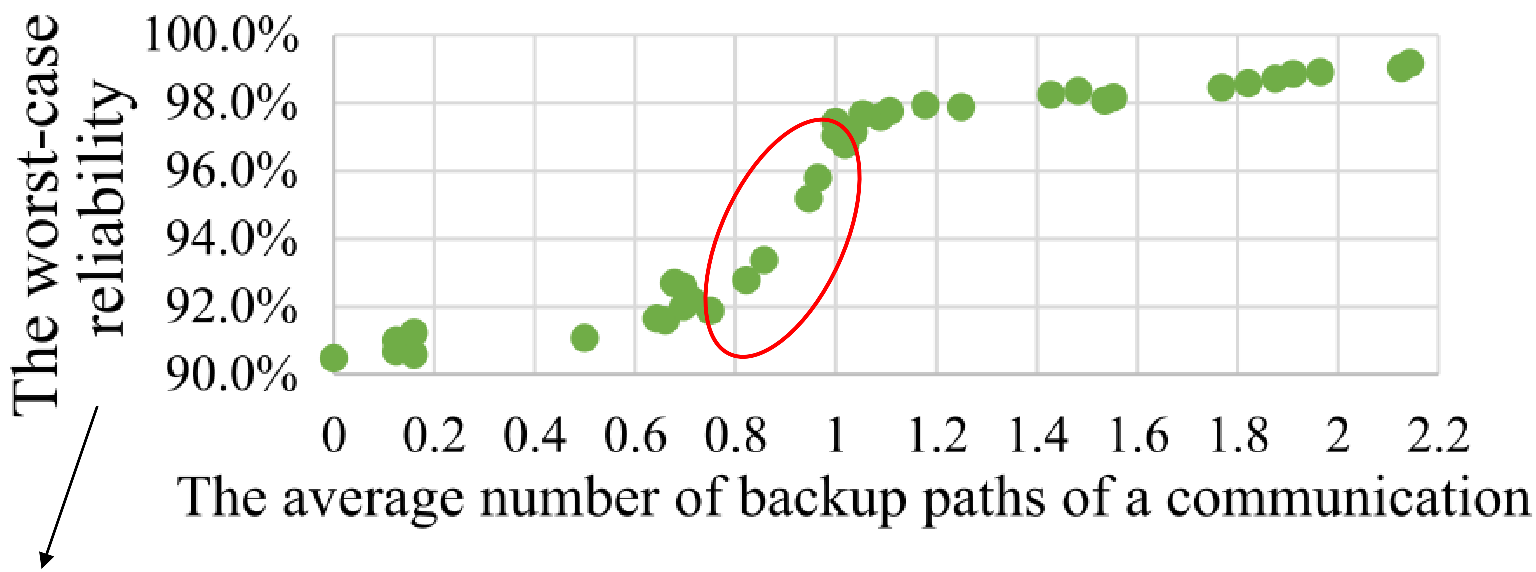
The **minimum P_c (P_{min})** among all master-slave communications

- Our design has the **largest P_{min}** compared to the other fault-tolerant designs in all cases by increasing the number of paths for the communications with low P_c.

Enhanced Reliability

Experimental Results

For an 8x8 network:

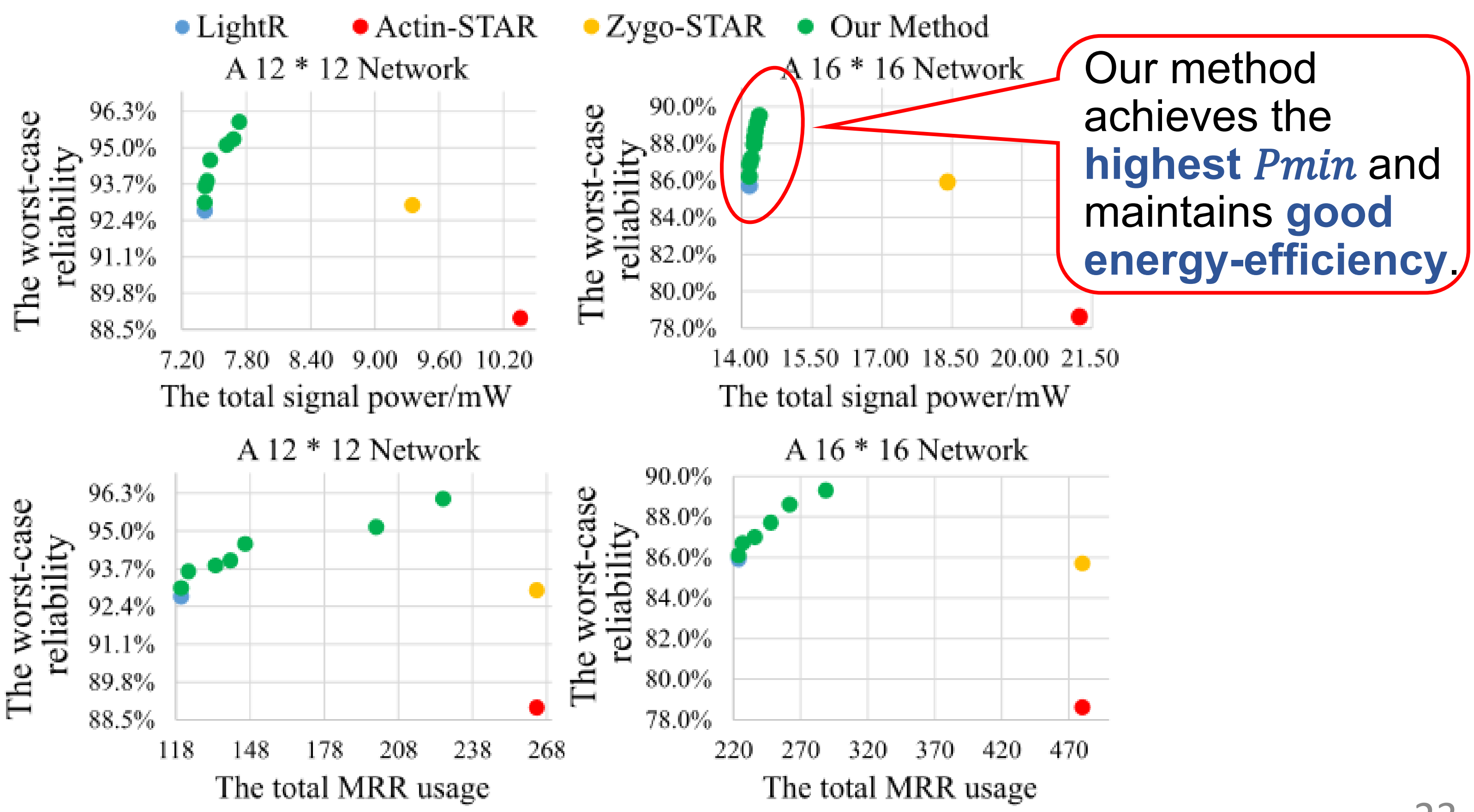


The **minimum P_c (P_{min})** among all master-slave communications

- Constructing more backup paths increases the P_{min}.
- When the average number of backup paths increases from 0.8 to 1, there is a large increase in P_{min}.

Experimental Results

Comparison to the state-of-the-art fault-tolerant designs in terms of energy efficiency and scalability:



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Conclusion

An Advanced Interconnect Technology – WRONoCs

- Ultra-high-speed communication
- Low power consumption

Reliability Concerns

- MRRs are sensible to thermal and process variations.
- Communication can fail due to the malfunctioning MRRs.

Our Method

- A Fault Model -> Modeling the default behaviors of an MRR
- A Backup Path Construction Method -> Customizing and minimizing the backup resources for the communications with various reliability requirements

- **Enhanced Reliability**
- **High Energy Efficiency**

Thank you for your attention :)