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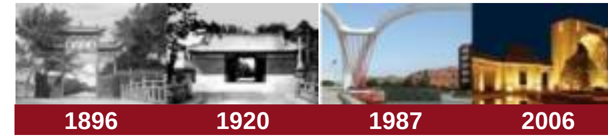


Temperature sensitivity analysis and power consumption optimization of optical networks-on-chip

Yaoyao Ye

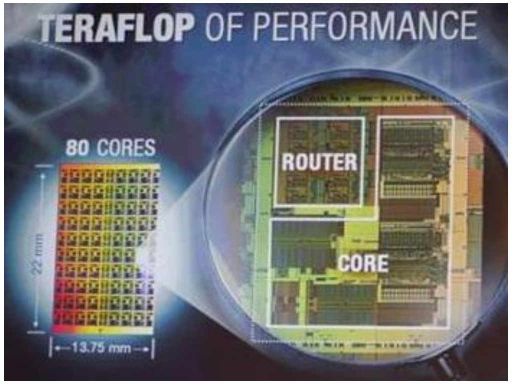
Shanghai Jiao Tong University, China

Outline

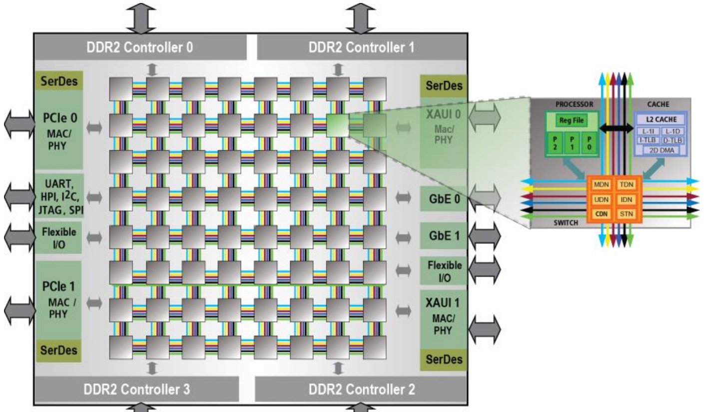
- Multiprocessor systems and optical network-on-chip (NoC)
- OTemp: an optical thermal effect modeling platform
- Case study: a 3D torus-based optical NoC with thermal-sensitive routing
- Conclusions

Energy-efficient multiprocessor system

- Increasing number of processors
  - Intel Polaris chip (80-core)
  - ClearSpeed (96-core)
  - Tilera (100-core)
  - Picochip (300-core)
- Network-on-chip (NoC)
  - High throughput
  - Scalable
  - Reusable
- Limitations of electrical interconnect
  - Parasitic resistance and capacitance
  - Delay, large power dissipation



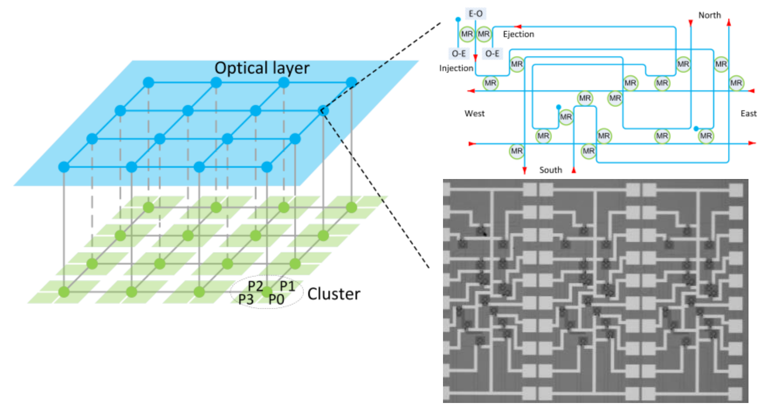
Intel's Polaris chip: 8x10 mesh



TILEPro64 processor: 8x8 mesh

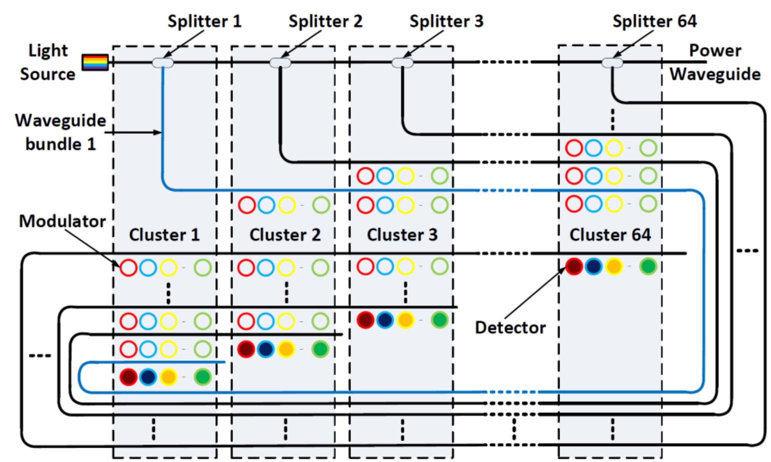
Optical network-on-chip

- Use optical interconnect for on-chip communication
  - High bandwidth density
  - Low power consumption
  - Low latency



A hierarchical hybrid optical-electronic NoC [Mo, ISVLSI'10]

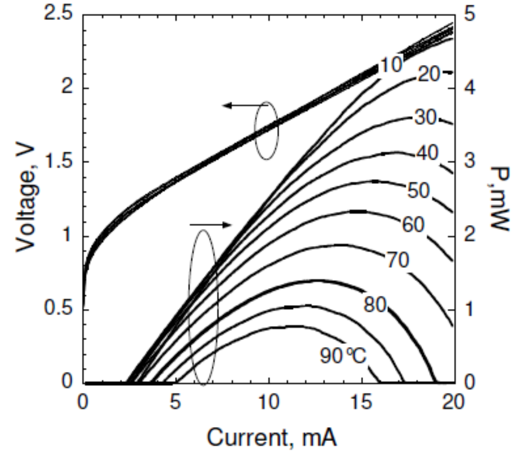
- Challenges
  - Thermo-optic effect
  - On-chip temperature variations
  - Counteract the power advantage of optical interconnect



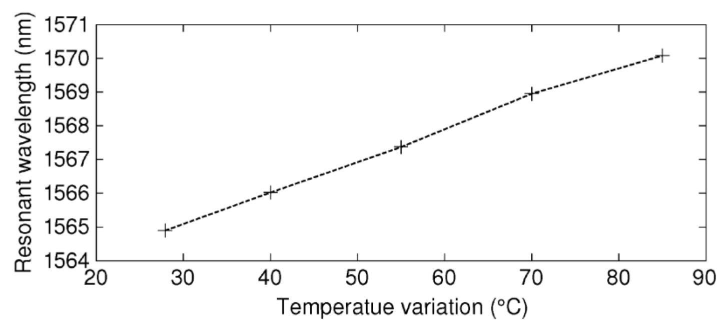
Corona: 2 to 6 speedup and 83% power reduction [Vantrease ISCA'08]

Thermal sensitivity of photonic devices

- Laser
  - VCSEL wavelength shift 0.07-0.1nm/K [Syrbu OFC/NFOEC'08]
  - power efficiency degradation
- Microresonator
  - wavelength shift 0.05-0.1nm/K [Padgaonkar'04]
- Thermal variations result in addition power loss



10Gbps 1550nm VCSEL [Syrbu OFC/NFOEC'08]



Measured thermal dependency of microresonator [Li TVLSI'10]

Related thermal management techniques

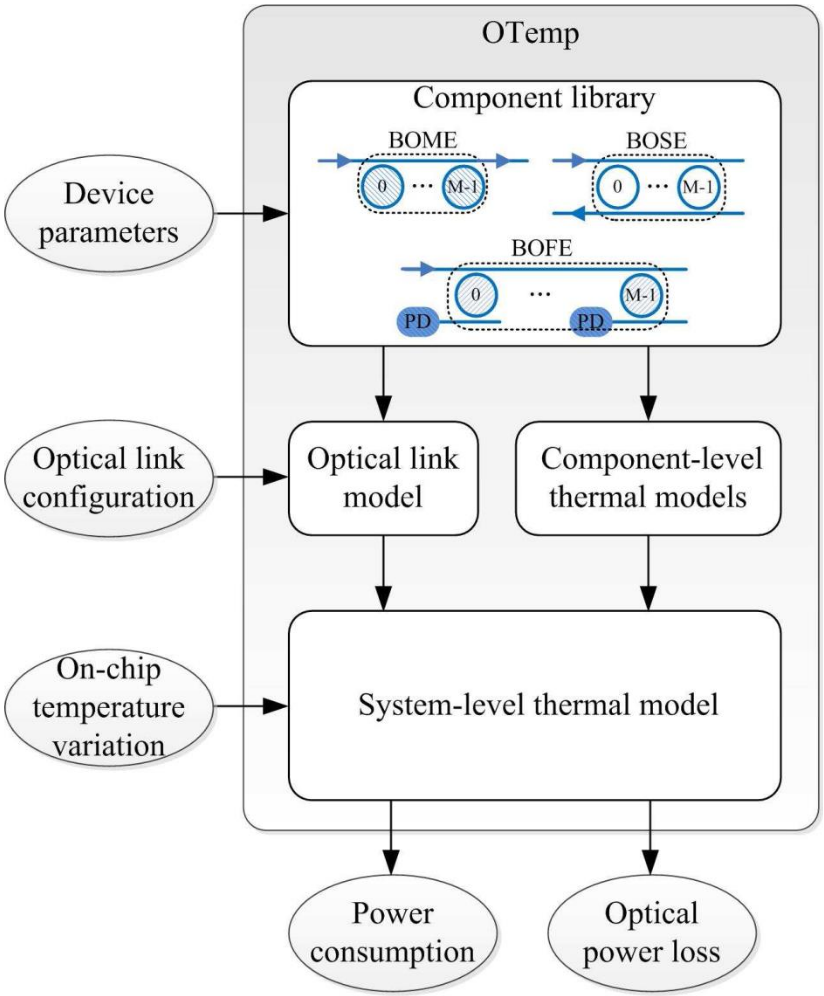
- Localized thermal-based adjustment
  - tuning range: tens of nm
  - power efficiency: 3.5mW/nm [F. Gan, Photon. Switch.'07]
- Electronic-based adjustment
  - tuning range: less than 1nm
  - power efficiency: 100μW/nm [Q. Xu, Optical Express'08]
- Run-time thermal management to avoid overheating
  - OS-based workload migration [Z. Li, TVLSI'10]
  - DVFS (dynamic voltage and frequency scaling)
  - unable to provide precise intra-core temperature control

Motivations

- How to analyze and model thermal effects in optical NoCs under temperature variations?
  - OTemp: an optical thermal effect modeling platform
- How to optimize power consumption of optical NoCs under temperature variations?
  - Low-temperature-dependence techniques
  - Thermal-sensitive routing

OTemp: an optical thermal effect modeling platform

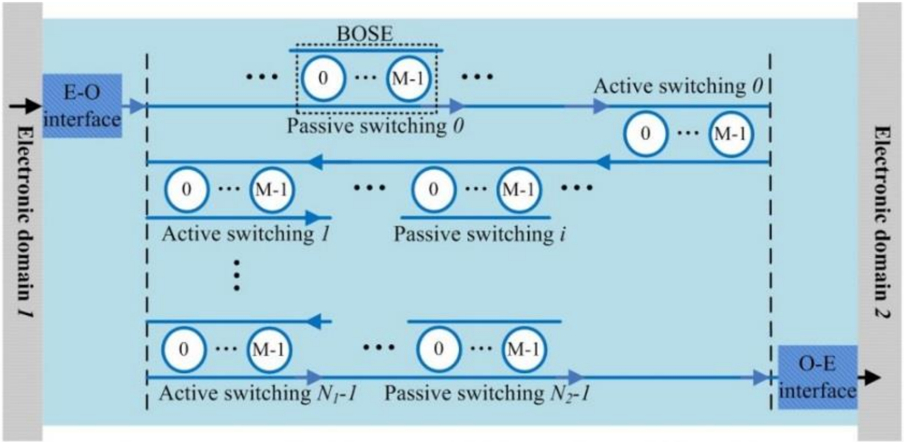
- Inputs
  - on-chip temperature variations
  - optical link configurations
  - device parameters
- Outputs
  - power consumption
  - optical power loss
- For both WDM-based and single-wavelength based optical links



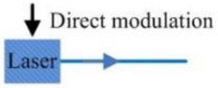
http://www.ece.ust.hk/~eexu/OTemp.html

Optical link model

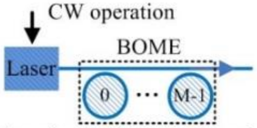
- Laser source
- Basic optical modulation element (BOME)
- Basic optical switching element (BOSE)
- Basic optical filter element （BOFE）
- Photodetector



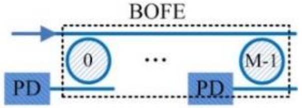
(a) An overview of the M-wavelength WDM-based optical link in ONoCs



(b) E-O interface with direct modulation



(c) E-O interface with separate modulators



(d) O-E interface

An M-wavelength WDM based optical link model

Thermal modeling of VCSEL laser

- Emission wavelength λ_{VCSEL}

$$l_{\mathrm{VCSEL}} \cdot n_{\mathrm{ave}} = m_{\mathrm{VCSEL}} \cdot \lambda_{\mathrm{VCSEL}}/2.$$

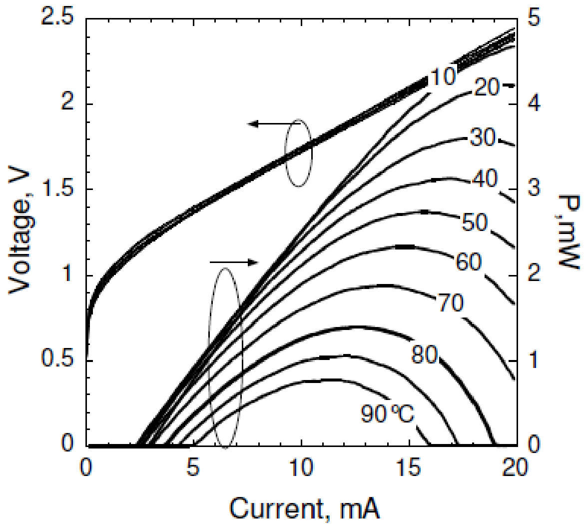
- Temperature-dependent wavelength shift

$$\lambda_{VCSEL} = \lambda_{VCSEL\_min} + \rho_{VCSEL}(T_{VCSEL} - T_{min})$$

- Output power under temperature T_{VCSEL}

$$P_{TX} = (I - \alpha - \beta(T_{VCSEL} - T_{th})^2)(\varepsilon - \gamma \cdot T_{VCSEL})$$

- For on-chip laser source, T_{VCSEL} varies over the on-chip temperature range



10Gbps 1550nm VCSEL
[Syrbu OFC/NFOEC'08]

Thermal modeling of BOSE

- In active switching, the insertion loss a M-wavelength BOSE, L_{BOSE_active} is:

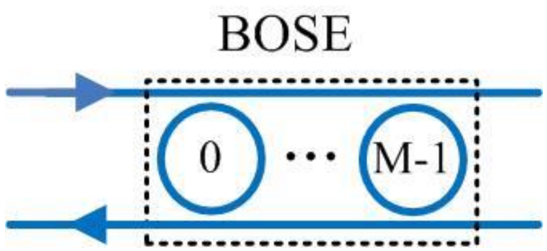
$$f_n = r_n - \frac{t_n^i t_n^o}{r_n - f_{n-1}^{-1} exp(j2\theta_{n-1})}$$

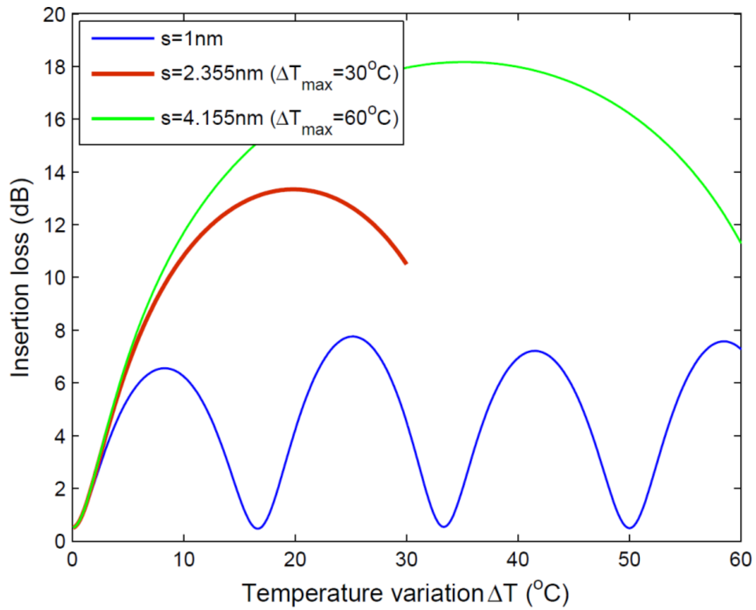
$$\omega_n = \frac{2\pi c}{\lambda_n + \rho_{MR} \cdot \Delta T}$$

$$r_n = \frac{2\kappa^2}{j2\tau(\omega - \omega_n) + (2\kappa^2 + \kappa_p^2)}$$

$$t_n^i = t_n^o = \frac{j2\tau(\omega - \omega_n) + \kappa_p^2}{j2\tau(\omega - \omega_n) + (2\kappa^2 + \kappa_p^2)}$$

$$L_{BOSE\_active} = -10log|f_{M-1}|^2$$





Insertion loss of an active 8-wavelength BOSE, Q=5000, s is the channel spacing

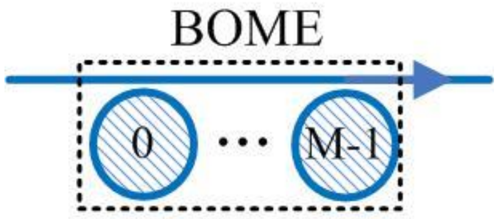
Thermal modeling of BOME

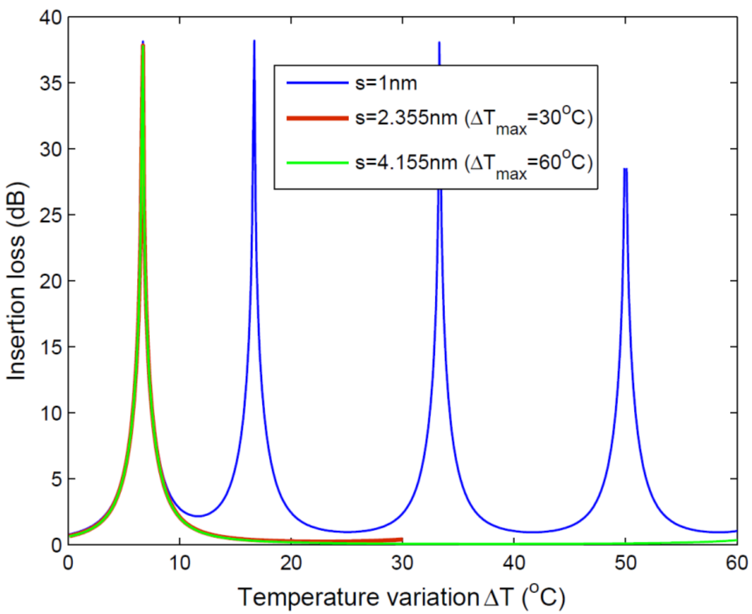
- Modulation is performed by switching the bias voltage
  - on resonance: modulate ‘0’
  - off resonance: modulate ‘1’
- BOME insertion loss to wavelength λ_0

$$L_{BOME\_0} = \sum_{i=0}^{M-1} 10log\frac{(\frac{i\cdot s-b+\rho_{MR}\cdot\Delta T}{\delta})^2+1}{(\frac{i\cdot s-b+\rho_{MR}\cdot\Delta T}{\delta})^2+(\frac{\kappa^2-\kappa_p^2}{\kappa^2+\kappa_p^2})^2}$$

- BOME insertion loss to wavelength λ_x

$$L_{BOME\_x} = \sum_{i=0}^{M-x-1} 10log\frac{(\frac{i\cdot s-b+\rho_{MR}\cdot\Delta T}{\delta})^2+1}{(\frac{i\cdot s-b+\rho_{MR}\cdot\Delta T}{\delta})^2+(\frac{\kappa^2-\kappa_p^2}{\kappa^2+\kappa_p^2})^2} + \sum_{j=1}^{x} 10log\frac{(\frac{j\cdot s-\rho_{MR}\cdot\Delta T}{\delta})^2+1}{(\frac{j\cdot s-\rho_{MR}\cdot\Delta T}{\delta})^2+(\frac{\kappa^2-\kappa_p^2}{\kappa^2+\kappa_p^2})^2}$$





Insertion loss of an 8-wavelength BOME to λ_7, Q=5000

Thermal modeling of BOFE

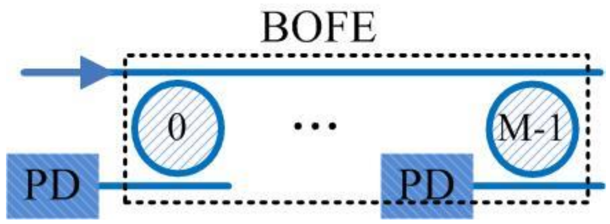
- Under temperature variation ΔT
- BOFE insertion loss to wavelength λ_0

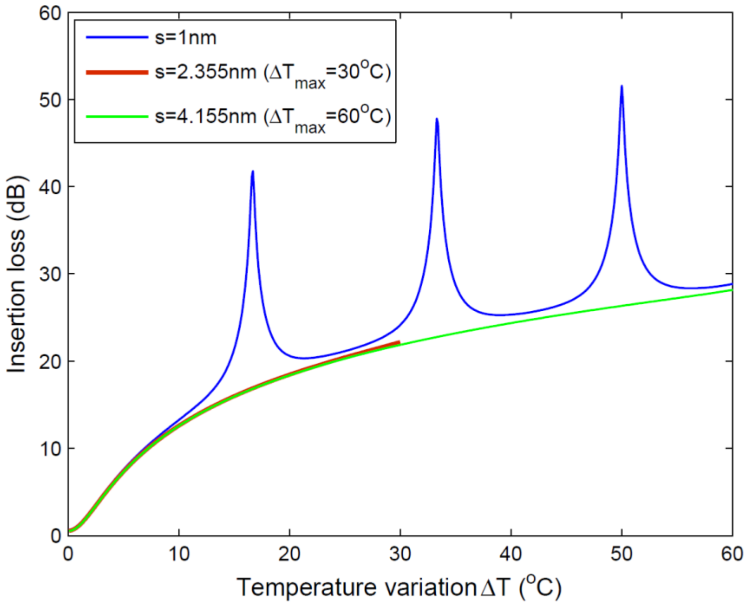
$$L_{BOFE\_0} = 10log((\frac{2\kappa^2+\kappa_p^2}{2\kappa^2})^2 \cdot (\frac{(\rho_{MR}\Delta T)^2+\delta^2}{\delta^2}))$$

- BOFE insertion loss to wavelength λ_x

$$L_{BOFE\_x} = 10log((\frac{2\kappa^2+\kappa_p^2}{2\kappa^2})^2 \cdot (\frac{(\rho_{MR}\Delta T)^2+\delta^2}{\delta^2})) + \sum_{i=0}^{x-1} 10log\frac{((x-i)\cdot s+\rho_{MR}\Delta T)^2+\delta^2}{((x-i)\cdot s+\rho_{MR}\Delta T)^2+\delta^2\cdot(\frac{\kappa_p^2}{2\kappa^2+\kappa_p^2})^2}$$

- A larger channel spacing can reduce the insertion loss, but still as high as 20dB for ΔT=30^{o}C





Insertion loss of an 8-wavelength BOFE to λ_7, Q=5000

Link-level thermal model

- Optical power reaching the receiver must be no less than the receiver sensitivity

$$10log((I - \alpha - \beta(T_{VCSEL} - T_{th})^2)(\varepsilon - \gamma \cdot T_{VCSEL})) - L_{BOME\_x} - \sum_{i=0}^{N_1-1} L_{BOSE\_active\_k} - \sum_{j=0}^{N_2-1} L_{BOSE\_parking\_j} - L_{BOFE\_x} - L_{WG} \geq S_{RX}$$

- More input power is needed by the transmitter to guarantee enough power reaching the receiver
- Thermal-based adjustment for BOSE, BOME, BOFE

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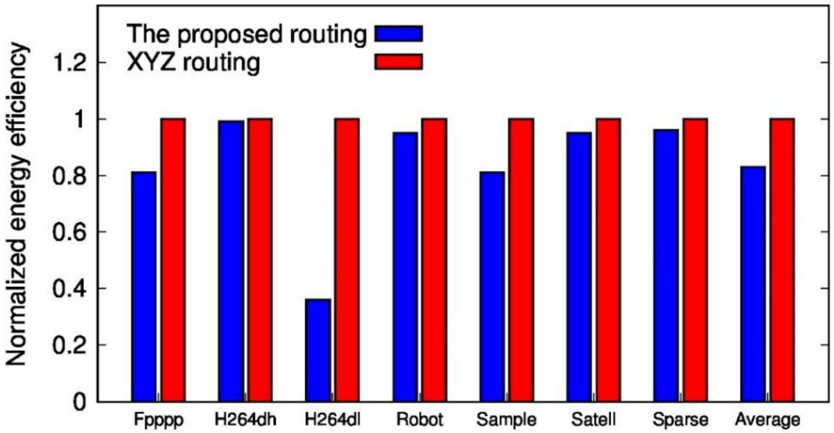
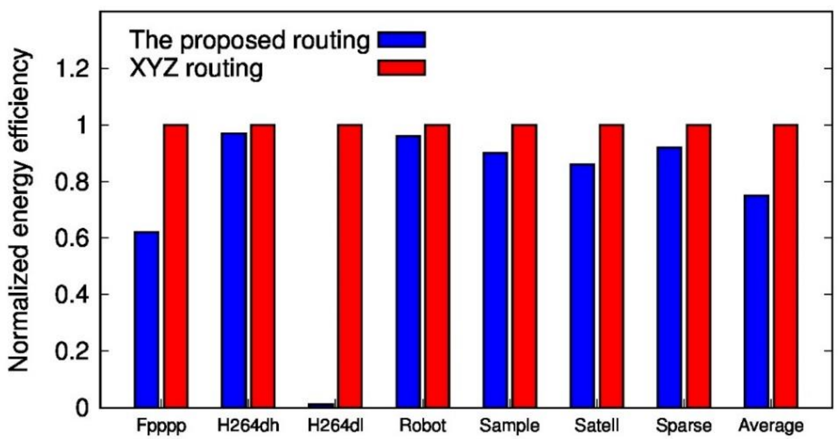
Case study: a 3D torus-based optical NoC with thermal-sensitive routing

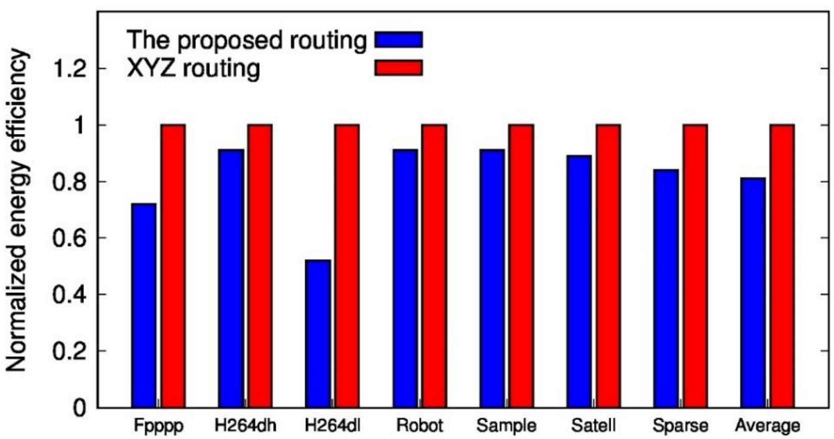
- Compared with XYZ routing, thermal-sensitive routing reduces power consumption by:
- 25% if w/o thermal tuning
- 19% if with thermal tuning
- 17% if with athermal MRs



Normalized energy efficiency with athermal MRs



Normalized energy efficiency without thermal tuning



Normalized energy efficiency with thermal tuning

Conclusions

- Thermal sensitivity of silicon photonics is an intrinsic characteristic as well as a potential issue
- Our approach
  - An analytical thermal model for optical NoCs
  - Important factors regarding thermal-aware power efficiency
  - A thermal-sensitive routing to optimize the power consumption under temperature variations
- Help support the further development of optical NoCs for energy-efficient multiprocessor systems

Thank you!