Optical Network-on-Chip for Many Core Design

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Motivation

- Hundreds of cores integrated on chip
  - Technology scaling
  - 3D integration
  - Many examples
    - STMicro P2012/STHORM
    - picoChip
    - Tilera Tile GX, Tile Pro
    - Scale-out
    - Intel Polaris

- Complex apps, stringent constraints
  - Massively parallel applications
    - Big-data analytics, graphics, augmented reality, communication etc.
    - Performance, power, scalability are key challenges

- Challenges
  - Computation
  - Communication
Many-core Design Trends

- Bus vs. Network-on-Chip (NoC)
- Functional and technological diversification
  - Integrated optics
- Optical Network-on-Chip (ONoC)
  - High data bandwidth
  - Low power interconnect
  - CMOS-compatible
- Multiple layers → multiple technologies (3D integration + heterogeneity):
  - Computation → electrical layer
  - Communication → optical layer
  - Through Silicon Vias (TSV)

Source [1]
ONoC - Top Level View

- **Transmitter**
  - Built using laser sources and drivers or modulators

- **Routing network**
  - Built using waveguides and optical switches

- **Receiver**
  - Built using photo detector and trans impedance amplifier (TIA)
Transmitter

- **Serializer**
  - $\text{clk}_2 = n_b \times \text{clk}_1$
- **Driver**
- **Laser**
  - Output power, central wavelength
  - **On-chip** vs. off-chip

Adapted from [2]
Implementation of Laser Sources

**On-chip laser source:**
- High flexibility and compactness
- Complex integration and high heat generation

**Off-chip laser source:**
- Easier manufacturing
- Higher losses, require feed-in lines, source of errors
  - Pre-compensation methods → poor performance and under-utilization of the bandwidth
- Integrated on-chip modulators required to encode the information onto a signal
Routing Network

- Consists of waveguides and optical switches

- Design alternatives:
  - Topology
  - Serial vs. parallel transmission
  - Unidirectional vs. bidirectional communication
  - Number of required wavelengths
    - Depends on routing network topology, number of transmitter/receiver pairs, use of WDM
  - Placement and routing
    - Crosstalk / thermal crosstalk, power requirements
    - Use of Wavelength Division Multiplexing (WDM)
  - Active vs. passive
Waveguide and WDM

• Waveguide
  • Medium to carry an optical signal
  • Silicon is suitable material for waveguides
    • Refractive index of silicon ($n_{Si}=3.45$) vs. air ($n_{air}=1.0$) or silicon oxide ($n_{SiO_2}=1.45$)
  • Characterized by:
    • Length, placement, number of crossings, bends -> propagation losses and crosstalk
    • Cross section dimension ~500 nm, loss 1dB/cm [ISCAS ‘13]
    • Wavelengths ~ 1.5 μm [2]

• Wavelength Division Multiplexing (WDM)
  • Different wavelength are transmitted simultaneously on the same waveguide
    → Higher throughput
  • Max number of WDM signals per waveguide
Optical Switch

Passive microdisk resonator

- Fixed resonant wavelength $\lambda_n$
  - Selecting and redirecting signal based on its wavelength
  - Signal’s wavelength is fixed

Active microdisk resonator

- Resonant wavelength changes dynamically
  - By applying additional photonic, electrical or thermal energy
  - Signal’s wavelength is fixed
Routing

Passive
- Wavelength routing
  - Wavelength determines the destination address
  - Little or no arbitration required
- Low latency
  - No prior path reservation needed
- Lack of scalability

Active
- Optical path is reserved by electrical signal that precedes the optical signal
- Higher latency
- More scalable
Photodiode
- Threshold power

Trans Impedance Amplifier (TIA)
- Data receive rate

Comparator
- Threshold voltage, speed, latency, power consumption

Deserializer
- \( \text{clk}_2 = n_b \times \text{clk}_1 \)
Optical Ring Network-on-Chip (ORNoC) in 3D Architecture

- Communication hierarchy:
  - Electrical NoC → intra-layer communication
  - ORNoC → inter-layer communication

Connectivity Matrix:

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0 → no communication: 50%!
1 → communication required
Optical Network Interface (ONI)

- Waveguide – optical “wire”
- Operation mode:
  - ejection
  - pass through
  - injection
- Wavelength reuse!
- Maximum # of wavelengths per waveguide – technological constraint
Communications in ORNoC

- ONI\textsubscript{src} → ONI\textsubscript{dest} defined with \textbf{1 wavelength} & \textbf{n waveguide partitions}
  - e.g. A→B: \textit{red wavelength} & \textit{p1}; A→D: \textit{blue wavelength} & \textit{p1, p2, p3}

- Benefits: no arbitration required, scalable, low power consumption
Design Methodology - Problem Definition

- **Inputs**
  - Connectivity matrix
  - Maximum # of wavelengths per waveguide (max_wl)

- **Objective: minimize # of waveguides**
  - Determine # of waveguides
  - Determine mapping: communications → (wavelength & waveguide partitions)

- **Algorithm**
  1. Add waveguide
  2. For each end-to-end communication
  3. Find a set of partitions to perform the communication
  4. Find available wavelength
  5. If (wavelength & waveguide partitions) NOT available go to 1.

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Design Methodology - Example

- **Inputs:**
  - 2 electrical layers, (2x2) ONIs per layer
  - Constraint: max_wl = 6

- **Results:**
  - Using different rotation direction reduces communication length and power
Experimental Results: Number of Waveguides

- **Configuration**
  - 2 electrical layers
    - From 2×2 to 6×6 ONIs per electrical layer
    - \( \text{max}_\text{wl} = \{8, 10, 16, 24\} \)

- **Results [DATE ‘11, VLSI-SOC ‘11]**
  - # waveguides
    - Increases with # of ONIs per layer
    - Decreases with increase of \( \text{max}_\text{wl} \)
  - E.g. for \( \text{max}_\text{wl} = 16 \) and for 36 (6x6) ONIs per each layer, ORNoC requires 66 waveguides
  - Combined with clustering:
    - 9 nodes per cluster, 36 clusters per layer, 4 layers
    - 1298 cores with 102 waveguides and \( \text{max}_\text{wl} = 64 \)
Conclusion and Future Directions

● Conclusion
  ● Wavelength reuse for multiple communications
  ● Same waveguide, at the same time, with no arbitration required!
  ● Automatic wavelength/waveguide assignment to communications
    ● Scalable: 1298 cores with 102 waveguides and max_wl = 64

● Future work
  ● Automated design of ONoC
    ● Power and losses estimation
    ● Error modeling
Acknowledgment

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Thank You
1. “A system-level exploration flow for optical network on chip (ONoC) in 3D MPSoC,” S. Le Beux et al.
2. “Reduction methods for adapting optical networks on chip technologies to specific routing applications,” I. O’Connor et al.
3. “Optical 4x4 hitless silicon router for Optical Networks-on-Chip (NoC),” N. Sherwood-Droz et al.


Waveguide (backup)

- **Waveguide:**
  - topology
  - geometry:
    - distance from others
    - number of crossings
    - bends and their dimension
    - cross section dimension
  - crosstalk
  - max number of WDM signals

\[
L_{\text{TOTAL}} \ (\text{dB}) = L_{\text{CV}} + L_{\text{W}} + L_{\text{Y}} + L_{\text{B}} + L_{\text{CR}}
\]

- \(L_{\text{CV}}\) – Source-waveguide coupling coefficient
- \(L_{\text{W}}\) – Transmission Loss
- \(L_{\text{Y}}\) – Y-coupler Loss
- \(L_{\text{B}}\) – Bending Loss
- \(L_{\text{CR}}\) – Waveguide-detector coupling coefficient

Source: “Optical Solutions for System Level Interconnect,” I. O’Connor
Optical Switch (backup)

- Optical switch:
  - Type, S-matrix (losses & defects), latency
  - Thermal characteristics
    - Heat emitted, reaction to heat

- Wavelength:
  - Material, geometry (radius), width at half power
  - Error in wavelength?
  - Q factor, Tolerance range \( \Delta n \) in order to get routed correctly
  - Free spectral range (FSR)
  - Max wavelength division multiplexing (WDM) window \( \sim \) FSR
Router Examples (backup)

R1: Router for serialized transmission w/ WDM, unidirectional (big losses for bidirectional):

Source: “Reduction methods for adapting optical networks on chip technologies to specific routing applications,” I. O’Connor et al.

R2: Router for likely serialized transmission no WDM, bidirectional:

Source: “Optical 4x4 hitless silicon router for optical Networks-on-Chip (NoC),” N. Sherwood-Droz et al.