BREAKING MULTICAST DEADLOCK BY VIRTUAL CHANNEL ADDRESS/DATA FIFO DECOUPLING

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On-Chip System with On-Chip Network

- Many tiles on a chip
- Communication among Tiles is supported by 2D Mesh Network
Adaptive Routing

- Allows packets being router through less congested channel.
Native Multicast Support

- Avoid redundant unicast packets
  - Decrease Network Load
  - Reduce Packet Latency

(a) XY Unicast

(b) XY Multicast

BufferWrite: 30 V.S. 8
Adaptive Routing + Native Multicast Support

- Allow dynamic multicast packet divergent points
  → Decrease Network Load
Path Based Adaptive Routing

(a) Choice 1
(b) Choice 2
(c) Choice 3
(d) Choice 4
(e) Choice 5
(f) Choice 6

(0,4)
(2,2)
Valid Path

<table>
<thead>
<tr>
<th>Choice</th>
<th>Route</th>
<th>Stop 0</th>
<th>Stop 1</th>
<th>Stop 2</th>
<th>Stop 3</th>
<th>OE Viol</th>
<th>Valid</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>WWNN</td>
<td>(2,2)</td>
<td>(1,2)</td>
<td>(0,2)</td>
<td>(0,3)</td>
<td>Free</td>
<td>Yes</td>
</tr>
<tr>
<td>2</td>
<td>WNWN</td>
<td>(2,2)</td>
<td>(1,2)</td>
<td>(1,3)</td>
<td>(0,3)</td>
<td>Even</td>
<td>No</td>
</tr>
<tr>
<td>3</td>
<td>WNNW</td>
<td>(2,2)</td>
<td>(1,2)</td>
<td>(1,3)</td>
<td>(1,4)</td>
<td>Even</td>
<td>No</td>
</tr>
<tr>
<td>4</td>
<td>NWNN</td>
<td>(2,2)</td>
<td>(2,3)</td>
<td>(1,3)</td>
<td>(0,3)</td>
<td>Odd</td>
<td>Yes</td>
</tr>
<tr>
<td>5</td>
<td>NWWN</td>
<td>(2,2)</td>
<td>(2,3)</td>
<td>(1,3)</td>
<td>(1,4)</td>
<td>Both</td>
<td>No</td>
</tr>
<tr>
<td>6</td>
<td>NNWW</td>
<td>(2,2)</td>
<td>(2,3)</td>
<td>(2,4)</td>
<td>(1,4)</td>
<td>Odd</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Odd-Even Turn Model (Chiu et. al.) to ensure the network is deadlock free. Only route 1,4,6 are valid. Route 2,3,5 violate the odd-even routing rule.
Path Based Adaptive Routing
Path Selection

- Channel Congestion ($CC_{x,y,j}$) is measured by the total Channel Demand ($CD_{x,y,i,j}$) by all router input buffers:
  \[
  CC_{x,y,j} = CD_{x,y,north,j} + CD_{x,y,east,j} + CD_{x,y,west,j} + CD_{x,y,south,j} + CD_{x,y,local,j}
  \]

- Path Congestion ($PC_i$) is the sum of the channel congestion along the path.
  \[
  PC_i = \sum CC_{x,y,j}
  \]

- Pick the valid path $i$ with the lowest $PC_i$
Observation Range

- Intuition: Bigger observation range leads to better network performance.

- Bigger observation range requires
  - More congestion status wires from the remote router
  - Longer cost computation path
    - Potentially affects router clock frequency
  - More adders and comparators
    - Higher Area Cost
Observation Range

Uniform Traffic Test:
• Low-Load Latency
  • Stay the same
• Throughput
  • 5x5 is 29% higher than 3x3
  • 7x7 is 6% higher than 5x5
  • 9x9 is 5.5% higher than 7x7
• RC Path
  • 5x5 is 219ps longer than 3x3
  • 7x7 is 439ps longer than 5x5
  • 9x9 is 453ps longer than 7x7
• We pick 5x5 to avoid RC stage becomes the critical stage

<table>
<thead>
<tr>
<th>Range</th>
<th>Throughput (flits)</th>
<th>Latency (cycles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>vc9</td>
<td>vc14</td>
<td>vc9</td>
</tr>
<tr>
<td>3 x 3</td>
<td>76444</td>
<td>105.43</td>
</tr>
<tr>
<td>5 x 5</td>
<td>97541</td>
<td>133848</td>
</tr>
<tr>
<td>7 x 7</td>
<td>104081</td>
<td>142282</td>
</tr>
<tr>
<td>9 x 9</td>
<td>106842</td>
<td>150109</td>
</tr>
<tr>
<td>XY</td>
<td>955529</td>
<td>118201</td>
</tr>
</tbody>
</table>

Route Computation Path
Virtual Destinations

- Not all destination lies within the observation range
- For those destinations, we assume they lie on the observation range boundary
Objective:

- Reduce the number of buffer write by diverging the packet as late as possible
Rule 1 (XY Destinations):
- If the packet has directions in North, East, West and South, packet will be routed to the corresponding direction.
Multicast Adaptive Routing

Rule 2 (Quadrant Destinations):

- In minimal routing, destinations at the quadrants can be routed horizontally ($D_h$) or vertically ($D_v$). If the packet has destination on either $D_h$ or $D_v$, quadrant destinations will be routed to that direction.

<table>
<thead>
<tr>
<th></th>
<th>Q2</th>
<th>N</th>
<th>Q1</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>O</td>
<td>E</td>
<td></td>
</tr>
<tr>
<td>Q3</td>
<td>S</td>
<td>Q4</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Q2</th>
<th>N</th>
<th>Q1</th>
</tr>
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<tbody>
<tr>
<td>W</td>
<td>O</td>
<td>E</td>
<td></td>
</tr>
<tr>
<td>Q3</td>
<td>S</td>
<td>Q4</td>
<td></td>
</tr>
</tbody>
</table>

Diagram showing the quadrants and routes.
Rule 3 (Quadrant Destinations):
- Group the destinations which can’t be routed by Rule 2 to a single routing direction.
Multicast Adaptive Routing

Rule 4 (Quadrant Destinations):

- Destinations which can’t be routed by Rule 3 are routed using unicast adaptive routing to the virtual destination at the corner of the observation range.

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Q2</td>
<td>W</td>
<td>Q1</td>
</tr>
<tr>
<td>Q3</td>
<td>S</td>
<td>Q4</td>
</tr>
</tbody>
</table>

![Diagram showing quadrants and routing]

```sql
Q2 N Q1
W O E
Q3 S Q4
```
Unicast Deadlock

- Lock because of channel dependence
- XY-Routing is free from Unicast Deadlock
- Previous Solutions:
  1. Ordered nodes and virtual channel (Dally et al.)
  2. West-First, North-Last and Negative-first (Glass et al.)
  3. Odd-Even Routing (Chiu)
Multicast Deadlock

- Lock because of channel dependence
- Even XY-Routing could suffer from Multicast Deadlock
- Example:
  - Tile(1,1) sends multicast packet 55 to Tile (0,1), (3,1)
  - Tile(2,1) sends multicast packet 77 to Tile(0,1), (3,1)
  - Packet 55 does not release (0,1) E until it gets (3,1) W
  - Packet 77 does not release (3,1) W until it gets (0,1) E
Previous Solution 1:
- Send four packets to regions $(X+,Y+),(X+,Y-),(X-,Y+)$ and $(X-,Y-)$ separately. (Lin et al.)
Previous Solution 2:
- Hamiltonian Path

Pre-compute deadlock free path and store it in the packet header.
Routers route the packet following the stored path (Lin et al.)
Multicast Deadlock

Previous Solution 3:
- Planar Network (Chien et al.)
  Use two subnet networks X+ and X-.
  X+ sub-network for packet with increasing X co-ordinate.
  X- sub-network for packet with non-increasing X co-ordinate.
Multicast Deadlock

Simple Solution:
- Use Virtual Cut-through routing instead of wormhole routing.
- Router (0,1) East and (2,1) West can store the whole packet 55
Multicast Deadlock

- (0,1) East channel and (3,1) West channel are empty when the deadlock occurs.
- (1,1) out has no new flit for (0,1) East (Packet 55)
- (2,1) out has no new flit for (3,1) West (Packet 77)
- Deadlock is broken if packet 55 releases (0,1) East Channel and packet 77 releases (3,1) West channel
Address-Data FIFO Decoupling
Example: Each Virtual Channel can store 2 addr flits + 2 data flits
Example: Virtual Channel can store 2 addr flits + 2 data flits

Step 6: (2,1)out does not have F6 → Body to Tail Modification

Step 8: (3,1) West is Free

Step 7 Packet 77 Releases (3,1) West

Step 9: Packet 55 obtains (3,1) West
Packet 77 Received

<table>
<thead>
<tr>
<th>F0(A)</th>
<th>F1(A)</th>
<th>F2(B)</th>
<th>F3(B)</th>
<th>F4(B)</th>
<th>F5(T)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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</tbody>
</table>

A: Address  B: Body  T: Tail
Synthetic Traffic

• Four Types of synthetic traffics:
  – Uniform Traffic
  – Transpose Traffic \((x,y) \rightarrow (N-1-y, N-1-x)\)
  – Transpose2 Traffic \((x,y) \rightarrow (y,x)\)
  – Tornado Traffic

• Multicast Group Size: 10
• Multicast Probability: 5%
Experimental Setup

- Mesh Size: 20x20
- Flit Size: 128-bit
- Simulation Cycle: 30000
- Packet Length: 10 flits
- #Virtual Channel:
  - 3 unicast channels (unicast router)
  - 2 unicast + 1 multicast channel (multicast router)
- Virtual Channel Depth:
  - 14 (Virtual Cut-Through)
  - 9 (Address-Data FIFO decoupling)
Low Congestion Latency (Uniform)

Cycles

Unicast    Multicast

90         95         100         105         110         115

Low Congestion Latency (Transpose)

Cycles

Unicast    Multicast

90         95         100         105         110         115

Low Congestion Latency (Transpose2)

Cycles

Unicast    Multicast

90         95         100         105         110         115

Low Congestion Latency (Tornado)

Cycles

Unicast    Multicast

90         95         100         105         110         115
Energy Consumption (Uniform)

Energy Consumption (Transpose)

Energy Consumption (Transpose2)

Energy Consumption (Tornado)
FPGA Traffic

- CPU controls the application jobs scheduling and placement
- Each tile contains its own configuration bitstream controller
Applications

(a) MPEG4 Encoder

(b) MPEG4 Decoder

(c) MPEG2 Decoder

(d) MPEG2 Encoder
Experimental Setup

- Mesh Size: 20x20
- Flit Size: 128-bit
- Simulation Cycle: 200,000,000
- Virtual Channel Depth: 14
- Max Packet Length:
  - 10 (Virtual Cut-Through)
  - 20 (Address-Data FIFO decoupling)
- #Virtual Channel:
  - 3 unicast channels (unicast router)
  - 2 unicast + 1 multicast channel (multicast router)
• Adaptive routing can reduce the configuration time by at most 10%.
• With address-data decoupling, configuration time can be reduced by at most 25%.
• Multicast support reduces configuration time by at most 40%.
• Adaptive routing can reduce the application runtime by at most 6%.
• With address-data decoupling, application runtime can be reduced by at most 10%.
• Multicast support reduces application runtime by at most 4%.

Average Application Runtime

<table>
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<tr>
<th>Cycles</th>
<th>padap_unicast_20</th>
<th>padap_unicast_10</th>
<th>padap_multicast_20</th>
<th>xy_unicast_20</th>
<th>xy_multicast_20</th>
<th>xy_multicast_10</th>
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</tbody>
</table>
• Adaptive routing can reduce the configuration energy by at most 4%.
• With address-data decoupling, configuration energy can be reduced by at most 5%.
• Multicast support reduces energy consumption by at most 20%.
## Hardware Cost

<table>
<thead>
<tr>
<th>Router type</th>
<th>XY/Adaptive</th>
<th>Unicast/Multicast</th>
<th>VC Depth</th>
<th>Area(M$\lambda^2$)</th>
<th>RC(ps)</th>
<th>SA(ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wormhole</td>
<td>XY</td>
<td>Unicast</td>
<td>9</td>
<td>208</td>
<td>375</td>
<td>1151</td>
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<tr>
<td>Decouple</td>
<td>XY</td>
<td>Multicast</td>
<td>9</td>
<td>308</td>
<td>528</td>
<td>1552</td>
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<tr>
<td>VCT</td>
<td>XY</td>
<td>Multicast</td>
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<td>396</td>
<td>515</td>
<td>1161</td>
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<tr>
<td>Wormhole</td>
<td>Adaptive</td>
<td>Unicast</td>
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<td>216</td>
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<td>1125</td>
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<tr>
<td>Decouple</td>
<td>Adaptive</td>
<td>Multicast</td>
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<td>1616</td>
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<tr>
<td>VCT</td>
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<td>Multicast</td>
<td>14</td>
<td>417</td>
<td>1197</td>
<td>1134</td>
</tr>
</tbody>
</table>

- With address-data decoupling, router can support packet with length 20 using 23% lesser area
- Address-data decoupling increases critical path by 35%
- Multicast support increases area by 50% in 2U+1M
This is the end of the presentation.
Thank You.