On-Chip Networks I: Topology/Flow Control

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History: From interconnection networks to on-chip networks

Box-to-box networks
Board-to-board networks
Chip-to-chip networks
On-chip networks

Focus on on-chip networks connecting caches in shared-memory processors

Multi-Chip: Supercomputers, Data Centers, Internet Routers, Servers
On-Chip: Servers, Laptops, Phones, HDTVs, Access routers
What’s an on-chip network?

E.g. Cache-coherent chip multiprocessor

Load reg1, addressA

Network transports cache coherence messages and cache lines between processor cores

Sharer that holds a copy of address A in its $
Designing an on-chip network

- Topology
- Flow control
- Router microarchitecture
- Routing
Interconnection Network Architecture

- **Topology**: How to connect the nodes up? (processors, memories, router line cards, ...)

- **Routing**: Which path should a message take?

- **Flow control**: How is the message actually forwarded from source to destination?

- **Router microarchitecture**: How to build the routers?

- **Link microarchitecture**: How to build the links?
Topology
Topological Properties

- Diameter

- Average Distance

- Bisection Bandwidth
Topological Properties

- *Routing Distance* - number of links on route
- *Diameter* - maximum routing distance
- *Average Distance*

- A network is *partitioned* by a set of links if their removal disconnects the graph
- *Bisection Bandwidth* is the bandwidth crossing a minimal cut that divides the network in half
Linear Arrays and Rings

Route A -> B given by relative address $R = B - A$

- Linear Array
- Torus
- Torus arranged to use short wires

Diameter?
Average distance?
Bisection bandwidth?

• Torus Examples:
  - FDDI, SCI, FiberChannel Arbitrated Loop, Intel Xeon
Multidimensional Meshes and Tori

- **$d$-dimensional array**
  - $n = k_{d-1} \times \ldots \times k_0$ nodes
  - described by $d$-vector of coordinates $(i_{d-1}, \ldots, i_0)$

- **$d$-dimensional $k$-ary mesh**: $N = k^d$
  - $k = d^{\sqrt{N}}$
  - described by $d$-vector of radix $k$ coordinate

- **$d$-dimensional $k$-ary torus** (or $k$-ary $d$-cube)
Routing & Flow Control Overview
**Packet**: Basic unit of routing and sequencing
- Limited size (e.g. 64 bits – 64 KB)

**Flit** (flow control digit): Basic unit of bandwidth/storage allocation
- All flits in packet follow the same path

**Phit** (physical transfer digit): data transferred in single clock
Routing vs Flow Control

- Routing algorithm chooses path that packets should follow to get from source to destination

- Flow control schemes allocate resources (buffers, links, control state) to packets traversing the network

- Our approach: Bottom-up
  - Today: Flow control, assuming routes are set
  - Next lecture: Routing algorithms
Properties of Routing Algorithms

- **Deterministic/Oblivious**
  - Route determined by (source, dest), not intermediate state (i.e. traffic)

- **Adaptive**
  - Route influenced by traffic along the way

- **Minimal**
  - Only selects shortest paths

- **Deadlock-free**
  - No traffic pattern can lead to a situation where no packets move forward

*(more in next lecture)*
Flow Control
Contention

- Two packets trying to use the same link at the same time
  - Limited or no buffering
- Problem arises because we are sharing resources
  - Sharing bandwidth and buffers
Flow Control Protocols

• Bufferless
  – Circuit switching
  – Dropping
  – Misrouting

• Buffered
  – Store-and-forward
  – Virtual cut-through
  – Wormhole
  – Virtual-channel
Circuit Switching

- Form a circuit from source to destination
- Probe to set up path through network
- Reserve all links
- Data sent through links
- Bufferless
Time-space View: Circuit Switching

- Why is this good?
- Why is it not?
Speculative Flow Control: Dropping

- If two things arrive and I don’t have resources, drop one of them
- Flow control protocol on the Internet
Time-space Diagram: Dropping

Unable to allocate channel 3

Disadvantages?
Less Simple Flow Control: Misrouting

• If only one message can enter the network at each node, and one message can exit the network at each node, the network can never be congested. Right?
  Wrong! Multiple hops cause congestion

• Philosophy behind misrouting: intentionally route away from congestion
• No need for buffering
• Problems?
Buffered Routing

• Link-level flow control:
  – Given that you can’t drop packets, how to manage the buffers? When can you send stuff forward, when not?

• Metrics of interest:
  – Throughput/Latency
  – Buffer utilization (turnaround time)
Techniques for link backpressure

• Naïve stall-based (on/off):
  – Can source send or not?

• Sophisticated stall-based (credit-based):
  – How many flits can be sent to the next node?

• Speculative (ack/nack):
  – Guess can always send, but keep copy
  – Resolve if send was successful (ack/nack)
    • On ack – drop copy
    • On nack - resend
Store-and-Forward (packet-based, no flits)

• **Strategy:**
  – Make intermediate stops and wait until the entire packet has arrived before you move on

• **Advantage:**
  – Other packets can use intermediate links
Could be allocated at a much later time without packet dropping

- Buffering allows packet to wait for channel
- *Drawback?*
Virtual Cut-through (packet-based)

- Why wait till entire message has arrived at each intermediate stop?
- The head flit of the packet can dash off first
- When the head gets blocked, whole packet gets blocked at one intermediate node
- Used in Alpha 21364
Time-space View: Virtual Cut-through

- Advantages?
- Disadvantages?

No breaks allowed
Flit-Buffer Flow Control: Wormhole

- When a packet blocks, just block wherever the pieces (flits) of the message are at that time.

- Operates like cut-through but with channel and buffers allocated to flits rather than packets
  - Channel state (virtual channel) allocated to packet so body flits can follow head flit
Time-space View: Wormhole

• **Advantages?**

• **Disadvantages?**
Virtual-Channel (VC) Flow Control

- When a message blocks, instead of holding on to links so others can’t use them, hold on to virtual links

- Multiple queues in buffer storage
  - Like lanes on the highway

- Virtual channel can be thought of as channel state and flit buffers
Time-space View: Virtual-Channel

- Advantages?
- Disadvantages?
Thank you!

Next Lecture: 
Router (Switch) Microarchitecture 
Routing Algorithms