On-Chip Networks II: Router Microarchitecture & Routing

Daniel Sanchez
Computer Science & Artificial Intelligence Lab
M.I.T.
Reminder: Packets, Flits, Phits

• 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

April 6, 2015
Reminder: Packet-Based Buffered Flow Control (no flits)

- Store-and-forward
Reminder: Packet-Based Buffered Flow Control (no flits)

- Store-and-forward

Channel 0 1 2 3

Cycle 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19

High latency (serialization)
Reminder: Packet-Based Buffered Flow Control (no flits)

- Store-and-forward
- Virtual cut-through: Do not wait for whole packet

High latency (serialization)
Reminder: Packet-Based Buffered Flow Control (no flits)

- Store-and-forward

- Virtual cut-through: Do not wait for whole packet

High latency (serialization)

Lower latency
Reminder: Packet-Based Buffered Flow Control (no flits)

- Store-and-forward
  - High latency (serialization)
  - Buffers allocated in packets \(\rightarrow\) large buffers & low utilization
  - Channels allocated in packets \(\rightarrow\) unfairness & low utilization

- Virtual cut-through: Do not wait for whole packet
  - Lower latency
Wormhole Flow Control (Flit-Based)

- Operates like cut-through but with buffers allocated to flits rather than packets
- When a packet blocks, just block wherever the flits of the packet are at that time

![Diagram showing flit-based flow control]

April 6, 2015
Wormhole Flow Control (Flit-Based)

• Operates like cut-through but with buffers allocated to flits rather than packets

• When a packet blocks, just block wherever the flits of the packet are at that time

Buffers allocated in flits → smaller buffers
Wormhole Flow Control (Flit-Based)

- Operates like cut-through but with buffers allocated to flits rather than packets
- When a packet blocks, just block wherever the flits of the packet are at that time

Buffers allocated in flits $\rightarrow$ smaller buffers
Channels still allocated in packets $\rightarrow$ channels blocked mid-packet can’t be used
Virtual-Channel (VC) Flow Control

- When a packet blocks, instead of holding on to channel, hold on to virtual channel
- Virtual channel = channel state + flit buffers
- Multiple virtual channels reduce blocking
Virtual-Channel (VC) Flow Control

- When a packet blocks, instead of holding on to channel, hold on to virtual channel
- Virtual channel = channel state + flit buffers
- Multiple virtual channels reduce blocking
- Ex: Wormhole (=1 VC/channel) vs 2 VCs/channel
Virtual-Channel (VC) Flow Control

- When a packet blocks, instead of holding on to channel, hold on to virtual channel
- Virtual channel = channel state + flit buffers
- Multiple virtual channels reduce blocking
- Ex: Wormhole (=1 VC/channel) vs 2 VCs/channel
Time-Space View: Virtual-Channel

- Advantages?
- Disadvantages?
Time-Space View: Virtual-Channel

Significantly reduces blocking

• Advantages?
• Disadvantages?
Time-Space View: Virtual-Channel

- Advantages?
  - Significantly reduces blocking

- Disadvantages?
  - More complex router, fair VC allocation required
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?
Router
Microarchitecture
Ring-based Interconnect
Ring Stop

Input

Latch

Output

April 6, 2015
Ring Stop

Input

Latch

Output

Allow input if no traffic on ring

April 6, 2015

Sanchez & Emer
Ring Stop

Allow input if no traffic on ring

If there is traffic on ring, should traffic on ring or new input get priority?
Ring Flow Control: Priorities

Rotary Rule – traffic in ring has priority
Ring Flow Control: Bounces

What if traffic on the ring cannot get delivered, e.g., if output FIFO is full?
Ring Flow Control: Bounces

What if traffic on the ring cannot get delivered, e.g., if output FIFO is full?

One alternative: Continue on ring (bounce)
Ring Flow Control: Bounces

What if traffic on the ring cannot get delivered, e.g., if output FIFO is full?

One alternative: Continue on ring (bounce)

What are the consequences of such bounces?
Ring Flow Control: Bounces

What if traffic on the ring cannot get delivered, e.g., if output FIFO is full?

One alternative: Continue on ring (bounce)

What are the consequences of such bounces?

Traffic on ring no longer FIFO
General Interconnect
Tilera, Knights Landing...
What’s In A Router?

- **It’s a system as well**
  - Logic – State machines, Arbiters, Allocators
    - Control data movement through router
    - Idle, Routing, Waiting for resources, Active
  - Memory – Buffers
    - Store flits before forwarding them
    - SRAMs, registers, processor memory
  - Communication – Switches
    - Transfer flits from input to output ports
    - Crossbars, multiple crossbars, fully-connected, bus
Virtual-channel Router
Router Pipeline vs. Processor Pipeline

- Logical stages:
  - BW
  - RC
  - VA
  - SA
  - BR
  - ST
  - LT
- Different flits go through different stages
- Different routers have different variants
  - E.g. speculation, lookaheads, bypassing
- Different implementations of each pipeline stage

- Logical stages:
  - IF
  - ID
  - EX
  - MEM
  - WB
- Different instructions go through different stages
- Different processors have different variants
  - E.g. speculation, ISA
- Different implementations of each pipeline stage
Baseline Router Pipeline

- Route computation performed once per packet
- Virtual channel allocated once per packet
- Body and tail flits inherit this info from head flit
Allocators In Routers

- **VC Allocator**
  - Input VCs requesting for a range of output VCs
  - Example: A packet of VC0 arrives at East input port. It’s destined for west output port, and would like to get any of the VCs of that output port.

- **Switch Allocator**
  - Input VCs of an input port request for different output ports (e.g., One’s going North, another’s going West)

- “Greedy” algorithms used for efficiency
Allocators In Routers

• VC Allocator
  – Input VCs requesting for a range of output VCs
  – Example: A packet of VC0 arrives at East input port. It’s destined for west output port, and would like to get any of the VCs of that output port.

• Switch Allocator
  – Input VCs of an input port request for different output ports (e.g., One’s going North, another’s going West)

• “Greedy” algorithms used for efficiency

• What happens if allocation fails on a given cycle?

April 6, 2015
VC & Switch Allocation Stalls

Cycle
Head Flit (packet A)
Tail Flit (packet B - holds VC)
Body Flit (packet A)

1 2 3 4 5 6 7 8
RC VA SA ST
SA ST
VC & Switch Allocation Stalls

Cycle

Head Flit (packet A)
Tail Flit (packet B - holds VC)
Body Flit (packet A)

1 2 3 4 5 6 7 8

RC VA SA ST
SA ST
SA ST
VC & Switch Allocation Stalls

Cycle
Head Flit (packet A)
Tail Flit (packet B - holds VC)
Body Flit (packet A)

Cycle
Head Flit
Body Flit 1
Body Flit 2
Body Flit 3
Pipeline Optimizations: Lookahead Routing [Galles, SGI Spider Chip]

- At current router, perform route computation for next router
  - Head flit already carries output port for next router
  - RC just has to read output → fast, can be overlapped with BW
  - Precomputing route allows flits to compete for VCs immediately after BW
  - Routing computation for the next hop (NRC) can be computed in parallel with VA

- Or simplify RC (e.g., X-Y routing is very fast)
Pipeline Optimizations: Speculative Switch Allocation [Peh&Dally, 2001]

• Assume that Virtual Channel Allocation stage will be successful
  – Valid under low to moderate loads

• If both successful, VA and SA are done in parallel

• If VA unsuccessful (no virtual channel returned)
  – Must repeat VA/SA in next cycle

• Prioritize non-speculative requests
Routing
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
Network Deadlock

- Flow A holds $u$ and $v$ but cannot make progress until it acquires channel $w$
- Flow B holds channels $w$ and $x$ but cannot make progress until it acquires channel $u$
Dimension-Order Routing

**XY-order**

- SA
- SB
- DA
- Sc
- DB
- Dc

Uses 2 out of 4 turns

**YX-order**

- SA
- SB
- DA
- Sc
- DB
- Dc

Uses 2 out of 4 turns

XY is deadlock free, YX is deadlock free, what about XY+YX?
Dimension-Order Routing

**XY-order**

Uses 2 out of 4 turns

**YX-order**

Uses 2 out of 4 turns

XY is deadlock free, YX is deadlock free, what about XY+YX? **NO!**
DOR – Turns allowed

• One way of looking at whether a routing algorithm is deadlock free is to look at the turns allowed.

• Deadlocks may occur if turns can form a cycle
Allowing more turns

- Allowing more turns may allow adaptive routing, but also **deadlock**

Six turn model
Turn Model [Glass and Ni, 1994]

• A systematic way of generating **deadlock-free routes** with small number of **prohibited turns**

• Deadlock-free if routes conform to at least **ONE** of the turn models (acyclic channel dependence graph)

---

West-First Turn Model

North-Last Turn Model
2-D Mesh and CDG

Can create a channel dependency graph (CDG) of the network.

Vertices in the CDG represent network links

Disallowing 180° turns, e.g., AB → BA
Cycles in CDG

The channel dependency graph $D$ derived from the network topology may contain many cycles.

Flow routed through links $AB$, $BE$, $EF$
Flow routed through links $EF$, $FA$, $AB$
Deadlock!
Key Insight

If routes of flows conform to acyclic CDG, then there will be no possibility of deadlock!

Disallow/Delete certain edges in CDG

Edges in CDG correspond to turns in network!
Acyclic CDG -> Deadlock-free routes

Turns could be prohibited ad-hoc, all the edges in red are deleted

Ad-hoc Acyclic CDG
West-first → Deadlock-free routes

Per the West-First prohibited turns, all the edges in red are deleted

West-First Acyclic CDG
Routing deadlocks in wormhole routing result from structural hazard at router resources, e.g., buffers.

How can structural hazards be avoided?
Routing deadlocks in wormhole routing result from Structural hazard at router resources, e.g., buffers.

How can structural hazards be avoided?

Adding more resources
Virtual Channels

- Virtual channels can be used to avoid deadlock by restricting VC allocation
CDG and Virtual Channels

April 6, 2015
Randomized Routing: Valiant

- Route each packet through a randomly chosen intermediate node

A packet, going from node $S_A$ to node $D_A$, is first routed from $S_A$ to a randomly chosen intermediate node $I_A$, before going from $I_A$ to final destination $D_A$.

It helps load-balance the network and has a good worst-case performance at the expense of locality.
To retain locality, choose intermediate node in the **minimal quadrant**

Equivalent to randomly selecting among the various minimal paths from source to destination