Multicast Snooping: A New Coherence Method Using A Multicast Address Network

Ender Bilir, Ross Dickson, Ying Hu, Manoj Plakal, Daniel Sorin, Mark Hill & David Wood

Computer Sciences Department
University of Wisconsin
`http://www.cs.wisc.edu/multifacet`

With sponsorship and/or participation from

National Science Foundation	Compaq Computer
Wisconsin Romnes Fellowships	Intel
IBM Graduate Fellowship	Sun Microsystems

Also Acknowledge: Anne Condon, Charles Fischer, & Milo Martin

Summary

- Want Shared-Memory Multiprocessors
  - Find data directly (like snooping)
  - Scale larger than an SMP (like directories)
  - Use prediction between processors to do both
- Multicast Snooping
  - For each coherence transaction, predict multicast “mask”
  - Deliver multicasts on “ordered” network
  - Processors just “snoop” transactions
  - Simplified “directory” audits masks to handle incorrect ones
- Preliminary numbers for SPLASH-2 on 32 processors
  - Limit multicasts to 2-6 processors (<< 32)
  - Find data directly on 84-95% of multicasts
  - But ... <many buts>

Outline

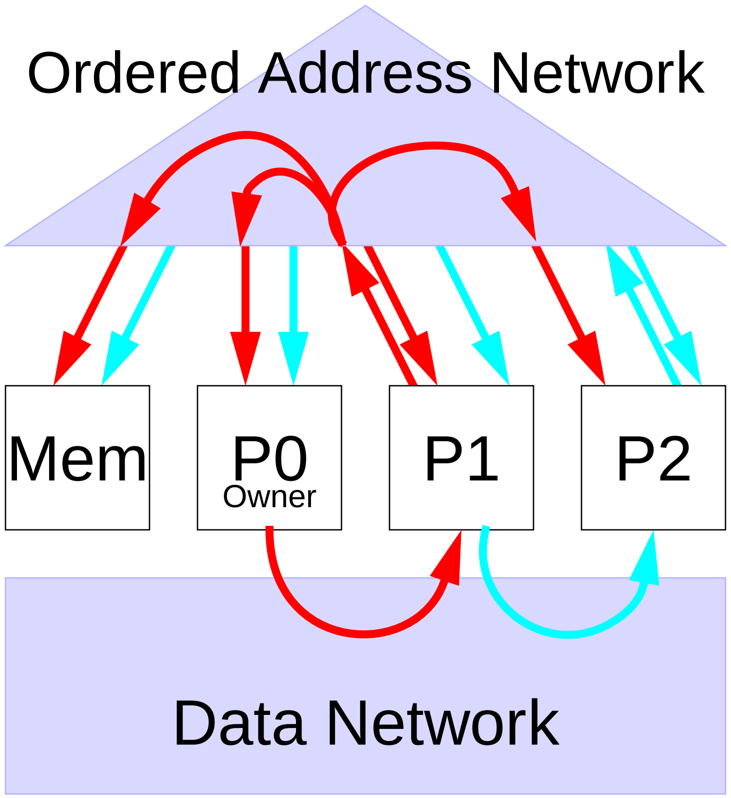
- Background
  - Snooping
  - Directories
- Multicast Snooping
- Some Experiments & Summary

Terminology

- Write-Invalidate MSI Protocol States
  - Modified - read/write, exclusive, & (potentially) dirty ("Owner")
  - Shared - read-only, (potentially) shared, & clean
  - Invalid - no access, not valid or not present

- Processors Issue
  - GETS B (Get Shared) to go from Invalid to Shared
  - GETX B (Get eXclusive) to go from Invalid/Shared to Modified
  - PUTX B (Put eXclusive) to go from Modified to Invalid

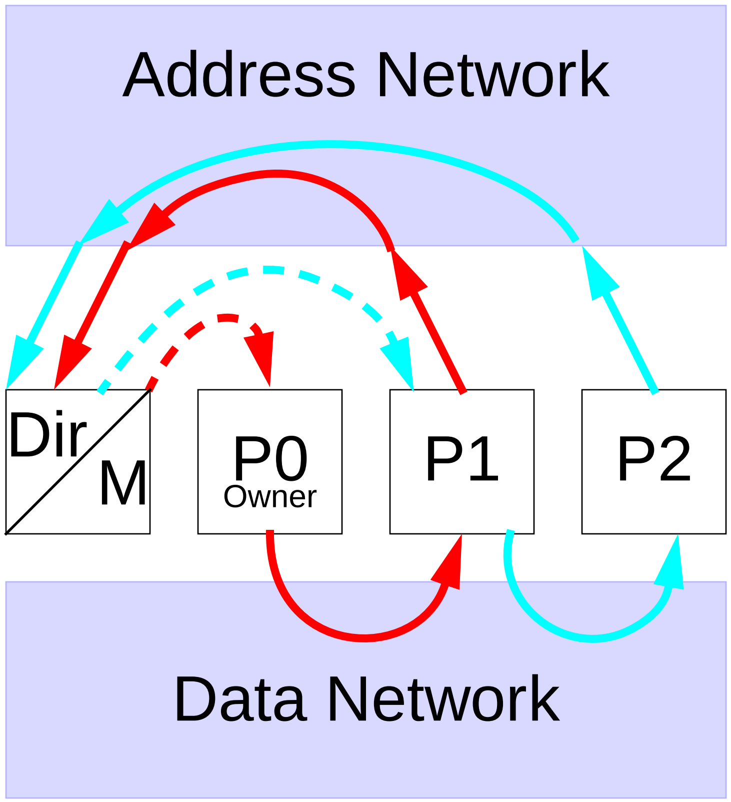
Broadcast Snooping



Requires High Address Network and Snoop Bandwidth

- Initial State - Block B:
  - P0: Modified
  - P1&P2: Invalid
- Example
  - P1: GETX B & P2: GETX B
- Broadcast all coherence transactions
- Totally Ordered Address Network Serializes Transactions
- P1 “wins” in this example

Directories



- Same initial state & example
- All coherence transactions to Directory
- Directory Serializes Transactions
- P1 “wins” in this example

Indirection Through Directory Can Increase Latency

Comparison of Coherence Methods

Coherence Attribute	Snooping	Directories	Multicast Snooping
Find previous owner directly?	Yes	Sometimes	Usually (good)
Always broadcast?	Yes	No	No (good)
Ordering without acknowledgements?	Yes	No	Yes (good)
Stateless (at memory)?	Yes	No	No but simpler
Ordered network?	Yes	No	Yes (challenge)

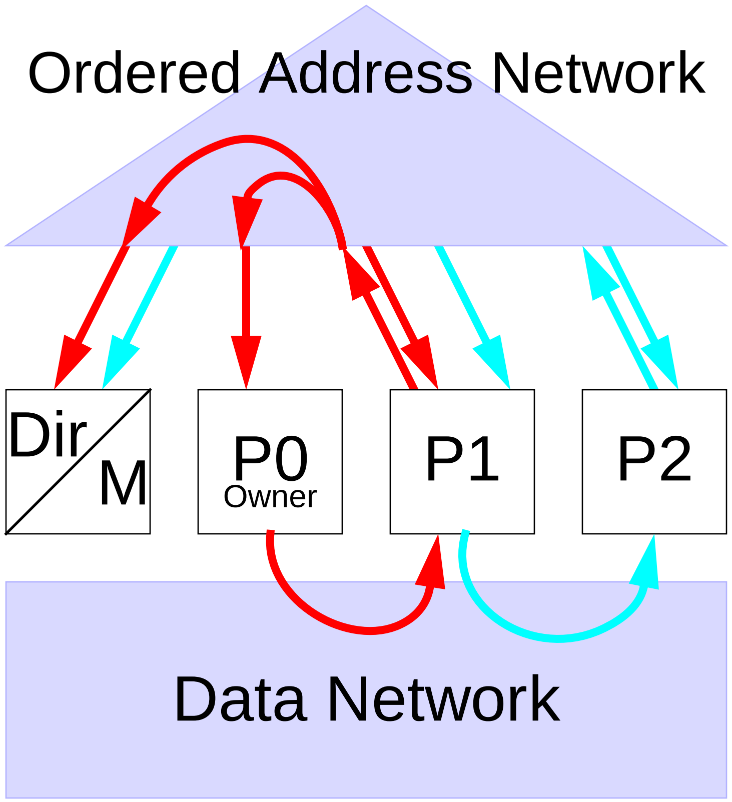
Outline

- Background
- Multicast Snooping
  - Basic Operation
  - Mask Auditing & Prediction
  - Ordered Multicast Address Network
- Some Experiments & Summary

Multicast Snooping

- On cache miss
  - Predict "multicast mask" (*e.g.*, bit vector of processors)
  - Issue transaction on multicast address network
- Networks
  - Address network that totally-orders address multicasts
  - Separate point-to-point data network
- Processors snoop all incoming transactions
  - If it's your own, it "occurs" now
  - If another's, then invalidate and/or respond
- Simplified directory (at memory)
  - Purpose: Allows masks to be wrong (explained later)

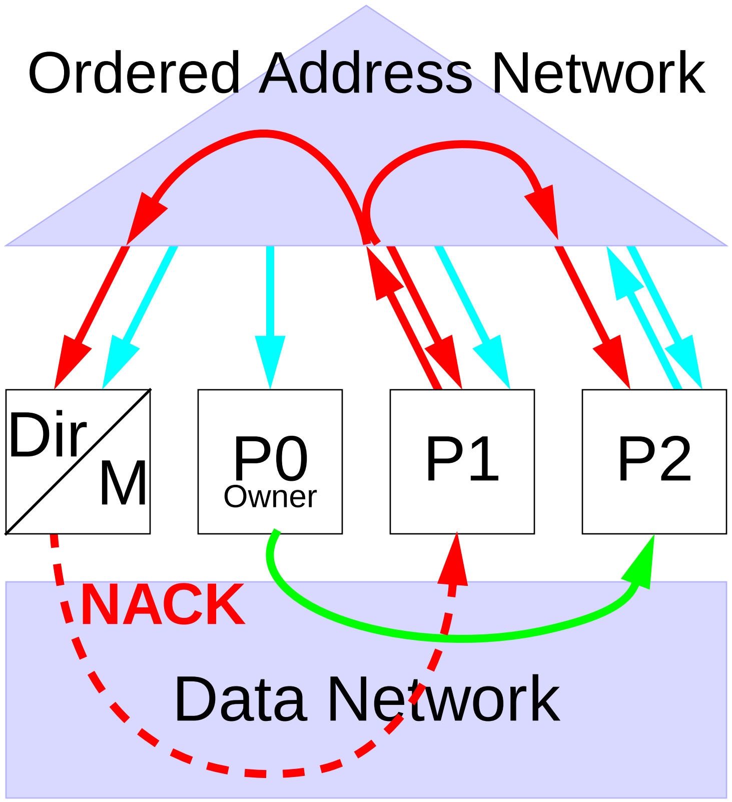
Multicast Snooping Example



No Indirection and Requires Less Address Network Bandwidth

- Multicast coherence transactions
  - P1: GETX B <Dir_B, P0, P1>
  - P2: GETX B <Dir_B, P1, P2>
- Totally Ordered Multicast Network Serializes Transactions
- P1 “wins” in this example

Multicast Snooping Example (Incorrect Mask)



- Multicast coherence transactions
  - P1: GETX B <Dir_B, P1, P2>
  - P2: GETX B <Dir_B, P0, P1, P2>
- Totally Ordered Multicast Network Serializes Transactions
- P1 “wins” in this example,

  But only gets NACK & must retry

Everything is Fine, With a Cost

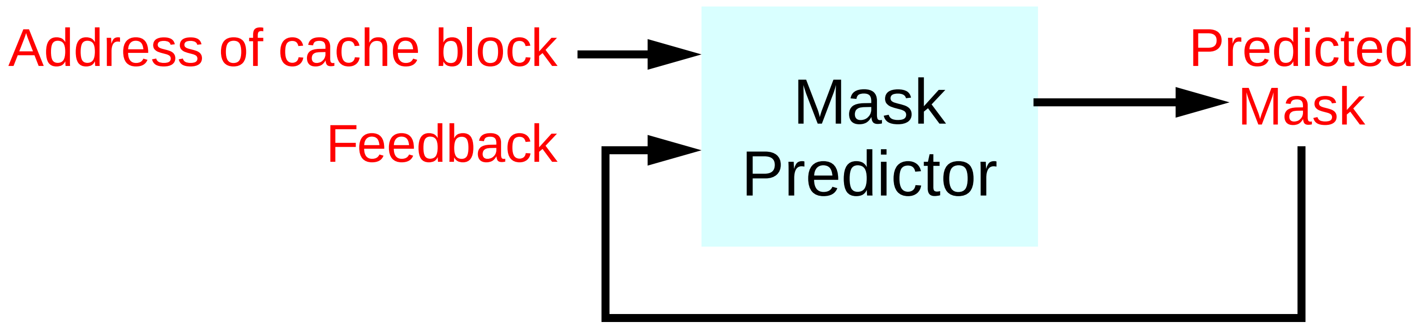
Mask Auditing at Simplified Directory

- Simplified Directory
  - Always in block B's multicast mask
  - Tracks owner and sharers
  - Makes instantaneous transitions
- Audits Mask
  - Does GETS include owner?
  - Does GETX include owner & all sharers?
- Audit Result
  - Success: Update directory state & sometimes send block B
  - Failure: Reply with nack containing "better" mask

But how do processors predict masks?

Predicting Masks

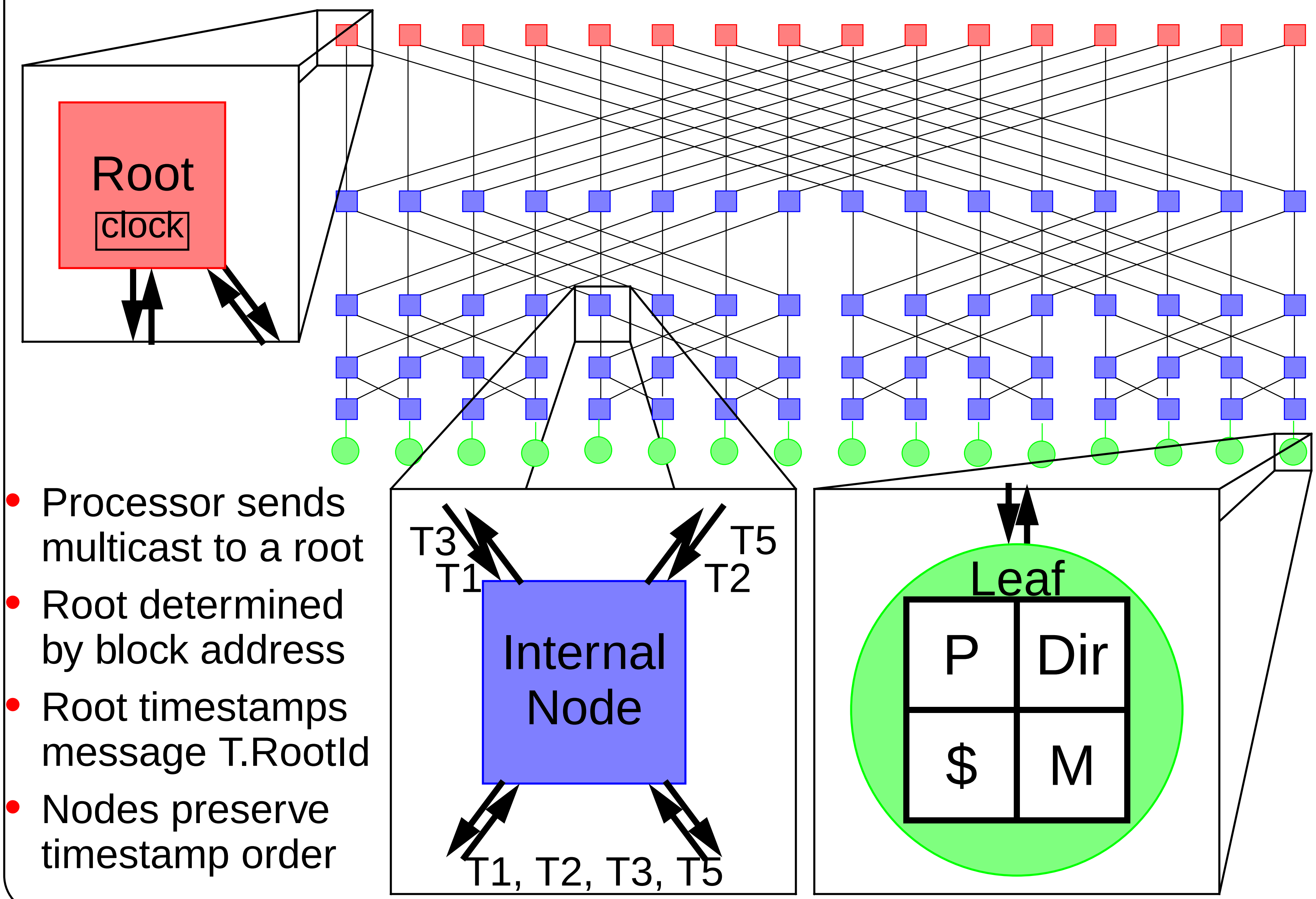
- Performed at Requesting Processor
  - Include owner (GETS/GETX) & all sharers (GETX only)
  - Exclude most other processors
- Many straightforward cases (e.g., stack, code, space-sharing)
- Many options (network load, PC, software, local/global, two-level)
- See paper for Sticky-Spatial(1) with a 4K-entry table



Implementing an Ordered Multicast Address Network

- Address Network
  - Must create the illusion of total order of multicasts
  - Need NOT deliver a multicast to all destinations at the same time
- Wish List
  - High throughput for multicasts
  - No centralized bottlenecks
  - Low latency and cost (~ pipelined broadcast tree)
  - ...
- A Solution
  - Isotach Networks [Reynolds, Williams, & Wagner, IEEE TPDS 4/97]
  - Conceptually add logical timestamps to address messages

Initial Proposal: Indirect Fat Tree



- Processor sends multicast to a root
- Root determined by block address
- Root timestamps message T.RootId
- Nodes preserve timestamp order

Outline

- Background
- Multicast Snooping
- Some Experiments & Summary

Hypothesis 1 of 2

- Hypothesis 1
  - Multicast Snooping uses significantly less address bandwidth than broadcast snooping.
- Experiment
  - Select mostly SPLASH-2 parallel benchmarks
  - Run 32-processor CC-NUMA on WWT2 execution-driven simulator
  - Run traces through Sticky-Spatial(1) mask predictor
  - Run traces through a 32-node binary fat tree simulator
- Result
  - Multicasts average 2-6 destinations (<< 32)
  - Allows initial network to deliver 2-5 multicasts per cycle (>> 1)

Hypothesis 2 of 2

- Hypothesis 2
  - Multicast Snooping finds data directly significantly more often than directory protocols.
- Experiment: Same as for Hypothesis 1
- Result
  - Directories find data directly 45-92%
  - Multicast Snooping
    - Adds 11-50% (absolute) for fft, moldyn, ocean, & raytrace
    - Only 2-4% (absolute) for cholesky, lu, radix, & water-nq
    - Wider difference for “infinite” caches & preliminary TPC-B numbers
- Future: better benchmarks, larger systems, and timing results

Summary

- Multicast Snooping
  - For each coherence transaction, predict multicast “mask”
  - Deliver multicasts on “ordered” network
  - Processors just “snoop” transactions
  - Simplified “directory” audits masks to handle incorrect ones
- Tentatively, multicast snooping allows a multiprocessor to:
  - Behave like snooping if address bandwidth adequate
  - Gracefully degrade toward directory-based solution
- More generally, Wisconsin Multifacet Project
  - Other opportunities for system-wide prediction & speculation
  - **`http://www.cs.wisc.edu/multifacet`**

BACKUP SLIDES

MSI Multicast Snooping

Requestor		Memory					Other Processors in Mask			Requestor	
Trans-action	Old State	Old State	Owner in mask?	All in mask?	Send to requestor	New State	Old State	Send to requestor	New State	New State	Success?
GETS	I	S, I	yes	x	data_ack	S				S	yes
		M(q)	yes	x		S	M	data_ack, data to mem	S	S	yes
			no	no	nack	same				I	no
GETX	S,I	S, I	yes	yes	data_ack	M(r)	S		I	M	yes
		S	x	no	nack	same	S		I	S	no
		M(q)	yes	yes		M(r)	M	data_ack	I	M	yes
		M(q)	no	no	nack	same	S		I	same	no
PUTX	M	M(r)	yes	yes		I				I	yes
	I	I, S, M(q)	x	x		same				same	no

Columns 1 and 2 give the requesting processor's transaction and state when it sees its own transaction.Columns 3-5 give the states a transaction can encounter at memory, while Columns 6-7 give the memory's response. Memory state M is augmented with "(r)" if the requestor is (was) the owner and with "(q)" otherwise. An "x" denotes "don't care." Column 8 gives the state that other processors may be in when they see a transaction, while Columns 9-10 give their response. Cases where these processors do nothing are omitted for brevity (observing a GETS in S, observing a PUTX in I, and when omitted from a multicast mask). Finally, Columns 11-12 give the requesting processor's final state and whether the transaction was successful. All other cases are impossible.

Predicting Masks: Sticky-Spatial(1)

6A40

Tag	Multicast mask	Last invalidator
3A00	00000011	0
6A40	10010000	3
6A80	00100000	2

OR together 1 spatial neighbor on each side

Mask for block	= 10010000
Mask for neighbor#1	= 00000011
Mask for neighbor#2	= 00100000
Mask for requester & directory	= 00000110
Predicted multicast mask	= 10110111

Intuition: Accessing an array or record

Implementing an Ordered Multicast Address Network

- On each network pulse T (pretend that the network in synchronous)
- Each Root J
  - Selects a queued multicast transaction (if any)
  - Assigns it logical timestamp T.J
  - Sends it down to the left, right, or both
  - And sends timestamp-only null messages down any idle down links
- Each Routing Node - Performs a “merge”
  - Selects a queued multicast transaction with oldest timestamp (if any)
  - Sends it down to the left, right, or both
  - And sends timestamp-only messages down any idle down links
- By induction, all links deliver transactions in pulse order
- Processors re-create multicast order using logical timestamp

(A) Select Parallel Benchmarks

- Use (mostly) SPLASH-2 Benchmarks

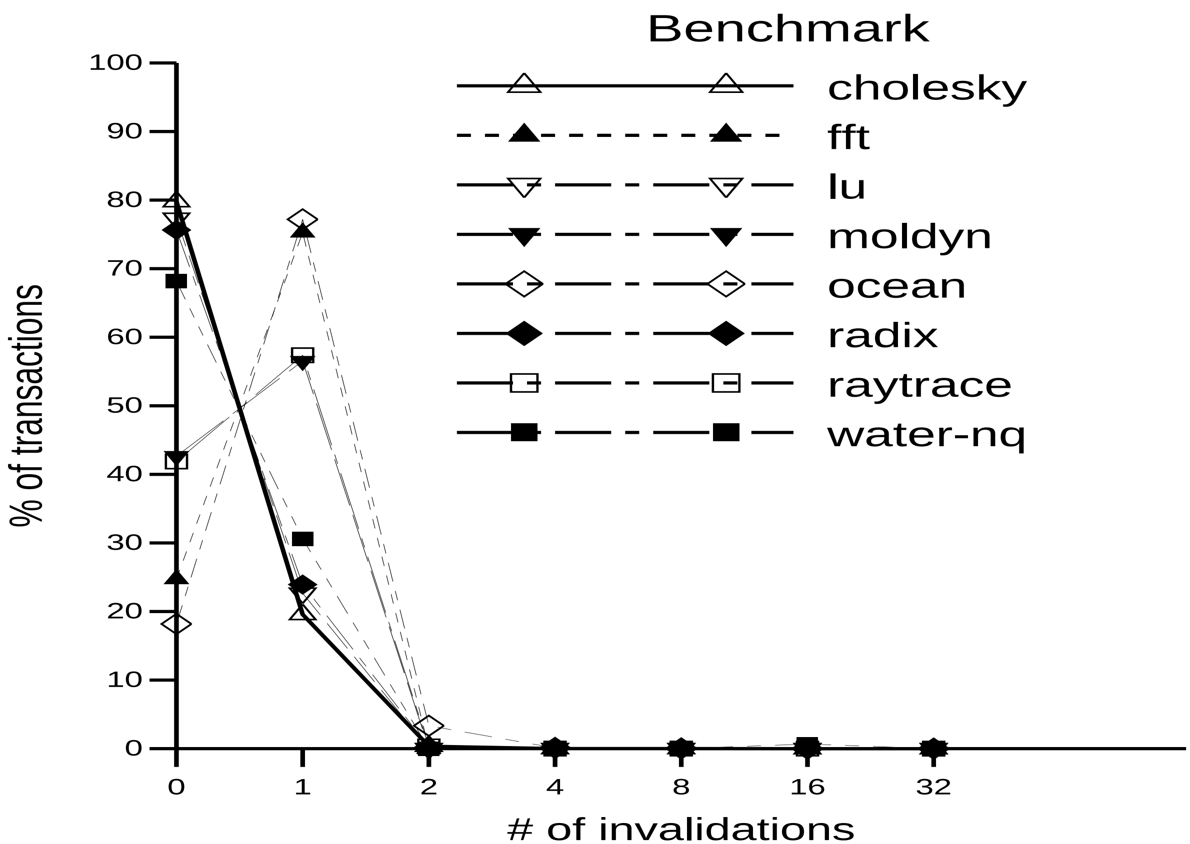
Benchmark	Description of Application	Input Data Set
cholesky	Blocked sparse matrix Cholesky factorization	tk16.O from SPLASH-2
fft	Complex 1-D radix-$\sqrt{n}$ 6-step FFT	64K points
lu	Blocked dense matrix LU factorization	512x512 matrices, 16x16 blocks
moldyn	Simulation of molecular dynamics	2048 particles, 15 iterations
ocean	Simulates large-scale ocean movements	130x130 ocean
radix	Integer radix sort	1M integers, radix 1024
raytrace	3-D scene rendering using raytracing	teapot from SPLASH-2
water-nq	Quadratic-time simulation of water molecules	512 molecules

(B) Run 32-processor execution-driven simulator

- Use Wisconsin Wind Tunnel II (WWT2)

Parameter	**Value**
# of processors	32
Type of system	CC-NUMA
Coherence mechanism	Directory protocol: full-map, write-invalidate, 3-state MSI
Data memory hierarchy	L1 cache, SPARC MBus, Local memory, Remote Block cache
L1 data cache	128KB, direct-mapped, 32-byte blocks, write-back
Remote block cache	512KB, direct-mapped, 32-byte blocks, writeback inclusion with L1 cache for read-write blocks
Local memory	96MB

(1) Is the mean number of sharers encountered by a coherence transaction small?



- Yes, so multicasts can have far fewer destinations than broadcasts

(2) Can plausible mask predictors usually include all necessary processors and limit multicasts to an average number of destinations much smaller than all processors?

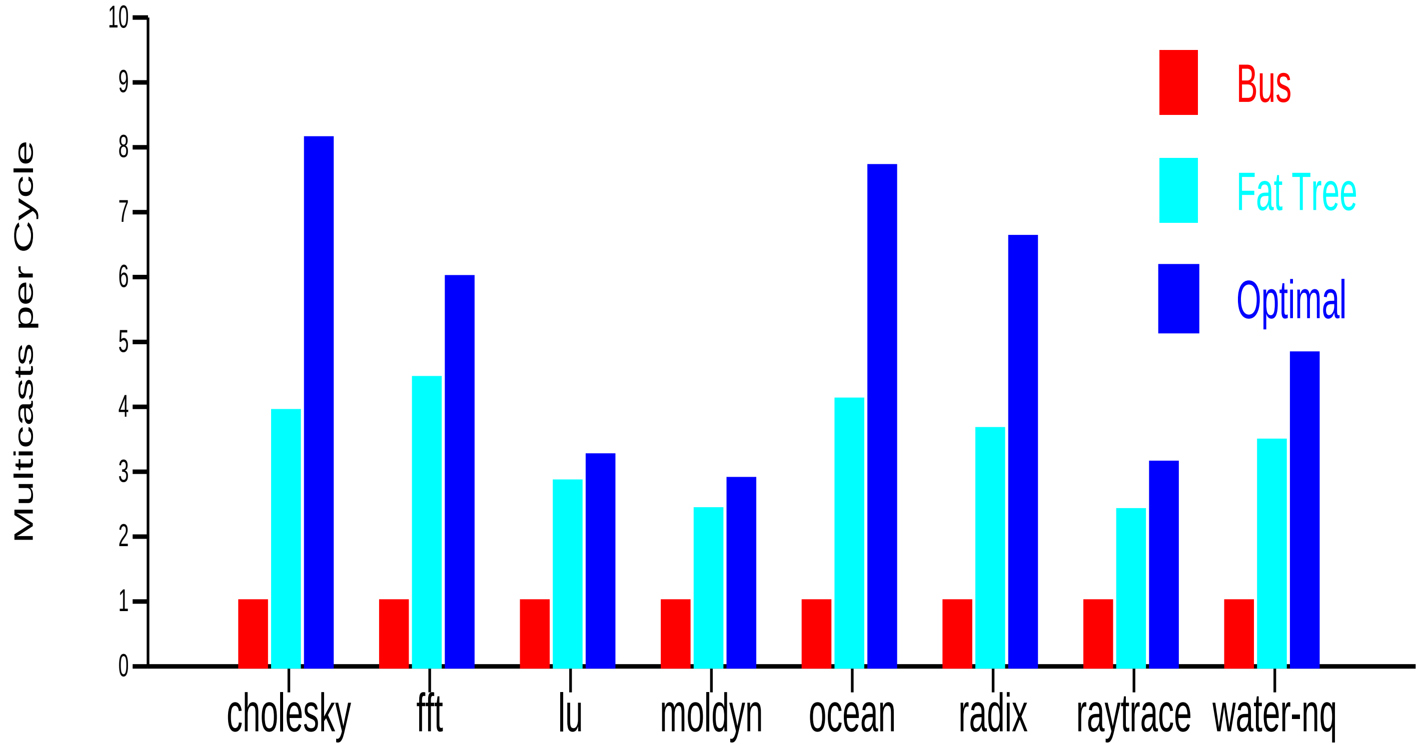
Benchmark	Prediction Accuracy (%)	Blocks at Home (%)	Average Nodes in Multicast (of 32)
cholesky	94	92	3.4
fft	73*	57	3.2
lu	95	93	2.4
moldyn	88*	56	5.4
ocean	95*	45	3.4
radix	84	80	3.0
raytrace	86*	75	5.6
water-nq	88	85	3.8

- Yes, so mask prediction can be effective

(D) Run through Network Simulator

- Simple Java Program
- Takes traces of mask predictions from previous step
- Simulates multicast address network
  - Binary fat tree
  - 32 processors
  - 32 roots
- Computes network throughput
- Network latency not meaningful since input trace does not have meaningful time

(3) Can our initial network deliver many multicasts per network cycle?



- Yes, much larger than broadcast snooping's one per cycle