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Towards millions of communicating threads

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Motivation

- Machine node with many cores inter-connected with Intelligent NIC
- Programming model: MPI+X
  - X: intra-node thread parallelism (e.g. OpenMP); can use lightweight threads (tasks)
- MPI performance does not scale with many threads

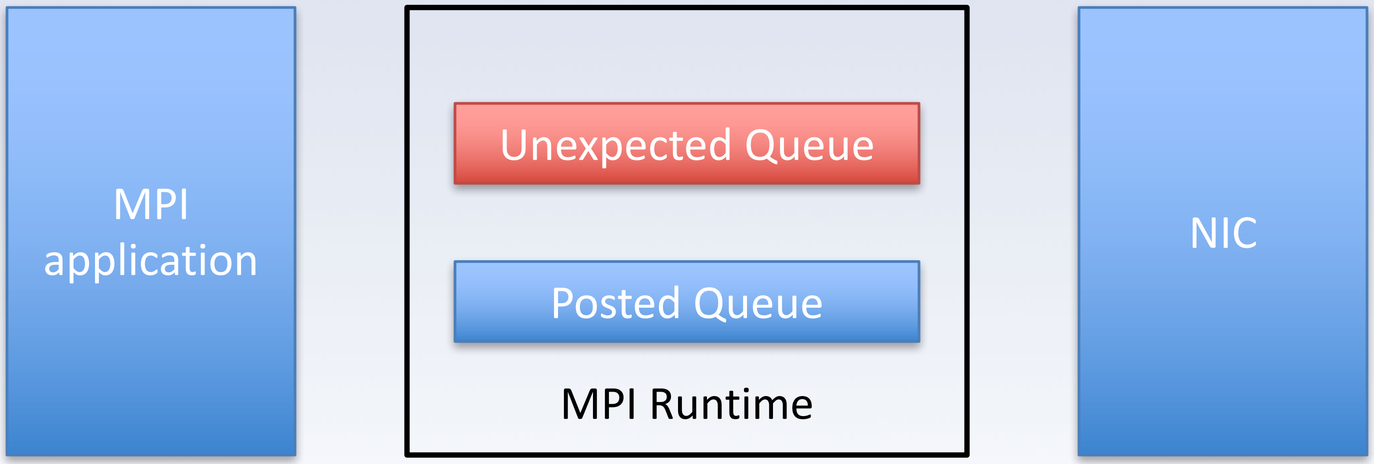
Motivation
MPI+X Performance Issues

- Semantics of message matching, implemented using 2-queue data structure
- Thread scheduler is not aware of status of communications
- Low-level communication layer is not designed for multi-core architecture because of many mutual-exclusion point

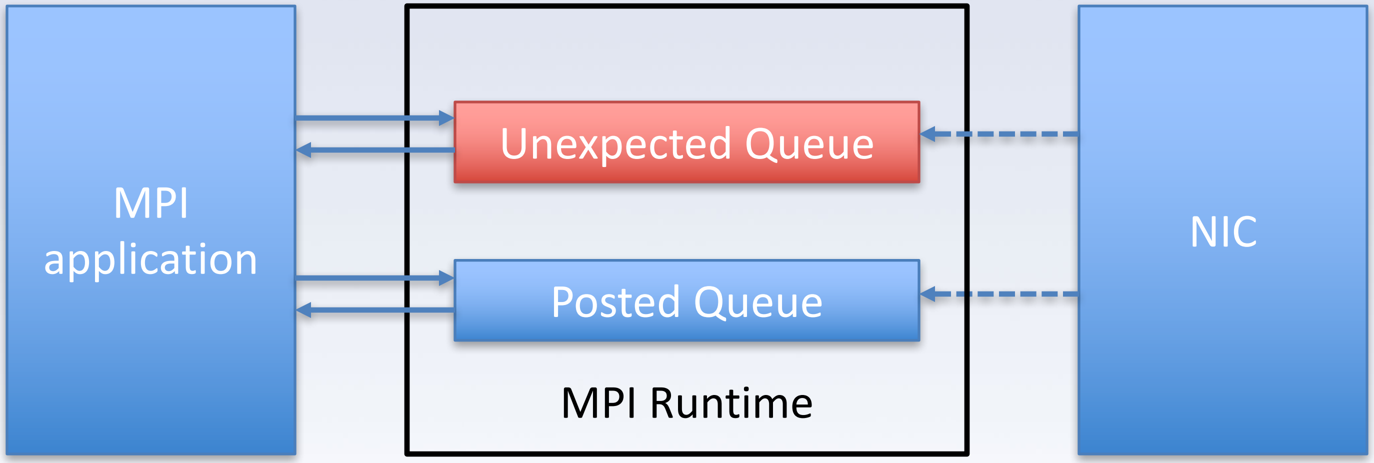
Our bottom-up approach

- Re-design the message matching mechanism for multi-threading
- Design an efficient communication interface between MPI library and thread scheduler
- Carefully manage resources to avoid mutual exclusion of many threads and optimize for cache locality

MPI point-to-point message-matching



MPI point-to-point message-matching



RECV issuer comes first:

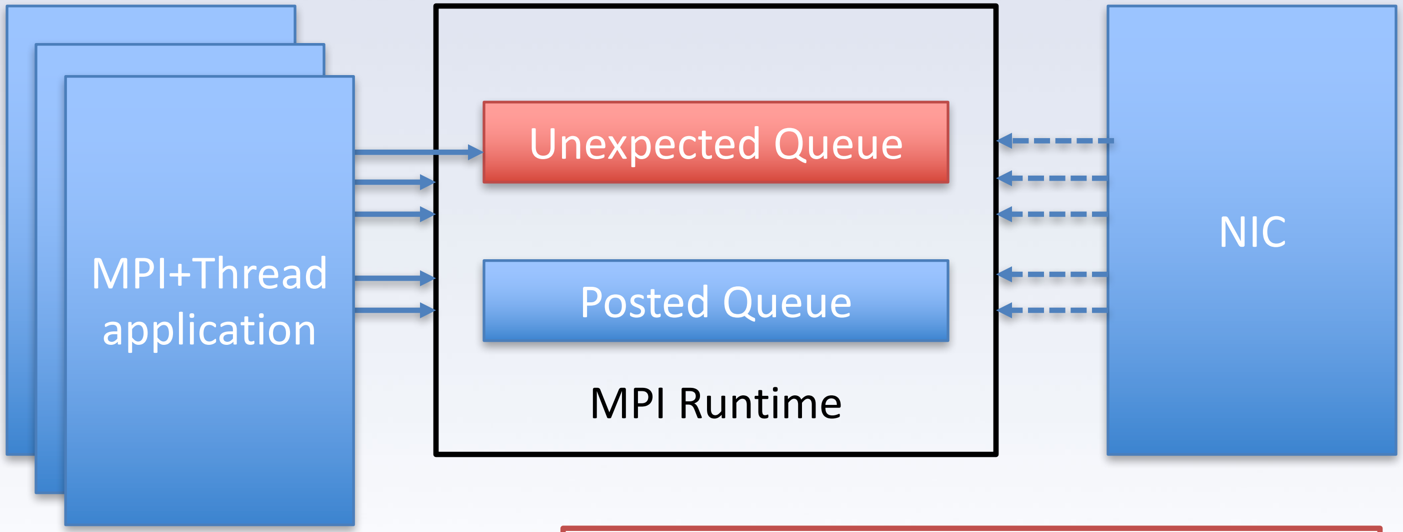
1. SEARCH(UQ)
2. PUSH(PQ)
3. SEARCH(PQ)
4. POP(PQ)

MSG arrives first:

1. SEARCH(PQ)
2. PUSH(UQ)
3. SEARCH(UQ)
4. POP(UQ)

MPI point-to-point message-matching

- Multi-threaded scenario



**Each thread is delayed by O(M*N) **
M: # pending messages
N: # number of threads

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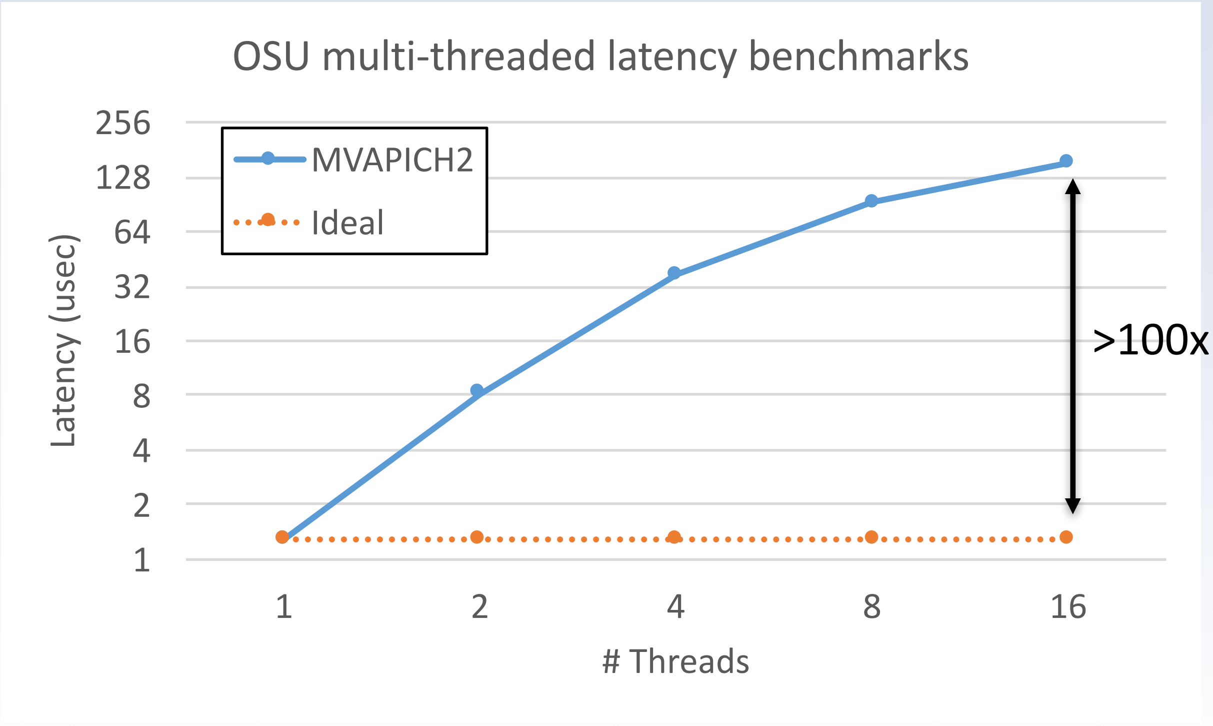
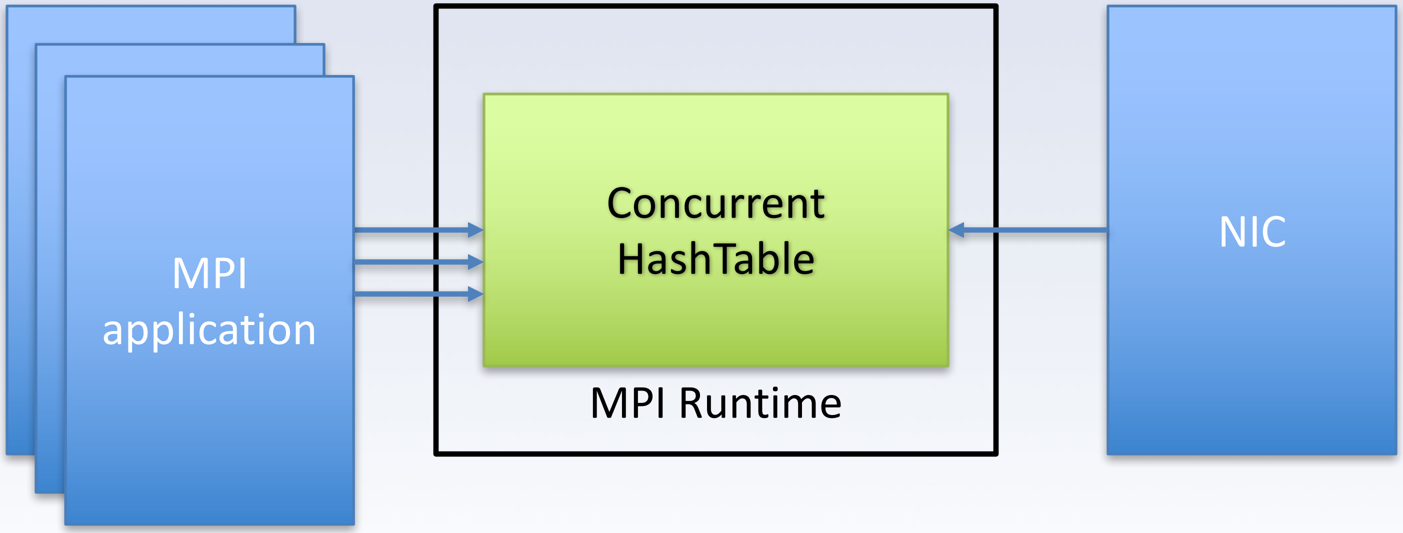
MPI point-to-point message-matching

Experiment is done on Stampede Cluster: 16 core – FDR Infiniband



Ideal case: multi-threaded performance should remain the same as single threaded

MPI point-to-point message-matching



- No mixing of wildcard and normal match

MPI point-to-point message-matching

- Specialized hash-table with one operation: **ACCESS(K,V)**:
  - found then remove and return value
  - otherwise insert into the table
- Symmetric notion of message matching:
  - IF ((V' = H.ACCESS(K,V)) == $\perp$)
    - No unexpected packet / No posted request
  - ELSE
    - V' is the matched entry (packet/request)
    - V' is removed from the hash table

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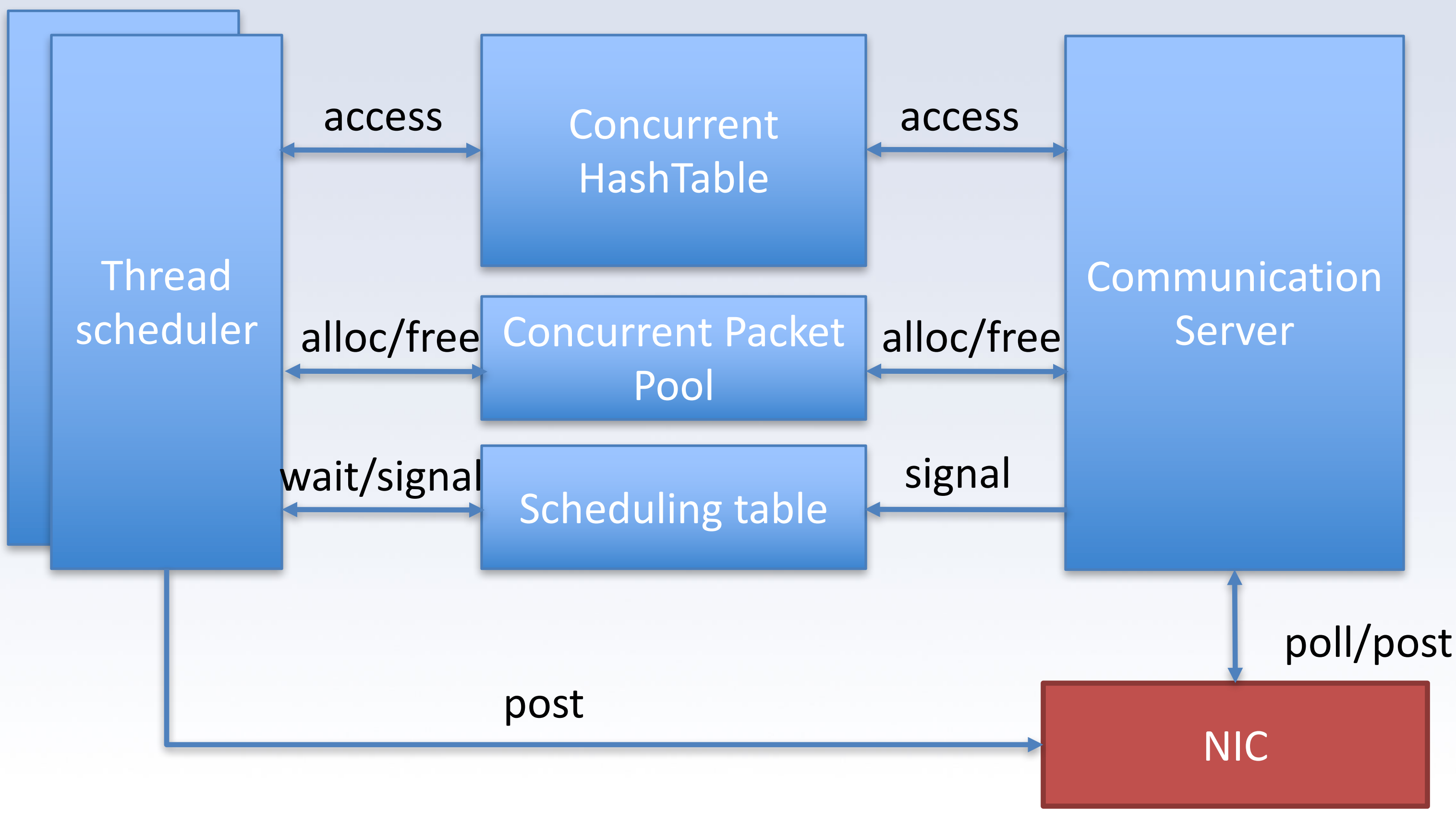
MPI thread scheduler

- What to do when a thread cannot complete its blocking request?
  - Current approach: randomly yield to other
- Better approach: communication-aware
  - de-scheduled when cannot complete
  - dedicates one or more core for communication progress; wake up thread when finished.

Proposed runtime architecture



Algorithm for receive matching (eager send)

THREAD: MPI_RECV

- V : Request
- V' : Packet
- IF ((V' = H.ACCESS(K,V)) == ⊥)
  – WAIT()
- ELSE
  – Finish and return

SERVER: POLL_CQ

- V : Packet
- V' : Request
- IF ((V' = H.ACCESS(K,V)) == ⊥)
  – Continue
- ELSE
  – SIGNAL()

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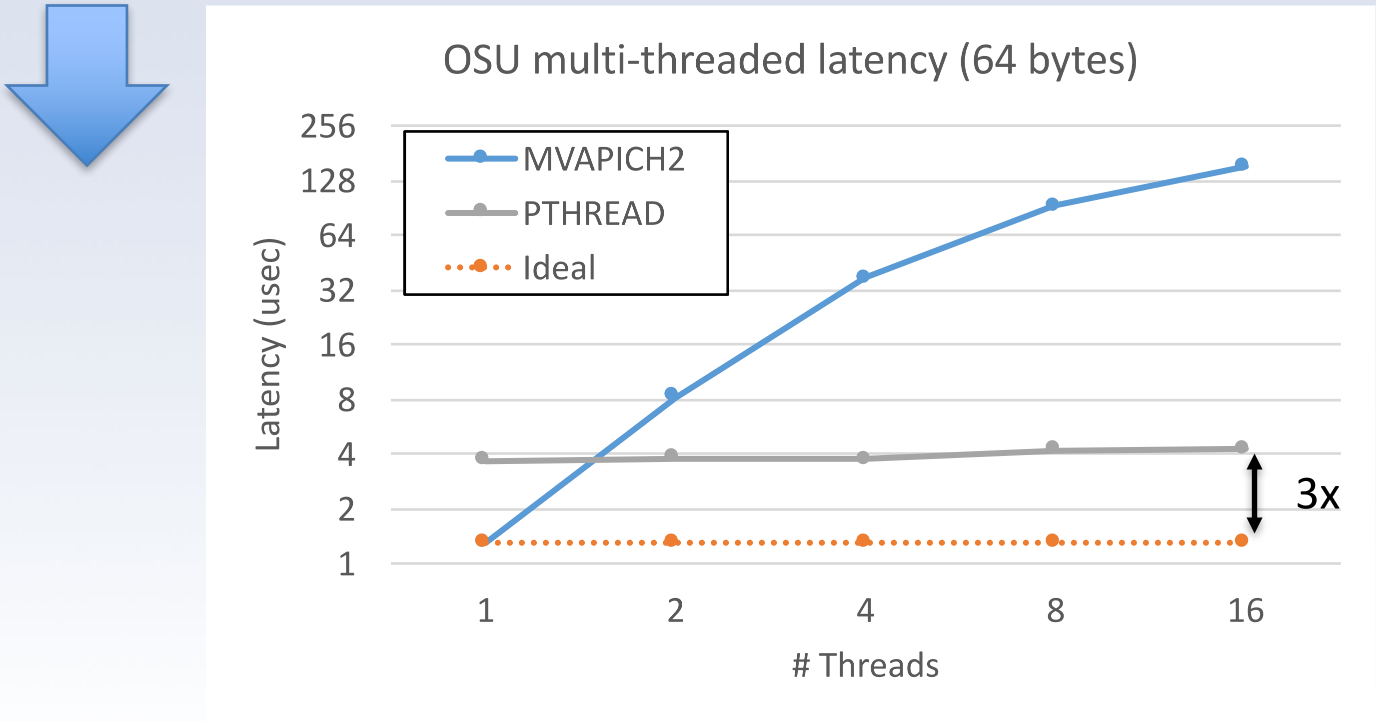
How to implement these efficiently ?

MPI Threading Interface

- Require two critical operations over a *synchronization object*
  - SIGNAL
  - WAIT
- Associate a request/thread with a *synchronization object*
  - Communication server find the object inside request and signal the waiting thread.
- Semaphore / condition variable
  - Implemented using waiting queue

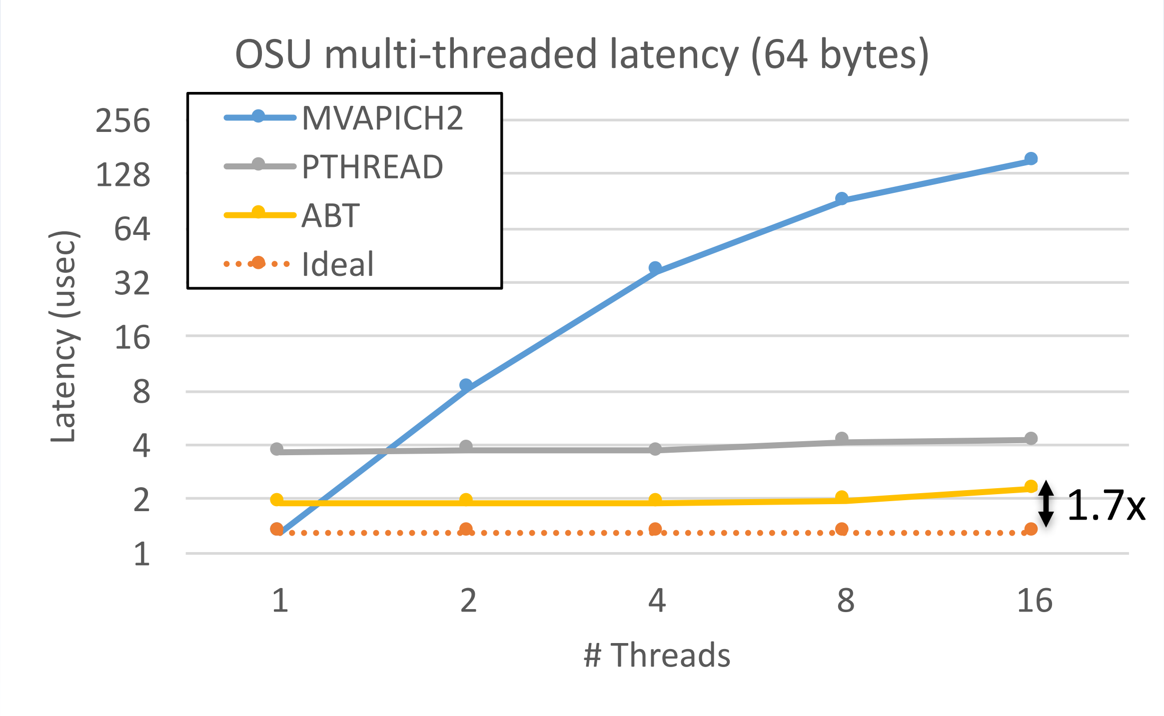
MPI Threading Interface: PThread

The lower the better



MPI Threading Interface: Argobots

The lower the better



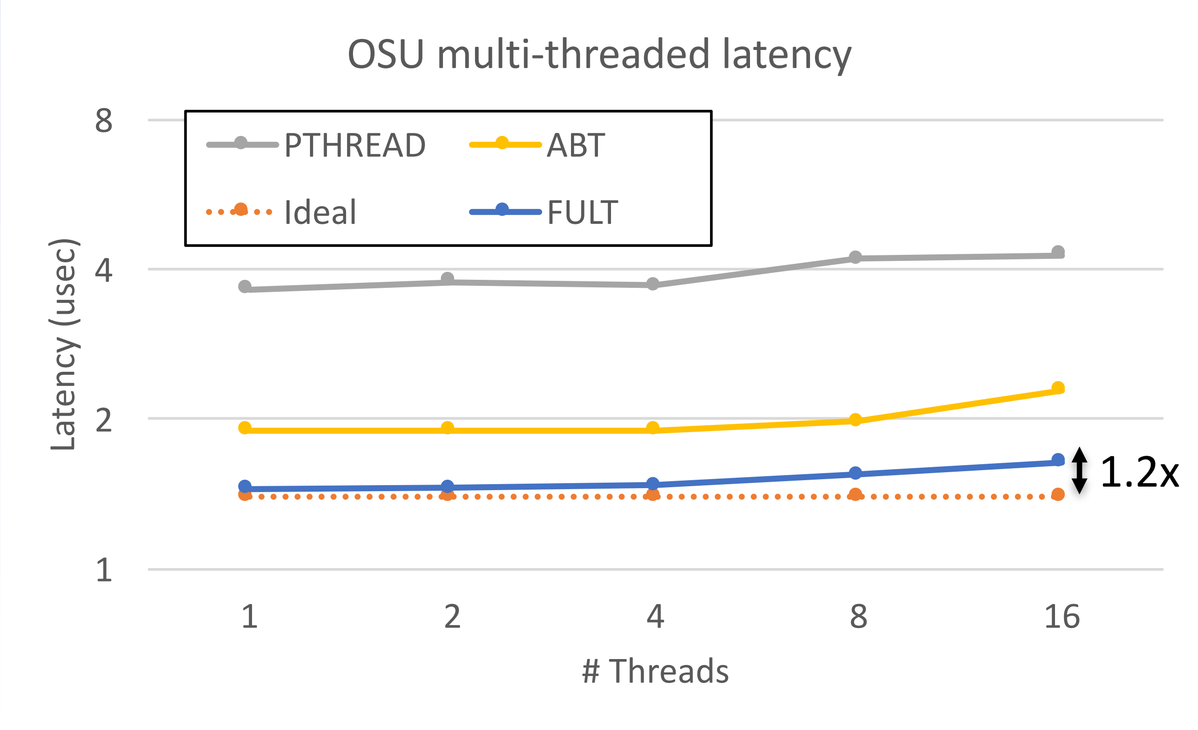
Can we do better than this?

MPI Threading Interface: FULT

- Key idea: using bit-vector for ready threads structure
  - 0: executing or blocked
  - 1: runnable
- SIGNAL: atomic bit-set instruction
- WAIT: context-switch to other runnable threads (find-first-bit-set instruction)

MPI Threading Interface: FULT

The lower the better



Summary: Initial assumption

A. MPI point-to-point:
   1. No wildcard ← O(1) message matching
   2. No pending requests with the same signature <communicator, rank, tag>

B. Integrated with user-level threads (ULT) ← No kernel interference
   1. No thread migration ← Fast signal/wait
   2. No fairness requirement

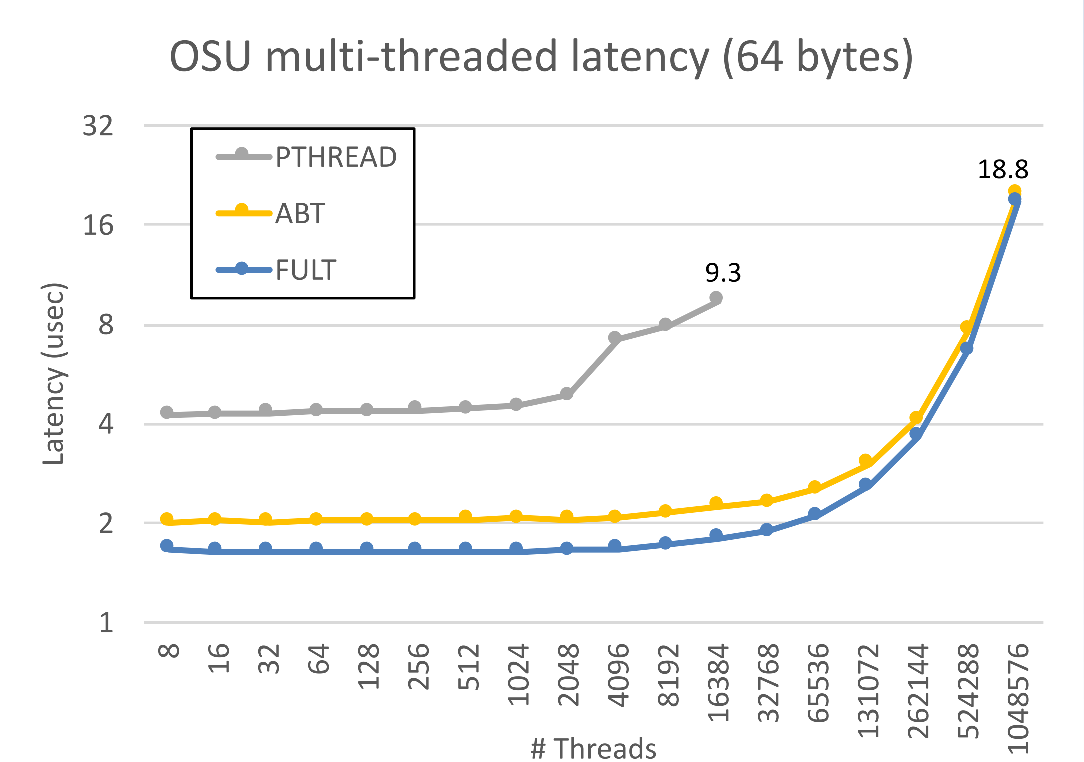
C. Based on NIC with modern features:
   1. Communication Server ← Separation of concern
   2. RDMA, address translation is done in hardware ← No mem registration

Runtime optimization and implementation

- Concurrent Hash Table: ACCESS
  - Open Hashing with Fat entry for cache locality
  - Per bucket spinlock is sufficient
- Packet Pool: ALLOC/FREE
  - Locality-aware: consumer will perform memory copy
  - NUMA-aware: pool per core, stealing for balancing
- Thread scheduler (FULT): WAIT/SIGNAL/YIELD
  - Two-level of bit-vector for large number of threads
  - YIELD == Self Signal then Wait

Scaling to 1M threads (over-decomposition)

The lower the better



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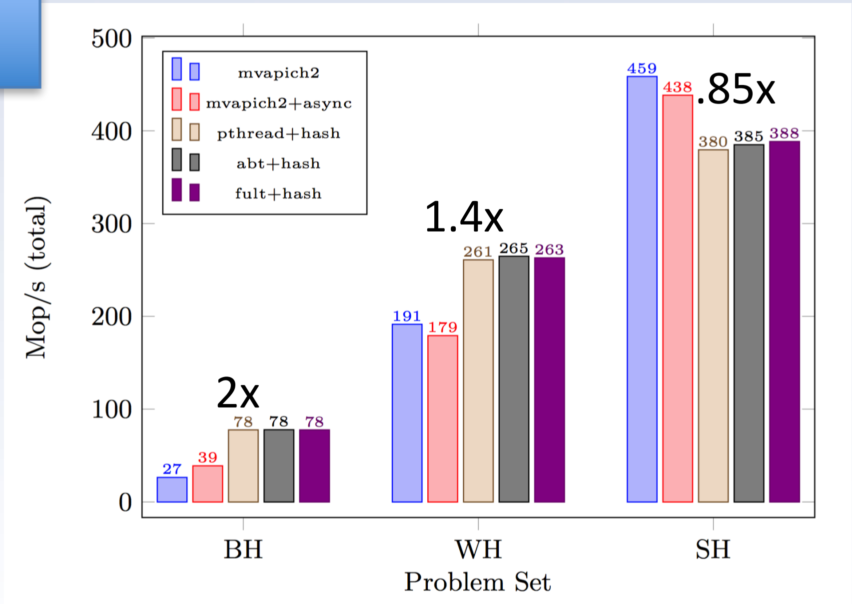
Communication Kernel Tested implementation

Notation	MPI	Scheduler	Core assignment
mvapich2	MVAPICH2 (2.1)	POSIX thread	1 core per rank
mvapich2+async	MVAPICH2 (2.1)	POSIX thread	2 cores per rank
pthread+hash	customized	POSIX thread	16 cores per rank
abt+hash	customized	ULT (Argobots)	16 cores per rank
fult+hash	customized	ULT (Fult)	16 cores per rank

- NAS Data Traffic:
  - Single-threaded performance with three different communication patterns.
- Unbalanced Tree Search:
  - Distributed work-stealing for tree traversal
- Graph500:
  - Breadth-First-Search over large distributed graph

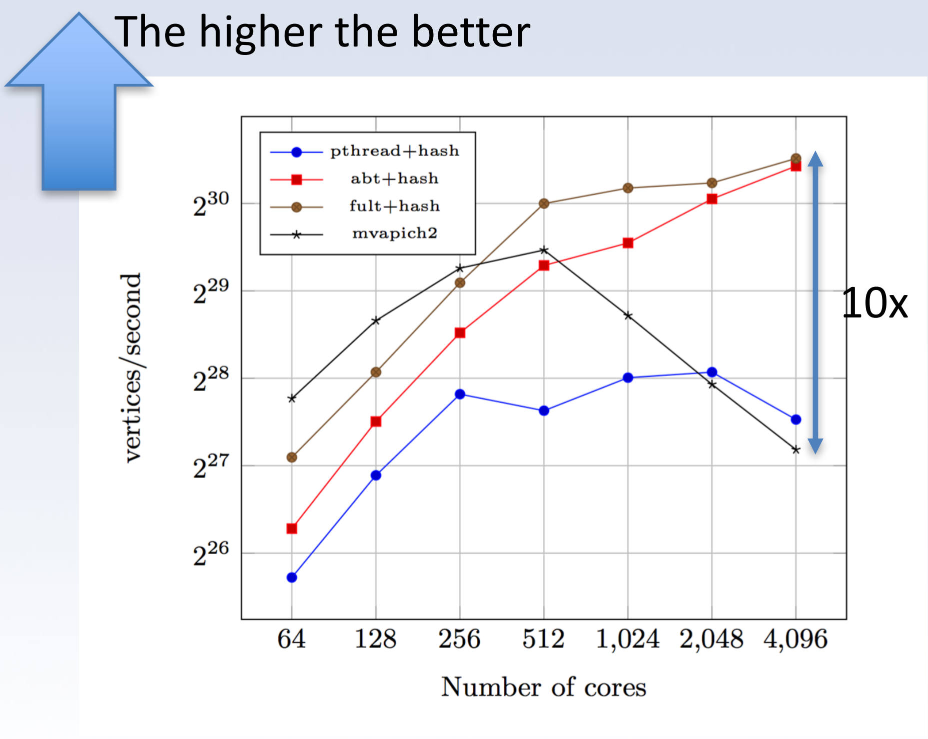
NAS Data Traffic

The higher the better



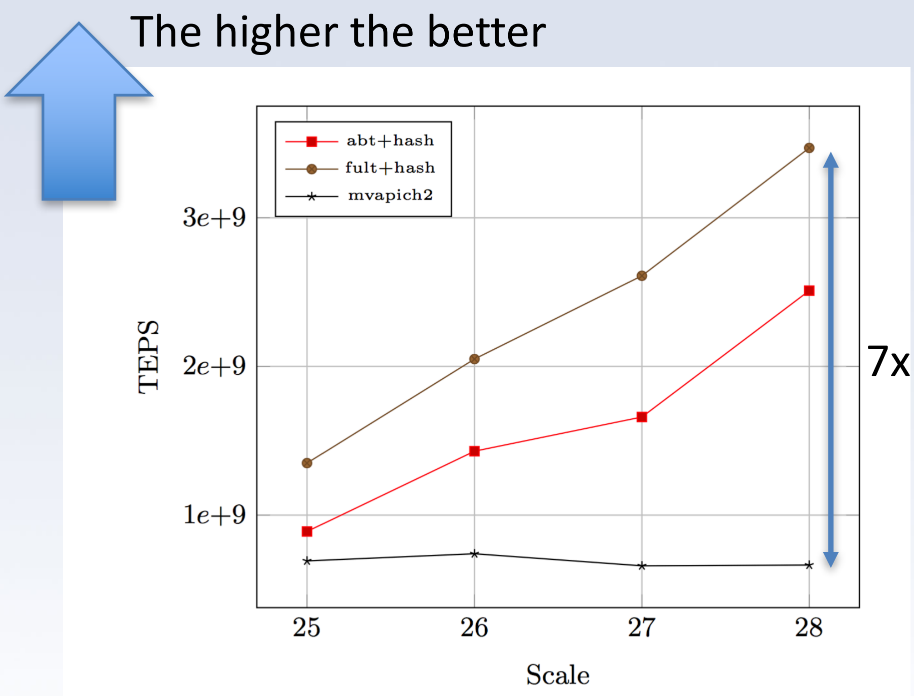
- BH: black hole – multiple sender, one receiver
- WH: white hole – one sender, multiple receiver
- SH: shuffle – all-to-all like communication
- 128 MPI rank, one per compute node.

Unbalanced Tree Search



- Distributed memory Work-Stealing implementation
- ~ 3M node binomial tree (T3XXL)
- Compare single-threaded ref. code with using threads for receiving work-stealing requests

Graph 500



- Multi-threaded by spawning threads to receive from different targets
- Weak scaling up to 4096 cores at graph scale-28.
- Compare ref. code with using threads for receiving vertices from multiple nodes.

Conclusion

- We have designed and implemented low-level MPI communication with a large number of threads.
- Our techniques include:
  - relaxation of wildcard semantics
  - tightly-coupled design of MPI and thread scheduler
  - resource management for cache locality

Future works

- MPI:
  - Waitany, Waitall, Waitsome…
- Thread scheduler:
  - Fairness and thread migration
- Low-level interface:
  - NIC offloading (Omnipath)
- Applications & Benchmarks

Related works

- Amer, Abdelhalim, et al. "MPI + threads: Runtime contention and remedies." *PPoPP*, 2015.
- Lu, Huiwei, et al. "MPI + ULT: Overlapping Communication and Computation with User-Level Threads." *HPCC*, 2015.
- Flajslik, Mario, et al. "Mitigating MPI Message Matching Misery." *ISC*, 2016.

Acknowledgement

- Alex Brooks, Nikoli Dryden (UIUC)
- Ron Brightwell (SNL)
- Pavan Balaji (ANL)

Thank you,
Question please!

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