Fast and Scalable Queue-Based Resource Allocation Lock on Shared-Memory Multiprocessors

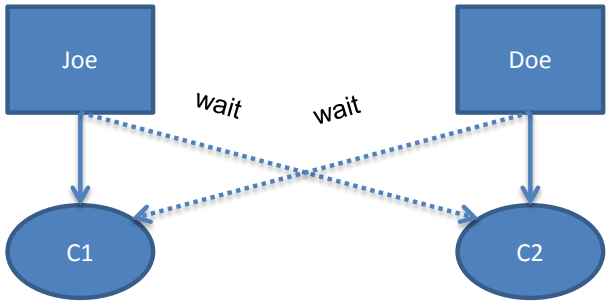
Deli Zhang, Brendan Lynch, and Damian Dechev

University of Central Florida, Orlando, USA

December 18, 2013

Mutual Exclusion on Multicore System

- Mutual exclusion locks are not composable



- Use of multiple mutual exclusion locks poses scalability challenge for date intensive application
  - BerkerlyDB spends over 80% of the execution time in its Test-and-Test-and-Set lock on a 32-core machine[1]

[1] Johnson et al., Shore-mt: a scalable storage manager for the multicore era. 2009

Resource Allocation Problem

Definition

Given a pool of k resources that require exclusive access, each thread may request $1 \leq h \leq k$ resources, and a thread remains blocked until all required resources are available.

- Resource allocation problem is a generalized mutual exclusion problem (k-mutual exclusion, h-out-k mutual exclusion)
- It is also an extension of the Dining Philosophers Problem (relaxing the static resource configuration)

Locking Protocols

- Assign a mutual exclusion lock to every resource
- Follow protocol to acquire locks one by one

Locking Protocols

- Assign a mutual exclusion lock to every resource
- Follow protocol to acquire locks one by one
  - Two-phase locking

Locking Protocols

- Assign a mutual exclusion lock to every resource
- Follow protocol to acquire locks one by one
  - Two-phase locking
  - Resource hierarchy

Locking Protocols

- Assign a mutual exclusion lock to every resource
- Follow protocol to acquire locks one by one
  - Two-phase locking
  - Resource hierarchy
  - Time-stamp locking

Locking Protocols

- Assign a mutual exclusion lock to every resource
- Follow protocol to acquire locks one by one
  - Two-phase locking
  - Resource hierarchy
  - Time-stamp locking
- Prone to conflict and retry

Batch Locking

- Centralized manager to distribute resources
- It handles resource request from one thread in one batch
  - Extended TATAS
  - Multi-resource lock

Extended TATAS

```
typedef uint64 bitset;

void lock(biteset* l,biteset r){
  biteset b;
  do{
    b = *l;
    if(b & r) //detect conflict
      continue;
  }while(CAS(l, b, b | r) != b);
}
```

- A bitset is an array of bits
- Represent a resource by one bit
- Detecting conflict by bitwise AND
- Handle acquisition in batch

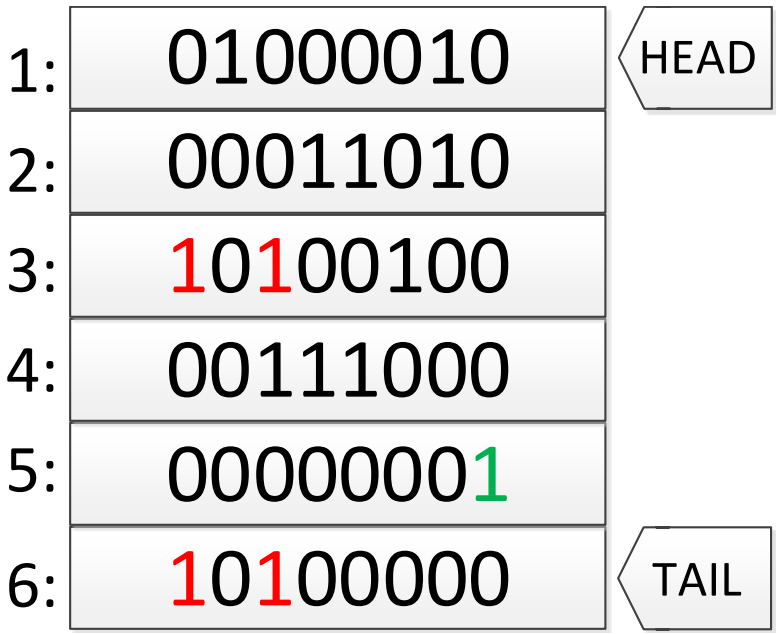
Extended TATAS

```
typedef uint64 bitset;

void lock(biteset* l,biteset r){
  biteset b;
  do{
    b = *l;
    if(b & r) //detect conflict
      continue;
  }while(CAS(l, b, b | r) != b);
}
```

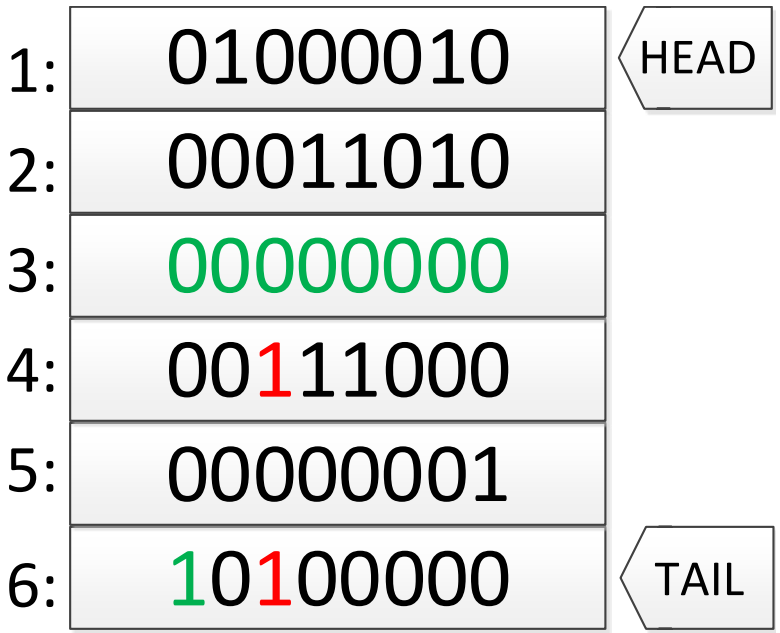
- A bitset is an array of bits
- Represent a resource by one bit
- Detecting conflict by bitwise AND
- Handle acquisition in batch
- Drawbacks
  - No fairness guarantee
  - Heavy contention
  - Limited number of resources

Queue-based Multi-resource Lock



- Ring buffer based concurrent queue
- Resolve conflicts in FIFO order
- Unbounded number of resources

Queue-based Multi-resource Lock



- Ring buffer based concurrent queue
- Resolve conflicts in FIFO order
- Unbounded number of resources

Data Structure

```
struct cell{
  atomic<uint32> seq;
  bitset bits;
}
struct mrlock{
  cell* buffer;
  uint32 siz;
  atomic<uint32> head;
  atomic<uint32> tail;
}
void init(mrlock& l, uint32 siz){
  l.buffer = new cell[siz];
  l.siz = siz;
  l.head.store(0);
  l.tail.store(0);
  for(uint32 i = 0; i < siz; i++){
      l.buffer[i].bits.set();
      l.buffer[i].seq.store(i);
  }
}
```

- Declaration
  - *Sequence number* as sentinel
  - `bits` as resource flags
  - Atomic queue `head` and `tail`
- Initialization
  - Allocate adjacent buffer cells
  - `bits` are initialized to 1s
  - `seq` are initialized to cell index

Lock Acquire

```
function ACQUIRE(mrlock* l, bitset r)
    loop
        pos ← l.tail, c ← ReadCell(l, pos), seq ← c.seq
        if seq - pos == 0 then
            if CAS(&l.tail, pos, pos + 1) succeeds then
                break
    c.bits ← r, c.seq ← pos + 1

    spin_pos ← l.head
    while spin_pos != pos do
        if IsDequeued(spin_pos) or NoConflict(spin_pos, r) then
            spin_pos++
    return pos
```

Lock Release

```
function RELEASE(mrlock* l, handle pos)
    ReadCell(l, pos).bits ← 0
    pos ← l.head
    while ReadCell(l, pos).bits == 0 do
        c ← ReadCell(l, pos)
        seq ← c.seq
        if seq - pos - 1 == 0 then
            if CAS(&l.head, pos, pos + 1) succeeds then
                c.bits ← ∼0
                c.seq ← pos + l.siz
        pos ← l.head
```

Sequence Number

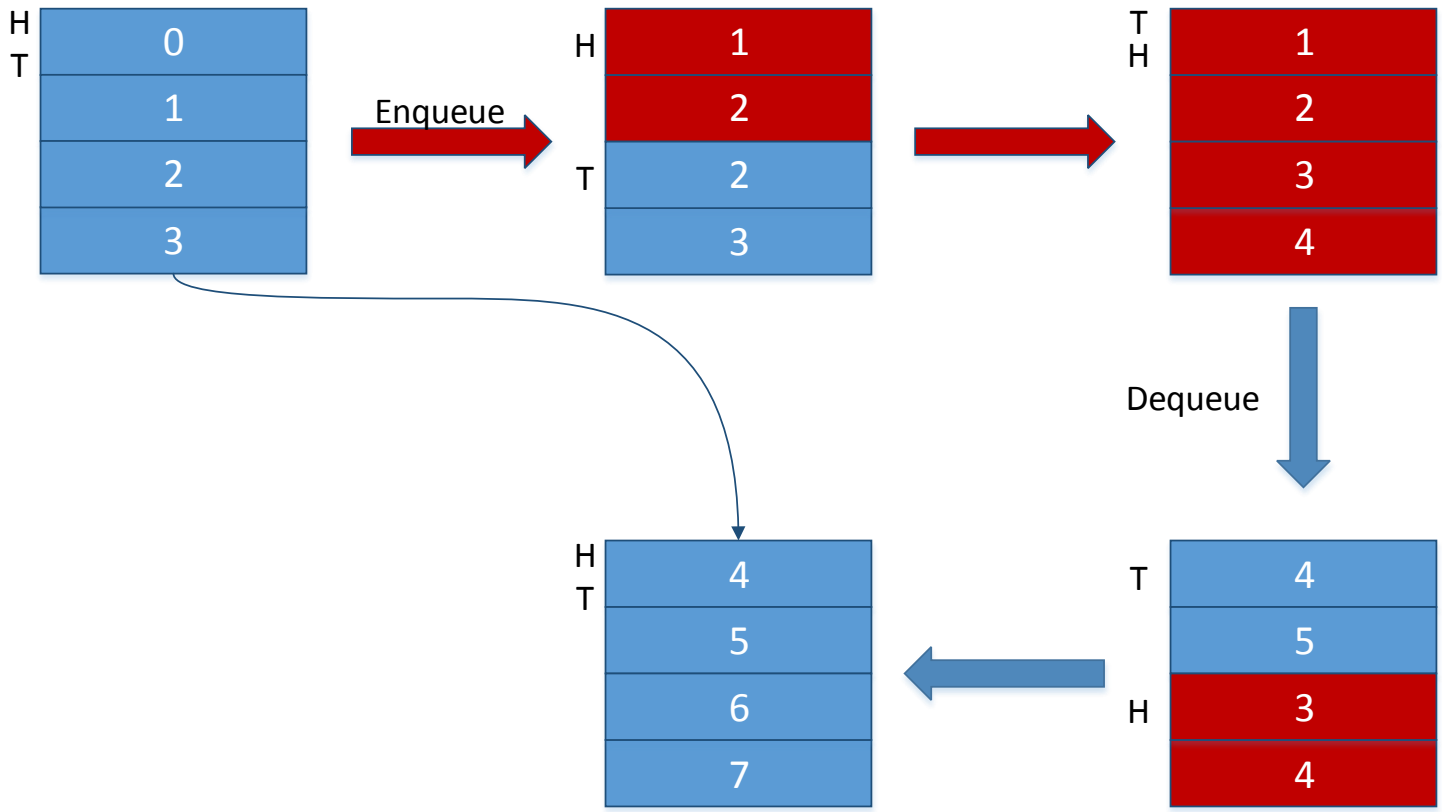


Figure: Updating flow of sequence numbers

Sketch of Correctness Proofs

- Concurrent update of the ring buffer is safe

Theorem

The head always precedes the tail; the tail is larger than head by at most N, where N equals to the size of the buffer.

- Non-atomic update of bitset is safe
  - Bitsets are initialized to 1s
  - Then written to specific request value by one thread

Theorem

In the presence of a single writer, intermediate values of the bitset during the write operation represent some **supersets** *of requested resources.*

Alternatives

- Two-phase locking
  - std::lock function with std::mutex (STDLock)
  - boost::lock function with boost::mutex (BSTLock)
- Resource hierarchy
  - with std::mutex (RHSTD)
  - with tbb::queue_mutex (RHQueue)
- Extended TATAS (ETATAS)

Testing Configurations

- 64-core NUMA system
  - 4 AMD Opteron CPUs with 16 cores per chip @ 2.1GHz
- Micro-benchmark
  - Tight loop to acquire/release locks
  - Randomize resource request prior to the loop
- Configuration
  - Resource: 2 to 1024
  - Threads: 2 to 64
  - Resource contention: 0% to 100% (number of resources requested per thread divided by the total number of resources)

16 Threads

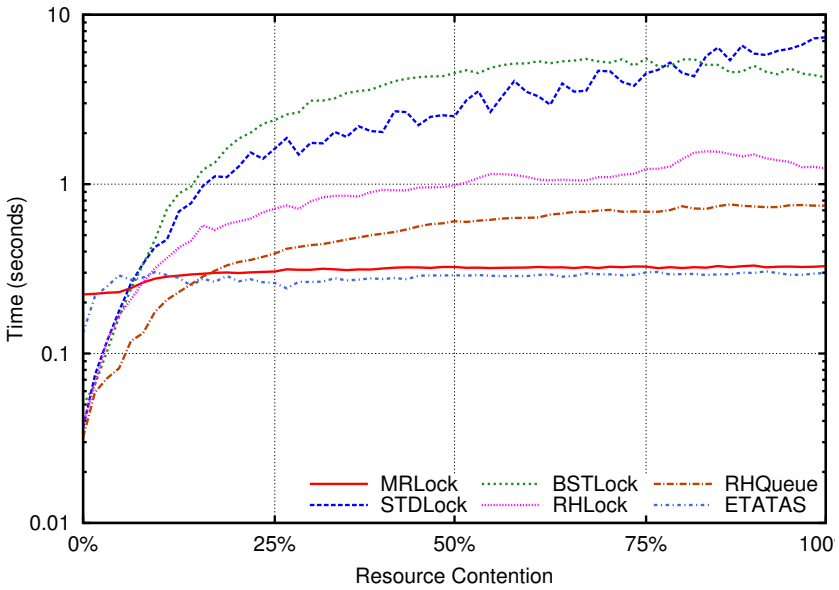


Figure: 64 Resources

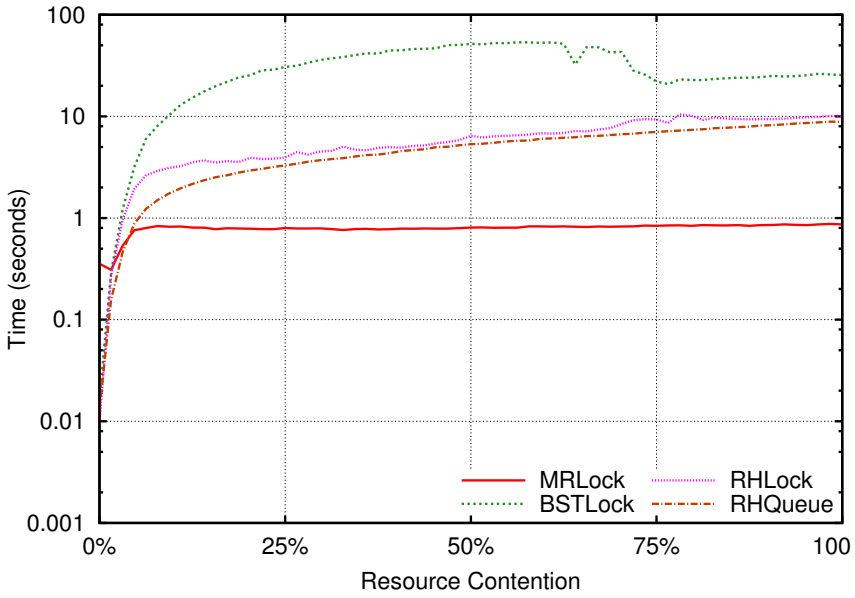


Figure: 1024 Resources

ETATAS, STDLock are excluded on the right because of lack of support for more than 64 resources.

Up to 64 Resources

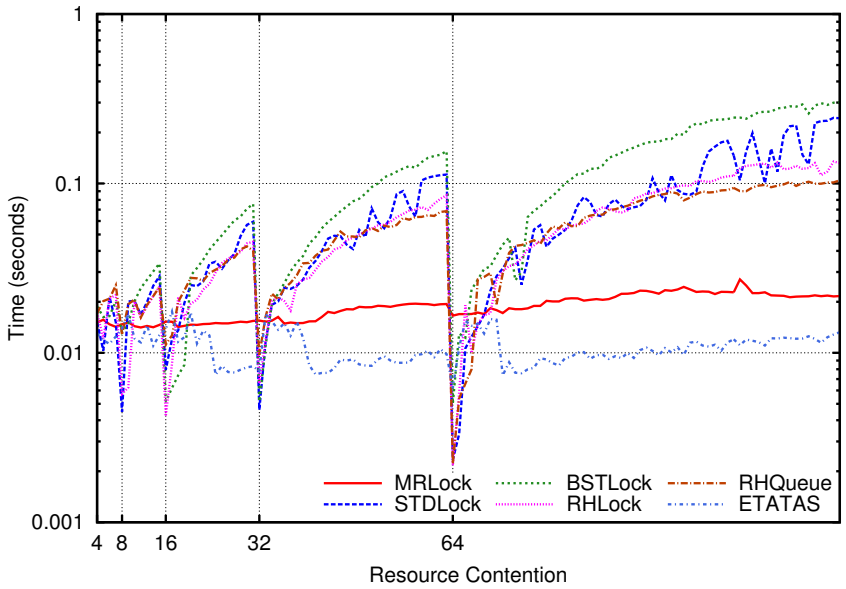


Figure: 2 Threads

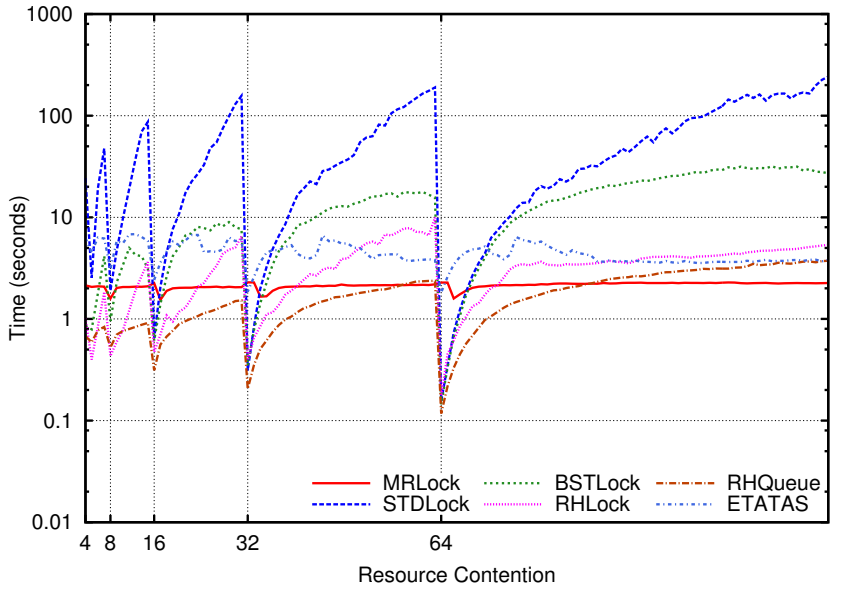


Figure: 64 Threads

Up to 1024 Resources

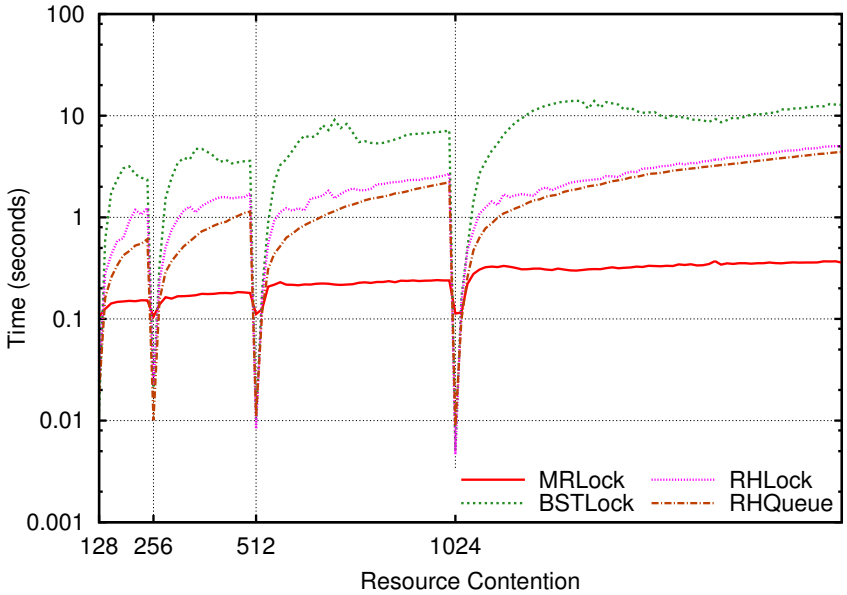


Figure: 8 Threads

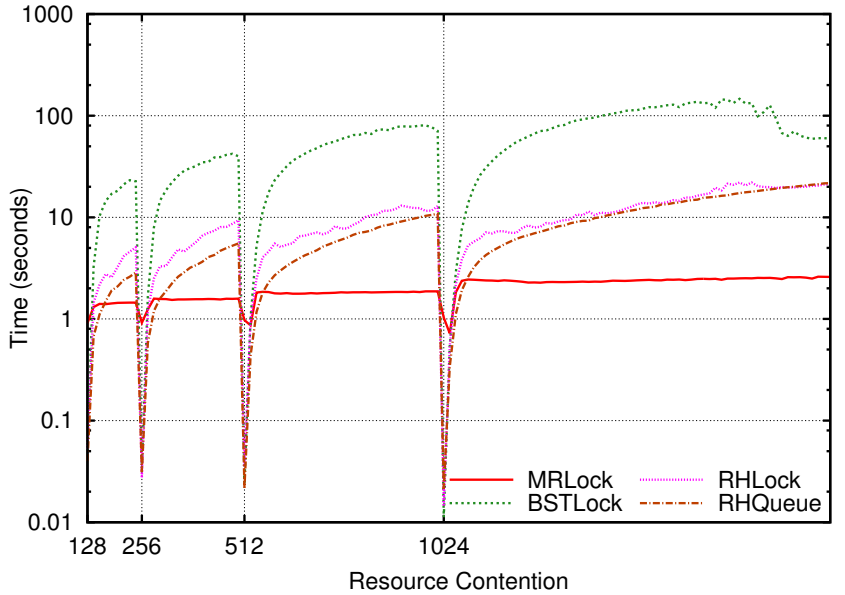


Figure: 32 Threads

Thread Scale

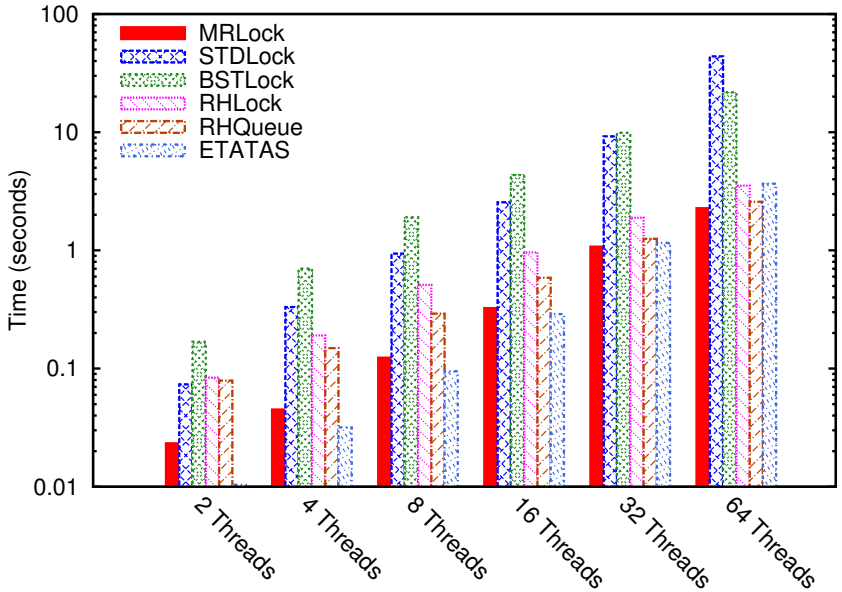


Figure: Contention 32/64 (50%)

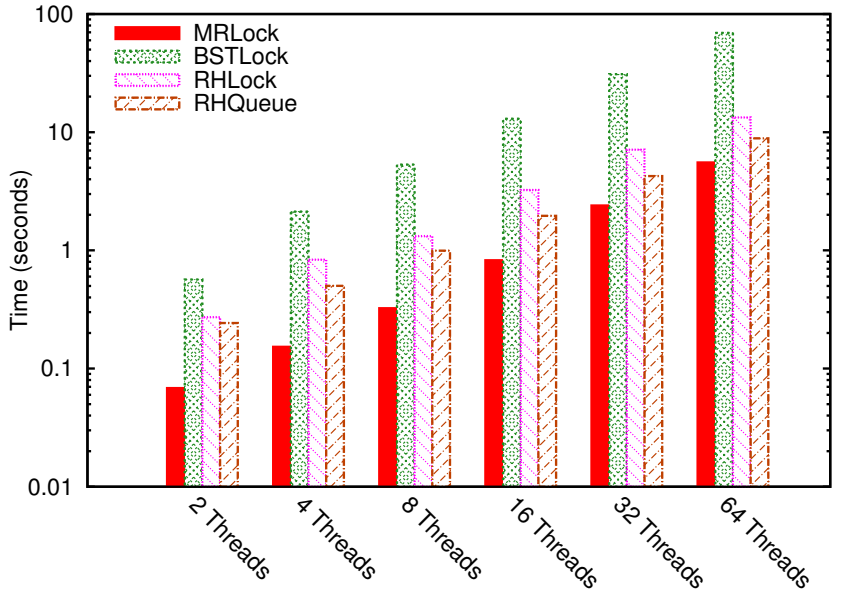


Figure: Contention 128/1024 (12.5%)

Conclusion and Future Work

- Algorithmic Advantage
  - FIFO ordering guarantees fair acquisition of locks
  - Support large number of resources with the use of bitset
  - Performance advantage under mid-to-high levels of contention
- Future Work
  - Adopting wait-free ring buffer to achieve starvation-freedom
  - NUMA-awareness
  - Adapting algorithm to compensate performance under low levels of contention

Questions?

Thank you!