Preemptible Atomics

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PURDUE
UNIVERSITY

(S3)

Why not Lock-based Synchronization?

Challenges of programming with mutual exclusion locks:

- ☑ avoiding data races
- ☑ choosing lock granularity
- ☑ enforcing lock acquisition order
- ☑ dealing with modularity and abstraction

& in hard real-time systems:

- ☑ bounding blocking time
- ☑ avoiding priority inversion

Preemptible Atomics

- Transactional concurrency control construct
  - *Designed for commodity uniprocessor embedded systems*
  - *Alternative to locks with, e.g., priority inheritance (PIP)*
- Atomicity
  - *All statements will execute, or none.*
- Strong Isolation
  - *High priority threads (HPT) preempt Atomics in LPTs*
  - *HPT execute without observing changes performed by LPT*

Example with Locks

```
class ThreadPoolLane {
  synchronized leaderExec(Request task) {
      if (borrowThreadAndExec(task))
        synchronized(rQueue) {
           rQueue.enqueue(task);
           numBuffered++;
      }
      ...
   }
class Queue  {
   final Object sObject = new Object();
   void enqueue(Object data)  {
       QueueNode node=getNode();
       node.value=data;
       synchronized(sObject) {
         // enqueue the object
       }
   }
```

from the UCI Zen real-time ORB

Example with Atomics

```
class ThreadPoolLane {
    @Atomic leaderExec(final Request task) {
        if (borrowThreadAndExec(task))

               rQueue.enqueue(task);
               numBuffered++;
        }
        ...
    }

class Queue  {

     @Atomic void enqueue(final Object data)  {
         QueueNode node=getNode();
         node.value=data;

           // enqueue the object
    }
```

Related Work

- *Bershad, Redell, Ellis.*
  Fast Mutual Exclusion for Uniprocessors, *ASPLOS, 1992.*
  -- no undo

- *Anderson, Ramamurthy, Jeffay,*
  Real-time Computing with Lock-Free Shared Objects, *RTSS, 1995.*
  -- non-blocking algorithms, no language support

- *Herlihy+, Harris+, Welc+,*
  Software Transactional Memory, *2003--2005.*
  -- weak isolation

- *Ringenburg, Grossman,*
  AtomCaml First-Class Atomicity with Rollback, *ICFP, 2005.*
  -- no real-time guarantees, simpler environment

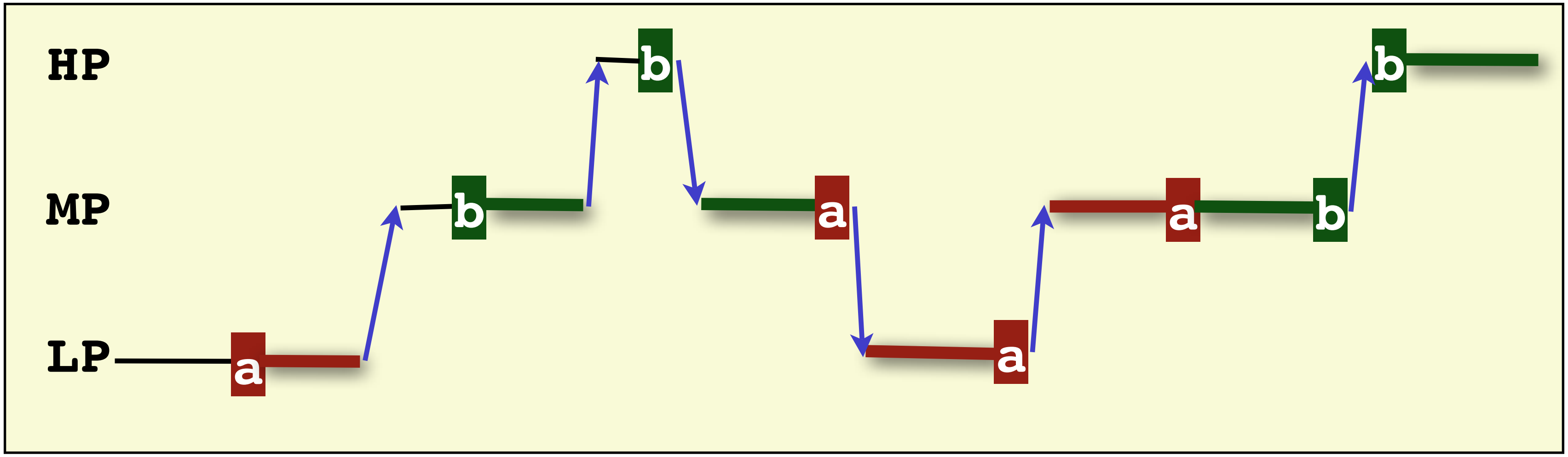
Semantics

```
@Atomic  method(...) { B }
```

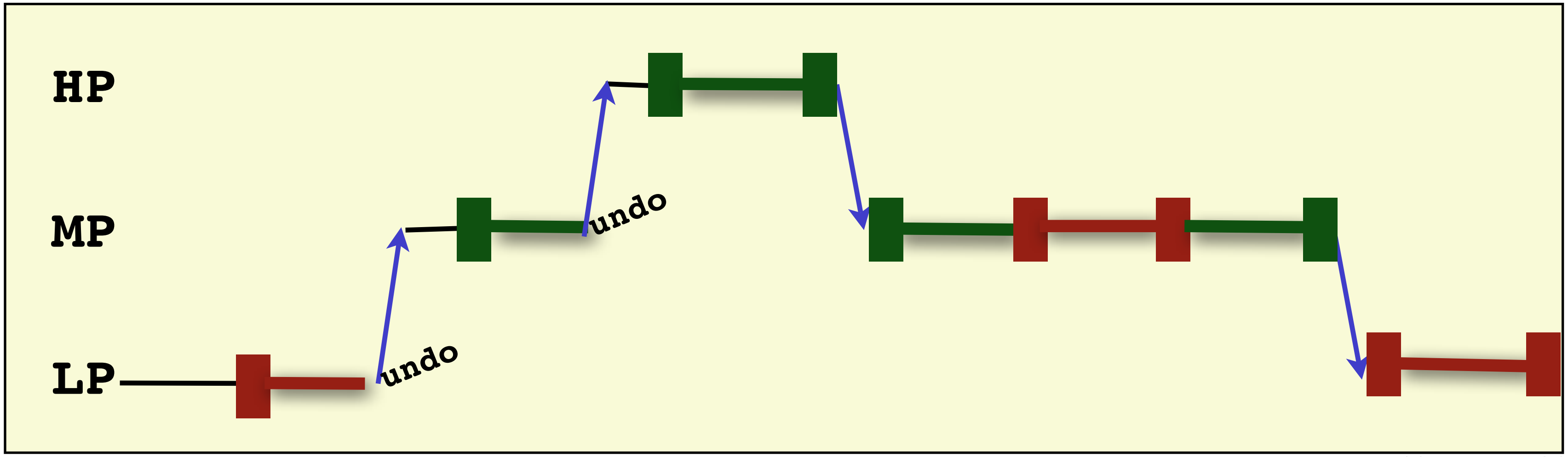
- `B` logically atomic
- `B` can be preempted by a higher-priority thread
- If preempted, `B’s` updates not be observed by HPT
- Nesting coalesced in a single atomic.

PIP locks vs Atomics

Locks with Priority Inheritance Protocol



Atomics



Schedulability

Assuming tasks scheduled with a rate monotonic scheme:

Theorem 1 *A set of n periodic tasks $\tau_i, 0 \leq i < n$ is schedulable in RM, iff*

$$\forall i \leq n, \exists R_i : R_i \leq p_i$$

$$R_i = C_i + \max_{j \in lp(i)} U_j + \sum_{j \in hp(i)} \left\lceil \frac{R_i}{p_j} \right\rceil (C_j + U_i + W_i)$$

Atomic vs. PIP | PCE

- **Priority Inheritance Protocol:**
  - A HPT may block for multiple LPT
  - Deadlock and data races
  - Non-real-time LPTs may cause unbounded blocking
    programmer error, but an easy one to make.
- **Priority Ceiling Protocol:**
  - HPTs may still have to wait for completion of a LPT
  - Hard to assign ceilings with libraries, changing thread priorities
- **Preemptible Atomic Region:**
  - HPTs only block for higher-level tasks.
  - At most one abort per context switch.
  - no dead-locks & no live-locks
    if schedulable

Refactoring Legacy Code

- Locks ⇒ Atomics = ~straightforward
- All uses of a particular lock must be made into atomic
- Consider:

```
public class Vector extends AbstractList ... {
   @Atomic public void insertElementAt(Object o ...
   @Atomic public int size() { ...
```

- *N.B. requires preemptible & logged* `System.arraycopy`

Locks and Atomics

- Atomic must coexist with PIP-locks
- Lock long lived, write-intensive methods
- HPT in an atomic needs to acquire lock held by a LPT:

  undo ⇒ boost and execute LPT ⇒ reexecute HPT

- *Wait / Notify can be used when needed*

IMPLEMENTATION

Implementation

- A method "`@Atomic f(){ x++; B(); }`" is translated to:

```
 while (true) {
   try{
     try {  Transaction.start();
        log(x);
        x++
       B_T();
     } finally { Transaction.commit(); break; }
  } catch(Retry _) { }      // undo performed by aborting thread
}
```

- `finally` implemented by catching all subclasses of `Throwable`
- `Retry` not a subclass of `Throwable`, not get caught by `finally`

Scaling-Up

- **I/O** - How do you undo a write to the screen? You don't. Could support buffering of output/replay of input or using compensations
- **Garbage collection** - Addresses stored in log need to be updated. GC must be preemptible and cannot preempt RT task. Now - Rollback the Atomic if a GC is triggered.
- **Dynamic class loading** - Could generate transactional versions of methods on the fly. Now - RT does not require dynamic class loading.
- **Reflection** - Methods invoked reflectively from an Atomic must be transactional. Simple check in the implementation of the reflection package.
- **Regions** - Memory allocated within a region must be returned on abort to avoid leaks.
- **Asynchronous Transfer of control** - Defer until interruptible, then abort.

Optimizations

- Turn an atomic into a nop

```
@Atomic m()  =>  @Uninterruptible m()
```

- Safe iff execution time is bounded
- Heuristic: short, non-looping methods
- (n.b. not safe for lock-based sync)

Extensions

- Prescient commits

  exception throwing code does not affect or rely on user allocated heap data

- Open nesting

  string interning requires that strings not be undone as the VM kernel has pointer on char array

- Exposed regions

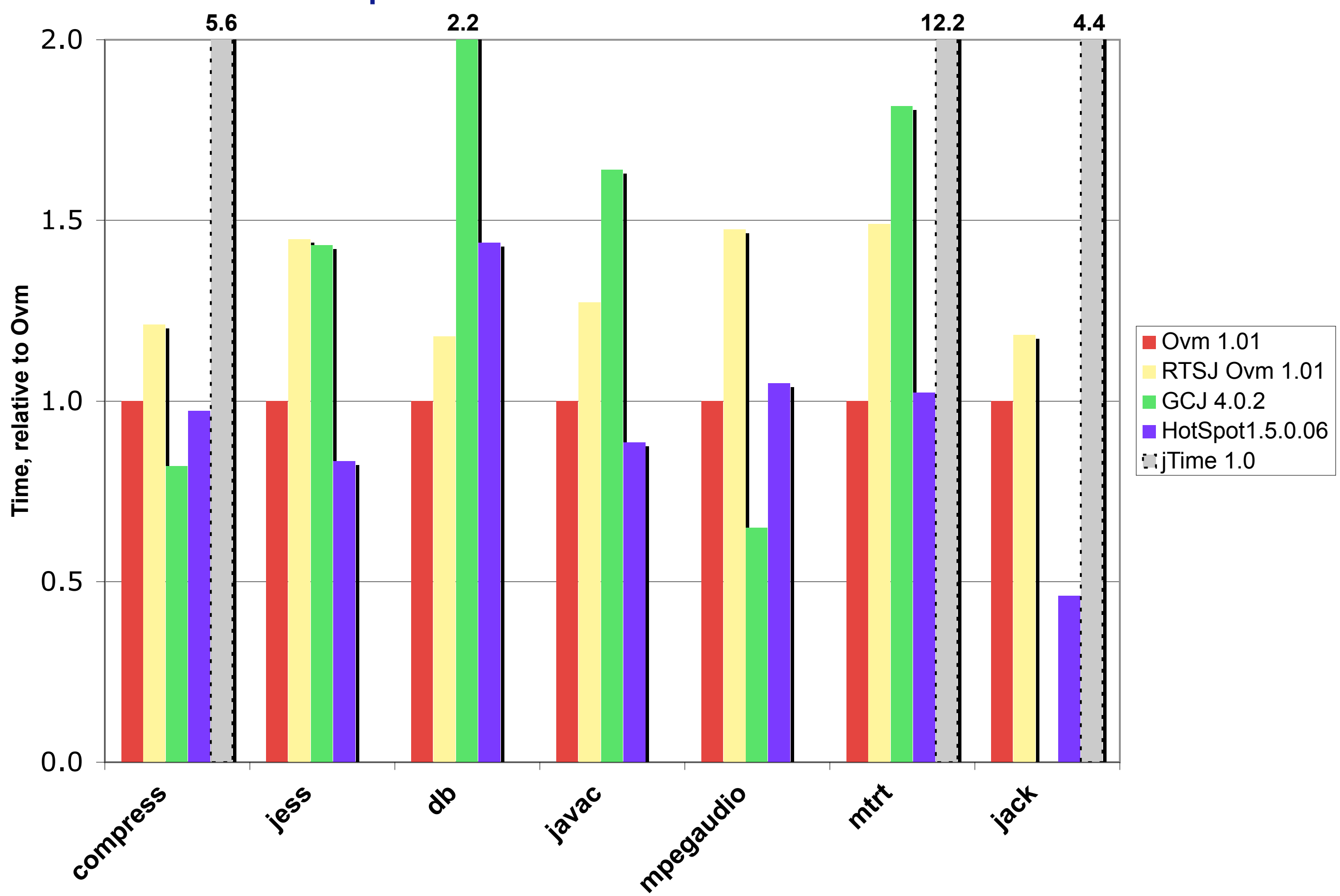
  operations are immediately made visible, aborts are deferred,

  e.g. for debugging

Evaluation

SpecJVM98

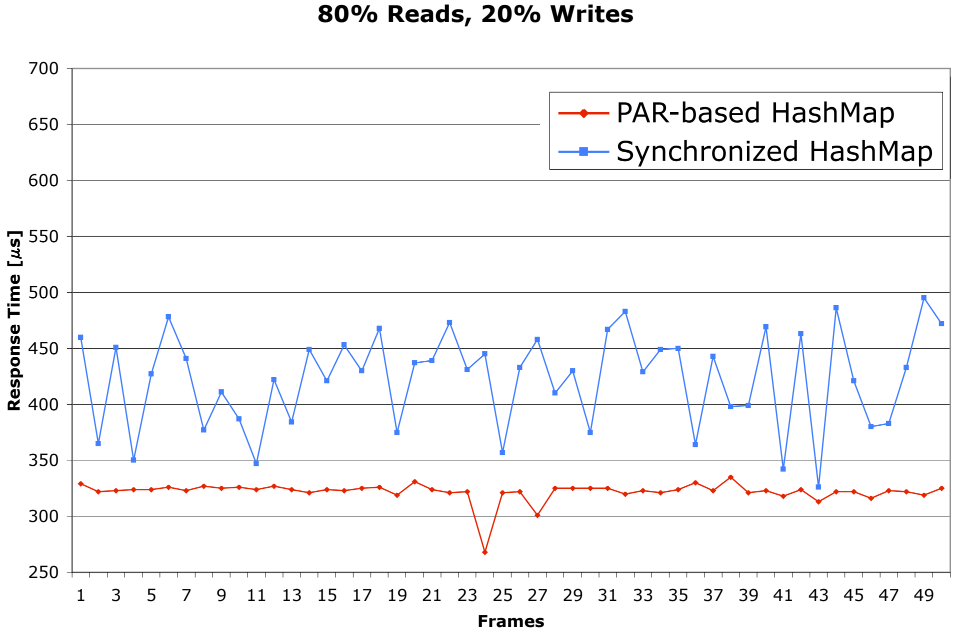
- Ovm performance is competitive.

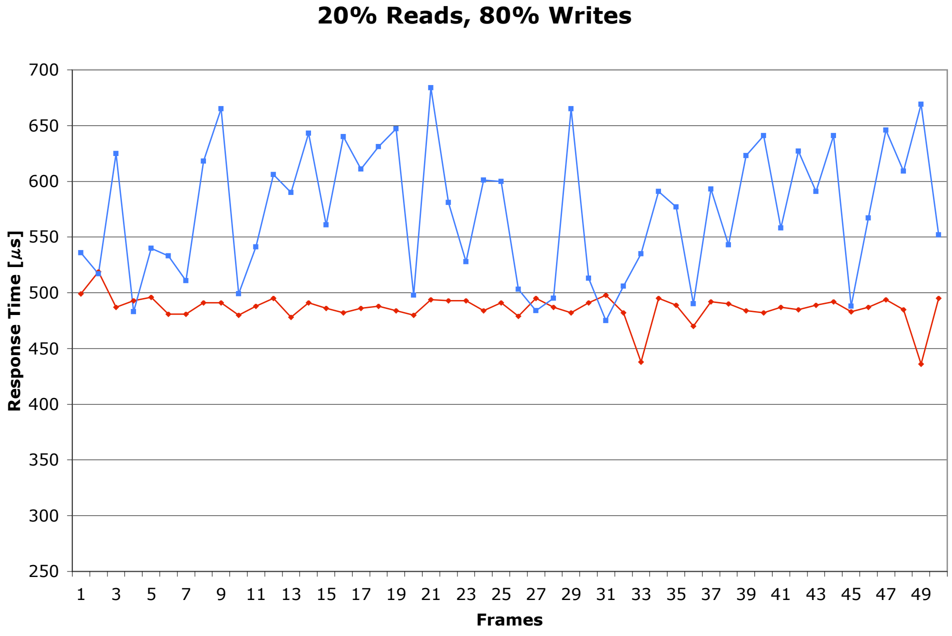


AMD Athlon XP1900+, 1.6GHz, 1GB RTLinux, 2.4.7-timesys-3.1.214

Microbenchmarks

- HTP response times





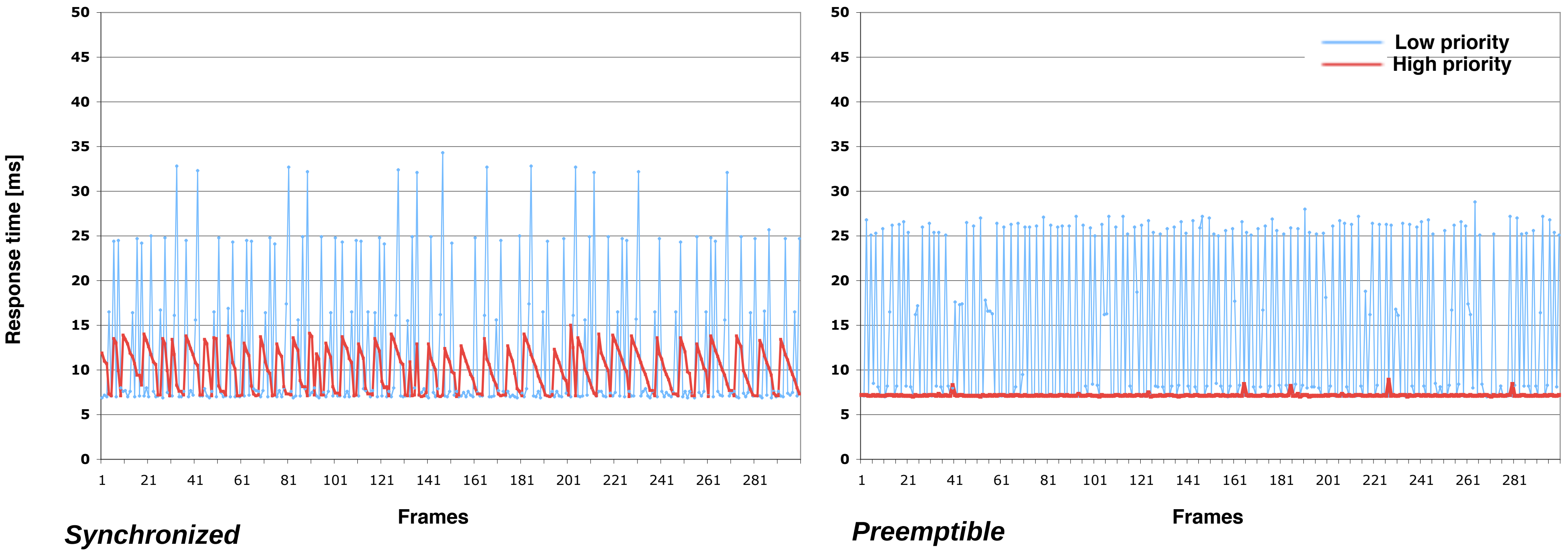
2 threads, performing mix of get/put ops into a HashMap

300Mhz PPC, 256MB memory, Embedded Planet Linux

Ovm RTSJ VM, AOT, priority preemptive, PIP locks

UCI's RT-ZEN

- Real-time CORBA ORB written in RTSJ, 179,000 LOC,
- ~600 synchronized stmts mechanically translated to atomics



30 HPT/70 LPT. Measure time to process a request

AMD Athlon XP1900+, 1.6GHz, 1GB RTLinux

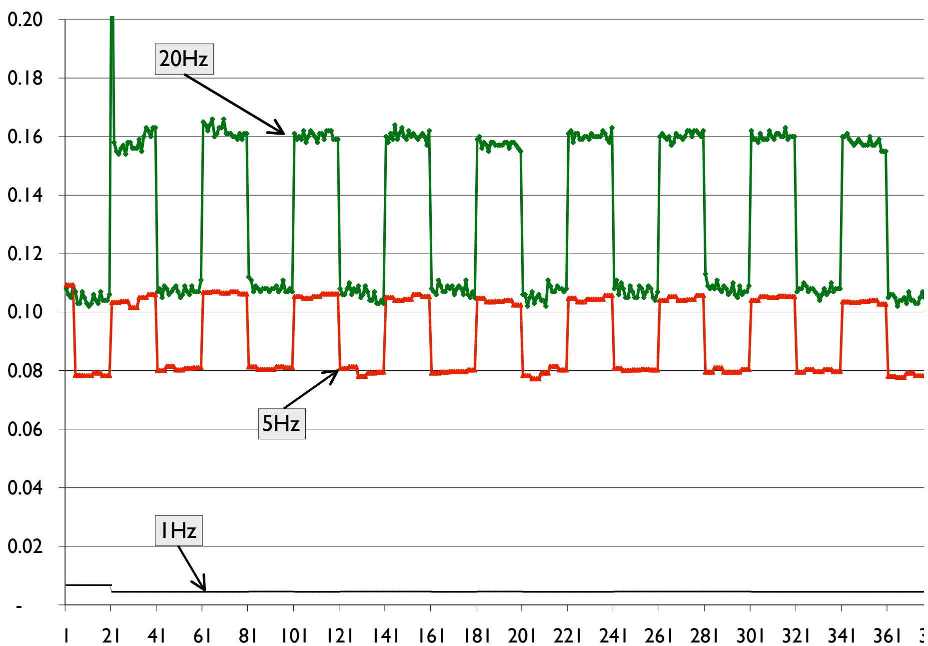
PRiSMj

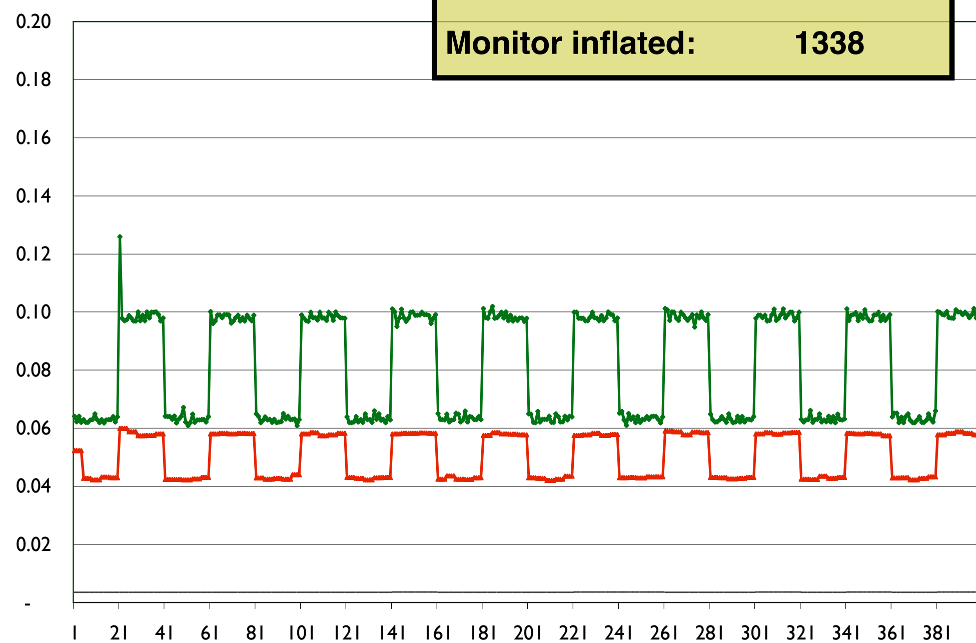
- Avionics applications from the Boeing Company
- Benchmark scenarios w. different workloads / components
- Oscillating modal behavior
- ~100 periodic threads in three main rate groups: 1, 5, 20Hz
- 953 Java classes, 6616 methods.
- Deployed on a ScanEagle

PRiSMj: 1X

- High responsiveness, small workloads

Atomics (aborts):	**3'180 (0)**
Reads Max (median):	**514 (6)**
Writes Max (media):	**115 (3)**
Monitor inflated:	**1338**





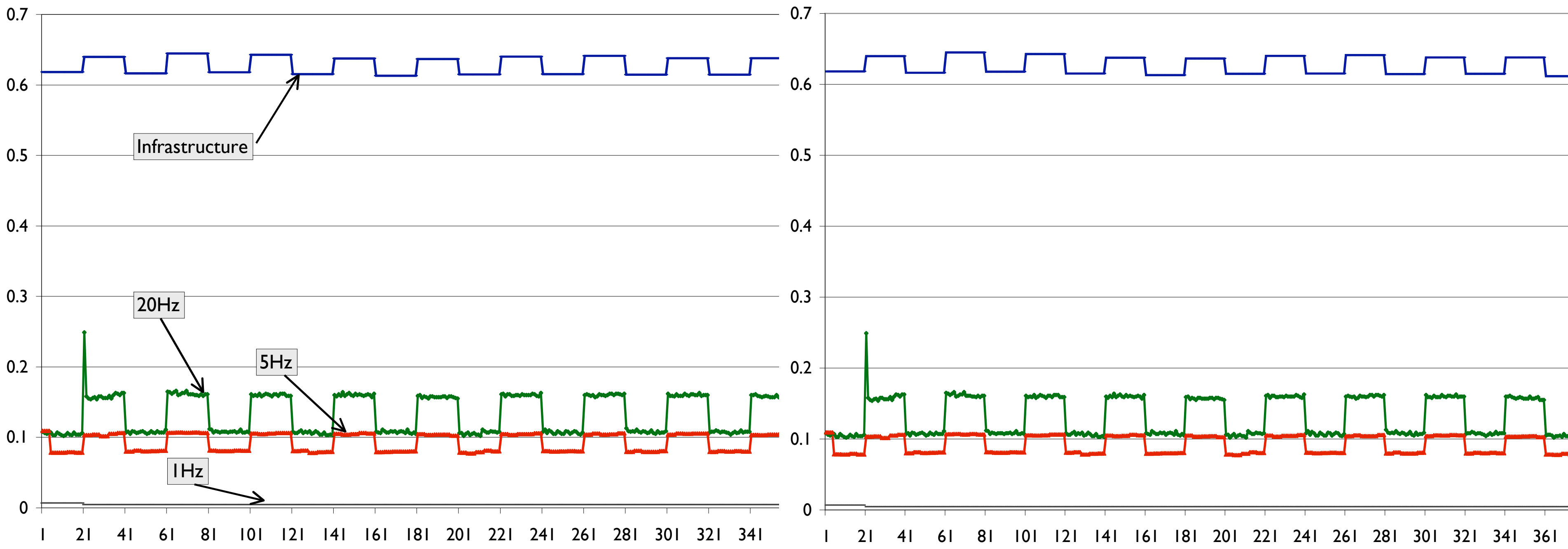
`300Mhz PPC, 256MB memory, Embedded Planet Linux`

`Ovm RTSJ VM, AOT, priority preemptive, PIP locks`

PRiSMj: 100X

- Large workloads

Atomics (aborts):	151'438 (5)
Reads Max (median):	5'399 (3)
Writes Max (median):	1'158 (0)



300Mhz PPC, 256MB memory, Embedded Planet Linux

Ovm RTSJ VM, AOT, priority preemptive, PIP locks

Conclusions

- Easier to write reusable correct concurrent real-time code
- Improve responsiveness with little impact on throughput
- Not a replacement for locks, another tool in the box

source code at http://ovmj.org

[Manson+. *Preemptible Atomic Regions for Real-time Java.* **RTSS'05**]

[Baker+. *A Real-time Java Virtual Machine for Avionics.* **RTAS'06**]