Predictable Execution: Operating Systems Issues

Michael B. Jones — Microsoft Research

Joint work with

John Regehr — University of Virginia

Goal: Coexisting Independent Real-Time Applications

- **Independently developed**
- **Predictable concurrent execution of**
  - **real-time *and* non-real-time apps**
- **Meeting all apps' timing needs**
  - **Informing apps when not possible**

Overview

- Developing soft real-time scheduler for Windows NT
  - Described in second half of talk
- Predictability issues
  - How large are observed worst-case thread scheduling latencies?
  - What causes them?
  - What has been done about them?
  - Described in first half of talk

Part I:

The Problems You’re Having May Not Be the Problems You Think You’re Having:

Results from a Latency Study of Windows NT

Research Context

- Developing soft real-time scheduler for Windows NT
- Predictability issues:
  - How large are observed worst-case thread scheduling latencies?
  - Can they be improved?
- Measured actual latencies

NT Latency Results

- Typically can schedule tasks every small number of milliseconds
- But ill-behaved drivers, hardware can take many milliseconds
  - Software delays of up to 16ms observed
  - Hardware delays of up to 30ms observed

Results from NT 5, Pentium II-333

Deferred Procedure Calls

- Analogous to Unix bottom halves
- Are preempted by interrupts
- Preempt normal threads
- May not block
- Are run in FIFO order
- Typical Uses:
  - I/O Completion Processing
  - Background Driver Housekeeping

Non-Problems

- Interrupts
  - Interrupt handlers needing substantial work queue DPCs
  - Never observed interrupt handler taking substantial fraction of ms
- Ethernet Packet Processing
  - With back-to-back 100Mbit incoming packets of UDP or TCP data:
    - Longest observed DPC 600µs
    - Longest delay of user code ~2ms
- Tested four common Ethernet cards

Problem: "Unimportant" Background Work

- DEC dc21x4 PCI Fast 10/100 Ethernet
- 6ms periodic DPC every 5s
  - Autosense processing
- Most of 6ms in five 0.88ms calls to routine that reads device register that:
  - Writes a HW register – 1.5µs
  - Stalls for 5µs
  - Writes HW register again – 1.5µs
  - Stalls for 5µs
  - Reads a HW register – 1.5µs
  - Stalls for 5µs
- And does this 16 times! (once per bit)

Another Long DPC: Intel EE 16

- Intel EtherExpress 16 ISA Ethernet
- 17ms DPC every 10s
- Card reset for no received packets

Amusing Observation

- Unplugging Ethernet makes latency worse!
  - Despite conventional wisdom to the contrary

Even Worse: Video Cards

- Video cards and drivers conspire to hog the PCI bus
- Dragging large window locks out interrupts for up to 30ms
- Obliterates sound I/O, for instance
- Can set registry key to ask drivers to behave, but not default
  - No problem when set correctly
- Manufacturers' motivation: WinBench ~ 5% improvement

Video Card Misbehavior Details

- Don’t check if card FIFO full before write
  - Eliminate a PCI read
- Stalls PCI bus if full to prevent overflow
  - Even with AGP, big blits are slow
- Problem observed on:
  - AccelStar II AGP
  - Matrox Millenium II
- Several other major cards also do this

Example Bug: Multimedia Timers

- MP HAL uses 976μs interrupt period
- Multimedia timers compute absolute time for next wakeup in whole ms
  - Converted to relative wakeup time and passed to kernel
- Interrupt occurs just before wakeup
  - Timer doesn't fire
  - Next time, fires twice to catch up
- Fix: compute wakeup in 100ns units

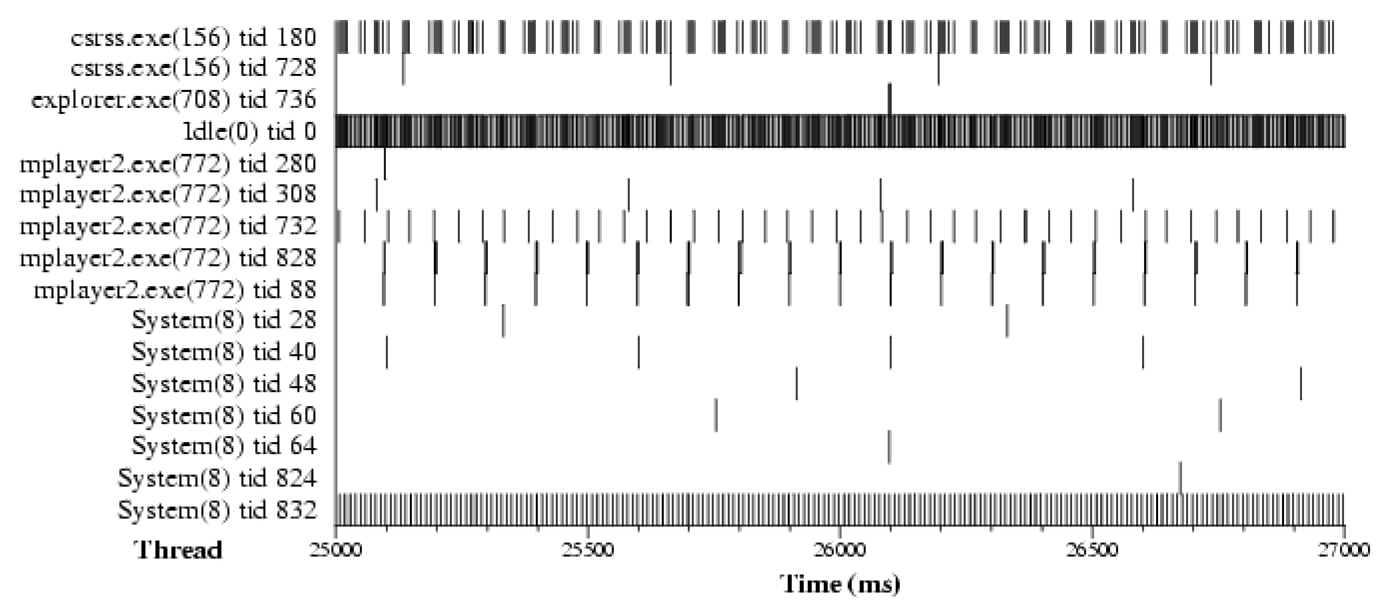
Windows Media Player Audio Dropouts

- Playback glitches when in contention with other apps
- Concerted effort to find, fix causes before Windows 2000 ship

Media Player Thread Structure (Simplified)

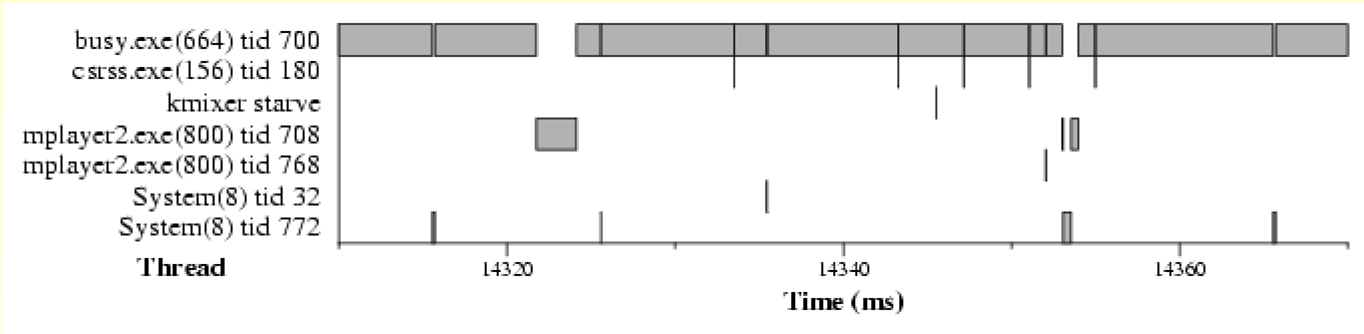
Thread	Period (ms)	Priority
Kernel Mixer	10	24
MP3 Decoder	100	9
Disk Reader	2000	8
User Interface	45	8

MP3 Playback w/o Contention



- **Working fine**
- **Kmixer thread *(bottom)* runs every 10ms**
- **MP3 decoder *(middle)* runs every 100ms**

Priority Inversion Caused By Competing Thread



- **Priority inversion at time 14324ms**
- **Busy thread *(top)* preempts decoder thread while holding kmixer buffer lock**
- **Kmixer *(bottom)* starves causing audio dropout**

- **Fix: Raise priority in decoder to that of kmixer before acquiring lock**
  - **Manual application of Priority Ceiling Protocol**

Lesson

Your Intuition About Performance is Wrong

Only Measurement Reveals the Truth!

Bottom Line

- **Yes, NT can do RT scheduling**
- **Have done a prototype**
  - **But will be of limited value if unscheduled activities continue taking tens of milliseconds**
- **NT developed, tested for *throughput***
  - **Not small numbers of ms of latency**
  - **Improvement will require**
    - **Systematic latency testing**
    - **Latency requirements specifications**

Progress Since Initial Work

- WHQL tests for video drivers
  - Verify PCI timing with hardware
- Many timing bugs found, fixed
  - E.g., media player priority inversion

- Attempting to institute systematic latency specifications and testing
  - Interrupt hold times & counts
  - DPC hold times & counts
  - Standards for use of priority values

Part II:

CPU Reservations and Time Constraints: Implementation Experience on Windows NT

Part II Outline

Introduction

Rialto Background

Windows NT Implementation

Performance and Traces

Related Work and Conclusions

What We Did

- **Created Rialto/NT**
  - **Based on Windows 2000**
  - **Added CPU Reservations & Time Constraints**
    - **Abstractions originally developed within *Rialto* real-time system at Microsoft Research**
- **What's new**
  - **Coexistence with Windows NT scheduler**
  - **Multiprocessor capability**
  - **Periodic clock**
    - **As opposed to fine-grained individually scheduled interrupts**

Real-Time

- Real-time computations have deadlines
- Examples
  - Fly-by-wire aircraft:
    - Missed deadline may endanger the aircraft
  - Soft modem:
    - Missed deadline may reset the connection
  - Video conferencing:
    - Missed deadline degrades audio or video quality

Why not use Windows NT as is?

- **Real-time using priorities requires global coordination**
  - **Windows is an open system**
    - **Priority inflation**
  - **No path for timing information**
- **There are scheduling algorithms that *do not* require global coordination**
  - **CPU Reservations and Time Constraints**
  - **Apps state timing requirements directly**
  - **Independently developed apps can run concurrently**

Teaser Capability

- **Apps can ask scheduler:**
  - **"Can I do 5ms of work between now+30ms and now+40ms?"**
- **Scheduler answers either:**
  - **"I guarantee it" or**
  - **"You probably can't"**
- ***Guaranteeing this 5ms work in future 10ms interval does not require reserving 50% of CPU for next 40ms***

How did we do it?

- Explicitly represent future time
- Map app declarations of timing needs into grants of future time

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Enables:

- Advance guarantees to applications, or
- Denial of requests up front

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Abstraction: CPU Reservation

- **Guaranteed execution rate and granularity for a thread**
  - ***X* units of time out of *every Y* units, e.g.**
    - 1ms every 5ms
    - 7.5ms every 33.3ms
    - one second every minute

Abstraction: Time Constraint

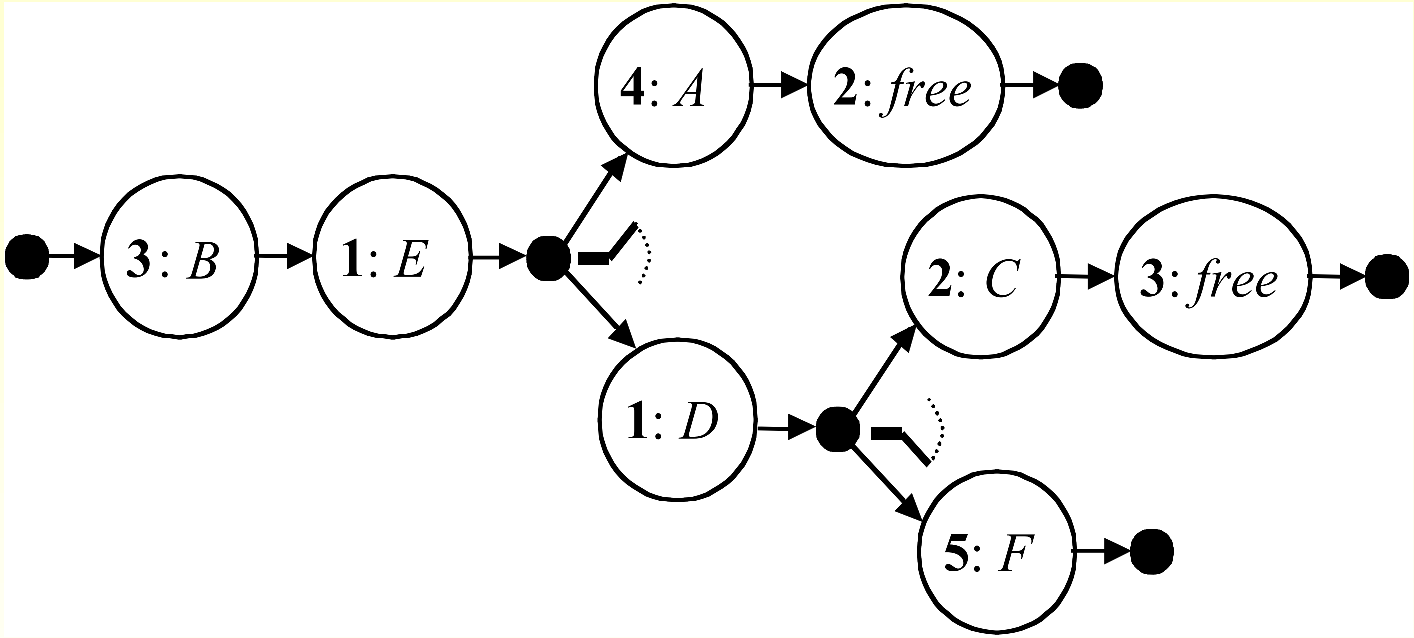
- **Deadline-based thread execution**
  - **Guarantees execution within interval, or**
  - **Proactively denies constraint request**

```
schedulable = BeginConstraint (time_interval, estimate);
if (schedulable) then
    Do normal work under constraint
else
    Transient overload -- shed load if possible
time_taken = EndConstraint ();
```

Implementation: Precomputed Scheduling Plan

- Tree-based periodic map of time
  - Supports widely varying periods
- Allocation of future time intervals
  - Ongoing for CPU Reservations
  - One-shot for Time Constraints
- Enables efficient:
  - Scheduling decisions
  - Feasibility analysis for constraints
  - Guarantees for reservations, constraints

Scheduling Plan Example



Thread	A	B	C	D	E	F
Amount	4ms	3ms	2ms	1ms	1ms	5ms
Period	20ms	10ms	40ms	20ms	10ms	40ms

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Using the Windows NT Scheduler

- **Rialto/NT uses existing priority scheduler to schedule its threads**
  - **Rialto/NT elevates thread priorities to cause dispatching**
- **Existing apps, abstractions work as before**
- **Windows NT scheduler also can schedule Rialto/NT threads**

Multiprocessor Issues

- One scheduling plan per processor
  - Tree walking happens on all plans
  - Heuristic: add new reservation to plans in increasing order of processor utilization
- Plans *not* pinned to particular CPUs
  - Allow NT scheduler to choose CPU
  - Rely on schedule properties, affinity to run threads mostly on same CPU
  - Permits opportunistic scheduling on other processors by existing scheduler

Affinity vs. Priority

- **Rialto/NT counts on priority elevation to cause thread dispatching**
  - **No contention because at most one elevated (Rialto/NT) thread per CPU**
- **On MP highest priority threads not always scheduled**
  - **Heuristics sometimes elevate thread affinity over thread priority**
- ***Changed scheduler to immediately dispatch Rialto/NT elevated-priority threads when ready***

Discrete Time

- **Windows NT clock interrupts on periodic basis**
  - **Typically 10-15ms, HAL-dependent**
  - **Can usually be set to 1ms period**
- **Discrete interrupts limit enforceable scheduling granularity**
- **So, Rialto/NT:**
  - **Initializes interrupt period to 1ms**
  - **Aligns rescheduling with clock interrupts**

Implementation Details

- Reschedule runs in DPC context
  - Use NT kernel timers to schedule DPCs
- Rialto/NT threads run at priority 30
  - Second highest Windows NT priority
  - Other values could be chosen
- New plans for reservations computed in requesting thread context
  - Optimistic concurrency control to avoid perturbing existing schedule

Non-invasive Implementation

- Easier to argue correctness
- Modified only two kernel routines
  - Changed behavior of one
- Added to the kernel:
  - 6000 lines of C
  - 4 system calls

Complication: Unpredictable Dispatch Latency

- **When latency occurs we:**
  - **Penalize the running thread**
  - **Keep the schedule on time**
- **Causes of scheduling latency:**
  - **Interrupt handlers**
  - **Kernel code running at high IRQL**
  - **Long DPCs**
- **Latencies controllable through concerted latency testing discipline**

Better Living Through Simulation

- **Rialto/NT runs in simulator in addition to kernel**
  - **Exactly the same sources**
- **Makes some debugging *much* easier**
  - **Reproducible runs**
  - **Better tools**
  - **No race conditions**
  - **Reboot time not in critical path**

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Test Platform

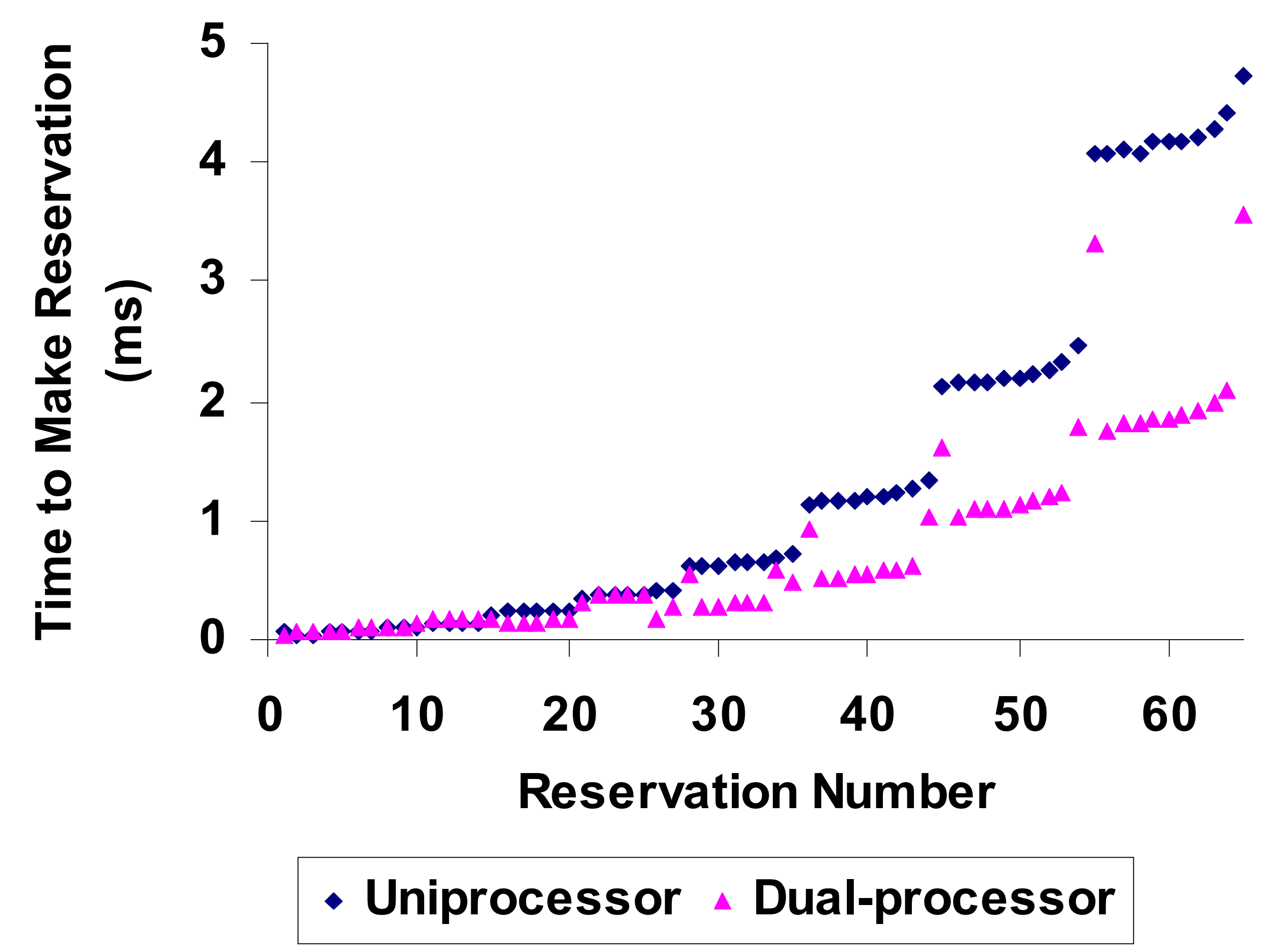
- 333 MHz Pentium II PCs
  - 128MB RAM
  - Intel EtherExpress Pro
  - Adaptec SCSI
- Single- and dual-processor tests

Context Switch Time

- **Tested:**
  - **10 threads on released Windows 2000 beta 3**
  - **10 Rialto/NT threads with CPU Reservations**
- **Rialto/NT adds 8μs to median context switch time**
  - **0.8% overhead at 1ms scheduling granularity**

Time to Acquire Reservations

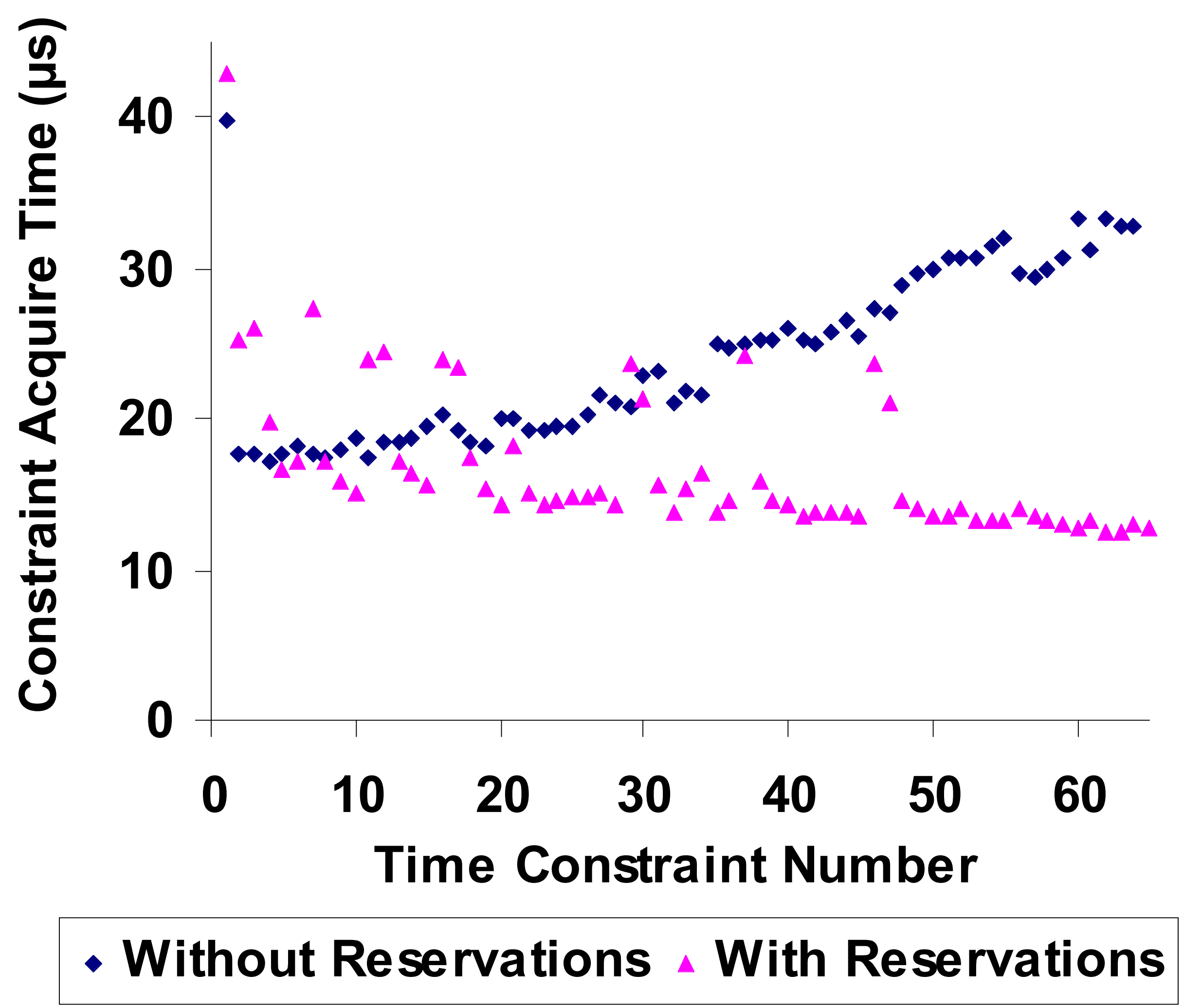
Reasonable even in pathological cases



Times to begin simultaneous reservations

Time to Acquire Constraints

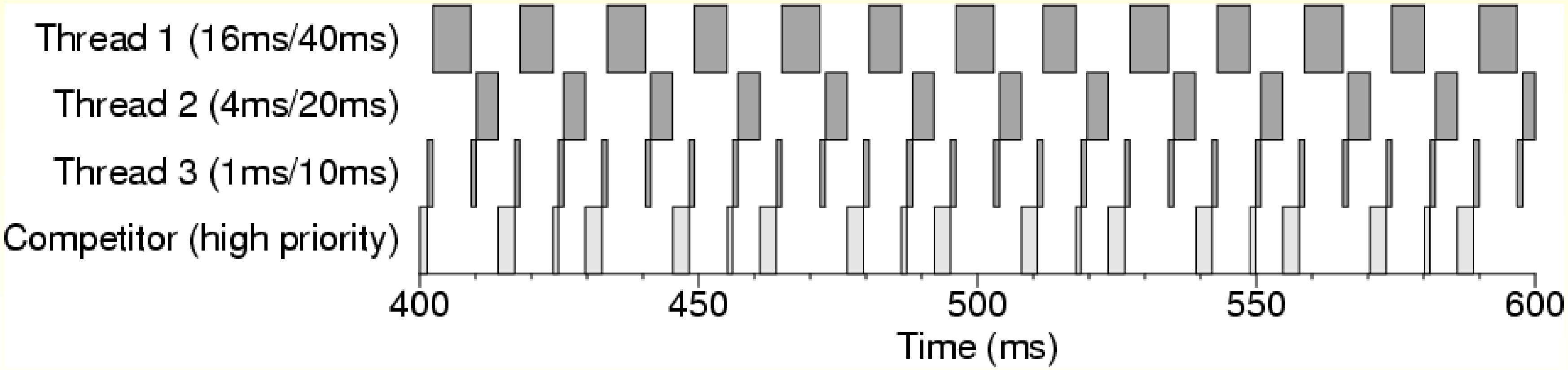
Reasonable even in pathological cases



Times to begin simultaneous constraints

Reservations with a Background Thread

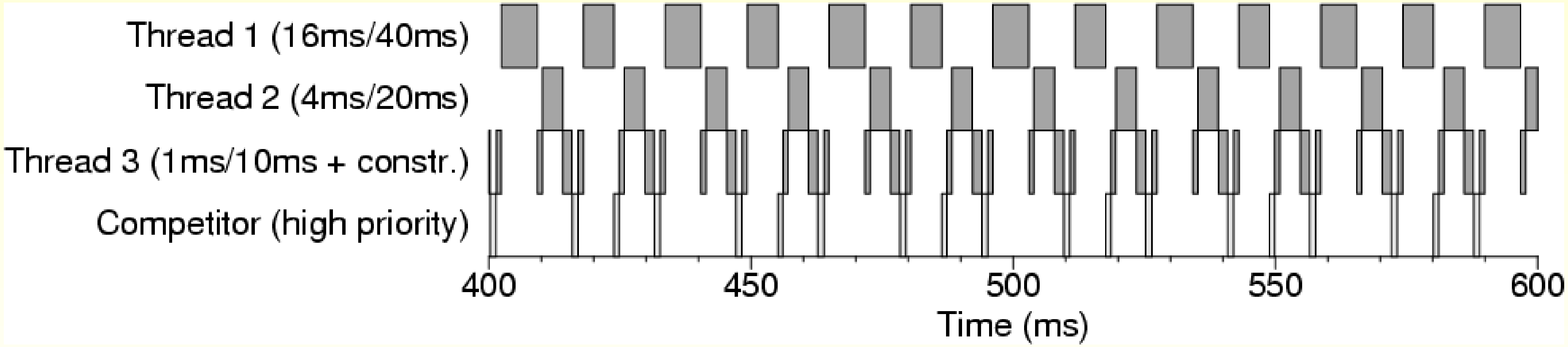
Threads run only during time assigned to their reservations



1 processor, 3 threads with reservations, 1 high-priority competitor thread

Reservations and Constraints

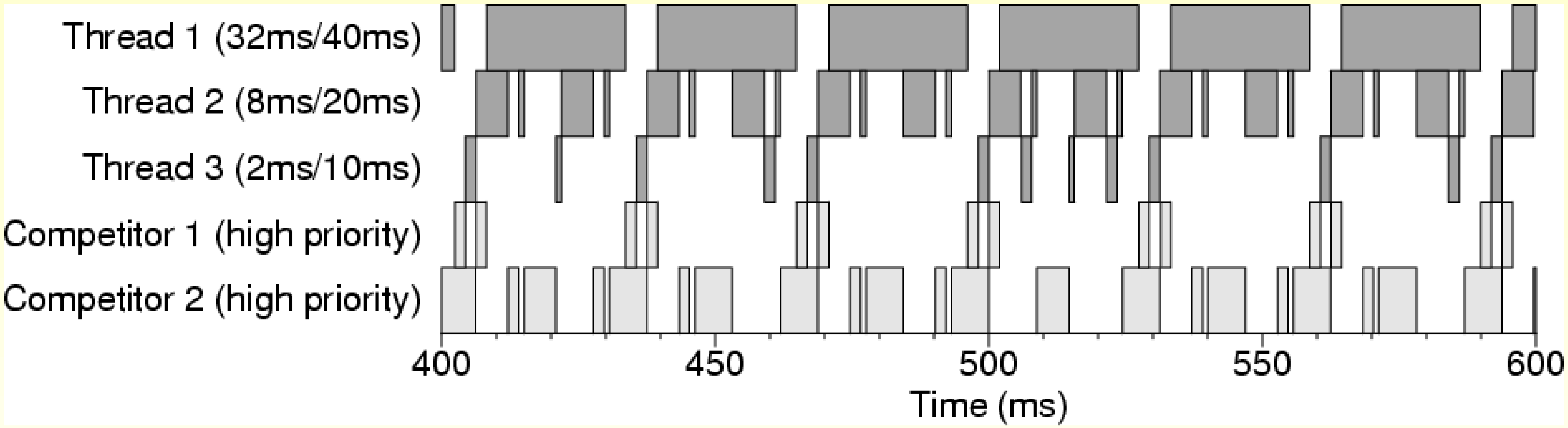
Thread 3 gains additional time with constraints



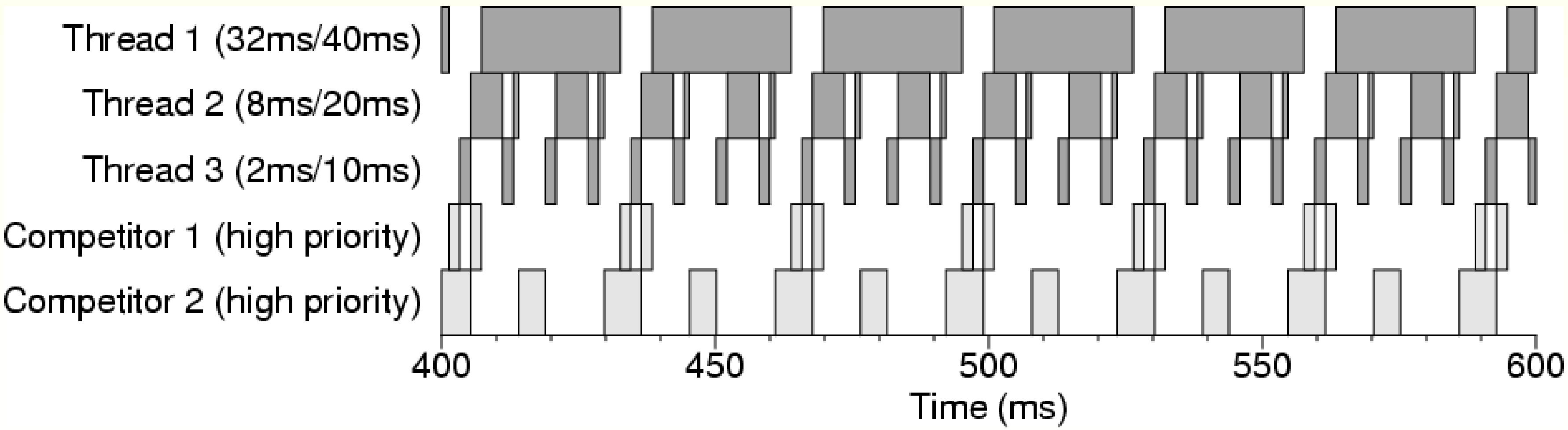
1 processor, 3 threads with reservations (one also using constraints), 1 high-priority competitor thread

Dual Processor Traces

Without affinity change: thread 3 not always scheduled



With affinity change: all threads properly scheduled



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Related Work

- Real-time add-ins for Windows NT
  - RTX from VenturCom, INtime from RadiSys, Hyperkernel from Imagination Systems
- Lin et. al '98
  - Windows NT soft real-time scheduling server
- Candea & Jones '98
  - Vassal loadable scheduler framework
- Lots of reservation- and deadline-based scheduling work

Further Research

- Evaluate when applied to real apps
  - Some work submitted to RTAS 2000
- Lots of policy issues
  - Resource management
  - Placement of reservations among CPUs

Conclusions

- Scheduling plan effective on MPs
- Plan adapted to use periodic clock
- New scheduler cooperatively coexists with, uses Windows NT scheduler
- Rialto/NT brings CPU Reservations and Time Constraints to Windows NT

Thanks for Your Invitation!

- **References:**
  - **Latency study published in 1999 RTAS**
  - **Rialto/NT published in 1999 USENIX Windows NT Symposium**

- **For more on this research see http://research.microsoft.com/~mbj/**
- **For a *great* priority inversion story be sure to follow the What really happened on Mars? link**